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SEMINAR OPTIČNE KOMUNIKACIJE

ZBORNIK

SEMINAR ON OPTICAL COMMUNICATIONS

PROCEEDINGS

Ljubljana, 25. – 27. 2023

Univerza v Ljubljani, Fakulteta za elektrotehniko
University of Ljubljana, Faculty of Electrical Engineering

SOK 2023
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26. SEMINAR OPTIČNE KOMUNIKACIJE

Ljubljana, 25. do 27. januarja 2023

ZBORNIK

26TH SEMINAR ON OPTICAL COMMUNICATIONS

Ljubljana, 25 to 27 January 2023

PROCEEDINGS

UREDILA/EDITORS:
Tomi Mlinar, Boštjan Batagelj

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Uredila / *Editors:* Tomi Mlinar, Boštjan Batagelj

Predgovor

Od izuma svetlobnega vlakna mineva že 50 let, pravi razmah gradnje optičnih omrežij do slehernega doma pa se je začel pred skoraj dvajsetimi leti. To velja tudi za Slovenijo, ki je po uporabi optičnih tehnologij že vsa leta v koraku z najbolj razvitimi državami sveta. Optična tehnologija je vodilna in vseprisotna v optičnih komunikacijskih omrežjih, pa tudi na drugih področjih. Optična vlakna so nepogrešljiv gradnik celičnih brezvrvičnih omrežij, saj si današnje pete generacije (5G) brez njih niti ne moremo predstavljati. Zahteve po zmogljivostih so enostavno prevelike za druge tehnologije. Ločevanje celičnih radijskih komunikacij po generacijah je prisotno že desetletja (trenutno se gradi 5G), v zadnjem času pa tudi fiksna omrežja ločujemo na podoben način. Tudi pri fiksnih omrežjih gradimo trenutno četrto generacijo, ki jo označujemo z F4G. Prenosne hitrosti dosegajo nekaj 100 Mbit/s, tudi simetrično. Naslednja generacija (F5G) naj bi končnim uporabnikom brez težav omogočala hitrosti dosti preko 1 Gbit/s, kar bo ob nizkih zakasnitvah in veliki zanesljivosti delovanja omogočalo uvedbo npr. video-storitev 8K, storitve navidezne resničnosti in izjemno interaktivno uporabniško izkušnjo tudi na velikih zaslonih. Sodobna optična tehnologija je zelo varčna. Za prenos enega bita informacije porabi le tisočinko energije, potrebne za prenos po brezžični zvezi. V bodoče pa si v optičnih komunikacijskih sistemih obetamo še nadaljnje izboljšanje spektralne učinkovitosti. To naj bi se zgodilo z vpeljavo optičnih gradnikov na osnovi mikrovalovne fotonike in integrirane optike.

Razvoj področja optoelektronike in optičnih komunikacij je spodbudil prve začetke in kasnejši razvoj nove izobraževalne dejavnosti na Fakulteti za elektrotehniko Univerze v Ljubljani že okoli leta 1980, torej precej prej, preden so se začele optične komunikacije uvajati tudi komercialno. Sledilo je oblikovanje predmeta Optične komunikacije na dodiplomskem in podiplomskem študiju. Strokovne seminarje Optične komunikacije je zasnoval zasl. prof. dr. Jožko Budin pod okriljem projekta TEMPUS JEN-04202 že davnega leta 1993. Pri uvajanju začetnih tečajev in pozneje seminarjev je bilo zasl. prof. dr. Jožku Budinu v pomoč večletno sodelovanje s partnerskimi organizacijami projekta, in sicer Mednarodnim centrom za teoretično fiziko (ICTP) v Trstu, Univerzo v Trstu, Univerzo v Padovi, Univerzo Strathclyde v Glasgowu in drugimi. Sodelovanje se je kasneje razširilo tudi na druge univerze in institucije po vsem svetu. Nobenega dvoma ni, da je seminar Optične komunikacije v preteklih desetletjih bistveno prispeval k strokovnemu izpopolnjevanju telekomunikacijskih strokovnjakov. Njegov osnovni namen je bil in je še razširjanje, izpopolnjevanje in osveževanje znanja o optičnih tehnologijah ter dvig strokovnosti zaposlenih na področju telekomunikacij v Sloveniji. Imel je ključno vlogo tudi pri uvajanju tehnologije optičnega vlakna v slovenski prostor.

Osemindvajset prispevkov v tokratnem zborniku 26. seminarja Optične komunikacije naslavlja mnoge zanimive teme, opozoriti pa velja na pasivna optična omrežja naslednje generacije, uporabo optičnega vlakna v senzorske namene, pospešen razvoj kvantnih komunikacij in vpeljavo strojnega učenja v optične komunikacije.

V uvodnem prispevku prvega dne Boštjan Batagelj povzema novosti na področju optičnih komunikacij in nas uvede v kvantno informacijsko-komunikacijsko tehnologijo. Sledi prispevek o regulaciji optičnih omrežij Žana Knafelca in dva prispevka predstavnikov slovenskih telekomunikacijskih operaterjev, Gorazda Penka iz T-2 in Andreja Pučka iz Telekoma Slovenije. Prvi opisuje prehod na pasivno optično omrežje naslednje generacije, drugi pa prenos sinhronizacije preko optičnega omrežja za potrebe mobilnega omrežja 5G. Milorad Sarić osvetljuje izzive, ki jih lahko pričakujemo pri gradnji pasivnih optičnih omrežij naslednje generacije. Drugi sklop prispevkov prvega dne je namenjen predstavitvi raziskovalne dejavnosti Fakultete za elektrotehniko, Instituta Jožef Stefan in Fakultete za matematiko in fiziko. Rok Žitko in Anton Ramšak povzemata izvedbo izmenjave kvantnega ključa med tremi državami in predstavita nov evropski projekt EuroQCI, v okviru katerega se bo gradila kvantna infrastruktura v Sloveniji. Sledi sklop treh povezanih prispevkov ekipe raziskovalcev, Janeza Krča, Andraža Debevca, Miloša Ljubotine in Marka Topiča, ki obdelujejo integrirano fotoniko za kvantne aplikacije, načrtovanje optičnih adiabatnih sklopnikov in polarizacijske razcepnike z dielektričnimi metamateriali v silicijevih fotonskih integriranih vezjih. Zadnji sklop zaključujejo prispevki doktorskih raziskovalcev Vesne Eržen, Kristjana Vuka Baliža in Andreja Lavriča.

Uvodni prispevek drugega dne seminarja je pregledni prispevek Matjaža Vidmarja o optičnih modulacijah. Nadaljuje Klaus Samardžić s prispevkom o vlogi distribuiranih prevezovalnikov OTN v komunikacijskih omrežjih. Sledi sklop treh prispevkov Uroša Petriča, Gorazda Mandlja in Milorada Sarića, ki opisujejo tehnologijo in primere uporabe optičnega vlakna kot porazdeljenega senzorja. Drugi sklop prispevkov drugega dne obdeluje različne načine uporabe optičnih tehnologij. Prispevek Jiříja Štefla govori o optičnih kabelskih sistemih za podatkovne centre in uporabo v vojaške namene, prispevek Petra Lukana opisuje izzive pri razvoju vlakenskih laserjev visokih moči v Sloveniji, Marija Mrzel Ljubič pa predstavlja arhitekturo in zmogljivosti optičnih vlaken v strelovodni vrvi energetskih operaterjev. Zadnji prispevek v tem sklopu je o vse bolj popularnih hitrih vtičnih modulih Petra Reinhardta.

Zadnji dan seminarja vsebuje šest prispevkov tujih vabljenih predavateljev. Edvin Škaljo iz Univerze v Sarajevu predstavlja uporabo optičnih vlaken v senzorskih aplikacijah, sledi Jakup Ratkoceri s prispevkom o programsko krmiljenih pasivnih optičnih omrežjih in Igor Milojević o uporabi tehnologije prihodnosti F5.5G. Z dvema prispevkoma sledi Darko Zibar iz Tehniške univerze na Danskem. Prvi njegov prispevek je o osnovah strojnega učenja, drugi pa o uporabi strojnega učenja v optičnih komunikacijah, Zadnji prispevek seminarja opisuje generiranje kvantnih naključnih števil na podlagi časov zaznavanja fotonov, ki ga je pripravil Ágoston Kristóf Schranz iz Univerze za tehnologijo in ekonomijo v Budimpešti.

Kakovostna izvedba dosedanjih tečajev in seminarjev, sodelovanje priznanih vabljenih strokovnjakov in znaten interes udeležencev utrjuje naše prepričanje, da je redno strokovno spopolnjevanje strokovnjakov na naglo razvijajočem se področju optičnih komunikacij koristno in potrebno. Organizatorji seminarja se zahvaljujemo vsem predavateljem za neprecenljiv prispevek, prav tako pa tudi podjetjem in posameznikom za sodelovanje in pomoč pri pripravi ter izvedbi seminarja. Zahvala gre odgovornim v naših podjetij in institucijah, ki so svojim strokovnjakom omogočili udeležbo na seminarju in s tem podprli to dejavnost.

Želiva vam, da v zborniku 26. seminarja Optične komunikacije najdete uporabne vsebine, ki vam bodo koristile v vašem poslovnem in osebnem življenju.

Tomi Mlinar in Boštjan Batagelj, urednika Ljubljana, januarja 2023

Foreword

50 years have passed since the invention of optical fiber, but the real boom in the construction of optical networks to every home began almost twenty years ago. This also applies to Slovenia, which has been keeping up with the most developed countries in the world for years after using optical technologies. Optical technology is leading and ubiquitous in optical communication networks, as well as in other areas. Optical fibers are an indispensable building block of cellular wireless networks, as today's fifth generation (5G) cannot even be imagined without them. The performance requirements are simply too much for other technologies. Separation of cellular radio communications by generation has been present for decades (5G is currently being built), and recently fixed networks have also been separated in a similar way. We are also currently building the fourth generation of fixed networks, which we call F4G. Transfer speeds reach some 100 Mbit/s, even symmetrically. The next generation (F5G) is supposed to enable end users with speeds well over 1 Gbit/s without any problems, which, with low delays and high operational reliability, will enable the introduction of e.g. 8K video service, virtual reality services and an extremely interactive user experience even on large screens. Modern optical technology is very economical. To transmit one bit of information, it consumes only a thousandth of the energy required for wireless transmission. In the future, however, we expect a further improvement in spectral efficiency in optical communication systems. This should happen with the introduction of optical building blocks based on microwave photonics and integrated optics.

The development of the field of optoelectronics and optical communications stimulated the first beginnings and the subsequent development of a new educational activity at the Faculty of Electrical Engineering of the University of Ljubljana already around 1980, i.e. much earlier, before the commercial introduction of optical communications. This was followed by the creation of the Optical Communications course for undergraduate and postgraduate students. Professional seminars on optical communications were designed by professor emeritus dr. Jožko Budin as part of the TEMPUS JEN-04202 project back in 1993. During the introduction of initial courses and later seminars, prof. dr. Jožko Budin worked with partner organizations from the project, namely the International Center for Theoretical Physics (ICTP) in Trieste, the University of Trieste, the University of Padova, the University of Strathclyde in Glasgow and others. The cooperation was later extended to other universities and institutions around the world. There is no doubt that the Optical Communications seminar has significantly contributed to the professional development of telecommunications experts over the past decades. This seminar also played a key role in the introduction of fiber optic technology in Slovenia.

Twenty-eight articles in this year's proceedings of the 26th Optical Communications Seminar address many interesting topics. The following topics should be noted: passive optical networks of the next generation, the use of optical fiber for sensor purposes, the accelerated development of quantum communications and the introduction of machine learning in optical communications.

In the introductory article of the first day, Boštjan Batagelj summarizes the innovations in the field of optical communications and introduces us to quantum information and communication technology. This is followed by a paper on the regulation of optical networks by Žan Knafelec and two papers by representatives of Slovenian telecommunications operators, Gorazd Penko from T-2 and Andrej Pučko from Telekom Slovenije. The first describes the transition to a next-generation passive optical network, while the second describes the transfer of synchronization over the optical network for the needs of the 5G mobile network. Milorad Sarić illuminates the challenges that can be expected in the construction of passive optical networks of the next generation. The second set of papers on the first day is dedicated to present the research activities of the Faculty of Electrical Engineering, the Jožef Stefan Institute and the Faculty of Mathematics and Physics. Rok Žitko and Anton Ramšak summarize the execution of the quantum key exchange between the three countries and present the new European project EuroQCI, within the framework of which quantum infrastructure will be built in Slovenia. Then follows a set of three related articles by a team of researchers: Janez Krč, Andraž Debevc, Miloš Ljubotina and Marko Topič, who deal with integrated photonics for quantum applications, the design of optical adiabatic couplers and polarization splitters with dielectric metamaterials in silicon photonic integrated circuits. The last section concludes with the contributions of doctoral researchers Vesna Eržen, Kristjan Vuk Baliž and Andrej Lavrič.

The introductory paper on the second day of the seminar is an overview on optical modulations by Matjaž Vidmar. Klaus Samardžić continues with a paper on the role of distributed OTN transporters in communication networks. Then follows a set of three articles by Uroš Petrič, Gorazd Mandelj and Milorad Sarić, which describe the technology and examples of the use of optical fiber as a distributed sensor. The second set of papers on the second day deals with different ways of using optical technologies. Jiří Štefl's contribution talks about optical cable systems for data centers and for military use, Peter Lukan's contribution describes the challenges in the development of high-power fiber lasers in Slovenia, and Marija Mrzel Ljubič presents the architecture and capabilities of optical fibers embedded in ground wire. The last paper in this series is about the increasingly popular fast plug-in modules, presented by Peter Reinhardt.

The last day of the seminar contains six contributions by invited foreign lecturers. Edvin Škaljo from the University of Sarajevo presents the use of optical fibers in sensor applications, followed by Jakup Ratkoceri with a paper on software-controlled passive optical networks and Igor Milojević on the use of future F5.5G technology. Darko Zibar from the Technical University of Denmark follows with two contributions. His first paper is Tutorial on machine learning, and the second is Application of machine learning techniques to optical communications. The last paper of the seminar describes the generation of quantum random numbers based on photon detection times, prepared by Ágoston Kristóf Schranz from the Budapest University of Technology and Economics.

The high-quality performance of previous courses and seminars, the participation of renowned invited experts and the significant interest of the participants reinforces our belief that regular professional development of experts in the rapidly developing field of optical communications is useful and necessary. The organizers of the seminar would like to thank all the lecturers for their invaluable contribution, as well as companies and individuals for their cooperation and help in the preparation and implementation of the seminar. Thanks go to those responsible in our companies and institutions who enabled their experts to participate in the seminar and thus supported this activity. Editors hope that in the proceedings of the 26th Optical Communication Seminar you will find useful content that will benefit you in your business and personal life.

Tomi Mlinar and Boštjan Batagelj, editors *Ljubljana, January 2023*

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Novosti v optičnih komunikacijah in uvod v kvantne komunikacije

Novelties in optical communications and introduction to quantum communications

Boštjan Batagelj

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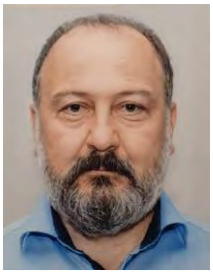
Povzetek

Sodobna optična omrežja, ki se raztezajo od visoko zmogljivih podmorskih optičnih povezav v hrbtenici do širokopasovnega dostopa v uporabnikovem domu, še zdaleč niso rekla zadnje besede razvoja niti v raziskovalni sferi in niti v industriji. V prihodnjih letih bomo priča rekordnim investicijam v podmorske optične kable, katerih lastniki bodo spletni velikani. Zmogljive optične komunikacijske zveze, ki jih pogojuje uporabljeno optično vlakno (komunikacijski kanal), oddajno-sprejemna oprema in njena elektronika ter vrsta prenosnega signala, pa se selijo do uporabnikovega doma. Optične zveza postajajo vse bolj zmogljive, varne in brezhibne. Prav k temu pa pripomorejo najnovejši tehnološki dosežki kvantnih informacijskih tehnologij in umetne inteligence. Na področju varnosti si v optičnem omrežju utirajo pot tehnike kvantnega šifriranja. Integrirana optika daje glavni doprinos na področju optičnih komunikacijskih naprav. Nove komunikacijske tehnike vključujejo koherentne komunikacije, večdimenzionalne modulacijske formate in tehnike multipleksiranja ter s pridom uporabljajo umetno inteligenco.

Abstract

Modern optical networks, which range from high-performance submarine optical links in the backbone to broadband access in the user's home, are far from saying the last word of development neither in the research sphere nor in industry. In the coming years, we will witness record investments in submarine optical cables owned by Internet giants. High-performance optical communication links, conditioned by the optical fiber (communication channel), the transceiver and its electronics, and the type of transmission signal, move to the user's home. Optical connections are becoming more and more powerful, secure and seamless. The latest technological achievements of quantum information technology and artificial intelligence contribute to this. In the field of security, quantum encryption techniques are paving the way in optical networks. Integrated optics makes a major contribution to the field of optical communication devices. New communication techniques include coherent communications, multidimensional modulation formats and multiplexing techniques, and take advantage of artificial intelligence.

Biografija avtorja



Boštjan Batagelj je izredni profesor na Fakulteti za elektrotehniko Univerze v Ljubljani, kjer predava predmete optične komunikacije, radijske komunikacije in satelitske komunikacije. Raziskovalno delo opravlja v Laboratoriju za sevanje in optiko, kjer se med drugim ukvarja z fizičnim nivojem prenosnih in dostopovnih telekomunikacijskim omrežji zasnovanih na radijski in optični tehnologiji. Je avtor več kot 300 člankov, desetih patentnih prijav in sodeluje v domačih ter mednarodnih raziskovalnih projektih s področja optičnih in radijskih komunikacij.

Author's biography

Boštjan Batagelj is an associate professor at the Faculty of Electrical Engineering of the University of Ljubljana, where he teaches the subjects of optical communication, radio communication and satellite communication. He performs his research work in the Radiation and Optics Laboratory, where he deals, among other things, with the physical level of portable and access telecommunication networks based on radio and optical technology. He is the author of more than 300 articles, ten patent applications and participates in domestic and international research projects in the field of optical and radio communications.

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Novosti v optičnih komunikacijah in uvod v kvantne komunikacije

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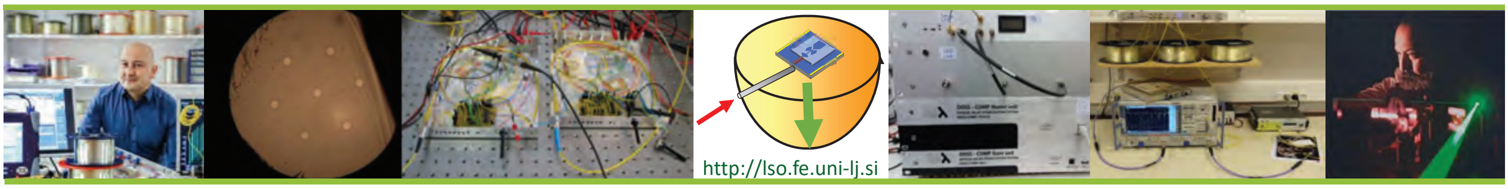
25. januar 2023



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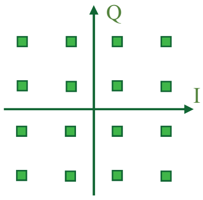
Vsebina predstavitve

- Novosti v optičnih komunikacijah
  - Kako povečati zmogljivost?
  - Kaj prinaša integrirana optika?
  - Kaj se dogaja na področju zlivanja optičnega in radijskega dostopovnega omrežja?
  - Kako bo pripomogla umetna inteligenca?
- Uvod v kvantne komunikacije
  - Zakaj moramo narediti optične komunikacije bolj varne?
  - Kako bo zgledala kvantna prihodnost?
  - V čem se kvantno omrežje razlikuje od običajnega omrežja?
  - Kako bo pripomogla integrirana optika?

Vlakno na najdaljših razdaljah

- Podoceanski optični kabli so od satelitov povsem prevzeli promet med kontinenti.
- Svetlobni ojačevalniki so ključna tehnologija za DWDM prenos.
- Trenutno je več kot 100 podmorskih zvez z zmogljivostjo večjo od Tbit/s.
- Februarja 2018 je bila dokončana do tedaj najbolj zmogljiva medkontinentalna povezava MAREA dolžine 6.644 km s skupno zmogljivostjo 160 Tbit/s, ki sega med ZDA (Virginia Beach) in Španijo (Bilbao).

- 8 vlakenskih parov * 25 DWDM kanalov * 400 Gbit/s na posamezni kanal = 160 Tbit/s
- Uporaba modulacijskega formata 16-QAM s 4 bit/simbol
- Dosežena spektralna učinkovitost 6,41 bit/s/Hz.



Vir: https://www.submarinenetworks.com/systems/trans-atlantic/marea
in https://acacia-inc.com/product/ac1200/

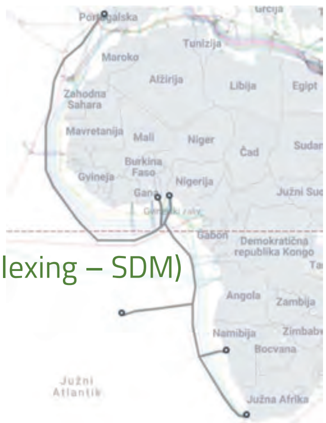
Podoceanski optični kabli

vir: https://en.wikipedia.org/wiki/Grace_Hopper_(submarine_communications_cable)

- Grace Hopper (Google) 2022
  - 16 vlakenskih parov * 22 Tbit/s / vlakno = 352 Tbit/s

vir: https://en.wikipedia.org/wiki/Oman_Australia_Cable

- Oman Australia Cable (OAC)
  - september 2022
  - 45 Tbit/s
  - unikatna trasa

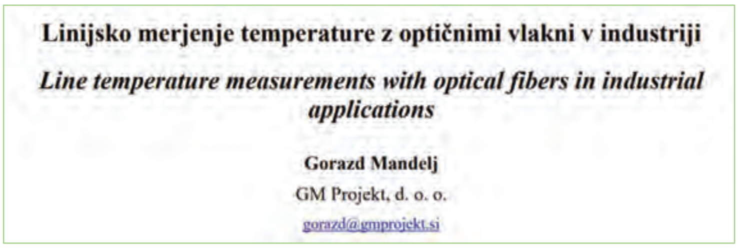


vir: https://www.submarinenetworks.com/en/systems/euro-africa/equiano

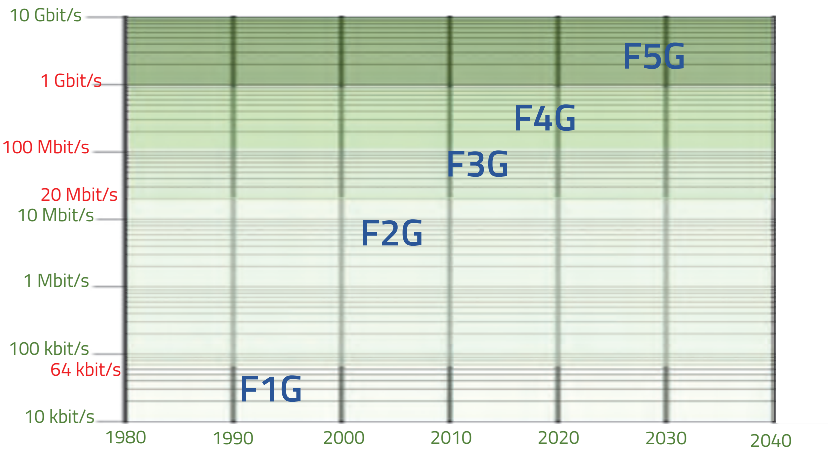
- Equiano (14. podoceanski kabel, ki ga je financiral Google)
  - v pogon bo spuščen začetek 2023
  - uporabljal bo tehnologijo prostorskega multipleksiranja (angl. space-division multiplexing – SDM)
  - 12 vlakenskih parov * 12 Tbit/s / vlakno = 144 Tbit/s
  - 20x večja zmogljivost od trenutnega kabla na zahodni obali Afrike

Vlakno kot senzor

- Odsluženi podoceanski kabli postanejo senzorji.
- Optično vlakno je zelo zanimiv senzor tudi na drugih področjih.



Razvoj fiksnega omrežja v dostopu



F1G
Prva generacija fiksnih omrežij so bila telefonska omrežja v obdobju od začetka 19. stoletja do konca 20. stoletja, ko se pojavijo prve podatkovne storitve z uporabo klicnega dostopa in tehnologije ISDN. (Hitrosti prenosov do 64 kbit/s.)

F2G
Fiksno telekomunikacijsko omrežje vstopi v širokopasovno dobo v obdobju devetdesetih let prejšnjega in v prvem desetletju tega stoletja. Tehnologija ADSL je ponovno oživila sto let staro bakreno omrežje. (Prenosi do 20 Mbit/s)

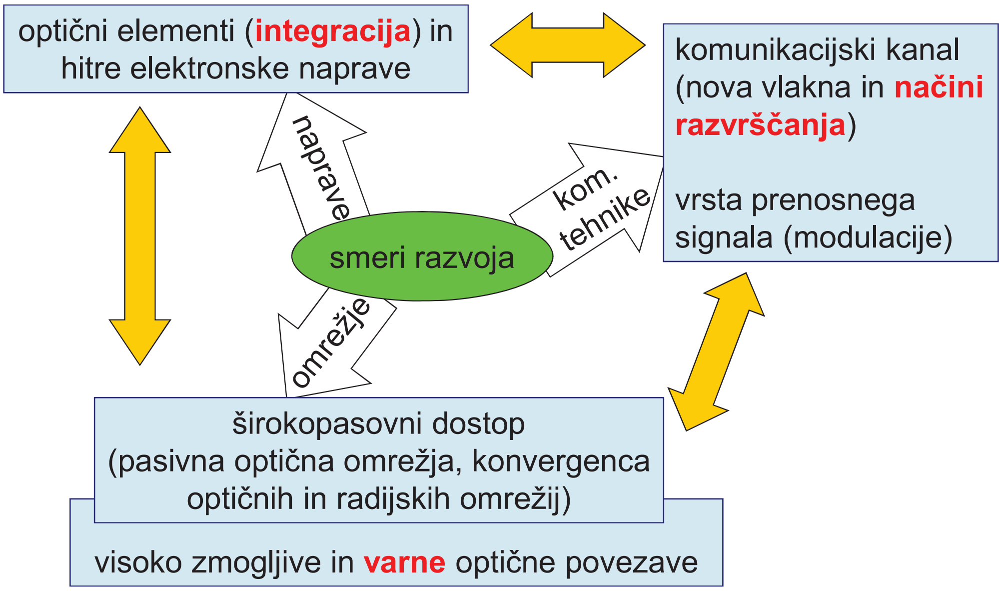
F3G
Ker tehnologija ADSL ni podpirala storitev nad 30 Mbit/s, so operaterji za doseganje večje hitrosti uvedli tehnologijo VDSL in mrežno arhitekturo optičnih vlaken. (Prenosi do 100 Mbit/s)

F4G
Četrto generacijo zaznamuje vzpostavitev širokopasovnega optičnega dostopovnega omrežja – vlakno do doma, ki omogoča storitve 4K in stabilne zmogljivosti dostopa 100 Mbit/s ali več.

F5G
Specifikacije pete generacije fiksnih omrežij so usmerjene na dostopovna omrežja, ki so v celoti izvedena iz optičnih vlaken, hitrost dostopa pa bo znašala več kot 1 Gbit/s.

vir: ETSI, Fifth Generation Fixed Network (F5G) https://www.etsi.org/technologies/fifth-generation-fixed-network-f5g
Boštjan Batagelj, Digitalni polet na krilih pete generacije, Delo, 23. 1. 2021 https://www.delo.si/novice/znanoteh/digitalni-polet-na-krilih-pete-generacije/

Novost v optičnih komunikacijah



vir: Boštjan Batagelj, "Research challenges in optical communications towards 2020 and beyond" *Informacije MIDEM, sep. 2014, letn. 44, št. 3, str. 177-184.*

Uporaba umetne inteligence (angl. Artificial Intelligence – AI) in strojnega učenja (angl. Machine Learning – ML) v optičnih komunikacijah

DTU Darko Zibar

Vir: JavierMata, et al. "Artificial intelligence (AI) methods in optical networks: A comprehensive survey" Optical Switching and Networking Volume 28, April 2018, pp. 43-57.

Kvantna IKT

- Kvantna informacijsko-komunikacijska teorija je širši pojem od klasične Shannonove informacijske teorije.

Kvantna IKT omogoča:

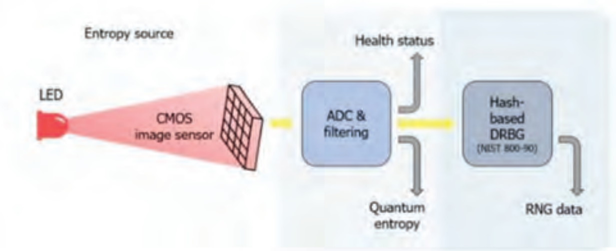
- kvantno generiranje naključnih števil
- kvantno šifriranje (šumno šifriranje)
- prenos ključa s pomočjo prepletenosti
- kvantno računalništvo
- kvantni internet
- kvantno steganografijo (skrivanje podatkov)
- kvantno teleportacijo
- kvantno senzoriko
- kvantno sinhronizacijo
- kvantno strojno učene (algoritmi)

vir: Boštjan Batagelj, "Varnost v bodočih optičnih komunikacijskih sistemih", Avtomatika, 2018, št. 167, str. 10-14, https://www.researchgate.net/publication/329363712

Kvantno generiranje naključnih števil v Samsung S20

- Samsung Galaxy A71 5G (**S20**) je bil prvi telefon s čipom za kvantno generiranje naključnih števil. (angl. Quantum Random Number Generator – QRNG)
- Čip **Quantis QRNG IDQ250C2** je kompatibilen s standardom NIST 800-90.
- Naključna števila se uporablja za različne postopke ugotavljanje avtentičnosti, denimo za 2FA (Two-Factor Authentication), biometriko, blockchain, generiranje ključev itd.

Quantis QRNG IDQ250C2



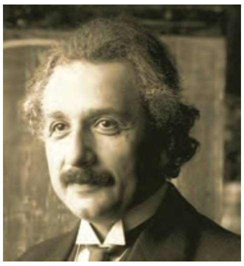
Povsem nepredvidljiva naključna števila generira s pomočjo šuma na fototipalu. Ta šum se pretvori v zaporedje števil, kar je vnos za algoritem za generiranje naključnih števil.

vir: https://www.monitor.si/novica/samsung-bo-ponudil-prvi-telefon-s-kvantno-tehnologijo

Oblikovalci I. kvantne revolucije (1/2)

Max Planck je leta 1900 zapisal postulat, da je elektromagnetno energijo mogoče izsevati v obliki kvantov. (Energija je lahko zgolj celoštevilski večkratnik osnovne enote – kvanta.)

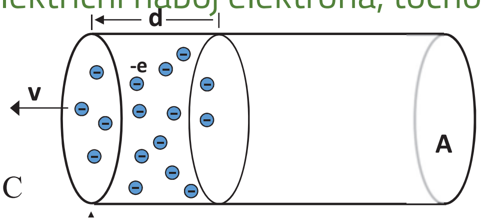
$$W = N \cdot W_{kvant} = N \cdot h \cdot f \qquad h = 6{,}625 \cdot 10^{-34}\ \text{Js}$$



Albet Einstein je leta 1905 pojasnil fotoefekt s pomočjo kvantiziranosti svetlobne energije, kjer je povedal, da z večanjem energije vpadne svetlobe (od določene frekvence dalje) narašča število kvantov energije – fotonov, z večanjem frekvence pa se povečuje energija posameznega fotona.

Robert Millikan je leta 1914 dokazal kvantno naravo elektronov, določil osnovni električni naboj elektrona, točno določil Planckovo konstanto.

$e = 1{,}60219 \cdot 10^{-19}$ C



Pri toku 1 A skozi presek žice v 1 s steče $1{,}60219 \cdot 10^{19}$ elektronov.

$$Q = n \cdot e \qquad n = \pm 1, \pm 2, \pm 3, \ldots$$

Oblikovalci I. kvantne revolucije (2/2)

Werner Karl Heisenberg je leta 1927 zapisal eno od temeljnih načel kvantne mehanike – Heisenbergovo načelo nedoločenosti, ki v kvantni fiziki določa, da je nemogoče istočasno s poljubno natančnostjo poznati določene pare spremenljivk, kot sta na primer lega ali gibalna količina izbranega delca.

$$\Delta x \cdot \Delta G = h$$

Pomemben doprinos na področju kvantne mehanike je imel tudi **Erwin Schrödinger**, ki je znan po razlagi superpozicije z miselnim paradoksom poskusa z mačko in njegovi Schrödingerjevi valovni enačbi.

- Tehnološko so se ideje I. kvantne revolucije uporabile za izdelavo sodobnih elektronskih naprav, kot so elektronska vezja, sončna celica, laser, atomska ura, slikanje z magnetno resonanco, elektronski ter tunelski mikroskop,..

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Superpozicija na primeru Schrödingerjevega paradoksa pri miselnem poskusu z mačko

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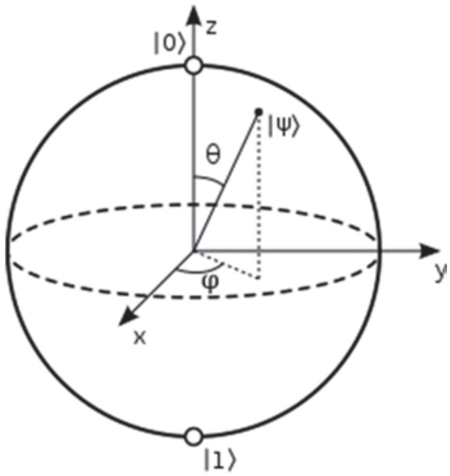
Od bitov do kubitov

- V kvantni mehaniki se za opis stanja dvonivojskih sistemov uporablja Blochova sfera.
- Točka na krogli predstavlja stanje dvonivojskega sistema.



- Klasični biti lahko zavzamejo eno od dveh diskretnih vrednosti – bodisi logično enico »1« (južni pol) ali logično ničlo »0« (severni pol).
- Če sta stanji zastopani z enako verjetnostjo, imamo opravka z verjetnostnimi biti (angl. probability bits – pbits).
- Kvantne informacije uporabljajo kvantne bite ali kubite, ki so v **superpoziciji** obeh stanj istočasno, kar pomeni, da so hkrati v logičnem stanju »1« in »0«. Ko je meritev izvedena, se superpozicija uniči in kubit je potisnjen v klasično stanje.
- Kubit istočasno obstaja na katerikoli točki krogle.

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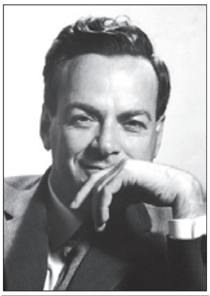
II. kvantna revolucija

- V drugi kvantni revoluciji znanstveniki uporabljajo kvantna pravila za osnovne ideje informacijsko-komunikacijske tehnologije.



- 1981 ameriški fizik (tudi nobelovec) Richard Feynman zatrdi, da klasični številski računalniki nikoli ne bodo zmogli v celoti simulirati kvantnih pojavov.
- Predlaga (podpre) idejo kvantnega računalnika, ki bo zmožen simulacije fizikalnih kvantnih pojavov.

- leta 1994 Peter Shor zapiše **kvantni algoritem**, ki lahko rešili problem faktorizacije v doglednem času.
- Kvantni računalnik z nekaj deset tisoč kubiti lahko nalogo praštevilske faktorizacije opravi v minuti.
- To omogoča enostavno razbitje RSA (Rivest–Shamir–Adleman) asimetričnega šifrirnega postopka, ki temelji na javnem in privatnem ključu.

Odpre se področje kvantne komunikacije, ki na daljavo s pomočjo kvantnega tehnologije prenese šifrirni ključ (angl. Quantum Key Distribution – QKD) za simetrični šifrirni postopek.

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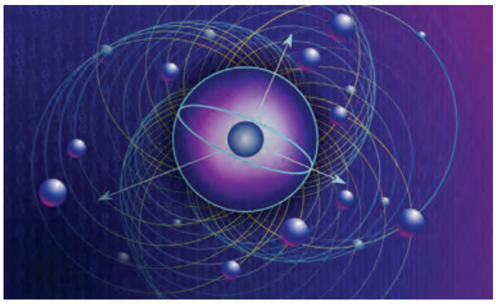
Prevlada kvantnih računalnikov



- superračunalniki lahko izvaja 10^{18} operacij s plavajočo vejico na sekundo (FLOPS)
- ekvivalenten kvantni računalnik potrebuje
  - 208 kubitov v IQP vezju (Instantaneous Quantum Polynomial-Time circuit)
  - 420 kubitov v QAOA vezju (Quantum Approximate Optimization Algorithm circuit)

en kubit izvede dva izračuna hkrati

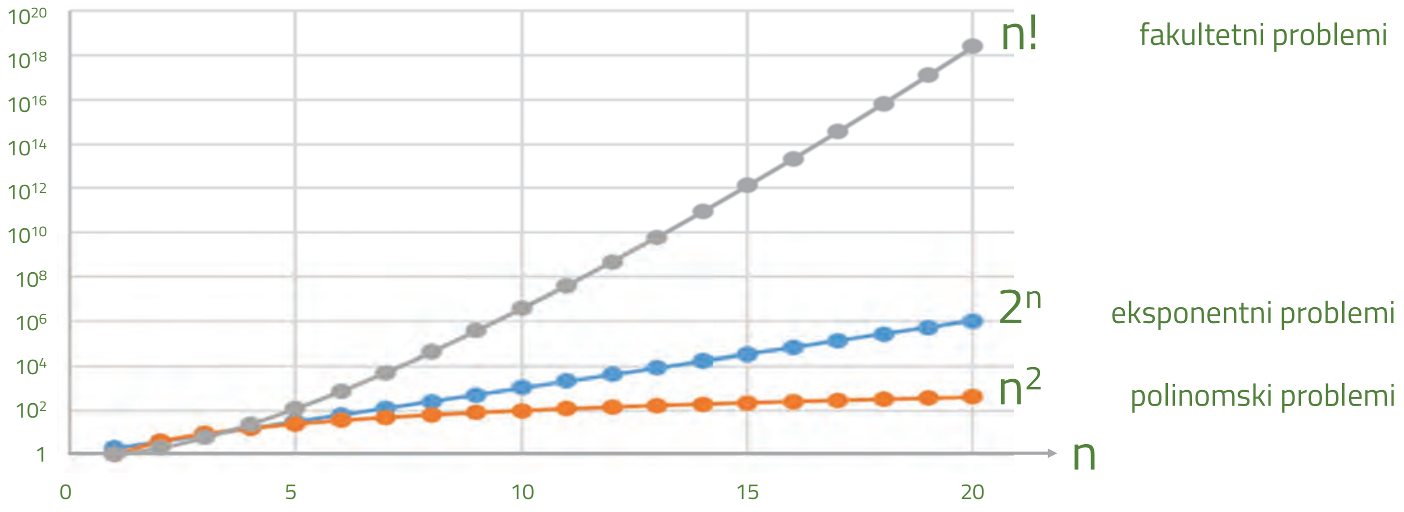
dva kubita povezana s kvantnim učinkom prepletenosti, lahko izvedeta $2^2 = 4$ izračune hkrati

trije kubiti lahko izvedejo $2^3 = 8$ izračunov hkrati

… 300 kubitov lahko izvedejo več izračunov, kot je atomov v nam poznanem vesolju

vir: Charles Q. Choi, "How Many Qubits Are Needed for Quantum Supremacy?", IEEE Spectrum, maj 2020, https://spectrum.ieee.org/tech-talk/computing/hardware/qubit-supremacy

Težavnost matematičnih postopkov računanja

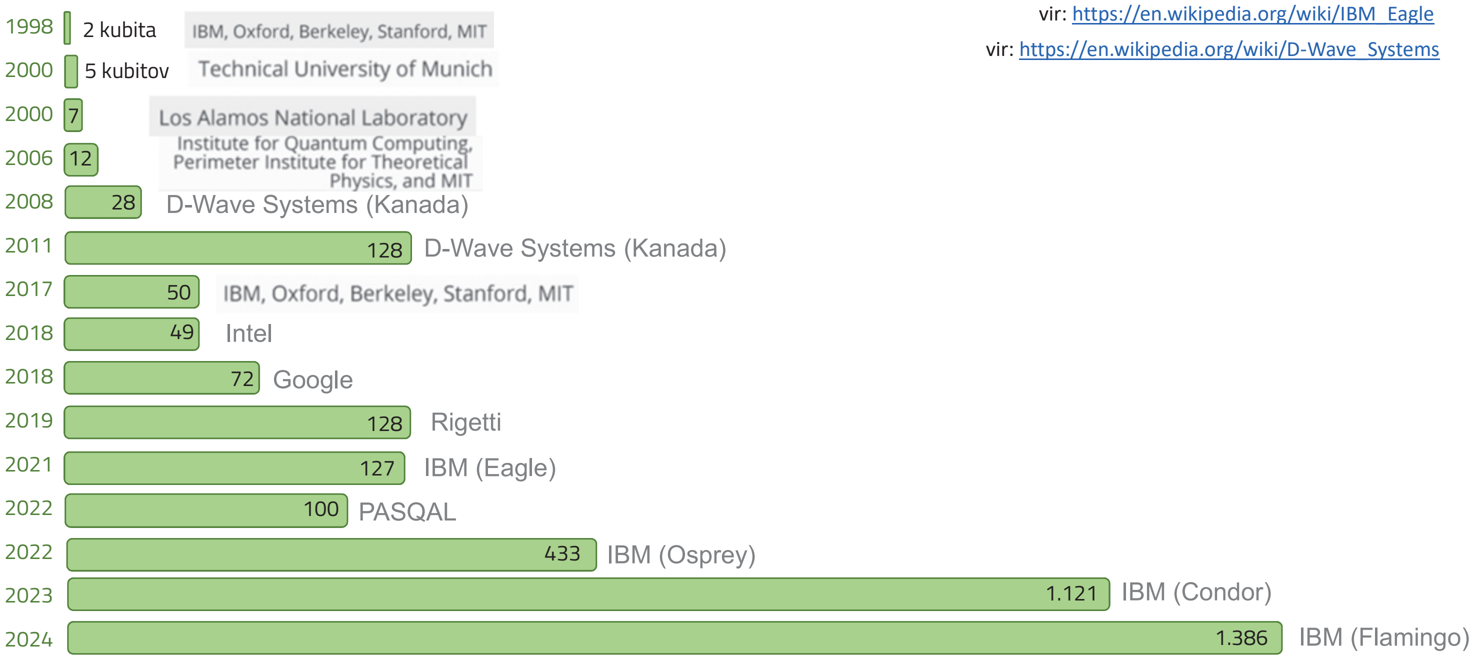


20 let kvantnega računalništva

vir: https://www.statista.com/chart/17896/quantum-computing-developments/

vir: https://en.wikipedia.org/wiki/IBM_Eagle

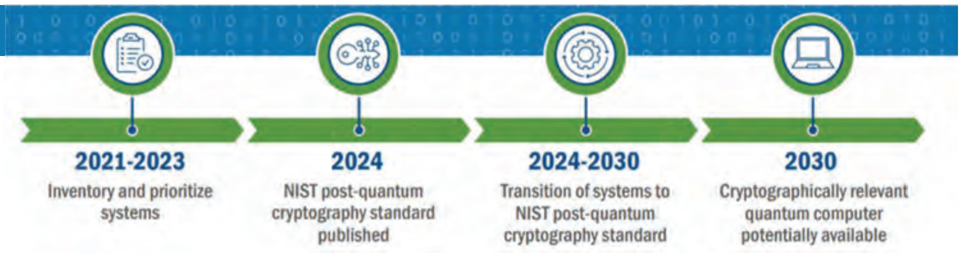
vir: https://en.wikipedia.org/wiki/D-Wave_Systems



Kako še naprej zagotoviti varne komunikacije?

- Inženirski ukrepi:
  - Podaljšanje ključev, ki jih uporabljamo pri sedanjih tehnikah šifriranja.
  - Uporaba kvantnih protokolov za kvantni prenos šifrirnih ključev (BB84, B92, E91)
  - Uporaba novih matematičnih algoritmov, ki jih ni mogoče razbiti s pomočjo kvantnih algoritmov, ki se izvajajo na kvantnih računalnikih.
    - Postopki, ki so **ne**zlomljivi s pomočjo kvantnih računalnikov (angl. Post-Quantum Cryptography - PQC)
      - Šifriranje na osnovi rešetk (angl. Lattice-based cryptography)
      - Šifriranje na osnovi kode (angl. Code-based cryptography) - McEliece algoritem
      - Šifriranje na osnovi multivarijant (angl. Multivariate cryptography)

časovnica NIST



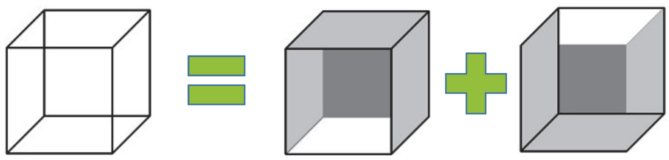
nacionalni inštitut za standarde in tehnologijo (NIST)

Kvantna komunikacija

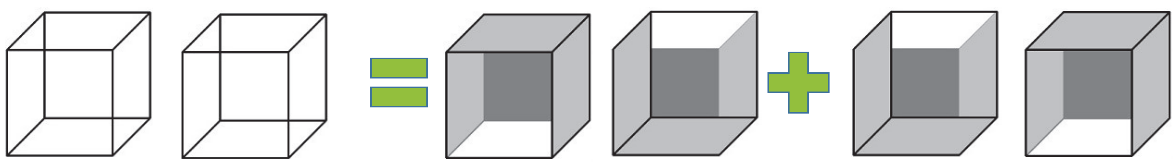
Osnovna fizikalna principa kvantne komunikacije sta:

- superpozicija (vsota dveh različnih rešitev problema je tudi rešitev),
- prepletenost (z določitvijo stanja enega delca je popolnoma definirano stanje drugega).

Superpozicija na primeru Neckerjeve kocke

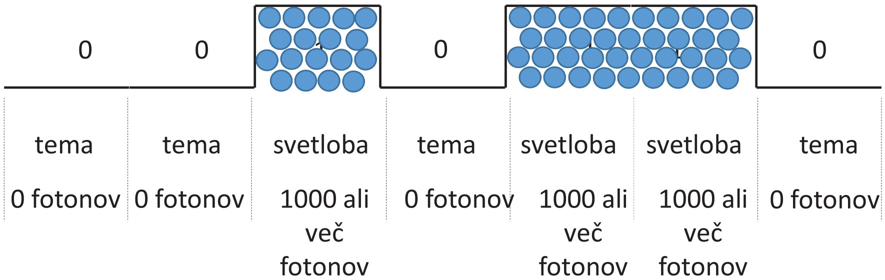


Prepletenost na primeru Neckerjevih kock

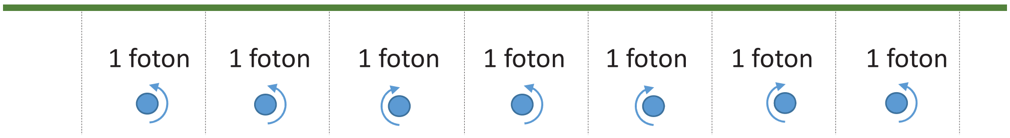


Števílska (digitalna) zveza

- Danes uporabljamo številske (digitalne) zveze.



- Za večjo varnost (težje prisluškovanje) zmanjšujemo število oddanih fotonov.

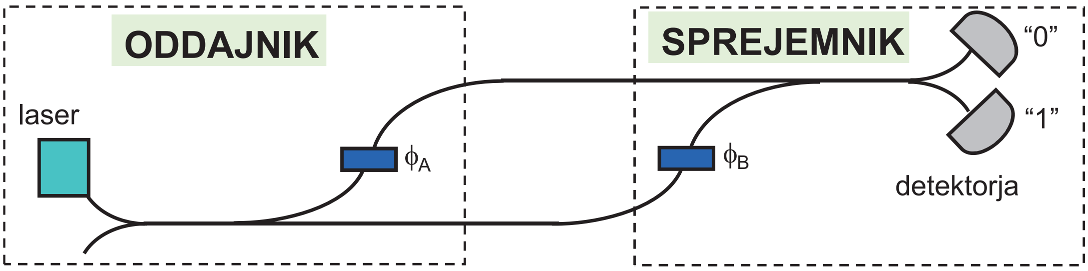


- Kot tehnološko najbolj izvedljivo se kaže, da bi kvantni računalniki uporabljali spine elektronov ali atomov, medtem ko se bo za prenos kvantnih informacij najverjetneje uporabljala svetloba.

Vir: C.H.Bennet, Quantum cryptography using any two nonorthogonal states, Physical Review Letters, Vol.68, 1992, str. 3121-3124

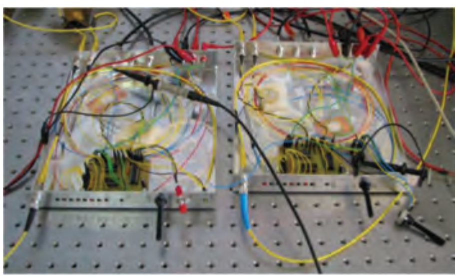
Praktična izvedba B92 v LSO

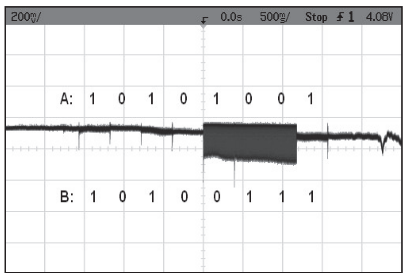
- Kodiranje bitov s spreminjanjem faze.
- Osnova je Mach-Zehnderjev vlakenski interferometer



vir: J. TRATNIK, B. BATAGELJ, Predstavitev ideje kvantnega šifriranja in pregled osnovnih tehnik kvantnega razdeljevanja ključa. Elektrotehniški vestnik, letn. 75, št. 5, str. 257-263, 2008.

vir: TRATNIK, Jurij. Poskus uporabe optičnega interferometra za varen prenos šifrirnega ključa: diplomsko delo. Ljubljana, 2007.





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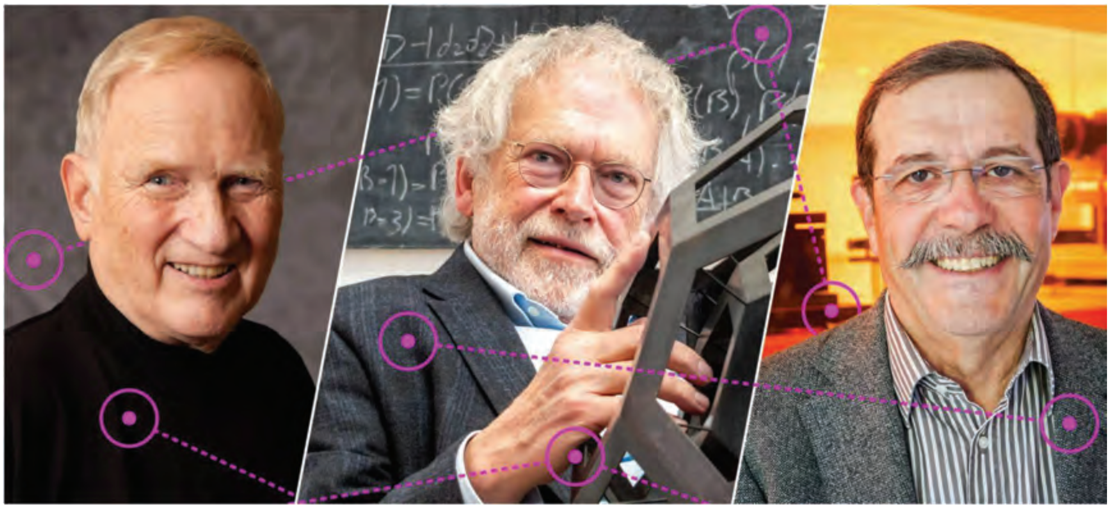
Nobelova nagrada za kvantno prepletenost

2022 Nobel Prize lectures in physics https://youtu.be/a9FsKqvrJNY



John Clauser Anton Zeilinger Alain Aspect

vir: https://www.quantamagazine.org/pioneering-quantum-physicists-win-nobel-prize-in-physics-20221004

vir: Artur K. Ekert, "Quantum cryptography based on Bell's theorem", Physical review letters, vol. 67, no. 6, pp. 661-663, 1991.

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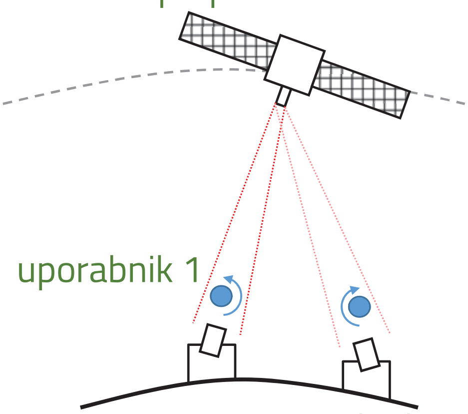
Kvantno razdeljevanje ključa s kvantno prepletenostjo po protokolu E91 (Artur Ekert, 1991)

centralni izvor prepletenih fotonov



uporabnik 1

uporabnik 2

- Protokol E91 temelji na kvantno prepletenih parih delcev.
- Pare prepletenih fotonov oddaja centralni izvor (angl. Spontaneous parametric down-conversion - SPDC), ki je ločen od uporabnikov.
- Prepletena fotona razdeli med uporabnika.
- Prepletena stanja so popolnoma korelirana.
- Rezultat posamezne meritve seveda ostaja povsem naključen in posledično nepredvidljiv.
- Vsakršen poskus prisluškovanja uniči omenjeno korelacijo, kar je mogoče tudi zaznati.
- Kvantno prepletenost je mogoče izrabljati za sinhronizacijo.

P. Kormar, "A quantum network of clocks", nature physics 10, 582 (2014).

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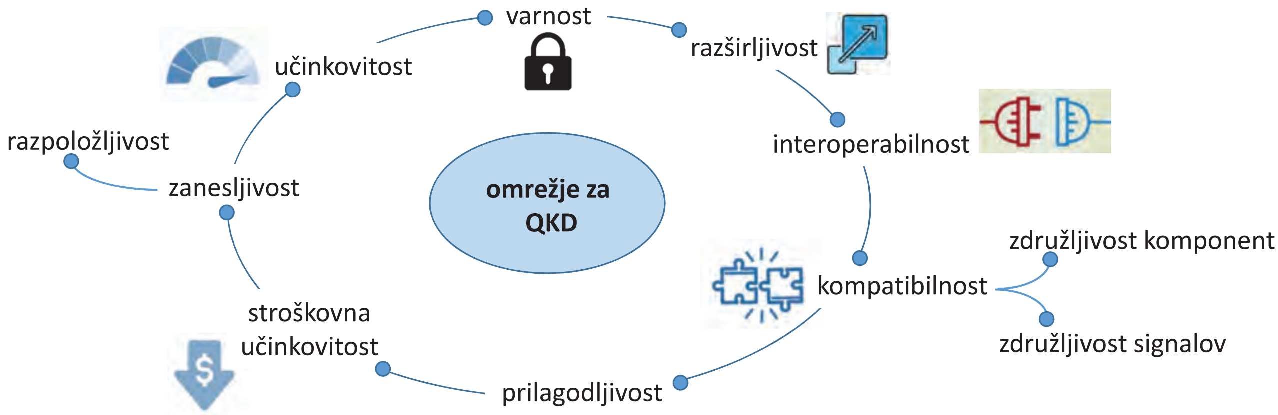
Načrtovalski kompromisi pri omrežju za razdeljevanje kvantnih ključev



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Prek kvantne komunikacije povezali tri mesta

Zaradi posebnega delovanja kvantno mehanskih šifrirnih ključev bo tehnologija omogočala doseganje doslej nedosegljive visoke stopnje varnosti.

Prek kvantne komunikacije so povezali tri mesta. FOTO: Danijel Novaković/STA

Saša Senica

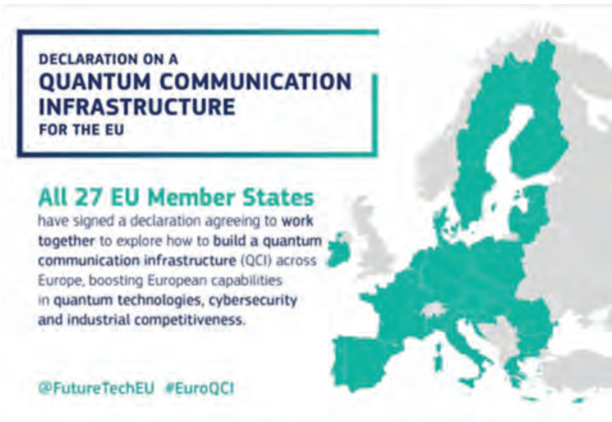
05.08.2021 ob 15:54

05.08.2021 ob 16:31

Danes je bil prvič v zgodovini omogočen popolnoma kvantno šifriran prenos med med vozlišči treh držav – Slovenije, Hrvaške in Italije. Med Ljubljano, Reko in Trstom so med srečanjem ministrov za digitalno politiko skupine G20 v Trstu prvič javno demonstrirali kvantno komunikacijo.

Kot je poudaril profesor dr. **Anton Ramšak**, dekan Fakultete za matematiko in fiziko (FMF) Univerze v Ljubljani in profesor kvantne mehanike, ne gre za najhitrejšo ali najkakovostnejšo

vir: https://www.delo.si/novice/znanoteh/prek-kvantne-komunikacije-povezali-tri-mesta



vir: https://www.e5.ijs.si/siquid-project/

vir: https://digital-strategy.ec.europa.eu/en/policies/european-quantum-communication-infrastructure-euroqci

Regulacija optičnih omrežij

Regulation of fibre networks

Žan Knafelc

Agencija za komunikacijska omrežja in storitve Republike Slovenije

zan.knafelc@akos-rs.si

Povzetek

V Sloveniji že več kot polovica gospodinjstev za dostop do interneta uporablja optično omrežje, ki je ključno za nadaljnji razvoj infrastrukturne konkurence. Zaradi vse večje prisotnosti konkurenčnih infrastruktur se predhodna (ex ante) regulacija tako postopoma umika s posameznih upoštevnih trgov in ostaja samo na geografskih območjih, kjer še ni vzpostavljene učinkovite konkurence, ki je pogoj za večjo izbiro, inovacije in nižje cene storitev za končne uporabnike. V prispevku so predstavljeni glavni trendi na trgu in zadnji naloženi korektivnih ukrepi s pogledom v prihodnost.

Abstract

In Slovenia, more than half of all households already use a fibre network to access the internet, which is key to the further development of infrastructure competition. As a result of the growing presence of competing infrastructures, ex ante regulation is thus gradually being withdrawn from individual relevant markets and remains only in geographic areas where effective competition has not yet been established, which is a prerequisite for greater choice, innovation and lower prices for end-users. This paper presents the main trends in the market and the latest corrective measures imposed with a view to the future.

Biografija avtorja

Žan Knafelc je na Agenciji za komunikacijska omrežja in storitve RS je zaposlen od leta 2007, zadnjih šest let kot vodja oddelka za regulacijo trga elektronskih komunikacij. Pred tem si je izkušnje nabiral pri mobilnem operaterju na področju razvoja in uvajanja storitev. Ima univerzitetno izobrazbo s tehničnega in ekonomskega področja.

Author's biography

Žan Knafelc has been employed at Agency for communication networks and services RS since 2007, the last six years as a head of market regulation department for electronic communications. Prior to that, he gained experience working for a mobile operator in the product management. He holds degrees in technical and economics area.

AKOS

Regulacija optičnih omrežij

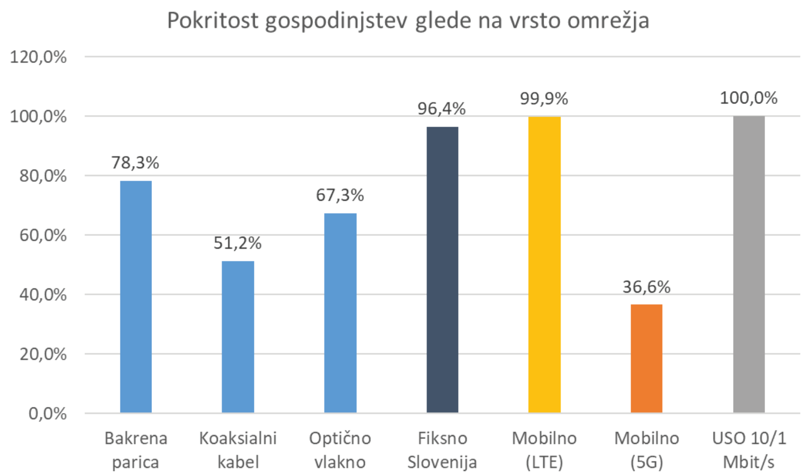
SOK 2023

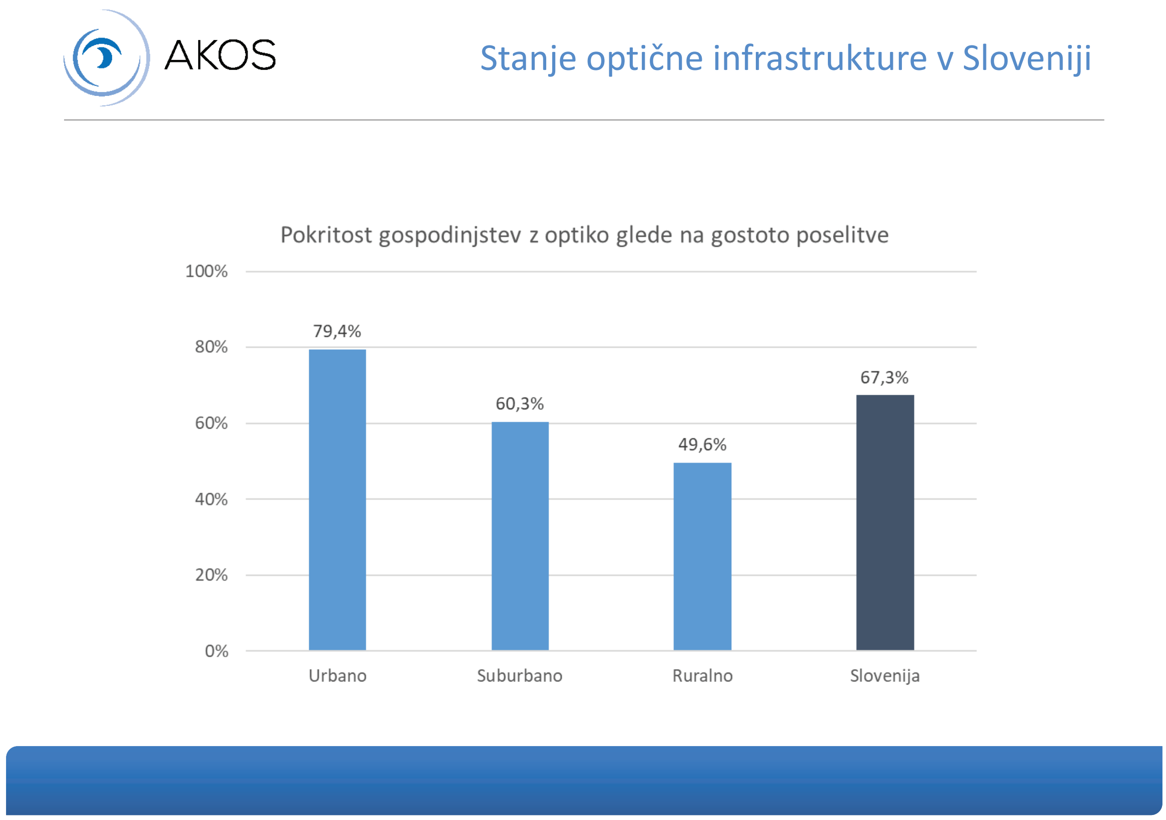
Žan Knafelc, AKOS

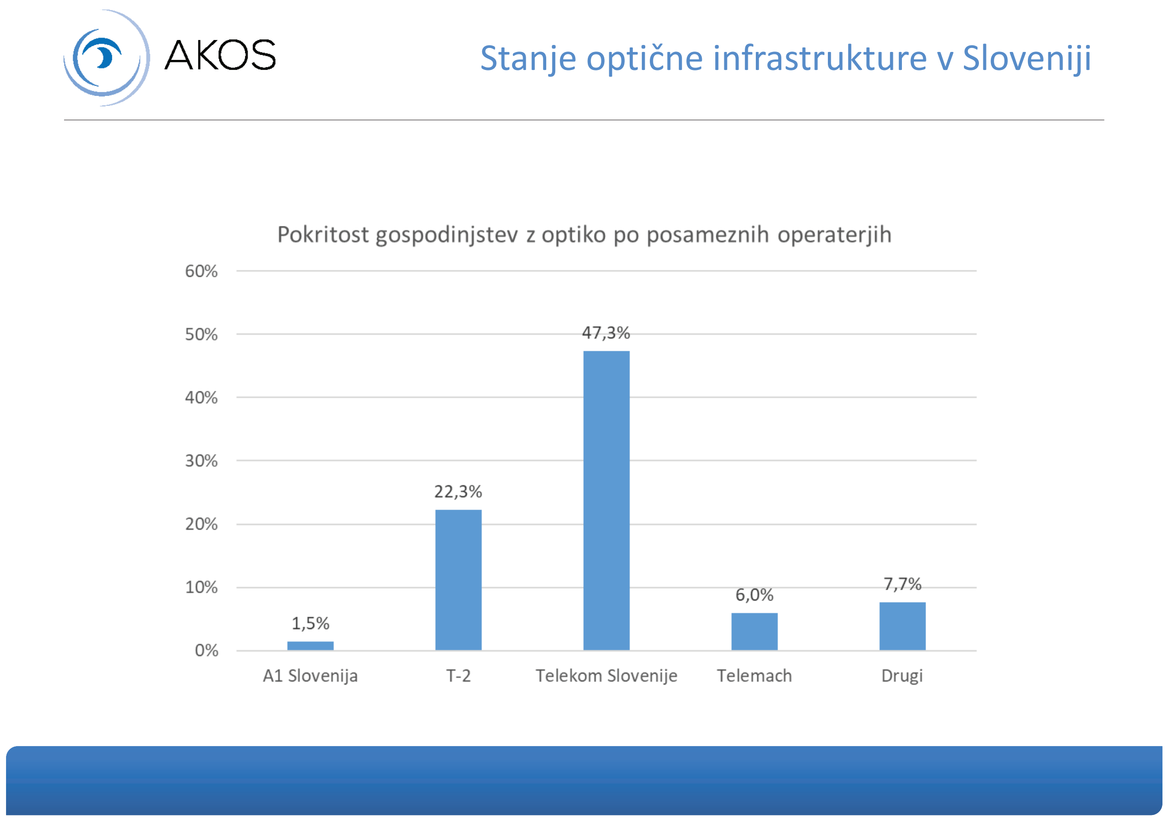
Ljubljana, 25. januar 2023

AKOS

Stanje omrežne infrastrukture v Sloveniji

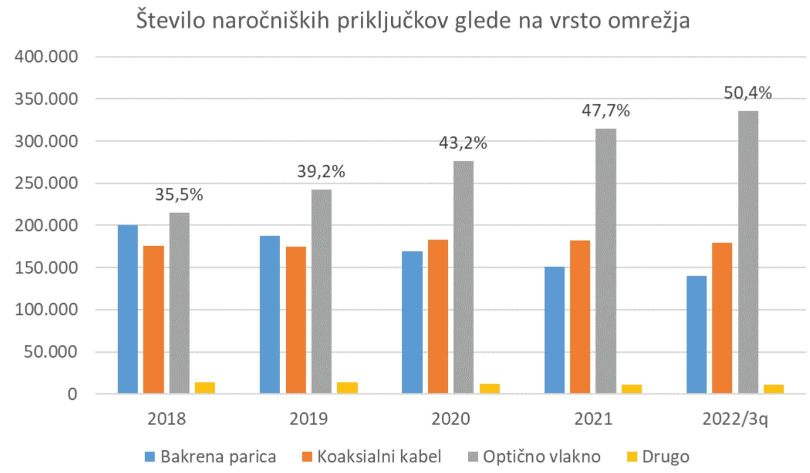



AKOS
Stanje optične infrastrukture v Sloveniji
Pokritost gospodinjstev z optiko glede na gostoto poselitve
100%
80%
60%
40%
20%
0%
79,4%
60,3%
49,6%
67,3%
Urbano
Suburbano
Ruralno
Slovenija


AKOS
Stanje optične infrastrukture v Sloveniji
Pokritost gospodinjstev z optiko po posameznih operaterjih
60%
50%
40%
30%
20%
10%
0%
1,5%
22,3%
47,3%
6,0%
7,7%
A1 Slovenija
T-2
Telekom Slovenije
Telemach
Drugi

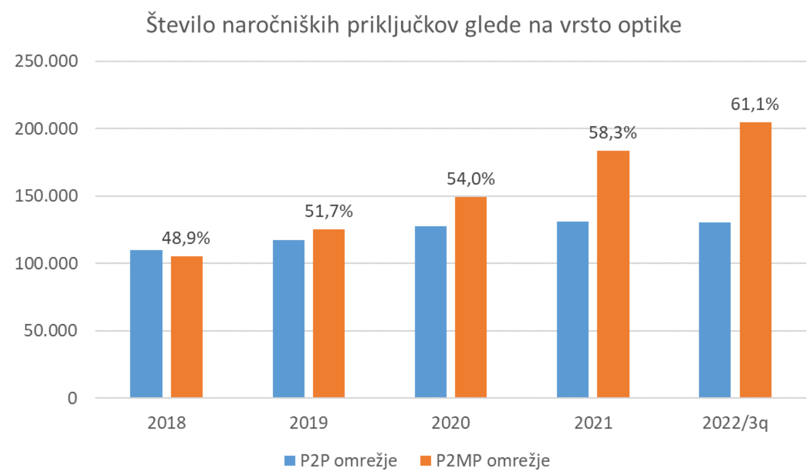
AKOS

Maloprodajni trg širokopasovnega dostopa



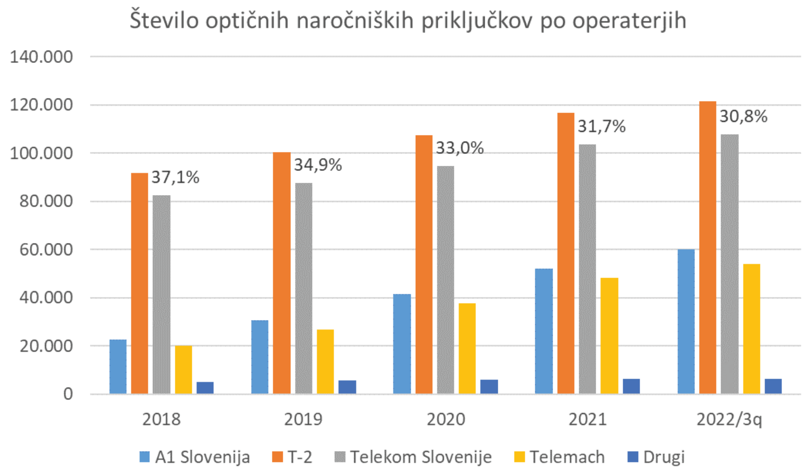
AKOS

Maloprodajni trg širokopasovnega dostopa



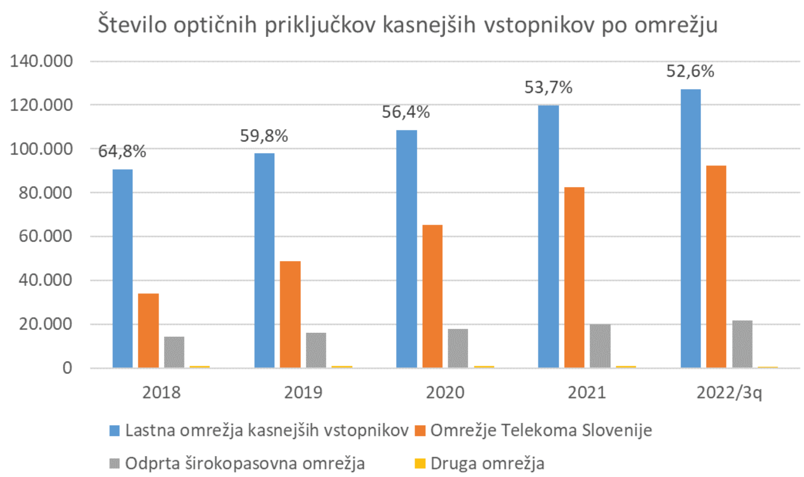
AKOS

Maloprodajni trg širokopasovnega dostopa



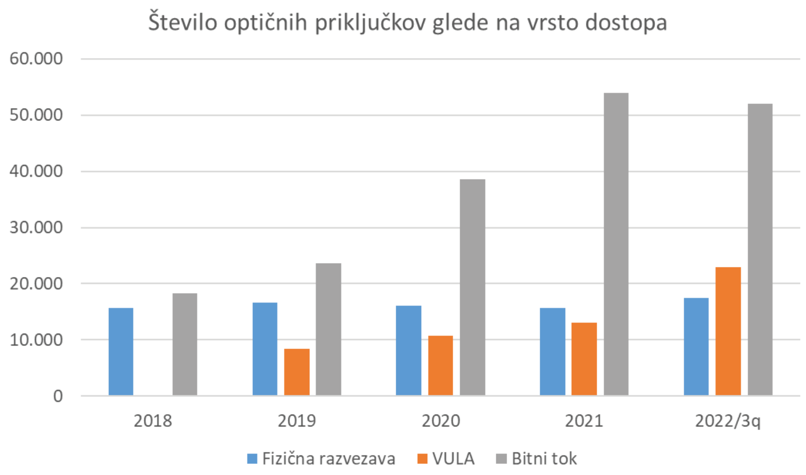
AKOS

Odvisnost kasnejših vstopnikov od drugih omrežij



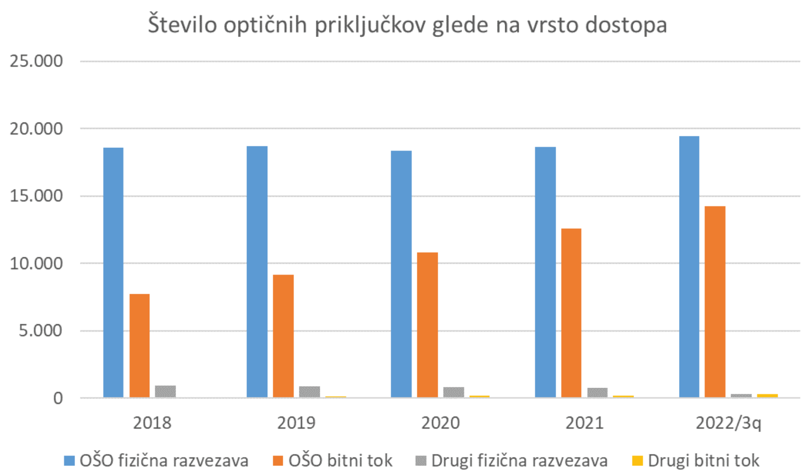
AKOS

Reguliran dostop do omrežja Telekoma Slovenije



AKOS

Veleprodajni dostop do OŠO in drugih omrežij



AKOS

Predhodna (ex ante) regulacija dostopa

- Regulacija operaterja s pomembno tržno močjo (142. člen ZEKom-2)
- Za SMP operaterja določen Telekom Slovenije (z regulativno odločbo naložene obveznosti – korektivni ukrepi)

- Kriterija za geografsko segmentacijo upoštevnih trgov 1 in 3b (ob upoštevanju prirejenega „Greenfield“ pristopa – brez regulacije):
  - Prvotni operater (Telekom Slovenije) manj kot 40 % in dva kasnejša vstopnika z najmanj po 10 % maloprodajnim tržni delež v naselju
  - Vsak od treh operaterjev s pokritostjo najmanj 65 % gospodinjstev (baker, optika in kabel)

AKOS

Predhodna (ex ante) regulacija dostopa

Lokalni dostop (veleprodajni upoštevni trg 1)

- Nacionalni trg (baker in optika)
- Kabel ni del trga (ni zamenljiv, ni zadostnega indirektnega pritiska)
- Geografska segmentacija ukrepov (15 naselij – 5,3% gospodinjstev brez cenovnih obveznosti, letno posodabljanje seznama)
- Dostop do fizične infrastrukture (vključno s stavbno) za fiksne storitve
- Fizična in virtualna razvezava (VULA)
- Backhaul (povezava od robnega do dostopovnega vozlišča)
- Veleprodajne cene temeljijo na preizkusu ekonomske ponovljivosti (ERT)

AKOS

Predhodna (ex ante) regulacija dostopa

Osrednji dostop (veleprodajni upoštevni trg 3b)

- Ni več na seznamu Priporočila o upoštevnih trgih (2020)
- 3CT (preizkus treh meril) → nujna nadaljnja regulacija
- Geografska segmentacija trga → reguliran (baker in optika) in dereguliran del trga (430 naselij – 42,5% gospodinjstev, letno posodabljanje seznama)
- Kabel ni del trga (ni zamenljiv, ni zadostnega indirektnega pritiska)
- Bitni tok (regijski in nacionalni nivo)
- Veleprodajne cene temeljijo na preizkusu ekonomske ponovljivosti (ERT)

AKOS

Predhodna (ex ante) regulacija dostopa

Visokokakovostni dostop (veleprodajni upoštevni trg 4)

- Na seznamu Priporočila o upoštevnih trgih (2020) kot upoštevni trg 2
- Nacionalni trg (baker in optika)
- Kabel ni del trga (ni zamenljiv že na maloprodajnem trgu)
- Zakupljeni vodi (tradicionalni in Ethernet vmesniki)
- Visokokakovostni bitni tok
- SLA (vključno z odpravo napake najmanj naslednji delovni dan)
- Dostop do zaključnega segmenta omrežja (robna in dostopovna vozlišča)
- Veleprodajne cene temeljijo na stroškovnih cenah (LRIC+)
- Analiza učinkov regulacije (se izvaja)

AKOS

Predhodna (ex ante) regulacija dostopa

Postopen umik regulacije upoštevnih trgov (deregulacija)

- Priporočilo o upoštevnih trgih (2003) – 18 upoštevnih trgov
- Priporočilo o upoštevnih trgih (2020) – 2 upoštevna trga
- Nadaljnja regulacija mogoča le ob izpolnjevanju 3CT (preizkusa treh meril)
- Na začetku regulirani tudi maloprodajni trgi
- Geografska segmentacija ukrepov (cenovna deregulacija dela trga)
- Geografska segmentacija trga (deregulacija dela trga)
- Deregulacija celotnega trga
- Predhodna (ex ante) regulacija do vzpostavitve učinkovite konkurence na maloprodajnem trgu
- Naslednje Priporočilo o upoštevnih trgih – 1 upoštevni trg (dostop do fizične infrastrukture)?

AKOS

Simetrična regulacija, skupna uporaba in gradnja

Simetrična regulacija (136., 137. in 138. člen ZEKom-2)

- Skupna uporaba komunikacijskih objektov (zaradi varstva okolja, javnega zdravja, javne varnosti ali prostorskih ureditev)
- Skupna uporaba stavbne fizične infrastrukture
- Skupna uporaba napeljav, kablov in skupnih zmogljivosti v stavbah

Skupna uporaba GJI (139. in 140. člen ZEKom-2)

- Dostop do obstoječe fizične infrastrukture
- Dostop do neuporabljenih optičnih vlaken (druga GJI)

Skupna gradnja (12. člen ZEKom-2)

- Obveznost objav novih gradenj na portalu infrastrukturnih investicij

AKOS

Več informacij in povezave do portalov agencije

- Analize upoštevnih trgov – https://www.akos-rs.si/telekomunikacije/raziscite/regulacija-upostevnih-trgov
- eAnalitik – https://eanalitik.akos-rs.si/
- Geoportal – https://gis.akos-rs.si/
- Portal infrastrukturnih investicij – https://investicije.akos-rs.si/
- AKOS test net – https://www.akostest.net/sl/
- Ponudba operaterjev – https://www.primerjajoperaterje.si/
- Portal za medijsko in informacijsko pismenost – https://www.mipi.si/

Email:
zan.knafelc@akos-rs.si

Nadgradnja P2P FTTH in GPON dostopovnih omrežij v PON omrežja naslednje generacije

Upgrade of P2P FTTH and GPON access networks to next-generation PON networks

Gorazd Penko

T-2, d.o.o.

gorazd.penko@t-2.com

Povzetek

V prispevku so predstavljeni razlogi za prehod podjetja T-2 iz iz koncepta arhitekture omrežja P2P FTTH (točka-točka FTTH) v P2MP FTTH (točka-več točk FTTH). Podana je standardizacija tehnologij xPON z osnovnimi principi delovanja in pripadajočo arhitekturo, ki temelji na referenčnem modelu ITU-T. Nadalje je opisan pristop k načrtovanju omrežja PON s pripadajočimi simulacijami in izračuni ter osnovne tehnične karakteristike in funkcije gradnikov omrežij tipa PON, kot so: OLT, ONU, razdelilnik, različni tipi modulov PON SFP, itd. V prispevku so predstavljene tehnične možnosti nadgradnje obstoječega omrežja GPON s tehnologijo XGS-PON in možnosti, ki jih ponuja tehnologija NG-PON2. Opisan je tudi koncept podatkovnega statističnega multipleksa v dostopovnem omrežju. V zaključku je opisan koncept uvajanja tehnologije XGS-PON »Pay as you grow«.

Abstract

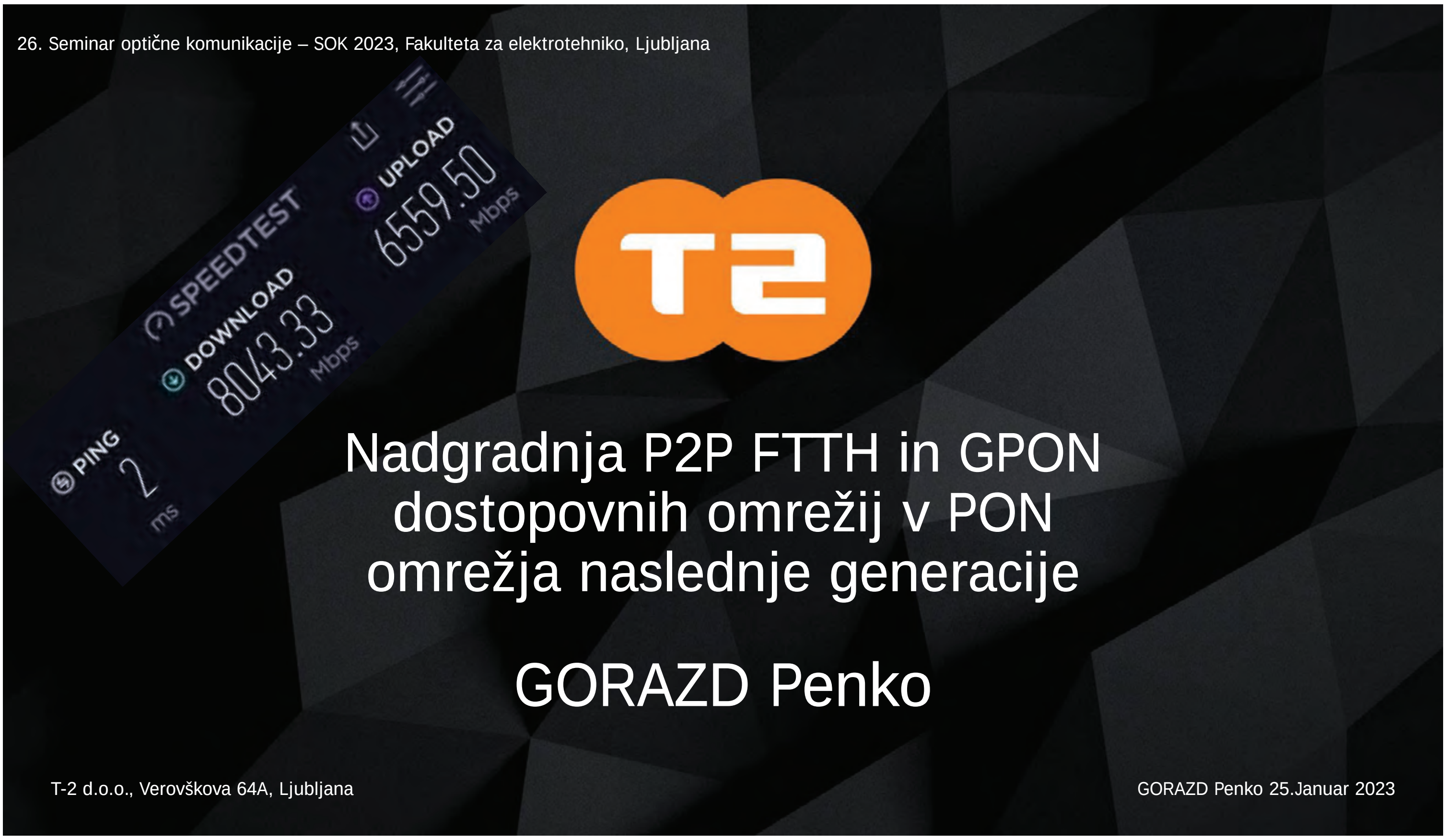
In this presentation the reasons for T-2's transition from the point-to-point (P2P) to point-tomultipoint (P2MP) FTTH concept are presented. The standardization of xPON technologies with the basic principles of operation and the associated architecture based on the ITU-T reference model are described. An approach to network planning with associated simulations and calculations is also given. The basic building blocks of xPON networks such as OLT, ONU, splitter, CEx (coexistence element), different types of SFP modules and their basic technical characteristics are presented. The advantages and disadvantages of P2MP compared to P2P FTTH are set forth. In the continuation of the paper the technical possibilities of upgrading the existing GPON technology with XGS-PON or NG-PON2 are presented. NG-PON2 offers the technical possibility of a multioperator environment on the same FTTH physical infrastructure. The paper concludes with the optical part of the lecture, the concept of introducing the XGS-PON »Pay as you grow« technology.

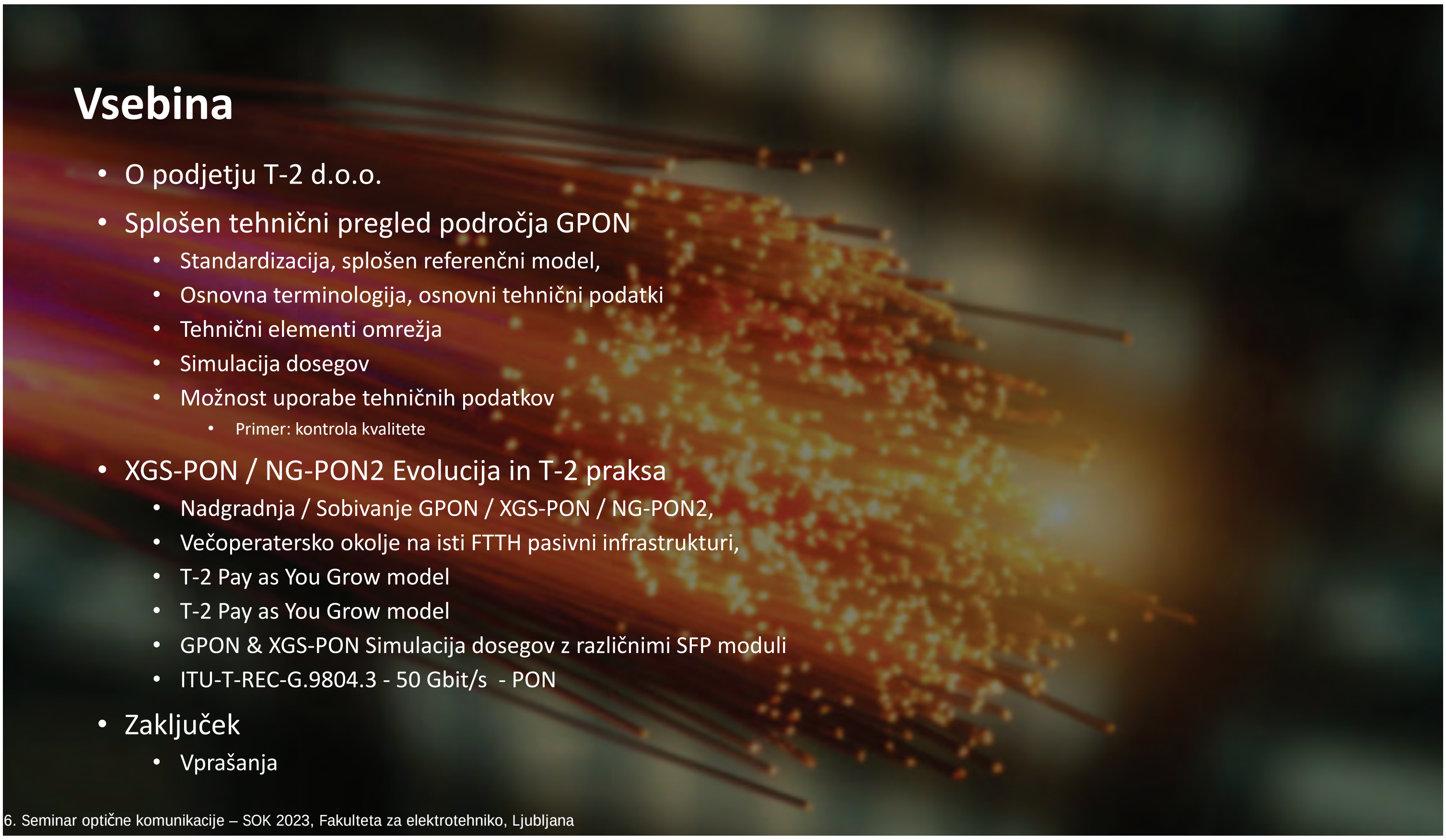
Biografija avtorja

Gorazd Penko je vodja oddelka Referenčnnega laboratorija telekomunikacijskega operaterja T-2, d.o.o, pristojnega za tehnološki razvoj fiksnih dostopovnih omrežij P2P/FTTH, xDSL in P2MP/FTTH, ter CPE IAD naročniških naprav. Diplomiral je na Univerzi v Ljubljani, Fakulteti za elektrotehniko. V letu 1998 se je iz področja vzdrževanja podatkovnih omrežij pridružil razvojnemu oddelku Telekoma Slovenije na področju razvoja in komercialne uvedbe tehnologije ADSL v Sloveniji (kasneje tudi ADSL2+). Leta 2006 se je pridružil podjetju T-2, d.o.o. Od leta 2007 do 2010 je bil vodja oddelka xDSL, kjer je sodeloval pri razvoju, načrtovanju in upravljanju omrežij xDSL. Pred tem je delal kot operater omrežja. Njegova naloga je bila razvoj, nadzor, upravljanje in uvajanje novih širokopasovnih tehnologij VDSL1 in VDSL2 (med prvimi v Evropi). Sodeluje na številnih mednarodnih konferencah na področju telekomunikacij, kot so Broadband World Forum, FTTH Council, Smart Home konferencah itd. V letu 2022 se je udeležil mednarodne konference FOAN (Fiber Optics Access Networks) z avtorsko prezentacijo »GPON / XGS-PON / NG-PON2 Evolution With a Comparison of Wi-Fi 6 Mesh Versus Wi-Fi 5 Mesh in a Residential Building - Experience in T-2«. Bil je in je še vedno projektni vodja številnih projektov, vključno z dostopovnimi omrežji GPON, XGS-PON in dostopovnimi tehnologijami naslednjih generacij.

Author's biography

Gorazd Penko is curently working as Head Of Reference Laboratory for development P2P/FTTH, xDSL, P2MP/FTTH, xDSL and CPE IAD at T-2 telecommunication company. He graduated at University of Ljubljana, Faculty of electrical engineering. His work in telecommunications development department area started in 1998, at Telekom Slovenije with the development and commercial introduction of ADSL technology (the latter ADSL2+) In 2006 he joined T-2. From 2007 to 2010 he was Head of xDSL department, where he has been involved in development, planning and management of xDSL networks. Before that (2006-2007) he worked as a Network operator; his task included development, supervision, management and introduction of new VDSL1 and VDSL2 broadband technology (among the first ones in Europe). He participates in many International Conferences in the field of telecommunications, such as Broadband World Forum Europe, FTTH Council, Smart Home conferences etc. In 2022, he participated in the international conference FOAN (Fiber Optics Access Networks) with the author's presentation "GPON / XGS-PON / NG-PON2 Evolution With a Comparison of Wi-Fi 6 Mesh Versus Wi-Fi 5 Mesh in a Residential Building - Experience and T-2". He was and still is a project manager of many projects, including GPON, XGS-PON and next generation access networks.


26. Seminar optične komunikacije – SOK 2023, Fakulteta za elektrotehniko, Ljubljana
SPEEDTEST
PING
2
ms
DOWNLOAD
8043.33
Mbps
UPLOAD
6559.50
Mbps
Nadgradnja P2P FTTH in GPON dostopovnih omrežij v PON omrežja naslednje generacije
GORAZD Penko
T-2 d.o.o., Verovškova 64A, Ljubljana
GORAZD Penko 25.Januar 2023


Vsebina
• O podjetju T-2 d.o.o.
• Splošen tehnični pregled področja GPON
• Standardizacija, splošen referenčni model,
• Osnovna terminologija, osnovni tehnični podatki
• Tehnični elementi omrežja
• Simulacija dosegov
• Možnost uporabe tehničnih podatkov
• Primer: kontrola kvalitete
• XGS-PON / NG-PON2 Evolucija in T-2 praksa
• Nadgradnja / Sobivanje GPON / XGS-PON / NG-PON2,
• Večoperatersko okolje na isti FTTH pasivni infrastrukturi,
• T-2 Pay as You Grow model
• T-2 Pay as You Grow model
• GPON & XGS-PON Simulacija dosegov z različnimi SFP moduli
• ITU-T-REC-G.9804.3 - 50 Gbit/s - PON
• Zaključek
• Vprašanja
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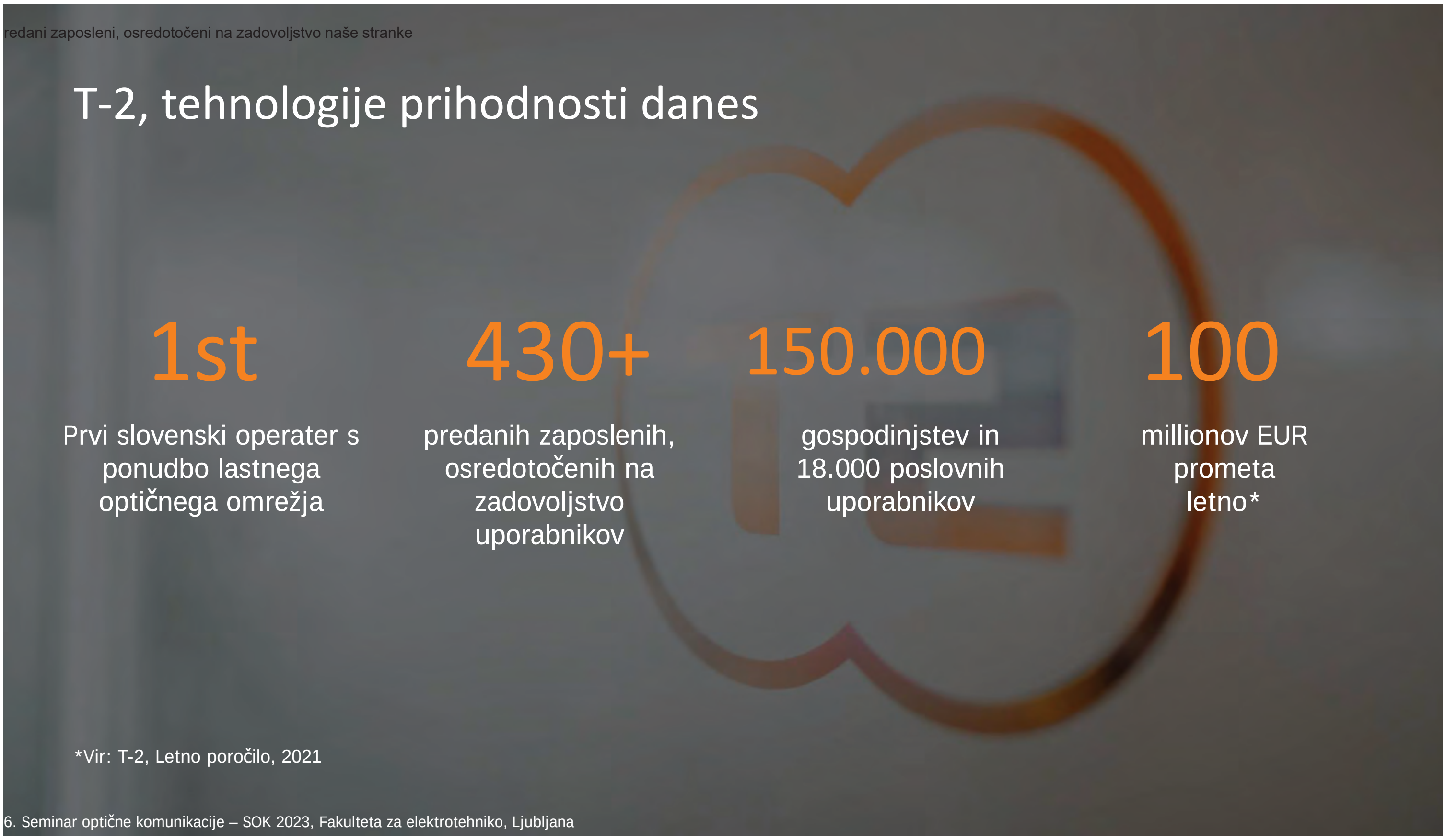
redani zaposleni, osredotočeni na zadovoljstvo naše stranke
T-2, tehnologije prihodnosti danes
1st
Prvi slovenski operater s ponudbo lastnega optičnega omrežja
430+
predanih zaposlenih, osredotočenih na zadovoljstvo uporabnikov
150.000
gospodinjstev in 18.000 poslovnih uporabnikov
100
millionov EUR prometa letno*
*Vir: T-2, Letno poročilo, 2021
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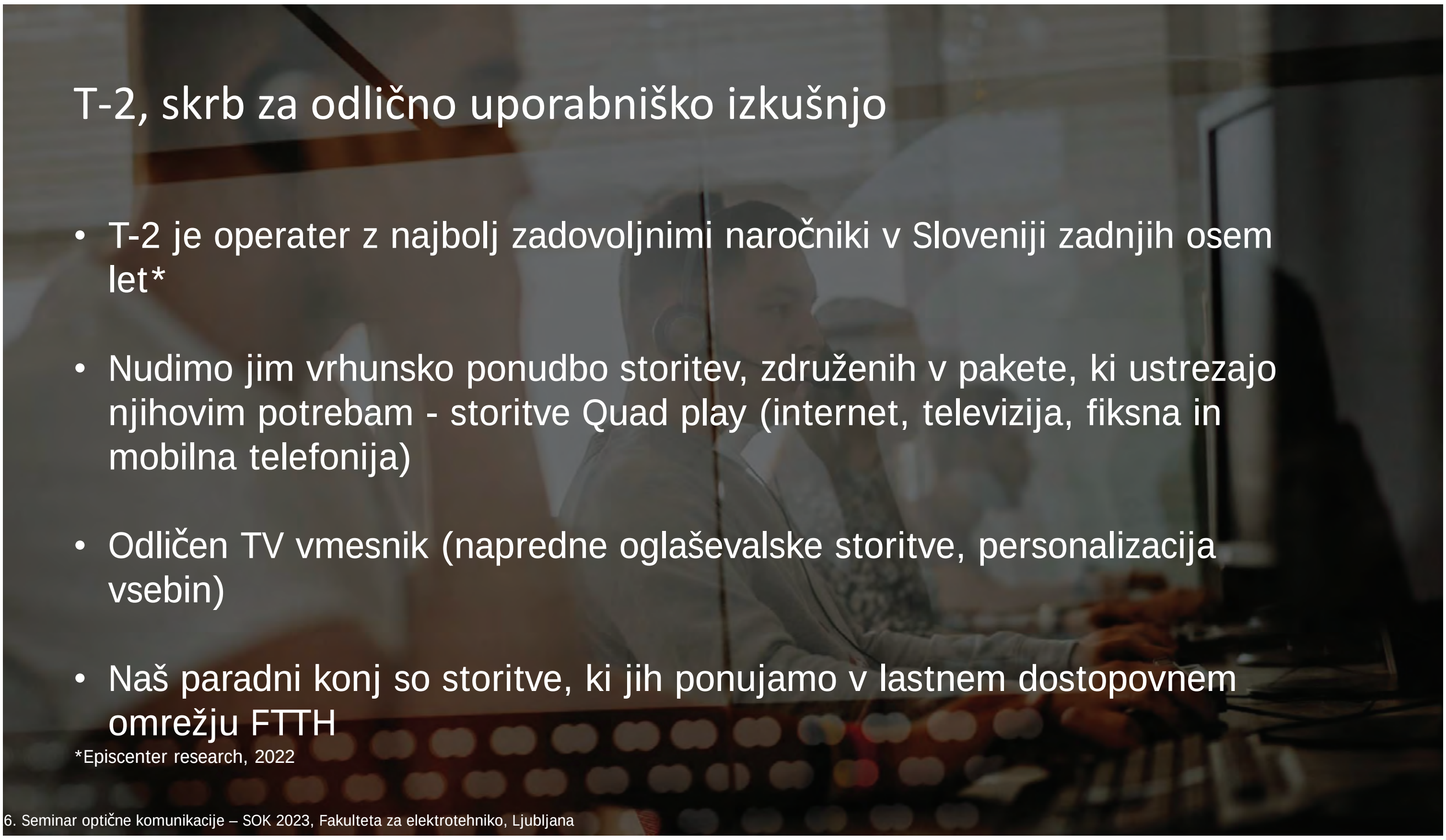
T-2, skrb za odlično uporabniško izkušnjo
• T-2 je operater z najbolj zadovoljnimi naročniki v Sloveniji zadnjih osem let*
• Nudimo jim vrhunsko ponudbo storitev, združenih v pakete, ki ustrezajo njihovim potrebam - storitve Quad play (internet, televizija, fiksna in mobilna telefonija)
• Odličen TV vmesnik (napredne oglaševalske storitve, personalizacija vsebin)
• Naš paradni konj so storitve, ki jih ponujamo v lastnem dostopovnem omrežju FTTH
*Episcenter research, 2022
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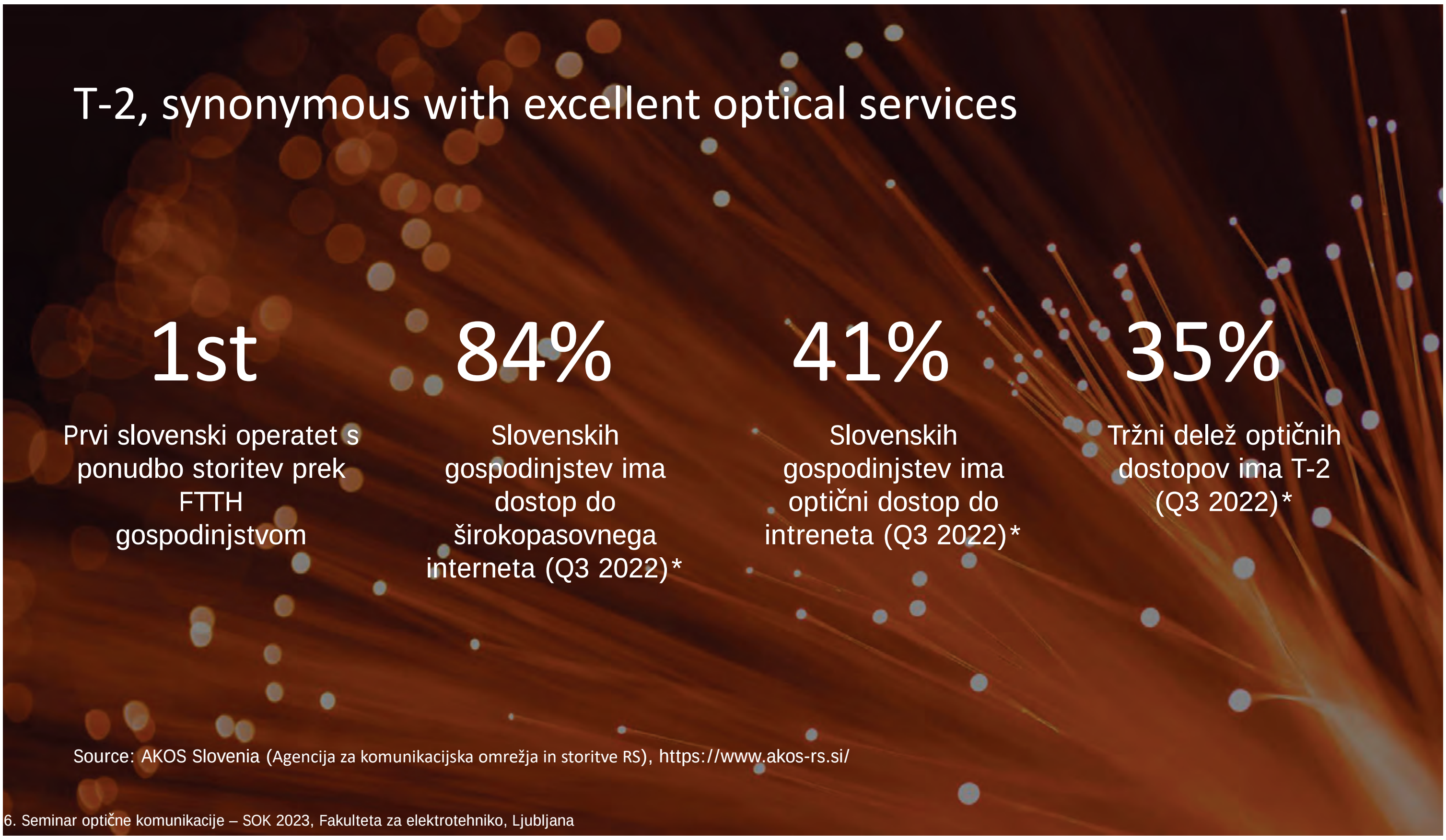
T-2, synonymous with excellent optical services
1st
Prvi slovenski operatet s ponudbo storitev prek FTTH gospodinjstvom
84%
Slovenskih gospodinjstev ima dostop do širokopasovnega interneta (Q3 2022)*
41%
Slovenskih gospodinjstev ima optični dostop do intreneta (Q3 2022)*
35%
Tržni delež optičnih dostopov ima T-2 (Q3 2022)*
Source: AKOS Slovenia (Agencija za komunikacijska omrežja in storitve RS), https://www.akos-rs.si/
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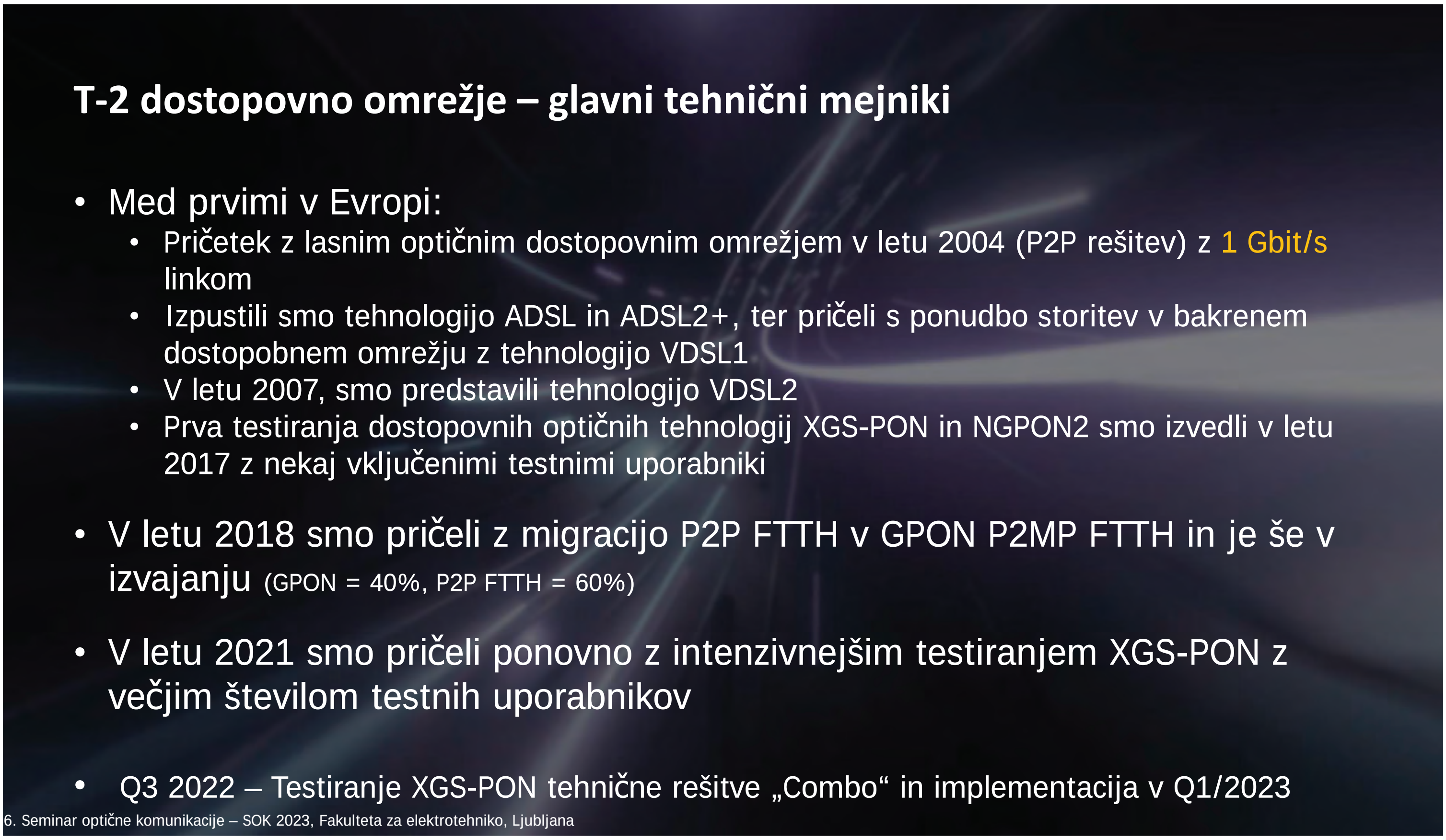
T-2 dostopovno omrežje – glavni tehnični mejniki
• Med prvimi v Evropi:
• Pričetek z lasnim optičnim dostopovnim omrežjem v letu 2004 (P2P rešitev) z 1 Gbit/s linkom
• Izpustili smo tehnologijo ADSL in ADSL2+, ter pričeli s ponudbo storitev v bakrenem dostopobnem omrežju z tehnologijo VDSL1
• V letu 2007, smo predstavili tehnologijo VDSL2
• Prva testiranja dostopovnih optičnih tehnologij XGS-PON in NGPON2 smo izvedli v letu 2017 z nekaj vključenimi testnimi uporabniki
• V letu 2018 smo pričeli z migracijo P2P FTTH v GPON P2MP FTTH in je še v izvajanju (GPON = 40%, P2P FTTH = 60%)
• V letu 2021 smo pričeli ponovno z intenzivnejšim testiranjem XGS-PON z večjim številom testnih uporabnikov
• Q3 2022 – Testiranje XGS-PON tehnične rešitve „Combo“ in implementacija v Q1/2023
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GPON ITU-T Recommendations series G.984.x

- **G.984.1**: General characteristics
  - Parameter description of GPON network
  - Requirements of protection switch-over networking
- **G.984.2**: Physical Media Dependent (PMD) layer specification
  - Specifications of ODN parameters
  - Specifications of 2.488Gbps downstream optical port
  - Specifications of 1.244Gbps upstream optical port
  - Overhead allocation at physical layer
- **G.984.3**: Transmission convergence layer specification
  - Specifications of TC layer in the GPON system
  - GTC multiplexing architecture and protocol stack
  - GTC frame
  - ONU registration and activation
  - DBA specifications
  - Alarms and performance
- **G.984.4**: ONT management and control interface specification
  - OMCI message format
  - OMCI device management frame
  - OMCI working principle
- **G.984.5**: Enhancement band
  - Coexistence with future WDM PON technology n the same medium
- **G.984.6**: Reach extension
  - Architecture and interface parameters for GPON systems with extended reach using a physical layer reach extension device such as a regenerator or optical amplifier in the fibre link between the optical line termination (OLT) and optical network termination (ONT). The maximum reach is up to 60 km
- **G.984.7**: Long reach
  - Extending the maximum differential fibre distance of a G-PON system to 40 km versus the conventional 20 km defined in G.984.1
- **G.988:** ONU management
  - and control interface (OMCI) specification

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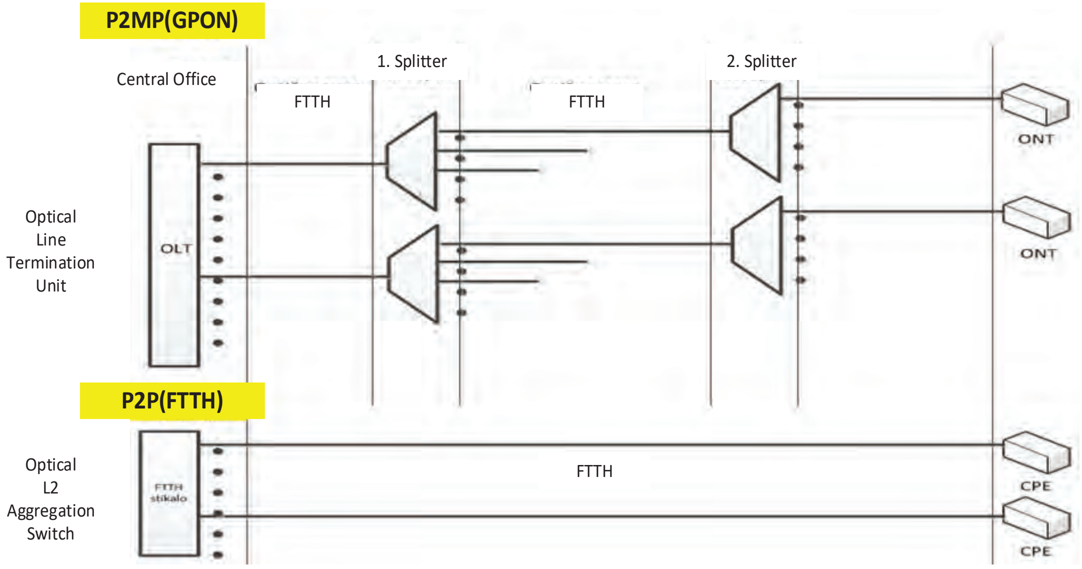
Osnovna primerjava P2MP (GPON) proti P2P-FTTH



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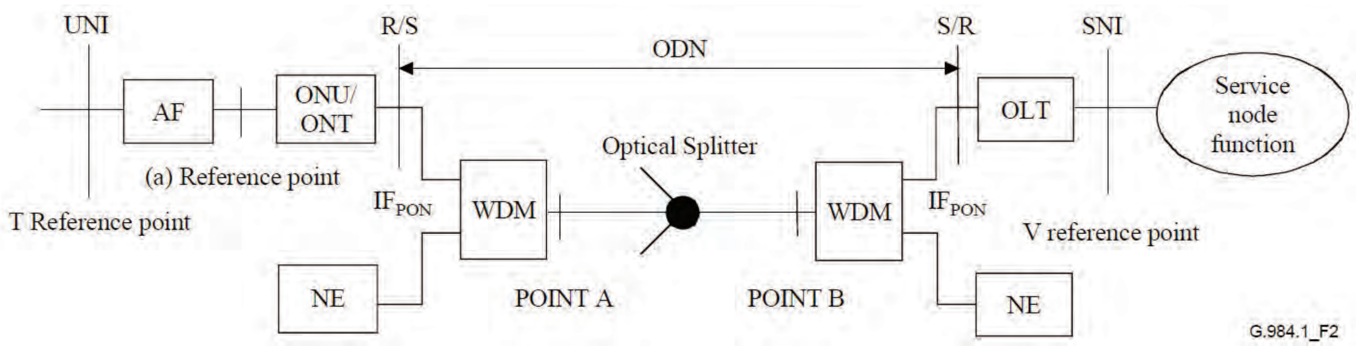
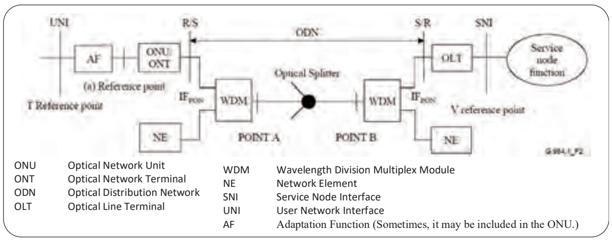
GPON Referenčni model omrežja (ITU-T G.994.1)



ONU	Optical Network Unit
ONT	Optical Network Terminal
ODN	Optical Distribution Network
OLT	Optical Line Terminal
WDM	Wavelength Division Multiplex Module
NE	Network Element
SNI	Service Node Interface
UNI	User Network Interface
AF	Adaptation Function (Sometimes, it may be included in the ONU.)

Osnovna terminologija GPON (1)



- **adaptation function (AF):**
  - Je dodatna oprema ali funkcionalnost, ki na strani uporabnika vmesnik ONU/ONT prilagodi uporabniku – vmesnik UNI (User Network Interface). AF se uporablja tudi za spremembo OLT omrežnega vmesnika na vmesnik SNI (Service Network Interface), ki ga uporablja operater.
- **differential fibre distance:**
  - Na OLT je priključenih več ONU/ONT. Diferencialna optična razdalja je optična razdalja med najbližjim in najbolj oddaljenim ONU/ONT od OLT.
- **logical reach:**
  - Logični doseg je opredeljen kot največja razdalja, ki jo je mogoče doseči za prenosni sistema GPON, ne glede na optični t.i.“power budget“.
- **optical access network (OAN):**
  - Je niz optičnih dostopovnih povezav, ki si jih delijo vmesniki optičnega sistema na strani omrežja. V praksi je OAN skupek ODN priključenih na isti OLT.

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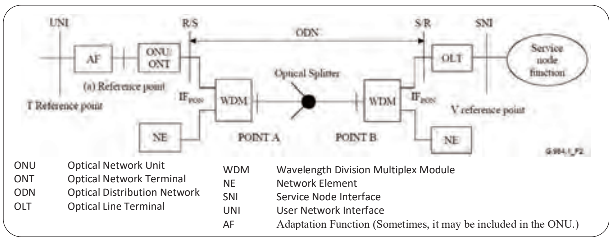
Osnovna terminologija GPON (2)



- **optical distribution network (ODN):**
  - V kontekstu PON je ODN skupek povezanih dostopovnih optičnih vlaken v t.i. drevo dopolnjeno z razdelilniki moči ali valovne dolžine, filtri ali drugimi pasivnimi optičnimi napravami
- **optical line termination (OLT):**
  - je naprava, na katero ja vključena skupna točka ODN in izvaja GPON protokol definiran v ITU-T G.994, ter prilagaja „upload“ PDUs (Protocol Data Units) servisnem vmesniku ponudnika storitev SNI.
- **optical network termination (ONT):**
  - Je naprava na strani uporabnika, katera terminira GPON protokol, ter izvede prilagoditev storitvam na strani uporabnika.
- **optical network unit (ONU):**
  - ONU je poseben primer ONT, ki lahko vsebuje tudi funkcionalnosti večih naročniških naprav.
- **physical reach:**
  - Fizični doseg je opredeljen kot največja fizična razdalja, ki je možen za določen prenosni sistem.

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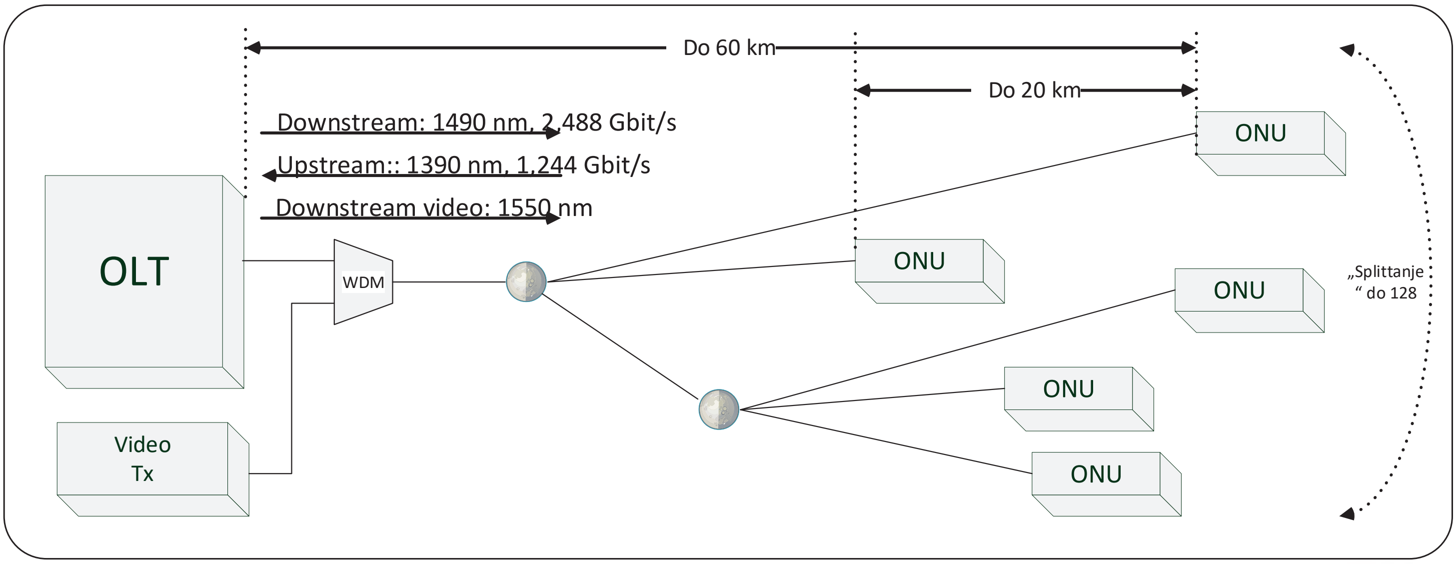
Osnovni tehnični podatki GPON (1)

- **Podatkovna hitrost (Bit Rate):**
  - Večina komercialnih sistemov: 1.2 Gbit/s up, 2.4 Gbit/s down;
  - Opcija: 2.4 Gbit/s up, 2.4 Gbit/s down
- **Logični doseg (Logical Reach):**
  - Maksimalen logični doseg opredeljen z ITU-T priporočilom je 60 km,
- **Fizičen doseg (Physical Reach):**
  - 10 in 20 km (do 40 km)
- **Diferencialna optična razdalja (Differential fibre distance):**
  - 20 km (40 km – long reach)
- **Delilna razmerja (Split Ratio):**
  - Do 1:128 (1:2, 1:4, 1:8, 1:16, 1:32, **1:64**, 1:128)
- **Valovne dolžine:**
  - Downstream: 1490 nm 1,488 Gbit/s
  - Upstream: 1310 nm 1,244 Gbit/s

Osnovni tehnični podatki GPON (2)



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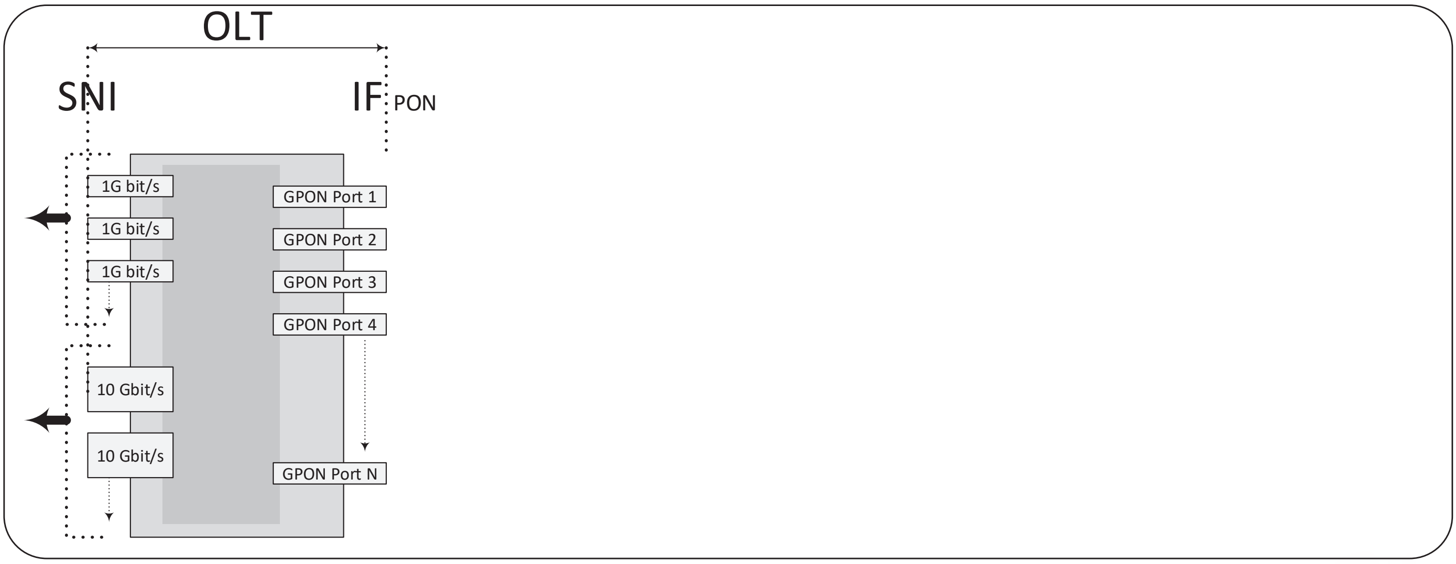
OLT – Optical Link Termination



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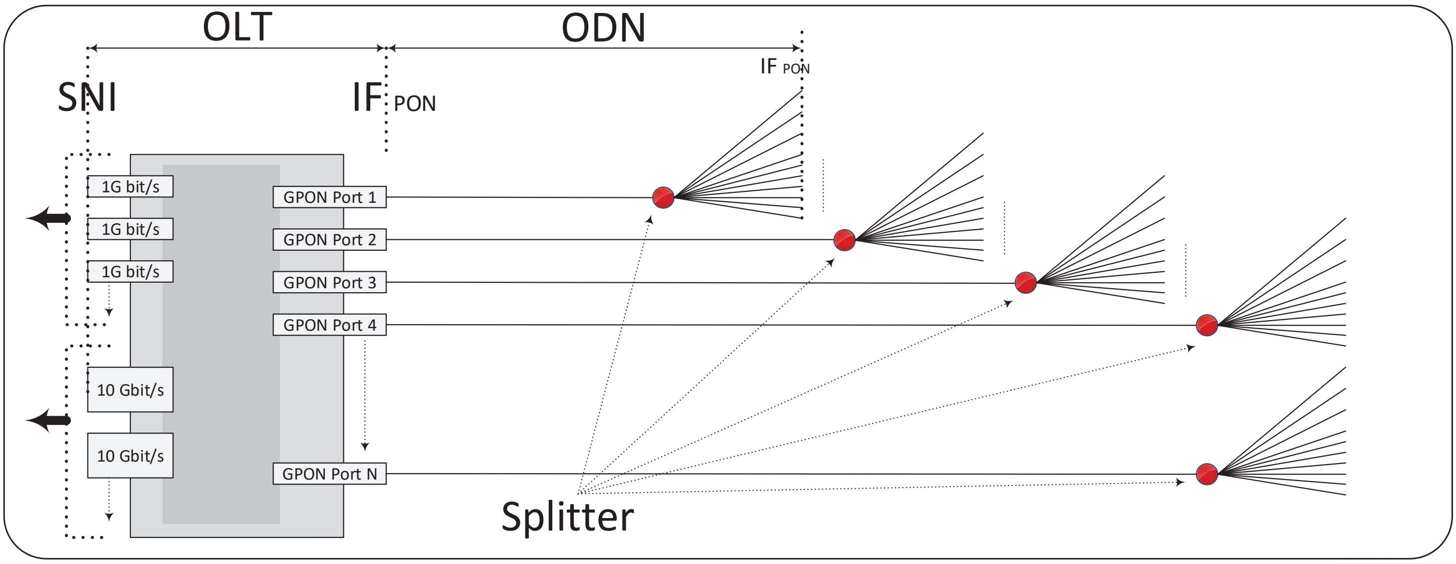
OLT + ODN (Optical Distribution Network)



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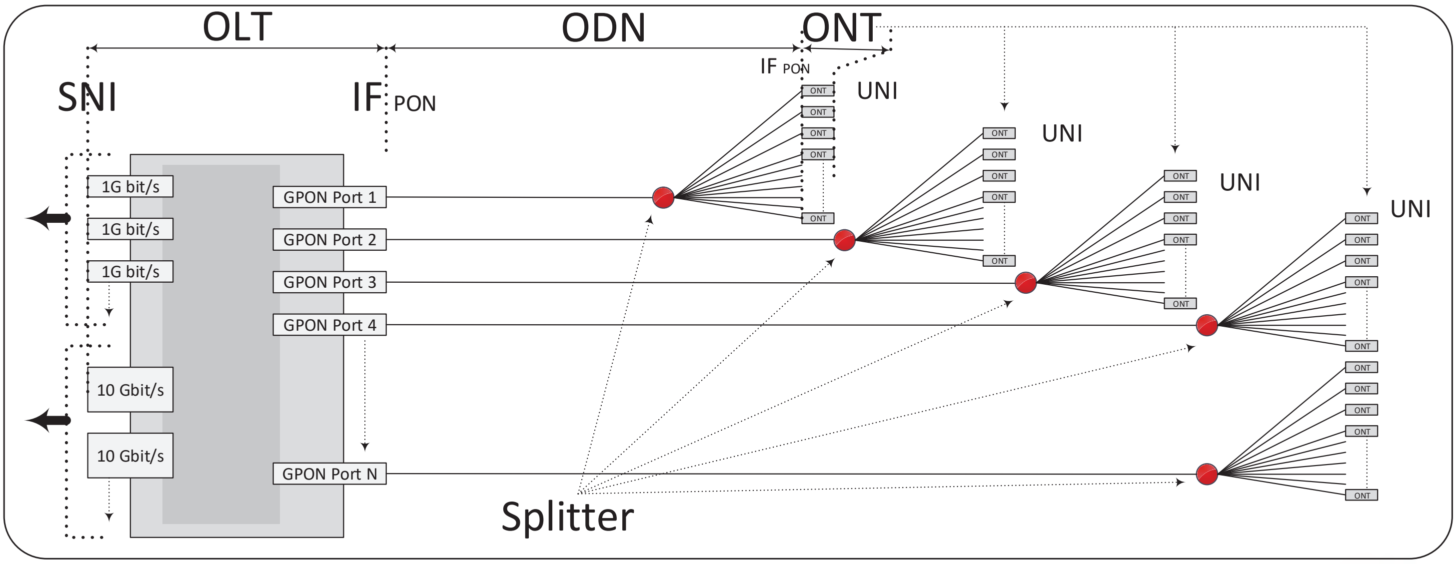
OLT + ODN + ONT (ONU) (Optical Network Termination)



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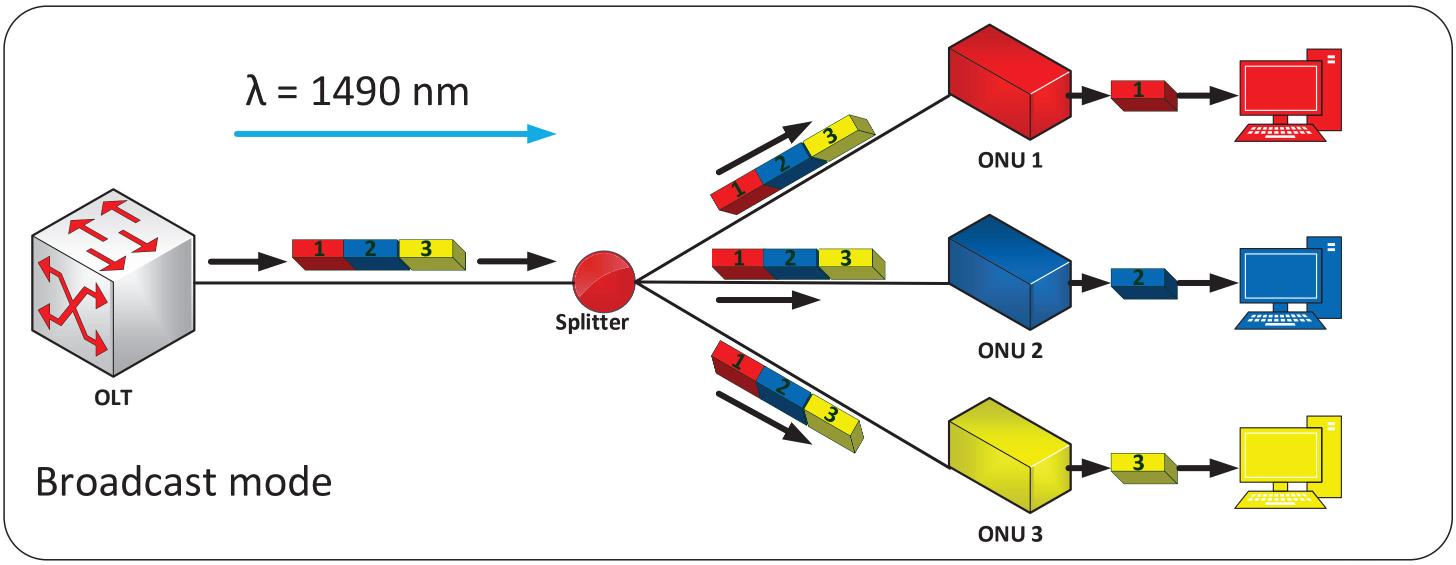
GPON – „Downstream“ princip delovanja



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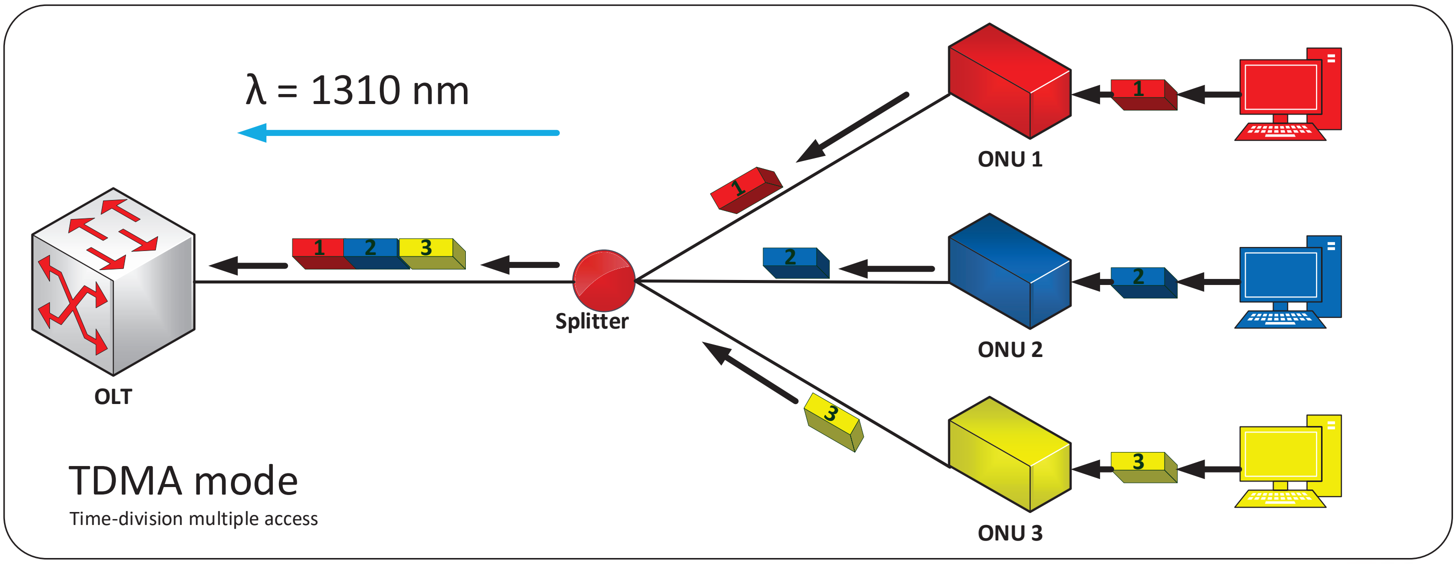
GPON – „Upstream“ princip delovanja



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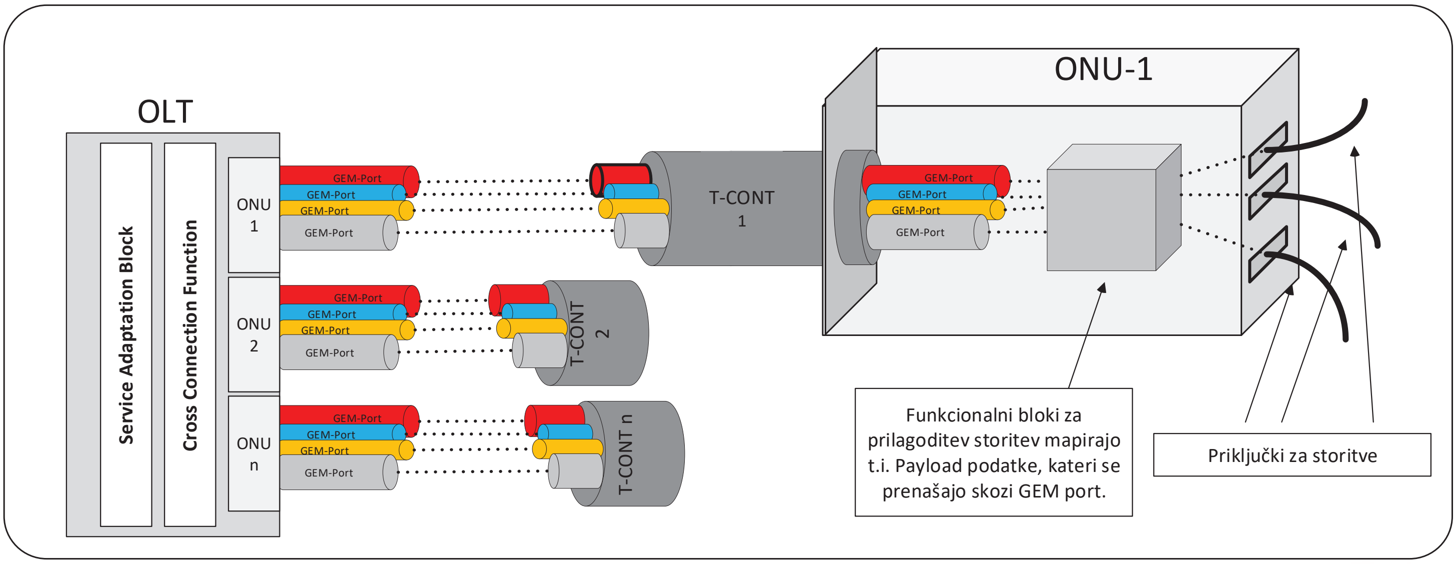
Logična shema povezave OLT / ONT



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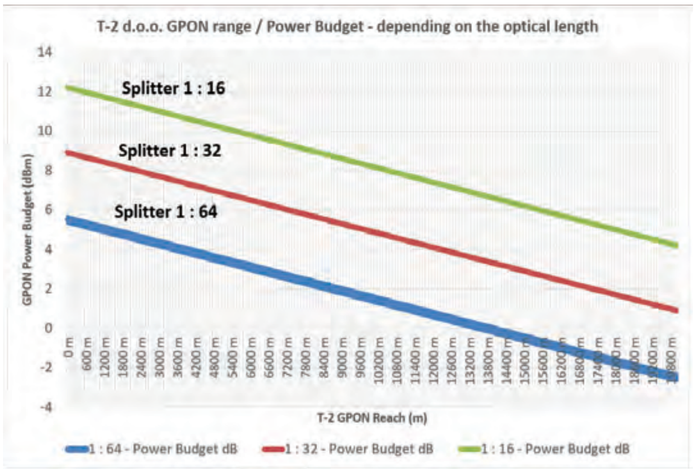
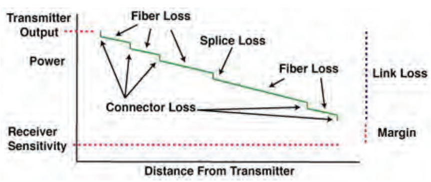
GPON – Simulacija dosega tehnologije

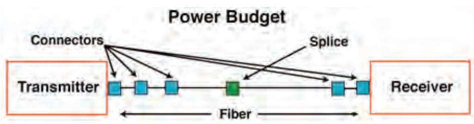
ONT (ONU) SFP B+ (average)	2,4	Tx (dBm)
Fiber Attenuation 1310 nm (+splices)	-0,4	dB/km
Connectors 6 x 0,5 dB	-3,0	dB
Reserve for installers	-3,0	dB
Splitter 1:64 attenuation	-20,9	dB
Splitter 1:32 attenuation	-17,5	dBm
Splitter 1:16 attenuation	-14,2	dBm

Baseline Attenuation for the simulation		
Splitter 1:64	-24,5	dBm
Splitter 1:32	-21,1	dBm
Splitter 1:16	-17,8	dBm
OLT SFP sensitivity C+	-30,0	dBm

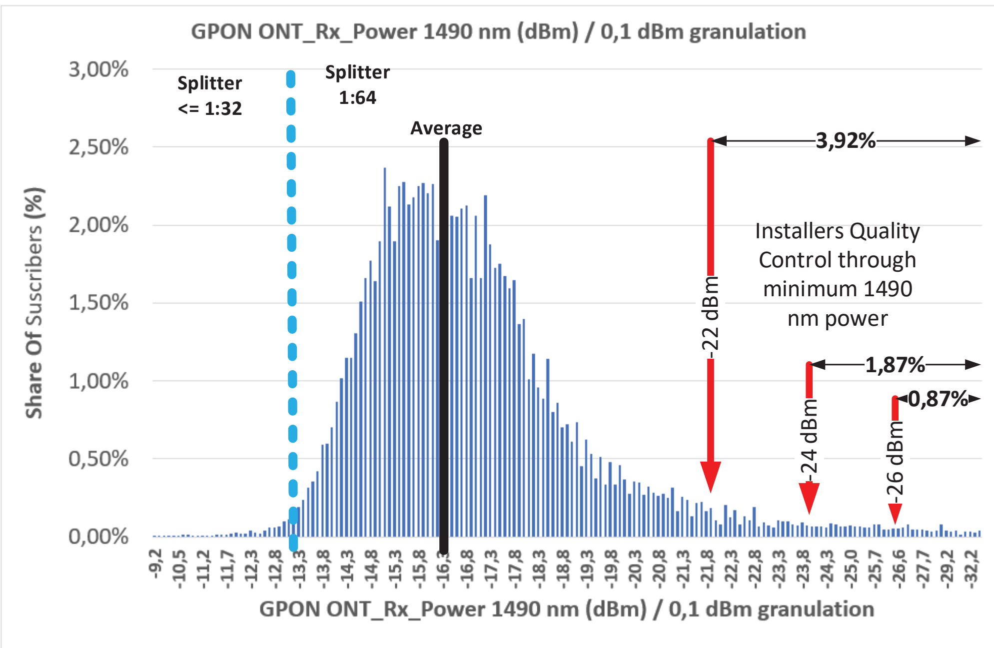
			Calculated GPON range (km)
Razpoložljiv Power Budget 1:64	5,5	dB	13,75
Razpoložljiv Power Budget 1:32	8,9	dB	22,25
Razpoložljiv Power Budget 1:16	12,2	dB	30,50







T-2 Kontrola kvalitete in napak (GPON)



Kontrola kvalitete dela monterjev in napak optičnih vlaken, konektorjev je definirana kot minimalna sprejemna moč na lokaciji uporabnika

Sprejemna moč ONU (1490 nm) se lahko meri z optičnim merilnikom moči signala in se lahko meri tudi prek OLT tehničnih podatkov

GPON dostopovni statistični multipleks (n=987)

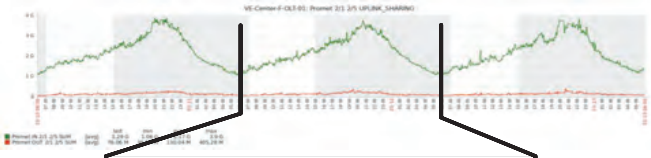
Internet Paket	Število uporabnikov
500 Mbit/s - 100 Mbit/s	418
1 Gbit/s - 200 Mbit/s	215
100 Mbit/s - 20 Mbit/s	208
brez interneta (TV, telefon)	37
100 Mbit/s - 10 Mbit/s	33
50 Mbit/s - 20 Mbit/s	28
10 Mbit/s - 10 Mbit/s	19
300 Mbit/s - 50 Mbit/s	8
750 Mbit/s - 150 Mbit/s	6
200 Mbit/s - 20 Mbit/s	4
100 Mbit/s - 100 Mbit/s	3
20 Mbit/s - 20 Mbit/s	3
500 Mbit/s - 100 Mbit/s	2
200 Mbit/s - 50 Mbit/s	1
50 Mbit/s - 10 Mbit/s	1
50 Mbit/s - 50 Mbit/s	1
Skupaj	**987**

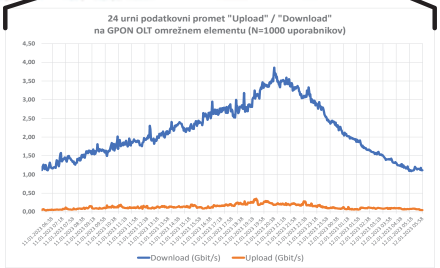
	GPON OLT podatkovni promet naročnikov (n= 987)		
	minimum	povprečje	maksimum
Download (Gbit/s)	1,060	2,170	3,900
Upload (Gbit/s)	0,038	0,130	0,045

	Vsota prodanih naročniških paketov (n=987)	
	povprečje	maksimum
Download (Gbit/s)	464,320	458,290
Upload (Gbit/s)	93,710	92,500

	GPON OLT podatkovni promet splitter 1 :64		
	minimum	povprečje	maksimum
Download (Gbit/s)	0,104	0,239	0,715
Upload (Gbit/s)	0,001	0,005	0,083

16port GPON OLT typical unicast data traffic





Splitter 1:64 – typical unicast data traffic

GPON podatkovni tok – dostopovni statistični multipleks

Internet Paket	Število uporabnikov
500 Mbit/s - 100 Mbit/s	418
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300 Mbit/s - 50 Mbit/s	8
750 Mbit/s - 150 Mbit/s	6
200 Mbit/s - 20 Mbit/s	4
100 Mbit/s - 100 Mbit/s	3
20 Mbit/s - 20 Mbit/s	3
500 Mbit/s - 100 Mbit/s	2
200 Mbit/s - 50 Mbit/s	1
50 Mbit/s - 10 Mbit/s	1
50 Mbit/s - 50 Mbit/s	1
Skupaj	**987**

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	minimum	povprečje	maksimum
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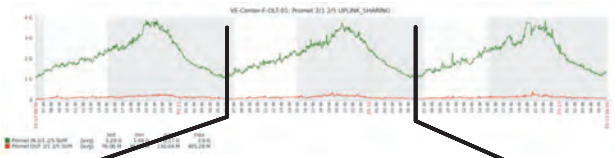
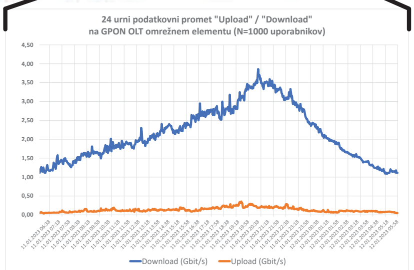
16port GPON OLT typical unicast data traffic





Splitter 1:64 – typical unicast data traffic

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P2MP (GPON) versus P2P FTTH

- Prednosti:
  - Bistveno nižja cena od P2P FTTH,
  - Manjša poraba prostora v optičnih centralah,
  - Manjše število lokacij z aktivno opremo,
  - Manjša poraba električne energije – 10x pa tudi do 20x manjša poraba
    - 1024 GPON Customers = 150W
    - 1024 P2P Customers = app. 1.500W (odvisno od tipa opreme
  - .....
- Slabosti:
  - Isti fizični medij si deli veliko število uporabnikov,
  - V fizičnem delu dostopovnega omrežja je implementirano statistično multipleksiranje podatkovnega prometa,
  - Zahteva več načrtovanja,...
  - Bolj zapleteno odpravljanje napak na "physical layer"......
  - ....

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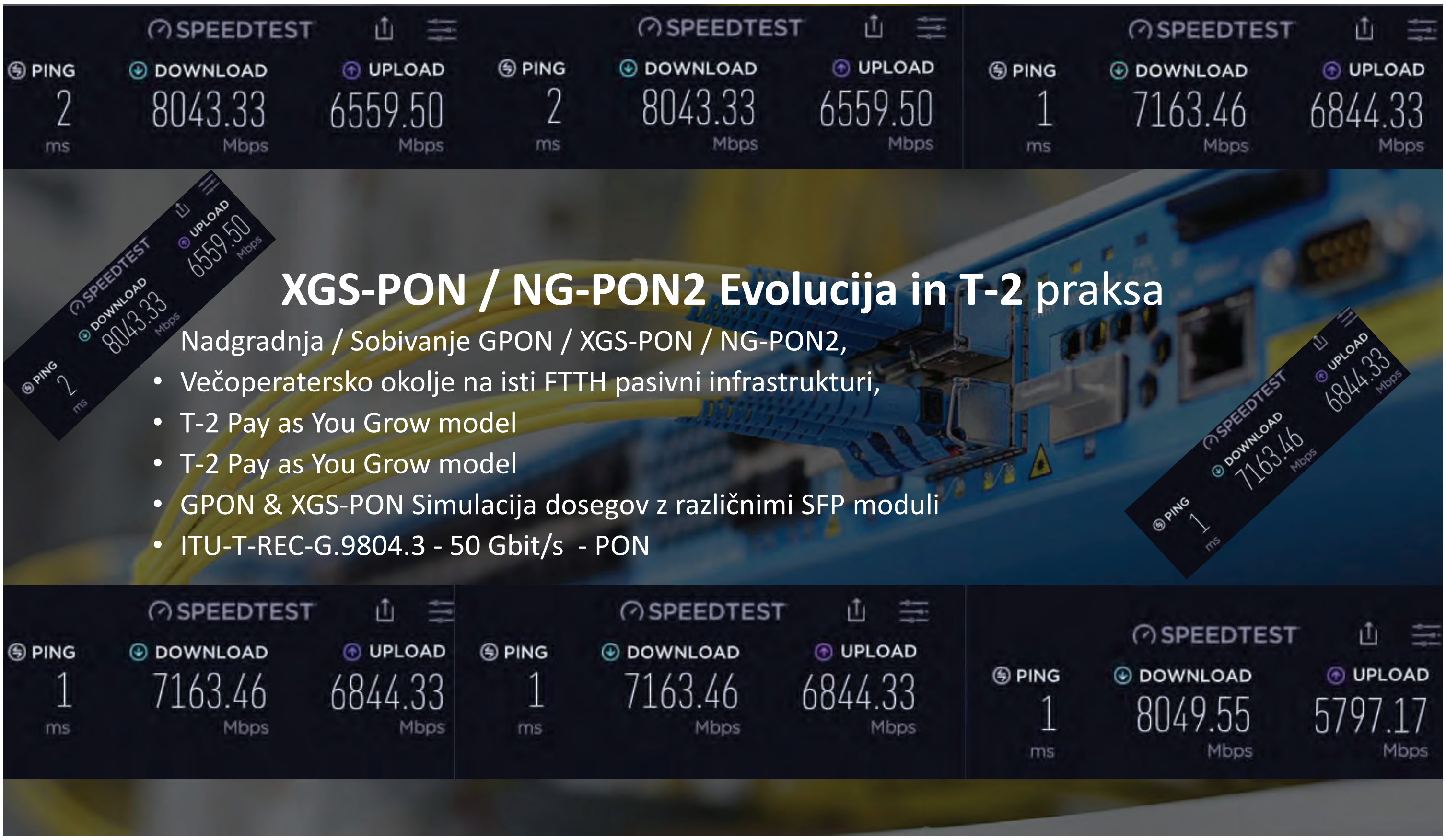

XGS-PON ITU-T Recommendations series G.984.x

- XG-PON (10 / 2,5 Gbit/s)
  - G.987: 10-Gigabit-capable passive optical network (XG-PON) systems: Definitions, abbreviations and acronyms
  - G.987.1: General requirements
  - G.987.2: Physical media dependent (PMD) layer specification
  - G.987.3: Transmission convergence (TC) layer specification
  - G.987.4: Reach extension
- **XGS-PON (10 / 10 Gbit/s)**
  - G.9807.1: 10-Gigabit-capable symmetric passive optical network (XGS-PON)
  - G.9807.2: 10 Gigabit-capable passive optical networks (XG(S)-PON): Reach extension

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NG-PON2 ITU-T Priporočila

- G.989: 40-Gigabit-capable passive optical networks (NG-PON2): Definitions, abbreviations and acronyms
  - G.989.1: General requirements
  - G.989.2: Physical media dependent (PMD) layer specification
  - G.989.3: Transmission convergence layer specification

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Soobstoj PON tehnologij na isti fizični optični infrastrukturi

Rec. ITU-T G.989.2 (02/2019)

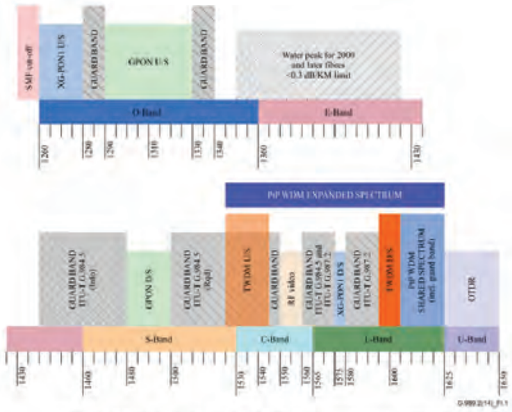

Figure I.1 – NG-PON2 wavelength plan – Coexistence representation

- Kaj potrebujemo ?
  - Standardiziran "wavelength bandplan„
  - Dodatne pasinne elemente omrežja:
    - CEx (Coexistence element)
    - WM (Wavelength Multiplekser)
- Standardizirano aktivno opremo standardizir... tehnologij:
  - GPON, XGS-PON, NG-PON2 (OLT, ONU/ONT)
- Optično in pasivno infrastrukturo(vlakna, razcepnike, opt. delilnike,..)

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Standardizirani CEx and WM (nekateri) (vir ITU-T G.984.5)

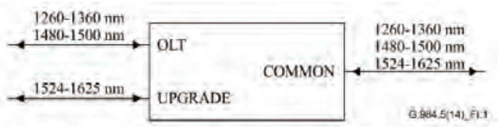

Figure I.1 – Reference diagram of WDM1 (deprecated)

Figure I.2 – Reference diagram of a WDM1r with G-PON and NGA support

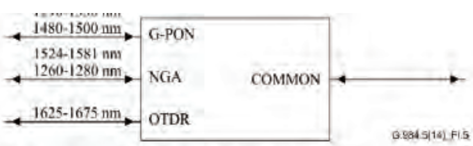

Figure I.5 – Reference diagram of a WDM1r with G-PON, NGA and OTDR support

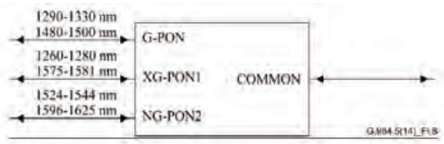

Figure I.8 – Reference diagram of a CEx with G-PON, XG-PON1 and NG-PON2 support

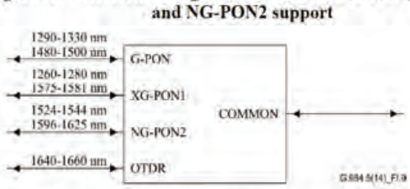

Figure I.9 – Reference diagram of a CEx with G-PON, XG-PON1, NG-PON2 and OTDR support

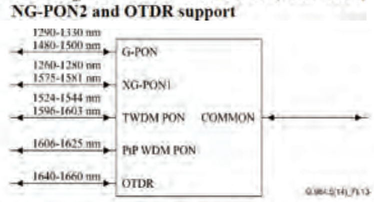

Figure I.13 – Reference diagram of a CEMx with G-PON, XG-PON, TWDM PON, PtP WDM PON and OTDR support

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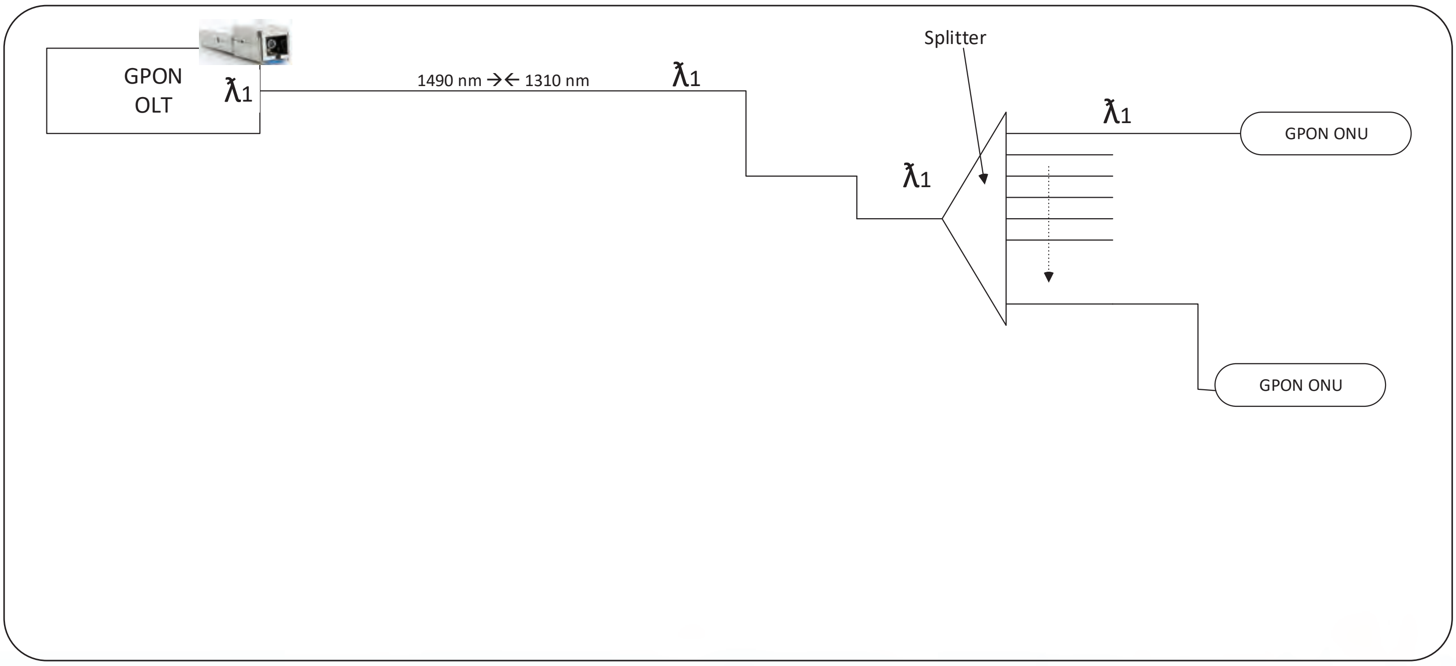
GPON – struktura



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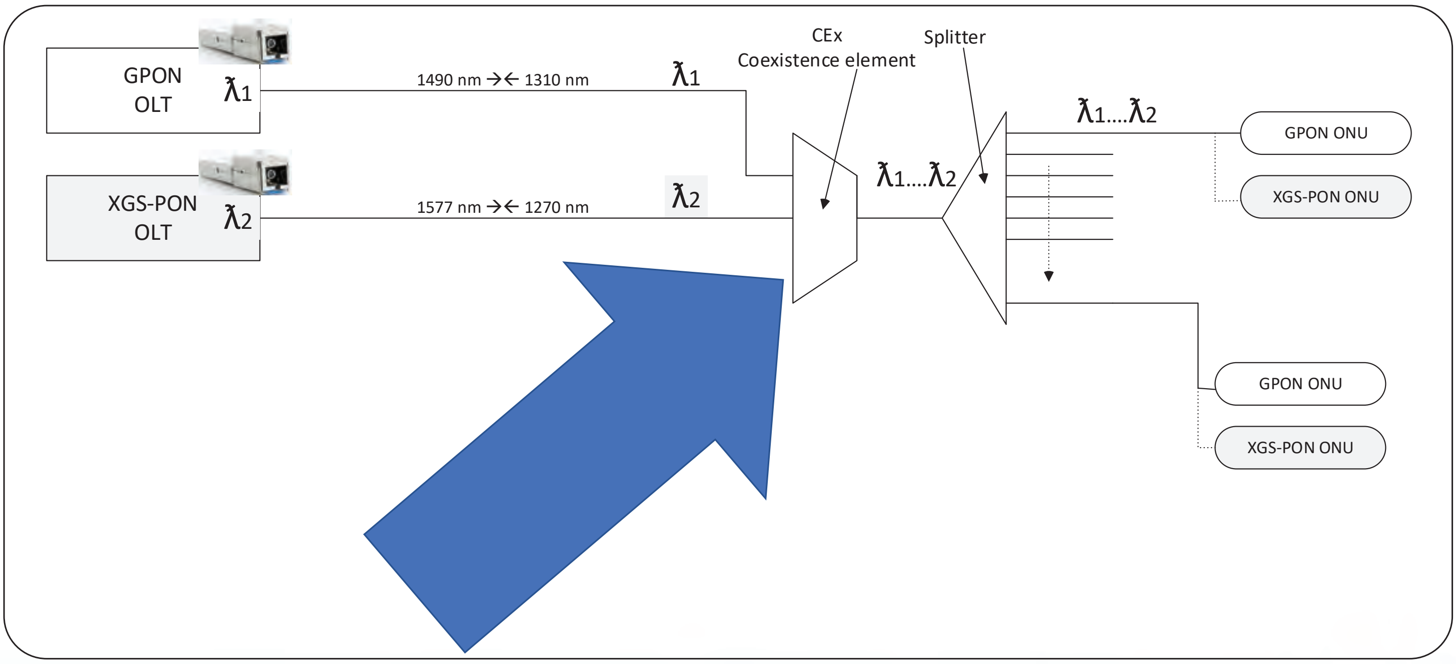
Nadgradnja / koeksistenca GPON in XGS-PON technologije



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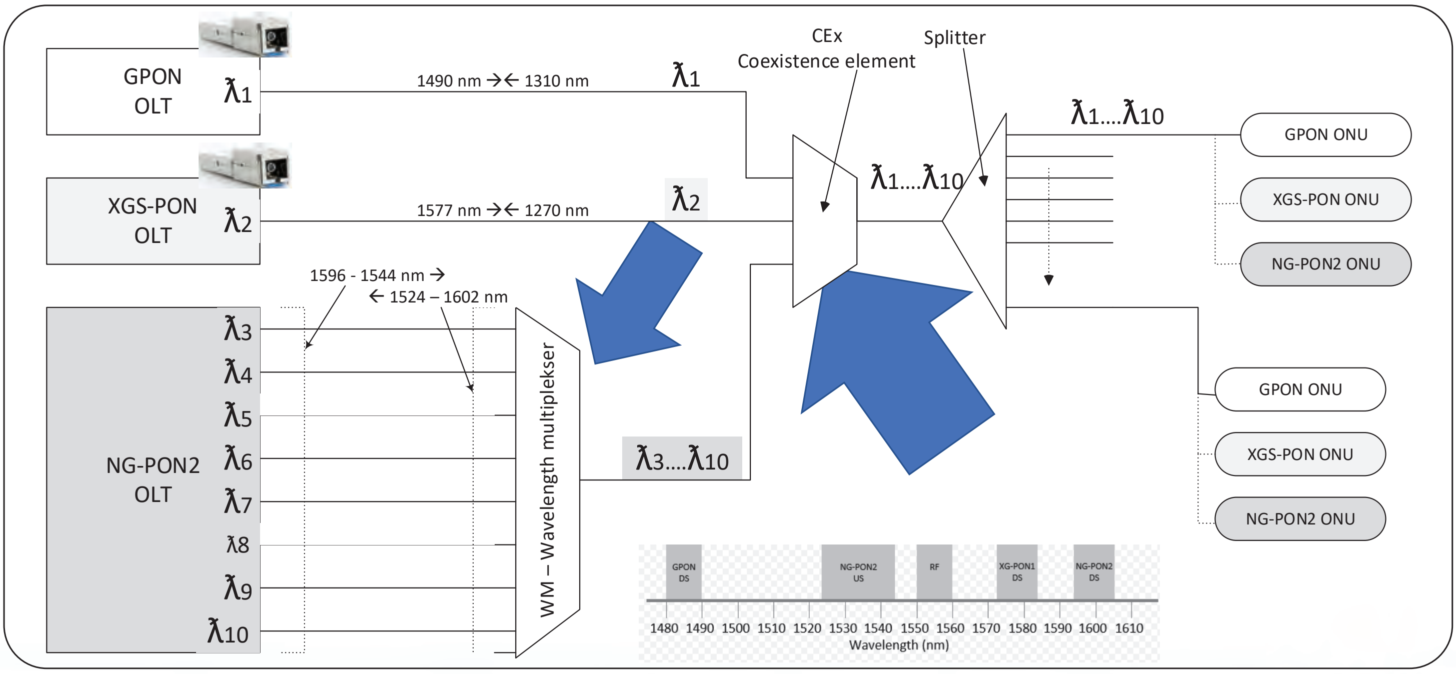
Nadgradnja / koeksistenca GPON / XGS-PON / NG-PON2



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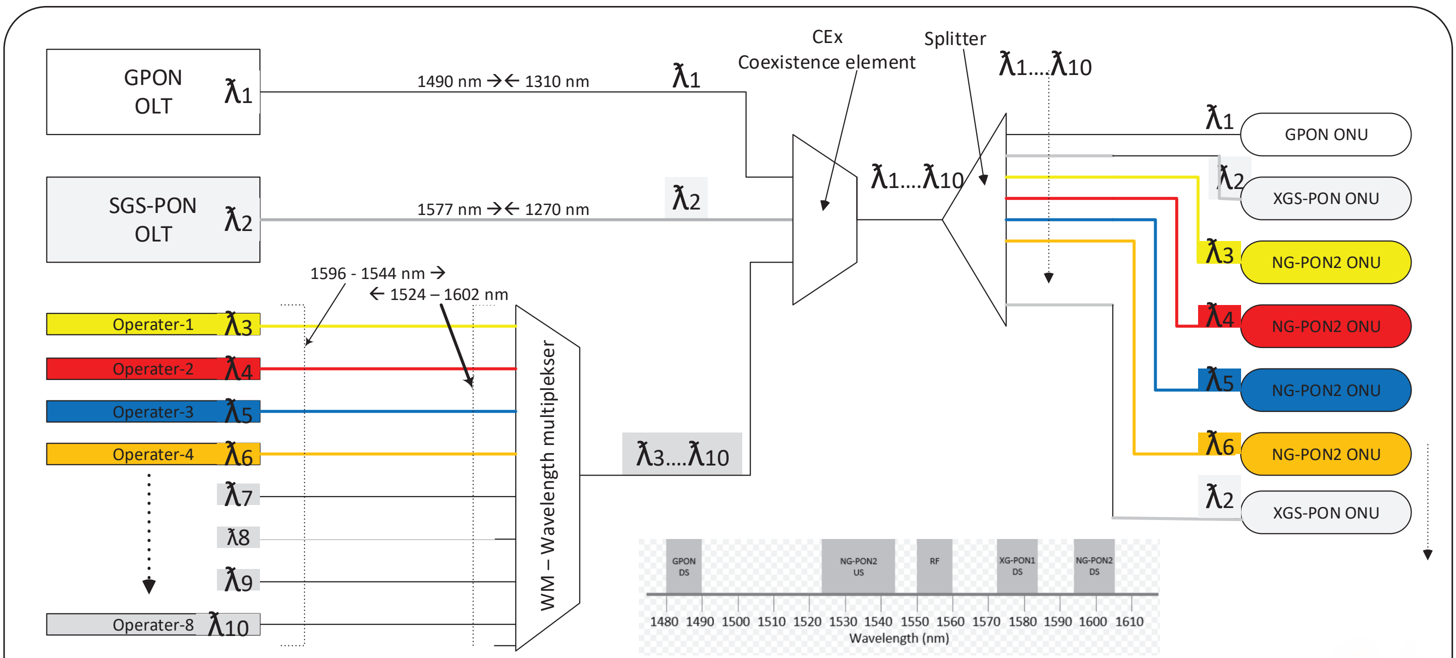
NG-PON2 in večoperatersko okolje na isti pasivni infrastrukturi



Večje število med seboj neodvisnih valovnih dolžin omogoča tudi uporabo NG-PON2 in XGS-PON v več - operaterskem okolju na isti pasivni infrastrukturi

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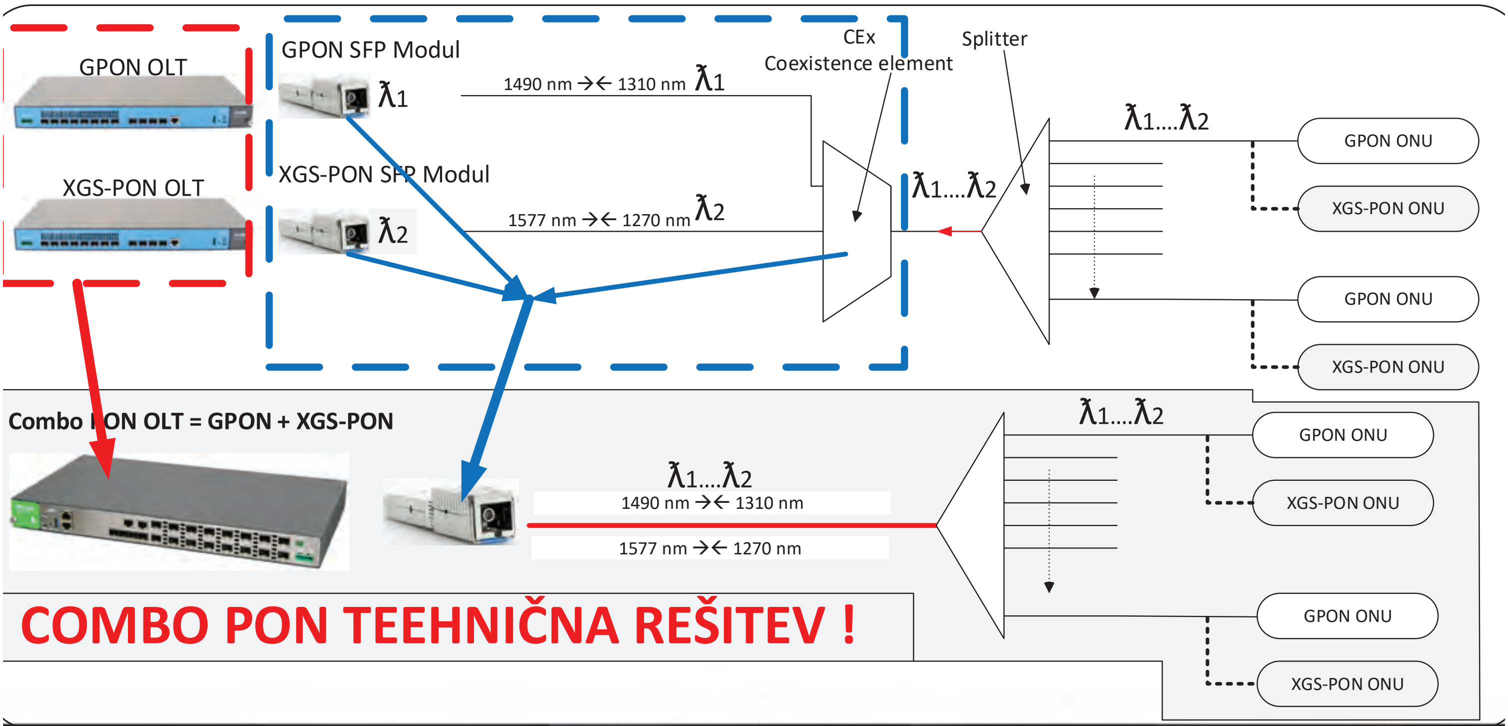
Combo PON TEHNIČNA REŠITEV



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Trenutno stanje področja XGS-PON (Combo)

- Zaključen pilotni projekt:
  - Combo PON instaliran v centralah (mestih)
  - Pokritost = „Raste“
  - Število vključenih uporabnikov v zaključni Combo pilotni projekt:
    - Cca. 1600 GPON uporabnikov na Combo OLT
    - Cca. 140 XGS-PON uporabnikov na Combo OLT
- Vprašanje:
  - Ali naročniki dejansko potrebujejo podatkovne hitrosti ki jih omogoča XGS-PON ?!
    - **Trenutno ni nobenih zahtev naročnikov za višje hitrosti 1 Gbit/s**
- **Trenutno: XGS-PON = „TEKMA“ PODROČIJ MARKETINGA IN PRODAJE !**

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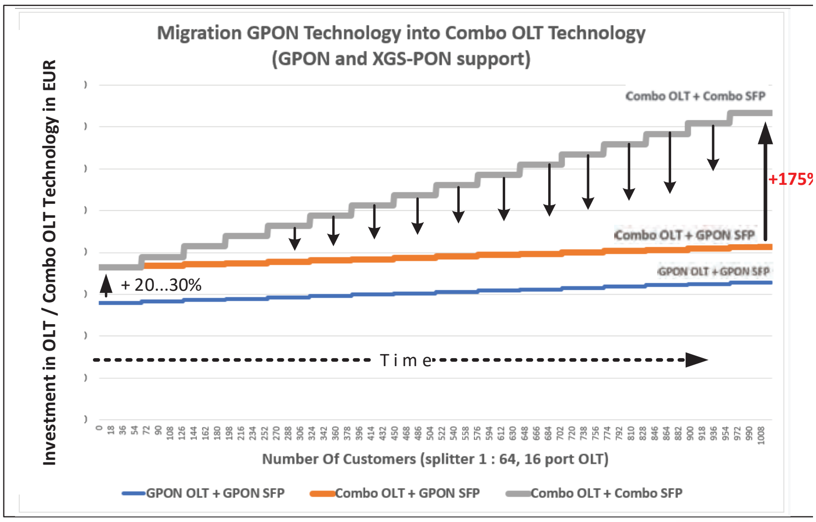
T-2 Pay as You Grow model implementacije

- **T-2 Tehnična odločitev:**
  Pay As You Grow
  - optimalna porazdelitev investicije glede na tržne razmere
- **Tehnična izvedba:**
  - Pričetek z Combo PON OLT HW (strojno opremo)
  - z GPON SFP moduli
  - .....
  - Nadomeščanje GPON SFP modulov z Combo SFP moduli



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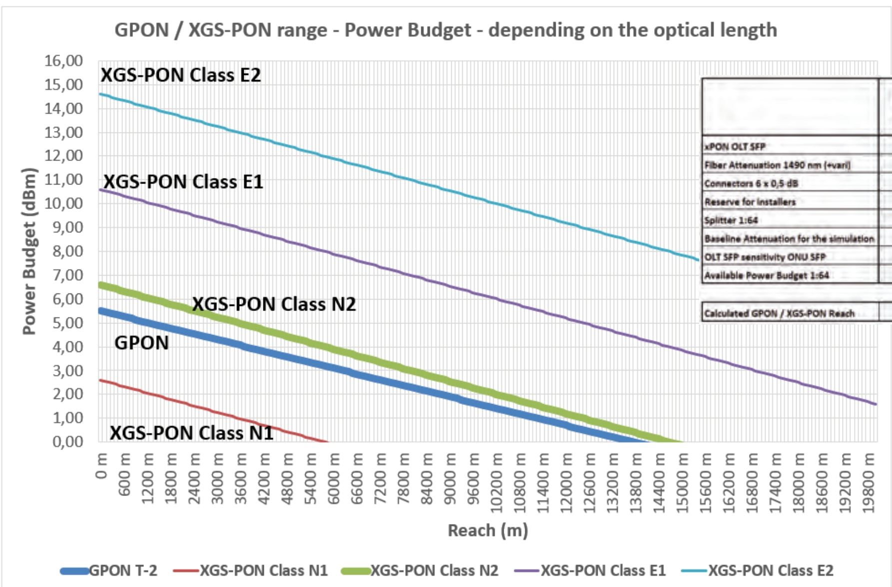
GPON & XGS-PON Simulacija dosegov z različnimi SFP moduli



	GPON B+ (povprečna vrednost v omrežju)	XGS-PON Class N1	XGS-PON Class N2	XGS-PON Class E1	XGS-PON Class E1	merska enota
xPON OLT SFP	2,4	3,5	5,5	7,5	9,5	Tx (dBm)
Fiber Attenuation 1490 nm (+vari)	-0,4	-0,45	-0,45	-0,45	-0,45	dB/km
Connectors 6 x 0,5 dB	-3	-3	-3	-3	-3	dB
Reserve for installers	-3	-3	-3	-3	-3	dB
Splitter 1:64	-20,9	-20,9	-20,9	-20,9	-20,9	dB
Baseline Attenuation for the simulation	-24,5	-23,4	-21,4	-19,4	-17,4	dBm
OLT SFP sensitivity ONU SFP	-30	-26	-28	-30	-32	dBm
Available Power Budget 1:64	5,5	2,6	6,6	10,6	14,6	dB
Calculated GPON / XGS-PON Reach	13,75	5,78	14,67	23,56	32,44	km

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ITU-T-REC-G.9804.3 - 50 Gbit/s - PON

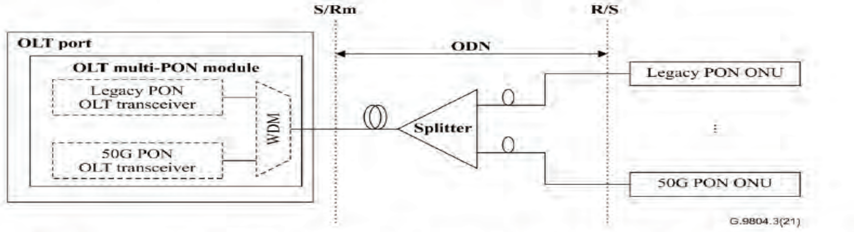

Figure 6-1 – General architectural reference diagram of 50G-PON coexisting with legacy PON using the OLT MPM method

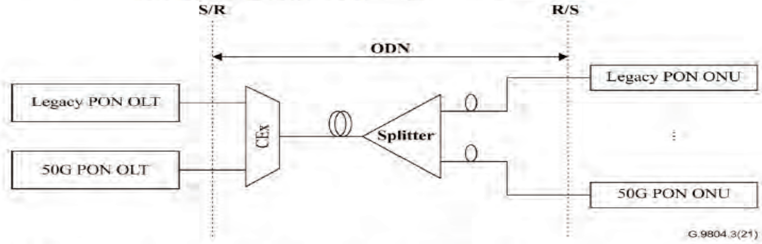

Figure 6-2 – General architectural reference diagram of 50G-PON coexisting with legacy PON using the external CEx method

Vir: ITU-T G.9804.3

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Zaključek

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Vprašanja

Hvala...

6. Seminar optične komunikacije – SOK 2023, Fakulteta za elektrotehniko, Ljubljana

Prenos sinhronizacije omrežja 5G v največjem in najsodobnejšem optičnem omrežju v Sloveniji

Transmission of 5G network synchronization in the largest and most modern optical network in Slovenia

Andrej Pučko

Telekom Slovenije

andrej.pucko@telekom.si

Povzetek

V prispevku je predstavljeno optično dostopovno omrežje Telekoma Slovenije (TS). Uvodoma so opisani trendi, strategijo in razvoj optičnega omrežja TS. V nadaljevanju so podrobneje opisani naslednji sklopi: optično hrbtenično omrežje TS, izvedba in delovanja tehnologije DWDM v omrežju TS in sinhronizacija (GM Clock), kjer je poudarek na podpori za PTP, NTP, SyncE in sinhronizaciji 5G preko DWDM.

Abstract

The paper presents the optical access network of Telekom Slovenije (TS). In the introduction, the trends, strategy and development of the TS optical network are described. The focus is on the following topics: TS optical backbone network, implementation and operation of DWDM technology in the TS network and synchronization (GM Clock), focusing on support for PTP, NTP, SyncE and 5G synchronization over DWDM.

Biografija avtorja

Andrej Pučko je diplomiral na Fakulteti za elektrotehniko Univerze v Mariboru. V Telekomu Slovenije je zaposlen že 20 let. Njegovo delovno področje obsega sisteme DWDM in SDH. Je skrbnik omrežja v jedrnem in dostopovnem omrežju in nudi podporo ključnim poslovnim uporabnikom Telekoma Slovenije. Ukvarja se tudi z raziskavami in razvojem novih transportnih storitev.

Author's biography

Andrej Pučko graduated from the Faculty of Electrical Engineering of the University of Maribor. He has been employed at Telekom Slovenije for 20 years. His field of work includes DWDM and SDH systems. He is the network administrator in the core and access network and provides support to key business users of Telekom Slovenije. He is also involved in research and development of new transport services.

Prenos sinhronizacije omrežja 5G v največjem in najsodobnejšem omrežju v Sloveniji

Andrej Pučko

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Optično dostopovno omrežje Telekoma Slovenije

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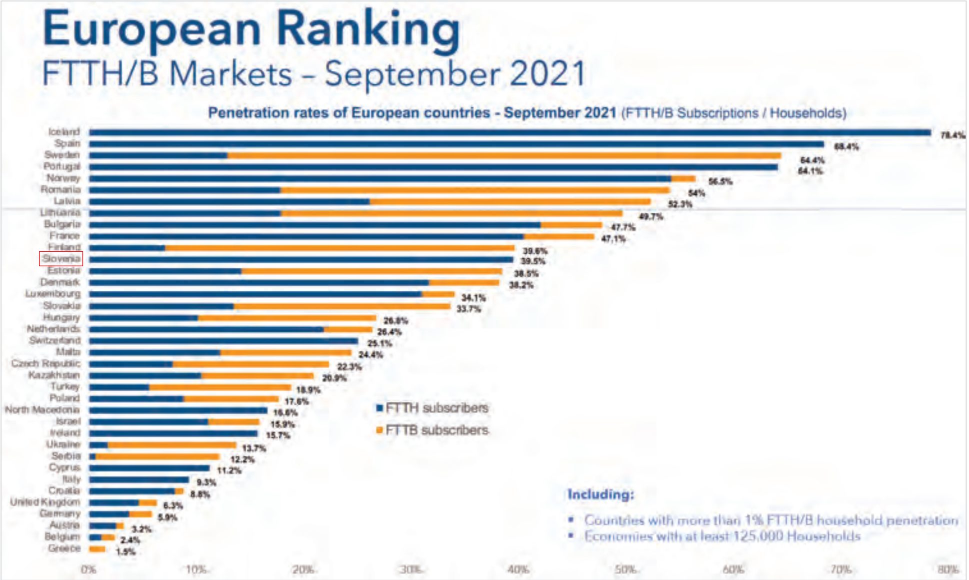
Trendi

- Giga Home evolucija
- Rast podatkovnega prometa in NGA priključkov
- Internet stvari
- Mobilnost
- Pospešena FTTH gradnja
- Konvergenca 5G in FTTH
- Novi poslovni modeli (Smart-x) in ekosistemi
- Varnost in zasebnost
- Kakovost in odlična uporabniška izkušnja
- Infrastrukturna konkurenca
- Nove tehnologije in višje potrebe po pasovni hitrosti
- Opuščanje bakrenih omrežij



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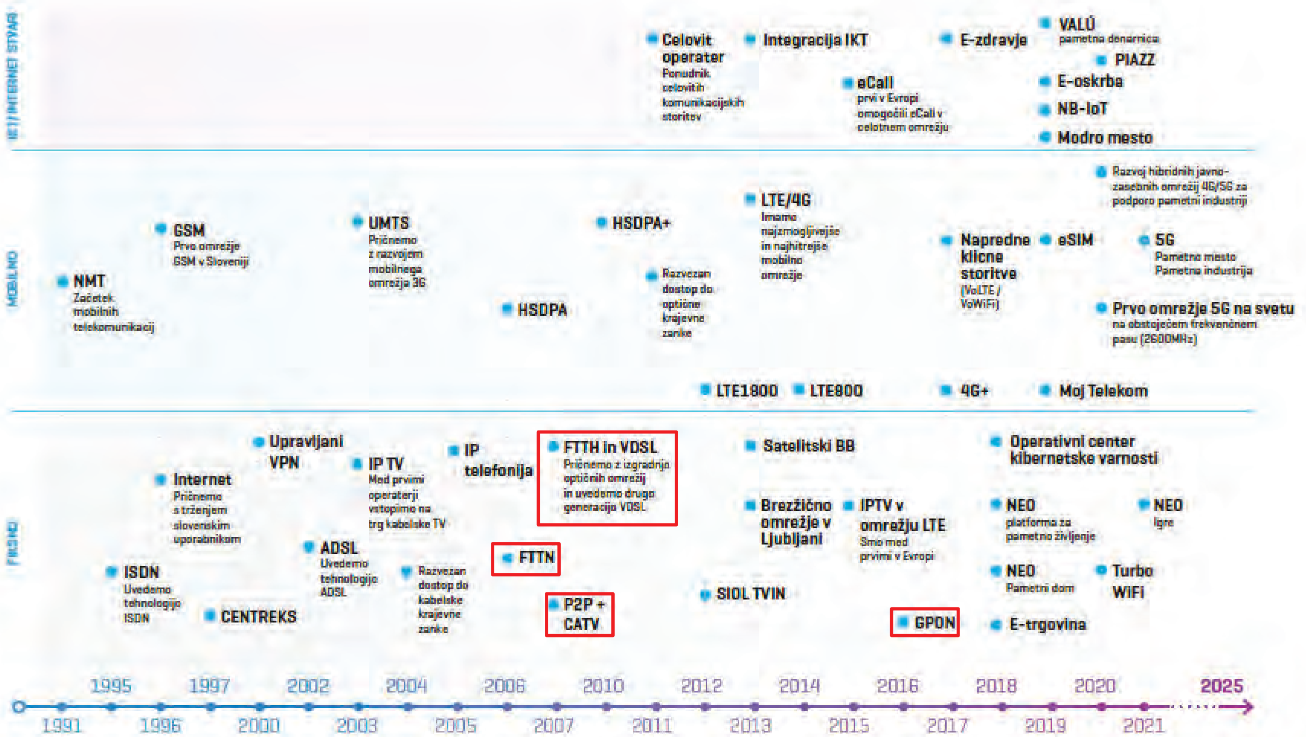
Razvoj omrežja in storitev Telekoma Slovenije skozi čas



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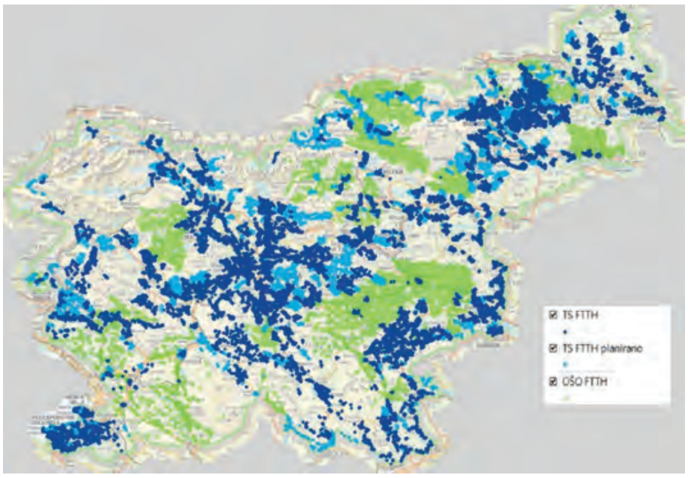
Širokopasovna strategija države

- 2016: Načrt NGN 2020 (do leta 2020 zagotoviti 100Mbit/s dostop 96 % gospodinjstev; preostalim 4 % pa 30Mbit/s)
- 2018: Dodatek k Načrtu NGN 2020
  - do leta 2025: šole, univerze, prometna središča 1Gbit/s simetrično
  - do leta 2025: vsa gospodinjstva 100Mbit/s z možnostjo nadgradnje na 1Gbit/s
  - do leta 2025: urbana območja ter pomembnejše ceste in železnice neprekinjeno pokrite s 5G

Gradnja FTTH Telekoma Slovenije:

- FTTH gradnja od leta 2007.
- Trenutno pokrivamo 440.000 gospodinjstev (53 % od 824.000).
- Odprto omrežje, pod enakimi pogoji za vse.
- Pokritost gospodinjstev: 26 % na ruralu, 43 % na suburbanih in 55 % na urbanih področjih.
- 43 % zgrajene optične infrastrukture Telekoma Slovenije na področjih, kjer je gostota naseljenosti pod 500 prebivalcev/km^2.



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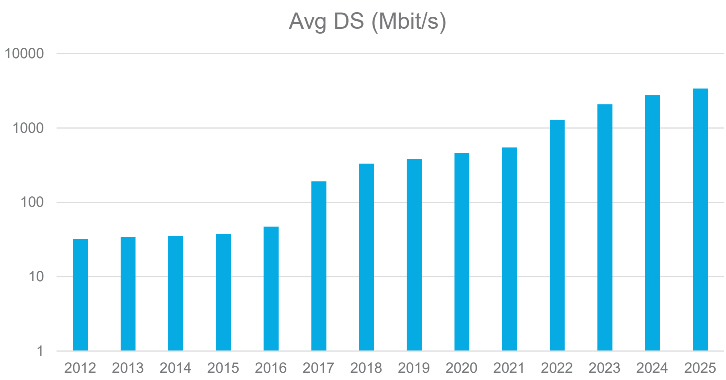
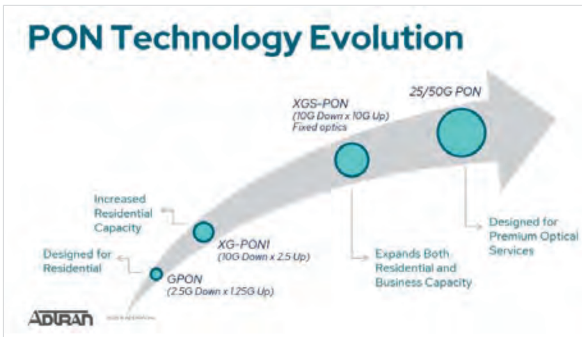
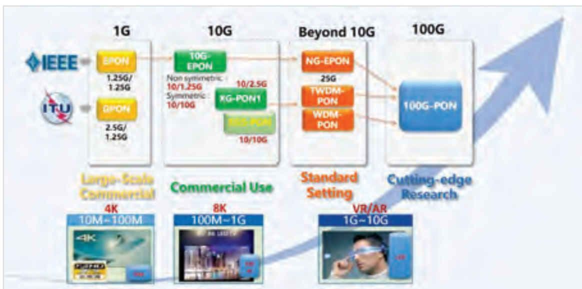
Trendi FTTH omrežij



Vir: Telekom Slovenije





Vir: https://www.academia.edu/38090047/Fiber_Home_GPON_Solutions

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DWDM omrežje Telekoma Slovenije

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7

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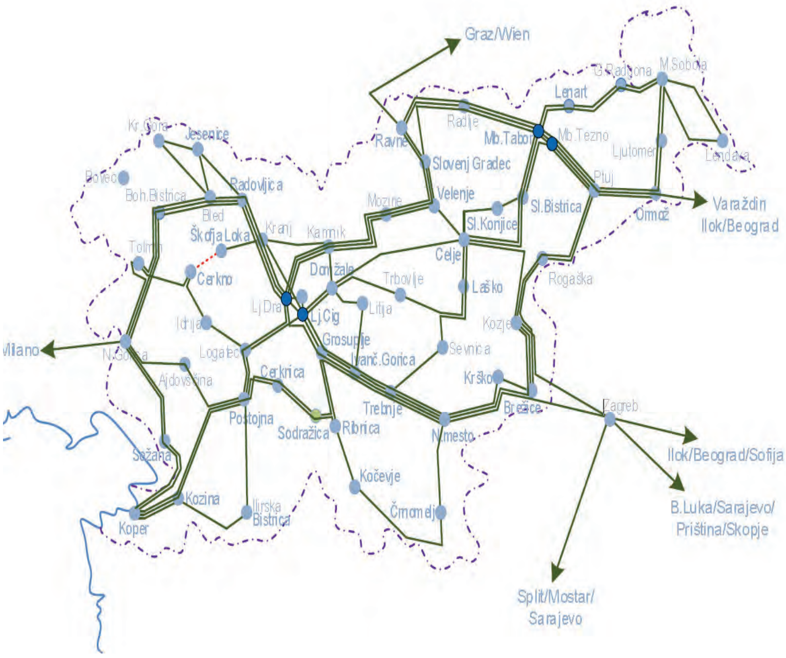
DWDM omrežje: Slovenija in ROO



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DWDM omrežje: Slovenija in ROO

Routing valovnih dolžin vsepovsod

Fixed OADM is an agility bottleneck

iROADM-4

C-F expandable in service to CD-F

iROADM-9

CDC-F: Compact, cost effective, and easy to configure

iROADM-20

Enables ROADM in metro → Enables C-F and CD-F ROADM → Enables CDC-F with higher number of degrees

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DWDM omrežje: Slovenija in ROO

Routing valovnih dolžin vsepovsod

DWDM:

- > 250 NEs
- 13 OTN NEs
- 34 ILA sites
- > 7000 km optičnih vlaken
- > 60 OMS 44-kanalni
- > 80 OMS 96-kanalni
- > 50 NEs za Sync (5G)

DWDM zasedba:

- Lambda 10G – 280
- Lambda 40G – 7
- Lambda 100G – 93
- Lambda 200G – 43

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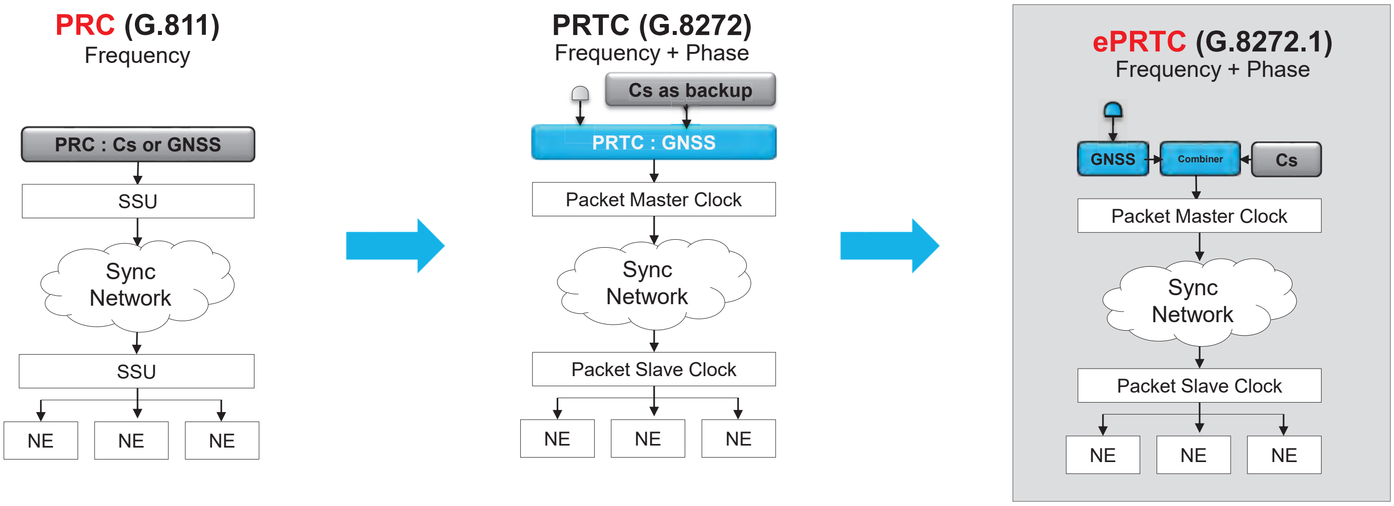
Cezijeva ura kot vir



PRC (PRECISION REFERENCE CLOCK)

PRTC (PRIMARY REFERENCE TIME CLOCK)
TE DO 100NS

ePRTC (ENHANCED PRIMARY REFERENCE TIME CLOCK
TE DO 50NS

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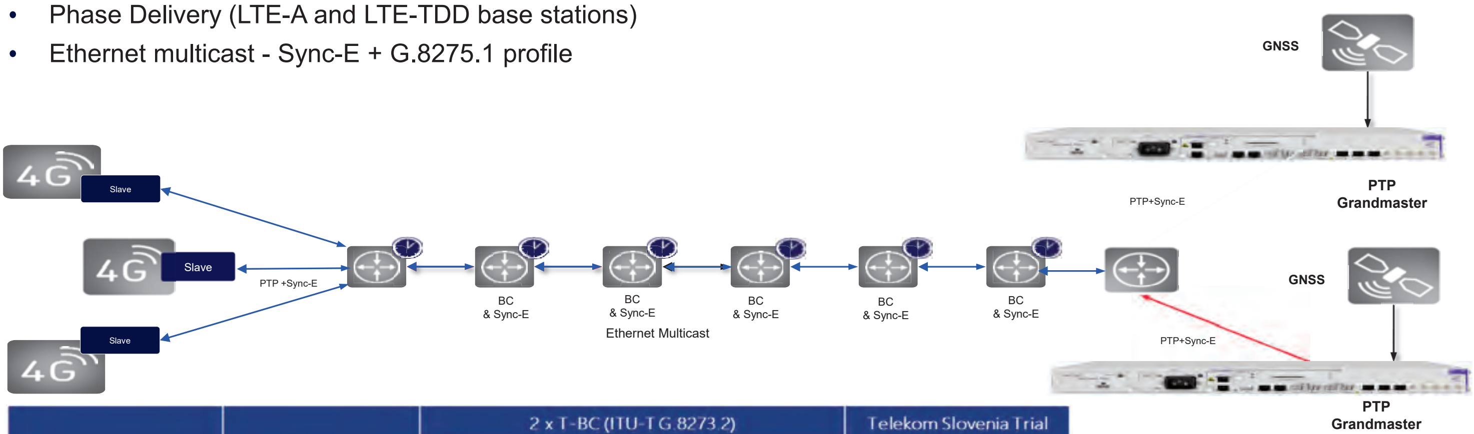
Mobilna distribucija faze G8275.1 z uporabo PTP

- Phase Delivery (LTE-A and LTE-TDD base stations)
- Ethernet multicast - Sync-E + G.8275.1 profile



+2	Parameter	2 x T-BC (ITU-T G.8273.2)			Telekom Slovenia Trial 2 x T-BC + ILA + Remote PRTC
		Already specified			
		Class A	Class B	Class C	
ITU-T G.8273.2 performance requirements (µs)	maxITEI	160	100	42	14.5
	cTE	±100	±40	±20	-6.9
	dTE_L (MTIE)	60	60	14	16.4
	dTE_L (TDEV)	6	6	3	1.3
	dTE_H	70	70	FFS	14

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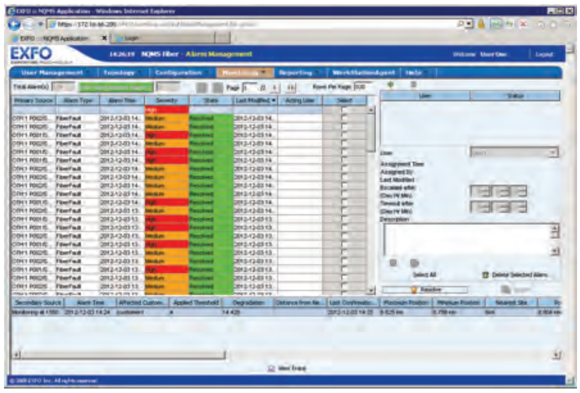
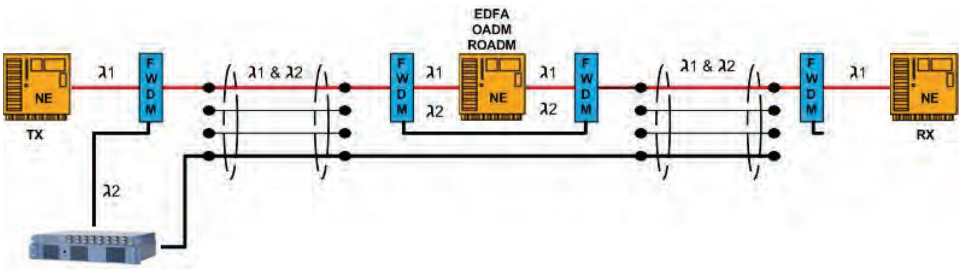
NQMS – fiber nadzor optičnih vlaken



Scenariji nadzora

Both Active (In-Service) and Passive (Dark) Fibre Monitoring



- All testing will be in a 'round robin' sequence
- Priority can be given to specific ports if required

Razvoj se nadaljuje

- Telekom Slovenije danes omogoča priklop na svoje optično omrežje več kot 440.000 gospodinjstvom v Sloveniji, kar je več kot polovici vseh gospodinjstev v državi.
- Ob tem nadaljujemo z aktivnostmi za nadgradnjo svojega optičnega omrežja s tehnologijo XGS-PON, kar bo omogočilo hitrosti prenosa do deset gigabitov v sekundi.

- V letu 2022 smo na svoje optično omrežje priključili 42.150 dodatnih gospodinjstev. V letu 2023 na ravni skupine načrtujemo investicije v višini 205,5 milijonov evrov (poleg vlaganj v širitev in nadgradnjo optičnega dostopovnega omrežja ter nadaljnji razvoj in modernizacijo mobilnega omrežja znesek vključuje tudi investicije v programske pravice in kapitalizacijo najemnin).
- Obstoječi in novi naročniki na optičnem omrežju Telekoma Slovenije lahko nadgradijo hitrosti svojega interneta na do 2 gigabita na sekundo v smeri do uporabnika.
- DWDM, prehod na „čisti" koherentni prenos, 96 kanalov po sekciji (OMS), vključitev valovnih dolžin hitrosti do 400G.

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NextGEN PON technologies and challenges they bring

Milorad Sarić

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Abstract

Demand for higher bitrates is constantly growing and limitations with current G-PON are getting more and more noticeable. During next year 10G PON technologies will out-deploy GPON. New PON architectures are also emerging to increase cascading capability and scalability. PON technologies coexistence will ease the required transition, but besides numerous benefits NextGEN PON will offer, there are some new challenges to consider along with the old maintenance challenges inherited from GPON.

Author's biography

Milorad Sarić is technical support engineer with 15 years' experience in presales and postsales support of test and measurement solutions.
He is employed at IBIS Instruments since 2018. He is member of IBIS technical T&M team and responsible for wireline communications solutions (Access Copper, CATV and Optical Networks) and General-Purpose instruments. Milorad graduated in 2007. at the Faculty of Electrical Engineering in Belgrade.


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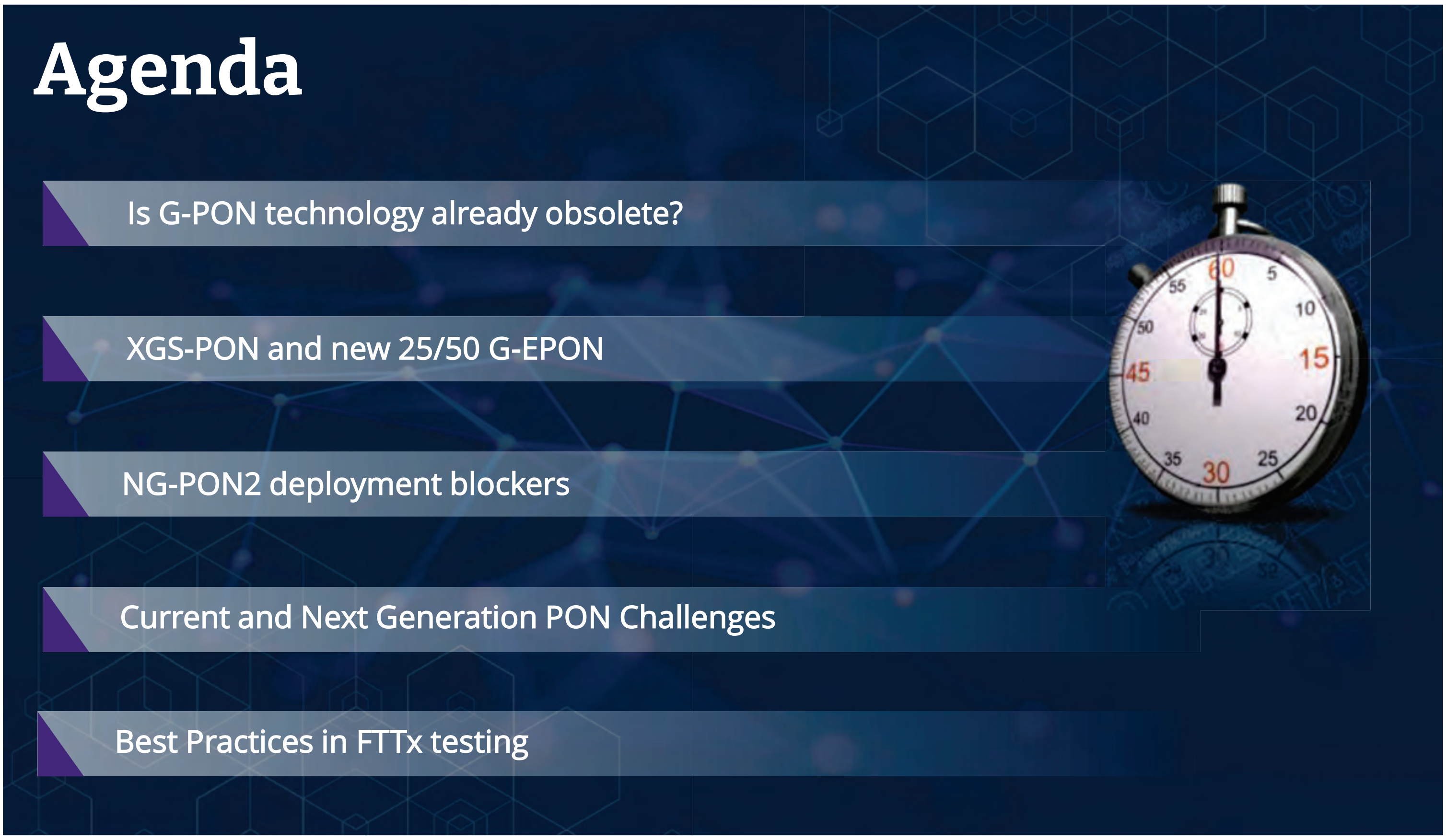
NextGEN PON technologies
and challenges they bring
Milorad Sarić
Technical support for Wireline portfolio
January 2023


Agenda
Is G-PON technology already obsolete?
XGS-PON and new 25/50 G-EPON
NG-PON2 deployment blockers
Current and Next Generation PON Challenges
Best Practices in FTTx testing

Is G-PON technology already obsolete?

Demand for higher bitrates is growing

	The past		The future	
PHOTO	12 MP smartphone photo	3MB	30-50 MB	180 degree photo digital sculpture
WEB	Average web page size in 2017	3MB	30-50 MB	3D web scene
VIDEO CALL	Video chat apps	1-5 Mbps	25-50 Mb/s	Holo-chat 1 person
VIDEO	4K, 8K	5-20 Mbps	100 Mb/s – 1 Gb/s	Free viewpoint video

Source: Nokia

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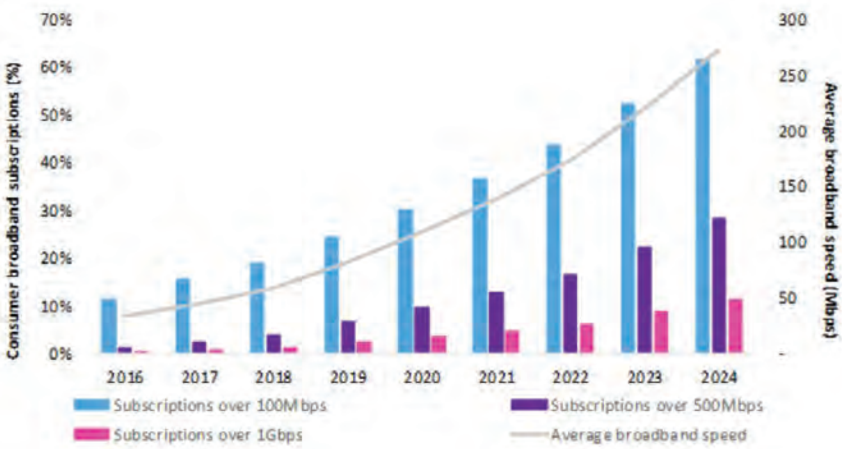
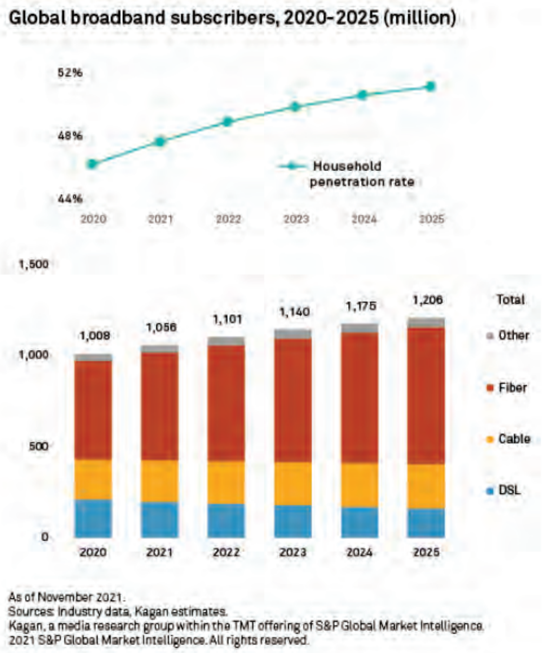
Global broadband subscriptions by speed





Source Omdia

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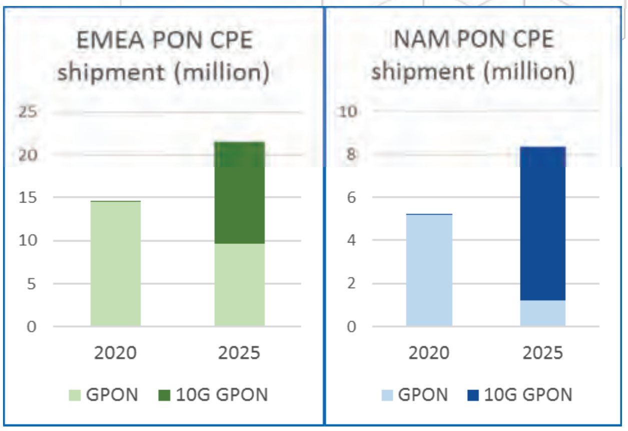
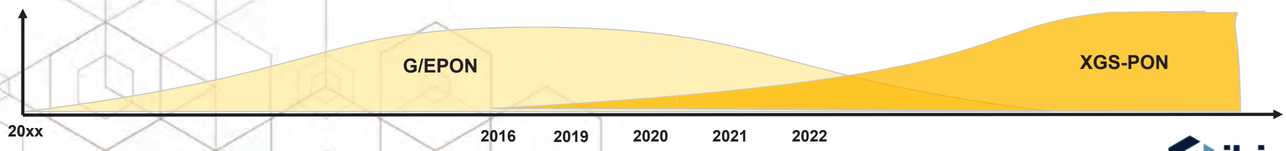
Market View

- **10G PON** technologies will out-deploy GPON and EPON
- Strong growth for Next Gen PON (XGS-PON) from 2021 onwards
- 10G EPON will stay flat
- NG-PON2 more expensive; low adoption

Source: Omdia Wireline Access July 2020





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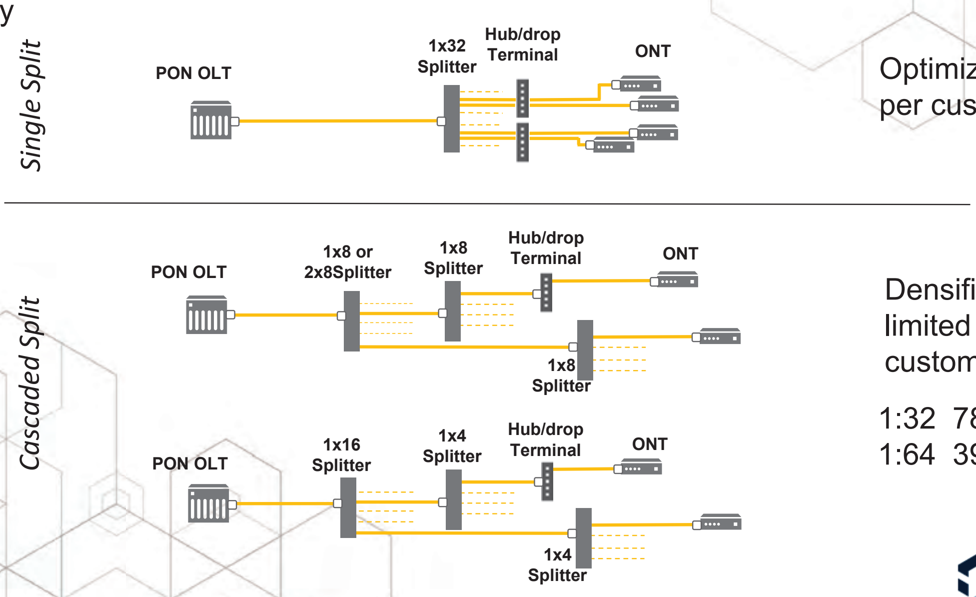
Existing PON Architectures according ITU-T G.984 (2003)

- The larger the split ratio, the more attractive for the service provider.
- Split ratio of up to 1x64 is largely deployed and is realistic for the physical layer, with the current technology



Optimized speed per customer

Densification but limited bit rate per customer

1:32 78Mbps down
1:64 39Mbps down

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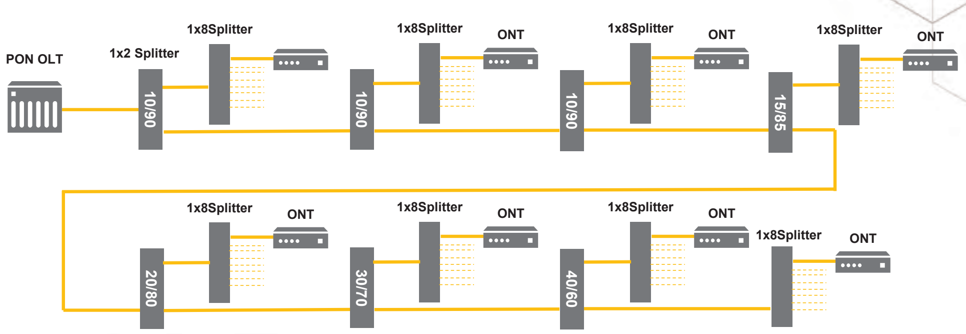
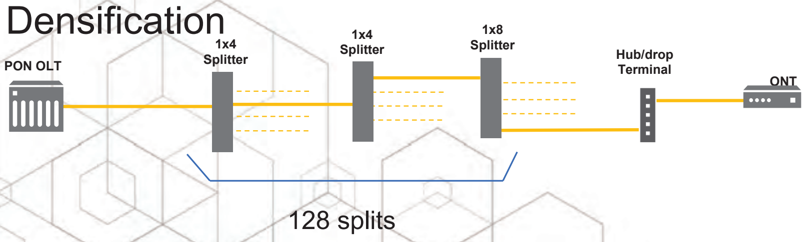
New Architectures

Unbalanced



Uneven splitting ratio to increase cascading capability and scalability. South America

Densification



Increase densification in standard PON architectures

but limited bit rate per customer.

1:32 78Mbps down
1:64 39Mbps down
1:128 19Mbps down

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XGS-PON and new 25/50 G-EPON

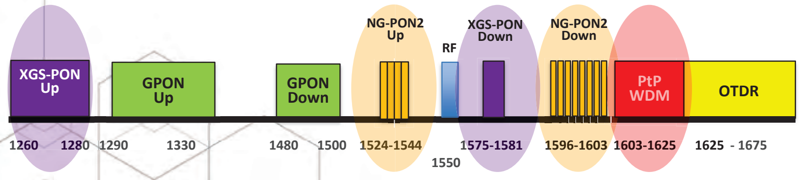
Next-Generation PON Standards

- Limitations with current G-PON/GE-PON standards
- Standards have been defined by ITU-T & IEEE:

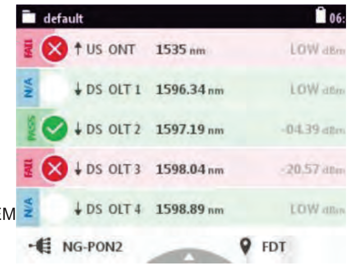
	G-PON	XGS-PON *(sym)*	NG-PON2	G-EPON	10G-EPON	25/50 G-EPON
Standards	ITU-T G.984 (2003)	ITU-T G.9807.1 (2016)	ITU-T G.989 (2015)	IEEE 802.3ah (2004)	IEEE 802.3av (2009)	IEEE 802.3ca (2020)
US / DS Data Rates	1.25 / 2.5 Gbps	10 / 10 Gbps	10 / 40/ 80 Gbps	1.25 / 1.25 Gbps	10 / 10 Gbps	25/25 or 50/50 Gbps
Splitting Ratio	up to 1:64 (128)	up to 1:128 (256)		up to 1:64	up to 1:128	up to 1:128
Fiber Type	G.652	G.652 / G.657 (for new inst.)		G.652	G.652 / G.657 (for new inst.)	
Max Loss	32 dB	35 dB	35 dB	29 dB	29 dB	33 dB
Co-existence	N/A	YES with G-PON		N/A	Yes with GE-PON	

PON Spectrum: WAVELENGTH EVOLUTION PLAN

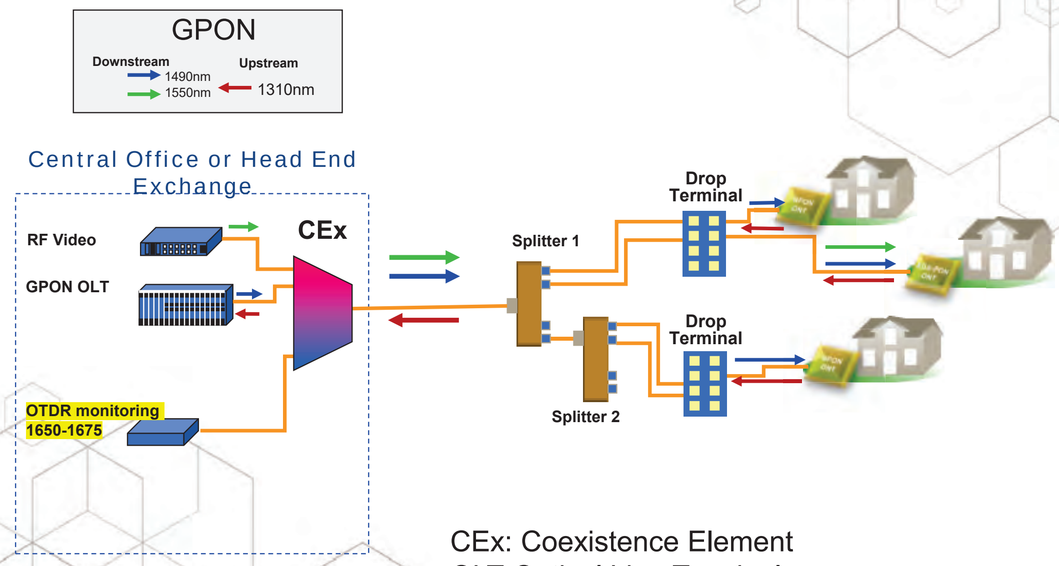
- Today's GPON systems utilize 2 wavelengths for communication
  - Downstream 2.5 Gbps at 1490 nm & upstream 1.25 Gbps at 1310 nm
- Overlay of 2 new λ for 10 Gbps services of XGS-PON
  - Downstream 10 Gbps at 1577 nm & upstream 10 Gbps at 1270 nm
- NG-PON2 supports multiple 10Gbps wavelengths
  - Downstream 4/8 x 10 Gbps at 4/8 TWDM wavelengths between 1596 – 1603 nm
  - Upstream 4/8 x 2,5 Gbps at 4/8 TWDM wavelengths between 1524 – 1544 nm
- Additional window for high speed P2P WDM channels: 1603 – 1625 nm
- RF overlay at 1550 nm is not impacted by PON service
- Wavelength window for in-service testing (OTDR): 1650 nm – 1675 nm

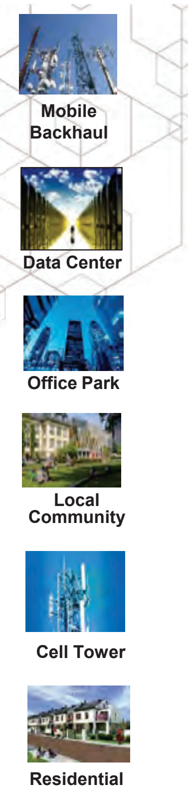


Source: FTTH EM



PON Coexistence Architecture (Similar for EPON)





CEx: Coexistence Element
OLT-Optical Line Terminal
ONU/ONT-Optical Network Unit/Terminal

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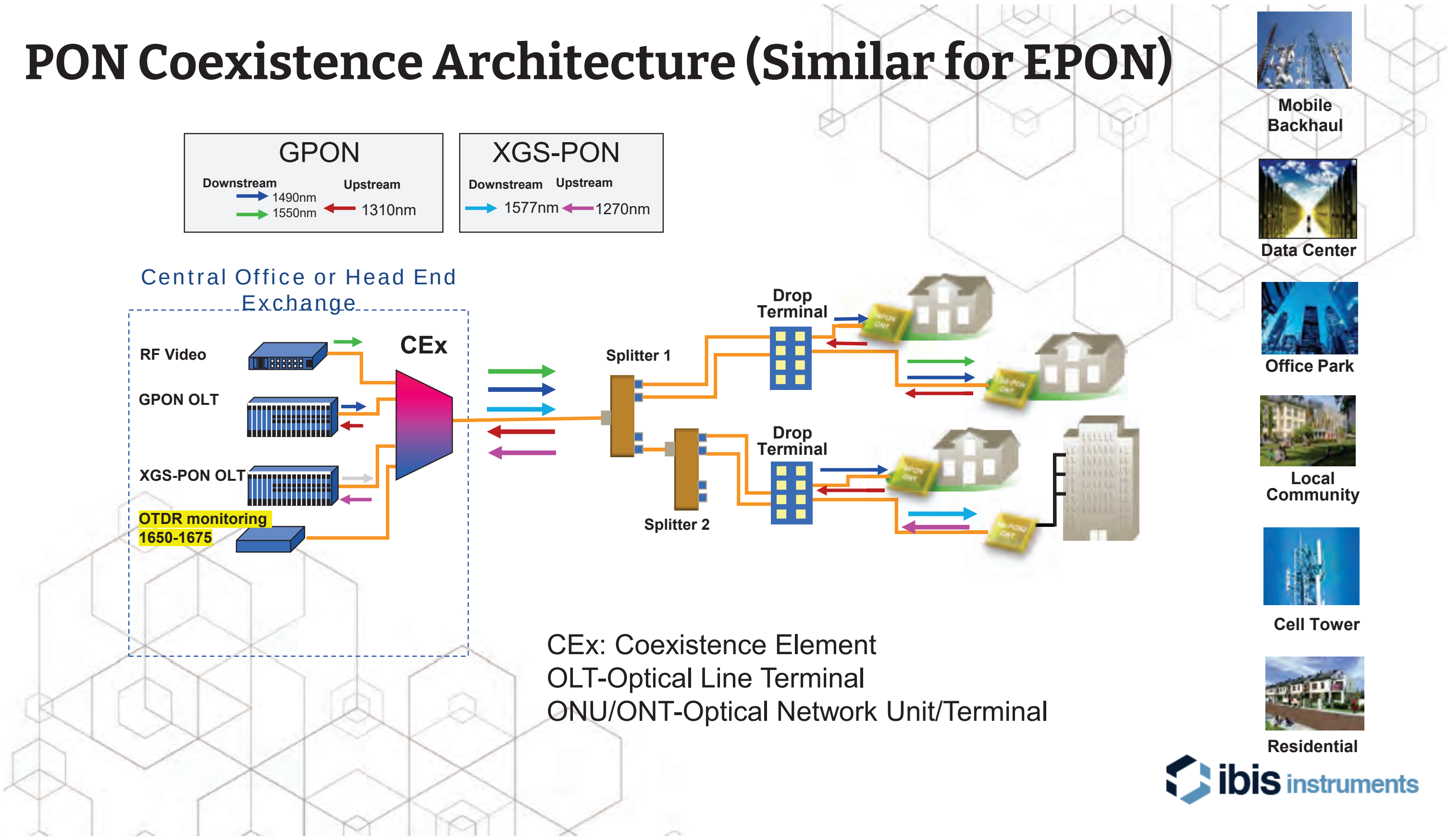

PON Coexistence Architecture (Similar for EPON)
GPON
Downstream
1490nm
1550nm
Upstream
1310nm
XGS-PON
Downstream
Upstream
1577nm
1270nm
Central Office or Head End Exchange
RF Video
GPON OLT
XGS-PON OLT
OTDR monitoring 1650-1675
CEx
Splitter 1
Splitter 2
Drop Terminal
Drop Terminal
CEx: Coexistence Element
OLT-Optical Line Terminal
ONU/ONT-Optical Network Unit/Terminal
Mobile Backhaul
Data Center
Office Park
Local Community
Cell Tower
Residential
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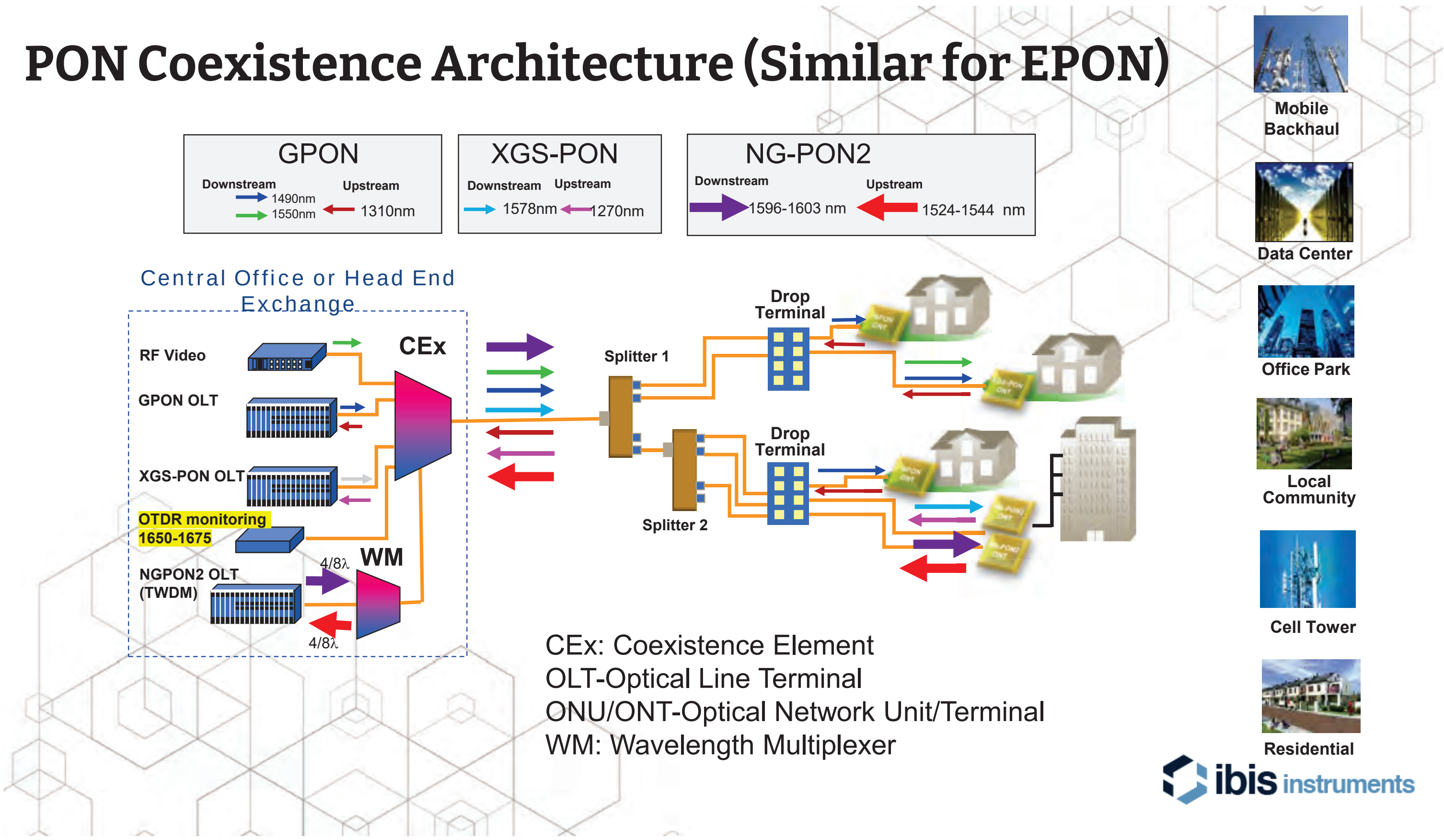

PON Coexistence Architecture (Similar for EPON)
GPON
Downstream
1490nm
1550nm
Upstream
1310nm
XGS-PON
Downstream
Upstream
1578nm
1270nm
NG-PON2
Downstream
1596-1603 nm
Upstream
1524-1544 nm
Central Office or Head End Exchange
RF Video
GPON OLT
XGS-PON OLT
OTDR monitoring 1650-1675
NGPON2 OLT (TWDM)
4/8λ
4/8λ
WM
CEx
Splitter 1
Splitter 2
Drop Terminal
Drop Terminal
CEx: Coexistence Element
OLT-Optical Line Terminal
ONU/ONT-Optical Network Unit/Terminal
WM: Wavelength Multiplexer
Mobile Backhaul
Data Center
Office Park
Local Community
Cell Tower
Residential
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25/50 G-EPON according to IEEE 802.3ca

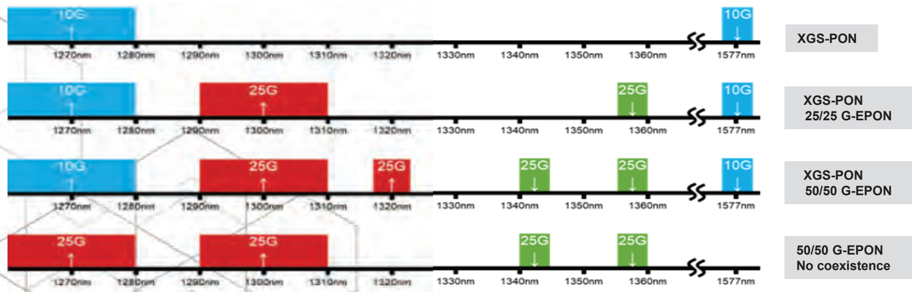
Approved in June 2020

Standard	Terminology	Bandwidth	Wavelengths	Core applications
25G/50G -EPON IEEE 802.3 ca	**High Speed EPON**	2 x 10G Up 2 x 25G Up 2 x 25G Down	Low O band Up High O band Down	Business services/MDU 5G Transport

Allows symetrical operation 25/25 or 50/50 Gbps as well as asymetrical 25/50 Gbps.

Used fixed wavelengths, instead of tunable wavelengths, and wideband optics in O-band without dispersion compensation are main advantages in comparison with NG-PON2.

25/50 G-EPON is designed to enable symmetrical 10G to coexist with either symmetrical 25G or 50G traffic on the same fiber as well. See various coexistence scenarios.



MDU **M**ultiple **D**welling **U**nit

Source: Calix

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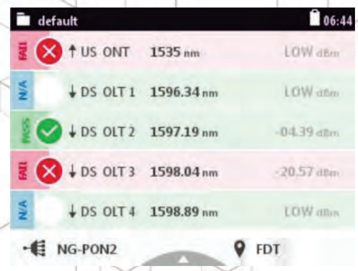
NG-PON2 deployment blockers

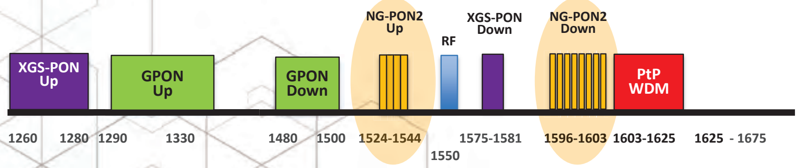
NG-PON2 Spectrum



- NG-PON2 supports multiple 10 Gbps wavelengths
  - Downstream 4/8 x 10 Gbps at 4/8 TWDM wavelengths between 1596 – 1603 nm
  - Upstream 4/8 x 2,5 Gbps at 4/8 TWDM wavelengths between 1524 – 1544 nm

NG-PON2 blockers:

- Multi-wavelength NG-PON2 requires **tunable optics** at the ONU (Optical Network Unit) endpoint.
- NG-PON2 is very sensitive to macrobendings mainly in house cabling. It requires G.657B/C cabling instalations. Upgrade of older G-PON networks to NG-PON2 **requires also upgrade of in house cabling (from G.652 to G.657B/C)!**



Source: FTTH EMEA D&O Committee FTTH Poland 2015

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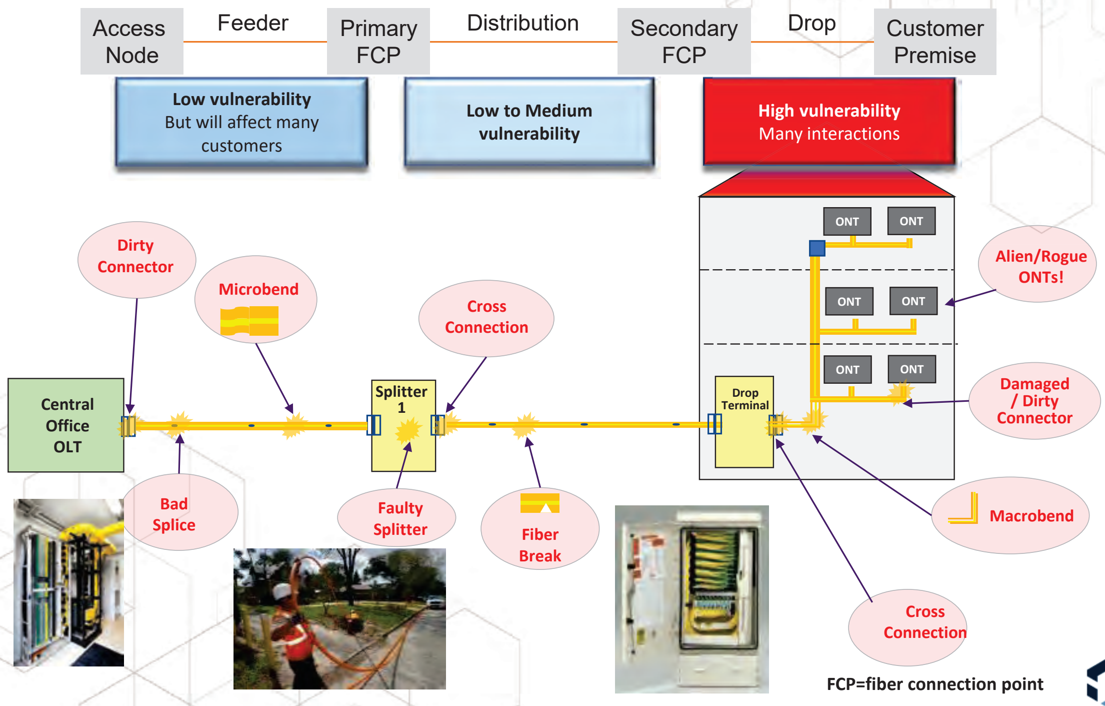
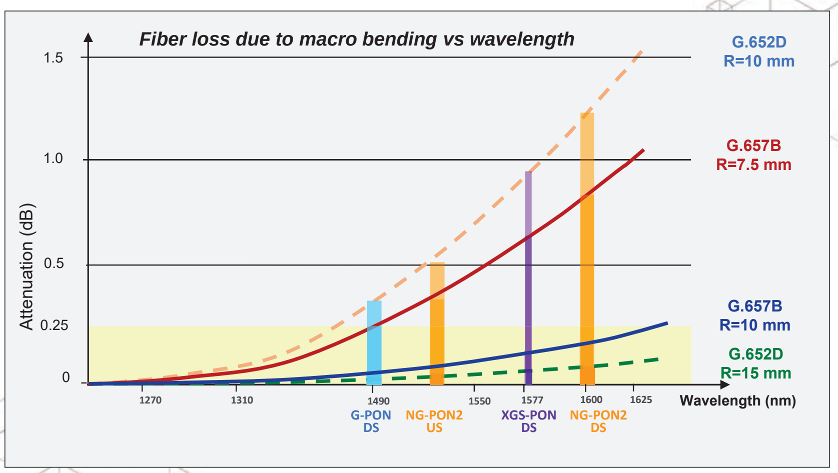
Current and Next Generation PON Challenges

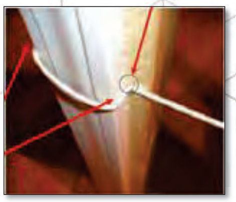
Main Physical Points of Vulnerability or Issues in an FTTH network



FCP=fiber connection point

Bending Constraints – Impact on NG-PON





According to Verizon, radius around corners can go down <10 mm

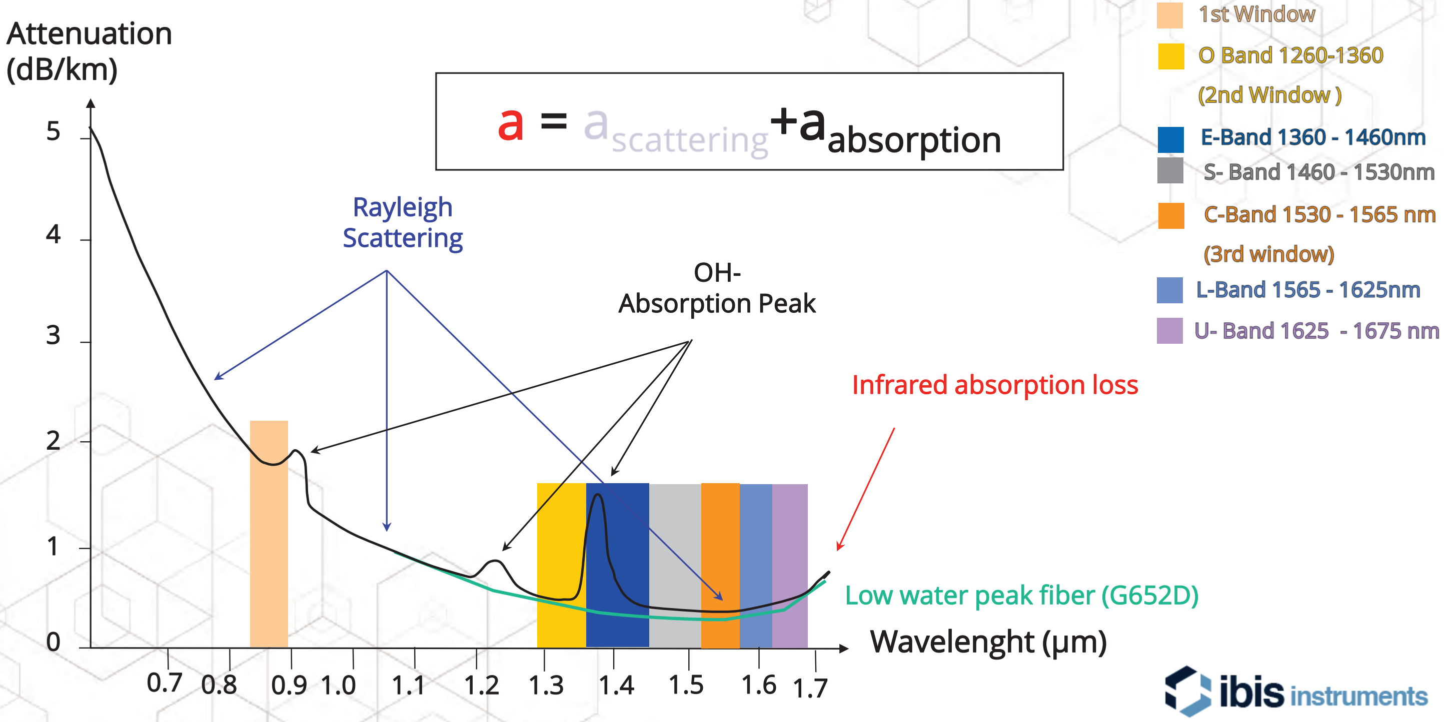
XGS-PON or NG-PON2 new construction is similar to G-PON with a special focus on loss induced by fiber bending

Longer wavelengths > higher sensitivity to macrobend (in house cabling!)

- Use of G.657B bend insensitive fiber (works down to 10 mm radius)

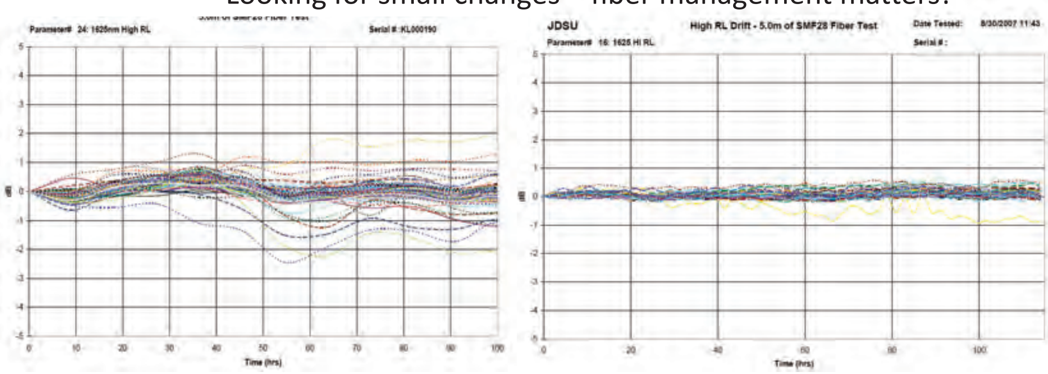
Characterization at 1625/1650 nm will become a strong requirement

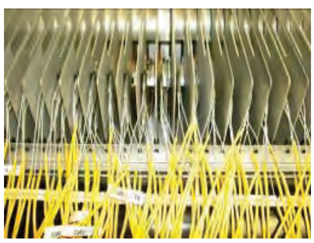
Spectral attenuation



Fiber Management is Key

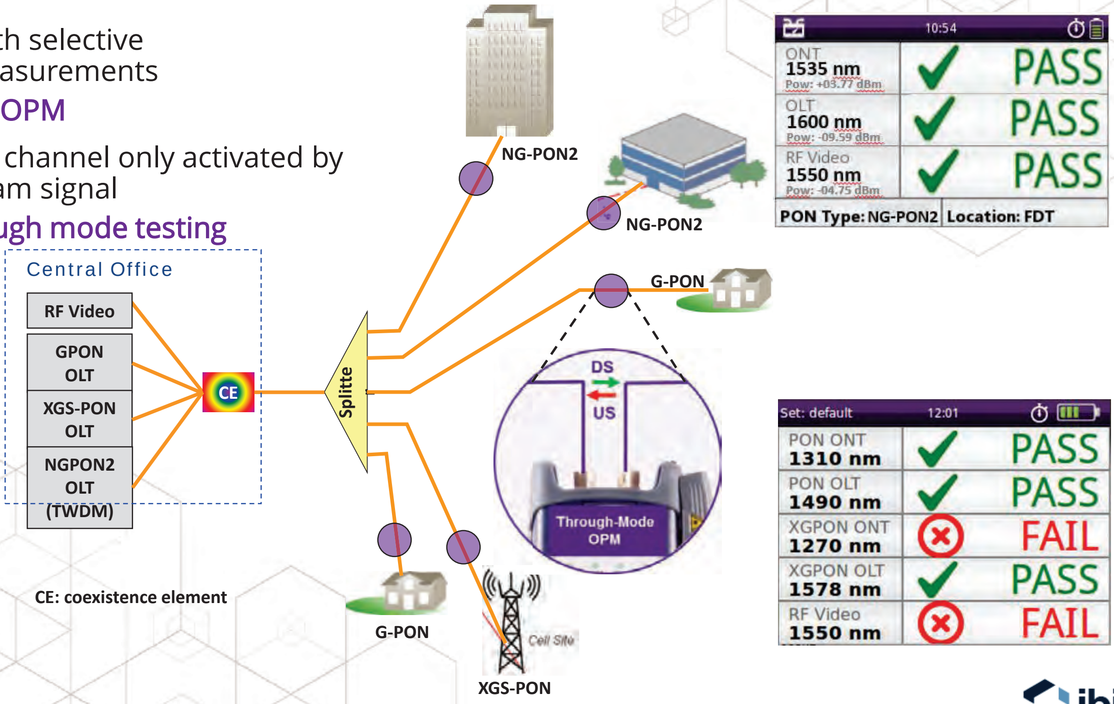
Looking for small changes – fiber management matters!





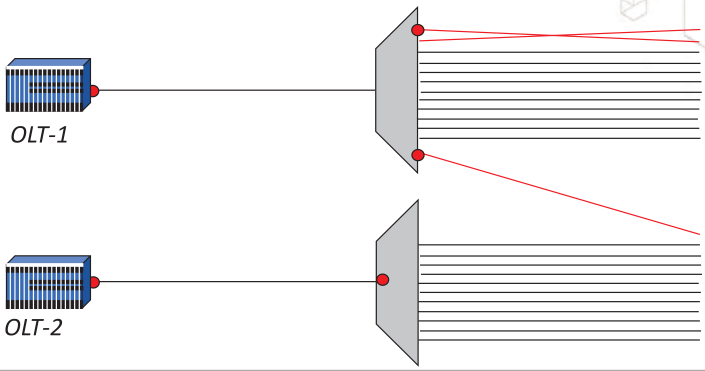
PON Service Activation Testing

- Wavelength selective power measurements
  - ➢ PON-OPM
- Upstream channel only activated by downstream signal
  - ➢ Through mode testing



ibis instruments

Patching Customers Correctly



Issue with Customer ID…?

Implement a **continuity test** during installation phase.
Viavi FC solution.

If continuity is not checked during installation phase:

Incorrect connections will not be found until ONT is turned-up
- dispatch

A customer who has been patched incorrectly might be brought down
- customer dissatisfaction

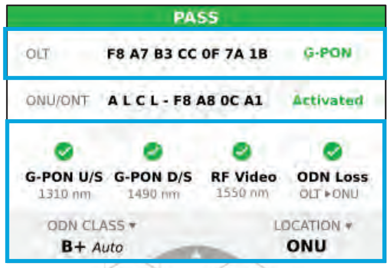
Continuity tests reduce OPEX and customer dissatisfaction

ibis instruments

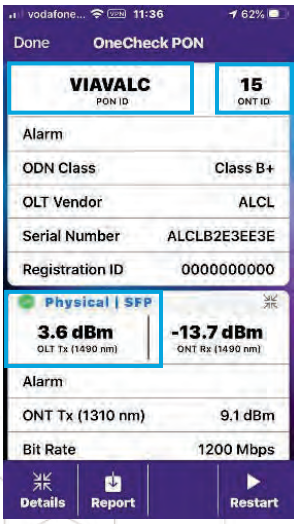
What are PON-ID and Activation Status?

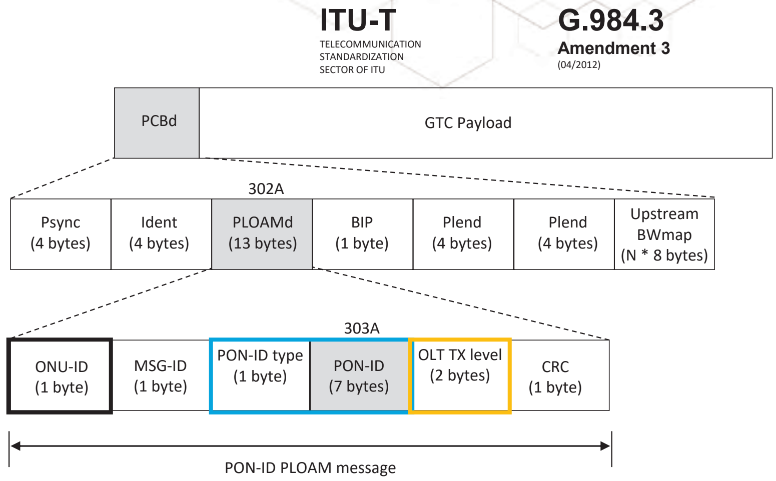
- Transmitted in GPON/XGS-PON frames downstream & upstream signals carrying PON specific information.
- **Key** to confirming that end user is connected and accepted on correct OLT port.

OLP-88 Power meter



NSC-100 (Companion)



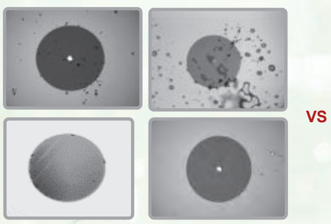


PLOAM = Physical Layer Operations, Admin' & Maint'

ibis instruments

Inspect *Before* You Connect™

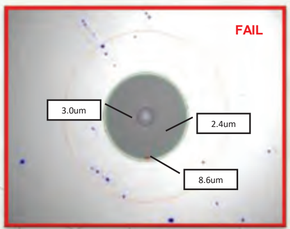
- Contamination is #1 source of high IL and RL in connectors
- Many connectors in FTTx installations
- Sources of contamination are everywhere!



Dirt, oil, pits, scratches not seen

SUBJECTIVE INSPECTION

VS



OBJECTIVE INSPECTION

Follow this simple **"INSPECT *BEFORE* YOU CONNECT"** process to ensure fiber end faces are clean prior to mating connectors

ibis instruments

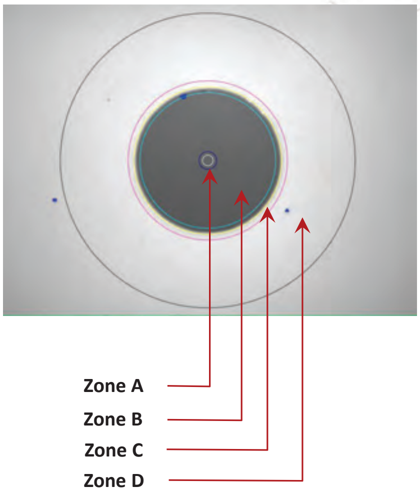
Contamination - Standards and Zones

IEC 61300-3-35 Ed.2.0 – "Fibre Optic Connector Endface Visual and Automated Inspection" has been updated (June 2015). It's designed as an interoperability standard for connector manufacturers and users.

- **ZONES are used to prioritize evaluation criteria (SM fiber example).**

  Zone A: Core Zone (0 to 25µm)
  Zone B: Cladding Zone (25 to 115µm)
  Zone C: Adhesive Zone (115 to 135µm)
  Zone D: Contact Zone (135 to 250µm)

- **Different *failure criteria* for defects and scratches are specified for each zone:**
  - **Quantity** and **Size**
  - **Location** relative to core



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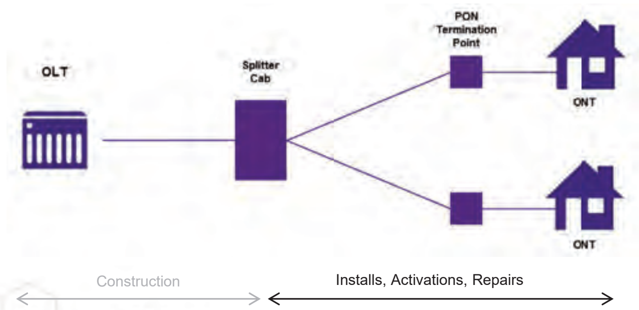
Best Practices in FTTx testing

Last Mile FTTx
Best Practice Test Checklist (IPQT)



Inspection & Cleaning
for both fiber cable and bulkhead connectors

Power Measurement
to verify the right light to ONT

Qualification of the Fiber and Its Elements
up to the first splitter (connectors, splices)

Throughput to ONT/Gateway and WiFi
in the home

ibis instruments

ibis instruments

Questions?

Demonstracije kvantne izmenjave šifrirnih ključev med tremi državami in evropski projekt EuroQCI

Demonstrations of quantum encryption key exchange between three countries and the European EuroQCI project

Rok Žitko, Anton Ramšak

Institut Jožef Stefan

Univerza v Ljubljani, Fakulteta za matematiko in fiziko

rok.zitko@ijs.si

Povzetek

Avgusta 2021 je uspela prva javna demonstracija meddržavnega kvantnega komunikacijskega omrežij, ki ga je vzpostavila skupina raziskovalcev s šifrirano komunikacijo med Italijo, Slovenijo in Hrvaško. Na slovenski strani so pri izvedbi izmenjave kvantnih ključev sodelovali fiziki s Fakultete za matematiko in fiziko Univerze v Ljubljani. V predavanju bo predstavljenih nekaj tehničnih podrobnosti o uporabi javnega optičnega omrežja in vzpostavitvi namenskih optičnih povezav ter varnega vozlišča v Postojni. Ta dosežek bo temelj za nadaljnji razvoj rešitev za kvantno izmenjavo ključev, ki se bo nadaljevala v okviru evropskega projekta EuroQCI, katerega cilj je vzpostaviti varno kvantno omrežje z zemeljskimi in satelitskimi optičnimi povezavami, ki bo povezalo vse članice Evropske unije.

Abstract

In August 2021, the first public demonstration of an international quantum communication network, established by a group of researchers with encrypted communication between Italy, Slovenia and Croatia, was successful. On the Slovenian side, physicists from the Faculty of Mathematics and Physics of the University of Ljubljana participated in the exchange of quantum keys. The lecture presents some technical details about the use of the public optical network and the establishment of dedicated optical connections and a secure hub in Postojna. This achievement will be the foundation for the further development of quantum key exchange solutions, which will continue within the framework of the European project EuroQCI, which aims to establish a secure quantum network with terrestrial and satellite optical links that will connect all the members of the European Union.

Biografija avtorja

Izredni profesor dr. Rok Žitko je doktor fizike, raziskovalec na Institutu "Jožef Stefan" in izredni profesor na Fakulteti za matematiko in fiziko Univerze v Ljubljani. Raziskovalno pot je začel v laboratoriju za tunelsko mikroskopijo na IJS, kasneje pa presedlal na teorijo večdelčnih kvantnih sistemov ter razvoj numeričnih metod na Odseku za teoretično fiziko IJS, še vedno pa rad zavije v kakšen laboratorij. Danes se največ ukvarja z drobnimi elektronskimi elementi, kvantnimi pikami, priključenimi na kontakte iz superprevodnih materialov, kot eno izmed zelo obetavnih platform za izdelavo različnih kvantnih naprav, denimo kvantnih računalnikov.

Author's biography

Associate Professor Dr. Rok Žitko is a doctor of physics, a researcher at the "Jožef Stefan" Institute and an associate professor at the Faculty of Mathematics and Physics of the University of Ljubljana. He began his research career in the laboratory for tunnel microscopy at the IJS, and later moved to the theory of multi-particle quantum systems and the development of numerical methods at the Department of Theoretical Physics at the IJS, and he still likes to visit a laboratory. Today, he mostly deals with tiny electronic elements, quantum dots connected to contacts made of superconducting materials, as one of the very promising platforms for the production of various quantum devices, such as quantum computers.


Qutes
Slovenian quantum technology community
Jožef Stefan Institute
QUANTUM FLAGSHIP
European Commission
DEMONSTRACIJA KVANTNE IZMENJAVE ŠIFRIRNIH KLJUČEV MED TREMI DRŽAVAMI IN EVROPSKI PROJEKT EUROQCI
ROK ŽITKO, ANTON RAMŠAK
INSTITUT JOŽEF STEFAN, LJUBLJANA
FAKULTETA ZA MATEMATIKO IN FIZIKO, UNIVERZA V LJUBLJANI
26. SEMINAR OPTIČNE KOMUNIKACIJE, 25. JAN 2023


“Nikoli ne opravljamo poizkusov z enim samim elektronom ali atomom ali (majhno) molekulo. V miselnih eksperimentih včasih predpostavimo prav to, pa zato vedno znova pridemo do trapastih zaključkov. (…) Zato je treba priznati, da ne moremo eksperimentirati s posameznimi delci nič bolj, kot lahko vzgajamo ihtiozavre v živalskih vrtovih.”
E. Schrödinger (1952)
David J. Wineland in Serge Haroche
Nobelova nagrada za fiziko 2012
“za prelomne eksperimentalne metode, ki omogočajo merjenje in nadzor nad posameznimi kvantnimi sistemi, pri čemer se ohranijo njihove kvantne lastnosti, kar se je predhodno smatralo kot nemogoče”
Vir slike: Wikipedia (javna last; CCA - photo by Bengt Nyman)

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi(x,t)}{\partial x^2} + V(x,t)\psi(x,t) = i\hbar\frac{\partial\psi(x,t)}{\partial t}$$

Erwin Schrödinger (1926)

SUPERPOZICIJA STANJ

$$\psi(x,t) = \alpha\,\psi_1(x,t) + \beta\,\psi_2(x,t)$$

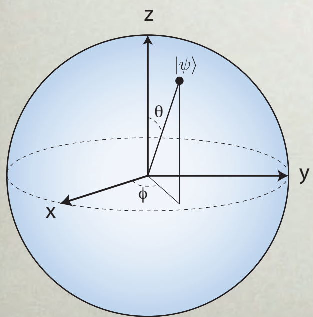
Vir slike: Wikipedia (javna last)

KUBIT

Informacija je neločljivo povezana s svojim fizičnim zapisom.

Rolf Landauer (1996)

računska baza: $|0\rangle, |1\rangle$



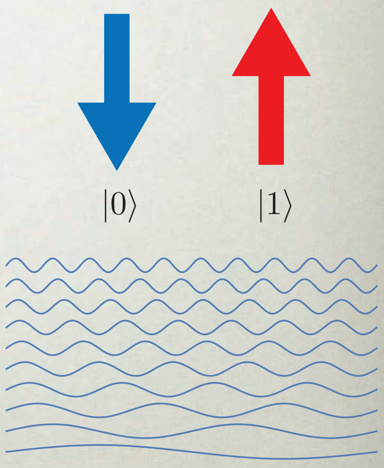
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

verjetnostni amplitudi

$$\alpha = \cos\frac{\theta}{2} \qquad \beta = e^{i\phi}\sin\frac{\theta}{2}$$

KVANTNE NAPRAVE

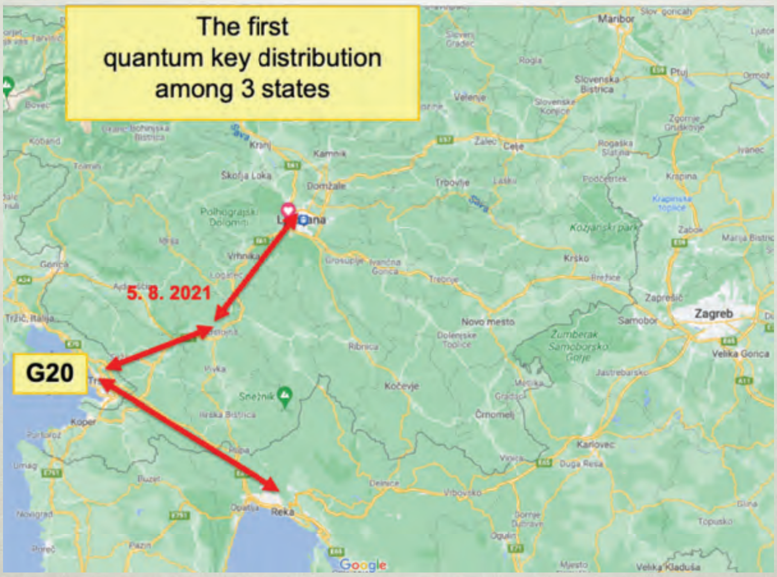
- danes:
  atomske ure
  generatorji naključnih števil
  kvantna distribucija ključev za šifriranje
  manjši kvantni računalniki
- prihodnost:
  inercijska navigacija
  natančna gravimetrija
  simulacije kvantnih sistemov (molekul)
  globalni kvantni internet
  kvantni računalniki z veliko kubiti



https://qt.eu http://www.qutes.si

Srečanje ministrov za digitalno politiko skupine G20 Trst, 5. 8. 2021

demonstracija kvantno šifriranega prenosa podatkov med tremi državami (Italija-Slovenija-Hrvaška)



Univerza v Trstu
Nacionalni institut za optiko (CNR-INO)
Tehnična univerza na Danskem (DTU)

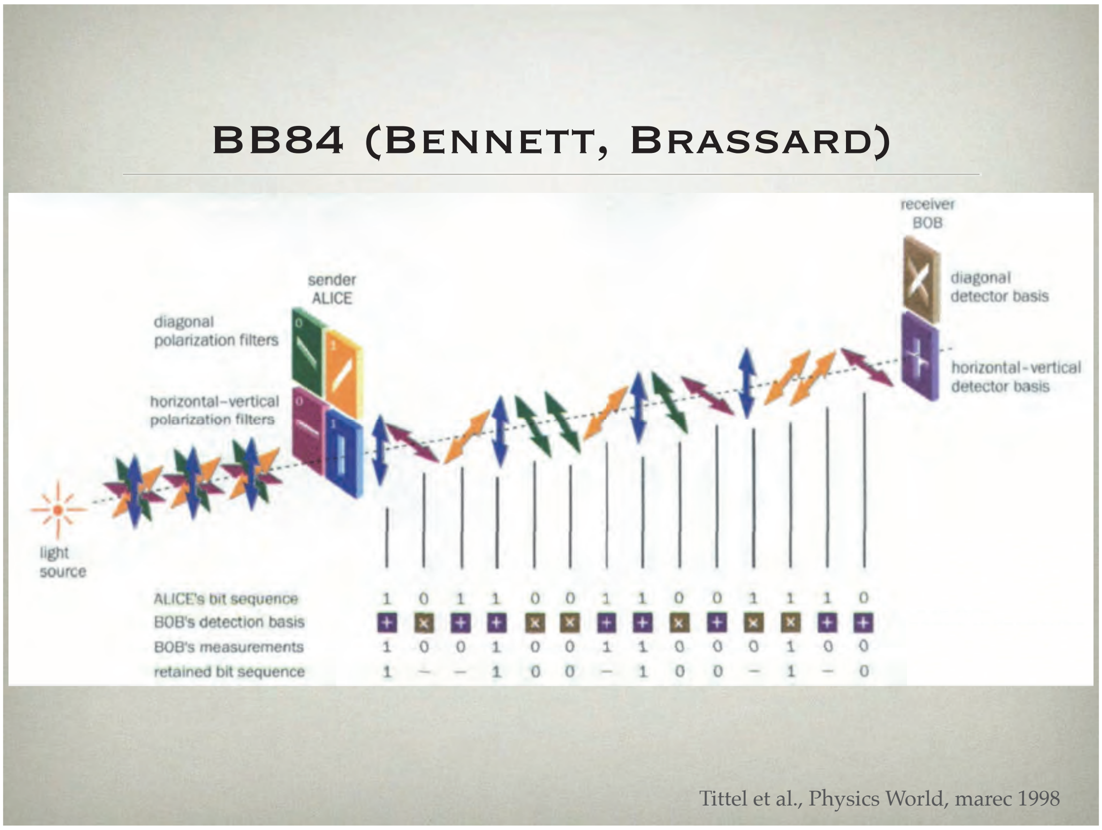
Fakulteta za matematiko in fiziko UL

Institut Ruđer Bošković, Zagreb
Fakultata za prometne vede, Uni. Zagreb

Tehnična izvedba:
QTI (spin-off CNR-INO)
Telsy

Optična infrastruktura:
TIM
Sparkle
Telekom Slovenije
OIV - Digitalni signali in omrežja
Stelkom
Lightnet

Podpora:
predsedstvo G20 2021
italianski ministrstvi MiSE, MAECI



RESEARCH ARTICLE

ADVANCED QUANTUM TECHNOLOGIES
www.advquantumtech.com

Deploying an Inter-European Quantum Network

*Domenico Ribezzo, Mujtaba Zahidy, Ilaria Vagniluca, Nicola Biagi, Saverio Francesconi, Tommaso Occhipinti, Leif K. Oxenløwe, Martin Lončarić, Ivan Cvitić, Mario Stipčević, Žiga Pušavec, Rainer Kaltenbaek, Anton Ramšak, Francesco Cesa, Giorgio Giorgetti, Francesco Scazza, Angelo Bassi, Paolo De Natale, Francesco Saverio Cataliotti, Massimo Inguscio, Davide Bacco, and Alessandro Zavatta**

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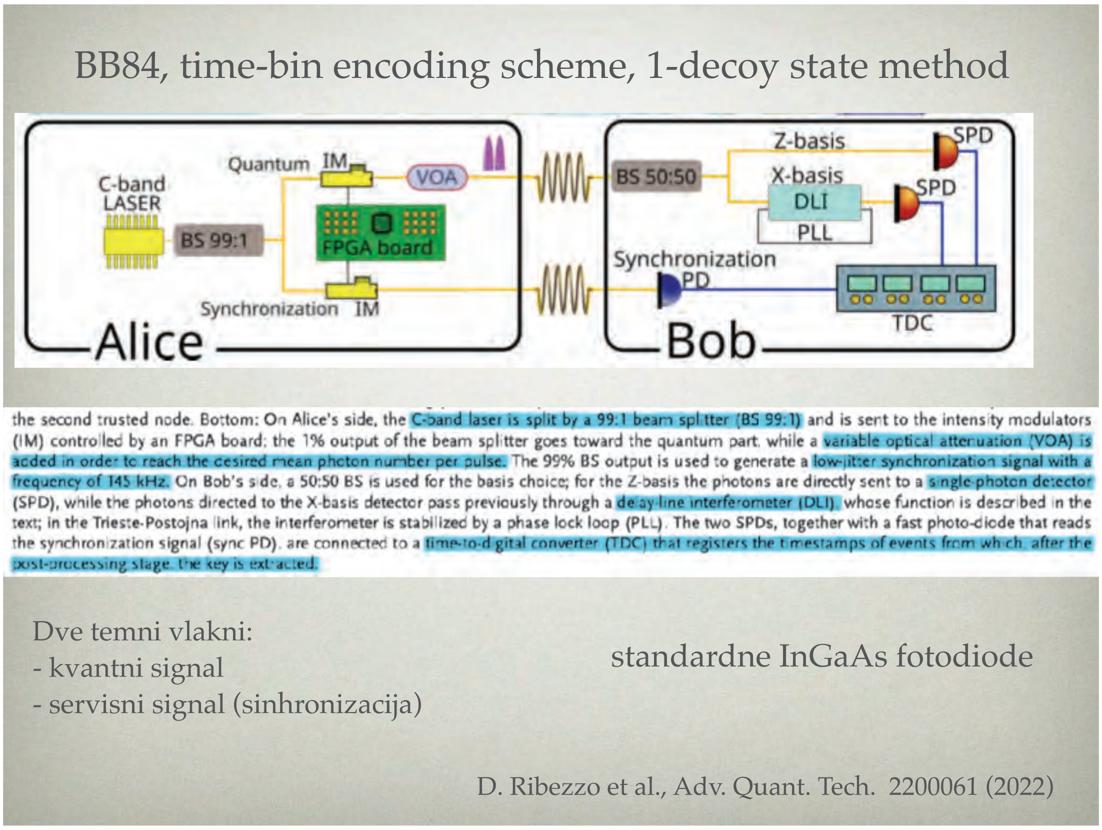
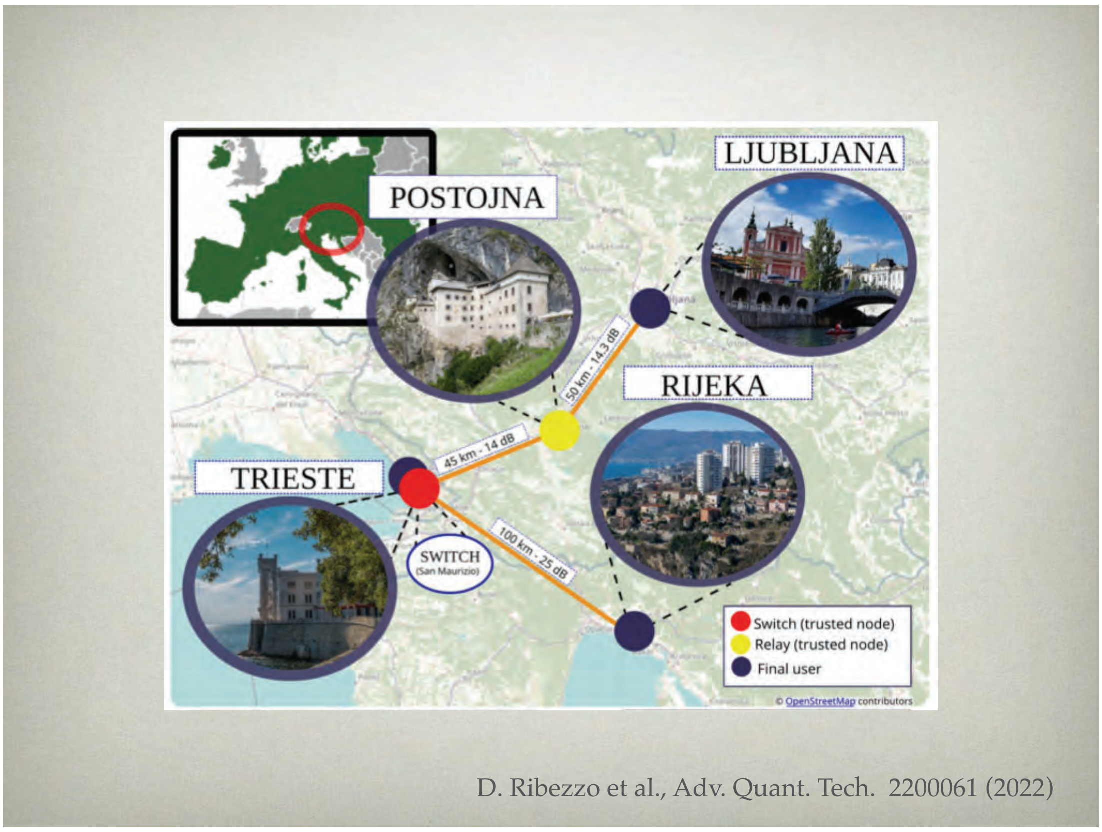
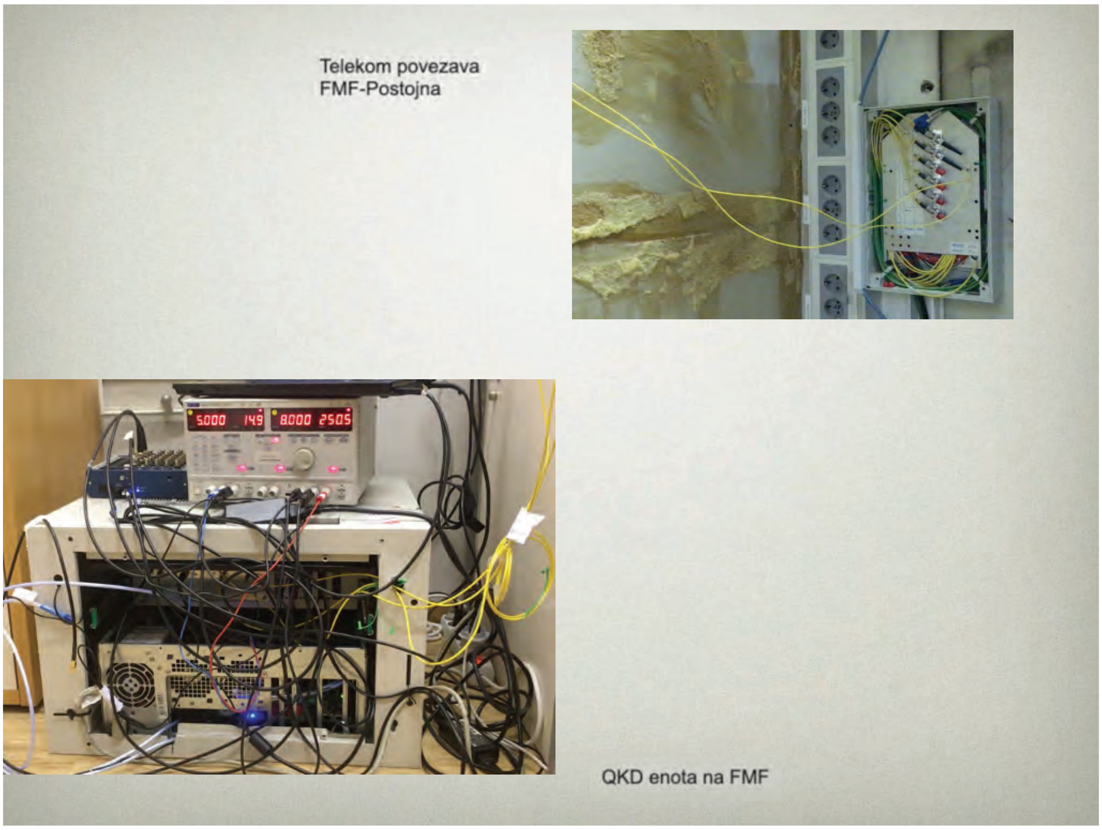
The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/qute.202200061

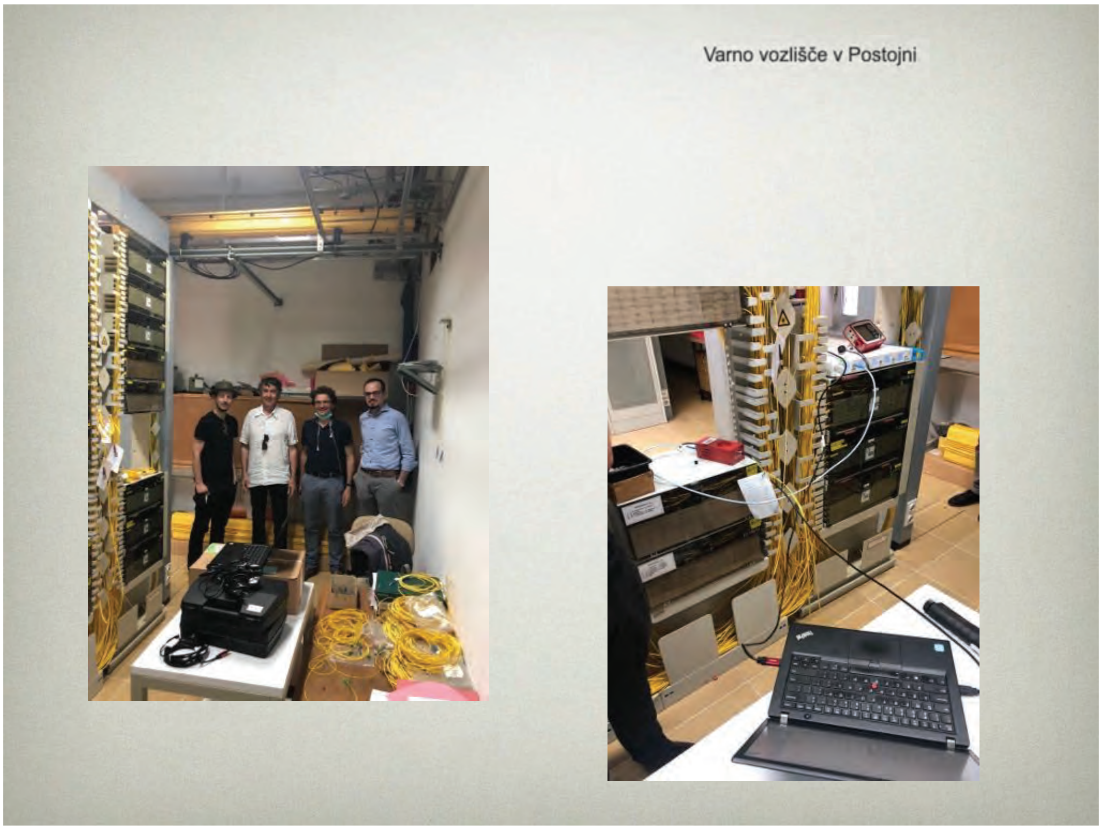
DOI: 10.1002/qute.202200061

Adv. Quantum Technol. 2022, 2200061 2200061 (1 of 8)

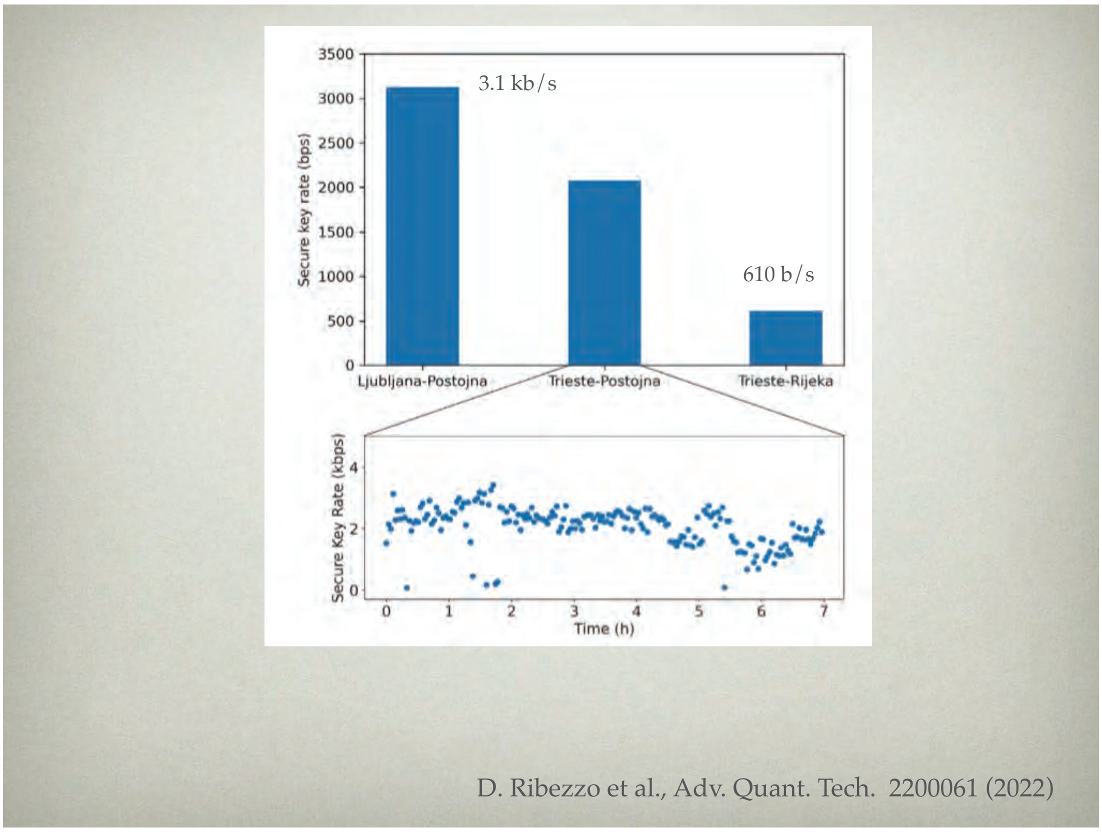

BB84, time-bin encoding scheme, 1-decoy state method
C-band LASER
BS 99:1
Quantum
IM
VOA
FPGA board
Synchronization
IM
Alice
BS 50:50
Z-basis
SPD
X-basis
DLI
PLL
SPD
Synchronization
PD
TDC
Bob
the second trusted node. Bottom: On Alice's side, the C-band laser is split by a 99:1 beam splitter (BS 99:1) and is sent to the intensity modulators (IM) controlled by an FPGA board; the 1% output of the beam splitter goes toward the quantum part, while a variable optical attenuation (VOA) is added in order to reach the desired mean photon number per pulse. The 99% BS output is used to generate a low-jitter synchronization signal with a frequency of 145 kHz. On Bob's side, a 50:50 BS is used for the basis choice; for the Z-basis the photons are directly sent to a single-photon detector (SPD), while the photons directed to the X-basis detector pass previously through a delay-line interferometer (DLI), whose function is described in the text; in the Trieste-Postojna link, the interferometer is stabilized by a phase lock loop (PLL). The two SPDs, together with a fast photo-diode that reads the synchronization signal (sync PD), are connected to a time-to-digital converter (TDC) that registers the timestamps of events from which, after the post-processing stage, the key is extracted.
Dve temni vlakni:
- kvantni signal
- servisni signal (sinhronizacija)
standardne InGaAs fotodiode
D. Ribezzo et al., Adv. Quant. Tech. 2200061 (2022)

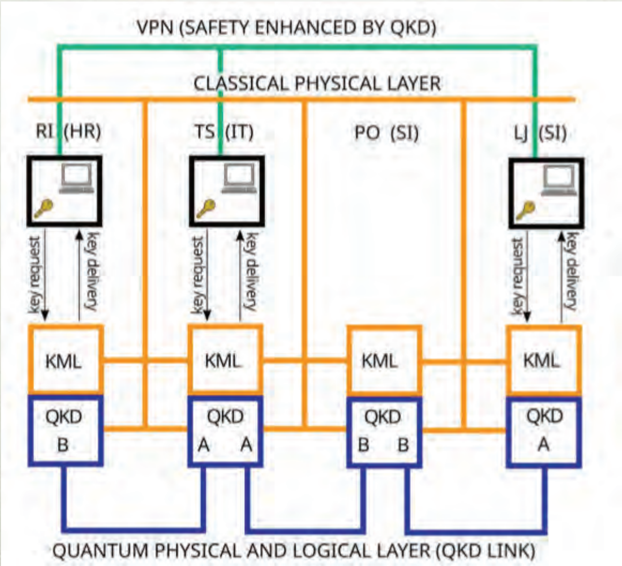

LJUBLJANA
POSTOJNA
50 km - 14.3 dB
RIJEKA
45 km - 14 dB
TRIESTE
SWITCH
(San Maurizio)
100 km - 25 dB
Switch (trusted node)
Relay (trusted node)
Final user
© OpenStreetMap contributors
D. Ribezzo et al., Adv. Quant. Tech. 2200061 (2022)


Telekom povezava
FMF-Postojna
QKD enota na FMF


Varno vozlišče v Postojni


QTI

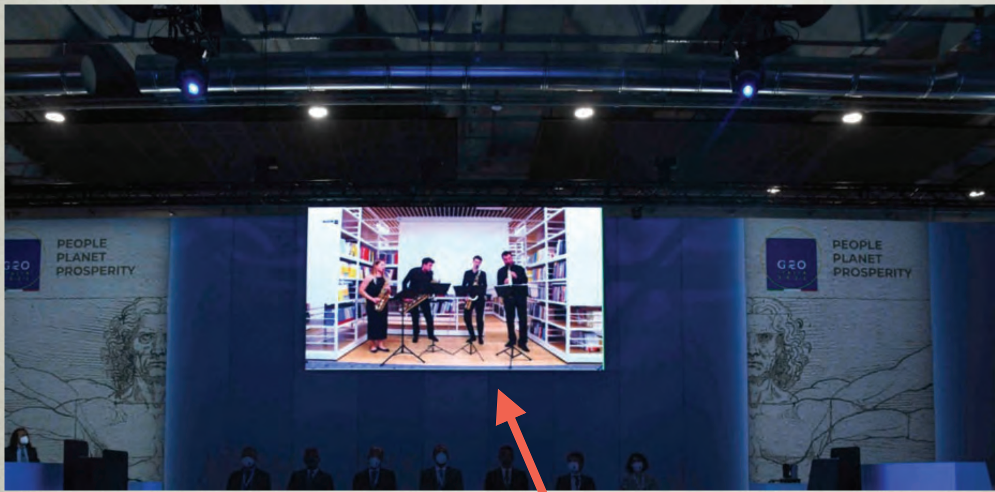

3.1 kb/s
610 b/s
Secure key rate (bps)
Ljubljana-Postojna
Trieste-Postojna
Trieste-Rijeka
Secure Key Rate (kbps)
Time (h)
D. Ribezzo et al., Adv. Quant. Tech. 2200061 (2022)



Koncert preko navideznega zasebnega omrežja (VPN)

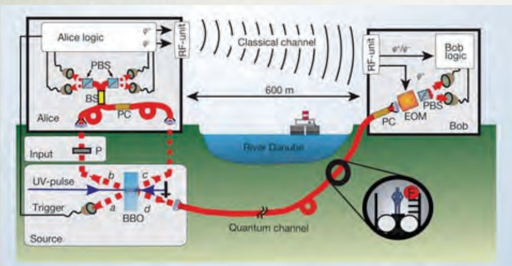
Akademija za glasbo UL, Akademija za glasbo UZ, konservatorij "Giuseppe Tartini" iz Trsta

Z uporabo videokonferenčnega sistema **OpenMeetings**



knjižnica FMF

Laboratorij za kvantno optiko in kvantno optomehaniko (FMF)



Projekt EuroQCI

EuroQCI

- projekt Evropske komisije in ESA
- komercialna optična omrežja + namenski komunikacijski sateliti
- evropska digitalna suverenost, industrijska konkurenčnost
- kibernetska varnost EU za prihodnja desetletja

Siquid

- Konzorcij: UL FMF (koordinator), IJS, Beyond Semiconductor, Urad vlade RS za varovanje tajnih podatkov (UVTP), Urad vlade RS za informacijsko varnost (URSIV)
- Cilji:
    - pilotska povezava med IJS in UL FMF
    - povezava državnih organov (7 lokacij v Ljubljani)
    - povezave do državnih meja

Izzivi

- različna (nezdružljiva) infrastruktura
- različni operaterji
- različni ponudniki opreme
- različni standardi oz. standardi v nastajanju
- različni QKD protokoli
- potreba po varnih vozliščih
- omejitve zaradi atenuacije signala

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

OCTOBER 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality be Considered Complete?

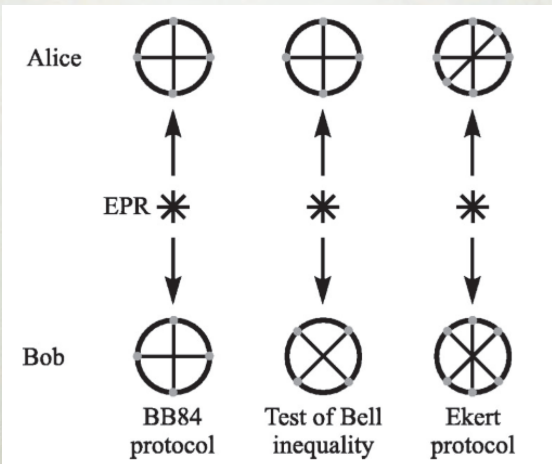
N. Bohr, *Institute for Theoretical Physics, University, Copenhagen*

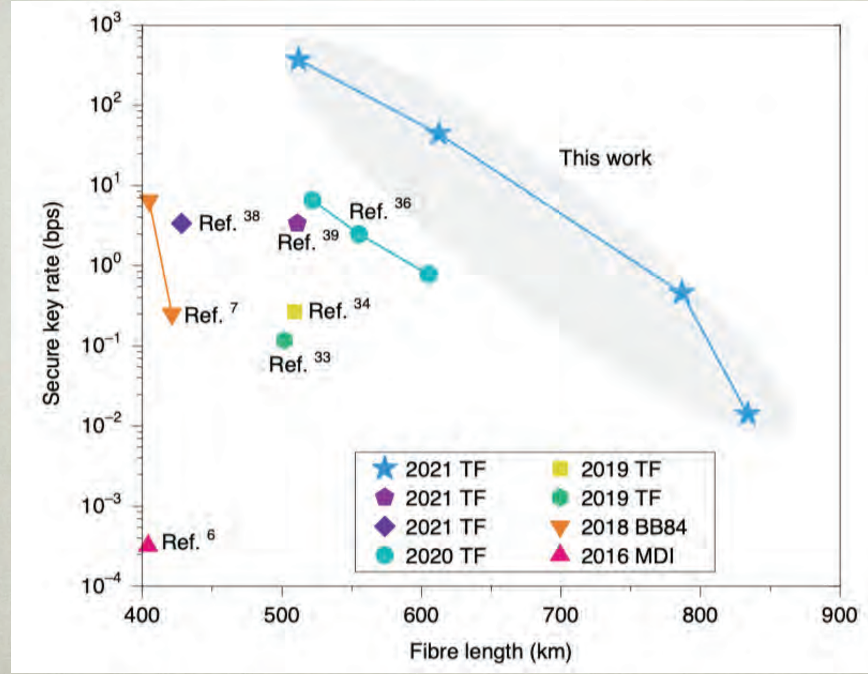
(Received July 13, 1935)

It is shown that a certain "criterion of physical reality" formulated in a recent article with the above title by A. Einstein, B. Podolsky and N. Rosen contains an essential ambiguity when it is applied to quantum phenomena. In this connection a viewpoint termed "complementarity" is explained from which quantum-mechanical description of physical phenomena would seem to fulfill, within its scope, all rational demands of completeness.

The Nobel Prize in Physics 2022

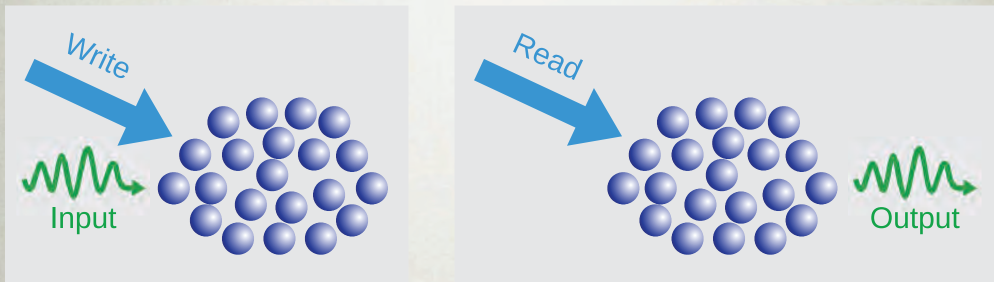
E91 (Ekert)

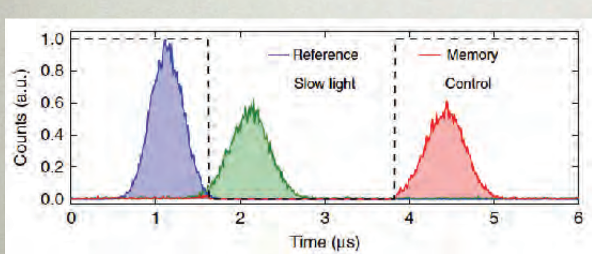




Wang et al., Nat. Photonics, **16** 154 (2022)

Kvantni spomin z atomi





Eugene Polzik, *Kopenhagen*
Nicolas Gisin, *Ženeva*
Julien Laurat, *Sorbonne*

Laboratorij za fiziko hladnih atomov

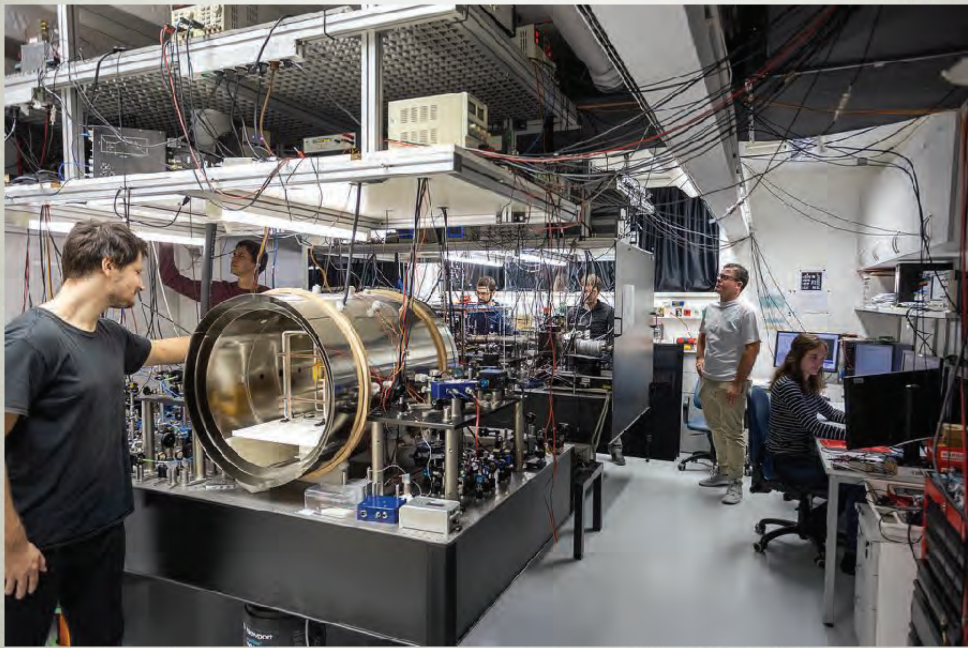
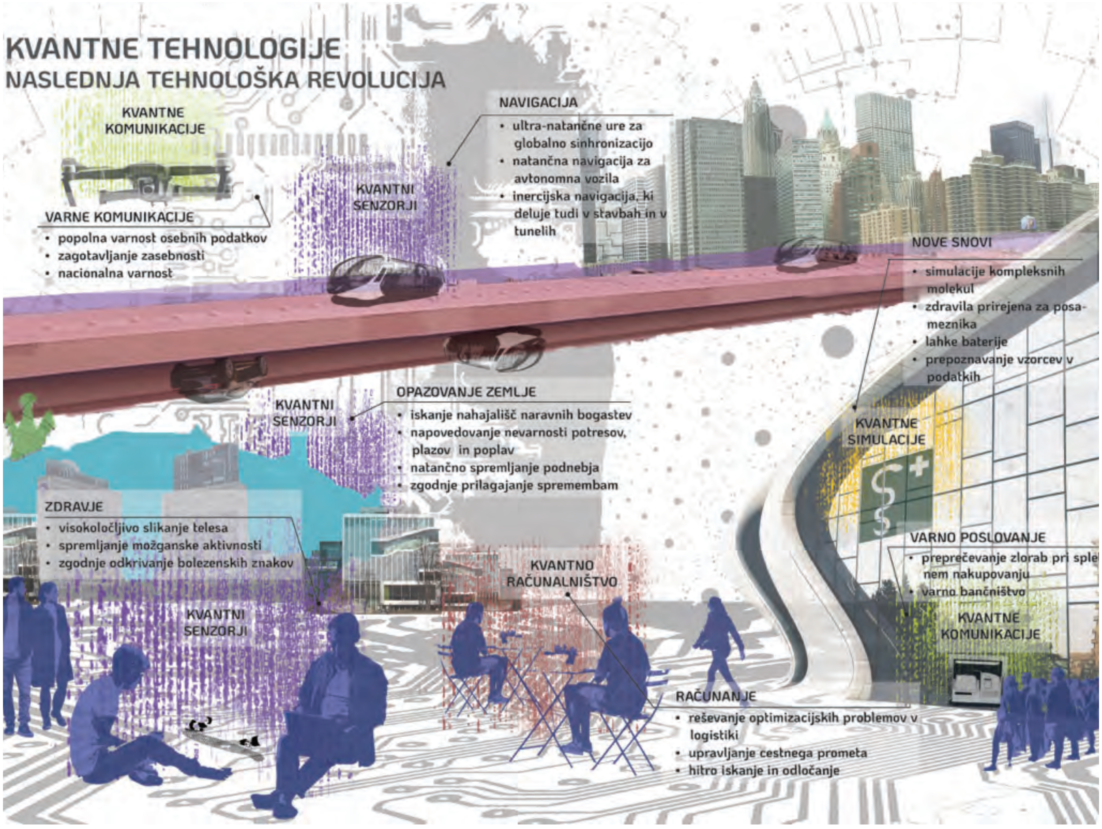


Foto: Marjan Verč



Integrirana fotonika za kvantne aplikacije

Integrated photonics for quantum applications

Janez Krč, **Andraž Debevc, Miloš Ljubotina, Boštjan Batagelj, Janez Trontelj in Marko Topič**

Univerza v Ljubljani, Fakulteta za elektrotehniko

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Povzetek

Integrirana fotonska vezja (PIC) se dandanes uporabljajo že v mnogih sodobnih aplikacijah, med njimi v optičnih komunikacijah, senzoriki in procesiranju signalov. Svetlobo oziroma fotone lahko koristno uporabimo tudi na področju kvantnih aplikacij. V našem prispevku bomo osvetlili usmeritve in predstavili nekatere izhodiščne rezultate projekta »uTP4Q« iz razpisa QuantERA, kjer si partnerji prizadevamo za izvedbo heterogene integracije izbranih gradnikov kvantne fotonike (enofotonski viri, modulatorji, enofotonski fotodetektorji, sklopni, povezovalni in ostali pasivni gradniki) v kvantno fotonsko integrirano vezje (QPIC). Posamezni gradniki bodo izdelani na različnih fotonskih platformah (indij-galij-arzenidni, litij-niobatni, superprevodne nanožičke) in s postopkom mikroprenosnega tiska nameščeni na skupno, nizkoizgubno platformo na osnovi SiN. Poskus končnega QPIC-a gre v smeri zagotavljanja funkcionalnosti od naprave neodvisne kvantne distribucije ključev (DI-QKD) za varne komunikacije.

Abstract

Photonic integrated circuits (PICs) are already used in many modern applications, including optical communications, sensors and signal processing. Light, or photons, can also be usefully used in the field of quantum applications. In our paper, we cover the directions and present some of the initial results of the "uTP4Q" project from the QuantERA tender, where our partners strive to implement the heterogeneous integration of selected quantum photonic building blocks (single-photon sources, modulators, single-photon photodetectors, coupling, connecting and other passive building blocks) into a quantum photonic integrated circuit (QPIC). The individual building blocks will be fabricated on different photonic platforms (indium-gallium-arsenide, lithium-niobate, superconducting nanowires) and placed on a common, low-loss SiN-based platform using a microtransfer printing process. The final QPIC experiment goes towards providing device-independent quantum key distribution (DI-QKD) functionality for secure communications.

Biografija avtorja

Dr. Janez Krč je redni profesor na Fakulteti za elektrotehniko Univerze v Ljubljani in namestnik vodje Laboratorija za fotovoltaiko in optoelektroniko na Katedri za elektroniko. Njegovo raziskovalno delo sega na področje opto-elektronskih simulacij, načrtovanja in karakterizacije sončnih celic, organskih in perovskitnih svetlečih diod in fotonskih integriranih vezij.

Author's biography

Dr. Janez Krč is a full professor at the Faculty of Electrical Engineering, University of Ljubljana, Slovenia, and a deputy chair of Laboratory of Photovoltaics and Optoelectronics at the Department of Electronics. His research work covers opto-electrical simulations, design and characterization of solar cells, organic and perovskite light emitting diodes and photonic integrated circuits.

Integrirana fotonika za kvantne aplikacije

Janez Krč, Andraž Debevc, Miloš Ljubotina, Boštjan Batagelj, Janez Trontelj in Marko Topič

Univerza v Ljubljani, Fakulteta za elektrotehniko – UL FE
Tržaška 25, 1000 Ljubljana
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Vsebina predstavitve

- Kvantne tehnologije
- Fotonska integrirana vezja - PIC
- Kvantna fotonska integrirana vezja - QPIC
- Aktivnosti UL FE in QuantERA projekt μTP4Q

  integrirana fotonika za kvantne komunikacije

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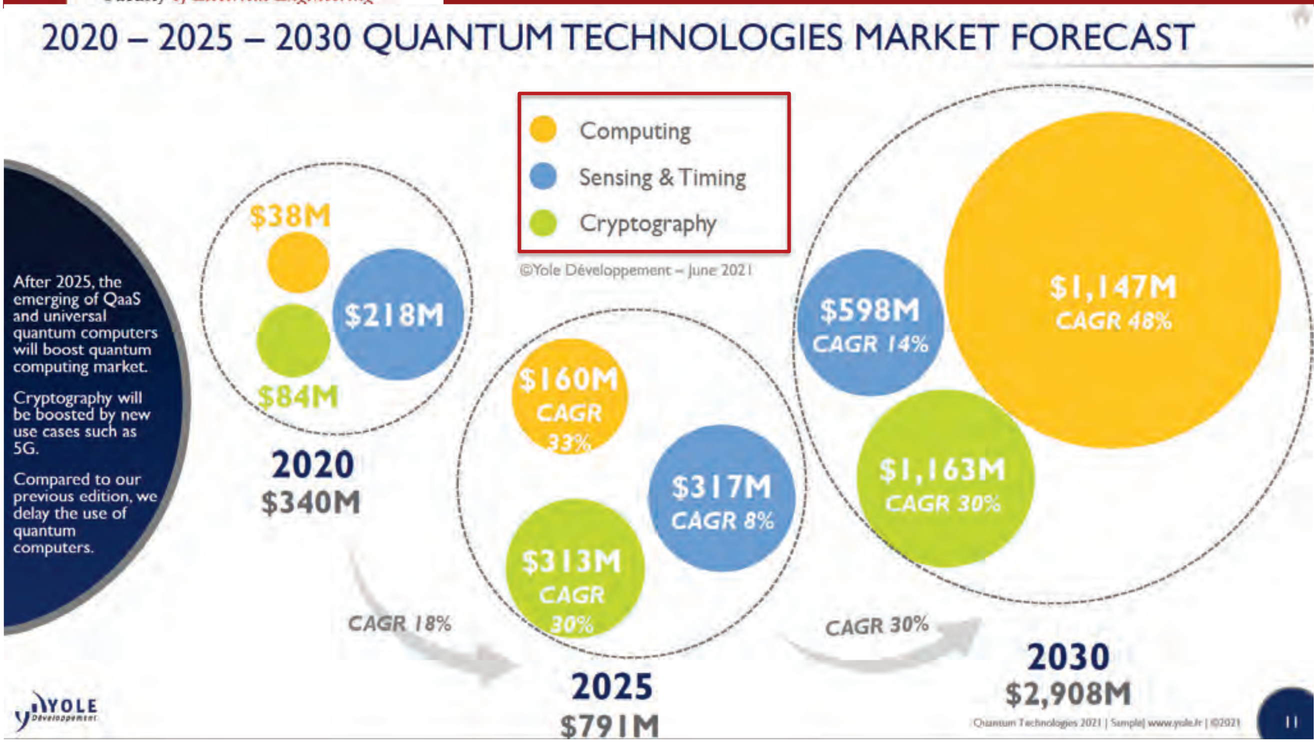

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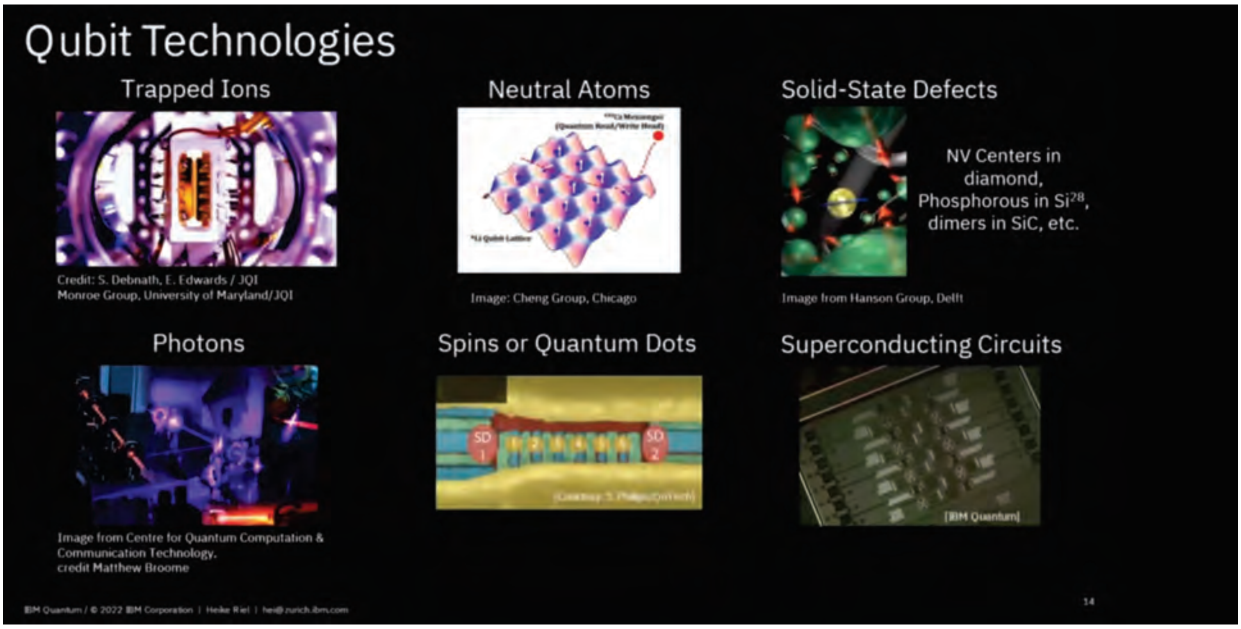
Kvantne tehnologije



Courtesy of dr. Heike Riel, IBM, SPIE 2022 conference

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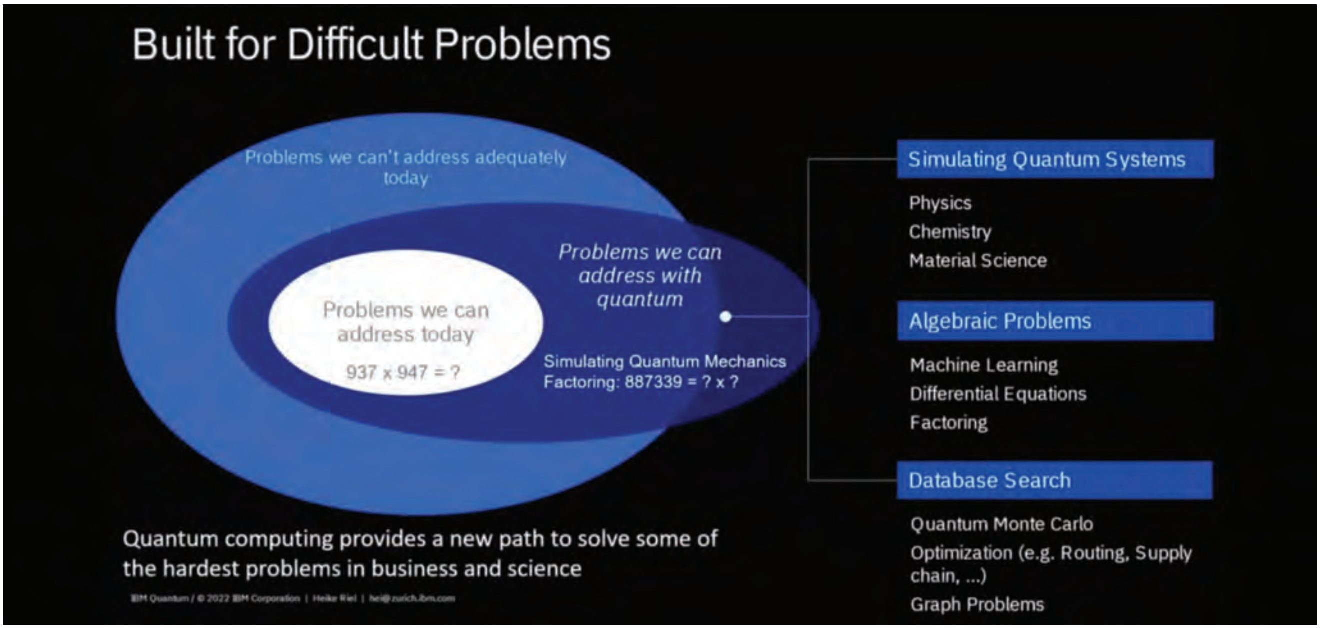
Kvantno računstvo



Courtesy of dr. Heike Riel, IBM, SPIE 2022 conference

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Kvantno računstvo

Comparison: Bits versus Qubits

Simulating a set of qubits demonstrates their potential advantage as information carriers.

Qubits	Digital bits required to represent an entangled state
2	512 bits
3	1024 bits
10	16 kilobytes
16	1 megabyte
20	17 megabytes
30	17 gigabytes
35	550 gigabytes
100	More than all the atoms of planet earth
280	More than all the atoms in the universe

IBM 2020 65 qubits

Courtesy of dr. Heike Riel, IBM, SPIE 2022 cobference

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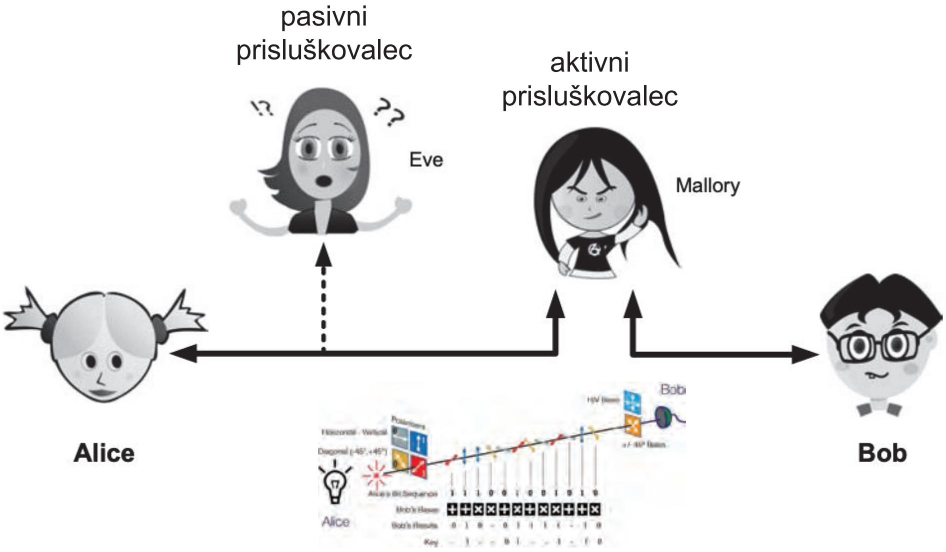
Kvantna komunikacija

Želimo vzpostaviti **varno** komunikacijo med Alice in Bob-om



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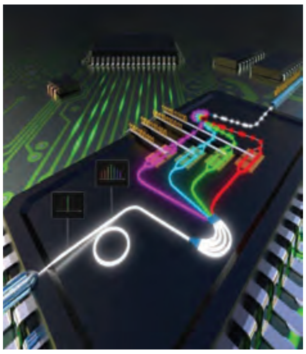

Fotonska integrirana vezja

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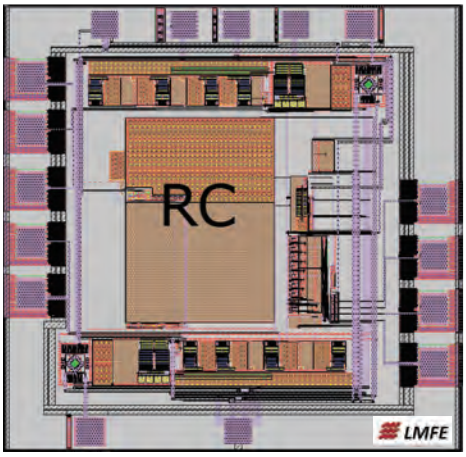
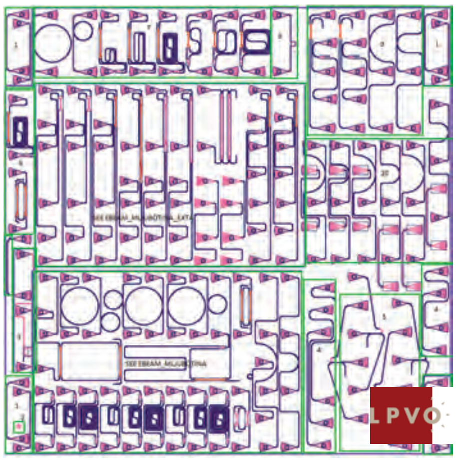
Elektronsko integrirano vezje - IC

- elektroni -



Fotonsko integrirano vezje - PIC

- fotoni -



- pasivne in aktivne fotonske komponente
- različne tehnologije (gl. naprej)
- možna uporaba tehnoloških korakov procesa CMOS
- znatno manjša poraba moči pri prenosu VF signala
- možno izredno hitro procesiranje

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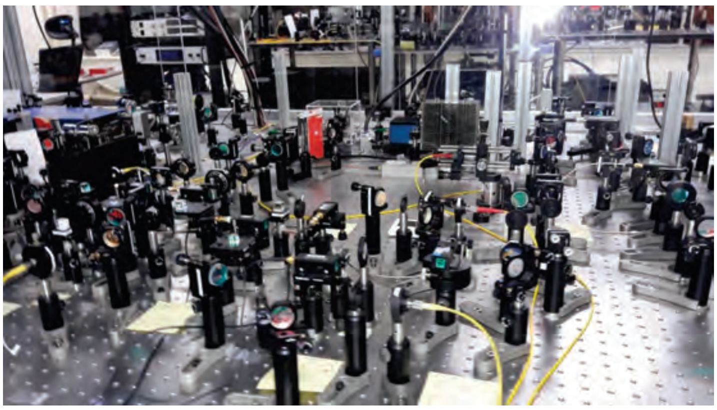
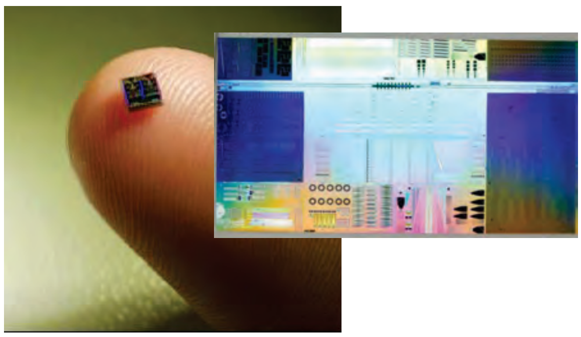
Integracija optičnih komponent



PIC



- majhno, lahko kombiniramo z IC
- kompaktnost, funkcionalnost
- odpadejo ohišja posameznih komponent
- uniformnost (enakost) komponent
- večja zanesljivost

- omejitve glede stopnje integracije

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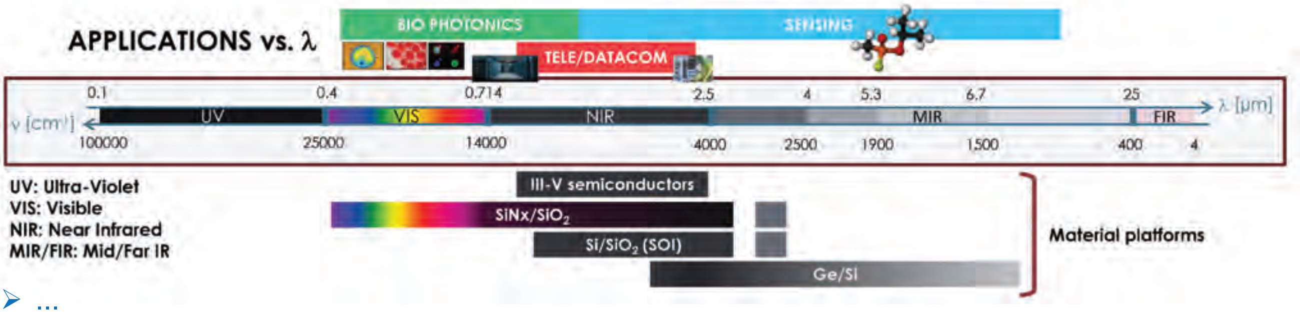
Tehnologije (material svetlovodne plasti)

Si, SiO_x, Si_4N_4, InP, GaAs, $LiNbO_3$, polimeri, GFP (Si, Ge, Sn)



- ...
- telecom, datacom
- optično procesiranje
- senzorika, metrologija
- kvantne tehnologije
- mikroskopija
- …

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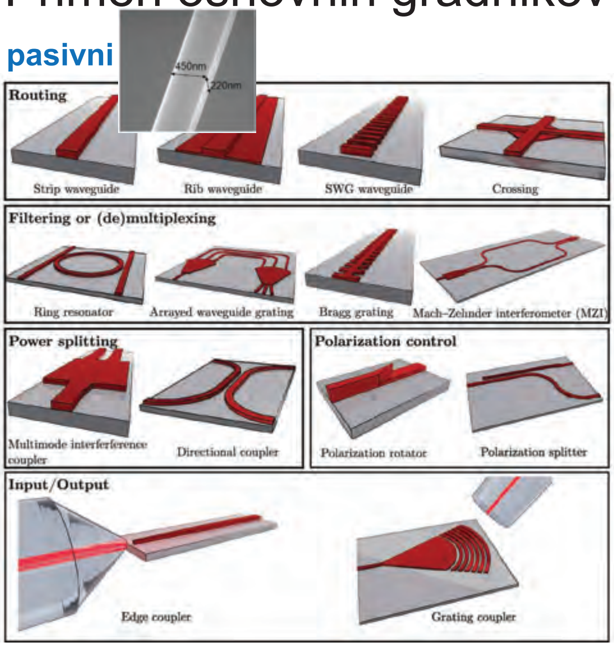
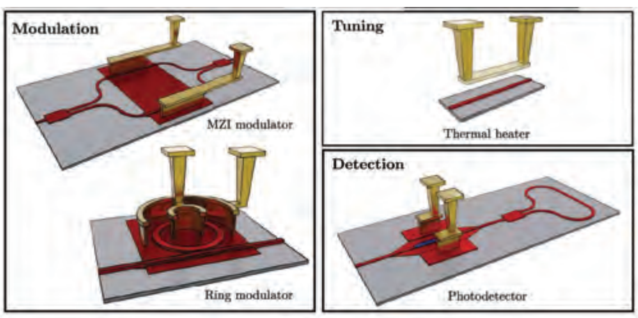
Primeri osnovnih gradnikov PIC (Si)

pasivni

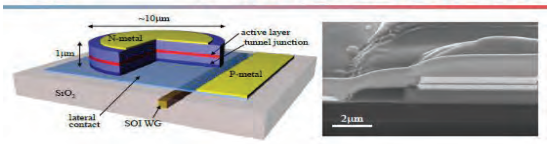


aktivni



Integrirani laserji – uporaba direktnih polprevodnikov!

InP Microdisk Laser on Silicon



W. Shi et al.: Scaling capacity of fiber-optic transmission systems, **Nanophotonics** 2020; 9(16): 4629–4663

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Kvantna fotonska integrirana vezja - QPIC

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QPIC

- kvantno računstvo
- kvantne komunikacije
- kvantne simulacije
- kvantna senzorika

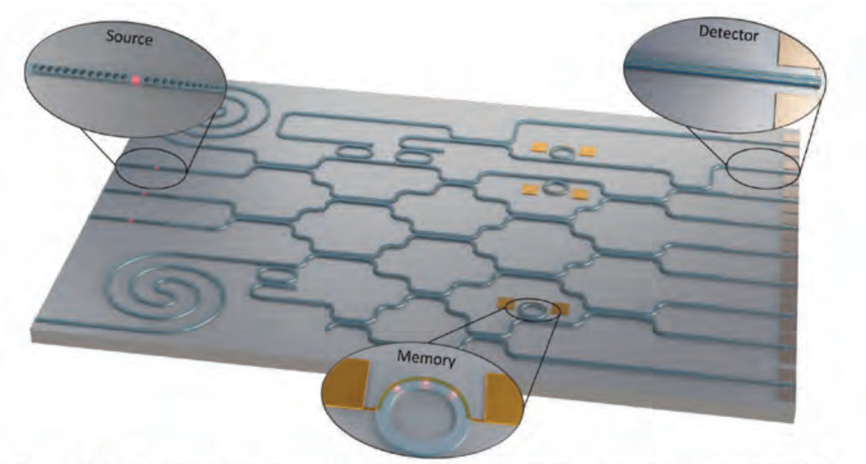

Figure 1: Quantum photonic integrated circuit, including non-linear optics (spirals) and quantum light sources (red dots) in nano-beam cavities, quantum memories (rings including ions), and superconducting detectors (strips), as well as active and passive photonic elements (taken from Nat Rev Phys (2021): https://doi.org/10.1038/s42254-021-00398-z)

Source: QPIC position paper 2022

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QPIC

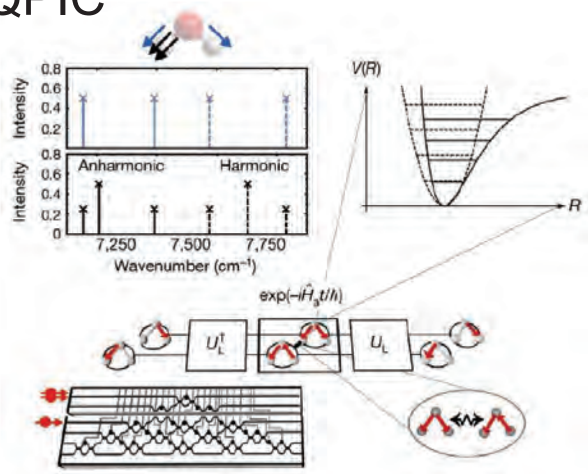

Figure 5: Quantum photonic integrated circuit with thermo-optic phase shifters (bottom) allows for simulating the vibrational quantum dynamics of molecules (taken from Nature (2018): https://doi.org/10.1038/s41586-018-0152-9)

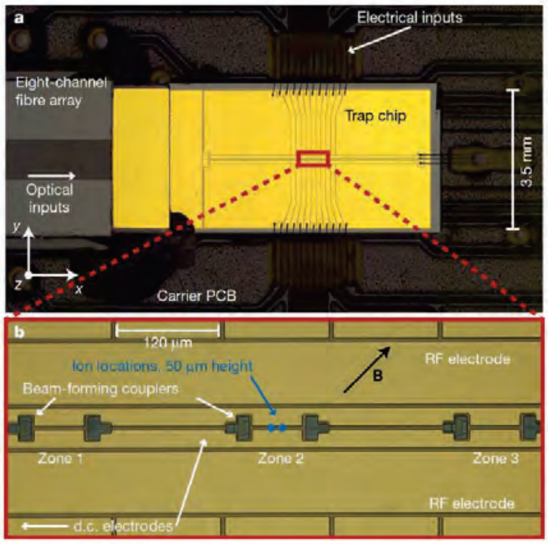

Fig. 4: Optical micrograph of an assembled ion trap device with an eight-channel fibre array attached. b, Higher-magnification view near the trap zones (taken from Nature (2020) https://doi.org/10.1038/s41586-020-2823-6)

Source: QPIC position paper 2022

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Aktivnosti na področju PIC na UL FE

- Laboratorij za fotovoltaiko in optoelektroniko - LPVO
- Laboratorij za mikroelektroniko - LMFE
- Laboratorij za sevanje in optiko - LSO

Sodelovanja: Univerza v Ghentu – imec, TU Delft, Nanofotonski Center v Valenciji, CSEM Švica, NBI Danska, ...

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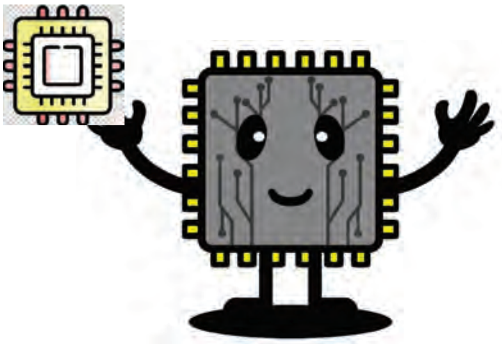
Tehnologija



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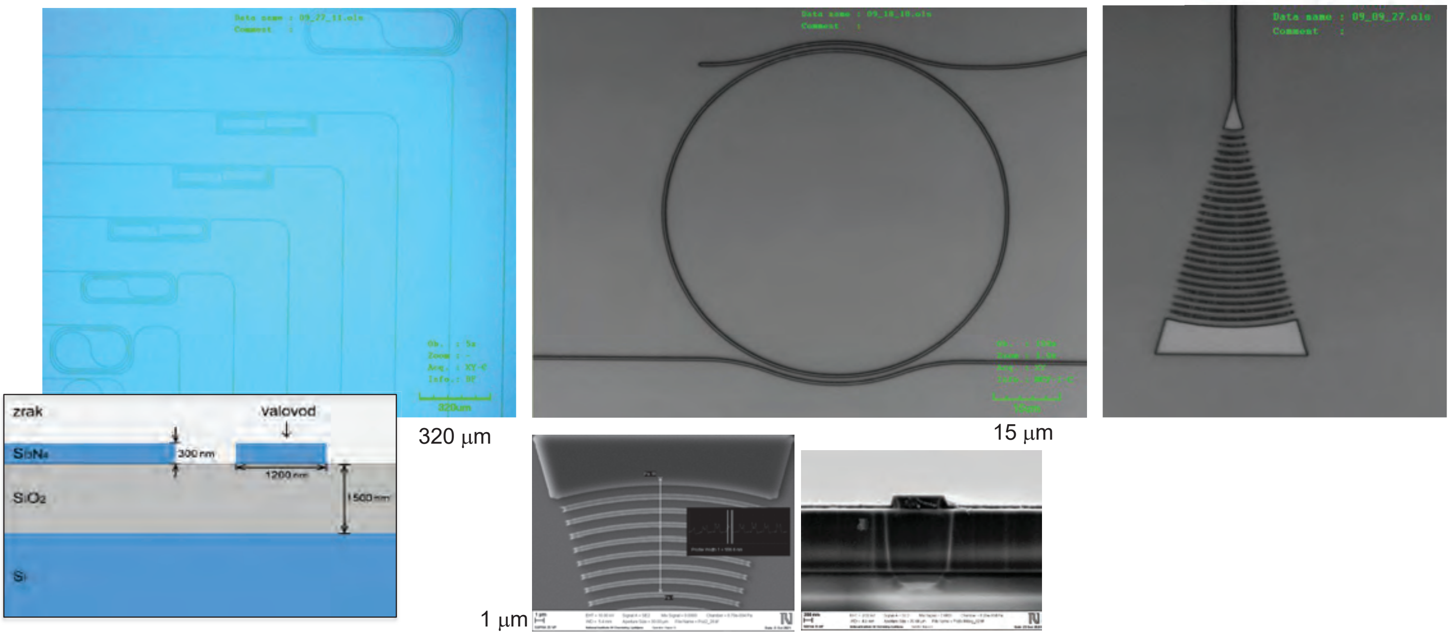
Slike prvih izdelanih struktur iz Si_3N_4 na FE (LMFE)



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Optična karakterizacija

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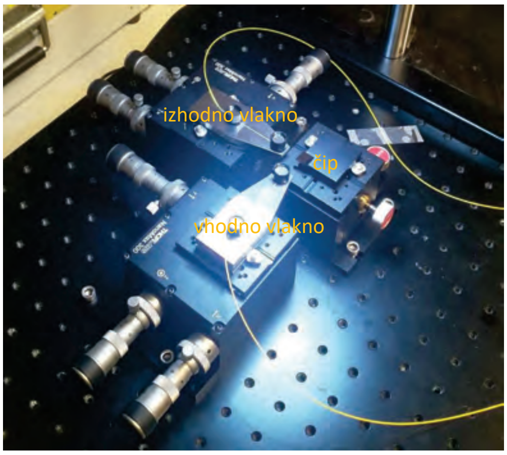
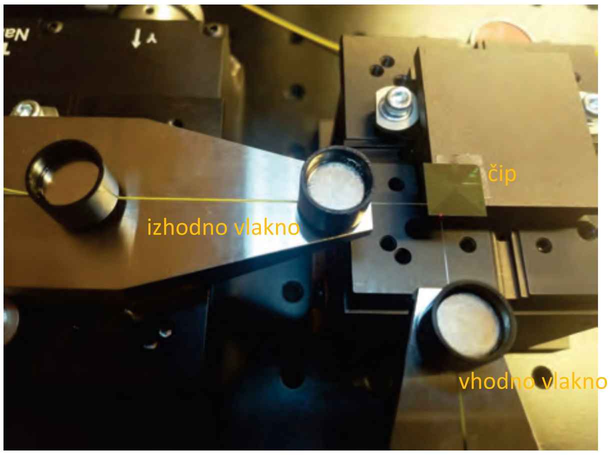
Precizne mizice za sklopitev vlakna s svetlovodom na PIC

- ročna ločljivost: 100 nm (s piezzo aktuatorji ~ 20 nm)
- omogoča horizontalno (na slikah) in vertikalno sklopitev vlaken





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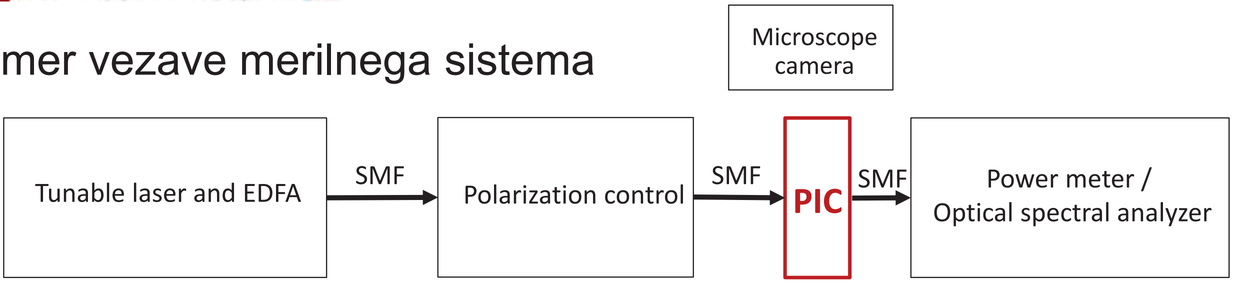
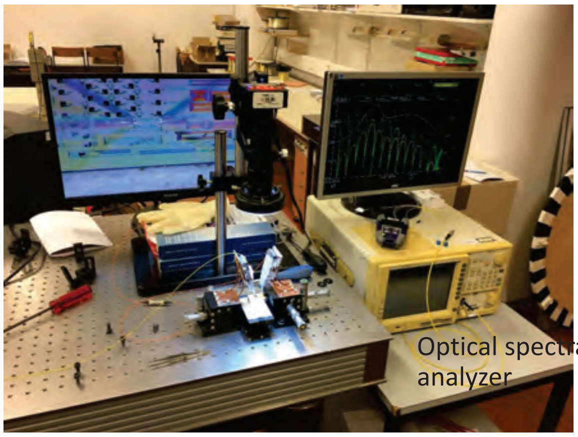
Primer vezave merilnega sistema



LSO & LPVO



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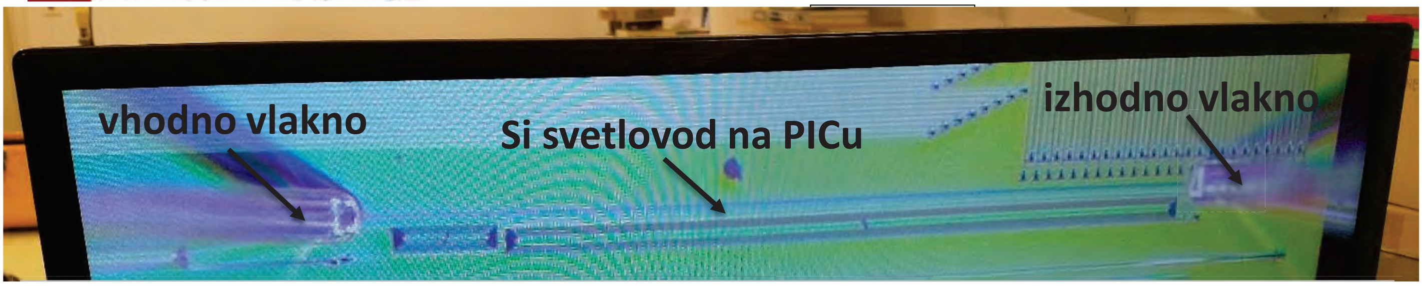
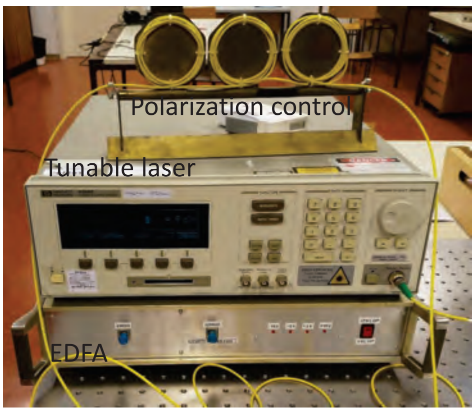
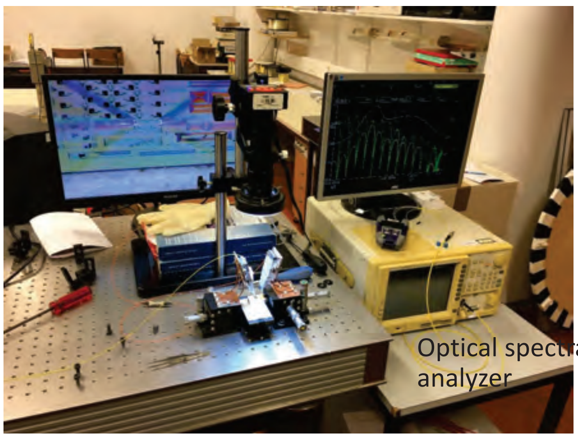




LSO & LPVO



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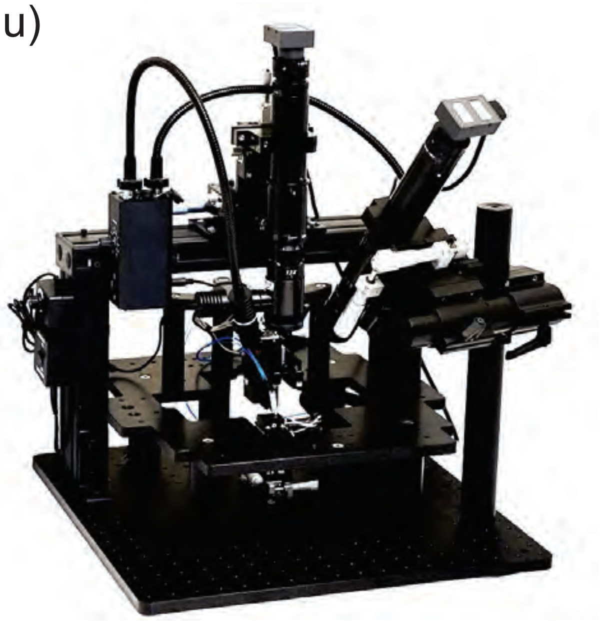
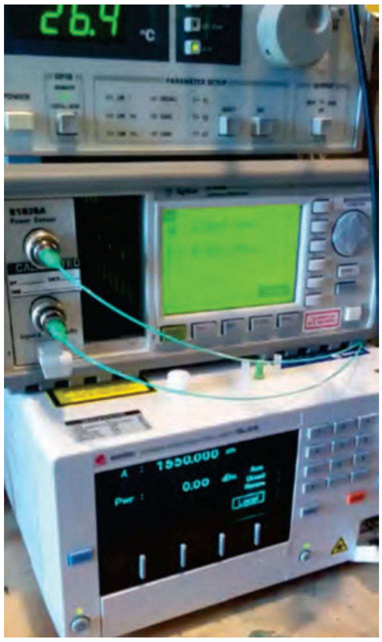
Nov avtomatski merilni sistem za PIC (v naročanju)





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Načrtovanje

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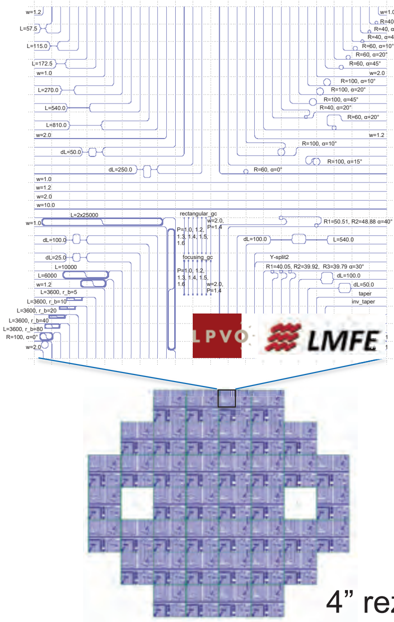
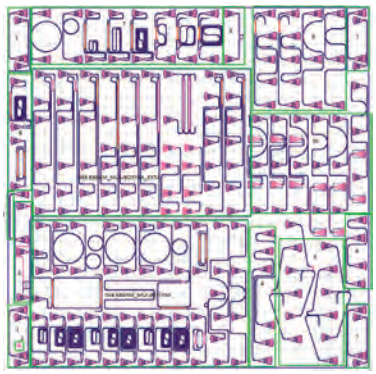
SiN testni PIC-i



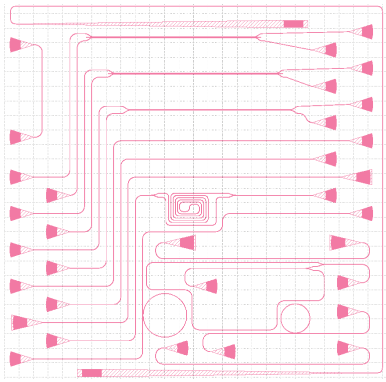
4” rezina

Si testni PIC



LPVO ANT APPLIED NANOTOOLS INC.

amorfni Si testni PIC



LPVO TUDelft NANOPHOTONICS TECHNOLOGY CENTER

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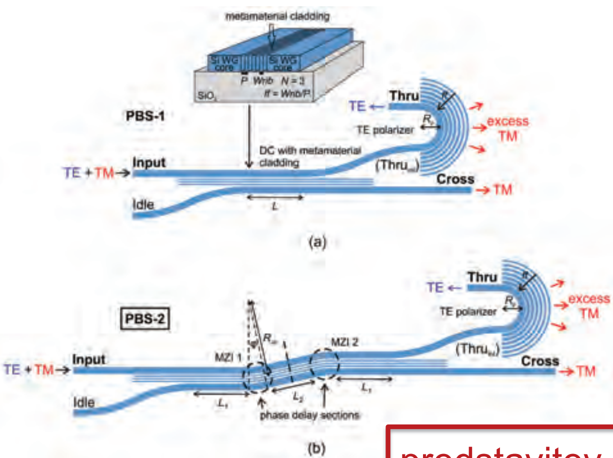
Research Article Vol. 30, No. 26 / 19 Dec 2022 / Optics Express 46693

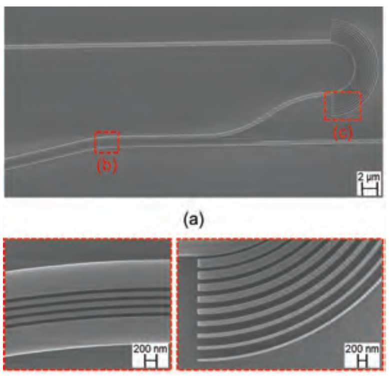
Optics EXPRESS

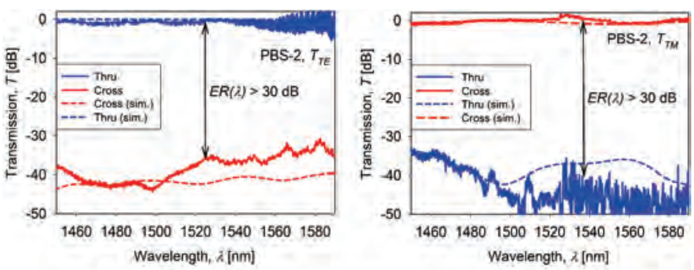
High extinction ratio and an ultra-broadband polarization beam splitter in silicon integrated photonics by employing an all-dielectric metamaterial cladding

ANDRAŽ DEBEVC, MARKO TOPIČ, AND JANEZ KRČ*

University of Ljubljana, Faculty of Electrical Engineering, Tržaška 25, 1000 Ljubljana, Slovenia







predstavitev A. Debevc et al. SOK 2023

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Projekti

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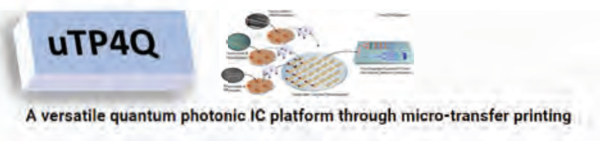
QUANTERA

Quantum PIC (QPIC)



Partner Number	Country	Institution/ Department
1 Coordinator	BE	Ghent University (UG)
2	DK	University of Copenhagen (NBI)
3	DK	Sparrow Quantum (SQ)
4	DE	University of Muenster (MU)
5	CH	Swiss centre for electronics and microtechnology (CSEM)
6	SLO	Univerza v Ljubljani (UL)

fwo REPUBLIC OF SLOVENIA GOV.SI Innovation Fund Denmark Technologiezentrum

Call topic
Applied Quantum Science

Start date
May 2022

Duration
36 months

Funding support
€ 1 547 570

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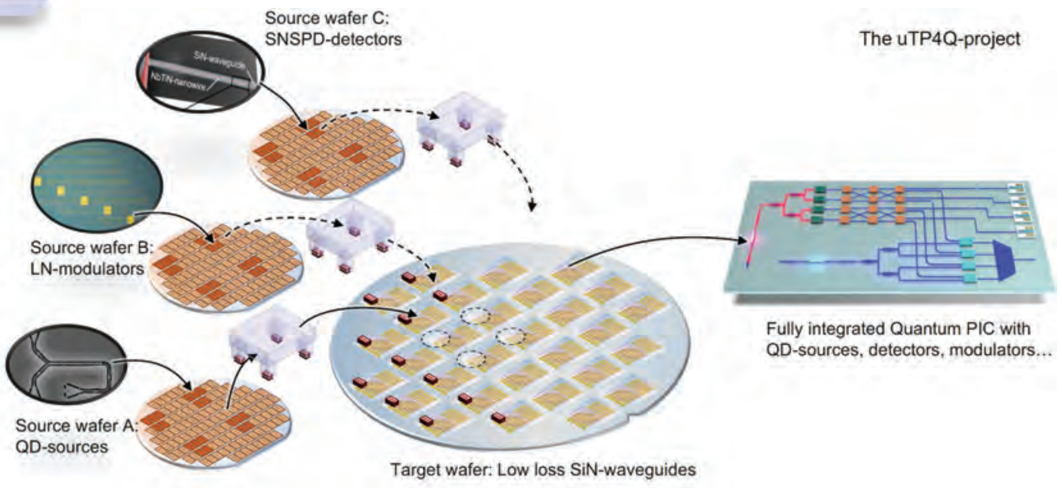
QUANTERA

Quantum PIC (QPIC)

uTP4Q A versatile quantum photonic IC platform through micro-transfer printing



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QUANTERA uTP4Q A versatile quantum photonic IC platform through micro-transfer printing

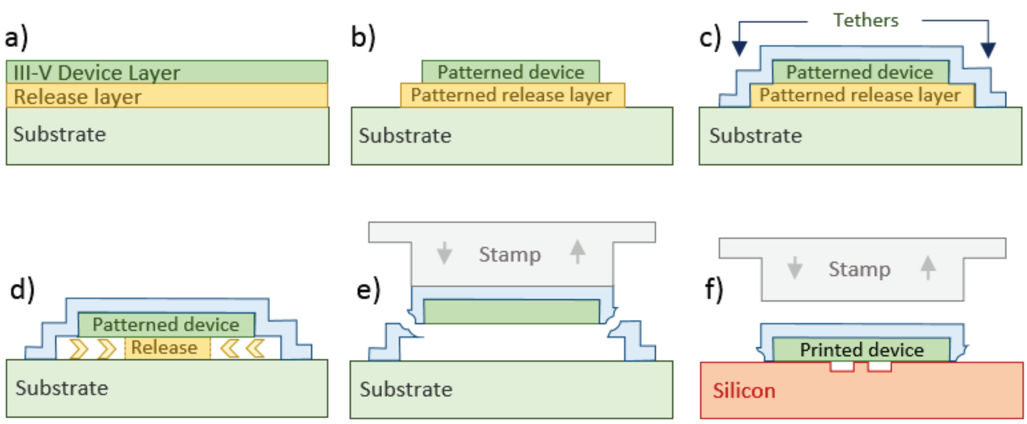
uTP4Q

Micro-transfer printing basics

Device processing, release, pick-up & print

GHENT UNIVERSITY

imec



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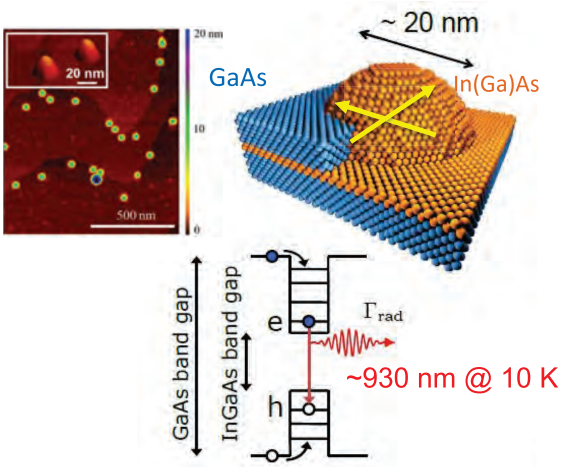
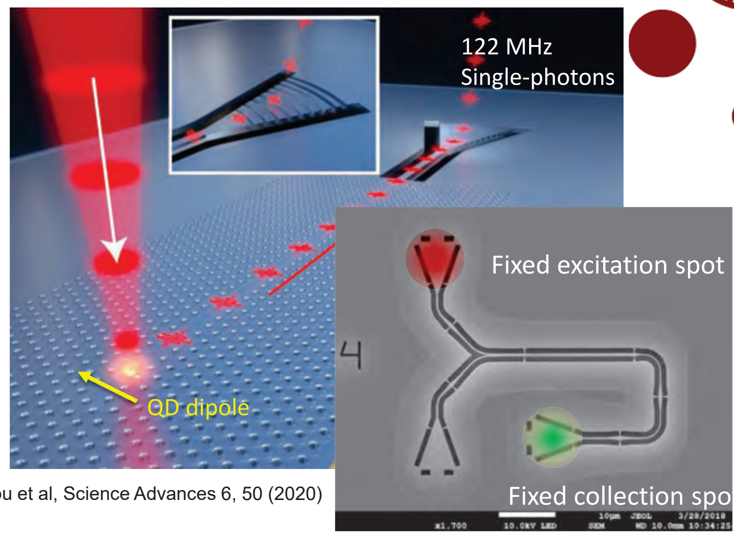
QUANTERA uTP4Q A versatile quantum photonic IC platform through micro-transfer printing

uTP4Q

Single photon sources In(Ga)As quantum dots



Lodahl et al, Rev. Mod. Phys. 87, 347 (2015).



Uppu et al, Science Advances 6, 50 (2020)

Uppu et al, Nat. Comm. 11, 3782 (2020)

J. Krč SOK 202323 31

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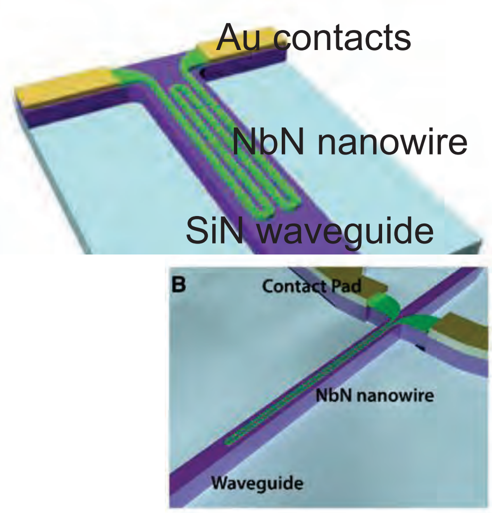
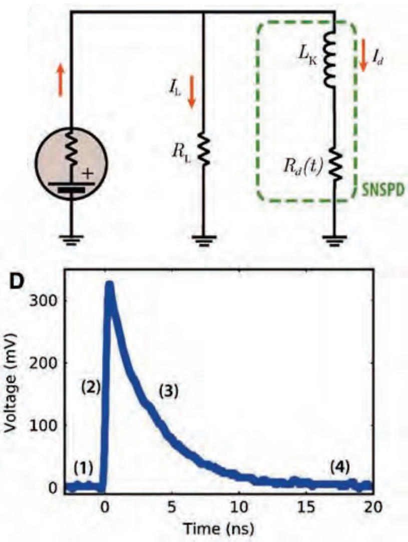
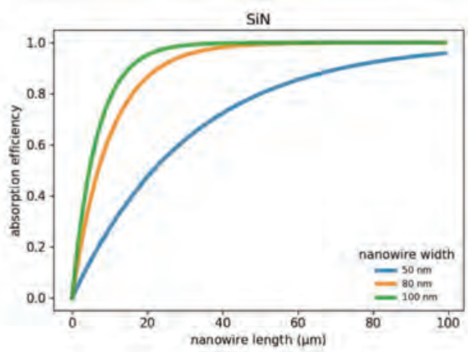
uTP4Q

WWU MÜNSTER
KIRCHHOFF - INSTITUT FÜR PHYSIK

Single photon detectors - NbN superconducting nanowires







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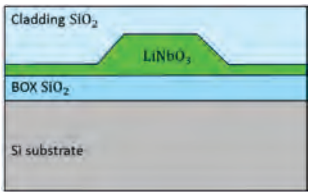
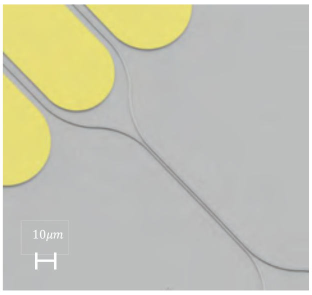
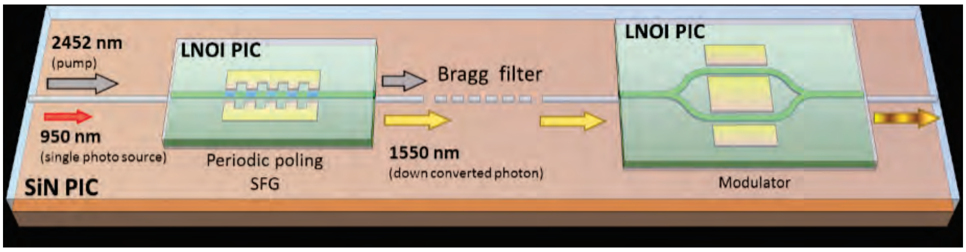
Modulators, switches, wavelength converters from LN







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SiN platform offers low losses

Silicon versus Silicon Nitride

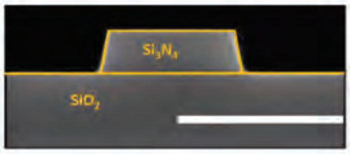
	Wavelength Range (nm)	Refractive Index (at 1550nm)	Waveguide Loss (dB/cm)	Non-linear Process	Thermo-optic Coefficient (K⁻¹)	Doping based Modulators (Gb/s)	Integrated Photodetector (GHz)	Layer Stack Flexibility
Silicon	1100 – 4000	3.48	1 – 1.5	Low	1.86×10^{-4}	>40	>60	Limited
Silicon Nitride	400 – 4000	2.0	0.001 – 0.5	High	2.45×10^{-5}	Not available	Not available	Excellent

Silicon & Silicon Nitride both offers excellent platform for different requirements

imec

Europractice & imec webinar on SiN MPW, 2022

Silicon nitride (SiN)



Silicon nitride: n=2
Silicon oxide: n=1.45
Moderately high index contrast

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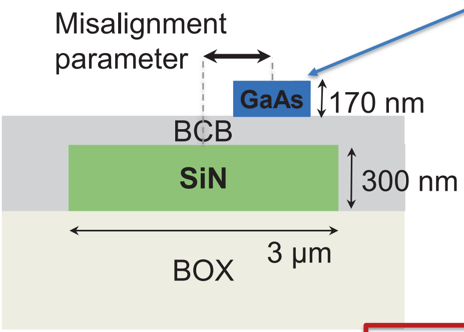
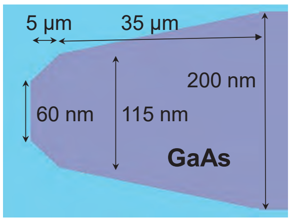
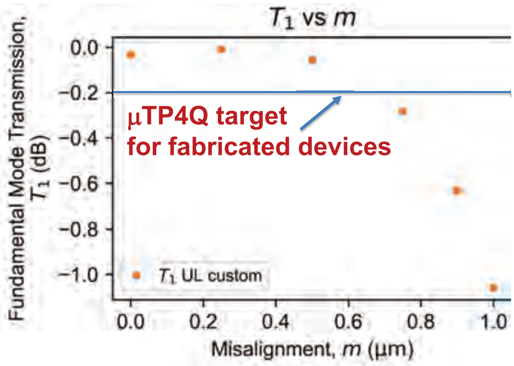
Importance of efficient coupling between components to SiN and to optical fibers

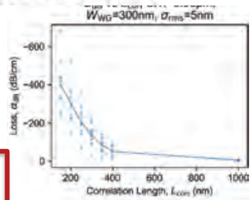
Cross-section:



Top view on GaAs taper:







predstavitev M. Ljubotina et al. SOK 2023

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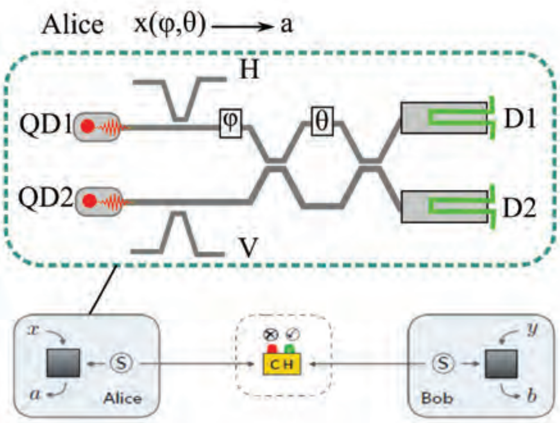
Device independent sending/receiving stations

Goal of WP5



E. Ruiz et al, PRA **106**, 102222, 2022

Each station (Alice or Bob) contains

- 2 QD sources (or 1 source, demultiplexed)
- A reconfigurable 2x2 Unitary gate
- Two SNSPD
- Some polarization-diversity grating with fiber coupling

Difficult because:

- Birth-to-death efficiency should be higher than ~85%.
- Indistinguishability between QD1/QD2 should be >95%

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Zahvala

Javna agencija za raziskovalno dejavnost Republike Slovenije

Fotovoltaika in elektronika (P2-0415)

QUANTERA

QuantERA II JTC 2021 project uTP4Q (št. pogodbe C3330-22-252001).

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uTP4Q

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Načrtovanje optičnih adiabatnih sklopnikov za integracijo gradnikov kvantne fotonike s platformo SiN

Design of optical adiabatic couplers for integration of quantum photonics building blocks with SiN platform

Miloš Ljubotina, Andraž Debevc, Marko Topič in Janez Krč
Univerza v Ljubljani, Fakulteta za elektrotehniko, Laboratorij za fotovoltaiko in optoelektroniko
milos.ljubotina@fe.uni-lj.si

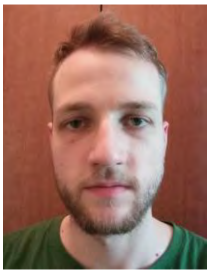
Povzetek

Uporaba fotonskih integriranih vezij (PIC) na področju kvantnih aplikacij zahteva zelo učinkovite fotonske strukture. Za največjo učinkovitost posameznih gradnikov kvantne fotonike je potrebno izkoristiti različne materialne platforme, ki služijo izdelavi (kvantnih) PIC. Gradnike, izdelane na različnih platformah, je z ustreznimi postopki heterogene integracije mogoče fizično združiti s skupno temeljno platformo. Ključen dejavnik za pravilno delovanje celotnega vezja je učinkovit optičen sklop integriranih gradnikov. V našem prispevku se bomo posvetili načrtovanju adiabatnih sklopnikov med kvantnimi gradniki in temeljno platformo SiN. Prikazali bomo rezultate simulacij načrtanih sklopnikov.

Abstract

The use of photonic integrated circuits (PICs) in the field of quantum applications requires highly efficient photonic structures. For the maximum efficiency of the individual building blocks of quantum photonics, it is necessary to use different material platforms that serve to manufacture (quantum) PICs. Building blocks built on different platforms can be physically combined to a common underlying platform through appropriate heterogeneous integration processes. A key factor for the correct operation of the entire circuit is an efficient optical assembly of integrated components. In our paper, we focus on the design of adiabatic couplings between the quantum building blocks and the underlying SiN platform. The simulation results of the designed clutches are shown.

Biografija avtorja



Miloš Ljubotina je leta 2020 končal magistrski študijski program Elektrotehnika na Fakulteti za elektrotehniko Univerze v Ljubljani. Istega leta se je na tej fakulteti vpisal v doktorski študijski program in postal mladi raziskovalec v Laboratoriju za fotovoltaiko in optoelektroniko, kjer se ukvarja s področjem integrirane fotonike. Njegova primarna raziskovalna dejavnost vključuje načrtovanje, optično modeliranje in karakterizacijo fotonskih integriranih vezij.

Author's biography

Miloš Ljubotina received his MSc in Electrical Engineering at the Faculty of Electrical Engineering, University of Ljubljana, Slovenia, in 2020. He is continuing his studies as a PhD candidate at the same faculty and a member of the Laboratory of Photovoltaics and Optoelectronics since October 2020.

His main research activities include design, optical modelling, and characterisation of photonic integrated circuits in the field of integrated photonics.

Načrtovanje optičnih adiabatnih sklopnikov za integracijo gradnikov kvantne fotonike s platformo SiN

Miloš Ljubotina, Andraž Debevc, Marko Topič in Janez Krč

University of Ljubljana, Faculty of Electrical Engineering,
Laboratory of Photovoltaics and Optoelectronics (LPVO),
Tržaška 25, 1000 Ljubljana, Slovenia

LPVO University of Ljubljana Faculty of Electrical Engineering

Vsebina

1. **Kratek uvod v tematiko in obravnavane strukture** (adiabatni sklopnik med GaAs in SiN za enofotonske vire, hrapav valovod GaAs)

2. **Simulacije optičnih izgub pri širjenju EM valovanja zaradi hrapavosti stranic valovoda GaAs** (hrapavost je posledica litografskega postopka)

3. **Preliminarni rezultati simulacij vpliva hrapavosti stranic valovoda GaAs na adiabatno sklapljanje med GaAs in SiN**

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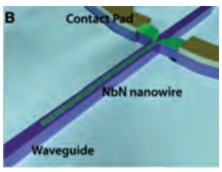
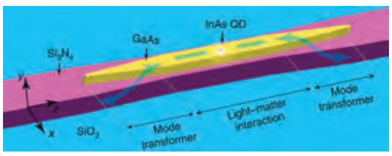
Motivacija (projekt µTP4Q)

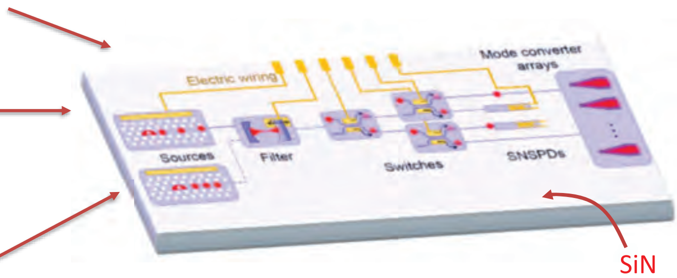
- Razvoj enotne platforme za QPIC za kvantno komunikacijo in računstvo



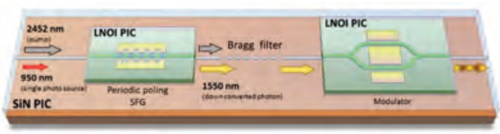
S. Ferrari et al., Nanophotonics, vol. 7, no. 11, Art. no. 11, Nov. 2018.



M. Davanco et al., Nat Commun, vol. 8, no. 1, Art. no. 1, Oct. 2017.



QuantERA 2021 uTP4Q project proposal



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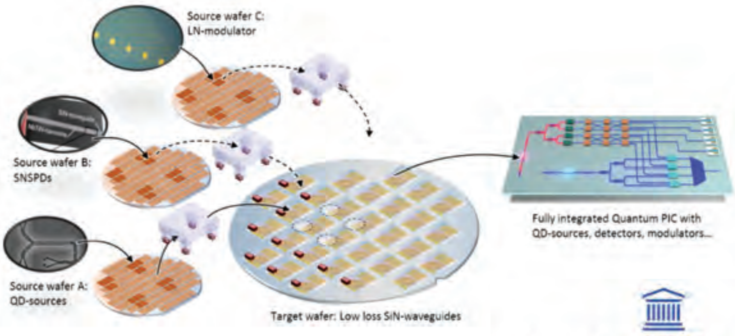
Mikroprenosen tisk (micro-transfer printing - μTP)

- μTP omogoča heterogeno integracijo več materialnih platform
- Točnost poravnave pod ±1.0 μm (3σ)



QuantERA 2021 uTP4Q project proposal

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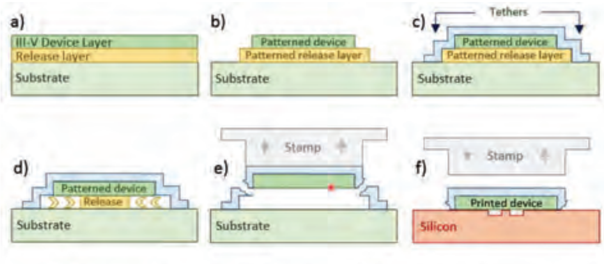

Transfer of released, micro-scale III-V devices to a Si target wafer

6th ePIXfab Silicon Photonics Summer School, 2021

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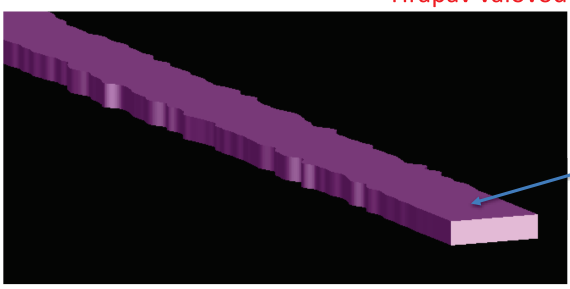
Adiabatni sklopnik med GaAs in SiN za enofotonske vire

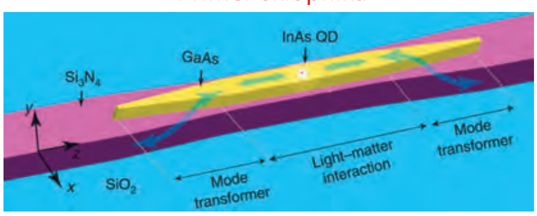
- Adiabatni sklopnik služi **učinkovitemu** prenosu EM valovanja (iz GaAs v SiN)
- Pomembno je upoštevati realne pogoje (neidealna poravnava, **hrapavost valovodov**, …)

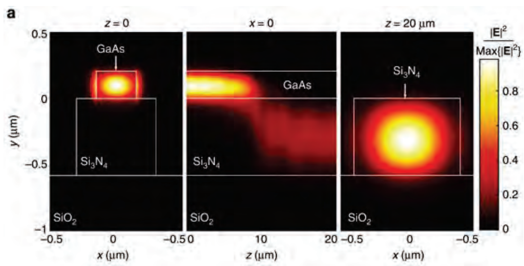
Hrapav valovod



GaAs

Primer sklopnika





M. Davanco et al., Nat Commun, vol. 8, no. 1, Art. no. 1, Oct. 2017.

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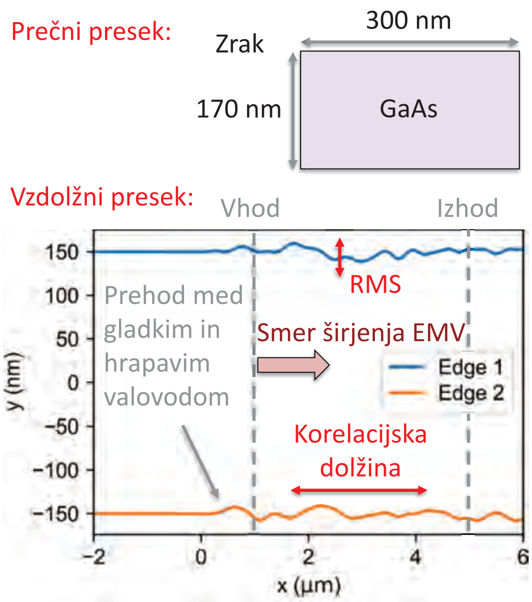
Simulacije izgub hrapavega valovoda GaAs (FDTD)

- Vakuumska valovna dolžina **930 nm**
- Stranice valovoda so spremenjene na podlagi naključno generiranega šuma določene **efektivne vrednosti (RMS)** in **korelacijske dolžine**
- Okvirne empirične vrednosti parametrov (NBI):
  - RMS hrapavosti: ~**4.7 nm**
  - Korelacijska dolžina: ~**200 nm** (velika std. dev.)
  - Izgube: **50-70 dB/cm**

Y. Wang et al., Appl. Phys. Lett., vol. 118, no. 13, 2021.



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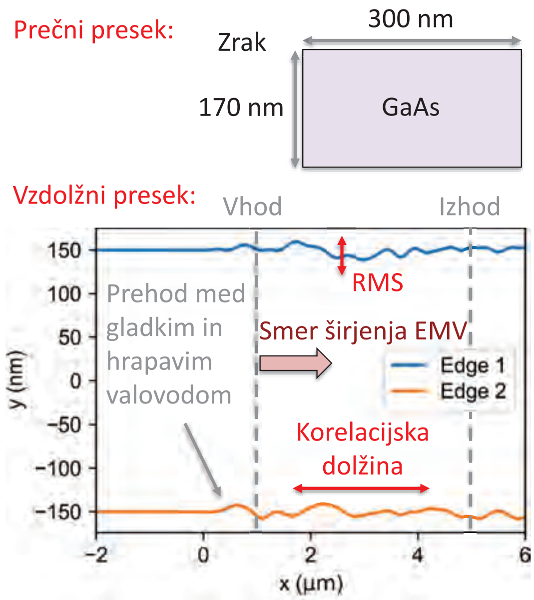
Simulacije izgub hrapavega valovoda GaAs (FDTD)

- Določamo odvisnost izgub od:
  - **Korelacijske dolžine** (zaradi negotovosti meritev)
  - **RMS hrapavosti** (kako majhen RMS je potreben za izgube okvirno 10 dB/cm?)
  - **Valovne dolžine** (možna optimizacija izgub)



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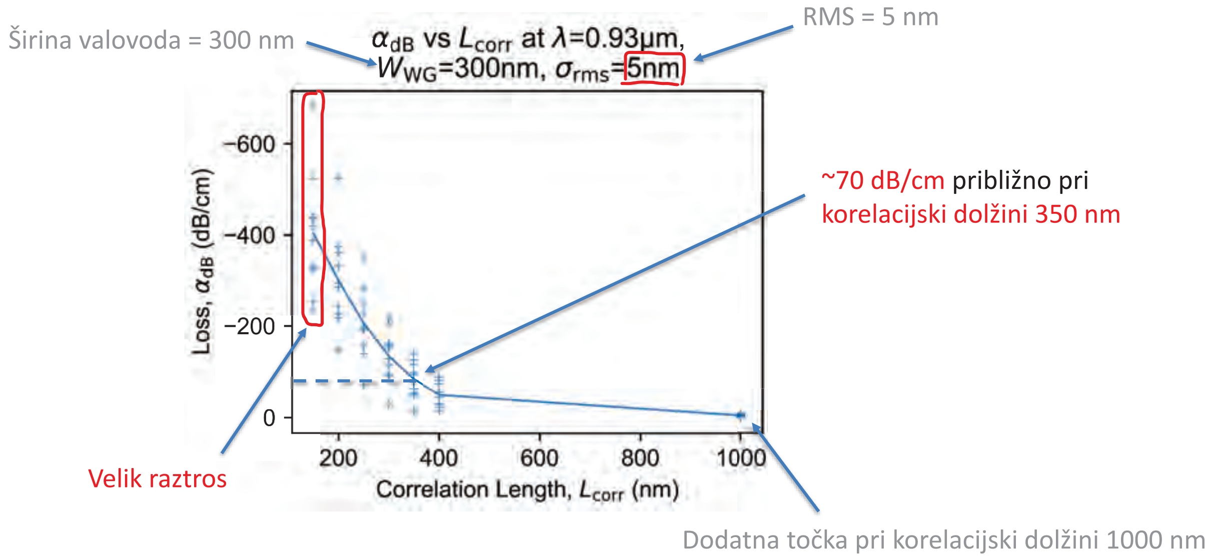
Odvisnost izgub hrapavega valovoda GaAs od korelacijske dolžine hrapavosti (FDTD)



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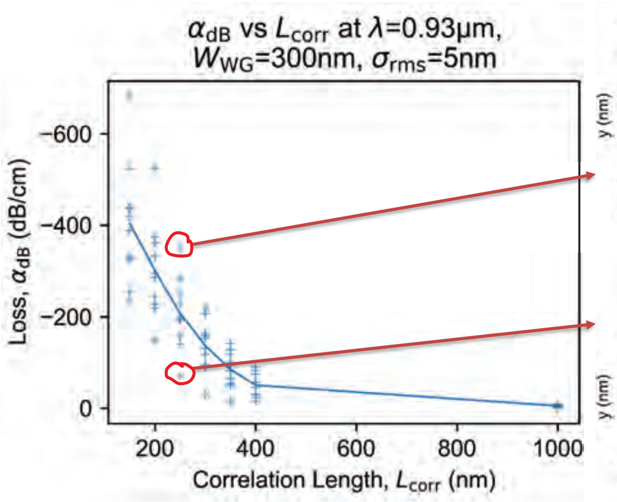
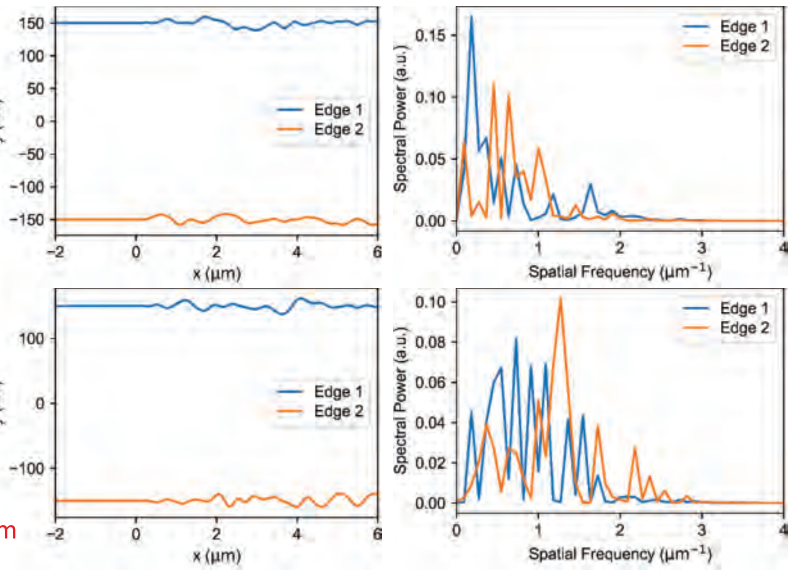
Možna bolj podrobna (Fourierova) analiza raztrosa izgub

Izgube proti korelacijski dolžini



Vzdolžni presek valovoda

Frekvenčni spekter hrapavosti



V spodnjem primeru je spekter pomaknjen proti višjim prostorskim frekvencam

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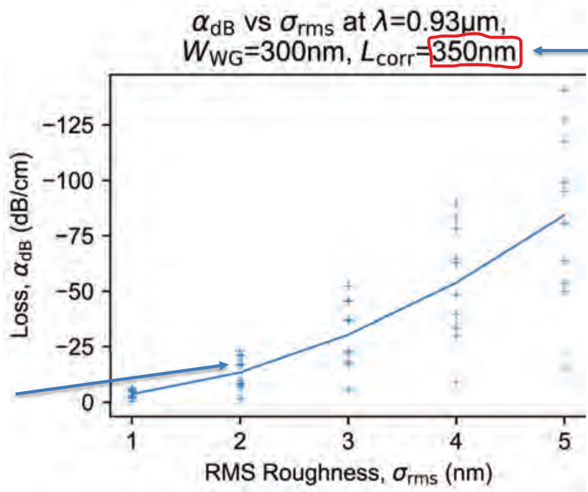
Odvisnost izgub hrapavega valovoda GaAs od RMS hrapavosti (FDTD)



Korelacijska dolžina, pri kateri se rezultati simulacij okvirno ujemajo z izhodiščno vrednostjo izgub

~10 dB/cm približno pri RMS 2 nm

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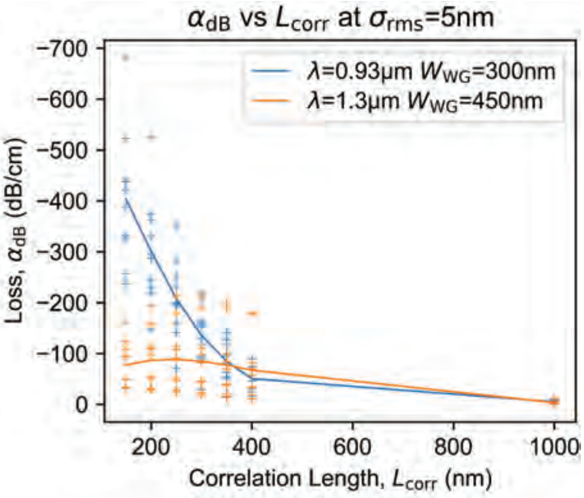
Izgube hrapavega valovoda GaAs pri daljši valovni dolžini (FDTD)

1. Valovod (enako kot prej):
   - Valovna dolžina **930 nm**
   - Širina **300 nm**
2. Valovod (daljša valovna dolžina):
   - Valovna dolžina **1300 nm**
   - Širina **450 nm**

Primerjava odvisnosti izgub od korelacijske dolžine dveh valovodov



Porast izgub pri krajših korelacijskih dolžinah je za 2. valovod veliko manjša

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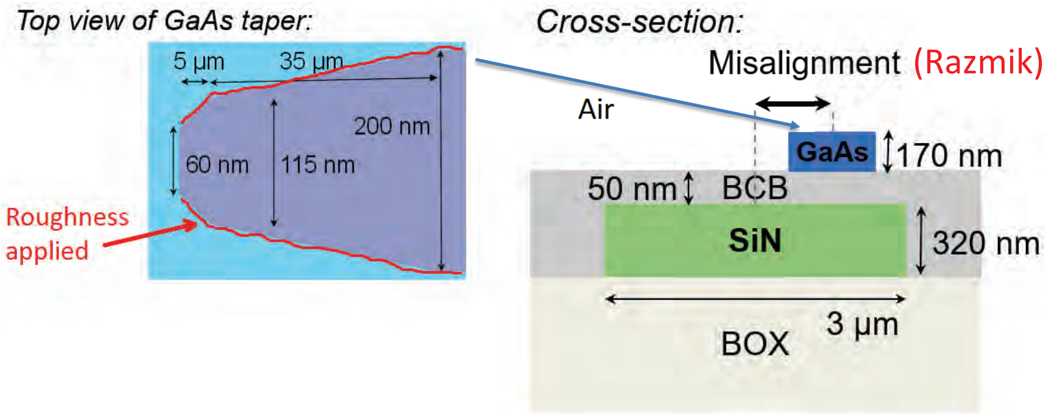
Adiabatni sklopnik med GaAs in SiN



G. Roelkens *et al.*, *IEEE J. Sel. Top. Quantum Electron.*, vol. 29, no. 3: Photon. Elec. Co-Inte. and Adv. Trans. Print., pp. 1–14, May 2023

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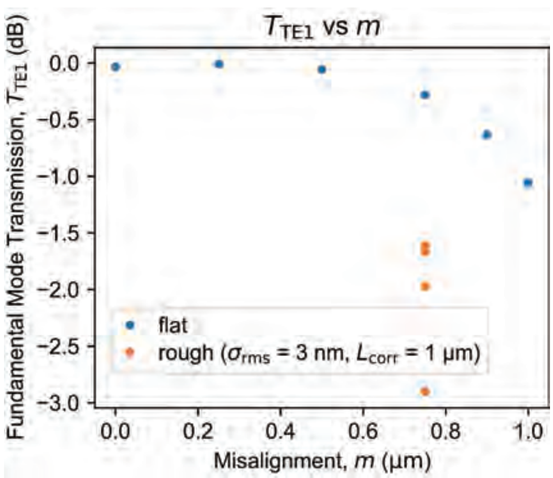
Vpliv hrapavosti valovoda GaAs na adiabatno sklapljanje med GaAs in SiN (FDTD)

- RMS = 3 nm, korelacijska dolžina = 1 µm, 4 različne začetne vrednosti generatorja psevdo-naključnih števil
- Transmisija pri ***m* = 0,75 µm** pade z -0,3 dB na -2,0 dB

Transmisija osnovnega rodu TE proti razmiku



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Zahvala

Leonardo Midolo, Inštitut Niels Bohr, Danska

Dries Van Thourhout in Jasper De Witte, Univerza v Gentu, Belgija

Javna agencija za raziskovalno dejavnost Republike Slovenije

Fotovoltaika in elektronika (P2-0415)

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QuantERA II JTC 2021 project uTP4Q (št. pogodbe C3330-22-252001).

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Hvala za pozornost

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Polarizacijski razcepnik z dielektričnimi metamateriali v silicijevih fotonskih integriranih vezjih

Polarization splitter with dielectric metamaterials in silicon photonic integrated circuits

Andraž Debevc, Miloš Ljubotina, Marko Topič in Janez Krč

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Povzetek

Fotonska integrirana vezja (PIC) na osnovi silicija se že dandanes komercialno uporabljajo v sistemih za optični prenos podatkov znotraj podatkovnih centrov s hitrostmi do 400 Gbit/s in v mnogih drugih aplikacijah. V splošnem so lastnosti gradnikov Si PIC odvisne tudi od polarizacije svetlobe. Zato pri večini aplikacij potrebujemo gradnike za kontrolo polarizacije. V našem prispevku bomo predstavili nov koncept integriranega polarizacijskega razcepnika, ki mešano polarizacijo na vhodu razdeli na TE-polarizacijo na enem izhodu, in TM-polarizacijo na drugem izhodu. Polarizacijski razcepnik temelji na podvalovnodolžinskih strukturah dielektričnih metamaterialov s pomočjo katerih lahko dosežemo visoko zmogljivost.

Abstract

Silicon-based photonic integrated circuits (PICs) are already commercially used today in optical data transmission systems within data centers at speeds up to 400 Gbit/s and in many other applications. In general, the properties of Si PIC components also depend on the polarization of light. Therefore, in most applications we need polarization control building blocks. In our paper, we present a new concept of an integrated polarization splitter, which splits the mixed polarization at the input into TE-polarization at one output and TM-polarization at the other output. The polarization splitter is based on sub-wavelength structures of dielectric metamaterials with the help of which we can achieve high performance.

Biografija avtorja

Andraž Debevc je leta 2017 končal magistrski študijski program Elektrotehnika na Fakulteti za elektrotehniko Univerze v Ljubljani. Istega leta se je na tej fakulteti vpisal na doktorski študij in postal mladi raziskovalec v Laboratoriju za fotovoltaiko in optoelektroniko. Trenutno deluje kot raziskovalec in asistent. Pri raziskovalnem delu se ukvarja s področjem fotonike. Njegova primarna raziskovalna dejavnost vključuje načrtovanje, optično modeliranje in karakterizacijo fotonskih integriranih vezij.

Author's biography

Andraž Debevc received his MSc in Electrical Engineering at the Faculty of Electrical Engineering, University of Ljubljana, Slovenia, in 2017. In October 2017 he became a PhD student and a member of the

Laboratory of Photovoltaics and Optoelectronics. He is currently working as a researcher and teaching assistant. His research work is related to photonics. The main research activities include design, optical modelling and characterization of photonic integrated circuits.

Polarizacijski razcepnik z dielektričnimi metamateriali v silicijevih fotonskih integriranih vezjih

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Vsebina predavanja

- Uvod
  - Silicijeva fotonska integrirana vezja (PIC)
  - Polarizacijska odvisnost komponent v fotonskih integriranih vezjih
  - Dielektrični metamateriali
- Polarizacijski razcepnik – koncept
- Metode
- Rezultati
  - Simulacije
  - Eksperimentalni rezultati

A. Debevc 26. seminar optične komunikacije , Ljubljana, 25. 1. 2023 2

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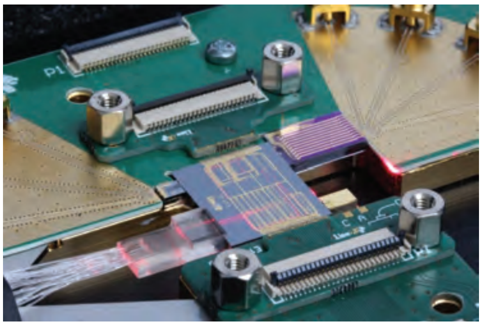
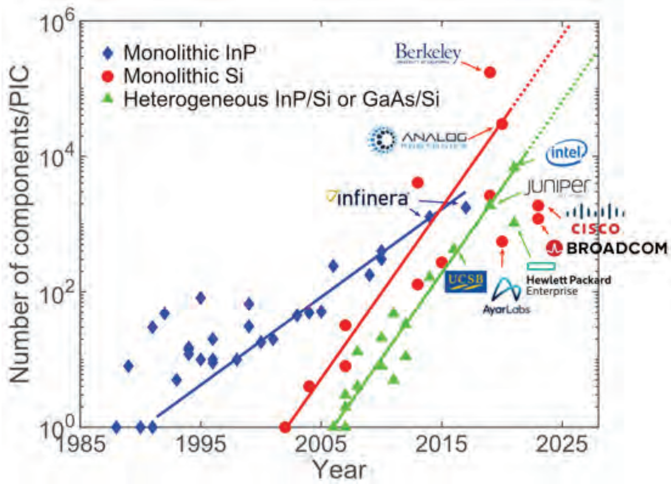
Fotonska integrirana vezja

- Integrirane fotonske komponente→ Fotonska integrirana vezja (PIC)
- Materiali:
  - Si, Si_3N_4, SiO_2 ,InP, $LiNbO_3$, polimeri,...



P. I. C. Magazine, https://picmagazine.net/article-gen/109911



Margalit et al., Appl. Phys. Lett., vol. 118, no. 22, p. 220501 (2021)

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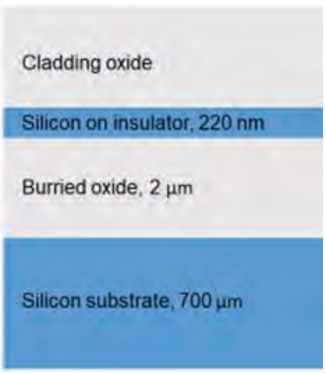
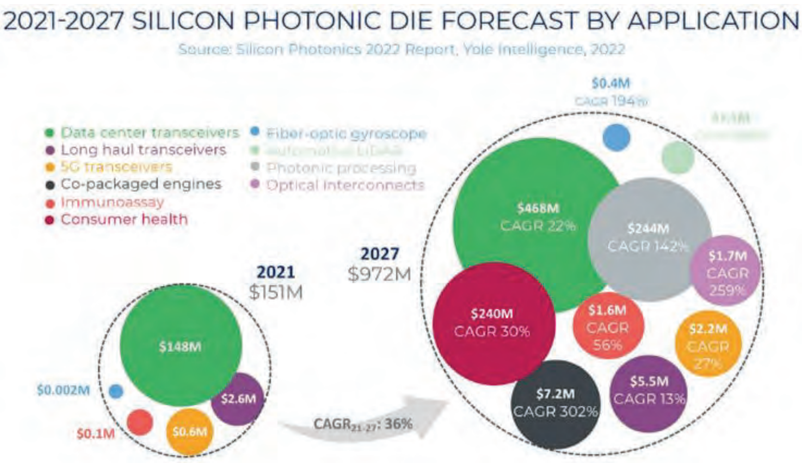
Silicijeva fotonika

- Možnost uporabe CMOS tehnologije za izdelavo





'Silicon photonics: to SOI and beyond!', *Yole Group*. https://www.yolegroup.com/press-release/silicon-photonics-to-soi-and-beyond/

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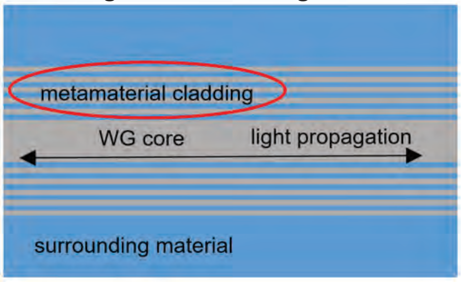
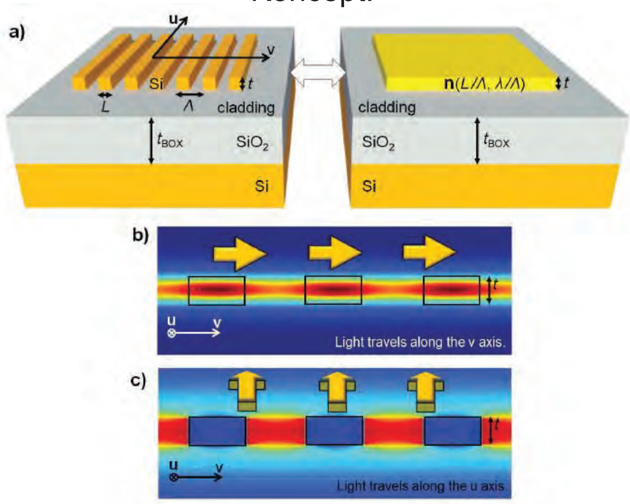
Dielektrični metamateriali

- Periodično izmenjavanje dveh (ali več) materialov z različnimi lomnimi količniki
- Anizotropnost lomnega količnika→vpliv na vodenje svetlobe
- Strukture se da izdelati s standardnimi tehnološkimi procesi (CMOS)

Valovod z oblogo iz dielektričnega metamateriala



Koncept:



Halir et al. , Proceedings of the IEEE, vol. 106, no. 12, pp. 2144–2157(2018)

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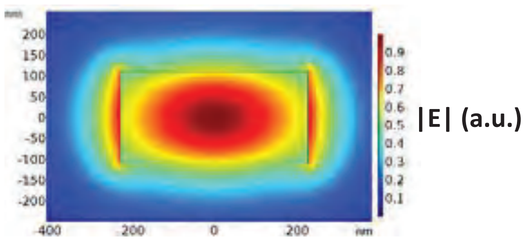
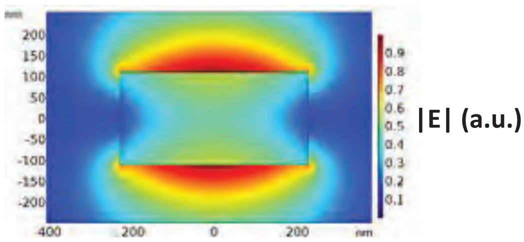
Polarizacijska odvisnost Si valovodov

- Valovodi in posledično tudi gradniki na Si PIC so izrazito polarizacijsko odvisni
- Za obvladovanje te polarizacijske odvisnosti so ključnega pomena gradniki za manipuliranje polarizacije
- Večina Si PIC aplikacij zahteva visoko zmogljive polarizacijske razcepnike, ki mešano polarizacijo na vhodu razdelijo na TE- in TM-rod

TE- rod



TM- rod



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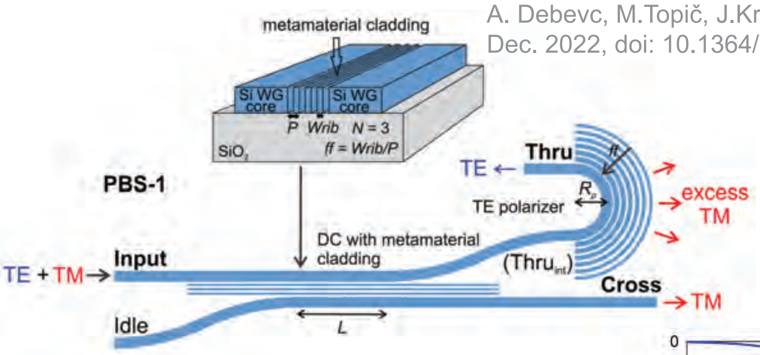
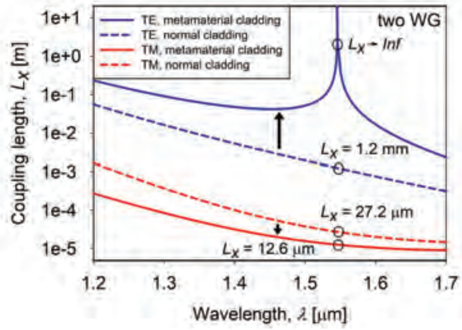
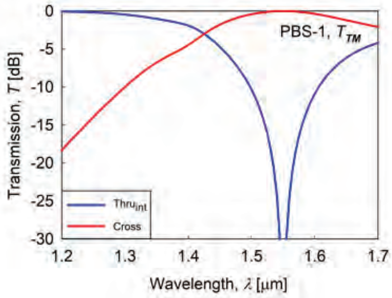
Koncept PBS-1

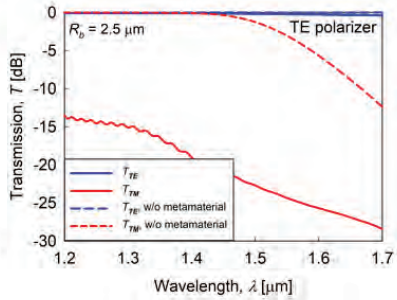
A. Debevc, M.Topič, J.Krč, *Opt. Express*, Dec. 2022, doi: 10.1364/OE.476333





- TM-rod se sklopi iz zgornjega valovoda v spodnji valovod, TE-rod ostane v zgornjem valovodu
- Thru izhodu dodamo TE-polarizator, da dosežemo večje slabljenje TM rodu





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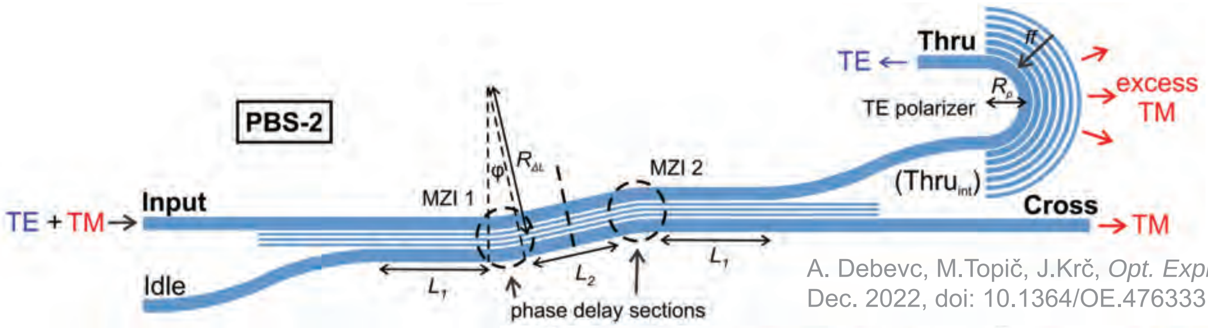
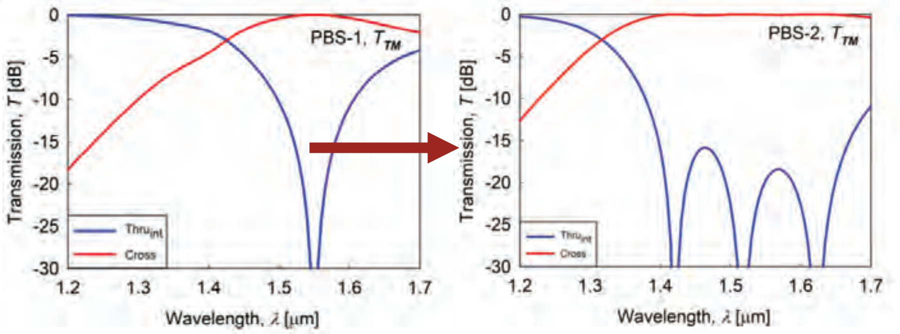
Koncept PBS-2



A. Debevc, M.Topič, J.Krč, *Opt. Express*, Dec. 2022, doi: 10.1364/OE.476333

- Struktura PBS-2 je načrtana z namenom doseganja večje pasovne širine



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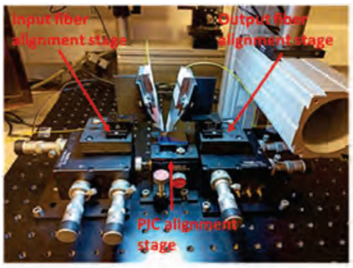
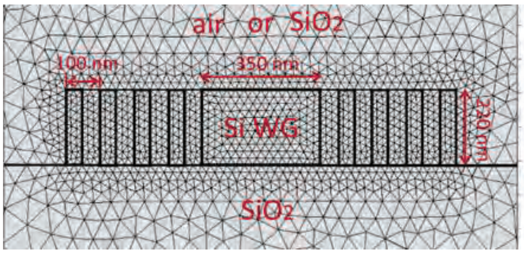
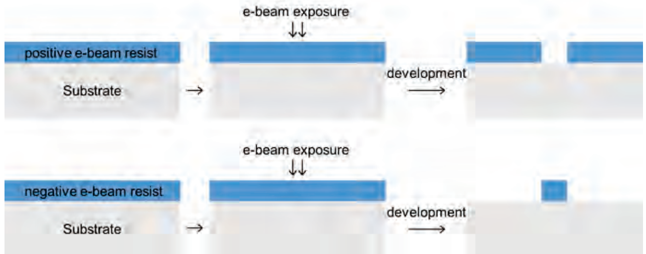
Metode

- Simulacijske metode
  - FEM analiza rodov
  - 3-D FDTD simulacije
- Izdelava čipa na SOI rezini
  - Litografija z elektronskim žarkom in RIE jedkanje (Applied Nanotools Inc.)
- Optična karakterizacija



Mreža FEM





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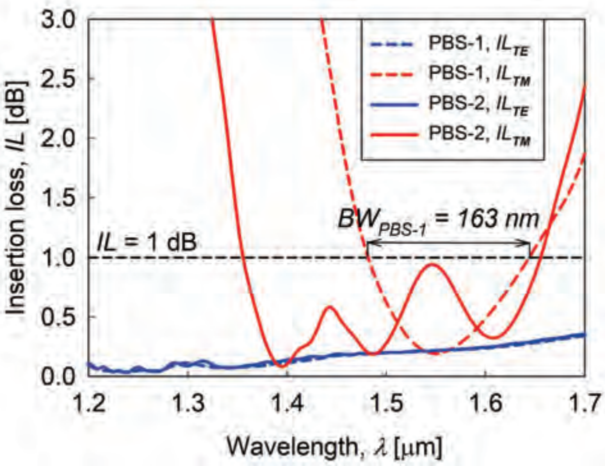
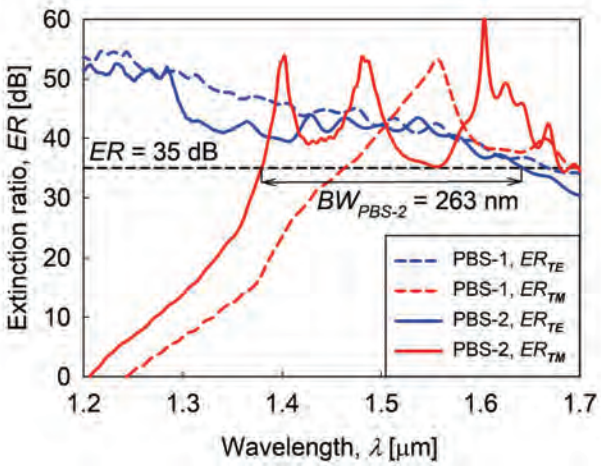
Rezultati simulacij (FDTD)





- ***IL* < 1 dB, *ER* > 35 dB**
- **$BW_{PBS\text{-}1}$ = 163 nm, $BW_{PBS\text{-}2}$ = 263 nm**

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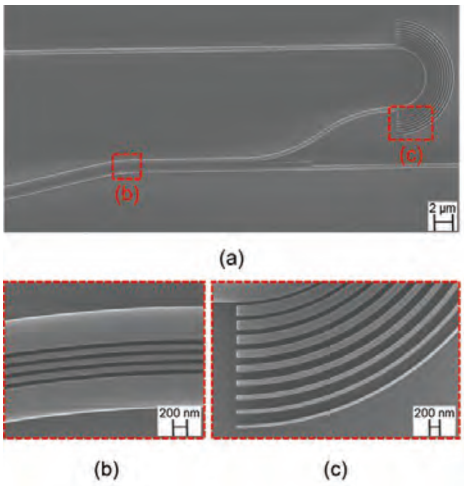
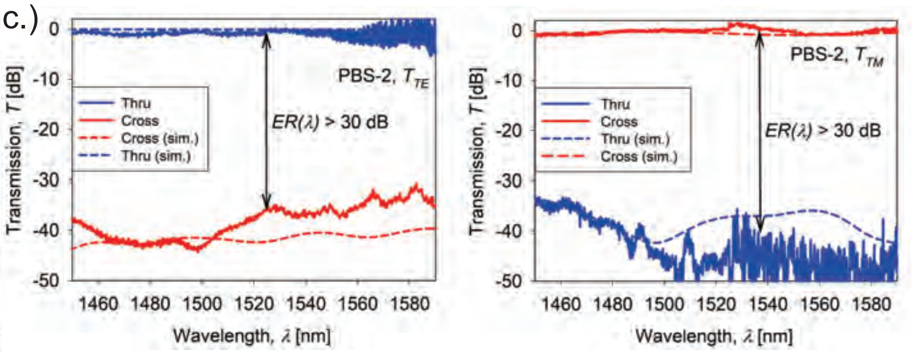
Izdelava in eksperimentalni rezultati

- Gradnik PBS-2 je bil izdelan na SOI rezini uporabo 100 keV litografije z elektronskim žarkom (Applied nanotools, Inc.)





- ***ER* > 30 dB, *BW* > 140 nm** (omejeno območje meritve zaradi valovnodolžinskega območja laserja)
- *IL* < 2 dB

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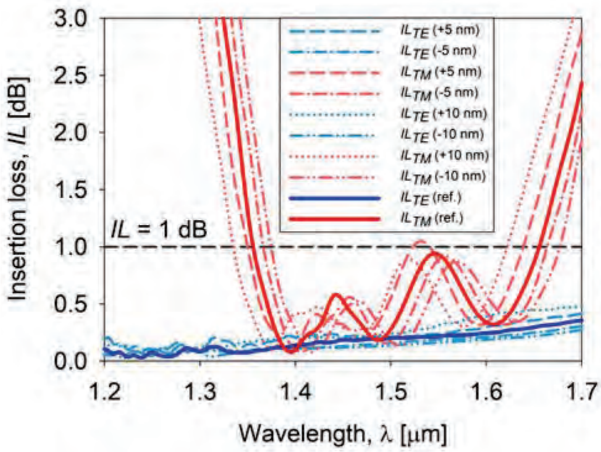
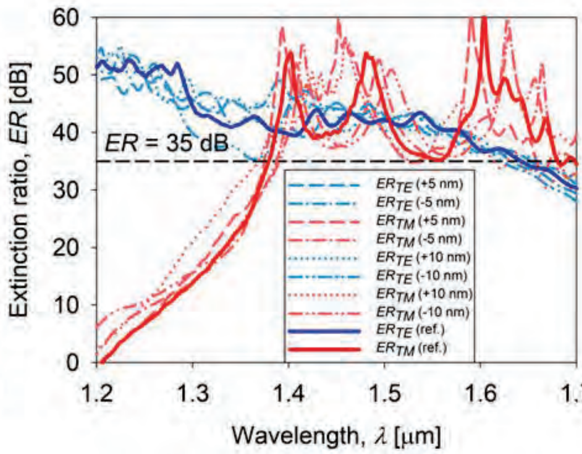
Občutljivost na tolerance pri izdelavi





- **Variacija velikosti vseh struktur v razponu +/- 10 nm ne vpliva na zmogljivost gradnika PBS-2**

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Zahvala

LSO Laboratorij za sevanje in optiko

Javna agencija za raziskovalno dejavnost Republike Slovenije

Fotovoltaika in elektronika (P2-0415)

REPUBLIKA SLOVENIJA MINISTRSTVO ZA IZOBRAŽEVANJE, ZNANOST IN ŠPORT

A. Debevc 26. seminar optične komunikacije , Ljubljana, 25. 1. 2023 13

Sistem stabilizacije injekcijske vklenitve Fabry-Periot laserske diode za uporabo v WDM-PON

Fabry-Periot laser diode injection lock stabilization system for use in WDM-PON

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Povzetek

Cenena in dobro poznana Fabry-Periot laserska dioda niha na več vzdolžnih (longitudinalnih) rodovih. S tehniko injekcijske vklenitve lahko Fabry-Periotov laser deluje kot enorodovni laser. Za zagotovitev stabilne optične vklenitve Fabry-Periotovega laserja mora biti pri vzbujevalni svetlobi zagotovljenih več pogojev. Predstavljeno tehniko stabilizacije je mogoče uporabiti v sistemu WDM-PON, ki je privlačna tehnologija optičnega dostopa. Za praktično izvedbo WDM-PON so zelo pomembni poceni komunikacijski viri svetlobe. V ta namen je v prispevku opisan sistem, ki ima potencial za zagotavljanje stabilne vklenitve.

Abstract

The inexpensive and well-known Fabry-Periot laser diode oscillates on several longitudinal lines. With the injection locking technique, the Fabry-Periot laser can operate like a single longitudinal line laser. To ensure stable optical locking of the Fabry-Periot laser, several conditions for the operation of an injection-locking system must be met. The presented stability technique can be used in WDM-PON system which is an attractive optical access technology. For the practical implementation of a WDM-PON, low-cost communications light-source units are very important. For this purpose, the presentation describes the system that has a potential to ensure the stability of optical injection locking.

Biografija avtorja

Vesna Eržen je po končani gimnaziji študij nadaljevala na Visoki šoli za varnostne vede Univerze v Mariboru. Kasneje se je iz družboslovnih ved preusmerila na področje naravoslovja in se po končanem študiju varnostnih ved (l. 2006) vpisala na Fakulteto za elektrotehniko Univerze v Ljubljani. Leta 2012 je diplomirala iz področja optičnih komunikacij, njeno delo pa se je nanašalo na podaljševanje dosega zveze v pasivnih optičnih omrežjih. Od 2012 do 2016 je bila zaposlena kot raziskovalka na projektu v Laboratoriju za sevanje in optiko na Fakulteti za elektrotehniko. Od 2017 poučuje na srednji šoli za strojništvo. Leta 2020 si je na Filozofski fakulteti pridobila še pedagoško-andragoško izobrazbo. Trenutno poučuje strokovne predmete tudi kot predavateljca na Višji šoli za strojništvo Škofja Loka in je doktorska študentka na Fakulteti za elektrotehniko Univerze v Ljubljani. Je avtorica in soavtorica več strokovnih člankov s področja optičnih komunikacij in poučevanja strokovnih predmetov po principih reševanja problemov.

Author's biography

After finishing high school, Vesna Eržen continued her studies at the University of Maribor School of Security Sciences. She later switched from the social sciences to the field of natural sciences and after completing her studies in safety sciences (2006) enrolled at the Faculty of Electrical Engineering of the University of Ljubljana. In 2012, she graduated in the field of optical communications. Her work related to extending the communication range in passive optical networks. From 2012 to 2016, she was employed as a project researcher in the Radiation and Optics Laboratory at the Faculty of Electrical Engineering. Since 2017, he has been teaching at a high school for mechanical engineering. In 2020, she obtained a pedagogic and andragogic education at the Faculty of Arts. She currently teaches professional courses as a lecturer at the Škofja Loka College of Mechanical Engineering and is a doctoral student at the Faculty of Electrical Engineering of the University of Ljubljana. She is the author and co-author of several professional articles in the field of optical communications and teaching professional subjects based on the principles of problem solving.

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Sistem stabilizacije injekcijske vklenitve Fabry-Periot laserske diode za uporabo v omrežjih WDM-PON

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E-pošta: vesna.erzen@scsl.si, bostjan.batagelj@fe.uni-lj.si

Vsebina

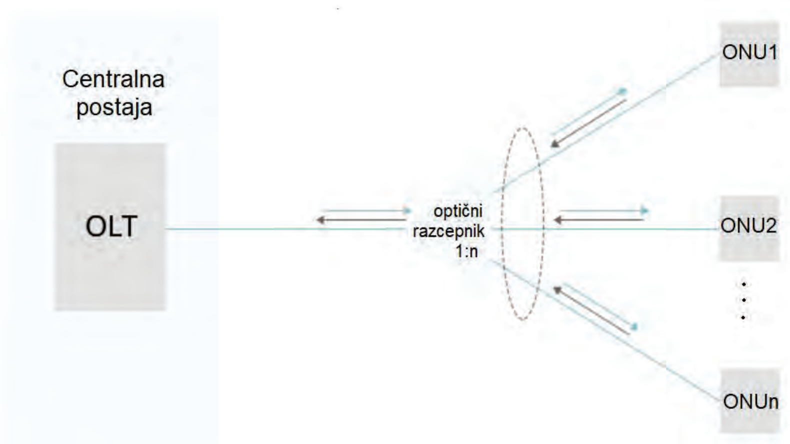
- Pasivna optična omrežja z valovno-dolžinskim razvrščanjem (WDM-PON)
- Uporaba injekcijsko vklenjene FP-LD v WDM-PON omrežjih
- Princip optične (injekcijske) vklenitve laserjev
- Značilnosti optične vklenitve laserjev
- Predstavitev tehnike za stabilizacijo FP-LD s pomočjo zunanje resonančne votline in opazovanja RF spektra
- Sklep

Motivacija: iskanje dovršene tehnične rešitve za dolgotrajno samodejno stabilizacijo injekcijske vklenitve FP-LD, ki bi bila uporabna v realnem, terenskem okolju v WDM-PON omrežjih

WDM-PON

- Passive Optical Network - PON
- Topologija: točka-več točk
- Gigabitni PON = GPON
- Dva načina dostopa do komunikacijskega kanala:
  1. TDM (časovno razvrščanje)
  2. WDM (valovnodolžinsko razvrščanje
- Prednost WDM-PON:
  - lasten valovnodolžinski kanal
  - ves čas na voljo vsakemu uporabniku
  - večja pasovna širina, nižje zakasnitve

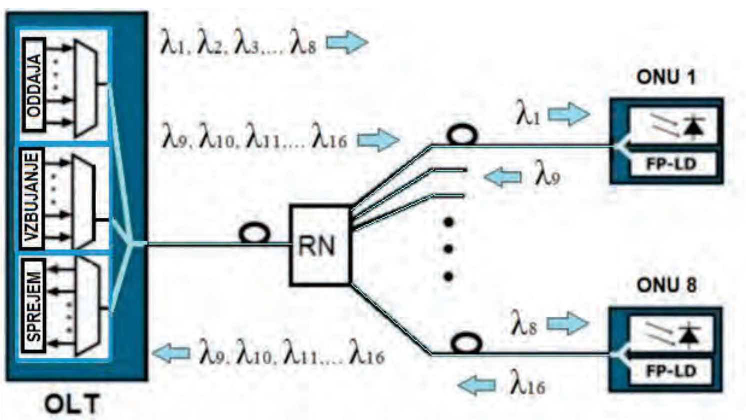
Motivacija: Iskanje tehnološke rešitve za cenovno dostopno in enako oprema za vse porabniške enote ONU.



- Centrala (Optical Line Terminal – OLT) vsebuje:
  - Optični oddajnik za oddajo dotočnih signalov (od λ1 do λ8)
  - Centralni svetlobni vir za vzbujanje in vklenitev FP-LD (od λ9 do λ16)
  - Sprejemniki odtočnega prometa v OLT (od λ9 do λ16)

Injekcijsko vklenjena FP-LD omogoča delovanje na enem vzdolžnem rodu.
V optičnih komunikacijah se uporablja kot brezbarvni optični oddajnik
Nizkocenovna alternativa dragim brezbarvnim (nastavljivim – TLS) laserjem.

Uporaba FP-LD v WDM-PON



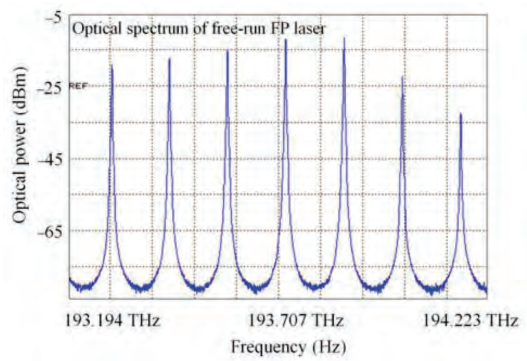
Fizikalni pojav optične vklenitve

- Optična vklenitev = frekvenčna in fazno uskladitev dveh laserjev
- Optične ali injekcijska vklenitev (angl. Injection locking – IL)
- Vloga nadrejenega (angl. Leader, Primary) in podrejenega (angl. Follower, Secondary) laserskega vira
- Fabry-Periot laserska dioda (FP-LD) v vlogi podrejenega vira
- Fazna in frekvenčna vklenitev FP-LD je posledica vzbujanja z nadrejenim laserjem
- Možnost vklenitve pod točno določeno izbranima parametroma frekvence vzbujalnega laserja in optične moči na FP-LD.

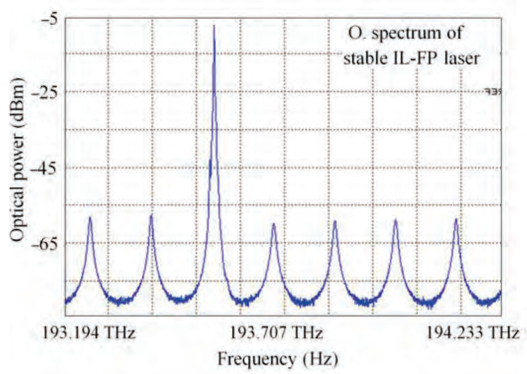
Injekcijsko vklenjena FP-LD za uporabo v WDM-PON omrežjih

- FP-LD v splošnem ne omogoča brezbarvnosti za uporabo v WDM-PON omrežjih. Optični spekter FP-LD v „prostem teku“: slika 1.
- Centralni svetlobni vir usmerjen v FP-LD omogoča injekcijsko vklenitev na določeno valovno dolžino pod določenimi pogoji. Optični spekter vklenjene FP-LD: slika 2.
- Spremenijo se lastnosti oddajanja: FP-LD omogoča brezbarvnost: slika 2.
- Vklenitev podrejenega (FP-LD) z nadrejenim laserjem omogoča uporabo FP-LD v enotah ONU v WDM-PON sistemu.
- Vklenjeno FP-LD v WDM-PON uporabimo za oddajo odtočnih signalov na točno določenih valovnih dolžinah v vseh uporabniških modulih.
- Predstavlja tehnološko in cenovno privlačno rešitev za uporabo v WDM-PON sistemih.

Slika 1:

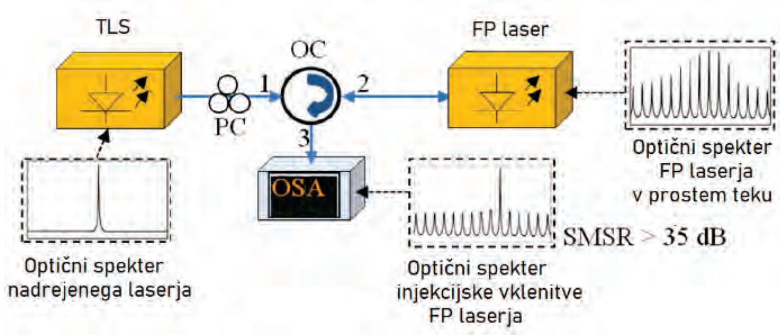


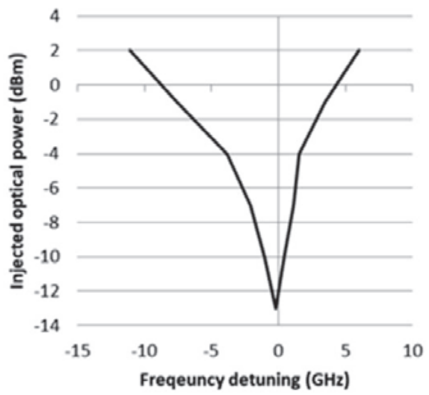
Slika 2:



Princip optične vklenitve

- Nadrejeni laser (TLS) niha na enem vzdolžnem rodu, podrejeni FP laser pa pred vklenitvijo na več rodovih.
- Vzbujalna svetloba določene frekvence potuje:
  - od nastavljivega laserskega vira (TLS) preko polarizatorja (PC) do optičnega cirkulatorja (OC)
  - do priključka 1 (OC) na priključek 2 do podrejenega laserja v prostem teku
  - vklenitev samo pod skrbno določenima pogojema vhodne optične moči in frekvenčnega razmika
  - svetloba vklenjene FP-LD se odbije in potuje nazaj proti OC na priključek 2
- Na priključku 3 opazujemo optični spekter na OSA
- Vklenitev povzroča nihanje na enem od rodov podrejenega laserja
- Pojav injekcijske vklenitve je polarizacijsko odvisen (slabost)





Značilnosti optične vklenitve

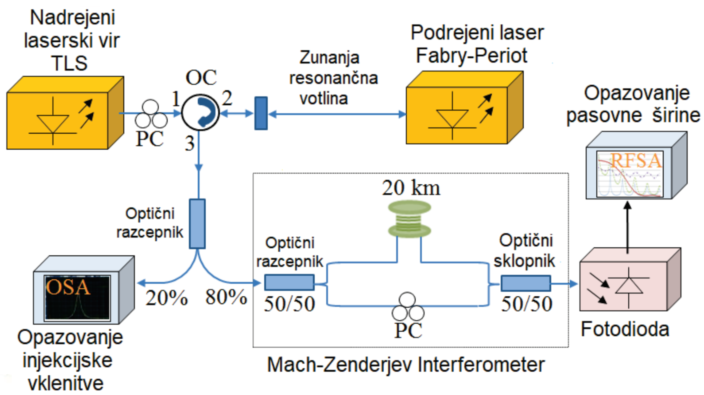
- Povečana frekvenčna stabilnost podrejenega laserja.
- Parametra vklenitve: optična moč nadrejenega laserja in frekvenčni odmik (Δω) (dovolj blizu skupaj)
- zemljevid vklenitve (angl. Locking map) => nelinearen pojav
- Vklenitveno področje narašča z naraščanjem vhodne optične moči.
- Znotraj vklenitvenega področja je stabilna in nestabilna vklenitev.
- Asimetrično področje stabilnosti
- Pri nizkih vhodnih močeh je stabilna vklenitev možna le za negativne vrednosti frekvenčne razlike
- z višanjem vhodne moči se področje stabilnosti povečuje; zajame tudi pozitivno frekvenčno razliko.
- Temperaturna odvisnost laserskega čipa; spremeni se valovna dolžina => laser ni več vklenjen
- Izziv: stabilizacija vklenitve s kontrolnim vezjem

Kontrola injekcijske vklenitve

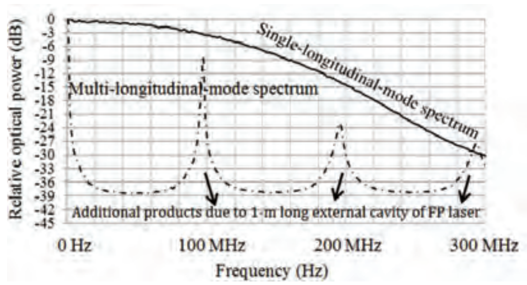
- Bistveno za učinkovito uporabnost pojava sinhronizacije (injekcijske vklenitve) so dodelane tehnike nadzora stabilizacije
- Preprečevanje nestabilne vklenitve zaradi temperaturne odvisnosti laserskega čipa => realno okolje.

Sistem stabilizacije injekcijske vklenitve Fabry-Periot laserske diode za uporabo v WDM-PON omrežjih

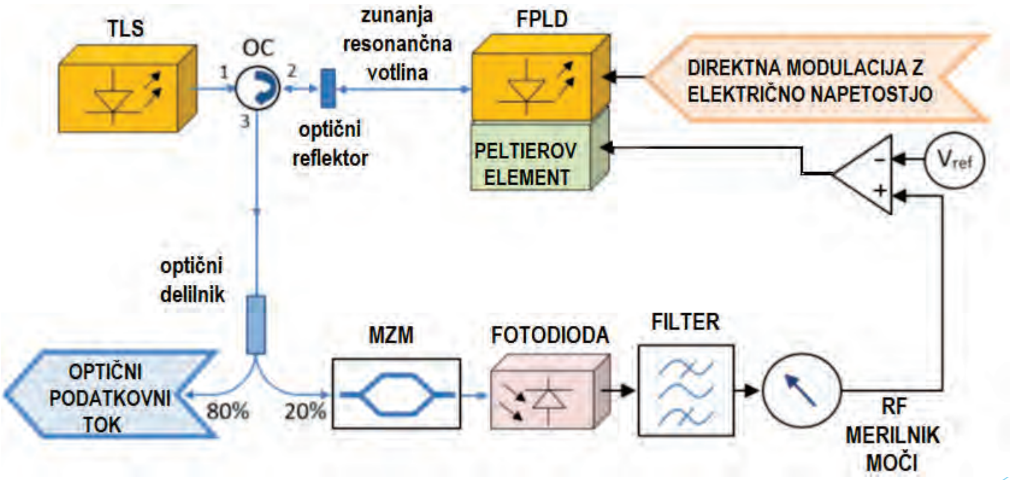
Sistem za opazovnje optične vklenitve



- Sistem za sočasno opazovanje signala na OSA in RF spektra.
- Konstantna injicirana optična moč (2 dBm na FP-LD)
- Sprememba vrednosti frekvenčnega odmika od negativnega proti pozitivnemu področju
- Sočasno opazovanje SMSR na OSA in dušenje RF komponent na RFSA
- Vloga MZM: amplitudna in fazna modulacija za opazovanje signala na RFSA
- Nizko-odbojni optični reflektor (konektor) na razdalji 1 m od FP-LD.
- Frekvenčne komponente vidne na RFSA so posledica zunanje resonančne votline (angl. External Cavity)



Idejna zasnova sistema za stabilizacijo Fabry-Periot laserske diode



ZAKLJUČEK

- Nizkocenovna Fabry-Periot laserska dioda niha na več vzdolžnih (longitudinalnih) rodovih.
- S tehniko injekcijske vklenitve lahko Fabry-Periotov laser deluje kot enorodovni laser.
- Optična vklenitev FP-LD zahteva izpolnitev več pogojev pri vzbujevalni svetlobi
- Predstavljeno tehniko stabilizacije je mogoče uporabiti v sistemu WDM-PON
- Za praktično izvedbo WDM-PON so zelo pomembni poceni komunikacijski viri svetlobe.
- V ta namen je bil predstavljen sistem, ki ima potencial za zagotavljanje stabilne vklenitve.
- **Pri stabilni optični vklenitvi se RF komponente (na RFSA) popolnoma zadušijo.**

Uporaba ločnega priključka mikroobročnega resonatorja za stabilizacijo enobočnega vlakenskega radijskega oddajnika

Using the drop port of a micro-ring-resonator to stabilize a single sideband radio-over-fiber transmitter

Kristjan Vuk Baliž in Boštjan Batagelj

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Univerza v Ljubljani, Fakulteta za elektrotehniko, Laboratorij za fotovoltaiko in optoelektroniko

Povzetek

Velik apetit modernih komunikacijskih omrežij po pasovni širini je porodil tehnologijo za vlakenski prenos radijskega signala v milimetrskem valovnem območju. Pri uporabi intenzitetne modulacije v izvedbi z zunanjim elektroptičnim modulatorjem se zaradi barvne razpršitve optičnega vlakna lahko pojavi kvarni učinek frekvenčno odvisnega presihanja moči. V izogib slednjemu predlagamo koncept vlakenskega oddajnika z vključenim mikroobročnim resonatorjem, katerega drop port izkoristimo za vzpostavitev zaprtozančenga regulacijskega sistema za stabilizacijo vlakenske radijske zveze.

Abstract

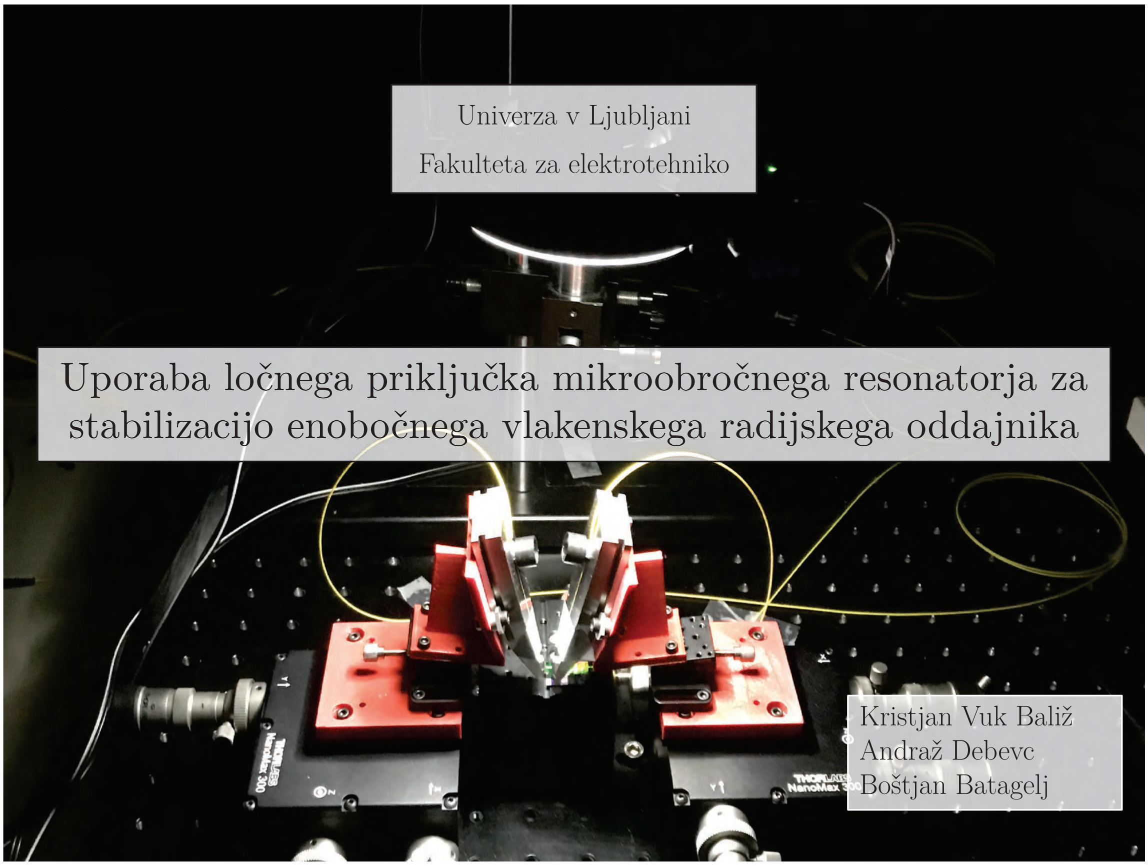
The ever increasing demand for bandwidth in modern communication networks has led to radio-over-fiber technology in the millimeter wave region. When intensity modulation using an external electro-optic modulator is applied, a chromatic-dispersion-induced phenomenon of frequency dependent power fading might arise. To overcome the latter, we propose a novel concept of fiber optic transmitter, featuring a micro-ring resonator where we exploit the drop port to establish a closed-loop regulation system to stabilize a radio-over-fiber link.

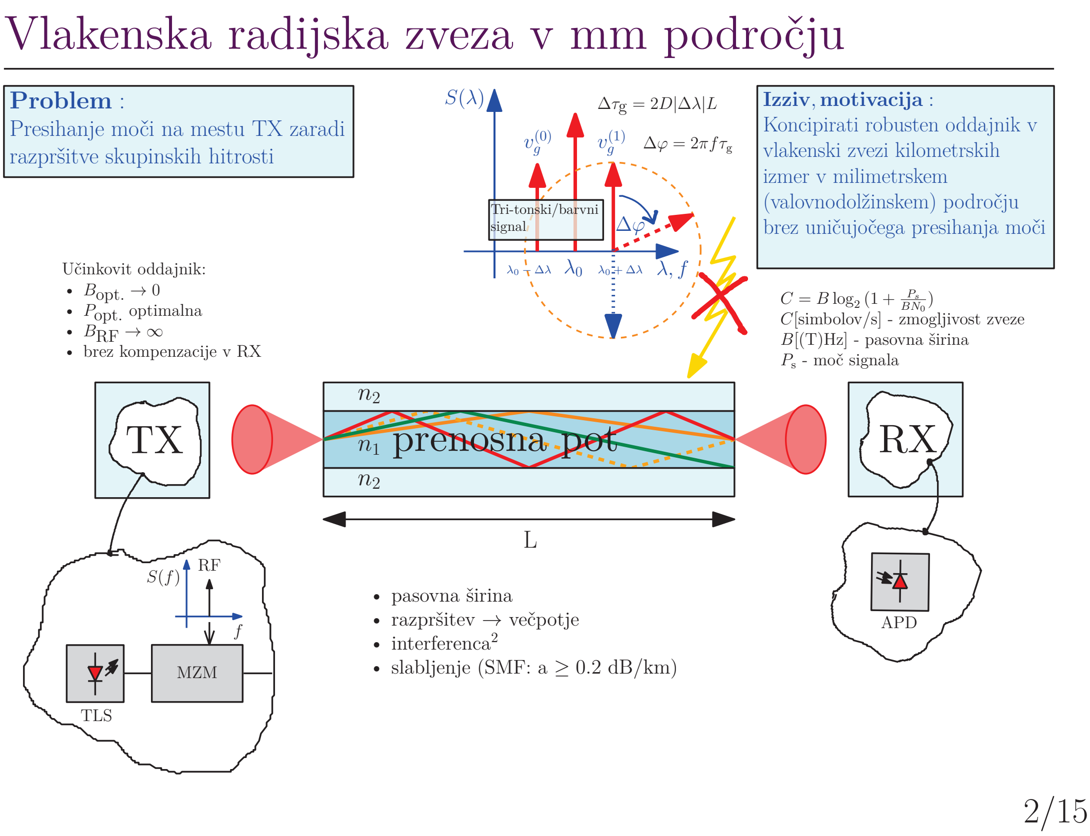
Biografija avtorja

Kristjan Vuk Baliž je leta 2019 magistriral na Fakulteti za elektrotehniko Univerze v Ljubljani. Trenutno je zaposlen na delovnem mestu (pedagoškega) asistenta na Fakulteti za elektrotehniko v Ljubljani. Interesna področja njegovega raziskovanja vključujejo vlakenske komunikacije, mikrovalovno fotoniko in integrirano fotoniko.

Author's biography

Kristjan Vuk Baliž received his master's degree from the Faculty of electrical engineering, University of Ljubljana, Slovenia, in 2019. He is currently employed as an assistant teacher at the Faculty of Electrical Engineering in Ljubljana. His research interests include fiber communication, microwave photonics and integrated photonics


Univerza v Ljubljani
Fakulteta za elektrotehniko
Uporaba ločnega priključka mikroobročnega resonatorja za stabilizacijo enoobočnega vlakenskega radijskega oddajnika
Kristjan Vuk Baliž
Andraž Debevc
Boštjan Batagelj


Vlakenska radijska zveza v mm področju
Problem :
Presihanje moči na mestu TX zaradi razpršitve skupinskih hitrosti
Izziv, motivacija :
Koncipirati robusten oddajnik v vlakenski zvezi kilometrskih izmer v milimetrskem (valovnodolžinskem) področju brez uničujočega presihanja moči
S(λ)
Δτg = 2D|Δλ|L
Δφ = 2πfτg
Tri-tonski/barvni signal
λ0
λ, f
Učinkovit oddajnik:
Bopt. → 0
Popt. optimalna
BRF → ∞
brez kompenzacije v RX
C = B log2 (1 + Ps/BN0)
C[simbolov/s] - zmogljivost zveze
B[(T)Hz] - pasovna širina
Ps - moč signala
TX
n2
n1 prenosna pot
n2
RX
L
S(f)
RF
f
MZM
TLS
APD
pasovna širina
razpršitev → večpotje
interferenca2
slabljenje (SMF: a ≥ 0.2 dB/km)
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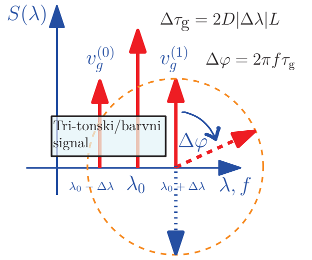
Izziv: Presihnje RF moči v vlakenski zvezi

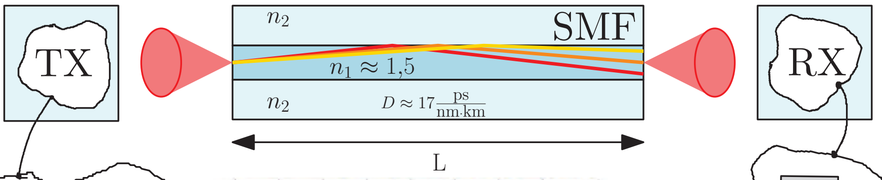
Okoliščine:

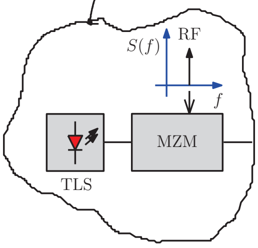
- tribarvni optični signal
- barvna razpršitev; valovno dolžinsko odvisna skupinska hitrost
- Pojav odvisen od parametrov optične zveze: dolžina prenosne poti (vlakna), modulacijska frekvenca, disperzivnost medija, lomni količnik
- Protiukrepi: kompenzacija disperzije, zveza v II. Valovnem oknu, nizek produkt BL, prenos z dvobarvnim signalom

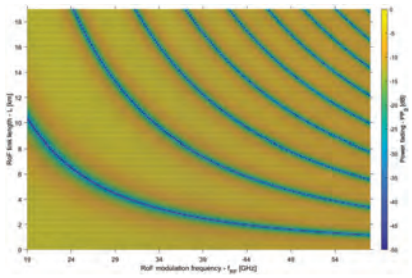


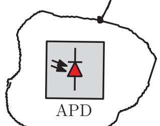
Izziv, motivacija: Koncipirati robusten oddajnik v vlakenski zvezi kilometrskih izmer v milimetrskem (valovnodolžinskem) področju brez uničujočega presihanja moči

$C = B\log_2\left(1+\frac{P_s}{BN_0}\right)$
C[simbolov/s] - zmogljivost zveze
B[(T)Hz] - pasovna širina
P_s - moč signala









Presihanje RF moči:

$PP_0[dB] = 10\log_{10}\left[\cos^2(\pi f_{RF} D 2\Delta\lambda L)\right]$

$$10\log_{10}\left[\cos^2\left(2\pi\left(\frac{\lambda_0^2}{c_0}\right) D f_{RF}^2 L\right)\right]$$

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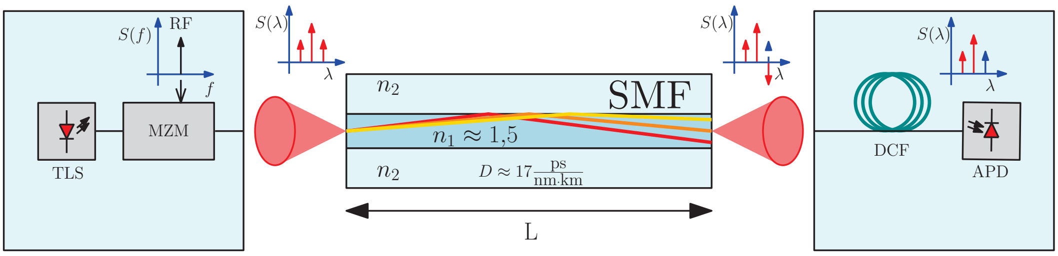
Rešitve: kompenzacija barvne razpršitve

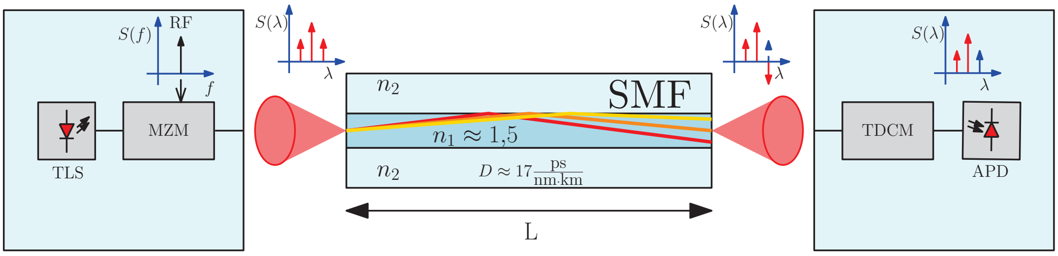
Tehnike za premoščanje presihanja moči, ki ohranjajo tribarvni signal, vendar potom kompenzacije razpršitve poskrbijo, da sta oba modulacijska boka na mestu sprejema sofazna.

Disperzijsko kompenzacijsko vlakno v (vsakem) RX

$D_{SMF}\cdot L_{SMF} + D_{DCF}\cdot L_{DCF} = 0$
D_{SMF}@1550 nm ≈ 17 ps/(nm · km)



Prilagodljivi modul za kompenzacijo disperzije (TDCM) v (vsakem) RX



ILGAZ, Mehmet Alp, VUK BALIŽ, Kristjan, BATAGELJ, Boštjan. A flexible approach to combating chromatic dispersion in a centralized 5G network. Opto-electronics review. 2020, vol. 28, no. 1, str. 35-42, ilustr. ISSN 1896-3757. http://journals.pan.pl/dlibra/publication/132498/edition/115766/content

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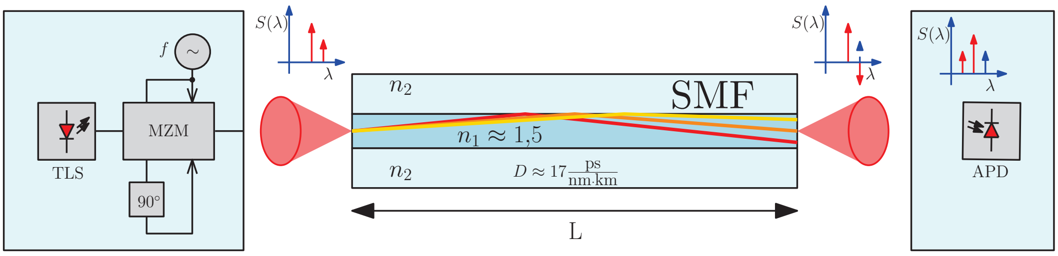
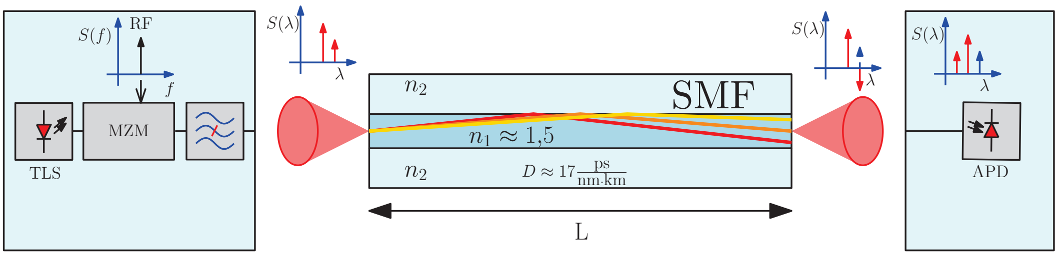
Rešitve: dvobarvni signal

Tehnike za premoščanje presihanja moči, ki signal prevedejo na dvotonski signal.

Dvojno krmiljeni MZM z ortogonalnima signaloma - kvadraturni mešalnik



Optično sito v TX



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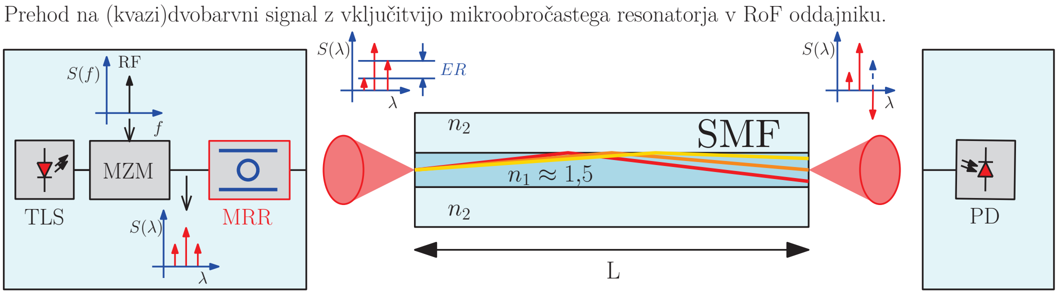
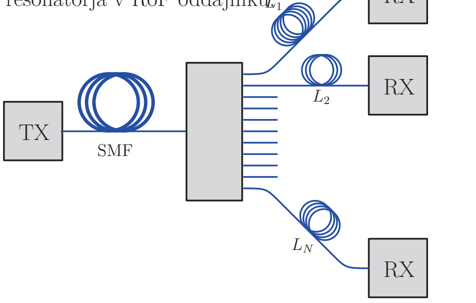
REŠITEV: Prehod na dvobarvni signal z MRR

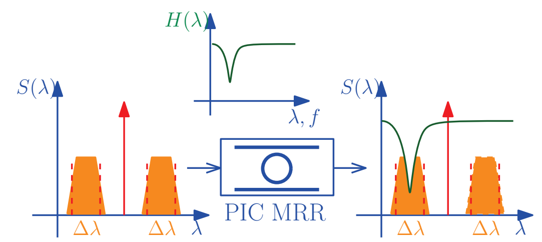
Prehod na (kvazi)dvobarvni signal z vključitvijo mikroobročastega resonatorja v RoF oddajniku.



Prehod na (kvazi)dvotonski signal z vključitvijo mikroobročastega resonatorja v RoF oddajniku



Končna pasovna širina fotonskega sita (MRR) - omejena pasovna širina modulacijskega signala B_{RF}



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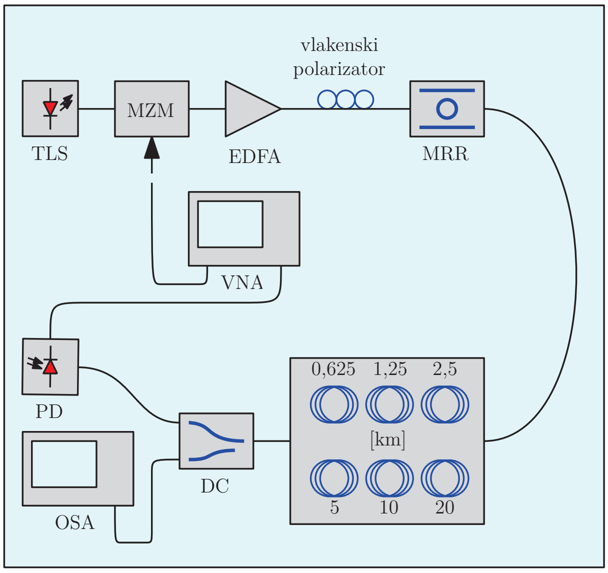
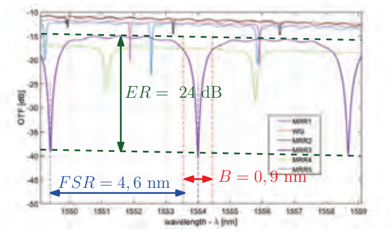
Merilna konfiguracija; meritve

Meroslovno ovrednotenje radijske vlakenske zveze z MRR

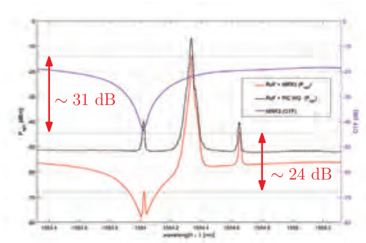
- presihanje RF moči v odvisnosti od dolžine vlakna
- RF prevajalna funkcija zveze



Optična prevajalna funkcija (OTF) od MRR



tribarvni signal, dvobarvni signal, OTF

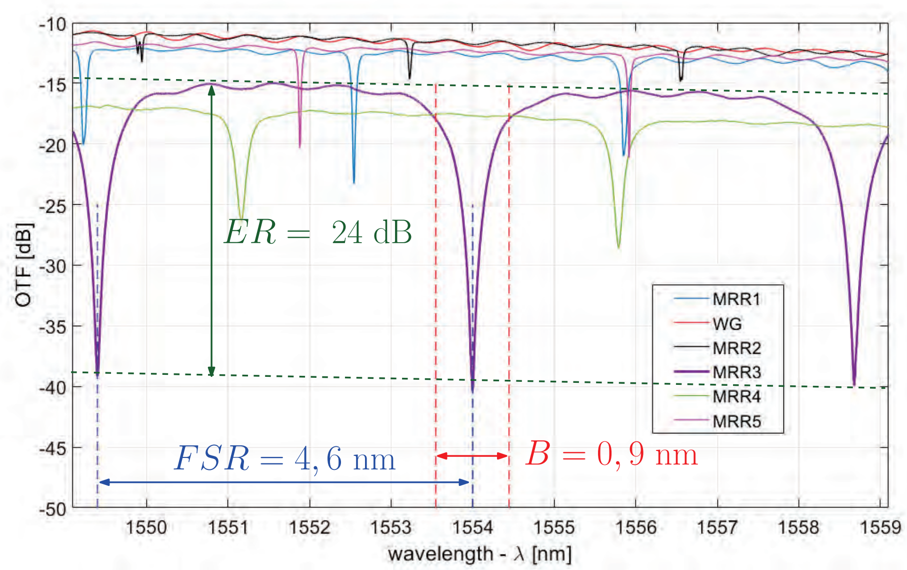


Merilna konfiguracija; meritve

Meroslovno ovrednotenje radijske vlakenske zveze z MRR

- presihanje RF moči v odvisnosti od dolžine vlakna

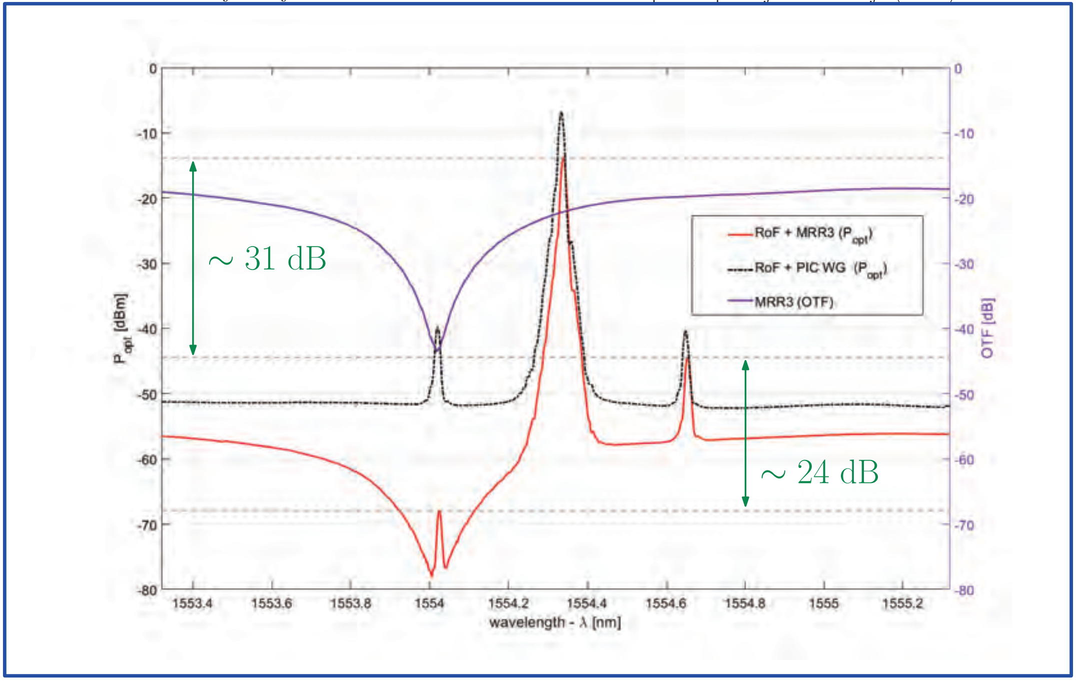
Optična prevajalna funkcija (OTF) od MRR



Merilna konfiguracija; meritve

Meroslovno ovrednotenje radijske vlakenske zveze z MRR

Optična prevajalna funkcija (OTF) od MRR



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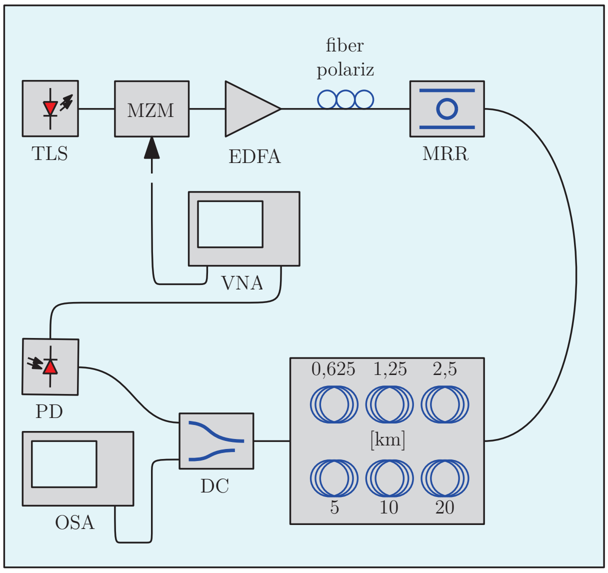
Merilna konfiguracija; meritve

Meroslovno ovrednotenje radijske vlakenske zveze

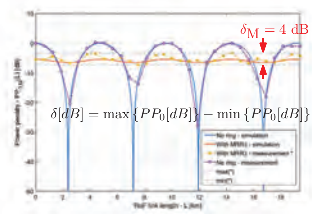
- presihanje RF moči v odvisnosti od dolžine vlakna
- RF prevajalna funkcija zveze



K. V. Baliž, A. Debevc, J. Krč and B. Batagelj, "Power-fading-mitigation approach in an intensity-modulated radio-over-fiber link using a single integrated micro-ring resonator," Optical Fiber Technology, vol. 73, p. 103008, 2022.

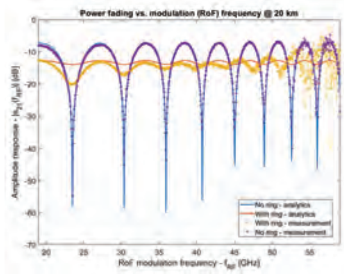
Presihanje RF moči v odvisnosti od dolžine vlakna

$$PP_{0,\mathrm{M}}(L) = 20\log\left|\frac{s_{21}(L)|_{f_{\mathrm{RF}}=39\mathrm{GHz}}}{s_{21}|_{L=0,f_{\mathrm{RF}}=39\mathrm{GHz}}}\right| + 2a/lL$$



Presihanje RF moči kot (prevajalna) function modulacijske frekvence

$$PP_{0,\mathrm{M}}(f_{\mathrm{RF}}) = 20\log\left|\frac{s_{21}(f_{\mathrm{RF}})|_{L=20\mathrm{km}}}{s_{21}|_{L=0,f_{RF}=39\mathrm{GHz}}}\right|$$



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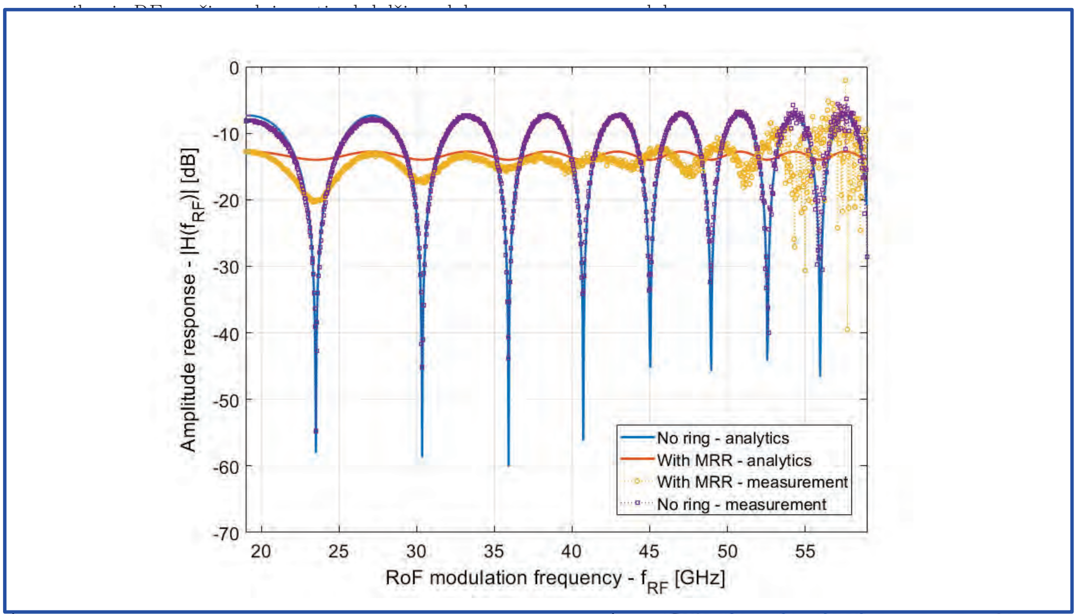
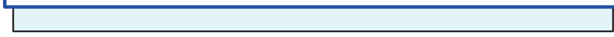
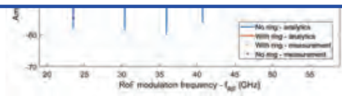
Merilna konfiguracija; meritve

Meroslovno ovrednotenje radijske vlakenske zveze

Presihanje RF moči v odvisnosti od dolžine







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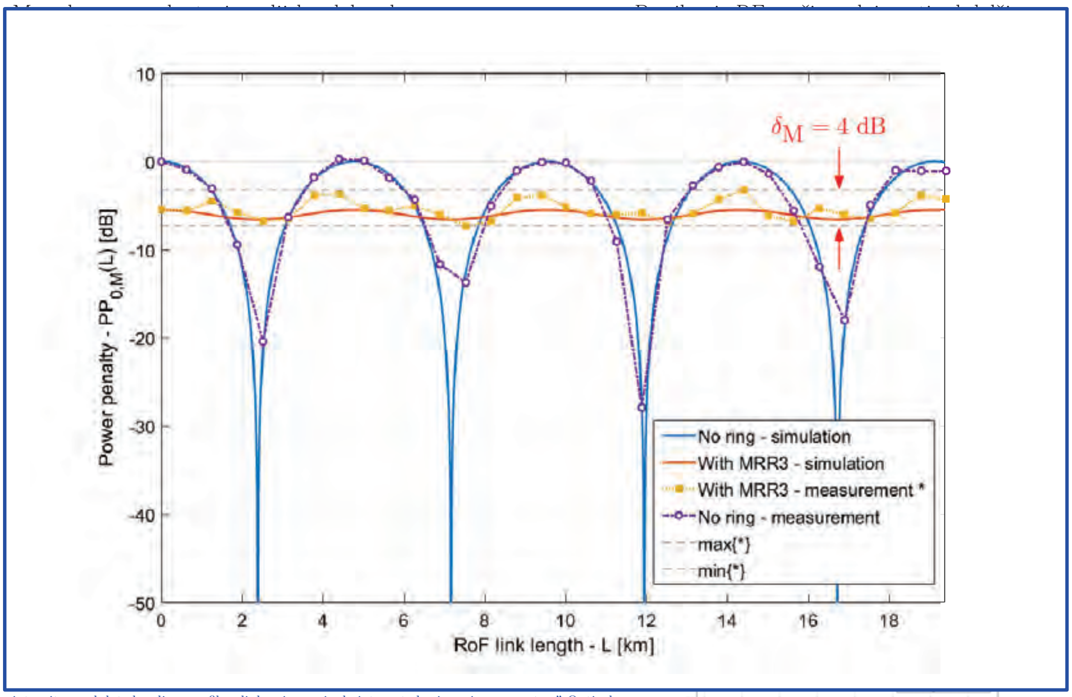
Merilna konfiguracija; meritve



intensity-modulated radio-over-fiber link using a single integrated micro-ring resonator," Optical Fiber Technology, vol. 73, p. 103008, 2022.

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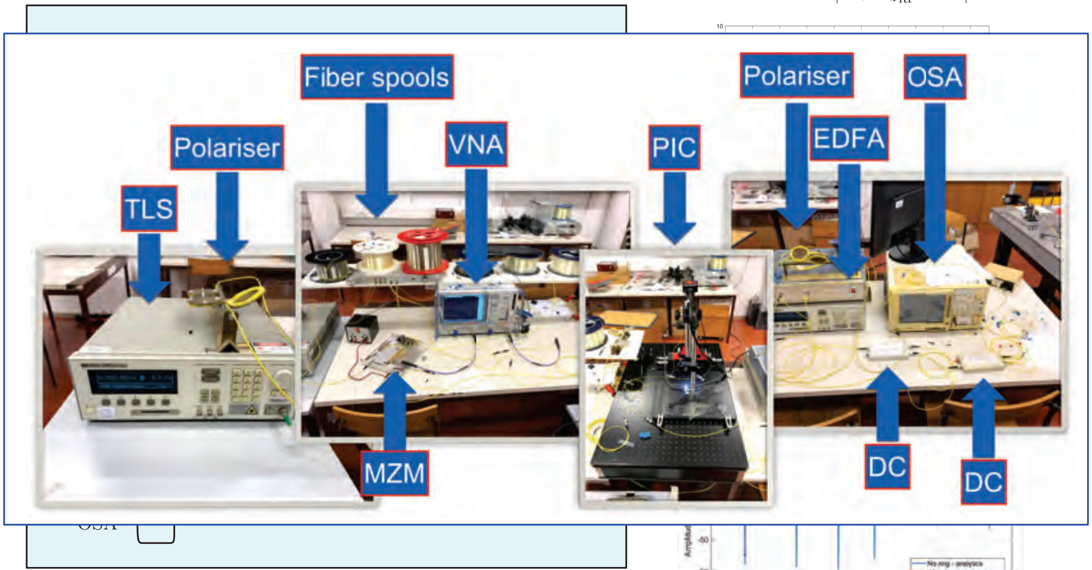
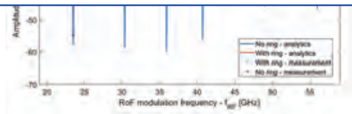
Merilna konfiguracija; meritve

Meroslovno ovrednotenje radijske vlakenske zveze
- presihanje RF moči v odvisnosti od dolžine vlakna
- RF prevajalna funkcija zveze

Presihanje RF moči v odvisnosti od dolžine vlakna

$$PP_{0,M}(L) = 20\log\left|\frac{s_{21}(L)|_{f_{RF}=39\mathrm{GHz}}}{s_{21}|_{L=0,f_{RF}=39\mathrm{GHz}}}\right| + 2a/lL$$





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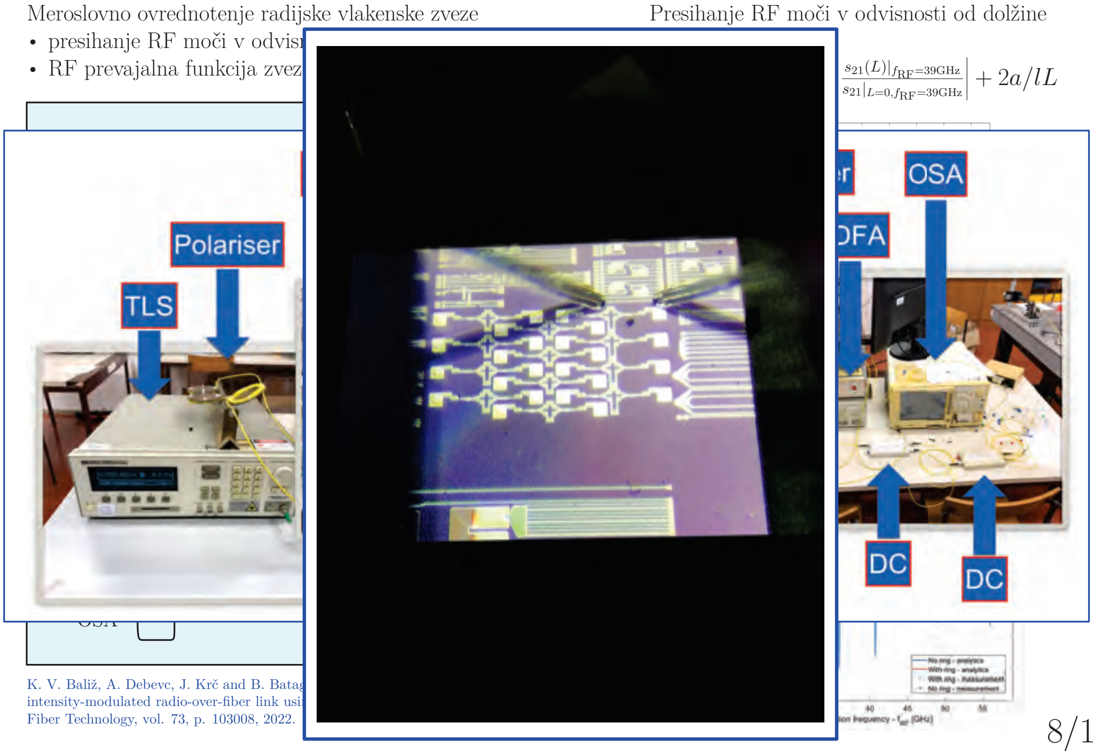
Merilna konfiguracija; meritve

Meroslovno ovrednotenje radijske vlakenske zveze
- presihanje RF moči v odvis
- RF prevajalna funkcija zvez

Presihanje RF moči v odvisnosti od dolžine

$$\left|\frac{s_{21}(L)|_{f_{RF}=39\mathrm{GHz}}}{s_{21}|_{L=0,f_{RF}=39\mathrm{GHz}}}\right| + 2a/lL$$



K. V. Baliž, A. Debevc, J. Krč and B. Batag
intensity-modulated radio-over-fiber link usi
Fiber Technology, vol. 73, p. 103008, 2022.

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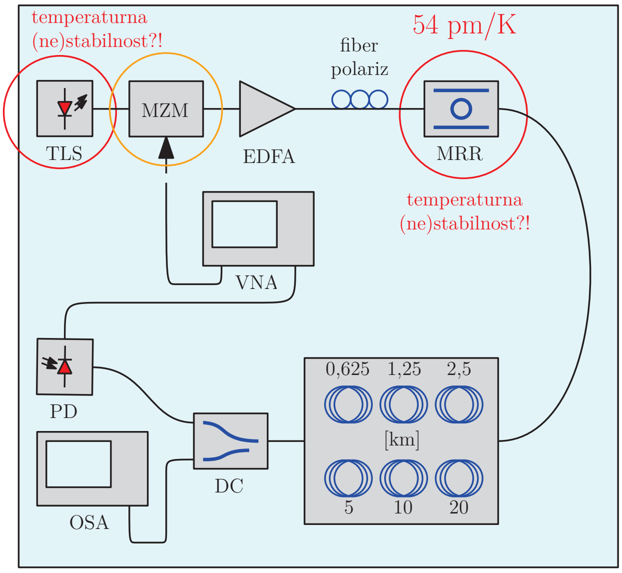
Merilna konfiguracija; meritve

Meroslovno ovrednotenje radijske vlakenske zveze

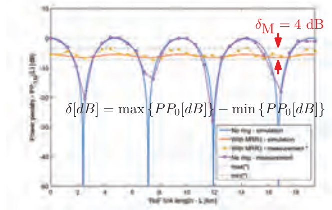
- presihanje RF moči v odvisnosti od dolžine vlakna
- RF prevajalna funkcija zveze



K. V. Baliž, A. Debevc, J. Krč and B. Batagelj, "Power-fading-mitigation approach in an intensity-modulated radio-over-fiber link using a single integrated micro-ring resonator," Optical Fiber Technology, vol. 73, p. 103008, 2022.

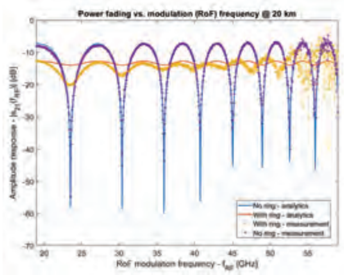
Presihanje RF moči v odvisnosti od dolžine vlakna

$$PP_{0,M}(L) = 20\log\left|\frac{s_{21}(L)|_{f_{RF}=39GHz}}{s_{21}|_{L=0,f_{RF}=39GHz}}\right| + 2a/lL$$



Presihanje RF moči kot (prevajalna) function modulacijske frekvence

$$PP_{0,M}(f_{RF}) = 20\log\left|\frac{s_{21}(f_{RF})|_{L=20km}}{s_{21}|_{L=0,f_{RF}=39GHz}}\right|$$

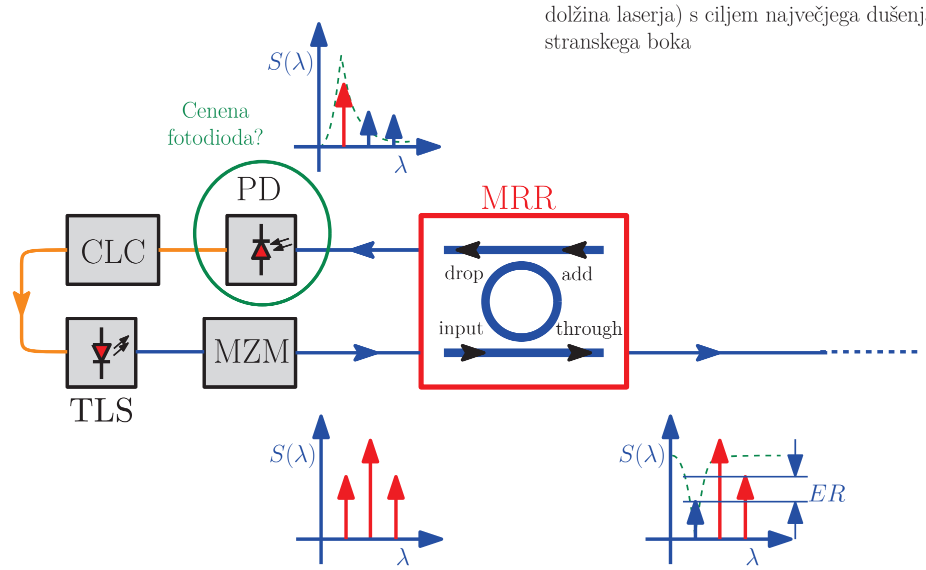


Zaprtozančni regulacijski sistem

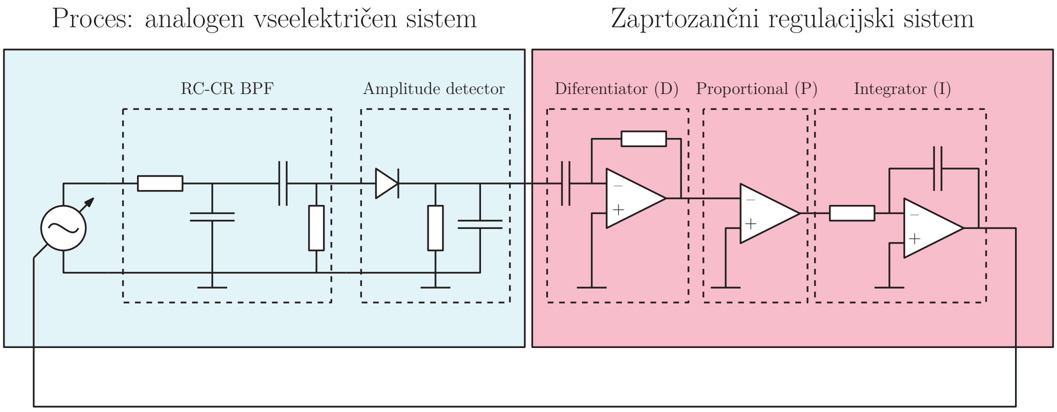
Closed-loop control - CLC

Princip delovanja

- ločni priključek zagotovi procesno spremenljivko regulacijskemu sistemu
- regulacijski sistem uglašuje sistem (npr. valovno dolžina laserja) s ciljem največjega dušenja stranskega boka



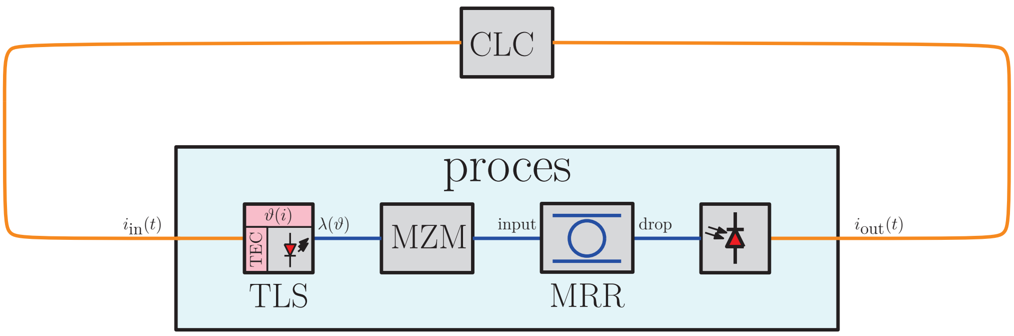
Rubrika ”naivno”

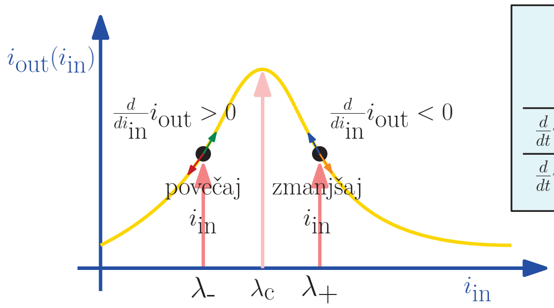


NALOGA: Vzdrževati (prvi) odvod procesne spremenljivke na/blizu nuli.

10/15

Zaprtozančni regulacijski sistem





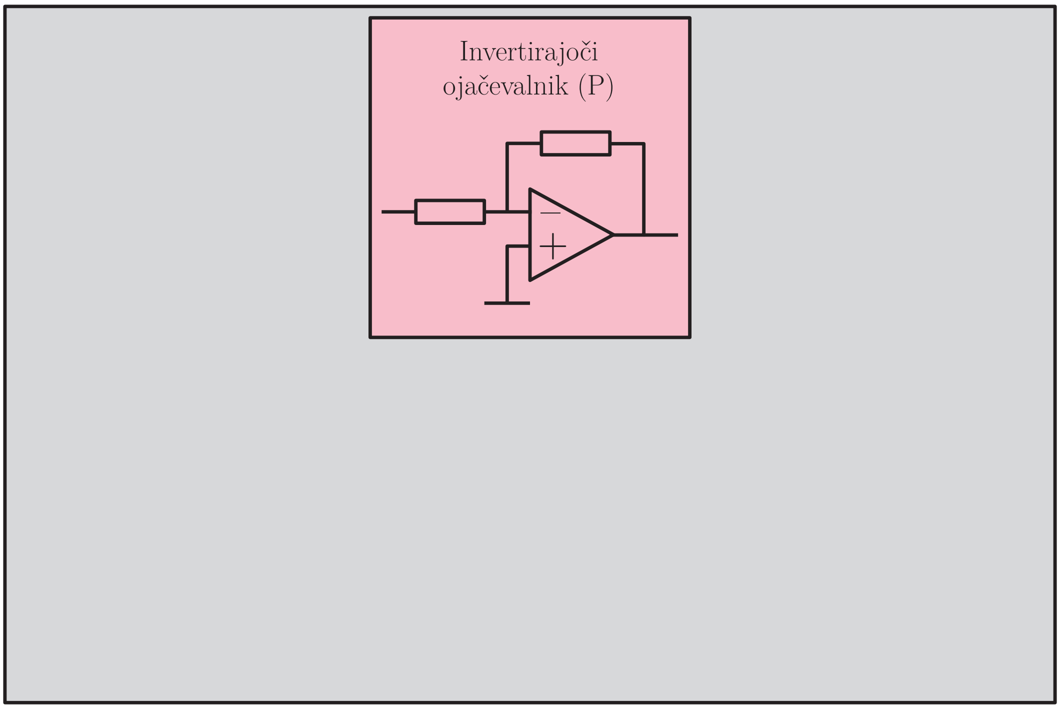
Naloga CLC

	$\frac{d}{dt} i_{out} < 0$	$\frac{d}{dt} i_{out} > 0$
$\frac{d}{dt} i_{in} < 0$	$\uparrow i_{in}$	$\downarrow i_{in}$
$\frac{d}{dt} i_{in} > 0$	$\downarrow i_{in}$	$\uparrow i_{in}$

Alterniraj i_{in}

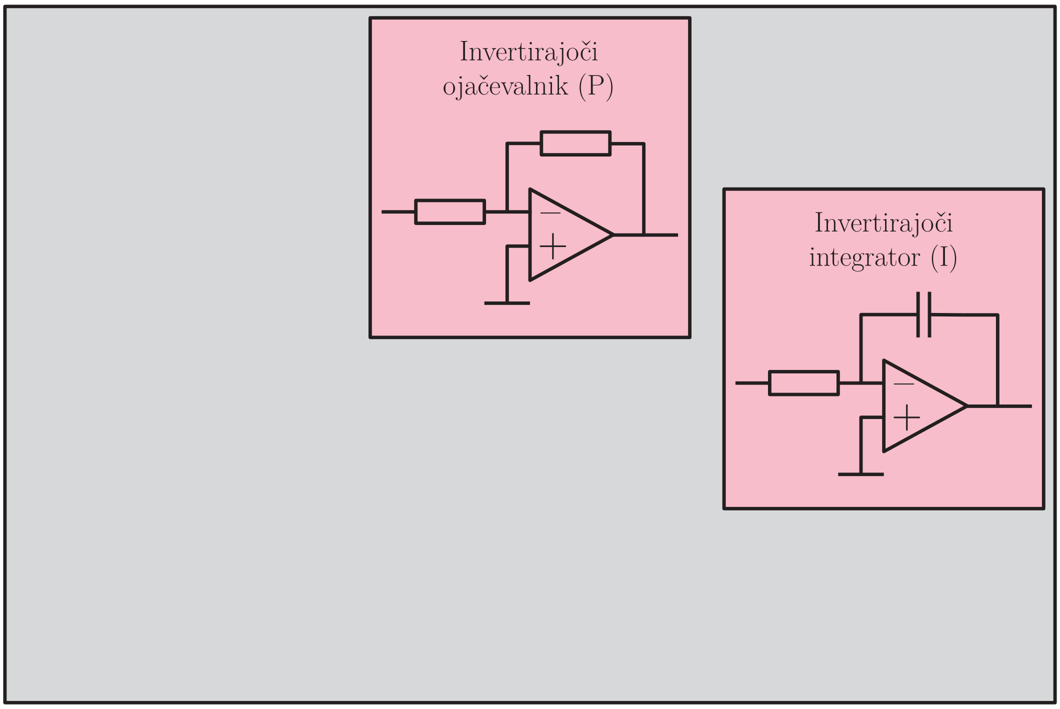
11/15

CLC: Gradniki



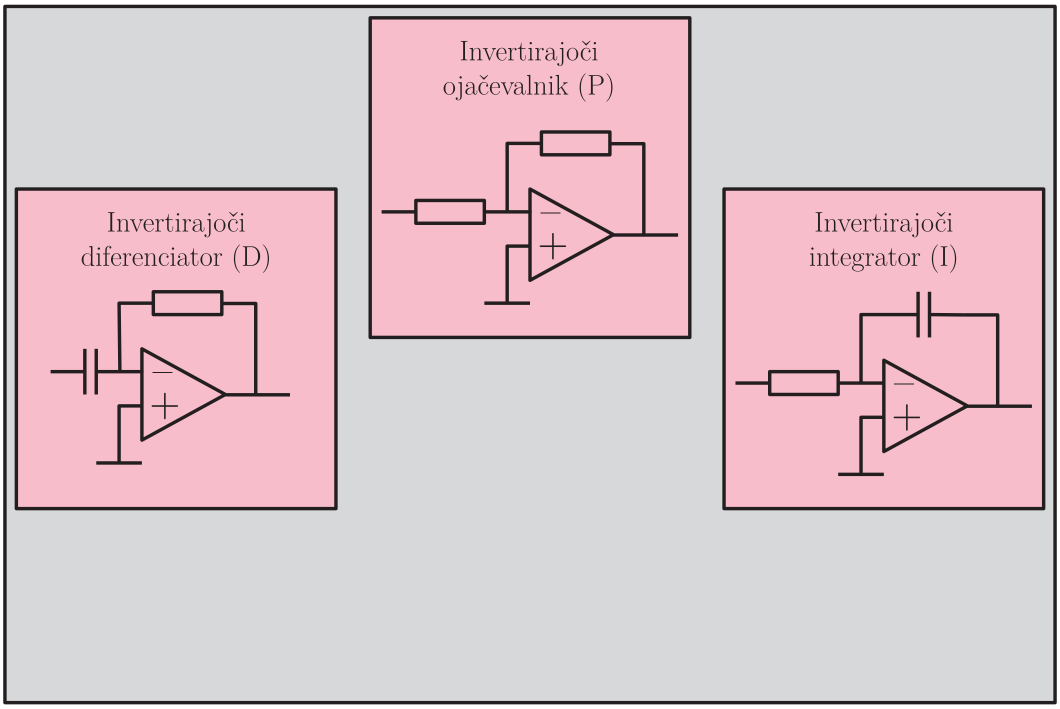
12/15

CLC: Gradniki



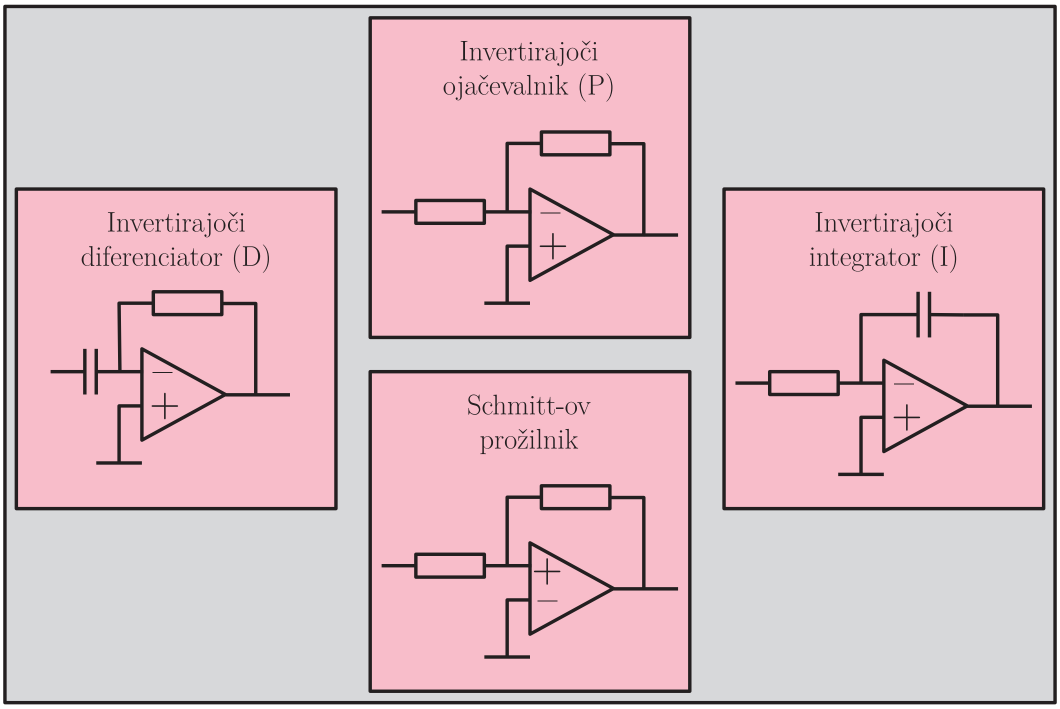
12/15

CLC: Gradniki



12/15

CLC: Gradniki



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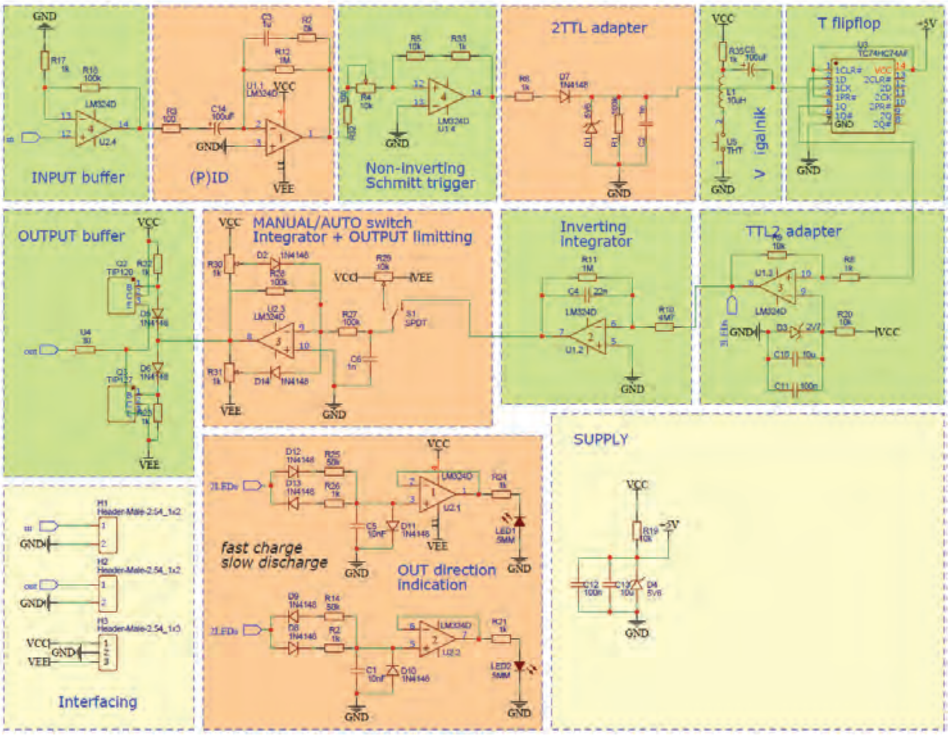
Prototipni CLC: električni načrt



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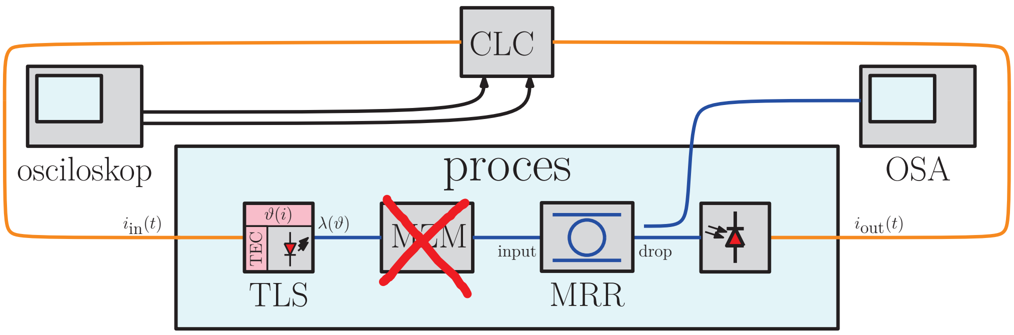
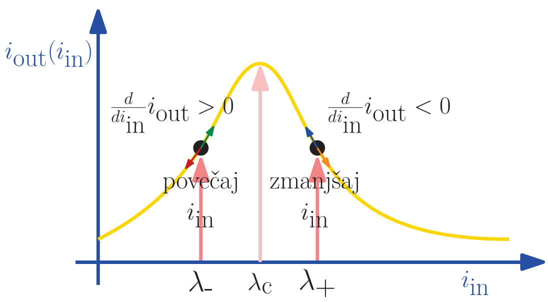
Eksperimentalni sistem; preizkus





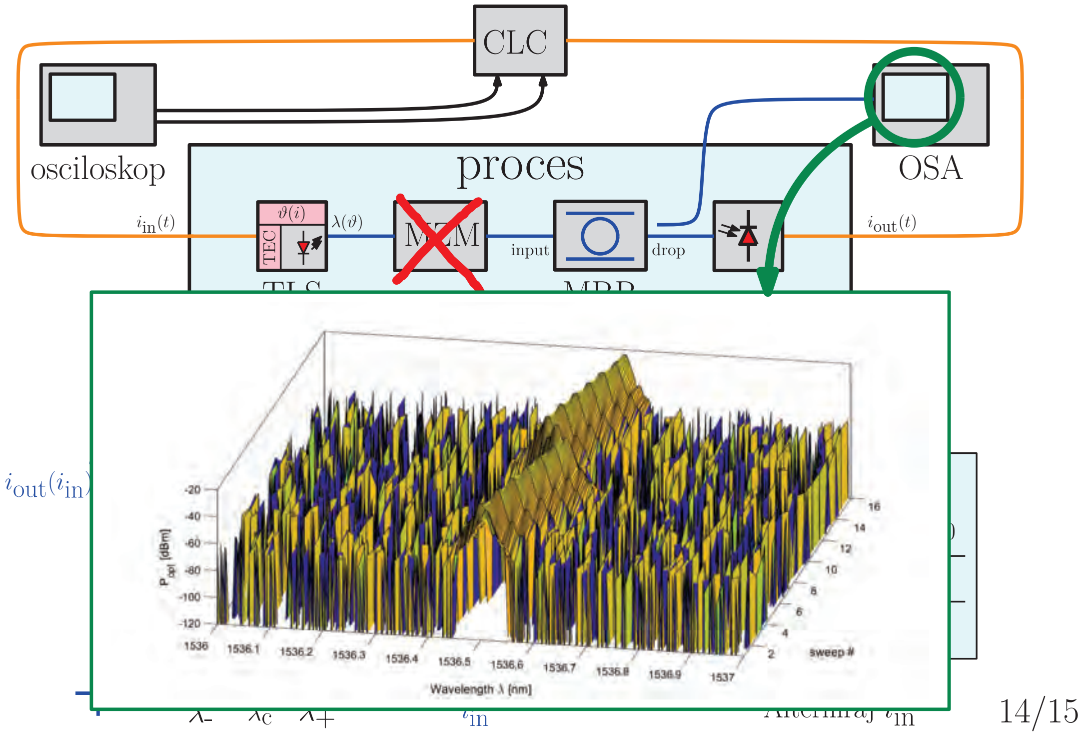
Naloga CLC

	$\frac{d}{dt} i_{out} < 0$	$\frac{d}{dt} i_{out} > 0$
$\frac{d}{dt} i_{in} < 0$	$\uparrow i_{in}$	$\downarrow i_{in}$
$\frac{d}{dt} i_{in} > 0$	$\downarrow i_{in}$	$\uparrow i_{in}$

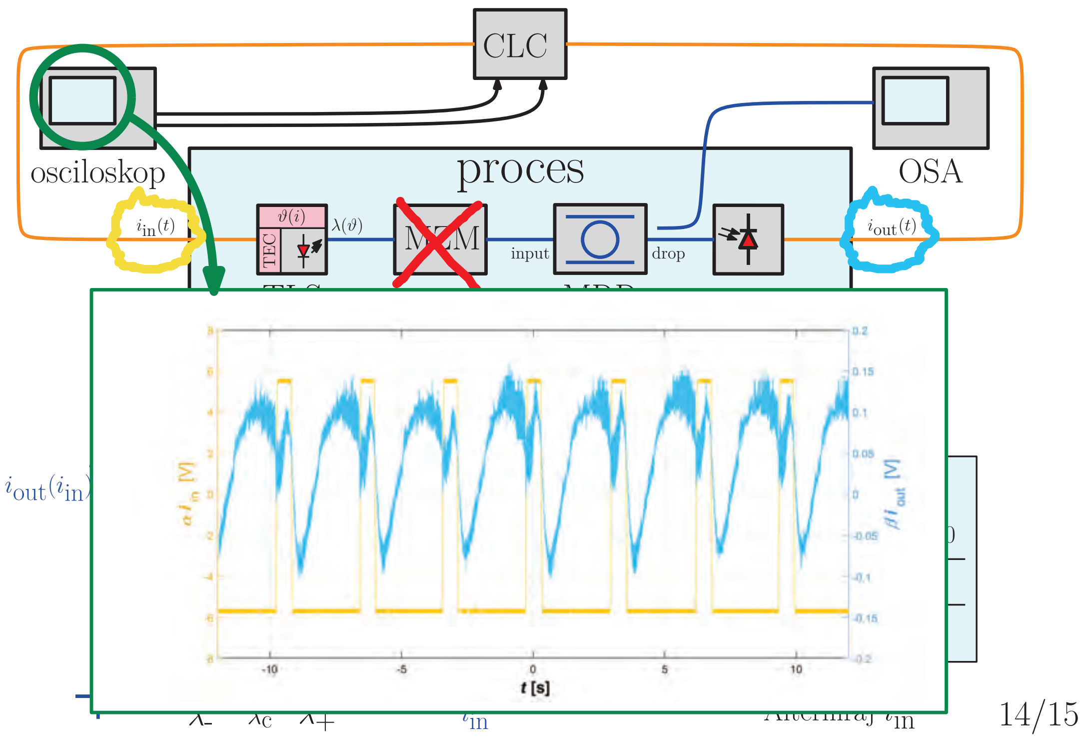
← Alterniraj i_{in}

14/15

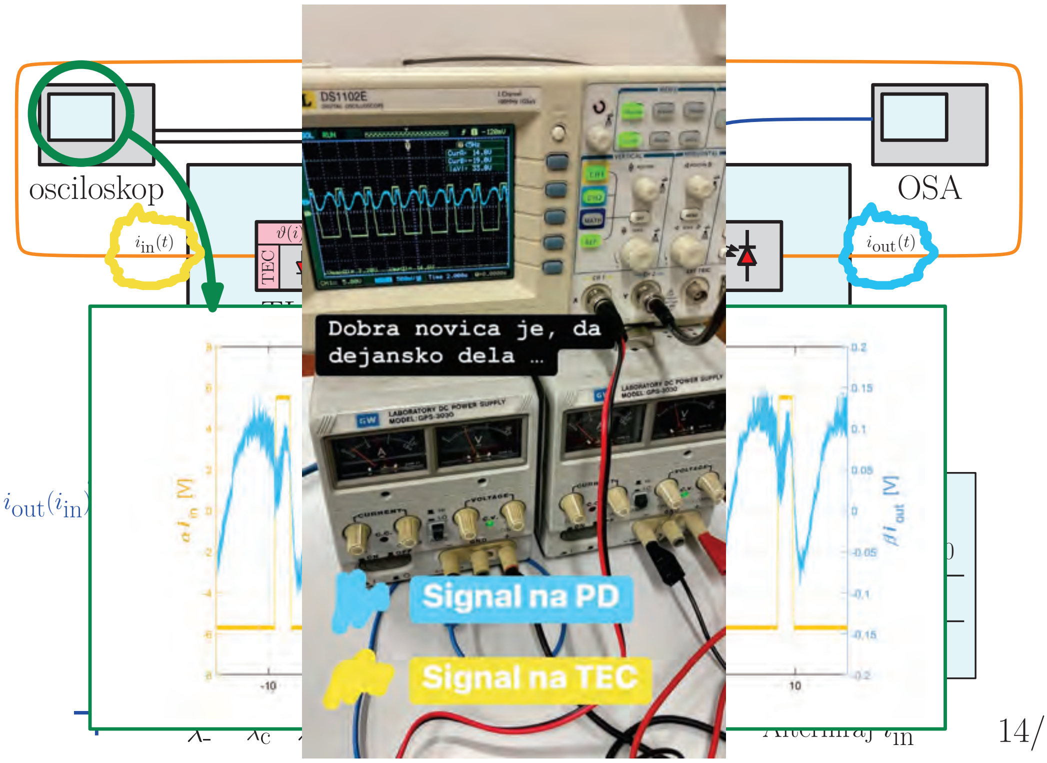
Eksperimentalni sistem; preizkus



Eksperimentalni sistem; preizkus



Eksperimentalni sistem; preizkus



14/15

Zaključek

- RoF oddajnik z MRR: potencialna rešitev presihanja moči v modernih vlakenskih radijskih zvezah
- vprašanje temperaturne (ne)stabilnosti (laser, MRR, tudi MZM)
- koncept uporabe ločnega (drop) priključka MRR za zaprtozančno regulacijo (CLC)
- razvoj, zasnova prototipa in preizkus CLC v realnem kontekstu
- nadaljnje aktivnosti: optimizacija CLC, kvantitativno ovrednotenje: vpliv CLC na performance RoF zveze

15/15

Merjenje faznega šuma oscilatorja s pomočjo optičnega kasnilnega voda

Measuring oscillator phase noise using an optical delay line

Andrej Lavrič, Boštjan Batagelj, Matjaž Vidmar

Univerza v Ljubljani, Fakulteta za elektrotehniko, Laboratorij za sevanje in optiko

andrej.lavric@fe.uni-lj.si

Povzetek

Razvoj mikrovalovne fotonike je prinesel nove rešitve za merjenje in generiranje visokofrekvenčnih signalov z uporabo optoelektronskih postopkov. Posebej zanimiv je postopek merjenja faznega šuma s kasnilnim vodom, kjer kot kasnilni vod služi analogna optična zveza. V prispevku je predstavljena realizacija merilne postavitve primerna za uporabo zunaj laboratorijskega okolja.

Abstract

The development of microwave photonics has brought new solutions for the measurement and generation of high-frequency signals using optoelectronic processes. Of particular interest is a process for measuring phase noise with a delay line, where an analogue optical link is used as the delay line. This lecture presents the realisation of a measurement set-up suitable for use outside the laboratory environment.

Biografija avtorja

Andrej Lavrič je po končani Elektrotehniško-računalniški gimnaziji v Ljubljani leta 2013 šolanje nadaljeval na Fakulteti za elektrotehniko Univerze v Ljubljani in leta 2019 magistriral s področja informacijsko-komunikacijskih tehnologij. V času študija je en semester obiskoval na Fakulteti za elektrotehniko in informacijske tehnologije na Univerzi Cirila in Metoda v Skopju, ter eno leto na Oddelku za elektrotehniko in računalništvo Univerze na Cipru, kjer se je podrobneje spoznal s tehnologijo mikrovalovne fotonike, katera je bila tudi osrednje tema njegove magistrske naloge »Uporaba frekvenčnega diskriminatorja z optično kasnilno linijo za merjenje faznega šuma«, za katero je prejel Univerzitetno Prešernovo nagrado. V času študija je sodeloval v več študentskih projektih in bil del zmagovalne ekipe, ki je osvojila prvo mesto na študentskem tekmovanju v načrtovanju »High-Performance Optoelectronic Oscillator« na »International Microwave Symposium« v Bostonu leta 2019. V študijskem letu 2019/2020 se je vpisal na doktorski študijski program Elektrotehnika na Fakulteti za elektrotehniko, Univerze v Ljubljani. Njegovo raziskovalno področje zajema mikrovalovno fotoniko s poudarkom na optoelektronskemu oscilatorju, pri čemer za povečanje občutljivosti meritev faznega šuma oscilatorjev predlaga uporabo optične kasnilne linije. Trenutno je gostujoči raziskovalec na University Duisburg-Essen.

Author's biography

After graduating from the Electrical and Computer High School in Ljubljana in 2013, Andrej Lavrič continued his education at the Faculty of Electrical Engineering of the University of Ljubljana and in 2019 obtained a master's degree in the field of information *and communication technologies. During his studies, he attended one semester at the Faculty of Electrical Engineering and Information Technology at Cyril and Methodius University in Skopje, and one year at the Department of Electrical Engineering and Computer Science at the University of Cyprus, where he learned more about microwave photonics technology, which was also central the topic of his master's thesis titled "Using a frequency discriminator with an optical delay line for phase noise measurement", for which he received the University Prešeren Prize. During his studies, he participated in several student projects and was part of the winning team that won first place in the student competition in the design of "High-Performance Optoelectronic Oscillator" at the "International Microwave Symposium" in Boston in 2019. In the academic year 2019/2020, enrolled in the electrical engineering doctoral study program at the Faculty of Electrical Engineering, University of Ljubljana. His research area covers microwave photonics with an emphasis on the optoelectronic oscillator, where he proposes the use of an optical delay line to increase the sensitivity of oscillator phase noise measurements. He is currently a visiting researcher at the University Duisburg-Essen.*

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Merjenje faznega šuma oscilatorja s pomočjo optičnega kasnilnega voda

Andrej Lavrič

izr. prof. dr. Boštjan Batagelj, prof. dr. Matjaž Vidmar

Univerza v Ljubljani, Fakulteta za elektrotehniko, Laboratorij za sevanje in optiko

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Redosled

- Fazni šum
- Merjenje faznega šuma
- Postopek s kasnilnim vodom
- Umerjanje merilnika z optičnim vodom
- Rezultati

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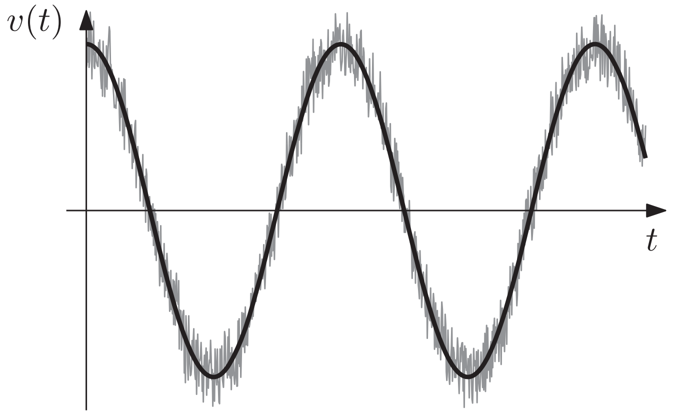
Fazni šum oscilatorja

$$v(t) = V_0[1 + \alpha(t)]\cos[2\pi f_0 t + \phi(t)]$$



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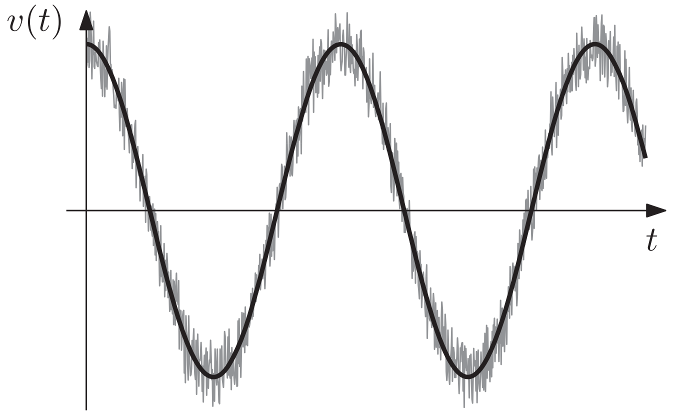
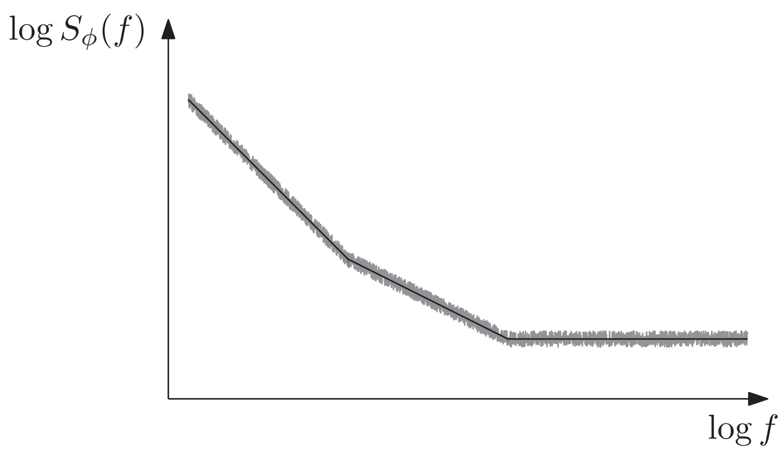
Fazni šum oscilatorja

amplitudni šum

$$v(t) = V_0[1 + \alpha(t)]\cos[2\pi f_0 t + \phi(t)] \longrightarrow S_\phi(f) = |\mathcal{F}\{\phi(t)\}|^2 \qquad \text{rad}^2/\text{Hz}$$

fazni šum





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Fazni šum oscilatorja

amplitudni šum

$v(t) = V_0$ … $)\}|^2$ rad^2/Hz

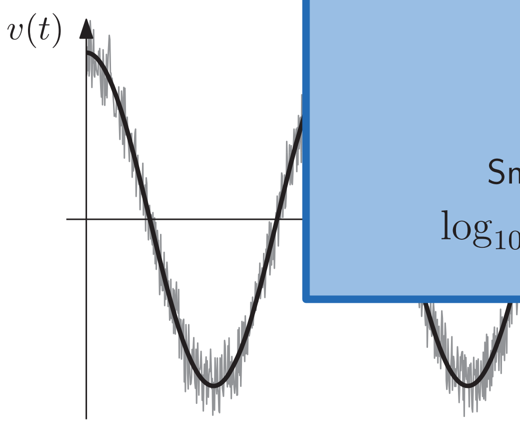
(Žal) se v praksi uporablja $\mathscr{L}$ z merskimi enotami dBc/Hz

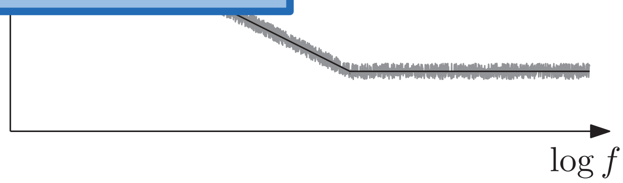
IEEE Std. 1139:

$$\mathscr{L}(f) = \frac{1}{2} S_\phi(f)$$

Smiselen zgolj v logaritmski skali

$$\log_{10} \mathscr{L}(f) = \log_{10} S_\phi(f) - 3\ \text{dB}$$





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Merjenje faznega šuma

- Neposredni postopek
- Postopek s faznim detektorjem
- Postopek s kasnilnim vodom
- Residualni postopek
- Križna korelacija

4/12

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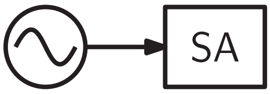
Merjenje faznega šuma



preprost
napačen!
uporaba v sili!

- Neposredni postopek
- Postopek s faznim detektorjem
- Postopek s kasnilnim vodom
- Residualni postopek
- Križna korelacija

4/1

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Merjenje faznega šuma

- ~~Neposredni postopek~~
- Postopek s faznim detektorjem
- Postopek s kasnilnim vodom
- Residualni postopek dvovhodna vezja
- Križna korelacija

4/1

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Merjenje faznega šuma

- ~~Neposredni postopek~~
- Postopek s faznim detektorjem
- Postopek s kasnilnim vodom
- Residualni postopek — dvovhodna vezja
- Križna korelacija

→ komercialni inštrumenti

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Merjenje faznega šuma

- ~~Neposredni postopek~~
- Postopek s faznim detektorjem
- Postopek s kasnilnim vodom → poudarek predstavitve
- Residualni postopek — dvovhodna vezja
- Križna korelacija

→ komercialni inštrumenti

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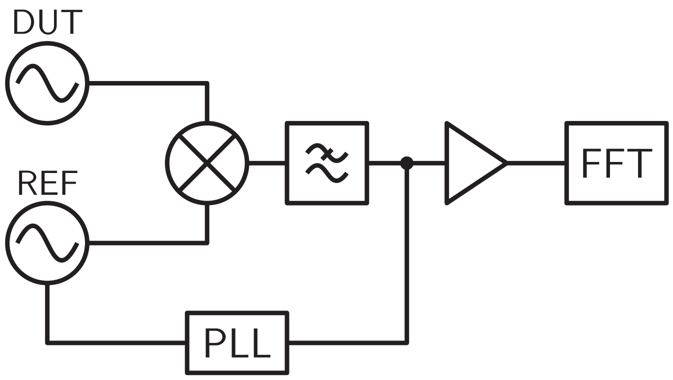
Postopek s faznim detektorjem



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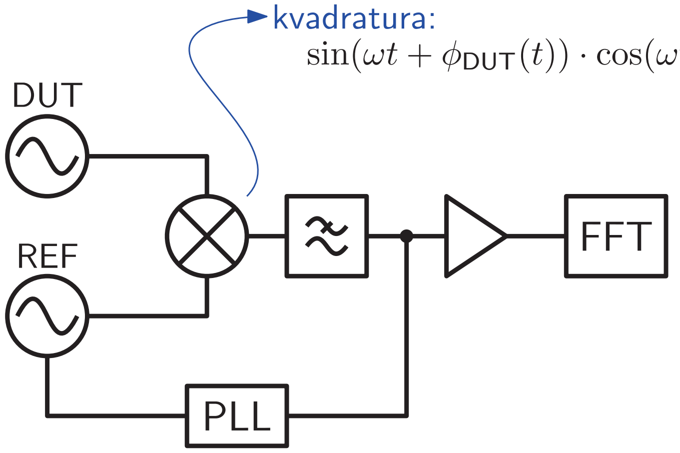
Postopek s faznim detektorjem

kvadratura:

$$\sin(\omega t + \phi_{\mathsf{DUT}}(t)) \cdot \cos(\omega t) = k_\phi \left[\sin(\phi_{\mathsf{DUT}}(t)) + \sin(2\omega t + \phi_{\mathsf{DUT}}(t))\right]$$

$$\approx k_\phi \phi_{\mathsf{DUT}}(t)$$



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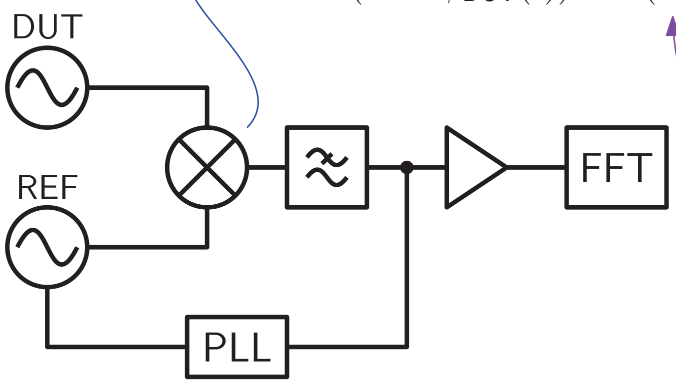
Postopek s faznim detektorjem

kvadratura:

$$\sin(\omega t + \phi_{\text{DUT}}(t)) \cdot \cos(\omega t) = k_\phi \left[\sin(\phi_{\text{DUT}}(t)) + \cancel{\sin(2\omega t + \phi_{\text{DUT}}(t))}\right]$$
$$\approx k_\phi \phi_{\text{DUT}}(t)$$

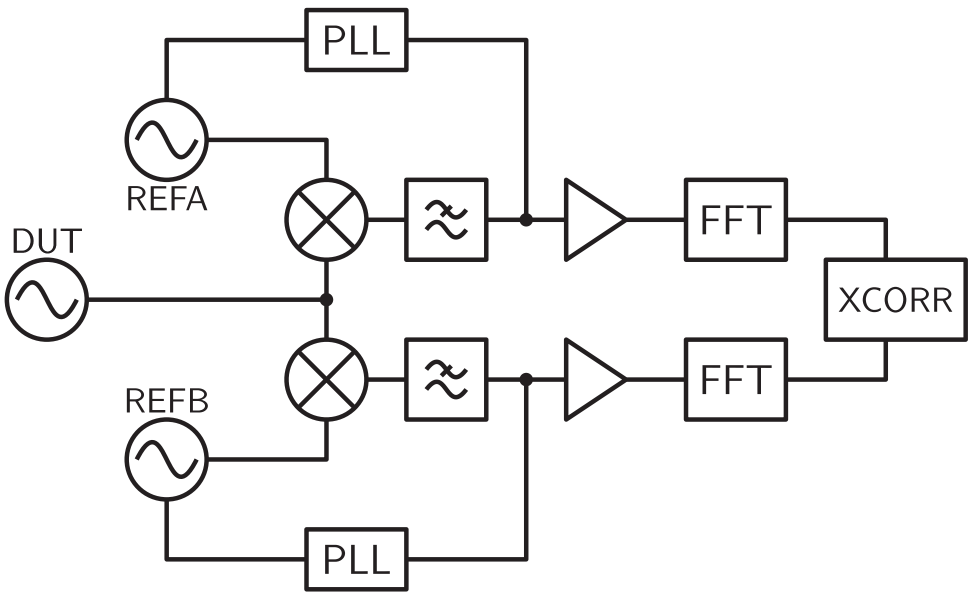


Omejitve:

$|\phi_{\text{REF}}(t)| \ll |\phi_{\text{DUT}}(t)|$

hiter ali počasen PLL?

Križna korelacija



$$S_{\phi,\text{meritev}} = S_{\phi,\text{DUT}} + \frac{S_{\phi,\text{A}} + S_{\phi,\text{B}}}{\sqrt{m}}$$

Holzworth HA7062C/D, Keysight E5052B, Rohde&Schwarz FSWP8/26/50

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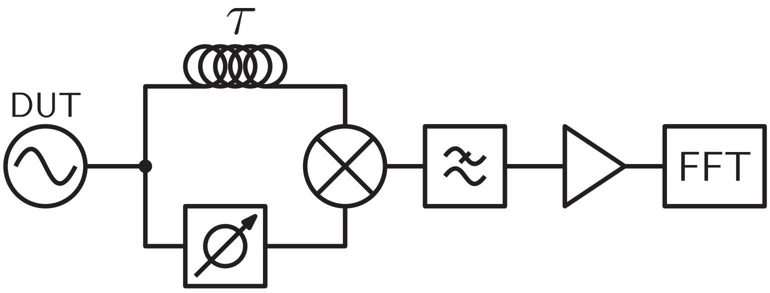
Postopek s kasnilnim vodom



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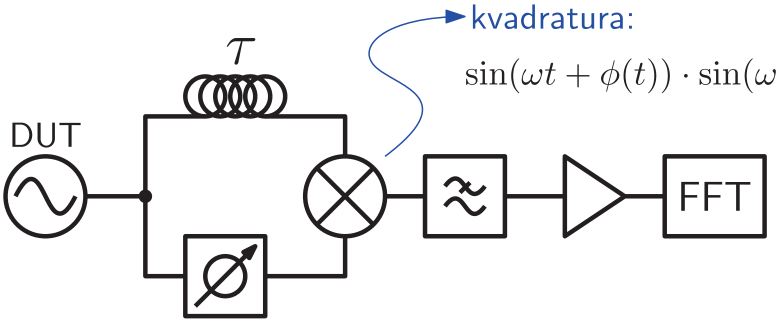
Postopek s kasnilnim vodom

kvadratura:

$$\sin(\omega t + \phi(t)) \cdot \sin(\omega(t-\tau) + \phi(t-\tau)) \approx k_\phi \left[\phi(t) - \phi(t-\tau)\right)$$



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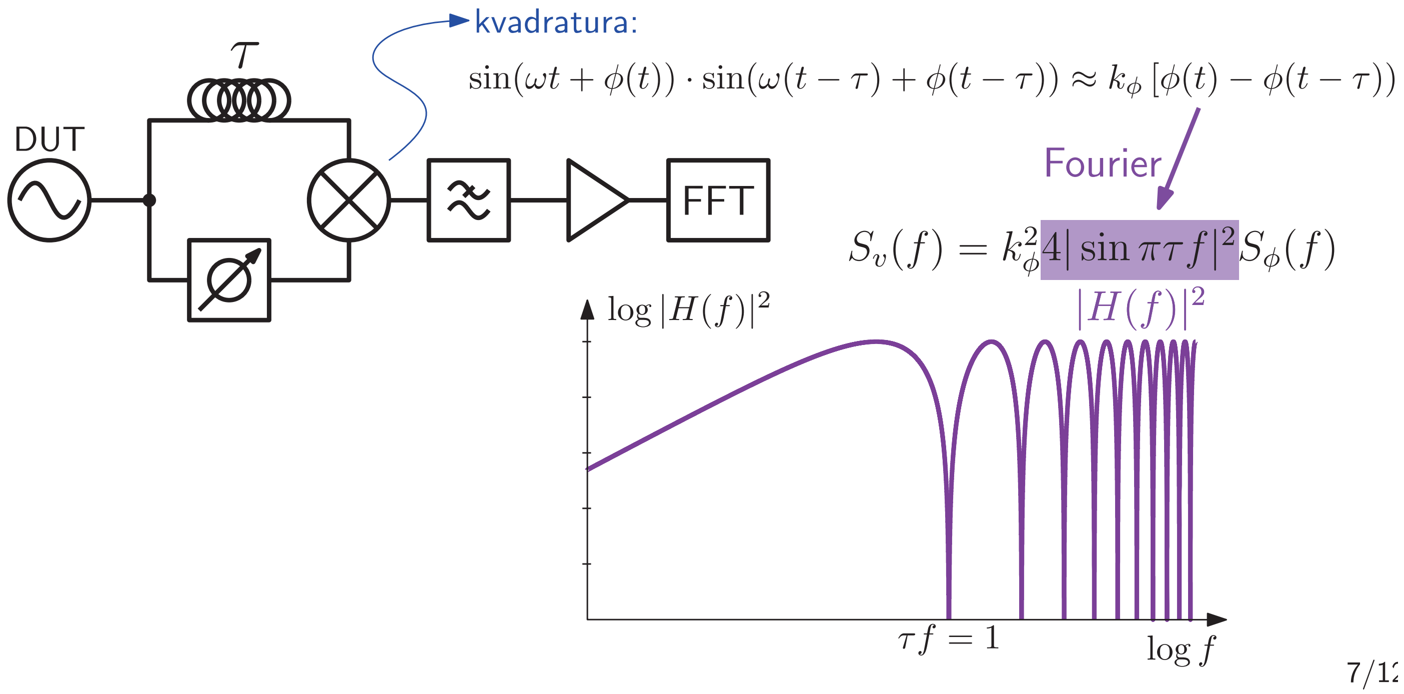
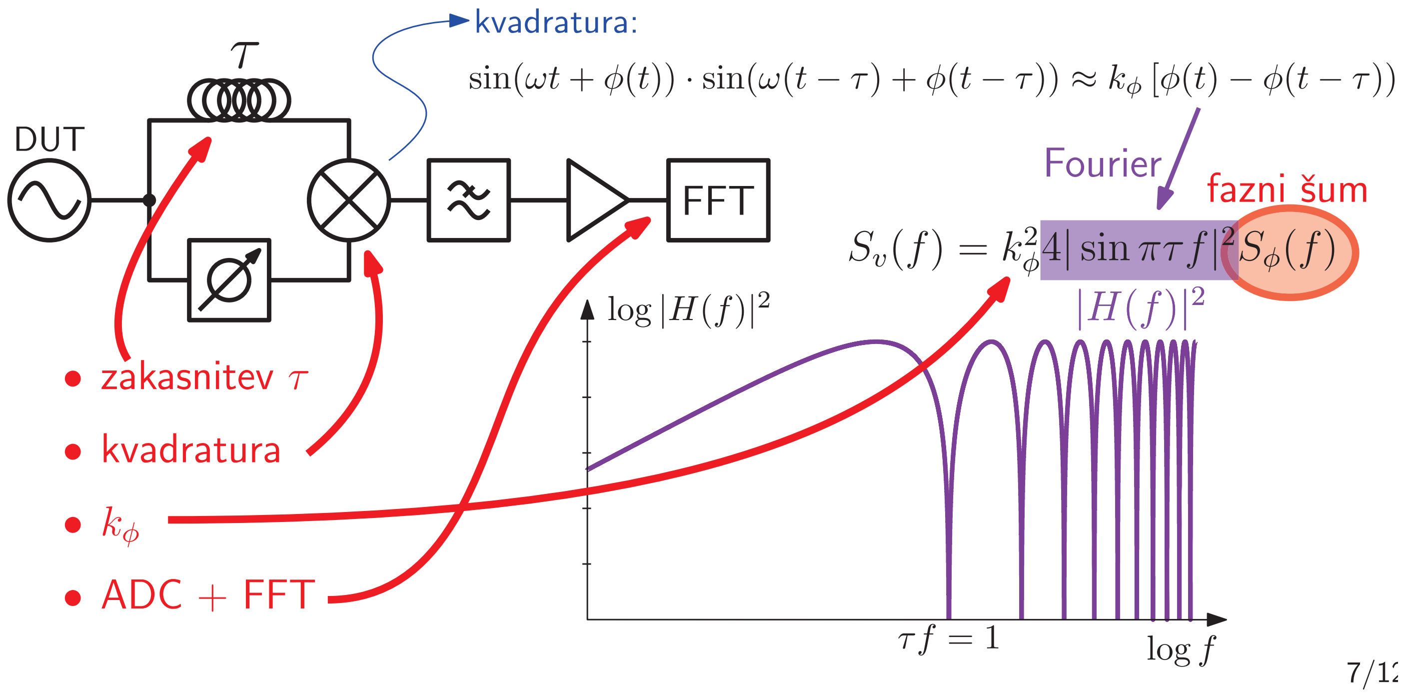
Postopek s kasnilnim vodom



Postopek s kasnilnim vodom



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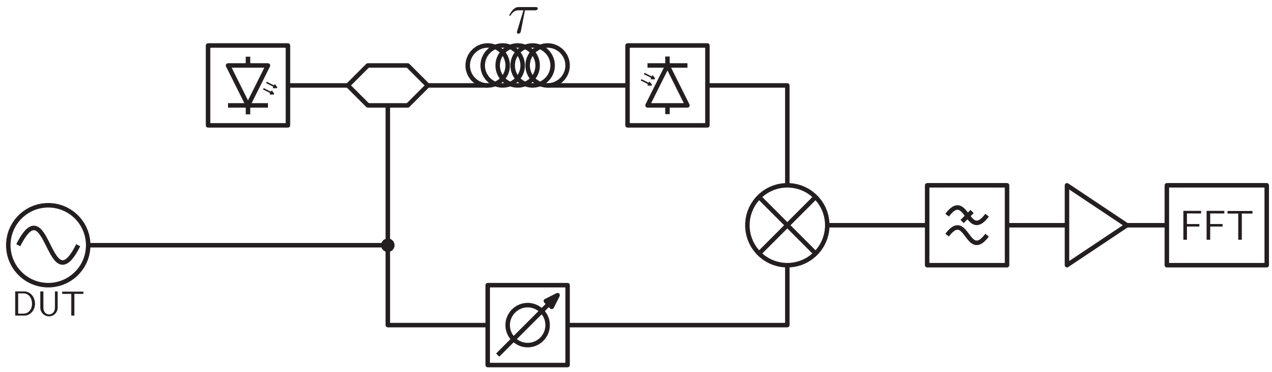
Merilnik z optičnim kasnilnim vodom



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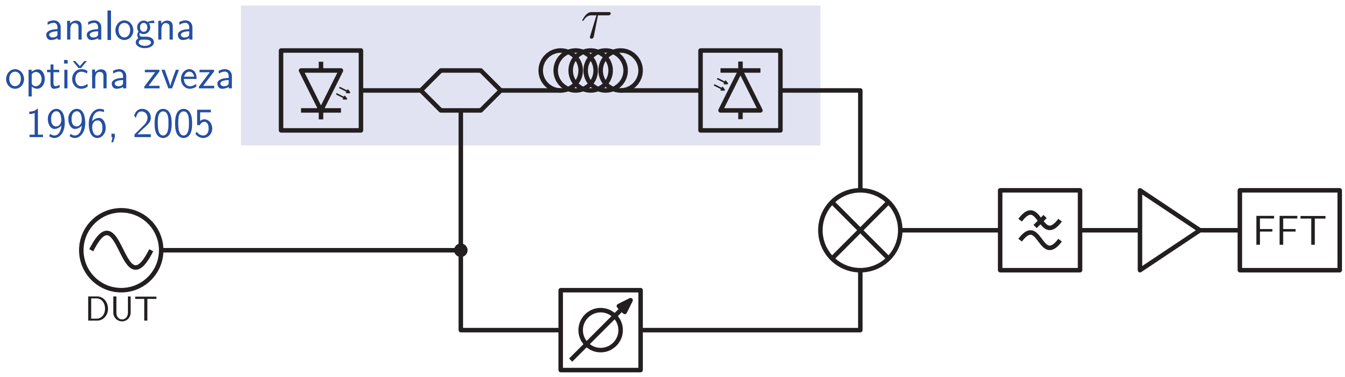
Merilnik z optičnim kasnilnim vodom



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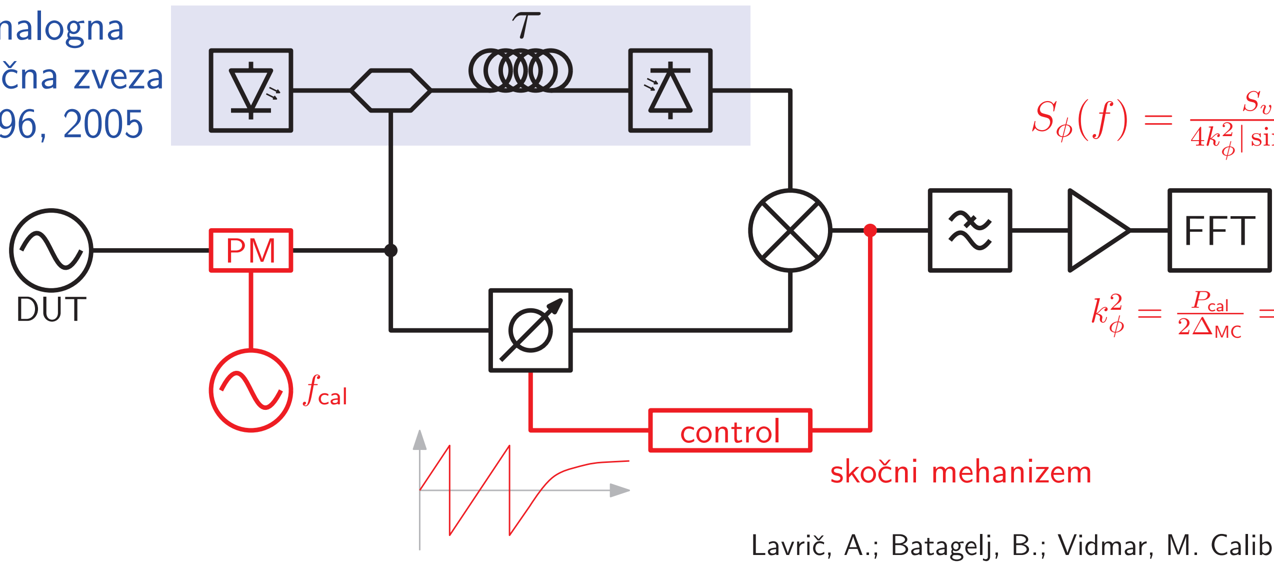
Merilnik z optičnim kasnilnim vodom

analogna
optična zveza
1996, 2005



$$S_\phi(f) = \frac{S_v(f)}{4k_\phi^2 |\sin \pi\tau f|^2}$$

$$k_\phi^2 = \frac{P_{\mathrm{cal}}}{2\Delta_{\mathrm{MC}}} = \frac{v_{\mathrm{cal}}^2}{m^2}$$

naše delo: avtomatsko umerjanje

Lavrič, A.; Batagelj, B.; Vidmar, M. Calibration of an RF/Microwave Phase Noise Meter with a Photonic Delay Line. Photonics 2022, 9, 533. https://doi.org/10.3390/photonics9080533

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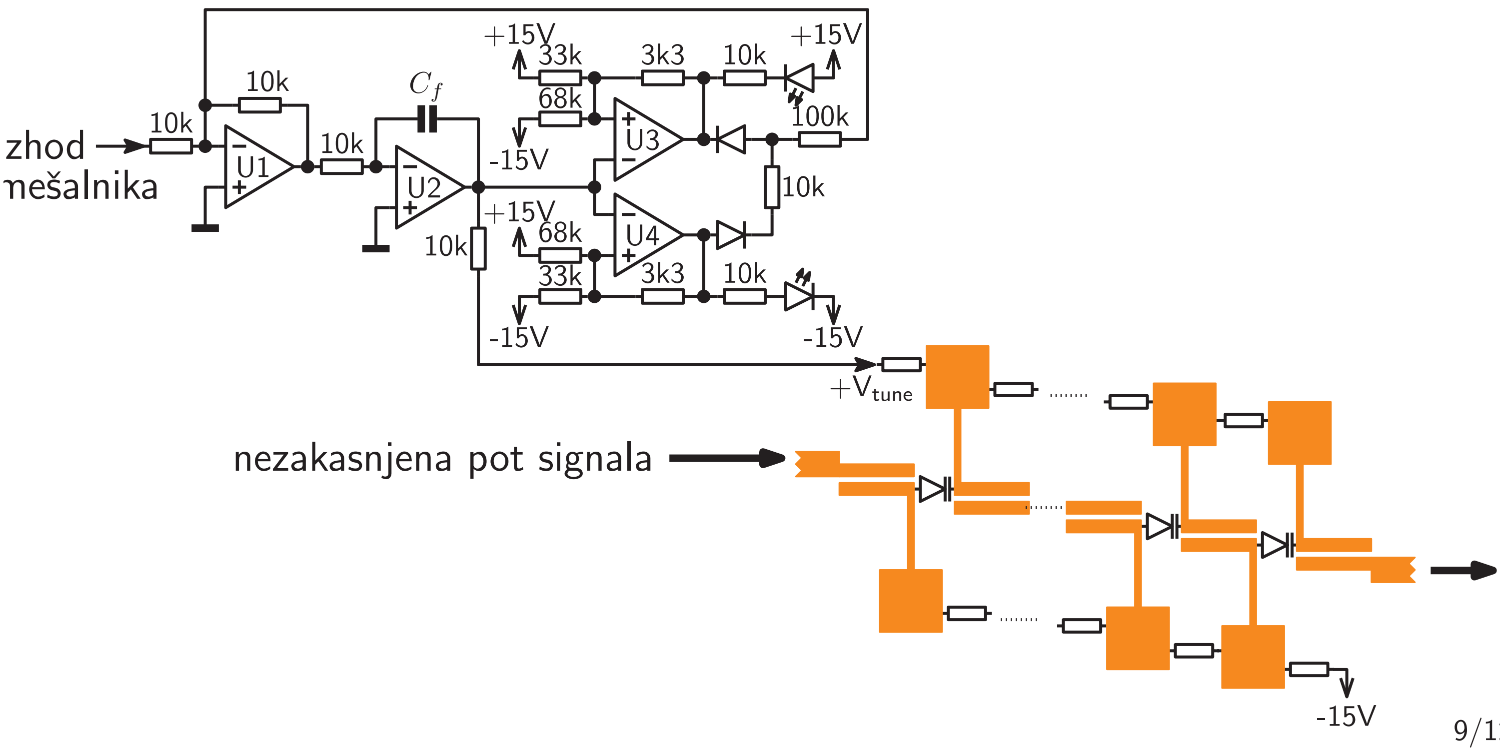

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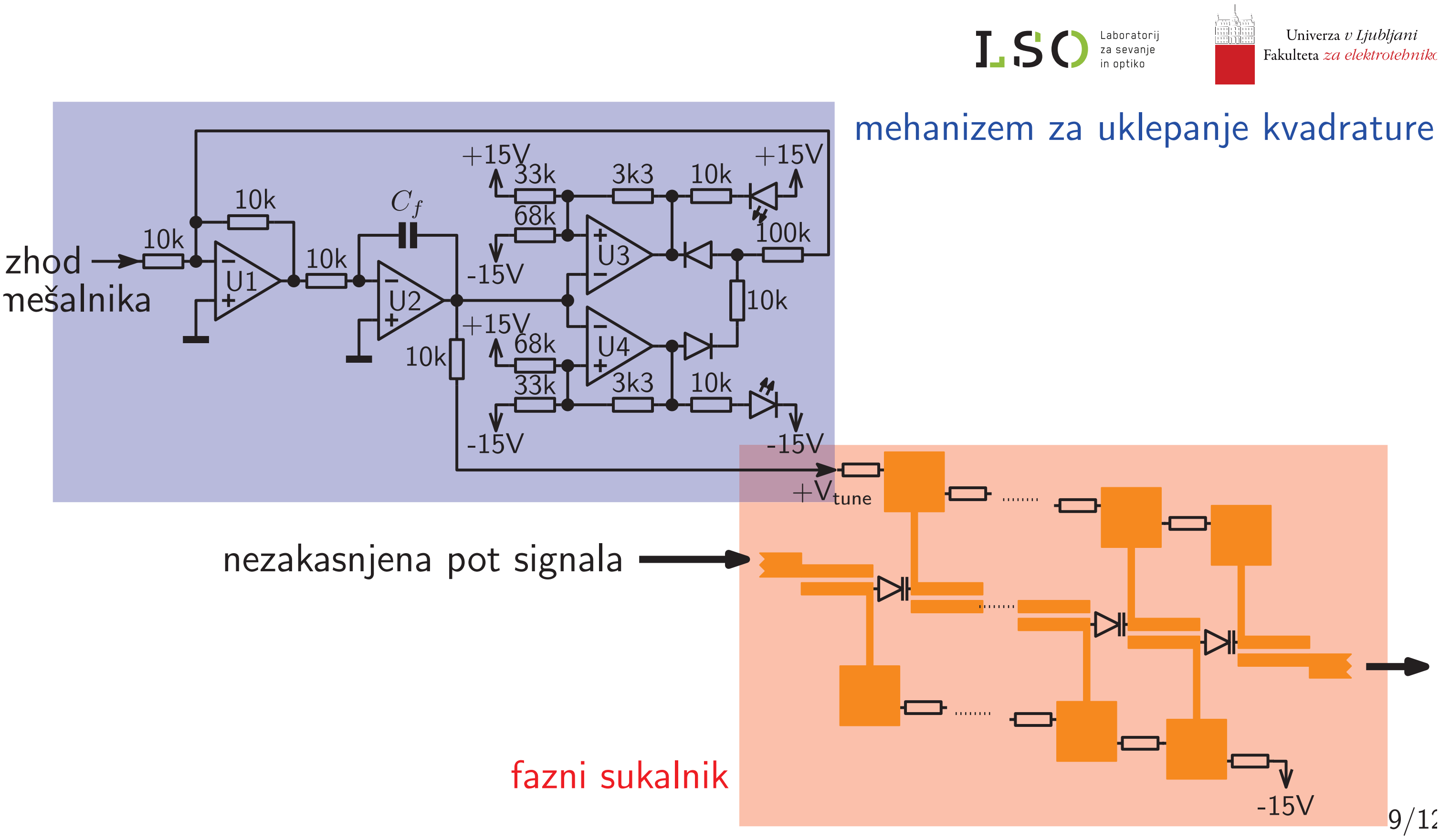
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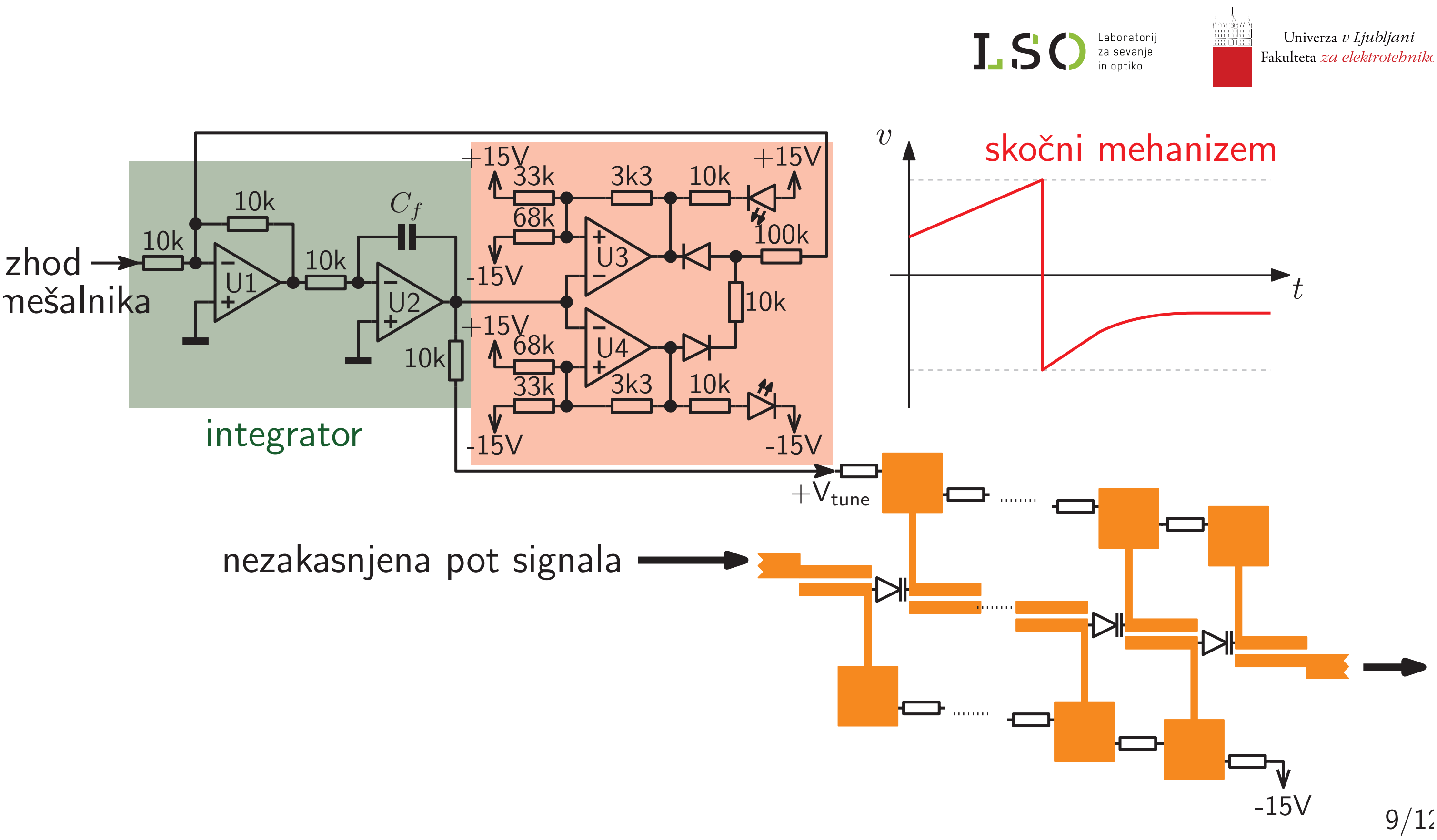
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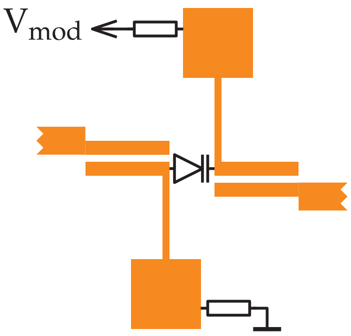
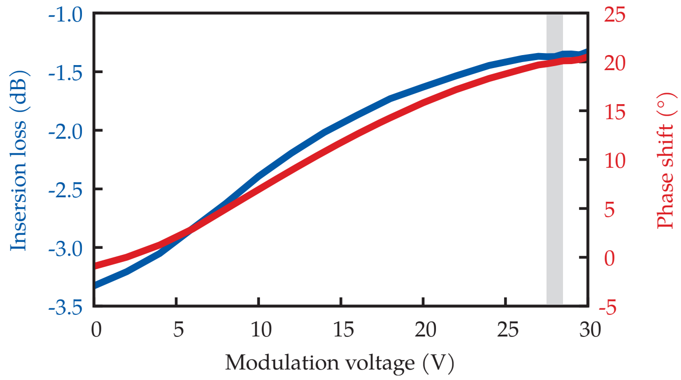
$$v_{\mathrm{DUT}}(t) = V_0 \cos[2\pi f_0 t + \phi(t) + \frac{m}{2}\cos(2\pi f_{\mathrm{cal}} t)]$$

$$k_\phi^2 = \frac{P_{\mathrm{cal}}}{2\Delta_{\mathrm{MC}}} = \frac{v_{\mathrm{cal}}^2}{m^2}$$





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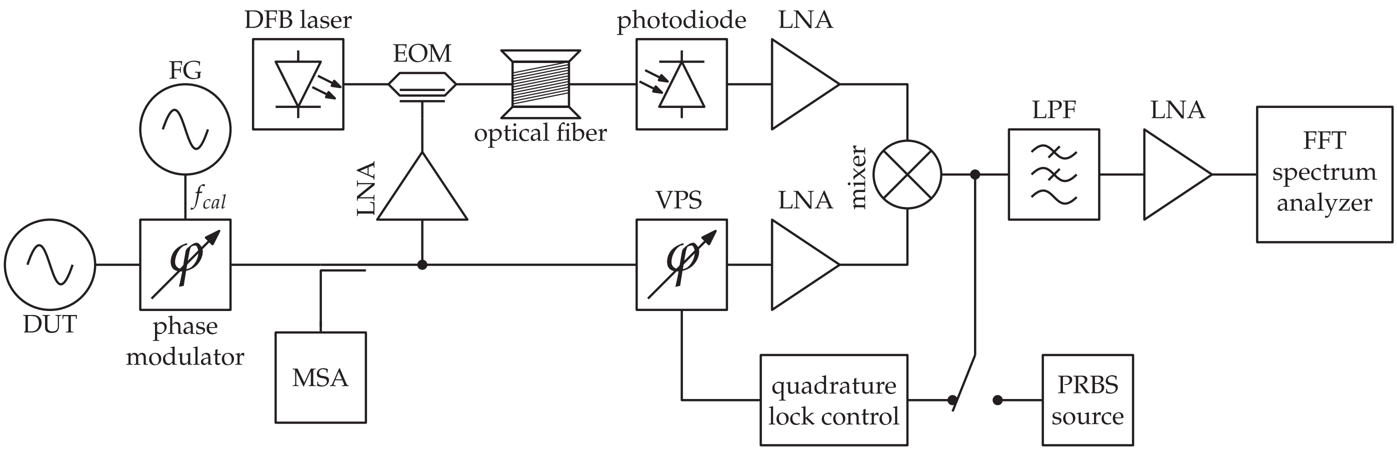

Lavrič, A.; Batagelj, B.; Vidmar, M. Calibration of an RF/Microwave Phase Noise Meter with a Photonic Delay Line. Photonics 2022, 9, 533. https://doi.org/10.3390/photonics9080533

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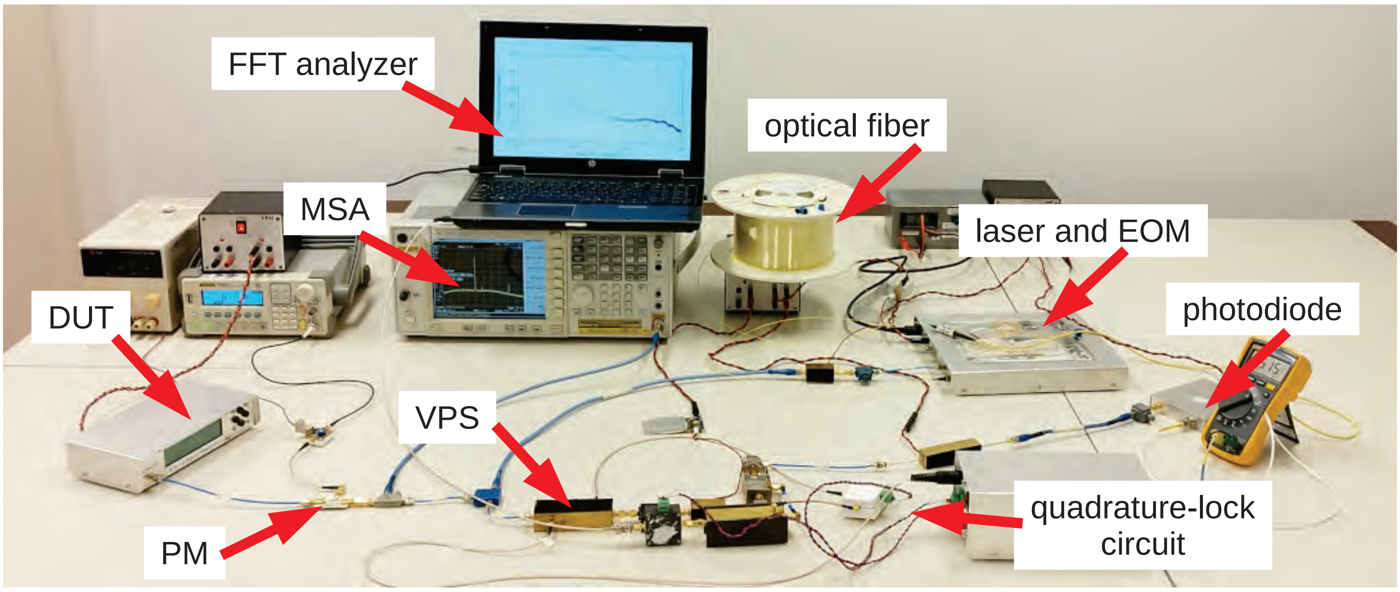

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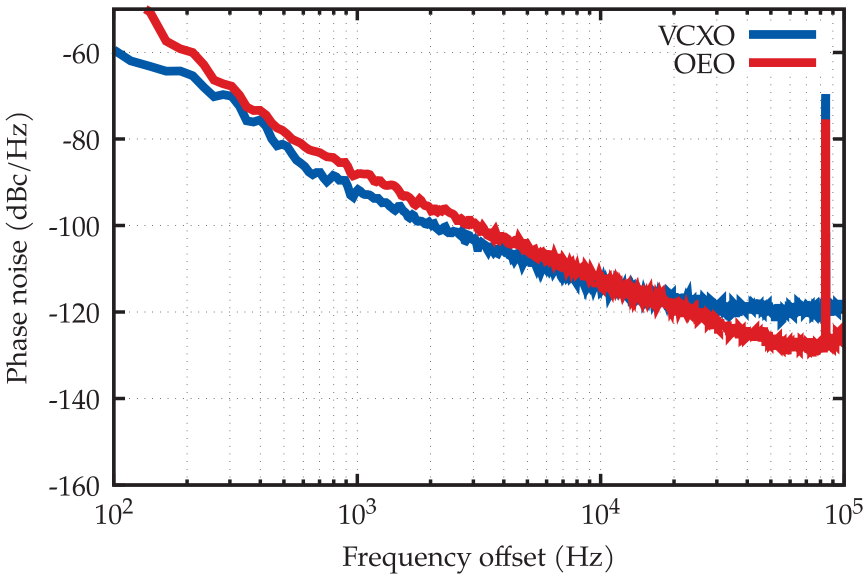

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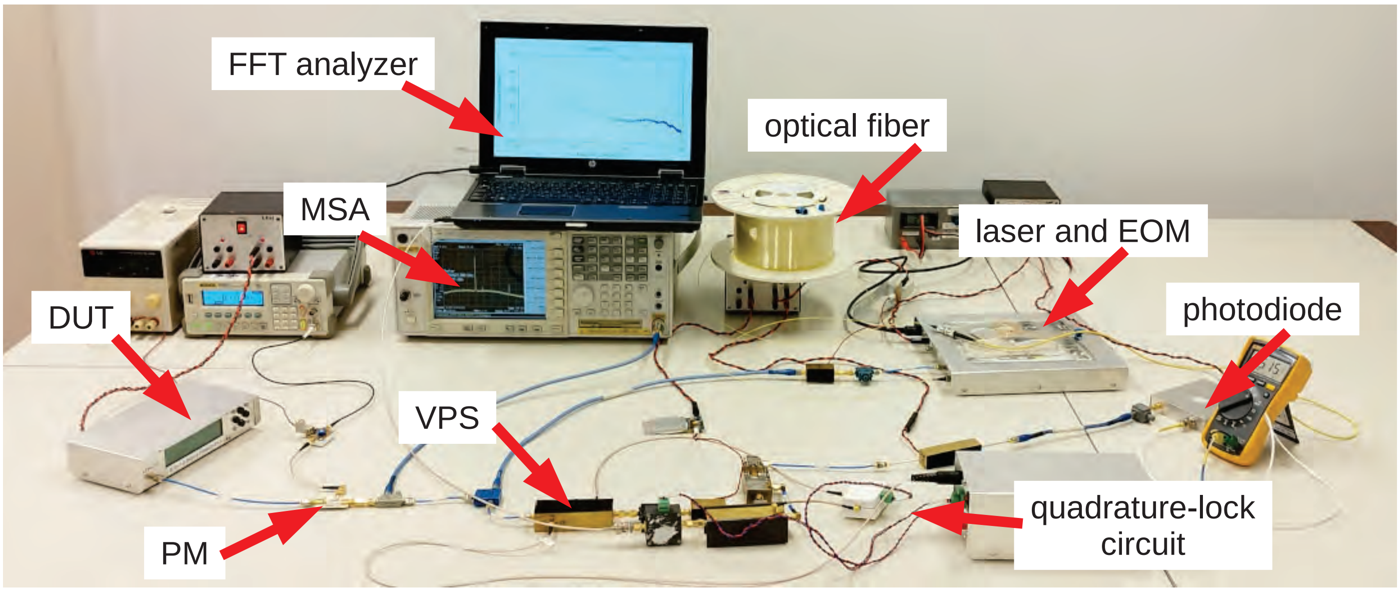

Vprašanja?

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Optične modulacije

Optical modulations

Matjaž Vidmar
Univerza v Ljubljani, Fakulteta za elektrotehniko
matjaz.vidmar@fe.uni-lj.si

Povzetek

V predavanju bodo sprva predstavljene omejitve optične prenosne poti, nato pa omejitve svetlobnih oddajnikov in sprejemnikov. Osrednji del bo namenjen različnim izvedbam optičnih modulacij od preproste jakostne modulacije do koherentnih in polarizacijskih optičnih zvez.

Abstract

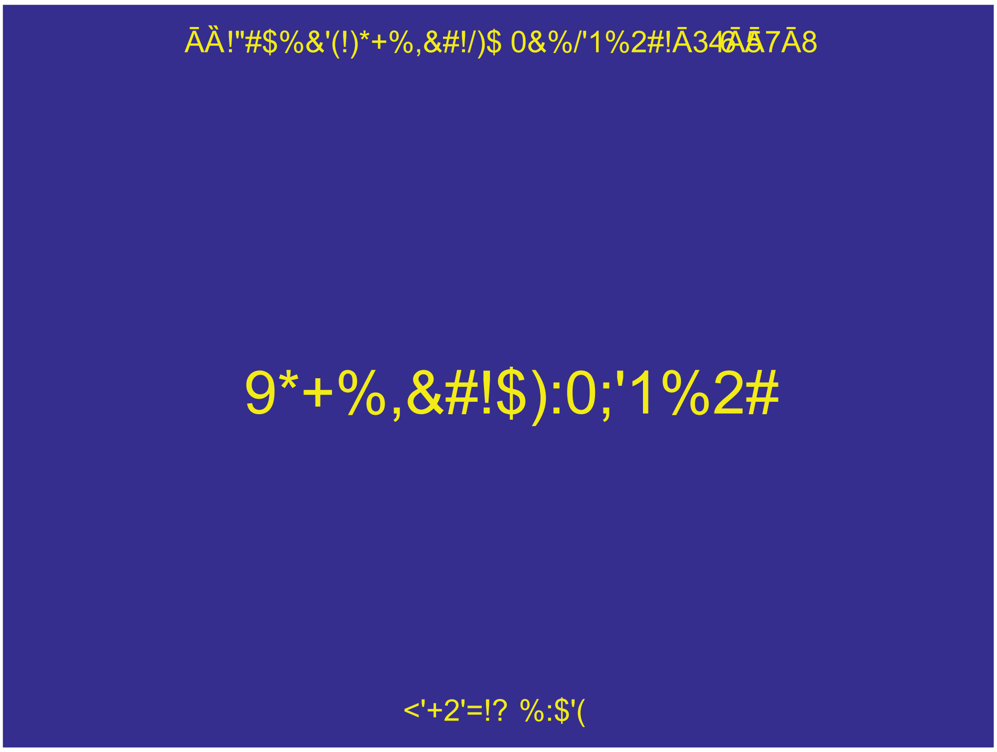
This lecture will initially present the limitations of the optical transmission path, and then the limitations of light transmitters and receivers. The central part will be dedicated to various implementations of optical modulations, from simple power modulation to coherent and polarization optical links.

Biografija avtorja

Matjaž Vidmar je doktoriral leta 1992 z naslovom teme »Metoda korekcije ionosferskih pogreškov pri satelitski navigaciji in prenosu časa«. V ZDA je razvijal satelitske oddajnike za organizacijo AMSAT. V sklopu sodelovanja z AMSAT-om je sodeloval pri razvoju komunikacijske in navigacijske opreme za satelit “AMSAT-Phase-3D”, ki je bil uspešno izstreljen v novembru 2000. Profesor Vidmar trenutno poučuje dodiplomske in podiplomske predmete s področja telekomunikacij na Fakulteti za elektrotehniko. Njegovo področje dela je mikrovalovna elektronika, ki obsega področja od letalske industrije do optičnih komunikacij.

Author's biography

Matjaž Vidmar received his PhD in 1992 from the University of Ljubljana, for developing a single frequency GPS ionospheric correction receiver. Mr. Vidmar is currently teaching undergraduate and postgraduate courses in Electrical Engineering at the University of Ljubljana, where he serves as head of the Radiation and Optics Laboratory (LSO) at the department for Electrical Engineering (FE). His current research interests include microwave and high speed electronics ranging from avionics to optical-fiber communications. Under his leadership, the LSO developed most of the 10Gbps electronics (pulse modulator, clock recovery) used in the Ester (ACTS 063) project and many 40Gbps circuits used in the ATLAS (IST 10626) project: EAM drivers, transmitter clock distribution, 40Gbps and 80Gbps clock-recovery circuits and 40Gbps PMD compensation receiver electronics. Mr. Vidmar also developed and built satellite hardware flown in space in 1990 on the Microsat mission and in 2000 on the AMSAT-P3D satellite.).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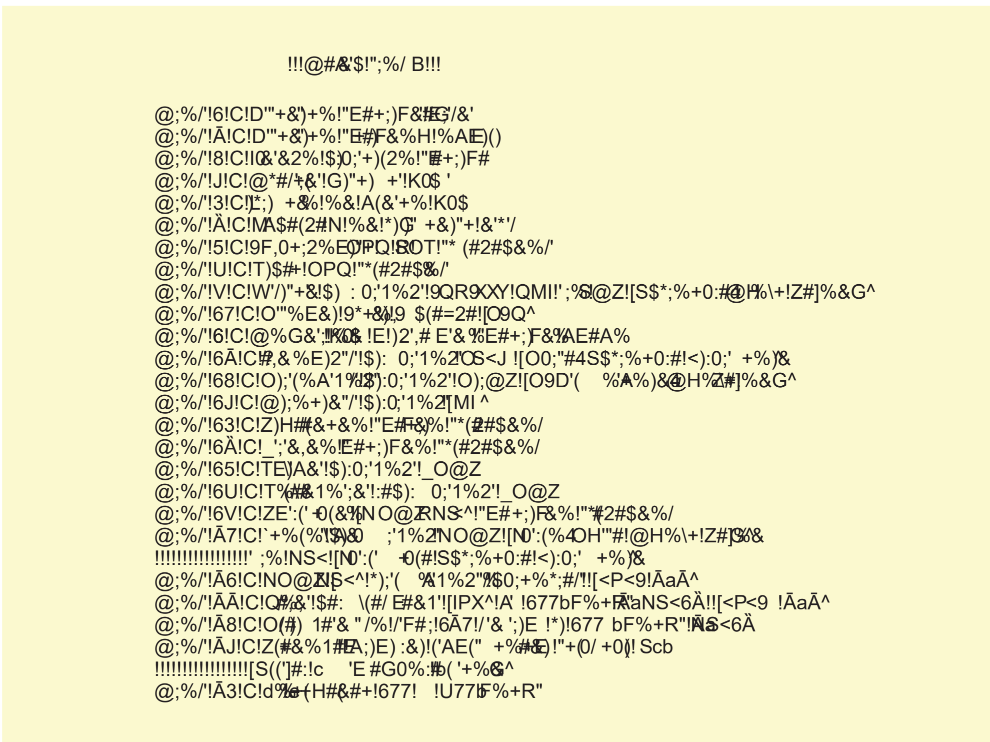

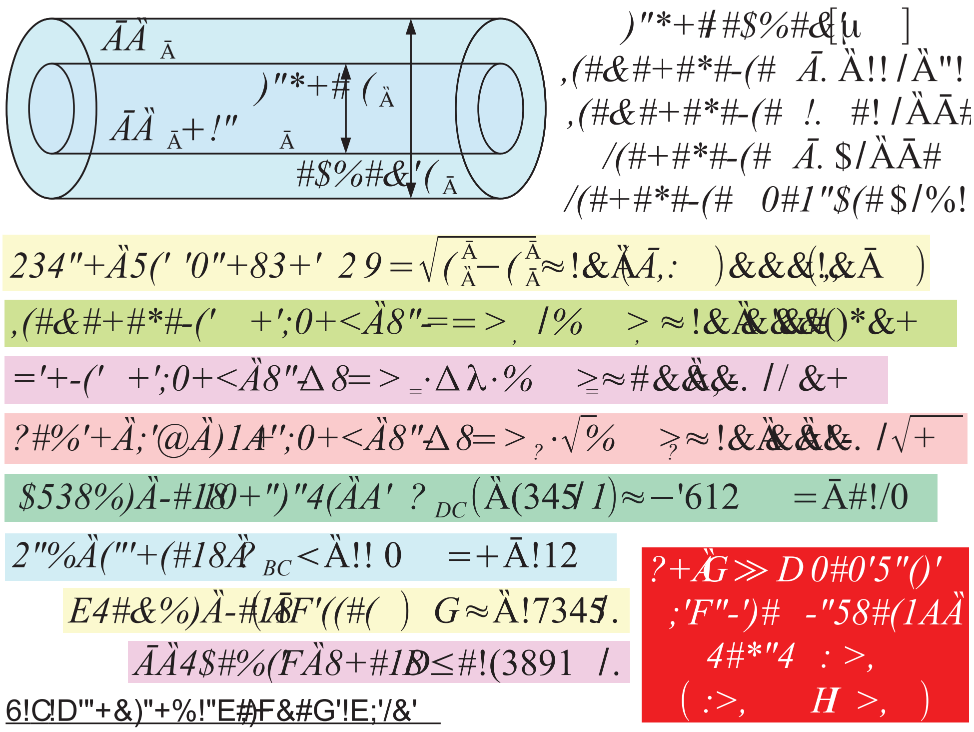

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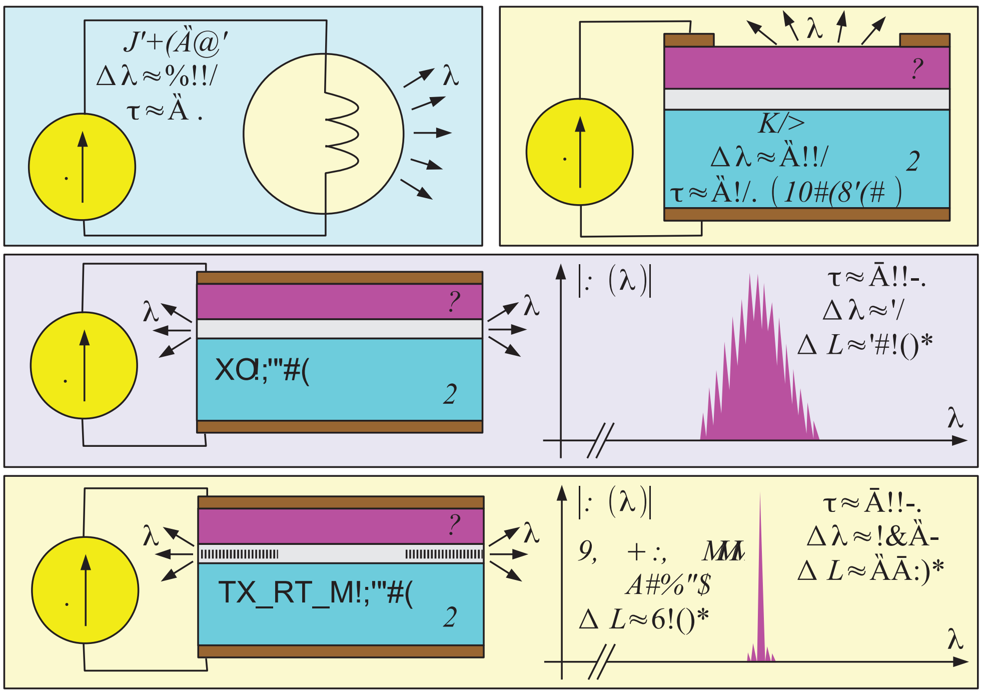

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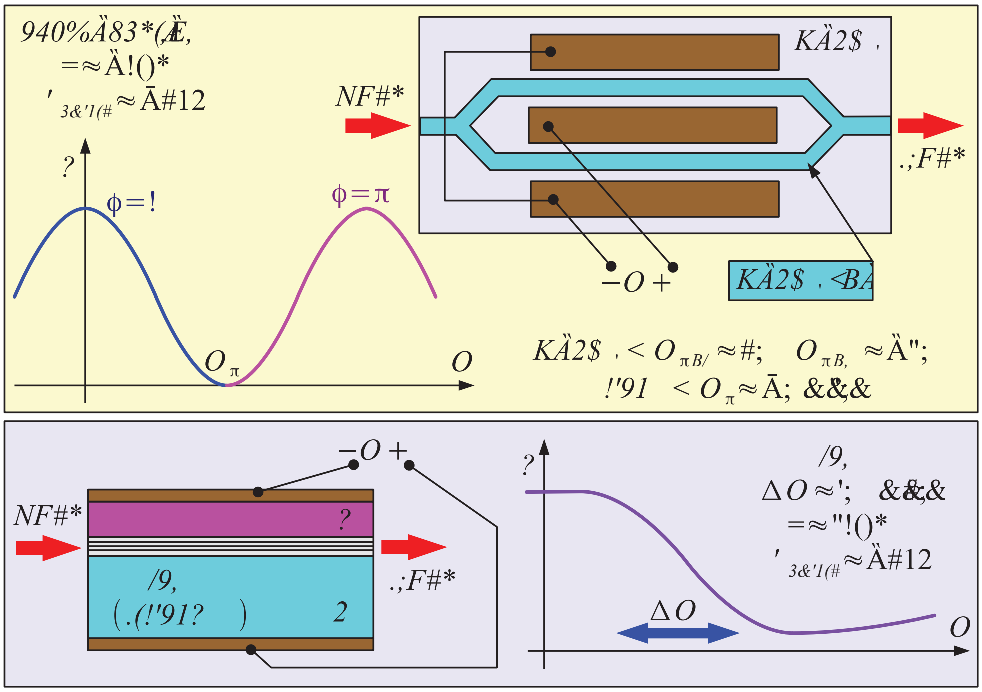

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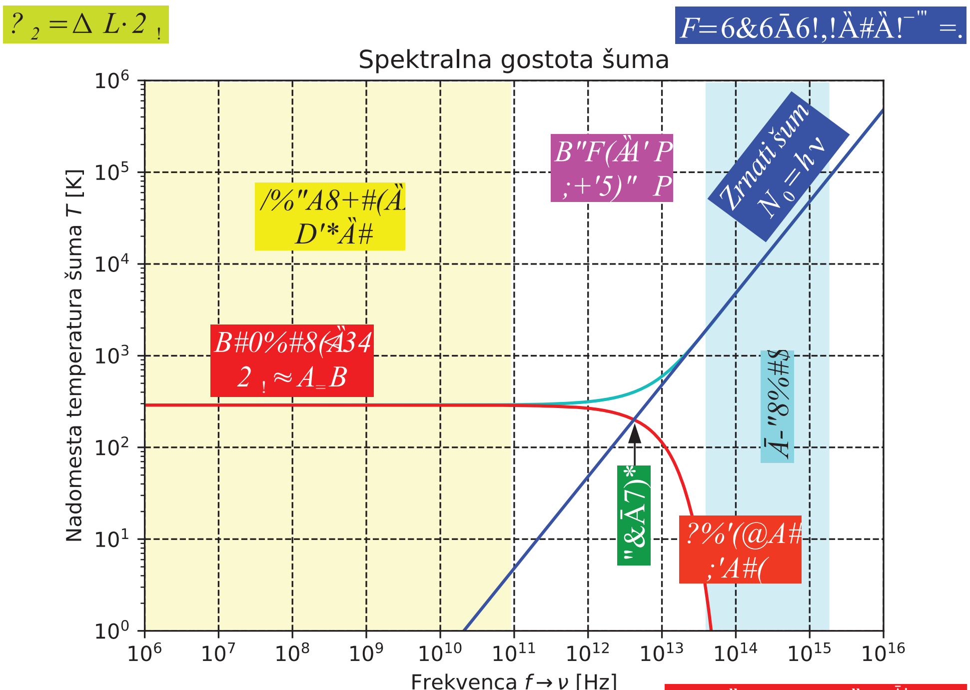

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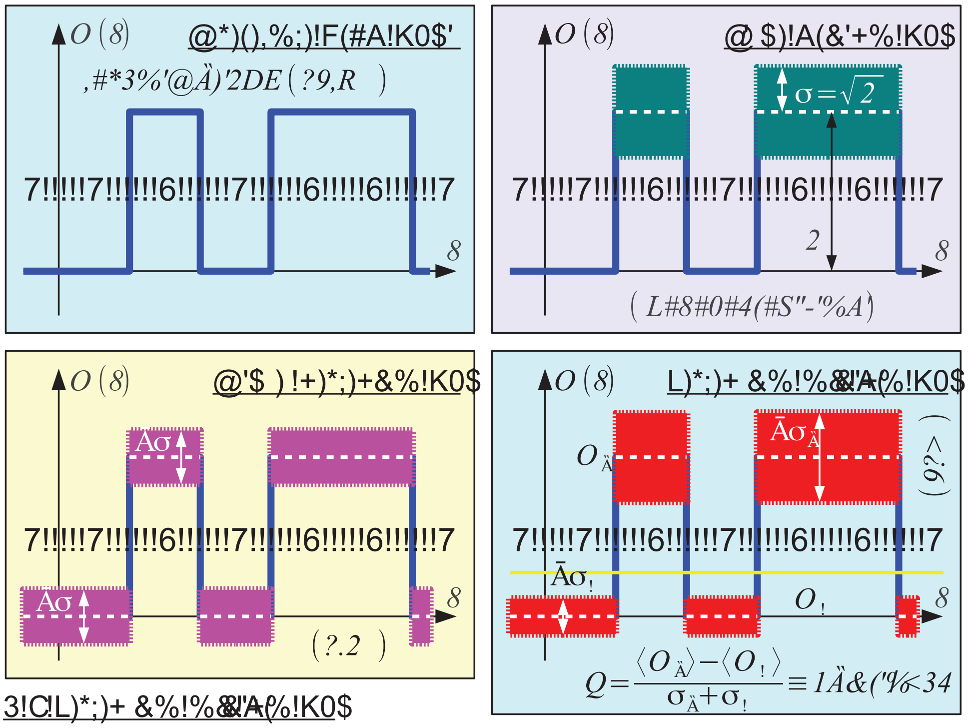

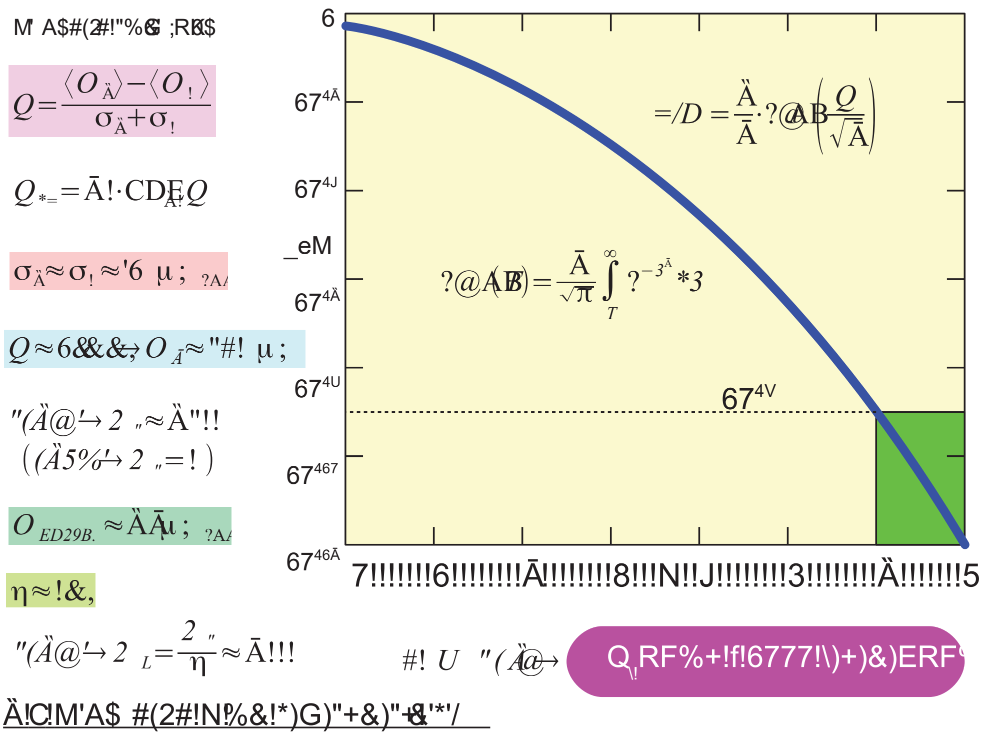

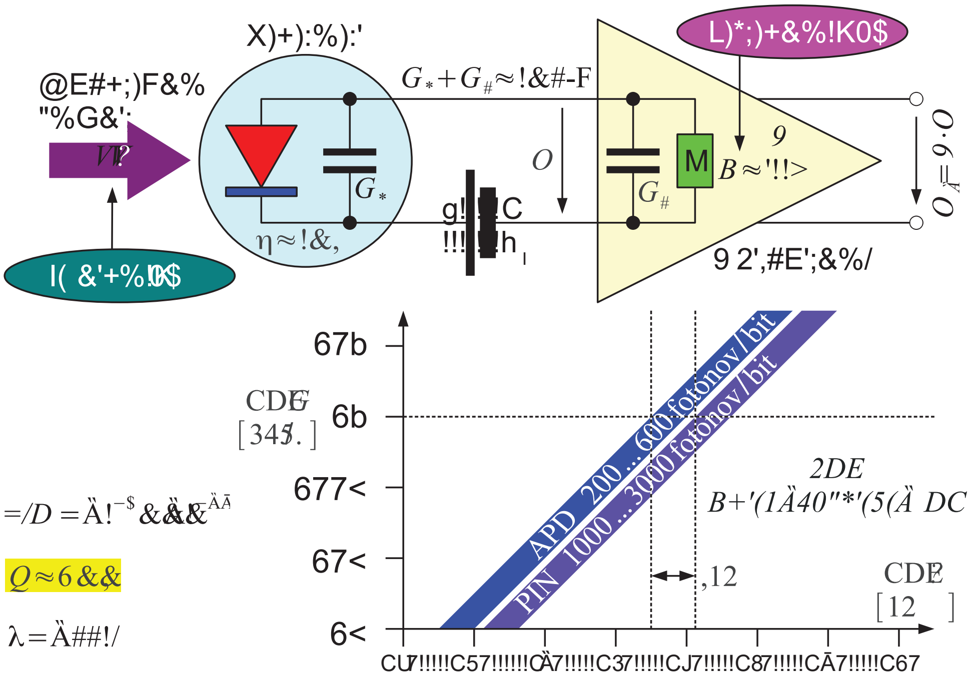
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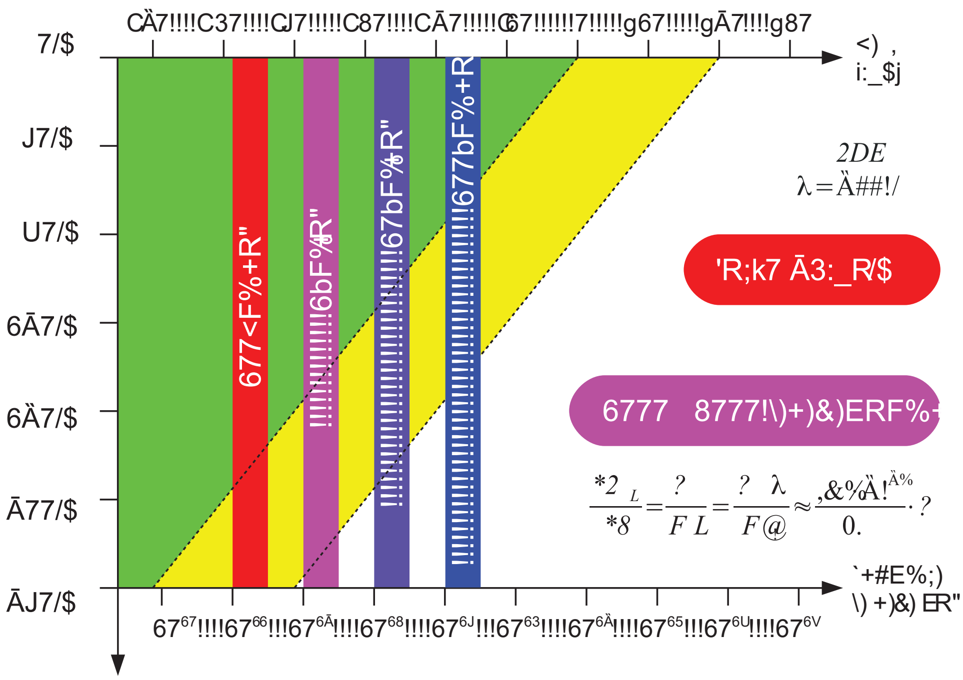

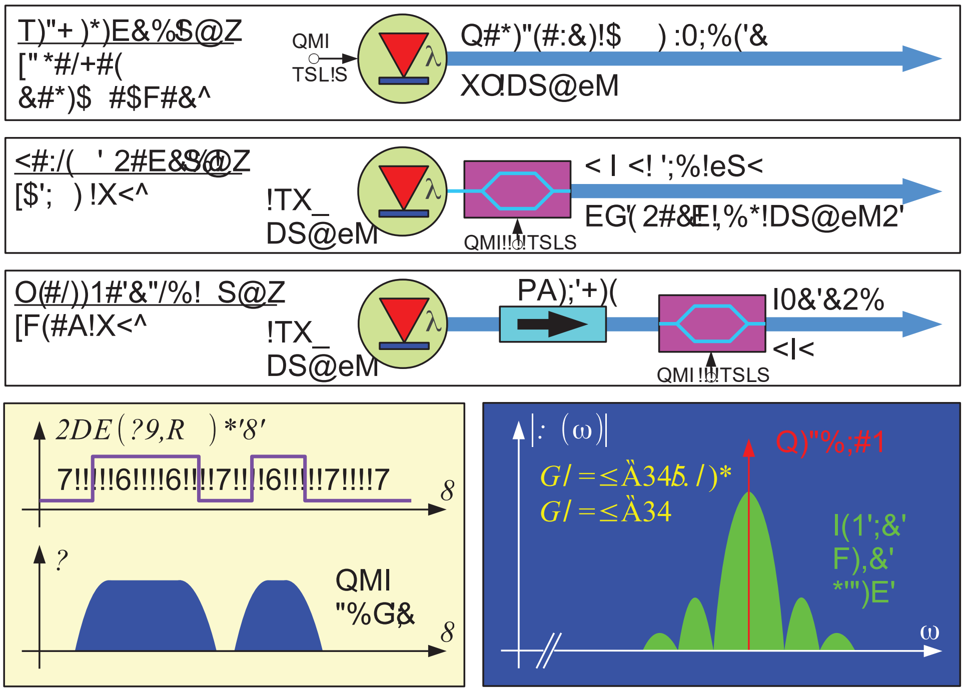

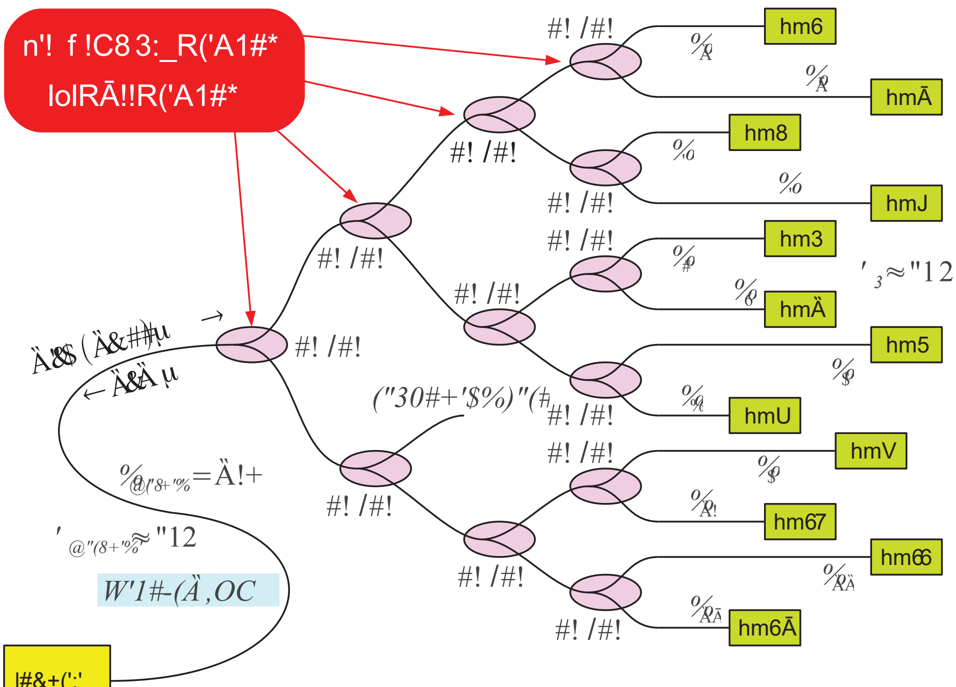

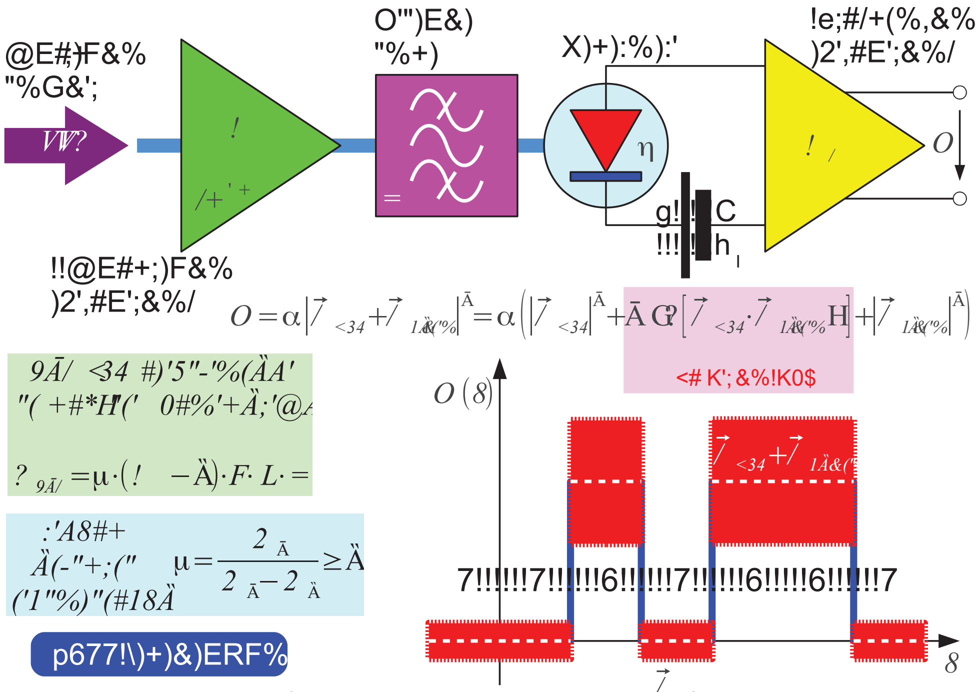

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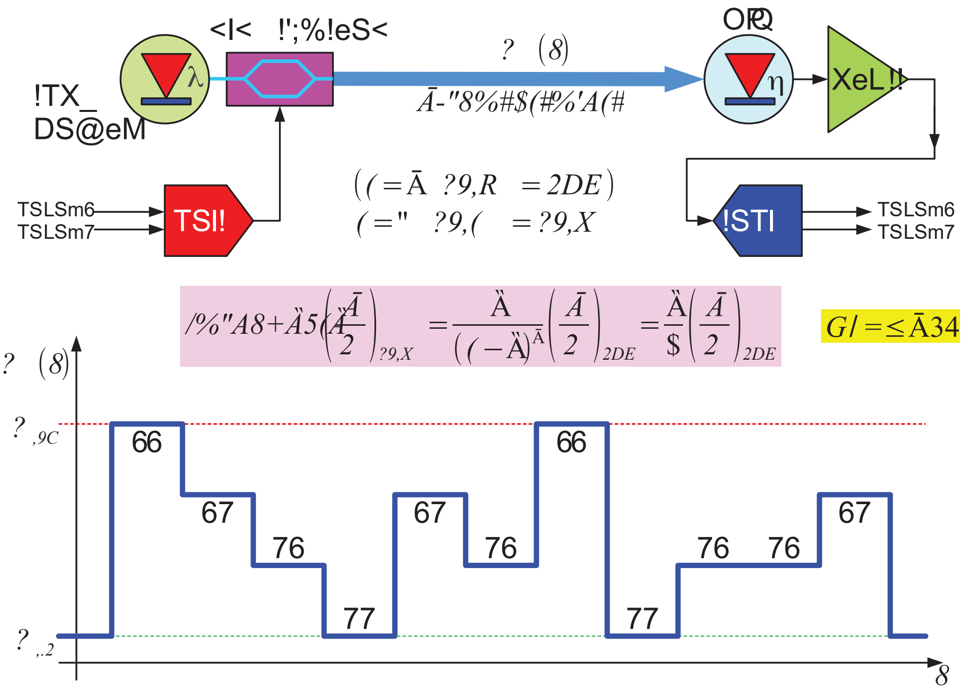

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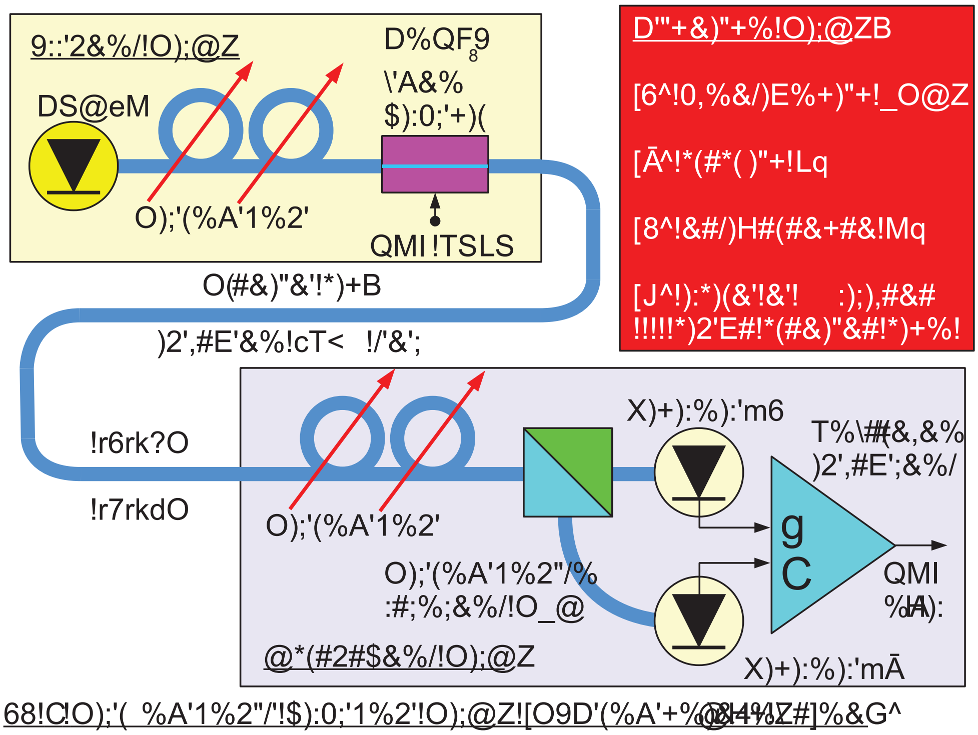

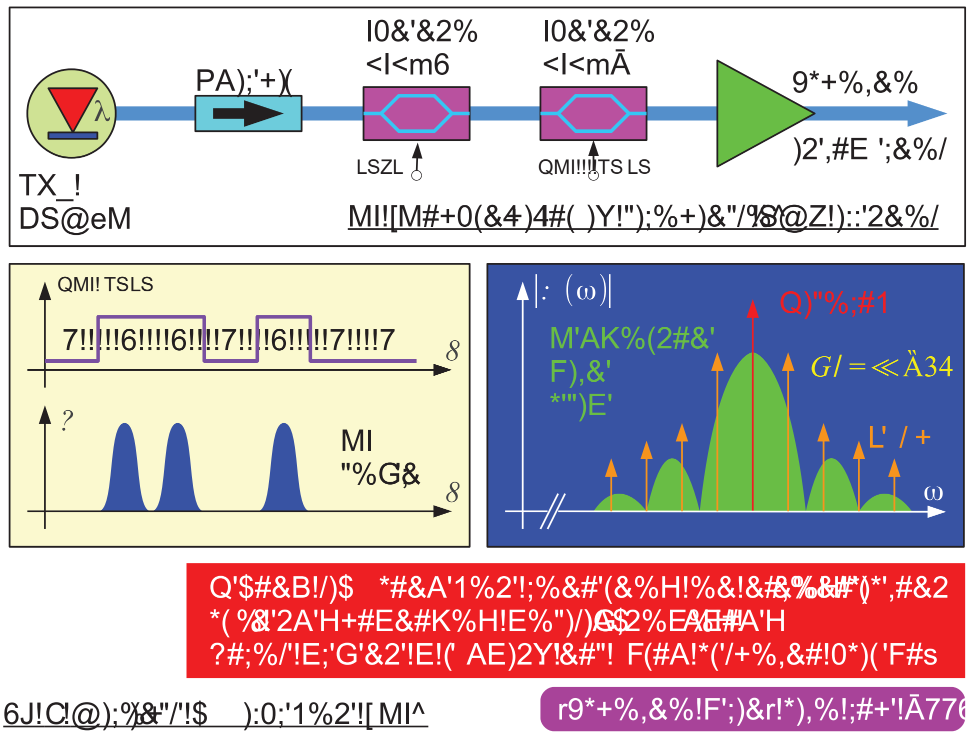

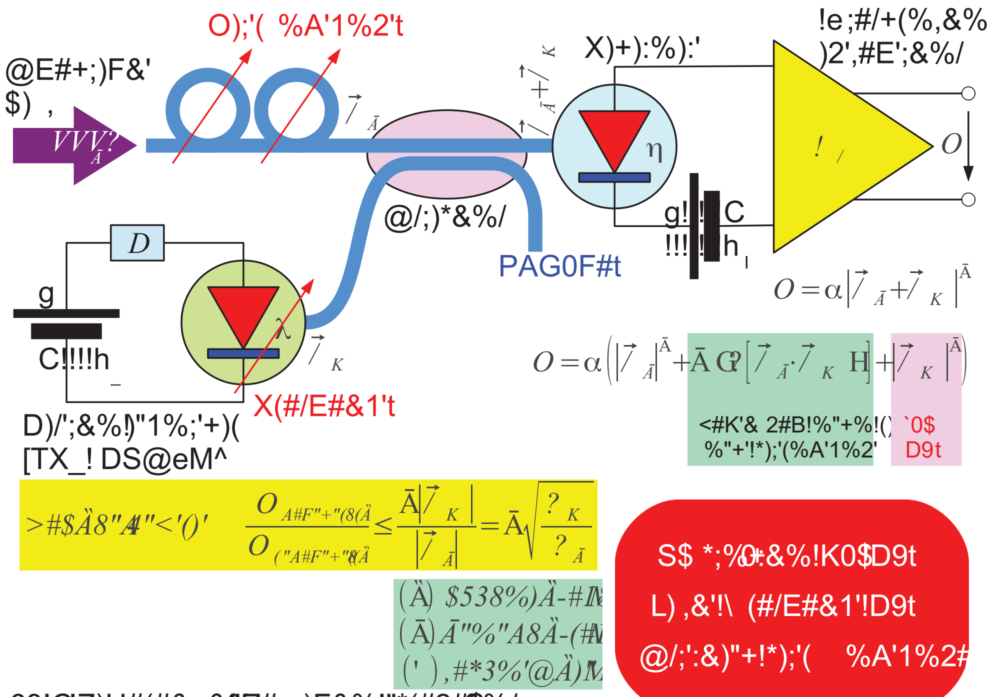

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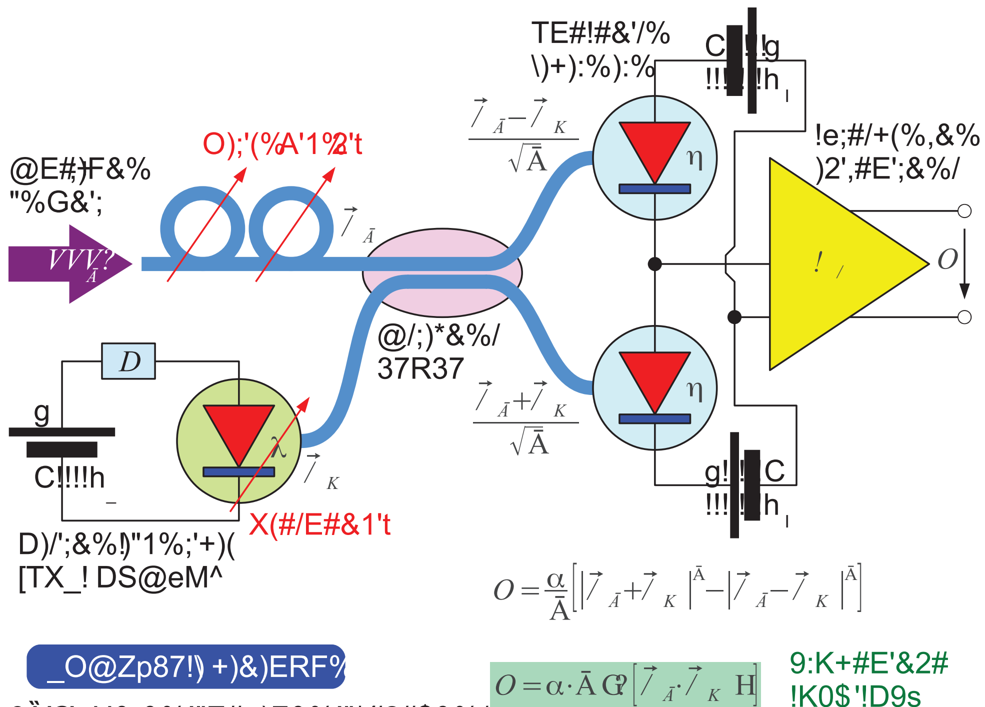

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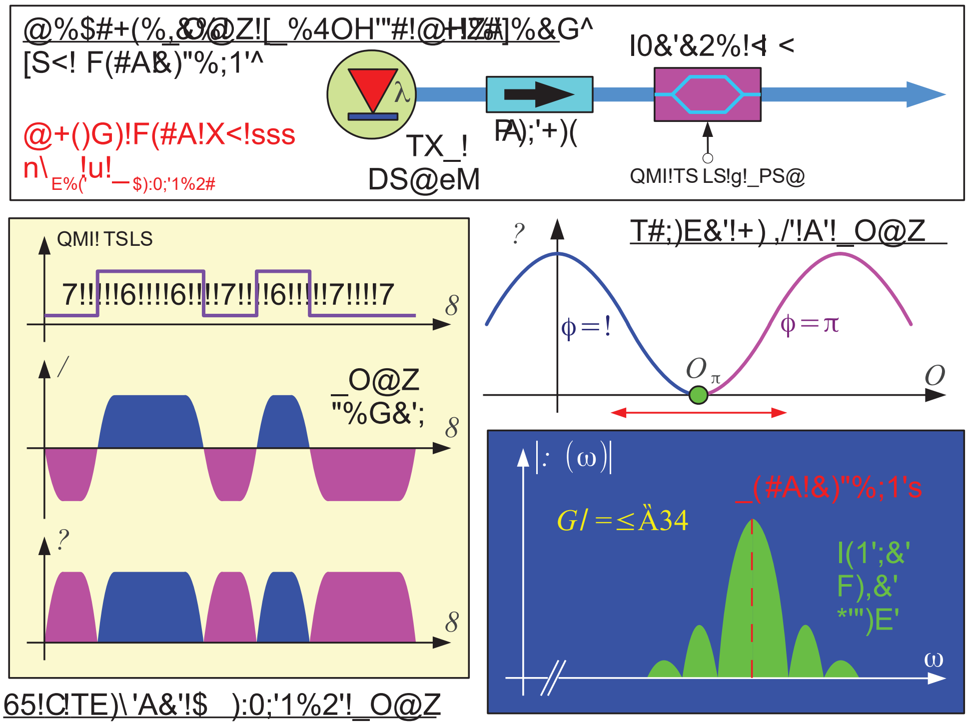

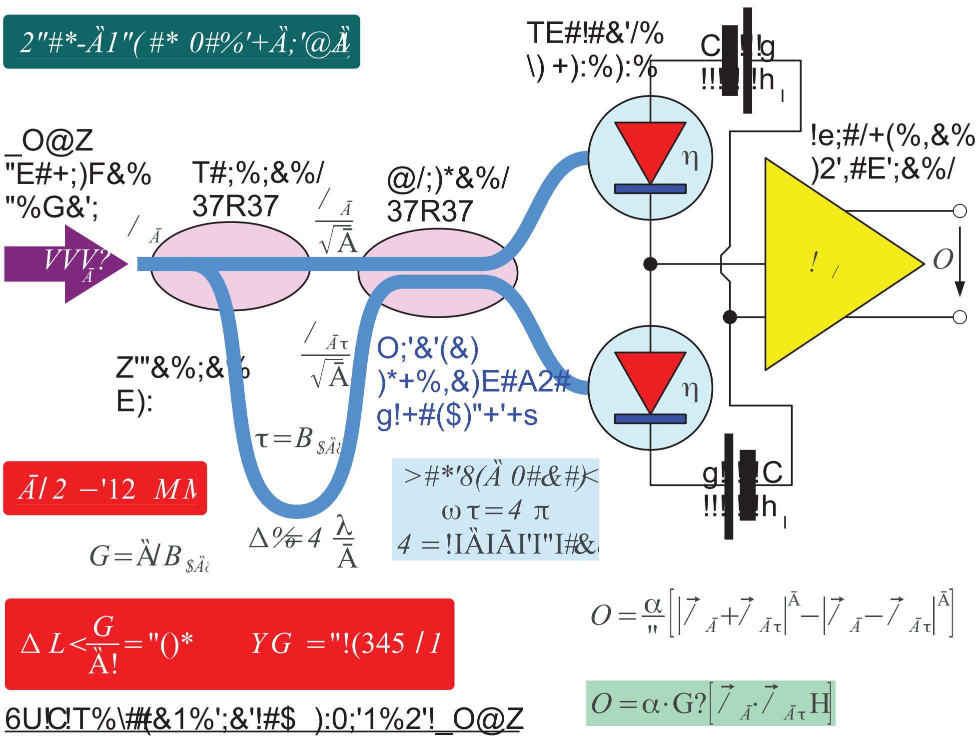

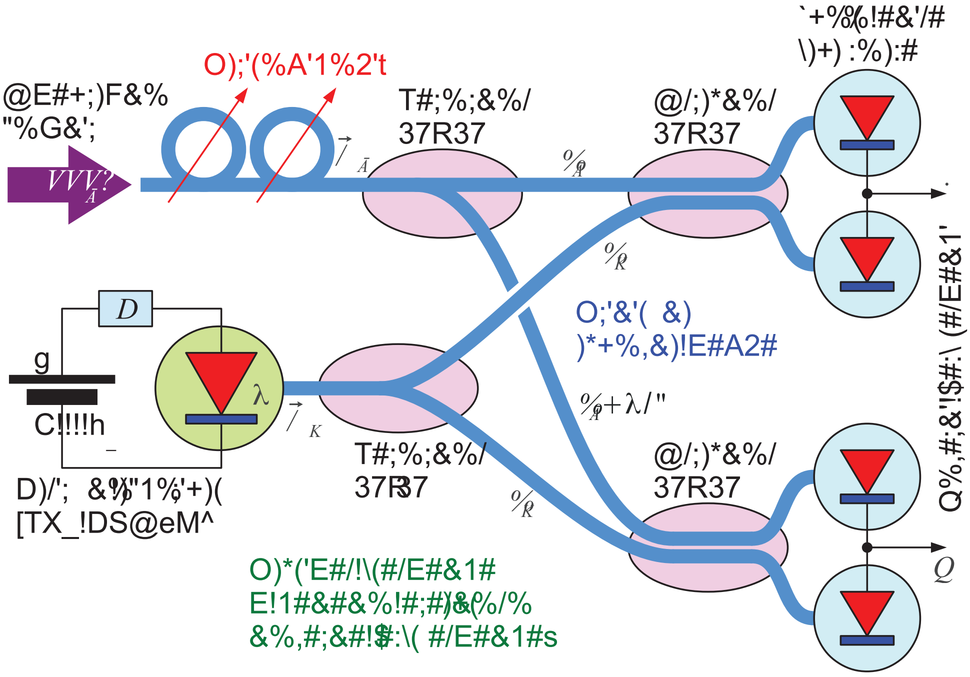

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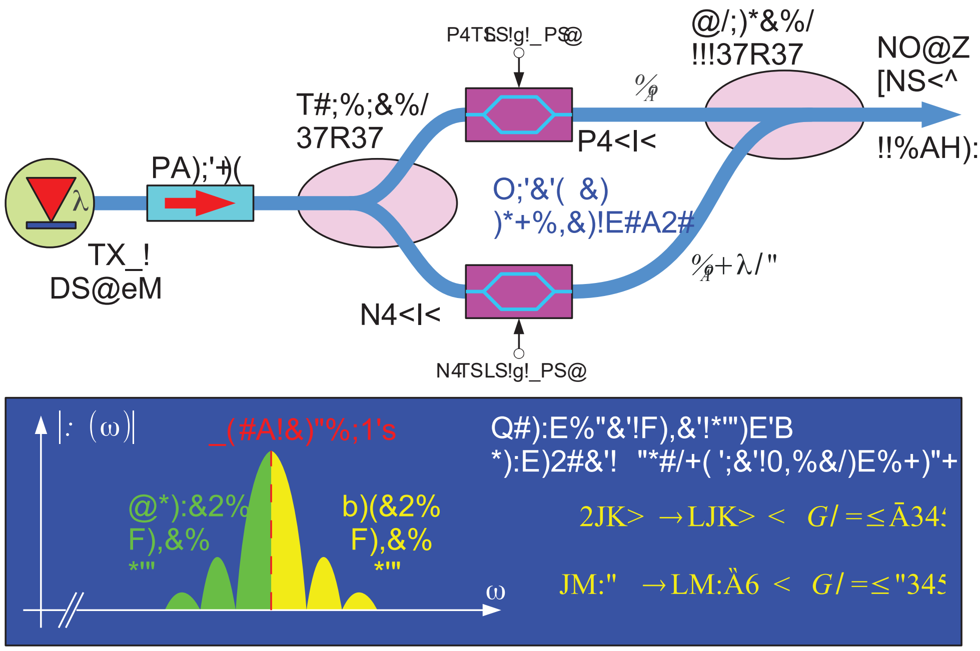

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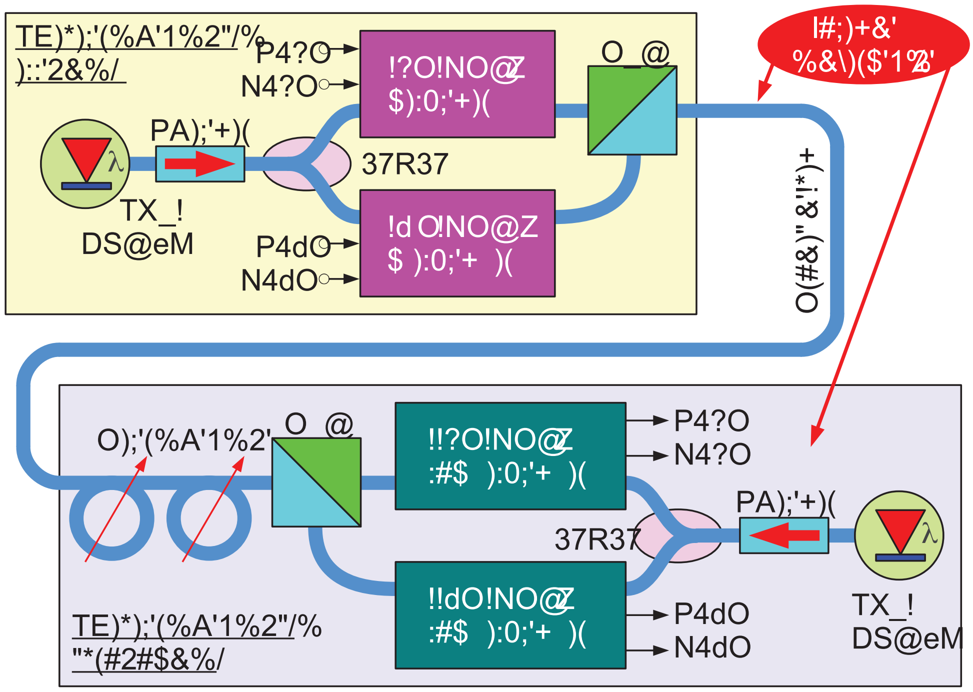

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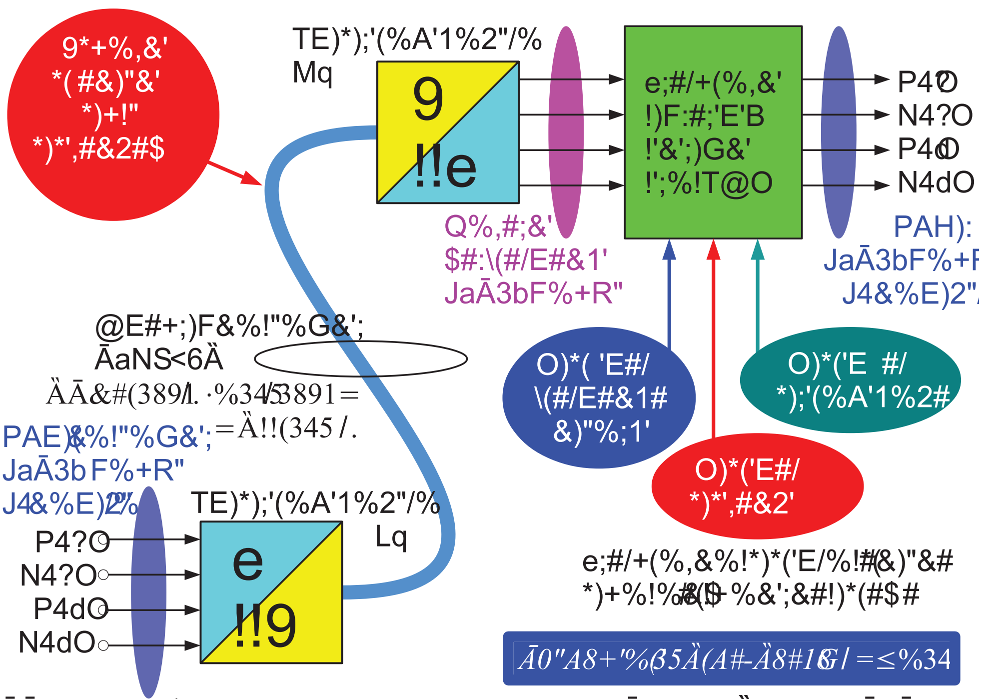

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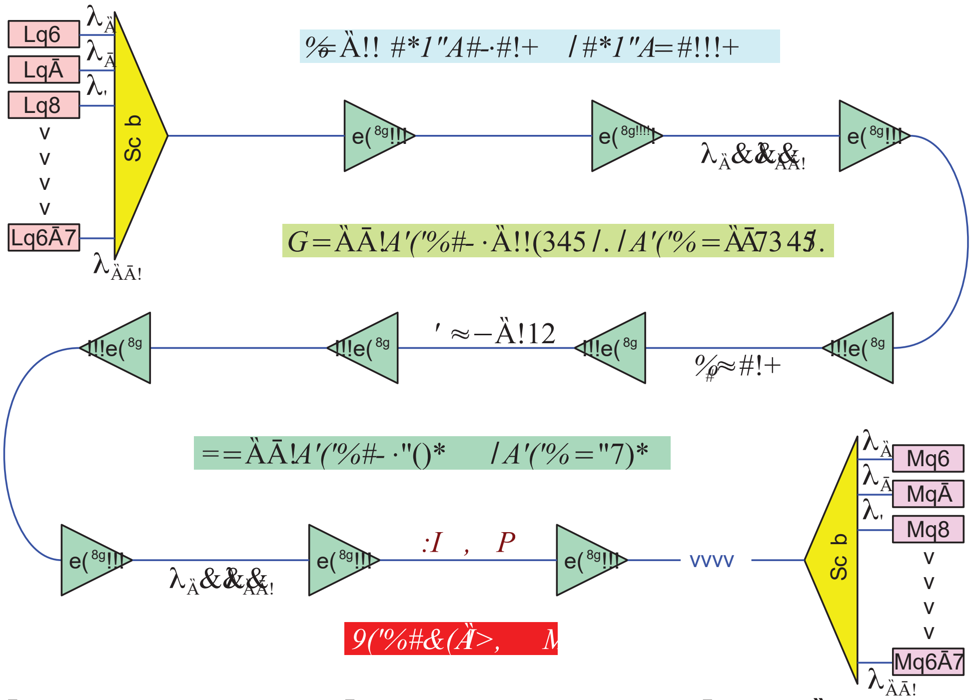

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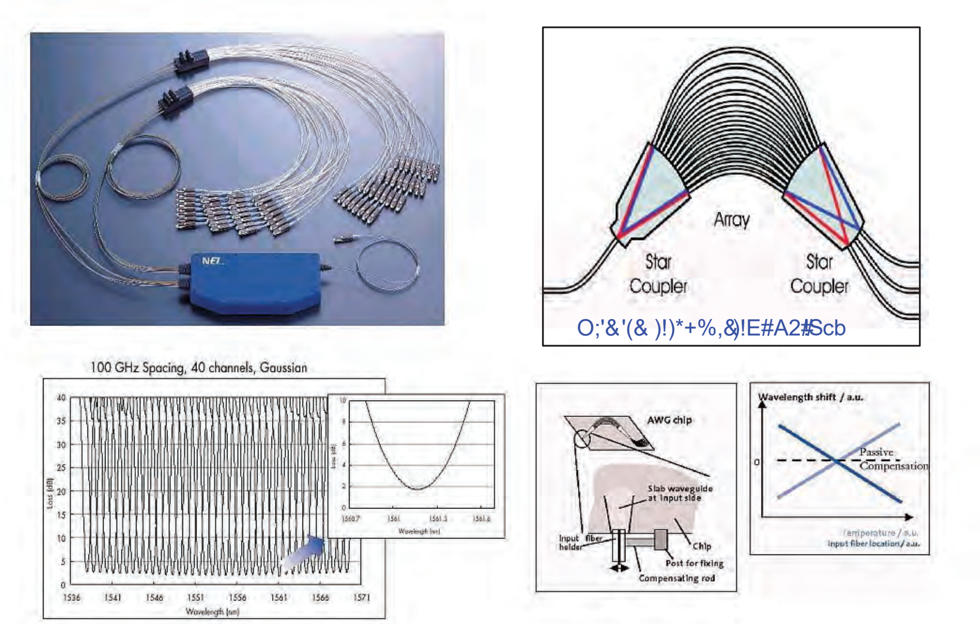

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Vloga OTN distribuiranih prevezovalnikov v regionalnih komunikacijskih omrežjih

The role of OTN distributed cross-connects in regional communication networks

Klaus Samardžić

Smart Com

klaus.samardzic@smart-com.si

Povzetek

Prvotni protokoli za optična transportna omrežja G.798 "Characteristics of Optical Transport Network hierarchy equipment functional blocks" so bili definirani na začetku tega stoletja in so imeli vidno vlogo pri arhitekturah sodobnih transportnih omrežjih, v katerih se uporablja valovno multipleksiranje optičnih signalov – WDM (Wavelength Division Multiplexing). Pri tem je bila osrednja arhitektura transportnih omrežij optično procesiranje signalov in ROADM (Reconfigurable Optical Add Drop Multiplexer). Možnosti uporabe OTN prevezovalnikov elektronskih signalov so bile omejene. Linijski signal z nekoherentnim načinom prenosa je bil omejen na hitrost 10 Gbit/s in ni omogočal smiselnih OTN gradbenih elementov za izvedbo prilagodljivega transportnega omrežja. Z vpeljavo linijskih signalov s koherentnim načinom prenosa in hitrostmi 400 Gbit/s in 800 Gbit/s je bilo omogočeno prenašanje uporabniških signalov s hitrostmi od 1 Gbit/s do 400 Gbit/s. Protokoli za OTN-omrežja so danes prilagojeni za učinkovit prenos signalov različnih oblik, kot so Ethernet, Fibre Channel in Common Public Radio Interface (CPRI). Implementacija agregacije, multipleksiranja in prevezovanja elektronskih signalov v OTN-arhitekturah omogoča graditev učinkovitih in prilagodljivih omrežij. Prispevek obravnava gradbene elemente in poda zgled možne arhitekture regionalnega omrežja v Sloveniji, z uporabo OTN-distribuiranih prevezovalnikov.

Abstract

Optical transport networks protocols described in G.798 "Characteristics of Optical Transport Network hierarchy equipment functional blocks" were defined at the beginning of this century and played a prominent role in the architectures of modern transport networks in which wave multiplexing of optical signals - WDM (Wavelength Division Multiplexing) is used. Architectures of transport networks were based on optical signal processing and ROADM (Reconfigurable Optical Add Drop Multiplexer). Possibilities of using OTN cross-connects for electronic signals processing were limited. The line signal using a non-coherent transmission mode was limited to a speed of 10 Gbit/s and did not allow meaningful OTN building blocks for the implementation of flexible transport networks. By introducing line signals using a coherent transmission mode and speeds of 400 Gbit/s and 800 Gbit/s, it is possible to transmit user signals from 1 Gbit/s to 400 Gbit/s. Protocols for OTN networks today are adapted to efficiently transmit signals of various formats, such as Ethernet, Fiber

Channel and Common Public Radio Interface (CPRI). The implementation of aggregation, multiplexing and cross-connection of electronic signals in OTN-architectures enables the implementation of efficient and flexible networks. The paper discusses the building elements and gives an example of a possible architecture of a regional network in Slovenia, using OTN-distributed cross-connects.

Biografija avtorja

Klaus Samardžić ima tridesetletne izkušnje pri razvoju in implementaciji komunikacijskih sistemov. Prvih deset let je sodeloval ali vodil razvoj komunikacijskih sistemov. V podjetju Fotona, takrat uveljavljenemu podjetju na področju optičnih sistemov, je sodeloval pri razvoju komunikacijskega sistema za prenos po optičnih vlaknih, ki je bil uspešno implementiran v Sloveniji in Sovjetski zvezi. V podjetju Smart Com, vodilnem sistemskem integratorju, že dvajset let sodeluje pri realizaciji komunikacijskih omrežij, z implementacijo optičnih in radijskih komunikacijskih sistemov v Sloveniji in na območju Jadranske regije. Kot pooblaščeni inženir Inženirske Zbornice Slovenije, z izkušnjami pri realizaciji projektov, ima vpogled v vse faze življenjskega cikla projekta, od načrtovanja, izvedbe in preizkusa sprejemljivosti do prehoda v operativno fazo. Takšne izkušnje mu omogočajo razumevanje potreb operaterjev komunikacijskih omrežij in želja uporabnikov komunikacijskih storitev. Razumevanje potreb vseh vpletenih strani mu pride prav pri sodelovanju v tržnih dejavnostih ali pri evaluaciji prihodnjega razvoja komunikacijskih storitev.

Author's biography

Klaus Samardžić has thirty years of experience in the development and implementation of communication systems. The first ten years he has participated or led the development of communication systems. In Fotona, at that time an established vendor of optical systems he colaborated in development of an optical fiber communication system and its successfull implementation in Slovenia and the Soviet Union. In Smart Com, a leading system integrator he has been involved in the realization of communication networks, implementing optical and radio communication systems in Slovenia and the Adriatic region for twenty years. As a Certified and Authorized Engineer for electrical engineering in civil works at Engineering Chamber of Slovenia with experience in the realization of communication networks projects he has insight into all phases of the project life cycle, from planning, implementation and acceptance testing to the transition into the operational phase. Such experiences allows him to understand the demands of communication networks operators and wishes of communication services users. When participating in marketing activities or evaluating the future development of provisioning communication services such understanding of the demands and wishes gives him the opportunity to offer solutions of mutual benefits for all involved parties.

Uvod

Pri snovanju in implementaciji komunikacijskih omrežjih so dva ključna faktorja obseg in čas. Pomen obsega omrežja je lahko razumljiv, za razumevanje aspekta časa je potrebno nekaj izkušenj pri snovanju omrežij. Po enem desetletju ali več snovalcu omrežja postane razumljiv utrip časa in dejstvo, da se vsako novo omrežje gradi za določen čas v odvisnosti od pomena, namena, obsega in uporabljene tehnologije. Verjetno se je večina tistih, ki gradijo lokalna (LAN- Local Area Network) podjetniška omrežja z uporabo protokolov IP/TCP (Internet Protocol / Transmission Control Protocol) že sprijaznila z dejstvom, da se oprema zamenja vsakih sedem let ali celo hitreje. Pri graditvi hrbteničnih transportnih omrežjih ponudnikov storitev ali večjih javnih podjetji, ki zagotavljajo kritično infrastrukturo družbe se pričakuje življenjska doba vsaj dvanajst let. Če bo življenjska doba daljša in je OpEx ustrezen se lastnik omrežja ne bo pritoževal. Ali bodo snovalci uspeli zagotoviti tehnično rešitev, ki bo omogočila učinkovito delovanje in optimalen CapEx (Capital Expenditures) ter OpEx (Operating Expenses) v daljšem času je v veliki meri odvisno od uporabe tehnološke rešitve, ki je že uveljavljena in obenem še dovolj 'sodobna'. Sodobnost določijo zahtevane komunikacijske storitve v omrežju in konkurenčne tehnološke rešitve. Komunikacijski terminalni vmesniki v hrbteničnih transportnih omrežij so že določen čas v največji meri omejeni na Ethernet, SDH (Synchronous Digital Hierarchy) in Fibre Channel protokole. SDH zaradi zgodovinskih razlogov, Fibre Channel kot niša pri povezovanju podatkovnih centrov in Ethernet kot vseprisotni vmesnik in prenosna tehnologija od računalnika, lokalnega omrežja do globalnega omrežja.

Na področju regionalnih omrežij za optično infrastrukturo je izbira konkurenčnih tehnoloških rešitev omejena. Standardizacija se na tem področju piše z veliko S in različne organizacije od ITU-T (International Telecommunication Union), … do OIF (Optical Internetworking Forum) določajo priporočila, ki jih industrija implementira skozi programske protokole in rešitve, integrirana vezja in ne nazadnje komunikacijske naprave.

Regionalna omrežja za optično infrastrukturo se že določen čas gradijo z uporabo treh slojev, ki spominjajo na sloje OSI modela: OTN– optično procesiranje signalov, OTN – električno procesiranje signalov in sloj IP usmerjanja. Pomen in funkcionalnosti na posameznih slojih so se v zadnjem desetletju večkrat spreminjali. Od uporabe vseh treh slojev do uporabe IPoWDM (Internet Protocol over Wavelength Division Multiplexing). Kaj je v določenem trenutku najbolj aktualno je odvisno od matrike vektorjev vpliva od proizvajalcev opreme, ki forsirajo svoje tehnološke rešitve do uporabnikov omrežij, ki bi radi imeli in uporabljali omrežje z obvladljivo kompleksnostjo.

Omenimo zanimiv časovni aspekt, tako imenovani časovni zamik (time lag). Optimalna tehnološka rešitev v določenem trenutku se bo začela upoštevati pri snovanju in implementaciji omrežij s časovnim zamikom, ki jer posledica inercije udeleženih od organizacij za standardizacijo, proizvajalcev podsklopov in programskih rešitev do proizvajalcev komunikacijske opreme in ne nazadnje zavedanja snovalcev omrežji o možnosti določenih rešitev. Prispevek, ki ga ravno berete naj bi prispeval k zmanjšanju časovnega zamika - inercije pri snovalcih in uporabnikih omrežij.

OTN – Optično transportno omrežje

O 5G omrežjih za mobilne uporabnike, Wi-Fi 6 in podobnih tehnologijah je slišal marsikdo saj gre za tehnologije s katerimi se srečujejo uporabniki. Če se omeni SDH (Synchronous Digital Hierarchy) bo vedelo kaj povedani samo izbrano število inženirjev, ki so delali za omrežne operaterje in so se ukvarjali s transportnimi omrežji za povezovanje digitalnih telefonskih central (se spomnite, tovariši). SDH rešitve in omrežja so preživela ISDN (Integrated Services over Digital Network) in podobne 'push' tehnologije in svojo napovedano 'prekinitev uporabe' za kar nekaj desetletij. Iz tega se lahko snovalec omrežji nauči pomembnega dejstva. Ni osebe s 'kristalno kroglo', ki lahko napove bodočnost. Bodočnost je vedno nepredvidljiva vsaj je odvisna od aktivnosti množice udeleženih. SDH transportni sistemi so zagotavljali prenos optičnega signala na dolge razdalje, multipleksiranje in prevezovanje hierarhije (155,52 Mbit/s – 9953,28 Mbit/s) linijskih električnih signalov in s tem fleksibilnost transportnega omrežja. Uporabniški signal je večinoma bil 2048 Kbit/s iz priključene digitalne telefonske centrale. Prenos signala je bil determinističen kar pomeni, da ni bilo potrebno izmišljati si 'zlato', 'srebrno' ali 'brončno' klaso pri zagotavljanju kvalitete prenosa, kot smo postali vajeni pri omrežjih, ki uporabljajo statistično multipleksiranje. Vsi uporabniški signali so imeli zagotovljeni prenosni kanal v linijskem signalu.

Zakaj je bilo potrebno določiti novo tehnologijo in transportno hierarhijo? Podatkovni promet je doživel izjemen razvoj in povezovanje lokalnih IP/TCP omrežjih ter uporabnikov s strežniki v Internet omrežju je zahtevalo novo arhitekturo in lastnosti omrežja. Podatkovni promet je za razliko od digitaliziranega govornega prometa asimetričen. Osnovi protokol vmesnikov terminalnih naprav je Ethernet in SDH ni bila optimalna rešitev.

Priporočila za optična transportna omrežja G.798 "Characteristics of Optical Transport Network hierarchy equipment functional blocks" so bili definirani na začetku tega stoletja in so imeli vidno vlogo pri arhitekturah sodobnih transportnih omrežjih, v katerih se uporablja valovno multipleksiranje optičnih signalov – WDM (Wavelength Division Multiplexing). Na začetku so se uporabljali linijski signal z nekoherentnim načinom prenosa in je hitrost bila omejen na 10 Gbit/s. OTN priporočila so se uporabljala pri linijskih vmesnikih na modulih WDM transportnih omrežjih – 'transponders' in 'muxponders'. Se pravi enostavnih gradbenih blokov, ki so signal terminalne naprave ovili v OTN okvir, ki je zagotavljal dolge razdalje prenosa, korekcijo napak (FEC – Forward Error Correction), ločeni nadzorni kanal za zagotavljanje nadzora delovanja sistema in tudi multipleksiranje uporabniških signalov v 10 Gbit/s linijski signal. V novi različici priporočil, ki je bila oznanjena leta 2009 je OTN bil prilagojen za Ethernet signale.

Funkcija multipleksiranja v transportnem omrežju je hitro postala nepomembna saj so operaterska Ethernet stikala (Carrier Ethernet Switches) in hrbtenični usmerniki vsebovali 10 Gbit/s Ethernet vmesnike.

V takšnem okolju se je kot OTN vodilni transportni sistem uveljavila arhitektura, ki je omogočala prenos čim več optičnih kanalov in optično prevezovanje v ROADM vozliščih. Sistem z recimo 48 optičnimi kanali z optičnimi signali 10 Gbit/s je zagotavljal 480 Gbit/s kapaciteto. Industija je napredek videla v večjem številu optičnih kanalov; recimo 96 kar je pomenilo 960 Gbit/s. Optični signali se prenašajo od enega do drugega konca omrežja in vmesno multipleksiranje ali prevezovanje linijskih signalov je omejeno s ceno in kompleksnostjo možnih rešitev.

Pri Nortel-u (danes Ciena) so na osnovi novih DSP (Digital Signal Processing) integriranih vezjih uspeli razviti koherenten način prenosa optičnega signala pri katerem se za modulacijo nosilnega signala uporablja razen amplitudne tudi fazna in polarizacijska modulacija. Naenkrat je bilo možno prenašati linijski signal 100 Gbit/s. In ko je enkrat princip znan je hiter razvoj odvisen samo od razvoja digitalnih integrirani vezij (Moore's law) in imaginacije snovalcev. Danes vodilna podjetja na področju razvoja integriranih vezjih in transportnih komunikacijskih sistemov ponujajo možnost snovanja omrežji z 800 Gbit/s linijskimi signali. Takšna kapaciteta enega linijskega signal je podobna kapaciteti prenosa z 96 optičnimi kanali z linijskimi signali hitrosti 10 Gbit/s.

Z razvojem digitalnih integriranih vezij je postalo možno tudi učinkovito multipleksiranje in prevezovanje OTN signalnih okvirjev na različnih nivojih hierarhije od 1 Gbit/s do 400 Gbit/s. Z možnostjo uporabe novih funkcionalnosti in gradbenih sklopov na nivoju OTN procesiranja električnega signala se postavi vprašanje smiselnosti uporabe ROADM rešitev v regionalnih omrežjih v recimo Sloveniji. Obenem se postavi vprašanje uporabe statističnega multipleksirana kot funkcionalnost v transportnih omrežjih. Seveda bo vsak uporabnik imel možnost določiti obseg statističnega multipleksiranja signalov znotraj svojega omrežja in najetih kapacitet v transportnem omrežju ampak transportno omrežje, ki zagotavlja kapacitete linijskih signalov N x 400 Gbit/s ali N x 800 Gbit/s lahko ponudi tudi zagotovljeno kapaciteto prenosa kar predstavlja najbolj enostaven in predvsem zanesljiv način zagotavljanja kvalitete prenosa.

V tem prispevku ni časa za obravnavo vseh možnih prijemov pri procesiranju Ethernet okvirjev in IP paketov na vhodu (policing) in izhodu (shaping) iz vmesnika naprav, ki zagotavljajo statistično multipleksiranje (Ethernet stikalo ali IP usmernik(). Bistveno je, da vsi ti prijemi poskušajo zagotoviti kvaliteto pri največjem obsegu prometnih tokov ne pa deterministično. Enostavna primerjava za tiste, ki nimajo časa spuščati se v detajle je naslednja. Če je optično procesiranja in prenos v omrežjih z ROADM funkcionalnostjo podobno potovanju z vlakom (European High-Speed Trains), in so omrežja z uporabo statističnega multipleksiranja podobna potovanju z avtobusom je uporaba omrežji z OTN električnim multipleksiranjem in prevezovanje podobna potovanju z avtom (upravljanje je določeno s centralnim nadzornim sistemom).

Na začetku tega prispevka smo omenili, da arhitekturo in tehnologijo transportnega omrežja v veliki meri določijo storitve uporabnika. Najbolj pomemben in vpliven uporabnik transportnega omrežja danes je 5G RAN (Radio Access Network) omrežje. Omrežje 5G ne more zaživeti brez sodobnega transportnega omrežja. In kaj so zahteve? Čim manjša zakasnitev signala, prilagodljivost prometnim tokom in zagotovljena kvaliteta prenosa signala. V prispevku z naslovom 'Optična transportna omrežja z linijskimi kapacitetami za mobilna omrežja 5G' objavljenem na seminarju http://sok.fe.uni-lj.si/2021/glavna.php so prikazane zahteve in podane rešitve za 5G dostopovna omrežja.

Katere so prednosti OTN?

Omogočajo graditev omrežij z lastnostmi, ki jih zahteva večina sodobnih storitev.

Učinkovita uporaba optičnega spektra. Večina uporabniških signalov v transportnih omrežjih je danes 1 Gbit/s, 10 Gbit/s ali 100 Gbit/s. Z vpeljavo 5G RAN omrežij se bo pojavila zahteva po prenosu 25 Gbit/s ali 50 Gbit/s. V primeru linijskega signala 400 Gbit/s, ki zasede eno optično valovno dolžino je smiselno čim bolj izkoristiti kapaciteto, ki je na razpolago. OTN priporočila omogočajo uporabo ODUflex načina multipleksiranja uporabniških signalov.

Vsebovana (inherentna) varnost signalov, ki se prenašajo. Varnost je zagotovljena s prenosom v posebnih kontejnerjih. Ni potrebe po dodatnem programskem generiranju dodatnih oznak signala ali kreiranju 'tunelov'. Nadzorni kanal je ločen od uporabniškega prometa.

Determinističen prenos signalov. Vsak uporabniški signal ima zagotovljeno kapaciteto prenosa skozi omrežje, ki ni odvisna od trenutnega stanja prometa v omrežju. V transportnih omrežjih javnih podjetji, ki zagotavljajo kritično infrastrukturo družbe, kot je to recimo Elektrogospodarstvo je od izrednega pomena zanesljivost prenosa ustreznega signala, recimo pri zagotavljanju zaščite daljnovodov. Pri ponudnikih omrežnih storitev je v odvisnosti od SLA (Service Level Agreement), ki je določen za uporabnika možno ponujati 'premium' storitev z zagotovljeno kapaciteto prenosa.

Virtualizacija omrežnega delovanja. V tem primeru se določene kapacitete prenosa v omrežju dodelijo posameznim uporabnikom tako, kot je to na primer pri 'network slicing' omrežja za različne storitve v 5G omrežju.

In ne nazadnje fleksibilnost omrežja, ki omogoča različne prometne matrike znotraj fizičnega omrežja in omogoča povezovanje poljubnih lokacij v omrežju z zahtevano kapaciteto prenosa znotraj linijskega signala.

Predlog arhitekture regionalnega transportnega omrežja, ki danes vsebuje vse lastnosti, da lahko obratuje več, kot deset let s sprejemljivim CapEx in OpEx je podan v treh slojih.

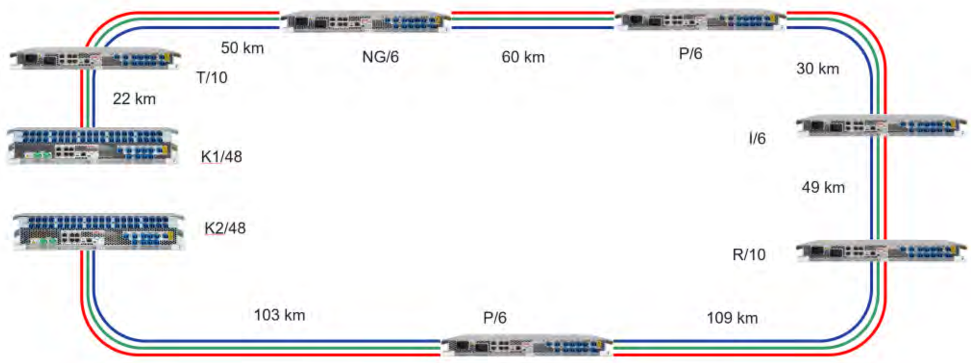
Arhitektura transportnega omrežja na sloju optičnega signala

Z vpeljavo linijskih signalov s koherentnim načinom prenosa in hitrostmi 400 Gbit/s in 800 Gbit/s je bilo omogočeno prenašanje uporabniških signalov s hitrostmi od 1 Gbit/s do 400 Gbit/s. Implementacija agregacije, multipleksiranja in prevezovanja elektronskih signalov v OTN-arhitekturah omogoča graditev učinkovitih in prilagodljivih omrežij. Arhitektura transportnih omrežij za optično procesiranje signalov, ki vsebuje ROADM (Reconfigurable Optical Add Drop Multiplexer) je pri tem odvečna v večini regionalnih omrežjih v Sloveniji. Dodatna možnost prilagodljivega usmerjanja optičnih signalov ne opraviči zahtevnost vzpostavitve in nadzora storitev v omrežju na več nivojih. Za regionalna omrežja predlagam uporabo odprtega WDM transportnega sistema s funkcionalnostjo na optičnem sloju. 'Odprt' optični transportni sistem pomeni, da se lahko priključijo optični signali iz naprav različnih proizvajalcev v primeru, da so ustrezne kvalitete. Največje število optičnih kanalov naj bi bilo 48. Na posameznih lokacijah se vgrajujejo optični filtra s 6 do 10 optičnih kanalov. V zbirnih vozliščih je na razpolago do 48 optičnih kanalov. Razdalja med vozlišči je z optičnimi parametri omejena na 80 do 110 km. Takšne razdalje u sistemu zadostujejo saj so bolj stroge nove zahteve do zakasnitev signala, ki so pri recimo 5G omrežij izredno zahtevne. Zaradi naravnih zakonov svetloba v optičnem vlaknu potuje 1,5 krat počasneje, kot v vakumu in potrebuje 5 µs za en kilometer.

Vrsta omrežja – storitve v 5G omrežju	Dovoljena zakasnitev signala	Vir priporočila
Mobile terminal – CU eMBB	4 ms	3GPP TR38.913
Mobile terminal – CU uRLLC	0,5 ms	3GPP TR38.913
Enhanced vehicle to everything Ev2x	3 – 10 ms	3GPP TR38.913
Fronthaul latency AAU-DU	100 µs	eCPRI

Tabela 1. Dovoljene zakasnitve v 5G omrežju mobilnih uporabnikov

S predlagano arhitekturo je možno implementirati podvojena HAB - zvezda vozlišča. Možno je graditi topologije za 4 do 8 optičnih vozlišč. Topologija naj bi omogočala prenos storitev - optičnih kanalov od vhoda do izhoda omrežja. Možna naj bi bila tudi povezljivost med posameznimi vozlišči. Sama vozlišča se lahko realizira z ločenimi funkcijski moduli (optični filtri, optični ojačevalniki, optični servisni kanal…) ali z že integrirano napravo, ki z uporabo ustrezne nadzorne opreme SDN (Software Defined Network) omogoča enostavno postavitev sistema, popoln nadzor prilagajanja optičnih nivojev in nastavitve delovanja. Uporaba standardnih gradbenih blokov in enotni nadzor omogoča zanesljivo delovanje in pregled nad stanjem optičnega omrežja v vsakem trenutku obratovanja.



Slika 1. Ciena platforma ELS za realizacijo odprtega L0 – WDM sistema

OTN arhitektura transportnega omrežja na sloju električnega signala

OTN procesiranje električnega signala omogoča graditev učinkovitih in prilagodljivih omrežij. Varnost prometa v omrežju in majhne zakasnitve signala so od velikega pomena. OTN pri teh dveh ključnih parametrih ima prednost pred procesiranjem signala na višjih slojih OSI sistema.

Tradicionalna enkapsulacija ODUk (Optical Data Unit) ima določeno standardno zmogljivost. Storitve majhne kapacitete so lahko enkapsulirane v prenosne kanale velike kapacitete. Posledica tega je zapravljanje omrežnih virov. Tehnologija prilagodljive pasovne širine pri kateri se uporablja ODU s prilagodljivo hitrostjo, znan kot ODUflex, lahko prilagaja razpon pasovnih širin kanala od 1,25 Gbit/s do 100 Gbit/s. Značilnosti takšnega prenosa je učinkovito izkoriščanje kapacitet OTN omrežja. ODUflex zagotavlja mehanizme prilagajanja kapacitete, s katerimi lahko uporabniki prilagodljivo konfigurirajo kapaciteto kontejnerja, v odvisnosti od obsega prometa storitev, tako da je mogoče učinkovito uporabiti pasovno širino in zmanjšati stroške prenosa. Storitve v dostopnem delu omrežji, kot so 5G in storitve zasebne linije, se spreminjajo skozi čas. Zato je potrebno prilagoditi kapaciteto prenosa brez izgube podatkov na podlagi dejanske pasovne širine storitve. V tem primeru se uporablja ITU-T Hitless Adjustment protocol ODUflex (G.HAO). Dinamično se dodeli N časovnih kanalov za ODUflex na podlagi kapacitete dostopovne storitve in nato preslika signal ODUflex v kanal ODU višjega reda. Če se kapaciteta dostopovne storitve spremeni, nadzorni sistem (Network Management System) prilagodi število dodeljenih časovnih kanalov, za vsa mesta med vhodom in izhodom iz omrežja z uporabo G.HAO. Na ta način se kapaciteta ODUflex dinamično prilagaja kapaciteti storitve. Posamezni uporabniški signali so enkapsulirani znotraj ODU ali ODUflex kontejnerja in ne omogočajo dostop iz kontejnerja enega uporabnika do kontejnerja drugega uporabnika. ODUflex se uporablja za različne vrste obstoječih storitev podatkovnih signalov, in je združljiv z zahtevami prenosa novih IP storitev. Pri ponujanju storitev v 5G omrežjih je postavljena zahteva po razdelitvi omrežja v omrežne segmente (network slices). Uporaba ODUflex omogoča učinkovito in naravno izolacijo posameznih omrežnih segmentov.

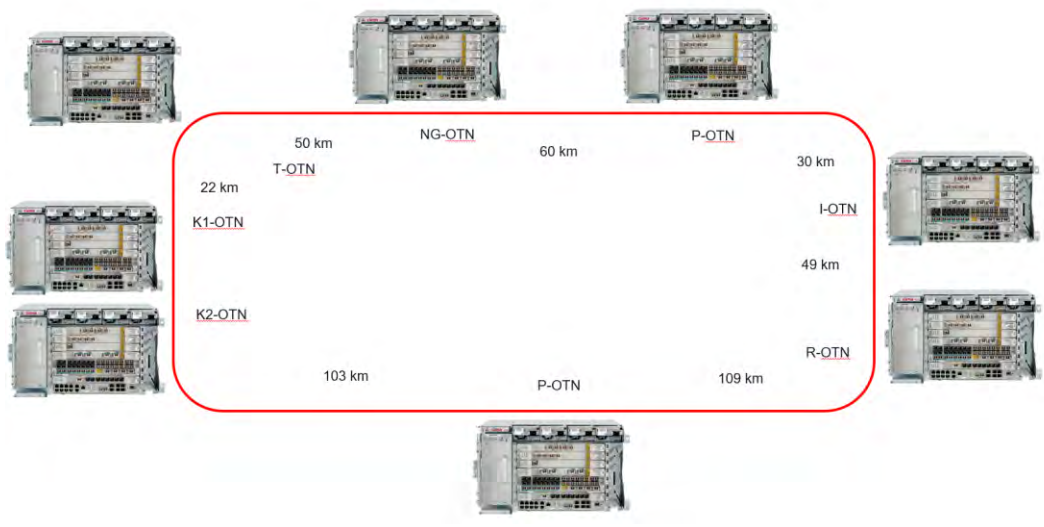
Tehnologija prenosa OTN zagotavlja izjemno nizko zakasnitvijo električnega signala. Zakasnitev enega vozlišča komercialne OTN opreme v sodobnih omrežjih je na splošno med 10 µs in 20 µs. Glavni razlog za to je, da je dodanih veliko nepotrebnih korakov preslikave in različnih scenarijev enkapsulacije storitev, kar močno poveča zakasnitev. Optimizacijo je mogoče izvesti na podlagi dejanskih zahtev. Zakasnitev enega vozlišča OTN naprave s posebno nizko zakasnitvijo lahko doseže raven 1 µs.

Naslednje metode se lahko uporablja za optimizacijo zakasnitev obstoječih naprav:

Optimizacija prenosnega kanala enkapsulacije v posebnih scenarijih. Trenutno OTN uporablja prenosne kanale hitrosti 1,25 Git/s. Na primer, uporabniška storitev Ethernet 25 Gbit/s je na vhodu razdeljena na 20 kanalov za prenos. Na izhodu se združijo signali 20 kanalov, da se obnovi izvirna storitev. Procesi delitev in združitve signala povzročajo visoko zakasnitev (približno 5 µs). Če se kanal prenosa poveča na 5 Gbit/s, se postopek demultipleksiranja poenostavi, zakasnitev se zmanjša na 1,2 µs.

Poenostavi se pot preslikave in enkapsulacije. V običajnem OTN postopku morajo Ethernet storitve opraviti vmesni generični postopek okvirjanja (GFP - Generic Framing Procedure) enkapsulacijo in obdelavo medpomnilnika ter se nato naložijo v ODUflex kontejner. Na OTU liniji signal gre skozi medpomnilnik in serijsko-vzporedna pretvorbo signala. Obenem se opravi filtriranje tresenja (jitter) signala časa. Skupna zakasnitev se poveča zaradi uvedbe medpomnilnika in večplastne preslikave ter enkapsulacije. V načinu preslikave celic (cell mapping) naslednje generacije se na podlagi kapacitete storitve izvaja urejanje vsebine prenosnih kanalov za enkapsulacijo se uporabljajo fiksni kontejnerji. S tem se zmanjša zakasnitev signala.

OTN podpira eno nivojsko multipleksiranje in več nivojsko multipleksiranje. Poenostavi se preslikava v ODU kontejner in pot multipleksiranja. Teoretično se latenca poveča za 518 ns po eni dodani stopnji multipleksiranja. Eno nivojsko multipleksiranje se lahko uporabiti za zmanjšanje zakasnitve prenosa v OTN napravah. Za Gigabit Ethernet storitve, zakasnitev več nivojskega multipleksiranja (GE->ODU0->ODU2->ODU3->ODU4->OTU4) znaša približno 4,7 µs in pri eno nivojskem multipleksiranju direktno iz ODU0 v ODU4 je zakasnitev približno 2,3 µs.



Slika 2. Ciena platforma 6500 za realizacijo L1 OTN storitev

Distribuirani prevezovalniki omogočajo uporabo funkcionalnosti OTN na vseh vozlišč v omrežju. Na trgu so na razpolago namenska ohišja za OTN prevezovalnik ali moduli za OTN prevezovanje, ki se vgrajujejo v več funkcijska ohišja. Tokrat je izbran modul OTN prevezovalnika z matriko velikosti 1,2 Tbit/s kar omogoča dva linijska signala kapacitete 400 Gbit/s in dva linijska signala kapacitete 200 Gbit/s. Izbira uporabniških vmesnikov je od Ethernet 1, 10, 25, 50, 100 Gbit/s, do SDH STM-1 in STM-4 ter OTN OTU-2 in OTU-4. Nadgraditev na večje kapacitete prenosa je enostavna z dodajanjem OTN modulov v ohišje.

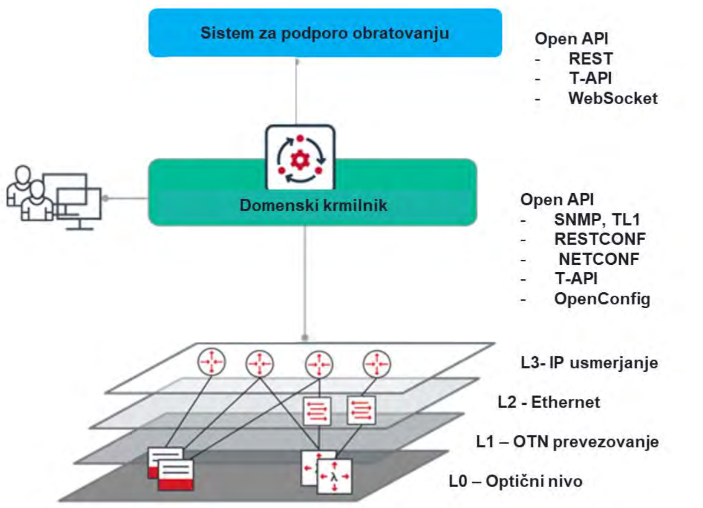
Omrežni sloj za procesiranje IP paketov

Pomen in funkcionalnosti enega od treh slojev so se v zadnjem desetletju večkrat spreminjali. Od uporabe vseh treh slojev do uporabe IPoWDM (Internet Protocol over Wavelength Division Multiplexing). Argumentov za uporabo samo dveh slojev pri IPoWDM je kar nekaj. Zagovorniki takšne rešitve pogosto omenijo, da gre za poenostavljeno arhitekturo saj so se znebili enega sloja. Morda je naključje, da so se znebili sloja, ki bi lahko imel najbolj pomembno vlogo pri transportnih omrežjih. Naj še enkrat omenim dve ključne funkcionalnosti, ki naj bi jih transportno optično omrežje vsebovalo: multipleksiranje in prevezovanje signalov v digitalni hierarhiji. Brez OTN električnega sloja transportno omrežje tega ne zmore in je naslednji korak integracija sloja IP usmerjanja v integralno napravo. V bistvu gre za hrbtenični usmernik z linijskimi vmesniki visoke hitrosti. Tukaj se postavi vprašanje smiselnosti procesiranja posameznih IP paketov na modulu, ki zagotavlja linijsko kapaciteto recimo 400 Gbit/s. Pri tem gre za regionalno omrežje, pri katerem je statistika prometa za razliko od LAN omrežja predvidljiva in prometne poti določene s strani operaterja. S tem funkcija statističnega multipleksiranja zgubi na pomenu. Iz izkušenj vodilnih operaterjev je ugotovljeno, da večina prometa v tako realiziranem regionalnem omrežju poteka med linijskimi vmesniki. Kar pomeni, da je večina funkcionalnosti procesiranja signala IP usmernika paketov neuporabljena. V nekaterih hrbteničnih omrežjih, recimo 'backhaul' omrežja 5G je funkcionalnost IP usmerjanja nujna zaradi zagotovitve prilagodljivosti različnim storitvam. V 'midhaul' omrežju 5G zadostuje prilagodljivost, ki jo ponudi sodobna distribuirana OTN funkcionalnost.

V predlagani arhitekturi so funkcionalnosti na optičnem WDM sloju, OTN električnem sloju in sloju IP usmerjanja realizirani v ločenih napravah. Prvi pomembni argument za takšno razdelitev funkcionalnosti je naslednji. Smo priče hitremu spreminjanju protokolov, ki se uporabljajo v regionalnih IP omrežjih. Različne verzije Multiprotocol Label Switching – MPLS, od IP/MPLS, preko MPLS-TP(Transport Profile) do najbolj obetavne različice, ki uporablja Segment Routing na osnovi MPLS funkcionalnosti se uporabljajo v 5G omrežjih. 'Življenjsko okno' IP usmernikov je krajše kot 'življenjsko okno' transportnih naprav v optičnih regionalnih sistemih. Tehnologija WDM se najbolj počasi spreminja. Drugi argument je kibernetska varnost sistema. V napravah, ki uporabljajo IP pakete pri prenosu vedno obstaja možnost skritih 'vrat' ali poti za dostop do kritičnih funkcijskih blokov naprav iz omrežja.

Sodoben NMS kot nujni pogoj učinkovitega in zanesljivega delovanja omrežja

Lastniki omrežja, ki se uporablja za delovanje kritične infrastrukture ali so ponudniki javnih komunikacijskih storitev želijo poenostaviti, pospešiti in avtomatizirati omrežne postopke-procese. Nekateri proizvajalci komunikacijske opreme že imajo komunikacijske naprave na posameznih nivojih integrirane v centralni nadzorni sistem (Network Management System) in je možna sledljivost in kreiranje storitev iz enega NMS centra. V primeru izbire različnih proizvajalcev za naprave na različnih nivojih omrežja se naprave drugih proizvajalcev integrirajo v NMS sistem, ki je najbolj razvit. Danes so najbolj razviti nadzorni sistemi, ki uporabljajo Software-Defined Networking (SDN) z domenskim krmilnikom. Sodobni domenski krmilnik z večslojnim SDN nadzorom infrastrukture in storitev v kombinaciji z integriranim spletnim načrtovanjem in optimizacijo s pomočjo "ene same steklene plošče" GUI (Graphical User Interface) zagotavlja planiranje, nadzor, krmiljenje in konfiguracijo storitev v omrežju. Tako je mogoče operativne poteke dela od začetka do konca zaključiti izjemno učinkovito. Omrežnim operaterjem se ni treba učiti in iskati podatke po različnih orodjih za ločene tehnološke plasti omrežja. Sodoben SDN center zagotavlja enoten pogled na optično, optično transportno (OTN) in IP usmerniško omrežje. Omogočeno je kreiranje



Slika 3. SDN nadzorni sistem za integralni nadzor storitev v omrežju

Sklep

Podana je rešitev regionalnega transportnega omrežja, ki se lahko prilagaja pomenu, namenu in obsegu omrežja skozi čas. To je doseženo z ločenimi gradbenimi elementi za posamezne OSI (Open Systems Interconnection model) nivoje. Poudarek je na uporabi funkcionalnost na nivoju OTN električnega procesiranja signala. V slovenskem prostoru ni potrebe po večji uporabi ROADM (Reconfigurable Optical Add Drop Multiplexer) elementov. S tem se poenostavi arhitektura na optičnem sloju omrežja in nadzor ter konfiguracija storitev na različnih nivojih OSI modela v omrežju. IP usmerniška funkcionalnost se uporabi v tistih segmentih omrežja kje je to optimalno. OTN tehnologija procesiranja elektronskega signala vsebuje funkcionalnosti, ki zagotovijo učinkovito in prilagodljivo ponujanje storitev v regionalnih transportnih omrežjih. Tehnologiji OTN v regionalnih omrežjih je zagotovljena prihodnost, saj omogoča varen, zanesljiv in učinkovit način za prenos velikih količin podatkov na velike razdalje. Prav tako je verjetno, da se bo tehnologija OTN sčasoma še naprej razvijala in izboljševala, v cilju prilagoditve sodobnim in novim komunikacijskim storitvam.

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https://www.oiforum.com

https://www.itu.int/en/ITU-T/Pages/default.aspx

https://www.3gpp.org

Next generation optical access networks, automation of testing procedures, complete visibility in QoE and QoS

Alfonso Domesi, Vratislav Blažek

EXFO

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Abstract

Each home, school, business, or customer has different requirements regarding upstream and downstream broadband speeds delivered over fiber—from essential to ultra-fast. Service providers are deploying both next-generation (XG-PON, XGS-PON, 10G-EPON, and NG-PON2) and legacy (GPON, EPON) passive optical technologies to provide the right requested speed by overlaying multiple new wavelengths on existing fibers. The coexistence of multiple services becomes challenging for field technicians because for each stage of the network lifecycle—deployment, activation, and troubleshooting—the correct tools and techniques can differ. Last but not least, automation and service monitoring are becoming more and more important as society is increasingly dependent on high-quality services. This session examines the latest trends in PON technologies and techniques for deploying and maintaining these fiber optic networks as efficiently as possible.

Authors' biography

Alfonso Domesi started his career in the telecommunications market in 1991 as a hardware and software development engineer. Over the years, he has tracked the evolution of transmission technologies, from the voice frequency analog modem to the current G.fast and optical fibers interfaces. He currently holds the position of EMEA Business Development Manager, with a dedicated focus on assessing new markets and technologies for EXFO's Physical Layer product portfolio.

Vratislav Blažek has international executive record of working for telco, multinational test and measurement solution and services companies and technology suppliers. His specialties are test & measurement, telco transport technologies, wireless 2G, 3G, LTE, IT software and service industry for technology suppliers in CEE, Russia & CIS Region. His current position is Regional Sales Manager at EXFO inc. for Eastern Europe, Russia & CIS. He finished Czech Technical University and received grade dipl. ing. in Telecommunication Engineering.


4G/
LTE
NEXT GEN OPTICAL
ACCESS
5G
Ljubljana, 26th January 2023
Vratislav Blazek
Regional Sales Manager
Alfonso Domesi
Business Development Manager - EMEA
SOK 2023
EXFO


The test,
monitoring
& analytics
experts
35+
years of pioneering essential solutions and technologies
100+
inventions protected by patents
No.1
in optical test solutions
1,900
employees in 25 countries and customers in 120 countries
250+
assurance systems deployed
95%+
of leading service providers using EXFO
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2


T&M portfolio
Intelligent and automated solutions
Lab, manufacturing and research
Physical layer field testing
Transport and datacom testing
Field test automation and software
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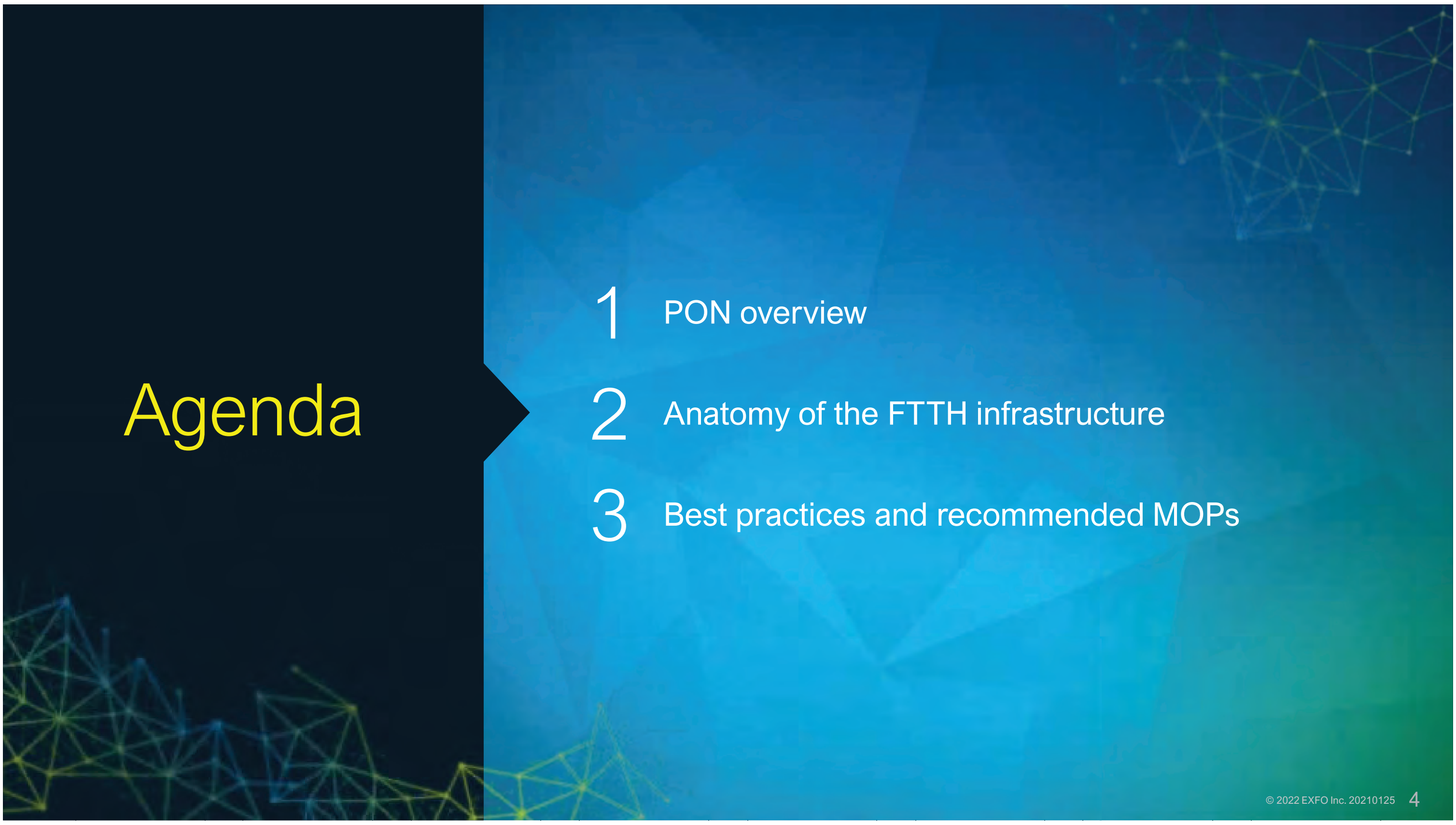
Agenda
1 PON overview
2 Anatomy of the FTTH infrastructure
3 Best practices and recommended MOPs
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PON overview
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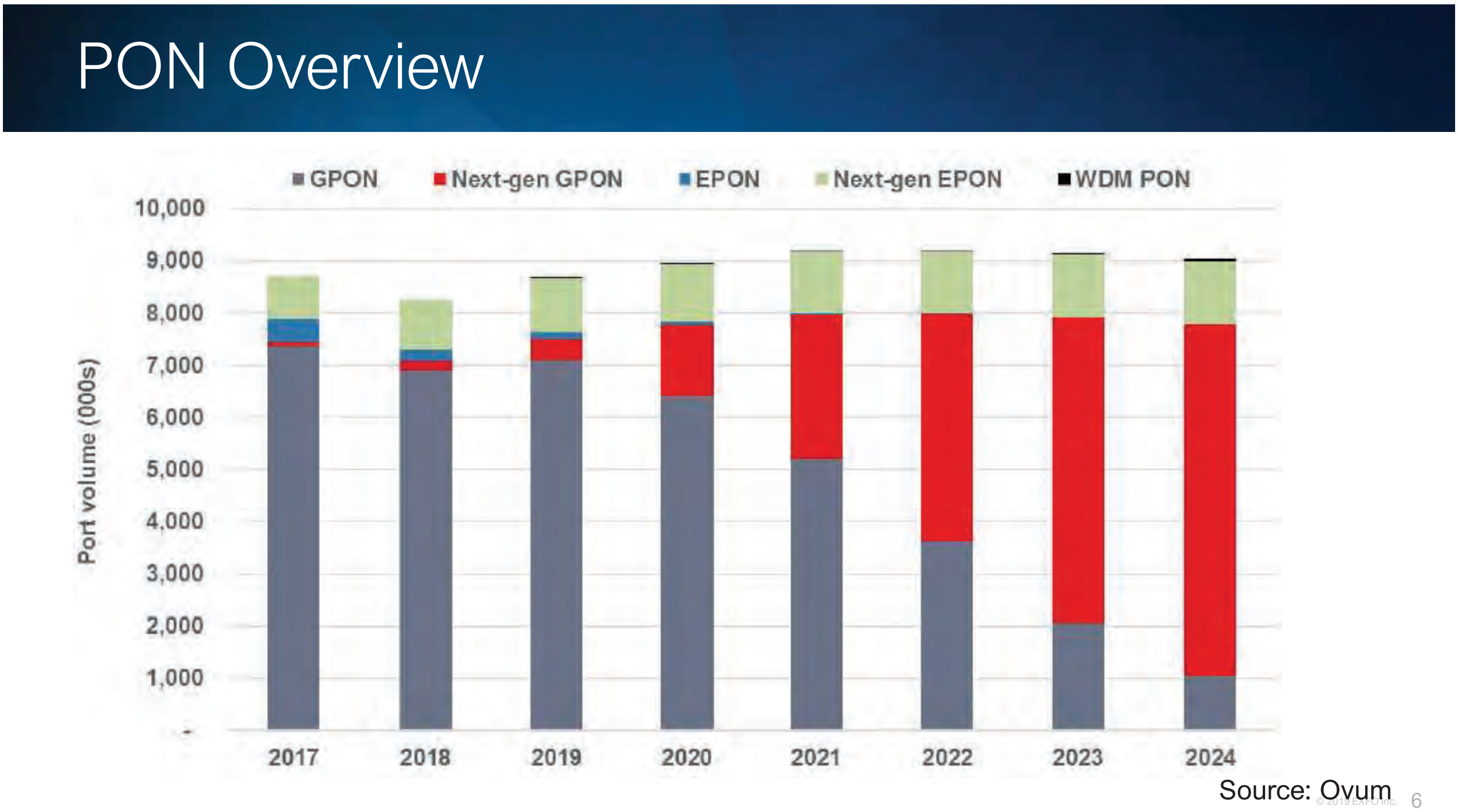
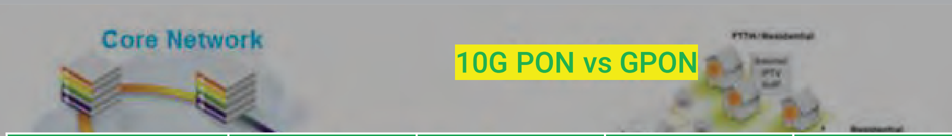
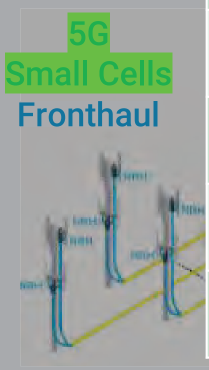

PON Overview
GPON
Next-gen GPON
EPON
Next-gen EPON
WDM PON
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
-
Port volume (000s)
2017
2018
2019
2020
2021
2022
2023
2024
Source: Ovum
6

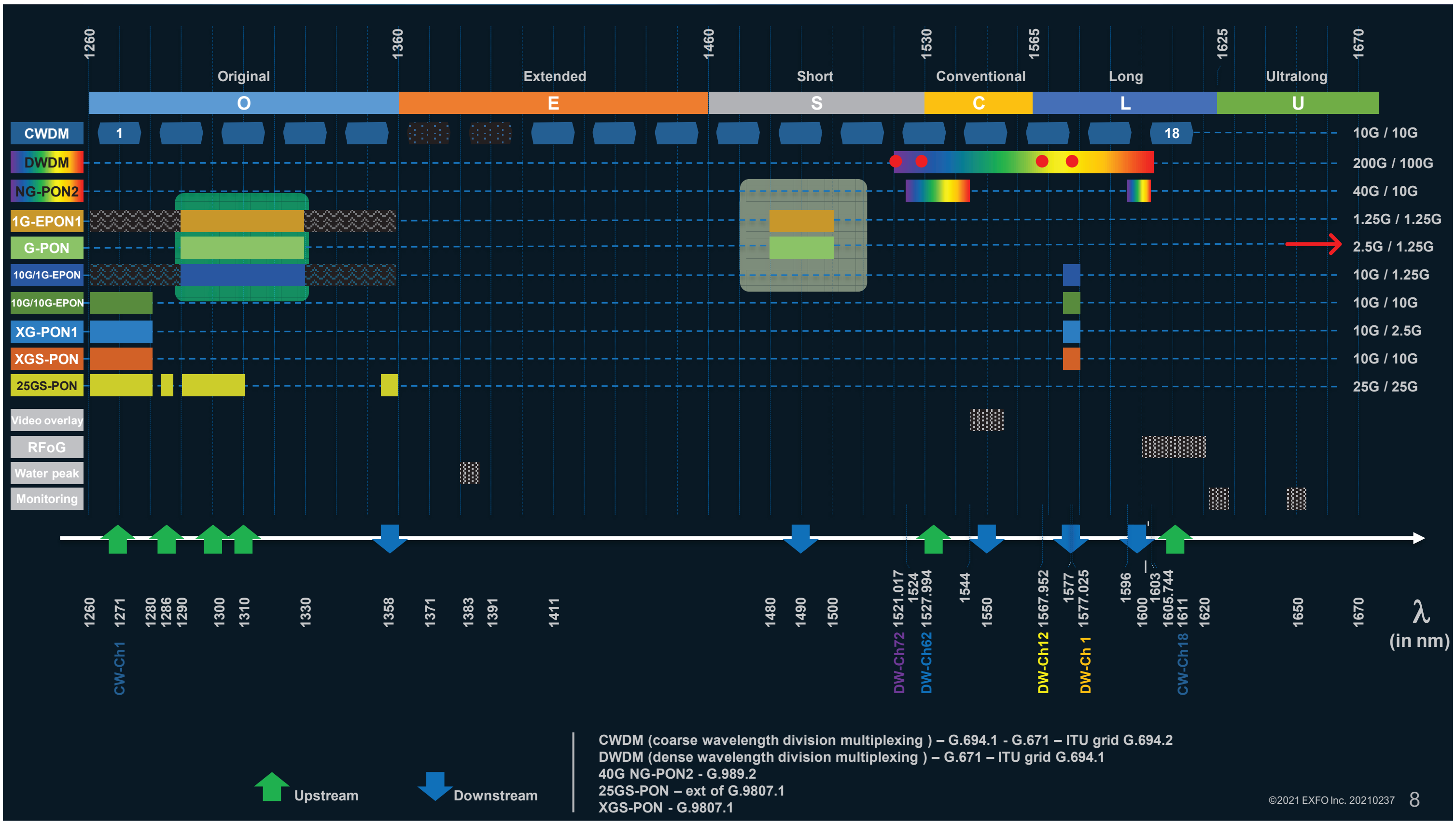
PON Overview

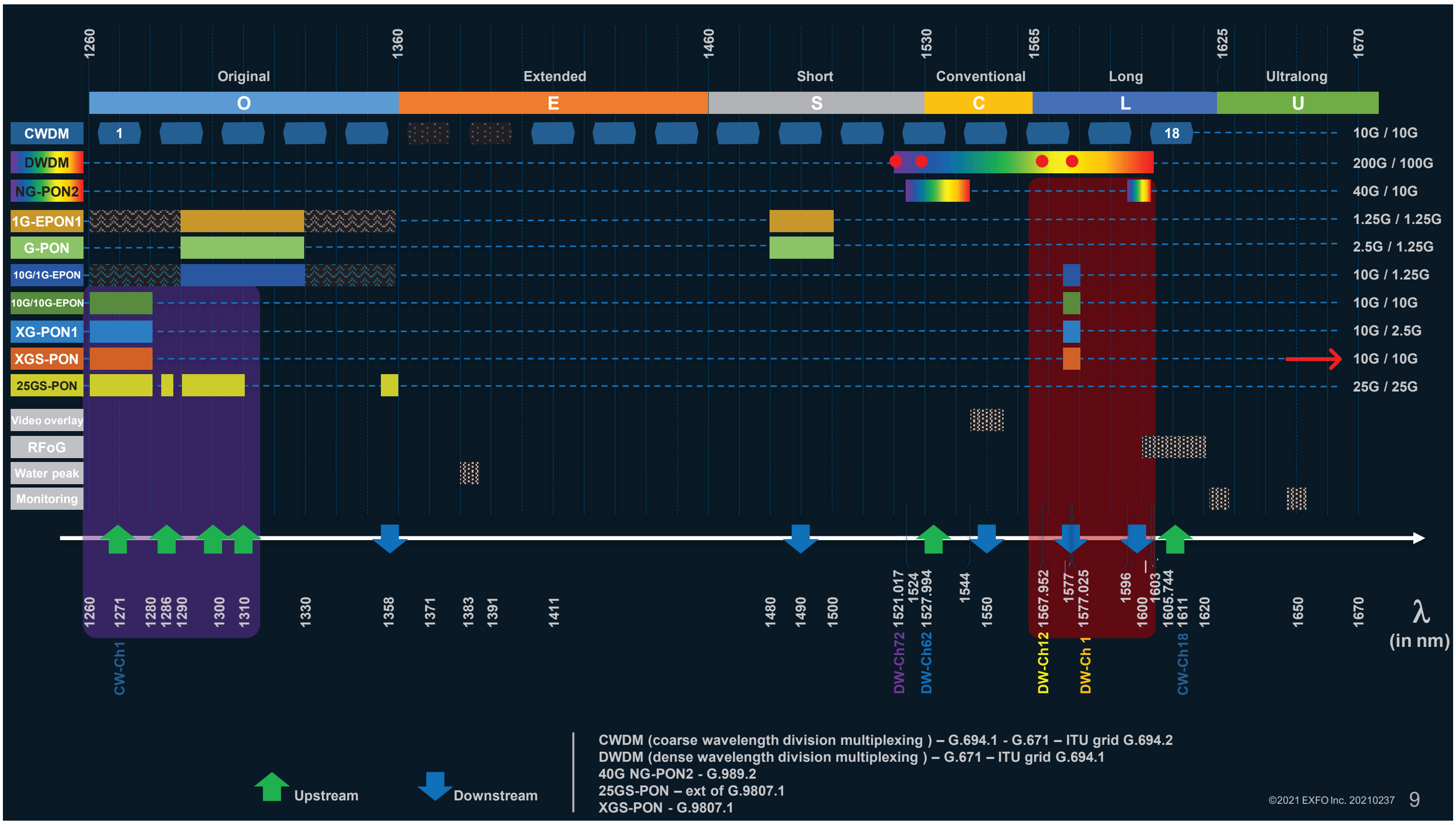




	GPON	XGS-PON	NG PON2	EPON	10G EPON
Standards	ITU-T G.984	ITU-T G.9807.1	ITU-T G.989	IEEE 802.3ah	IEEE 802.3av
DS/US Data Rates (Gbps)	2.4 / 1.2	10 / 10	40 /10	1.25 / 1.25	10 / 10
Splitter Ratio	Up to 64	Up to 128	Up to 128	Up to 64	Up to 128
Downstream (DS) λ	1490nm ±10	1577nm +2/-3	1596-1603nm	1490nm ±10	1577nm +2/-3
Upstream (US) λ	1310nm ± 20	1270nm ±10	1524-1544nm	1310nm ± 20	1270nm ±10

 7




Original
Extended
Short
Conventional
Long
Ultralong
O
E
S
C
L
U
CWDM
DWDM
NG-PON2
1G-EPON1
G-PON
10G/1G-EPON
10G/10G-EPON
XG-PON1
XGS-PON
25GS-PON
Video overlay
RFoG
Water peak
Monitoring
10G / 10G
200G / 100G
40G / 10G
1.25G / 1.25G
2.5G / 1.25G
10G / 1.25G
10G / 10G
10G / 2.5G
10G / 10G
25G / 25G
λ
(in nm)
CW-Ch1
DW-Ch72
DW-Ch62
DW-Ch12
DW-Ch 1
CW-Ch18
Upstream
Downstream
CWDM (coarse wavelength division multiplexing) – G.694.1 - G.671 – ITU grid G.694.2
DWDM (dense wavelength division multiplexing) – G.671 – ITU grid G.694.1
40G NG-PON2 - G.989.2
25GS-PON – ext of G.9807.1
XGS-PON - G.9807.1
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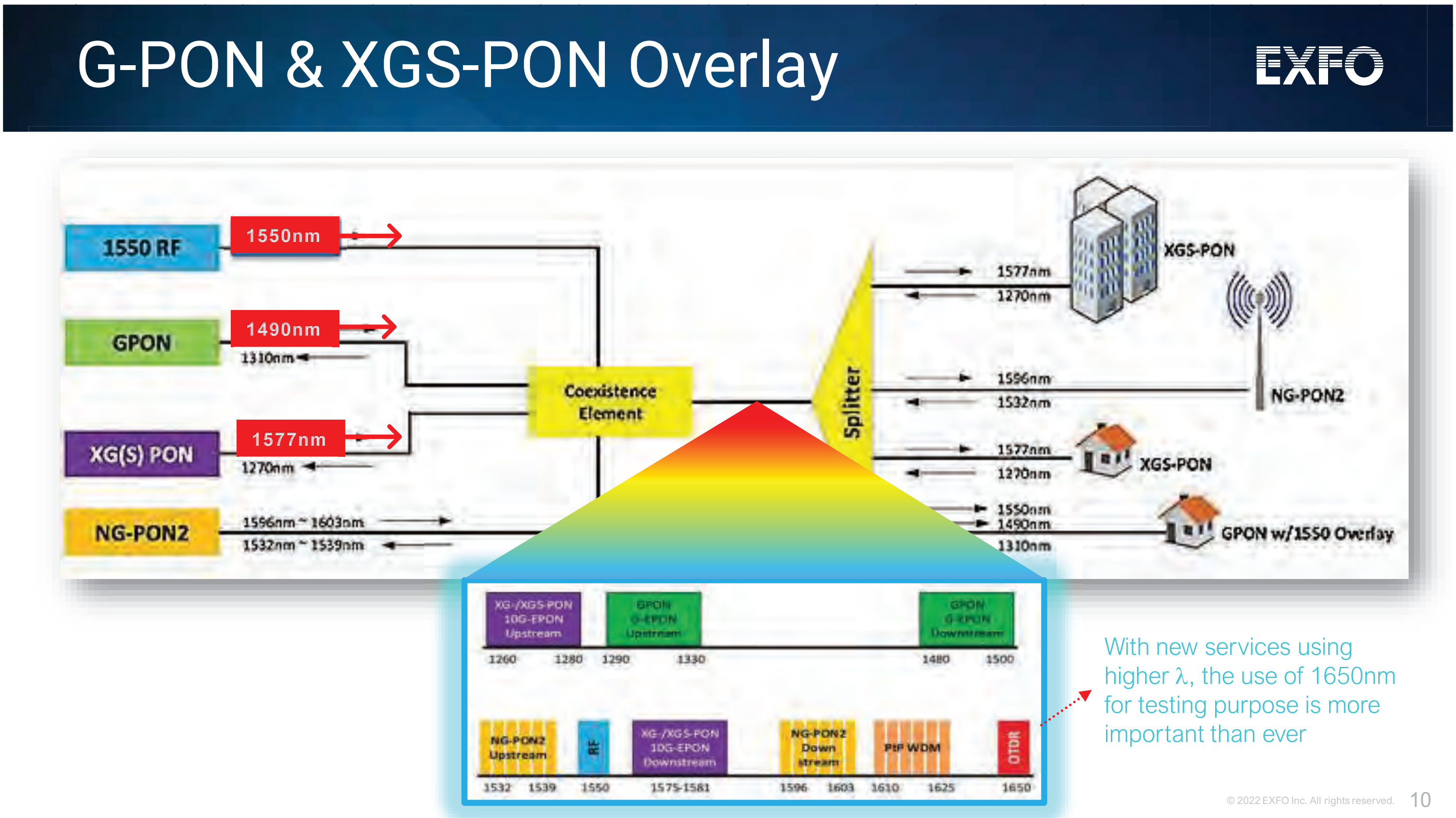
G-PON & XGS-PON Overlay
EXFO
1550 RF
1550nm
GPON
1490nm
1310nm
XG(S) PON
1577nm
1270nm
NG-PON2
1596nm ~ 1603nm
1532nm ~ 1539nm
Coexistence Element
Splitter
1577nm
1270nm
XGS-PON
1596nm
1532nm
NG-PON2
1577nm
1270nm
XGS-PON
1550nm
1490nm
1310nm
GPON w/1550 Overlay
With new services using higher λ, the use of 1650nm for testing purpose is more important than ever
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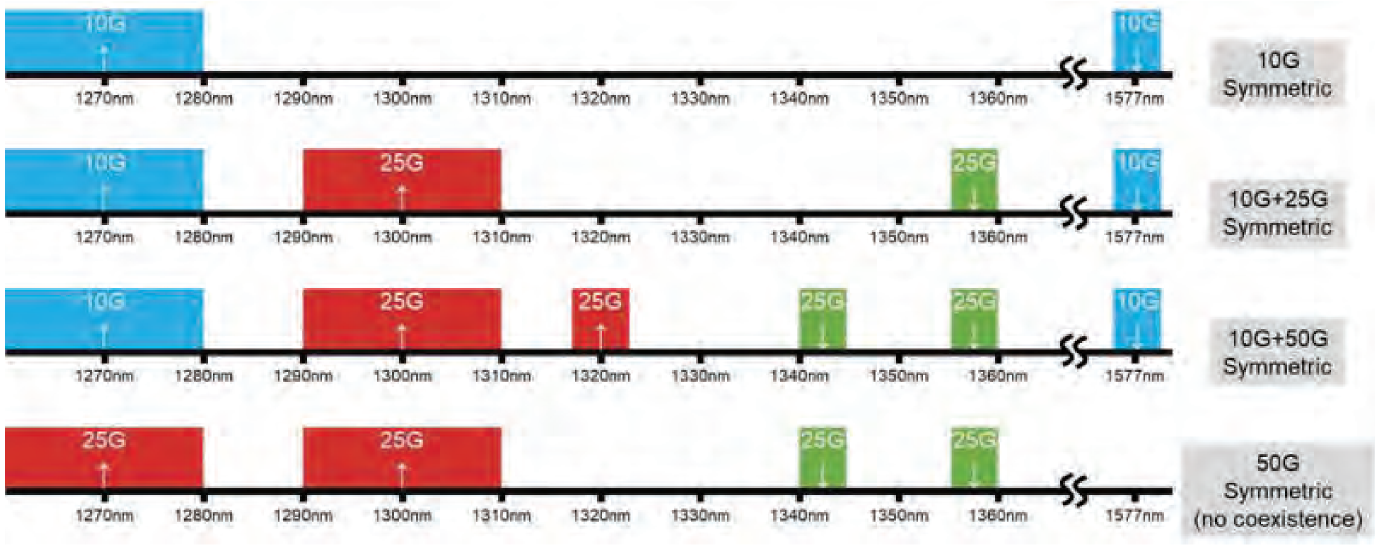
What about 25G PON?



25GS-PON MSA Group

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Anatomy of the FTTH infrastructure

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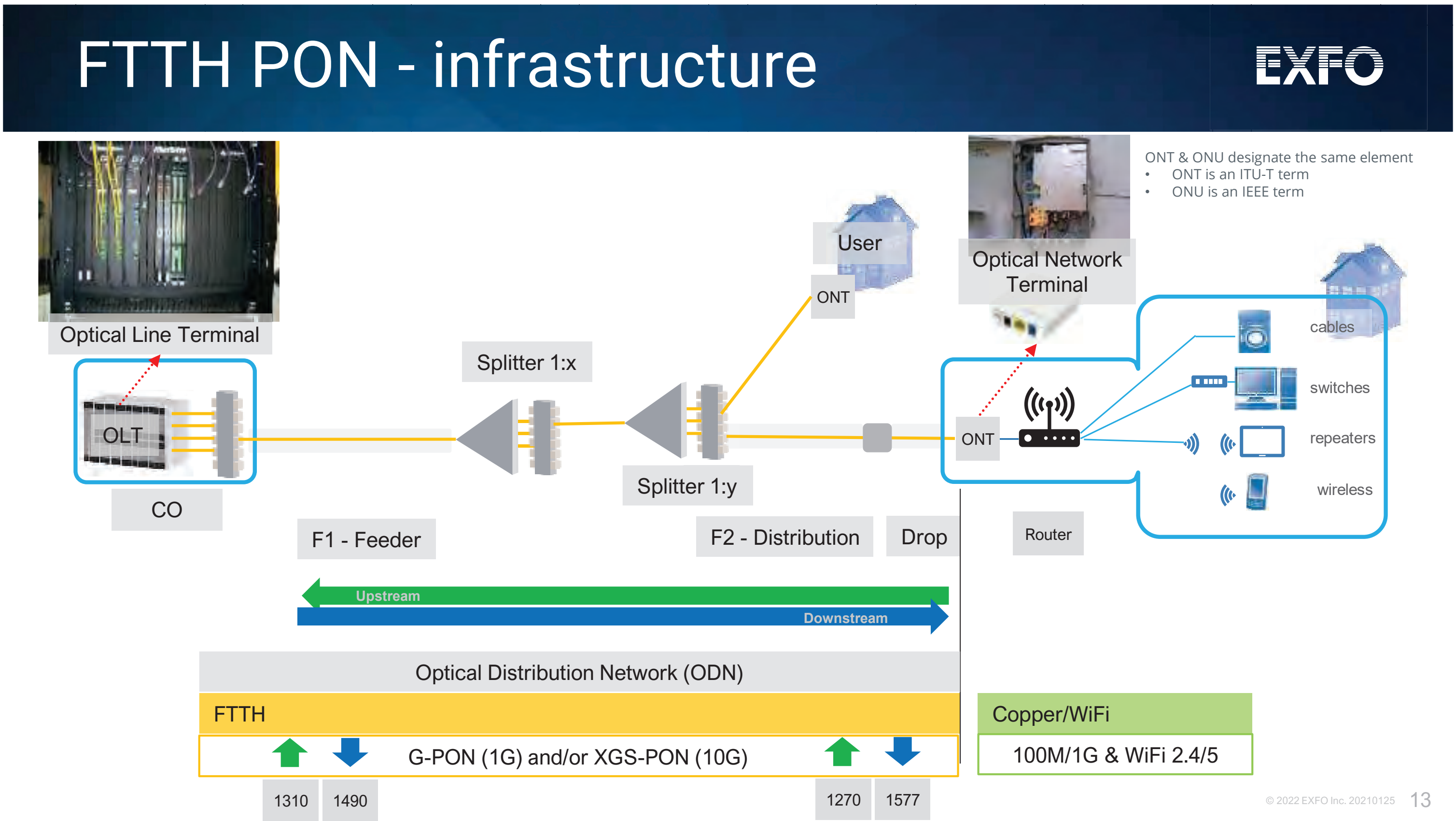
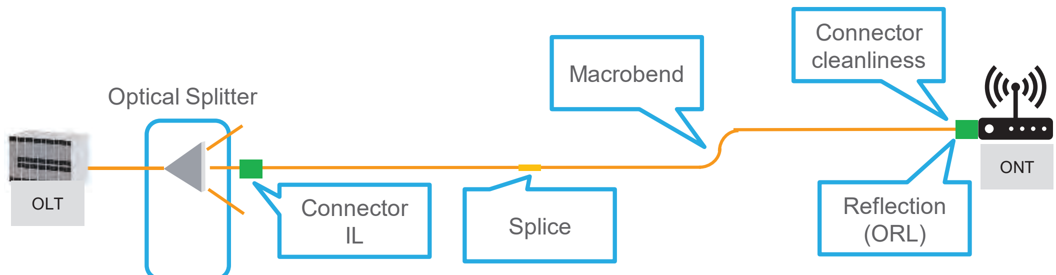
FTTH PON - infrastructure



FTTH PON - Critical parameters

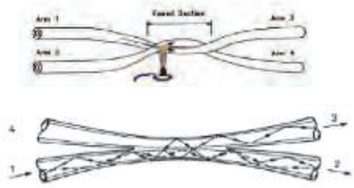
Loss Budget

It is critical to minimize the loss (attenuation) across the fiber cable and components.



Non reflective events inducing high loss depending on the ratio

Parameter	Specifications										
Operating Wavelength (nm)	1260 ~ 1650										
Type	1x2	1x4	1x8	1x16	1x32	2X2	2X4	2X8	2X16	2X32	2X64
Insertion Loss (dB) Max	<4.0	<7.3	<10.8	<14.0	<17.0	<4.2	<7.6	<11.2	<14.5	<18.2	<21.5



For every 3dB of loss you suffer a 50% penalty.

Loss	Power Loss %	Power Remaining %
0.10 dB	2%	98 %
0.20 dB	4.5%	95.5%
0.5 dB	11%	89%
1 dB	19%	79%
3 dB	50%	50 %
6 dB	75%	25 %
10 dB	90%	10 %
20 dB	99%	1 %
30 dB	99.9 %	0.1 %
40 dB	99.99%	0.01%
50 dB	99.999 %	0.001 %

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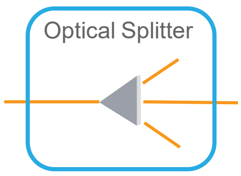
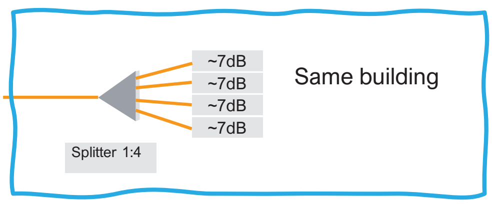
Optical Splitter

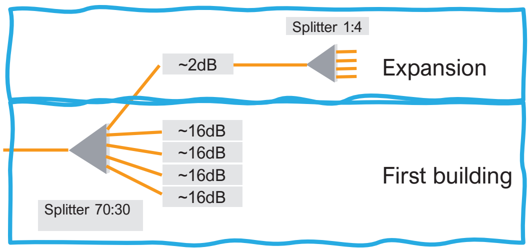


Choice based on the network design and topology

Classic symmetrical splitter

Special unbalanced splitter





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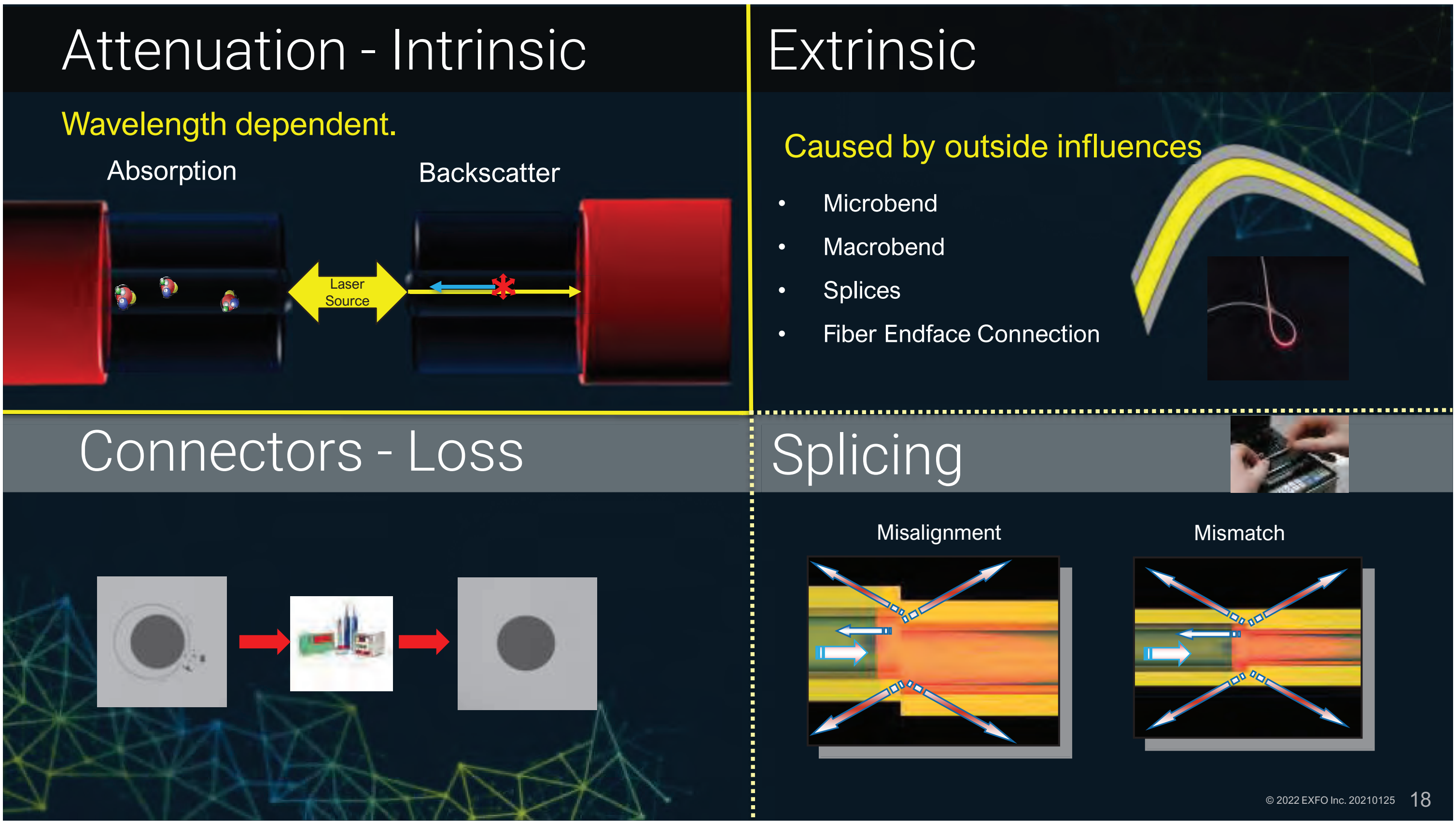
Attenuation - Intrinsic
Wavelength dependent.
Absorption
Backscatter
Laser Source
Extrinsic
Caused by outside influences
• Microbend
• Macrobend
• Splices
• Fiber Endface Connection
Connectors - Loss
Splicing
Misalignment
Mismatch
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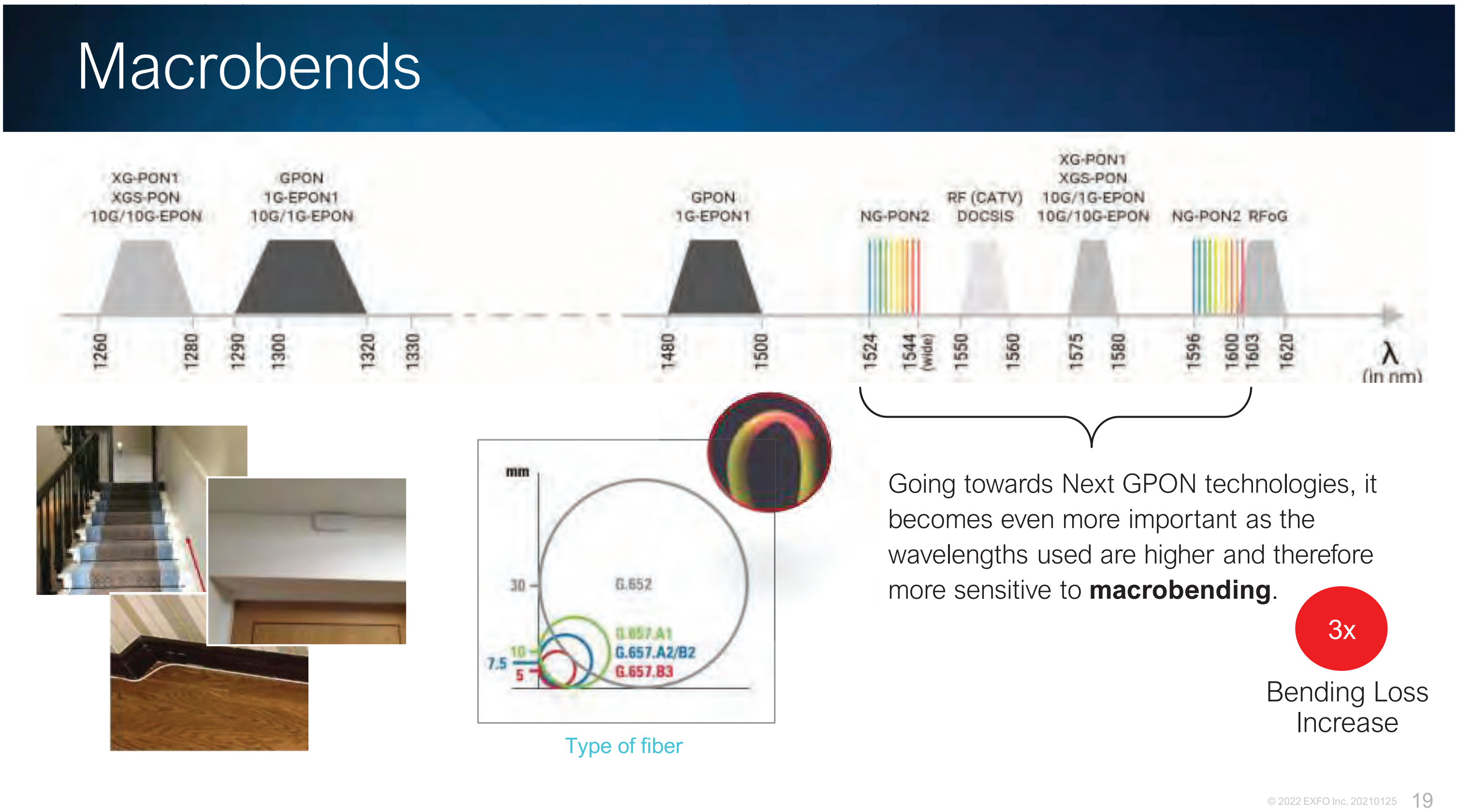
Macrobends
XG-PON1
XGS-PON
10G/10G-EPON
GPON
1G-EPON1
10G/1G-EPON
GPON
1G-EPON1
NG-PON2
RF (CATV)
DOCSIS
XG-PON1
XGS-PON
10G/1G-EPON
10G/10G-EPON
NG-PON2
RFoG
1260 1280 1290 1300 1320 1330 1480 1500 1524 1544 (wide) 1550 1560 1575 1580 1596 1600 1603 1620
λ (in nm)
mm
30
10
7.5
5
G.652
G.657.A1
G.657.A2/B2
G.657.B3
Type of fiber
Going towards Next GPON technologies, it becomes even more important as the wavelengths used are higher and therefore more sensitive to **macrobending**.
3x
Bending Loss Increase
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Optical Return Loss – ORL

EXFO

What if you have excess ORL?

NOISE!

HIGH

LOW

ORL is span reflection

Reflection is the measurement of reflection at a single point such as a connector. We want -40dB or better. -50dB is better than -40dB.

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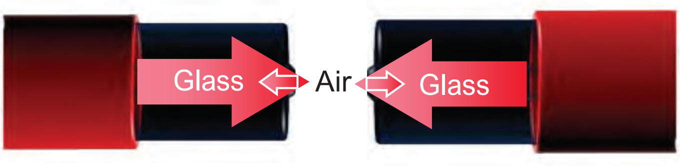
Reflection vs ORL

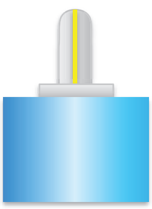
EXFO

Reflection

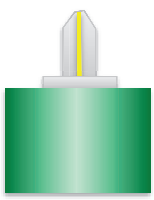
Light Is Reflected at Each End Face



UPC
<-55dB Reflection
0.001% return

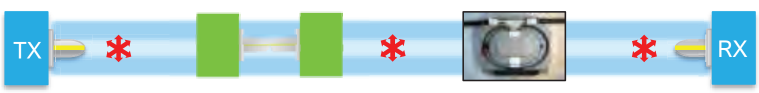


APC
<-65dB Reflection
0.0001% return



ORL

ORL is the reflected light that returns to the source.



Optical Return Loss of Single Mode Fiber vs Length

Length	ORL
1 Meter	70 dB
10 Meters	60 dB
100 Meters	50 dB
1000 Meters	40 dB
Infinity	32 dB

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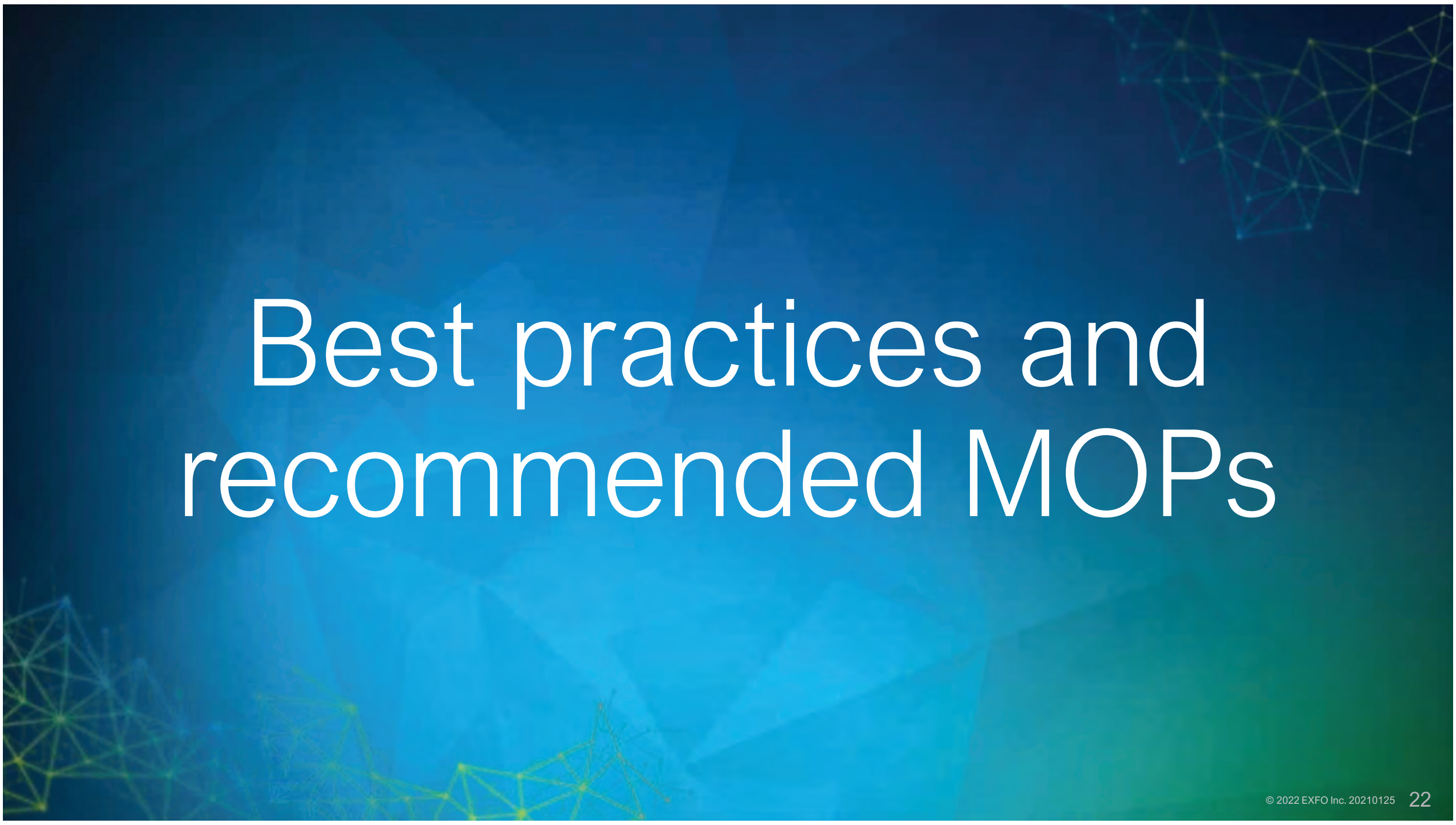
Best practices and recommended MOPs
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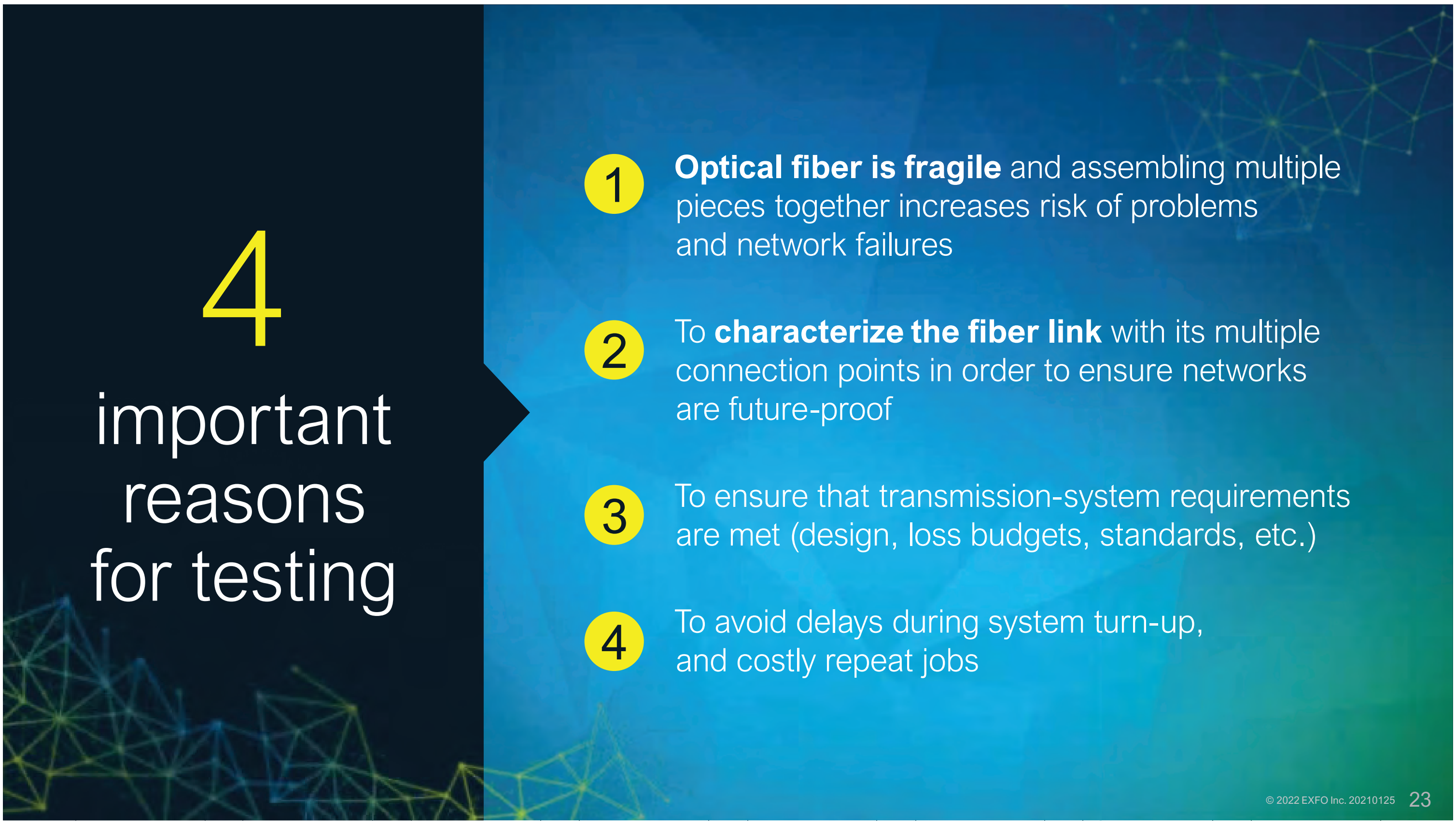
4 important reasons for testing
1 Optical fiber is fragile and assembling multiple pieces together increases risk of problems and network failures
2 To characterize the fiber link with its multiple connection points in order to ensure networks are future-proof
3 To ensure that transmission-system requirements are met (design, loss budgets, standards, etc.)
4 To avoid delays during system turn-up, and costly repeat jobs
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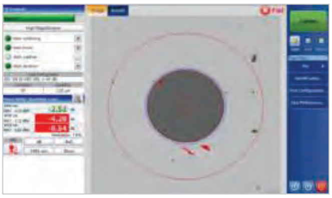
Testing strategy for a quality deployment

FTTH deployments

1. Connector endface cleanliness

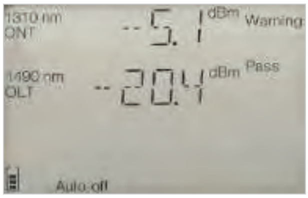


Fiber inspection scope

2. Fiber-link characterization

iOLM/OTDR/OFM

3. Link verification and Service activation



PM, Optical Fiber Multimeter

4. Speed test verification

Service tester

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What's inside tech's toolbox?

Measurements	Test equipment
Inspection of the connector	Fiber microscope (FIP)
Insertion loss (IL)	OTDR/OFM[1]/OLTS
Distance	OTDR/OFM[1]/OLTS[2]
Splice and connector's attenuation	OTDR/OFM[1]
Splitter presence and functionality	OTDR/OFM[1]
Connector's return loss (RL)	OTDR/OFM[1]
Fiber optical return loss (ORL)	OTDR/OFM[1]/OLTS[2]
Level of received power	PM/OFM
Speedtest	Service tester

[1]OFM is the new Optical Fiber Multimeter category launched by EXFO.
[2]EXFO OLTS tool provides fiber length and ORL values too.

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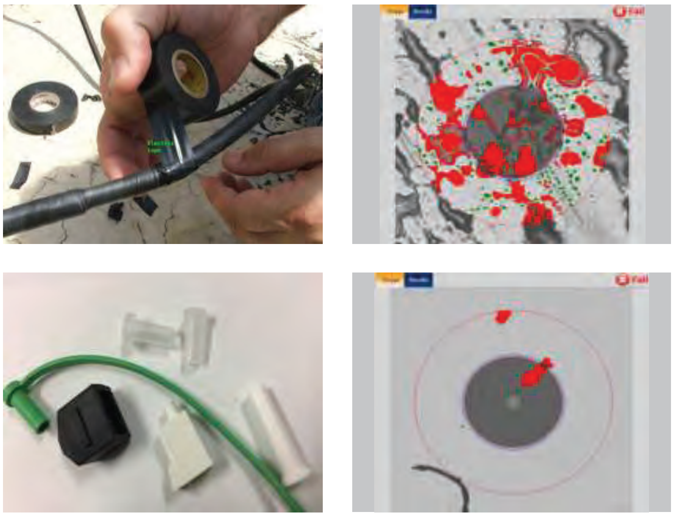
1 Optical connectors: the weakest point

Why are connectors dirty or damaged?



Really sensitive to dust and skin oil

Mishandling:

Everyone handling fiber optic should be properly trained on how to manipulate them to avoid contamination

Plastic covers:

Well protected connectors can be contaminated by their own dust cap due to electrostatic. Even new connectors must be inspected.

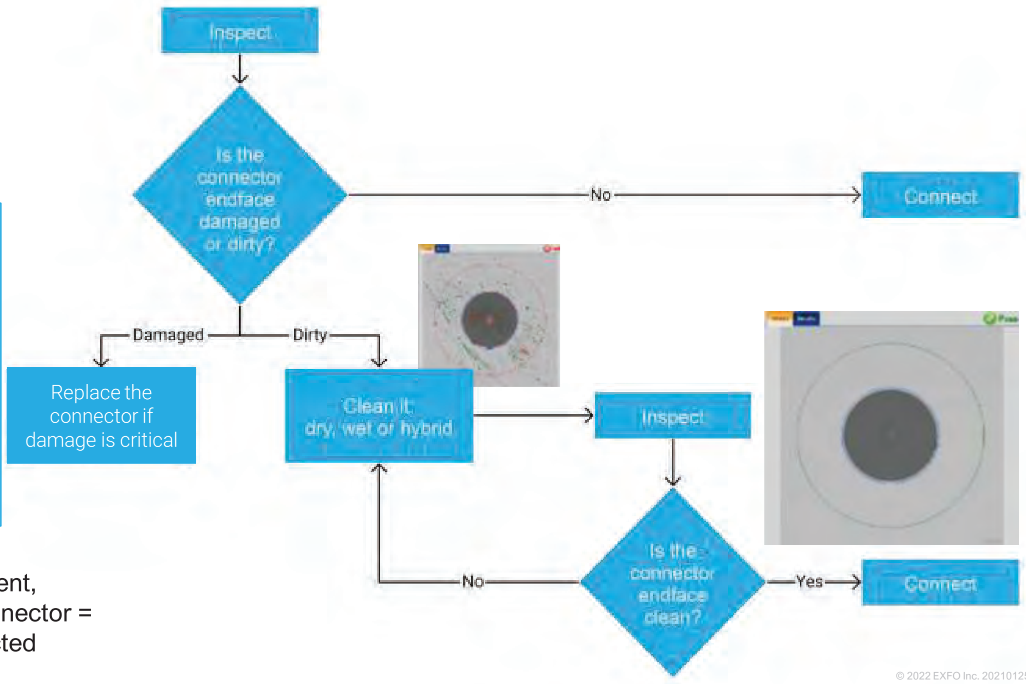
 27

1 Optical connectors: the weakest point

"Dirty connectors are the no.1 cause of network failures"

DAMAGED = REPLACE

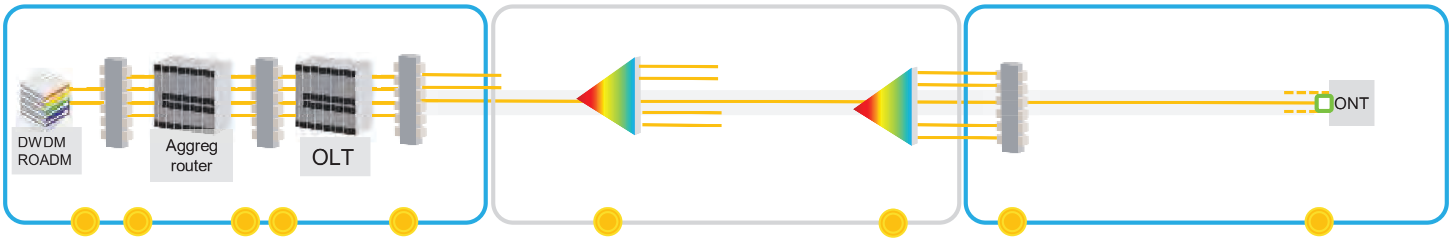
Cleaning a damaged connector is worthless!



In a P2MP environment, 1 damaged/dirty connector = 8+ connections affected

 28

1 Optical connectors: the right inspection tool



Fiber connector inspection

EXFO FIP-500

Accurate & repeatable

Zero-button automation

Easiest tip swap

FIP-500

A fiber inspection scope is the only tool that can help technicians validate connectors and make the right decision.

In a multi-fiber installations, optical performance, accuracy and repeatability are more important than ever.

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What is an OTDR?

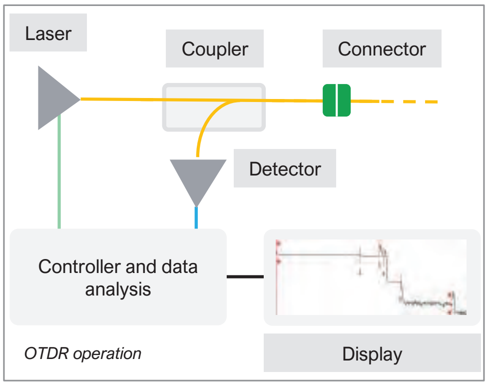
OTDR = Optical Time Domain Reflectometer

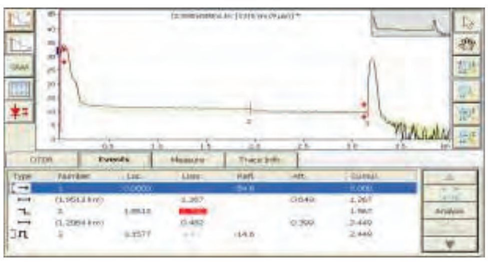
Definition

An OTDR is a complex device that:

1. Sends a pulse of light toward the fiber under test
2. Detects and measures difference between the launching time and the time of arrival of the returned signal
3. Determines the distance between the launching point and the event
4. Displays the received data for further analysis

An OTDR uses the Rayleigh scattering and Fresnel reflection effects that are present in an optical fiber link.





 30

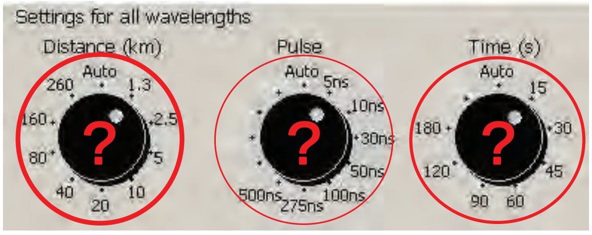
OTDR approach. Complex task...

OTDR setup changes depending on the event that we want to characterize.

Testing > Setting the correct parameters

Result > Understanding the details

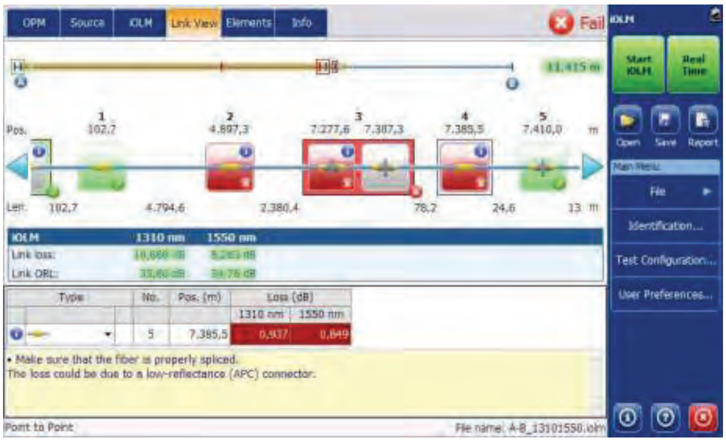
What length? **For how long?**



What is the best pulse width (PW)?

- Short PW - Best resolution but low dynamic
- Long PW - Low resolution but large dynamic

iOLM intelligent Optical Link Mapper

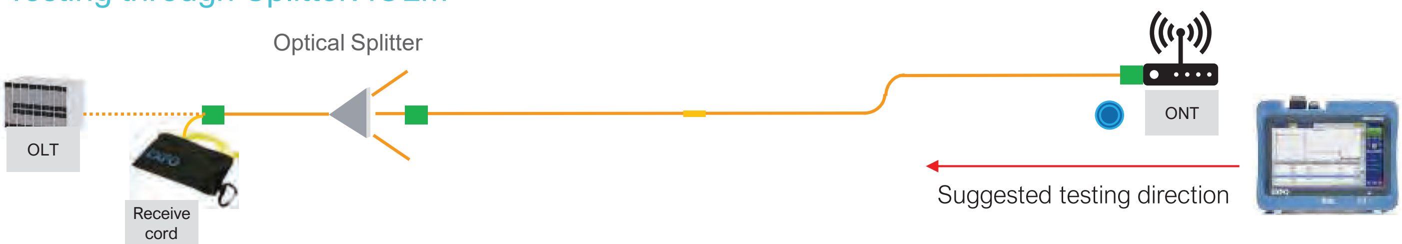


Advanced reflectometry: Dynamic and automatic multi-pulse acquisitions, tailored to the measured link and device specs

 31

2 Fiber-link characterization

Testing through Splitter: iOLM

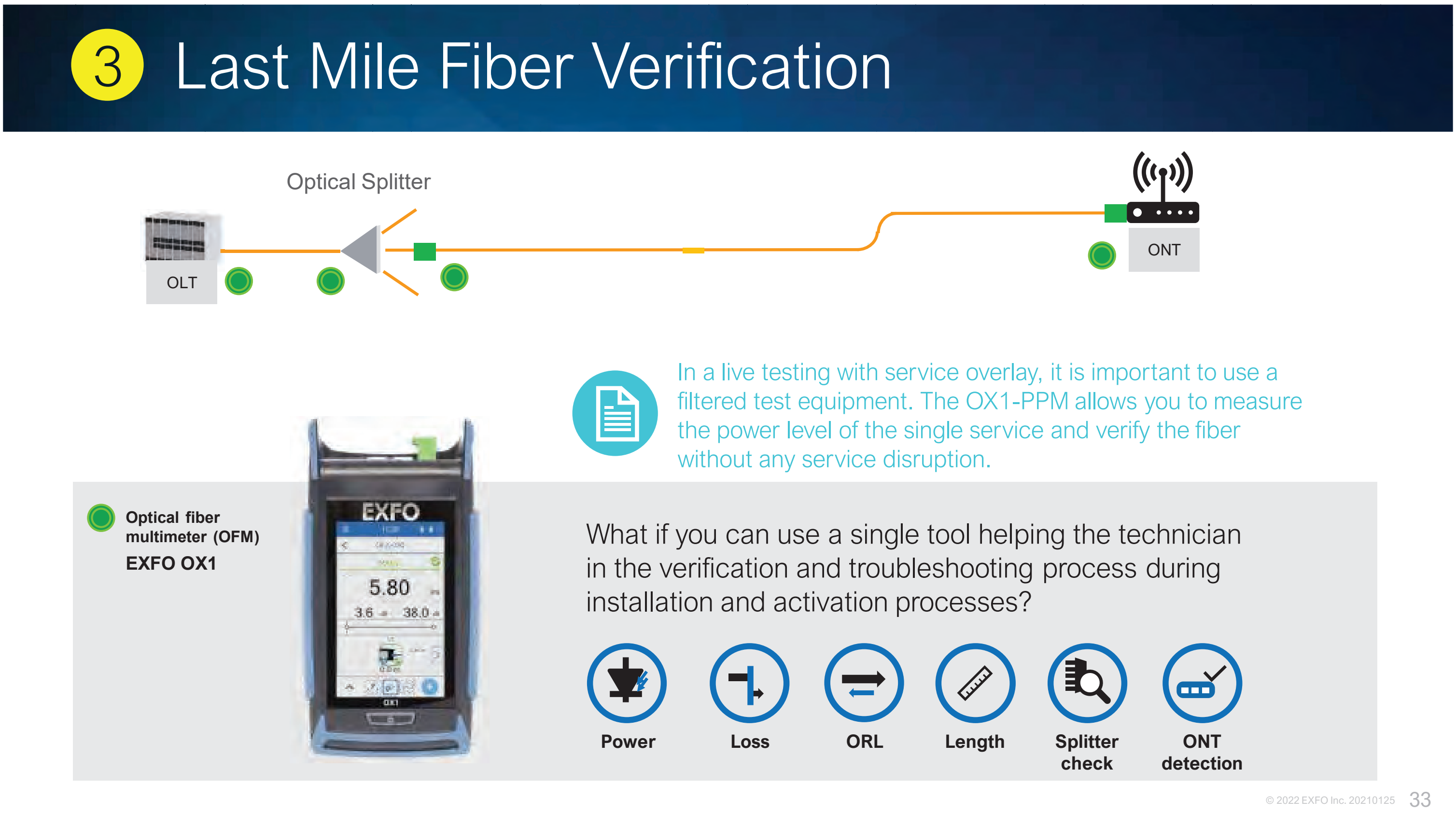


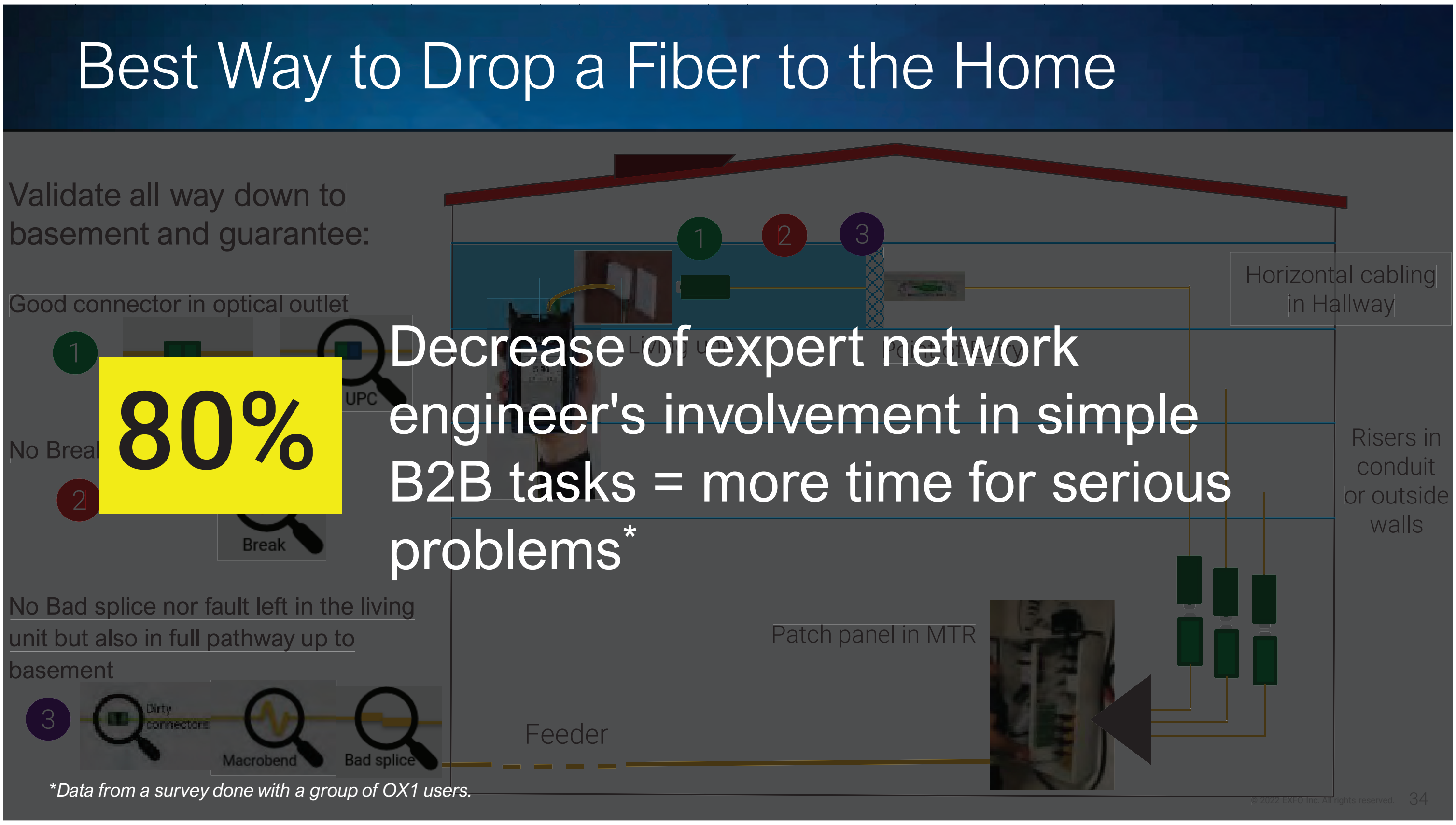
OTDR
EXFO MAX-730C

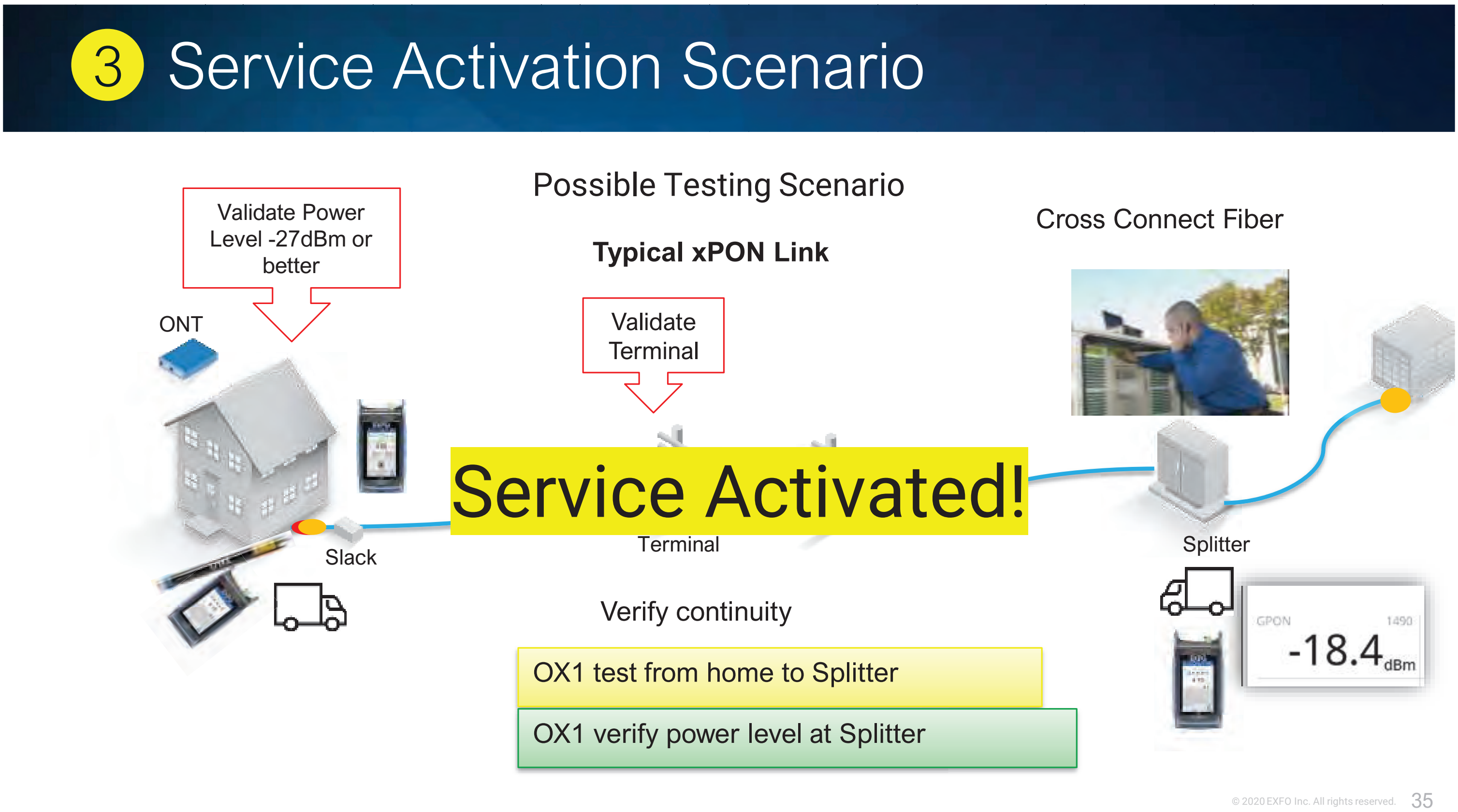
PON optimized OTDR is the preferred technology to characterize each element, and locate anything potentially impacting total budget loss (dB), such as macrobends, splices, bad connectors, fiber breaks, etc.

Important to select a device that handles unbalanced splitters in reliable, easy and quick mode.

 32


3
Last Mile Fiber Verification
Optical Splitter
OLT
ONT
In a live testing with service overlay, it is important to use a filtered test equipment. The OX1-PPM allows you to measure the power level of the single service and verify the fiber without any service disruption.
Optical fiber multimeter (OFM)
EXFO OX1
EXFO
5.80
What if you can use a single tool helping the technician in the verification and troubleshooting process during installation and activation processes?
Power
Loss
ORL
Length
Splitter check
ONT detection
© 2022 EXFO Inc. 20210125
33


Best Way to Drop a Fiber to the Home
Validate all way down to basement and guarantee:
Good connector in optical outlet
Horizontal cabling in Hallway
80%
Decrease of expert network engineer's involvement in simple B2B tasks = more time for serious problems*
Risers in conduit or outside walls
UPC
Break
No Bad splice nor fault left in the living unit but also in full pathway up to basement
Patch panel in MTR
Dirty connectors
Macrobend
Bad splice
Feeder
*Data from a survey done with a group of OX1 users.


3
Service Activation Scenario
Possible Testing Scenario
Typical xPON Link
Validate Power Level -27dBm or better
ONT
Validate Terminal
Cross Connect Fiber
Service Activated!
Slack
Terminal
Splitter
GPON
1490
-18.4 dBm
Verify continuity
OX1 test from home to Splitter
OX1 verify power level at Splitter
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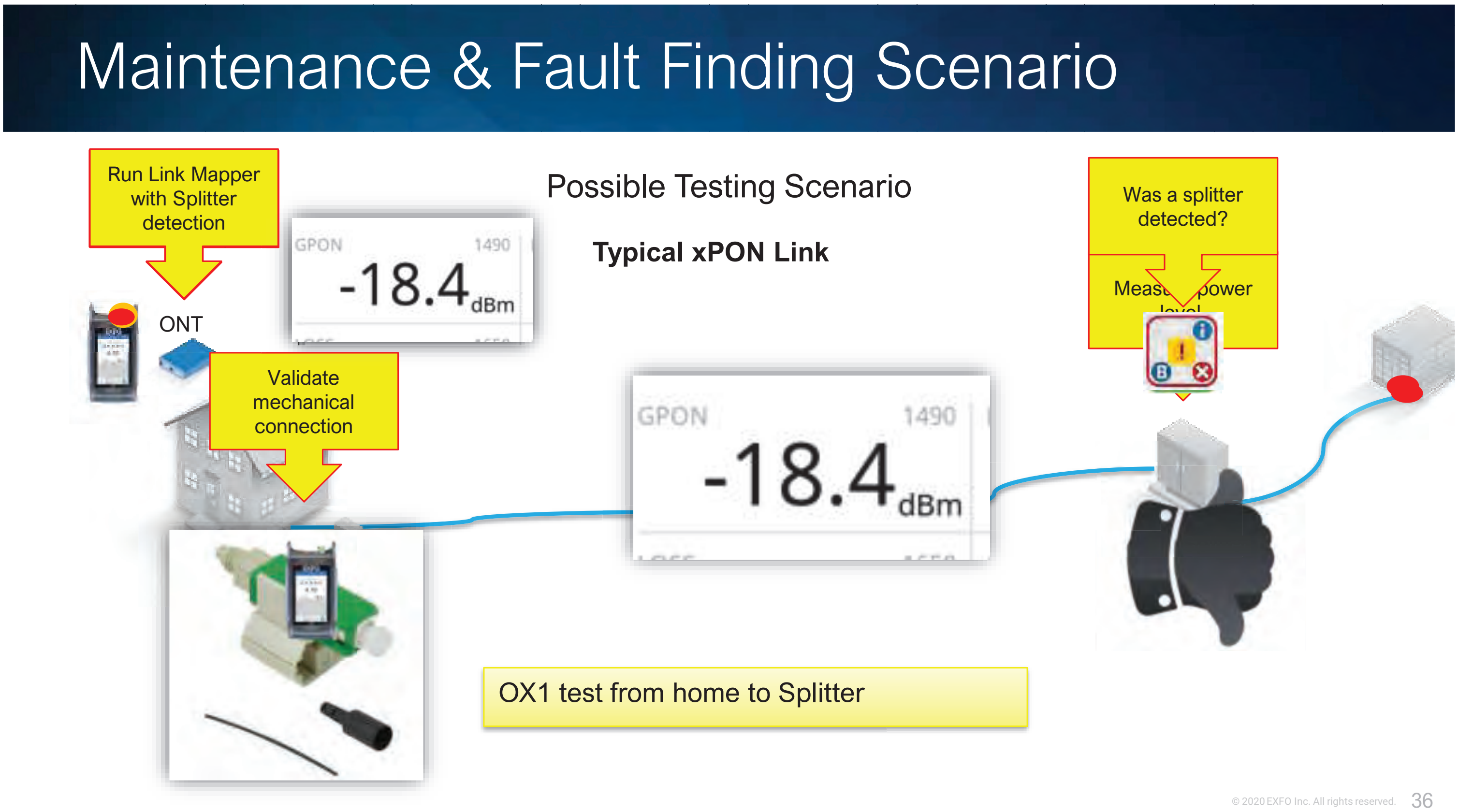
Maintenance & Fault Finding Scenario
Run Link Mapper with Splitter detection
ONT
GPON
1490
-18.4 dBm
Possible Testing Scenario
Typical xPON Link
Was a splitter detected?
Validate mechanical connection
GPON
1490
-18.4 dBm
OX1 test from home to Splitter
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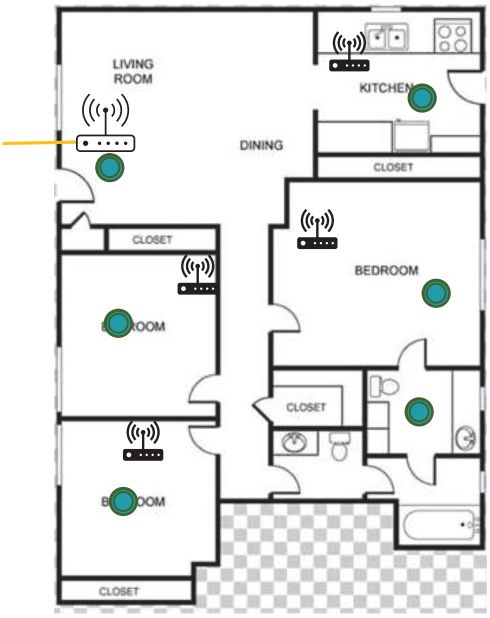
4 Service activation: speed test



EXFO EX10

Service tester
EXFO EX10

Final verification of available speed rate and Wi-Fi coverage needs a dedicated service layer tester that uses standard Ookla speedtest to align with real customer expectation.

The tester must be able to run the test over copper Ethernet port, GPON and XGS-PON interfaces, and Wi-Fi up to 6/6e standard.

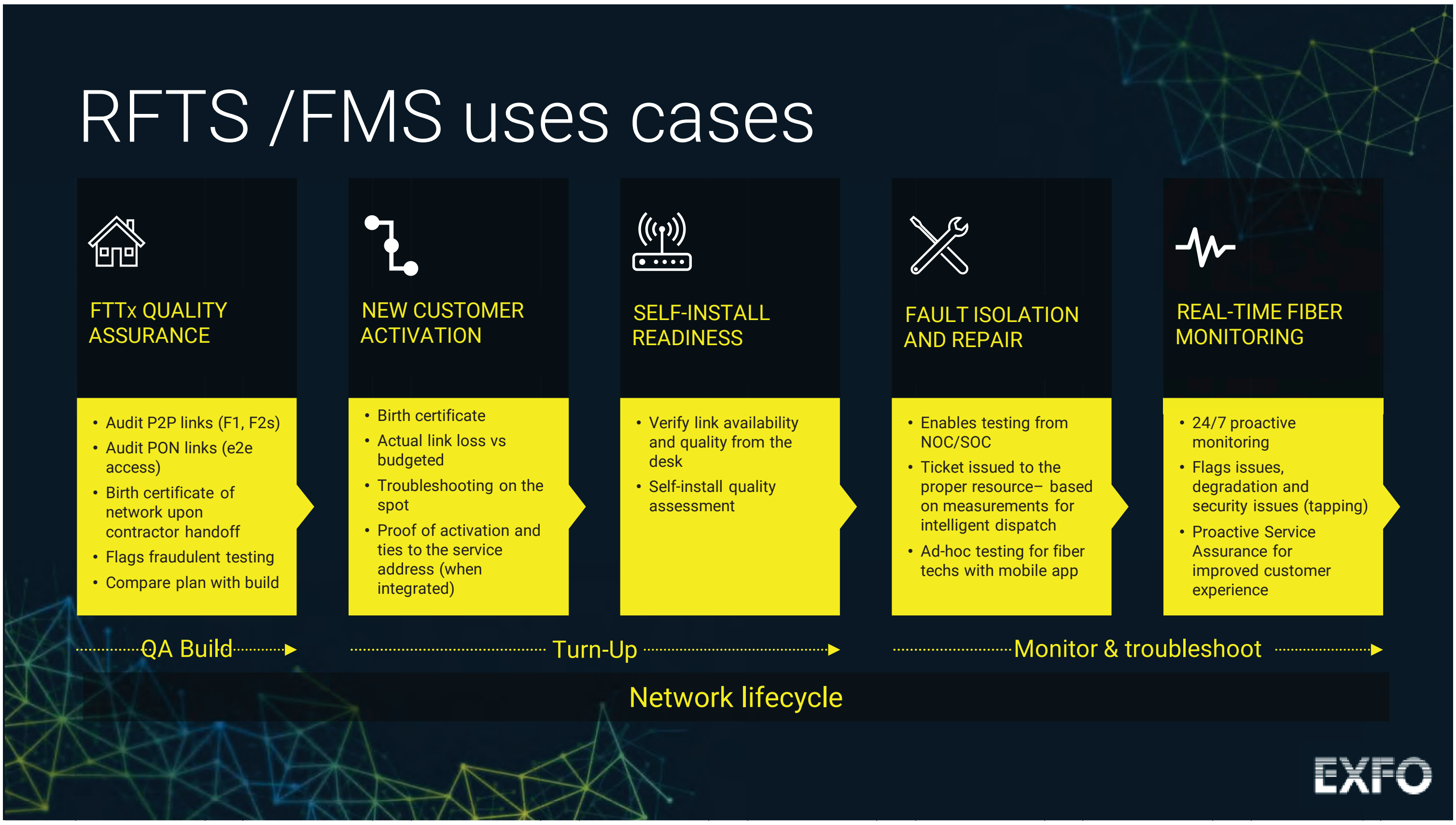
Multi-gigabit port (up to 10G) is a must to verify the full service.

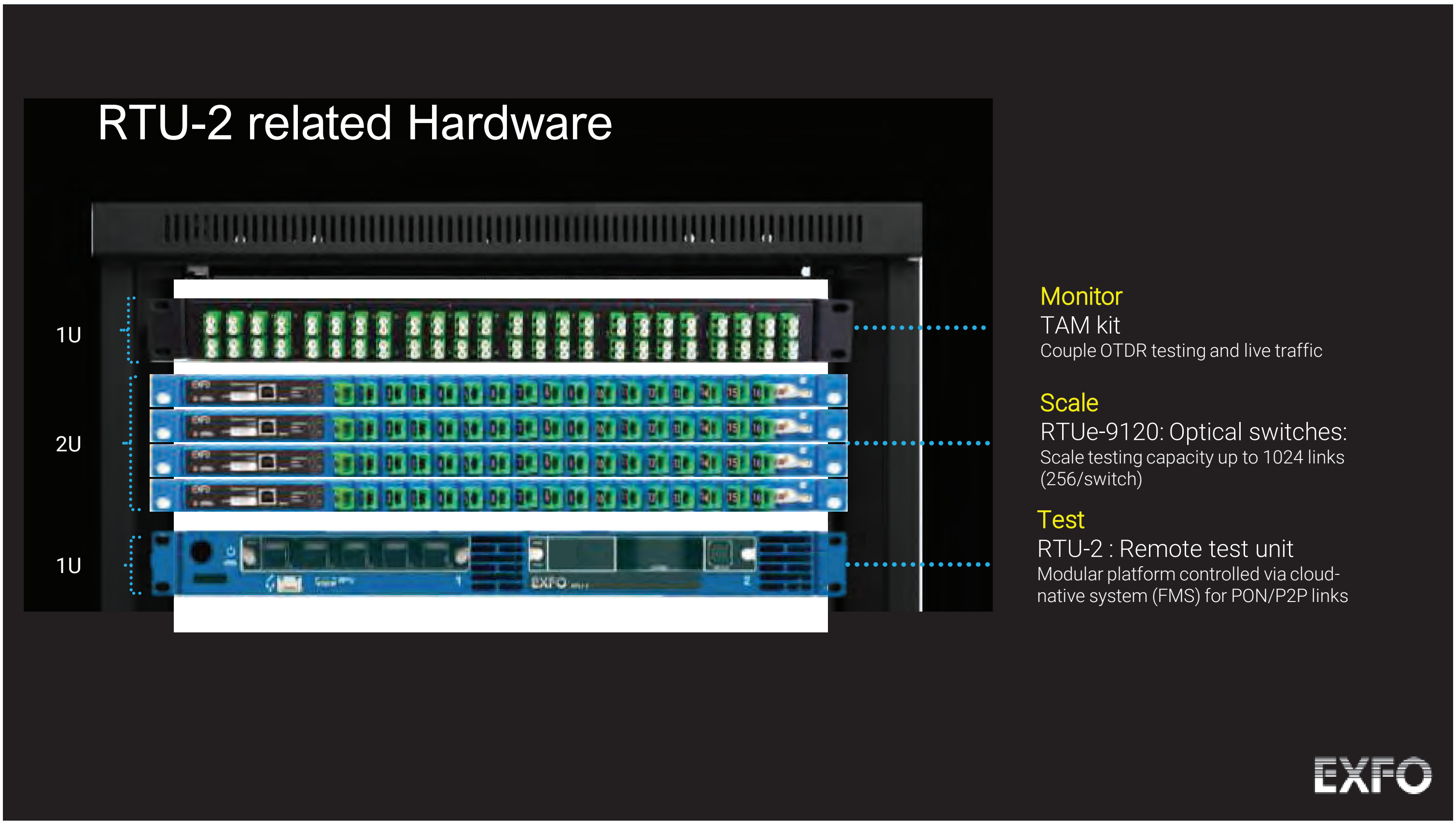
Conclusion & comments

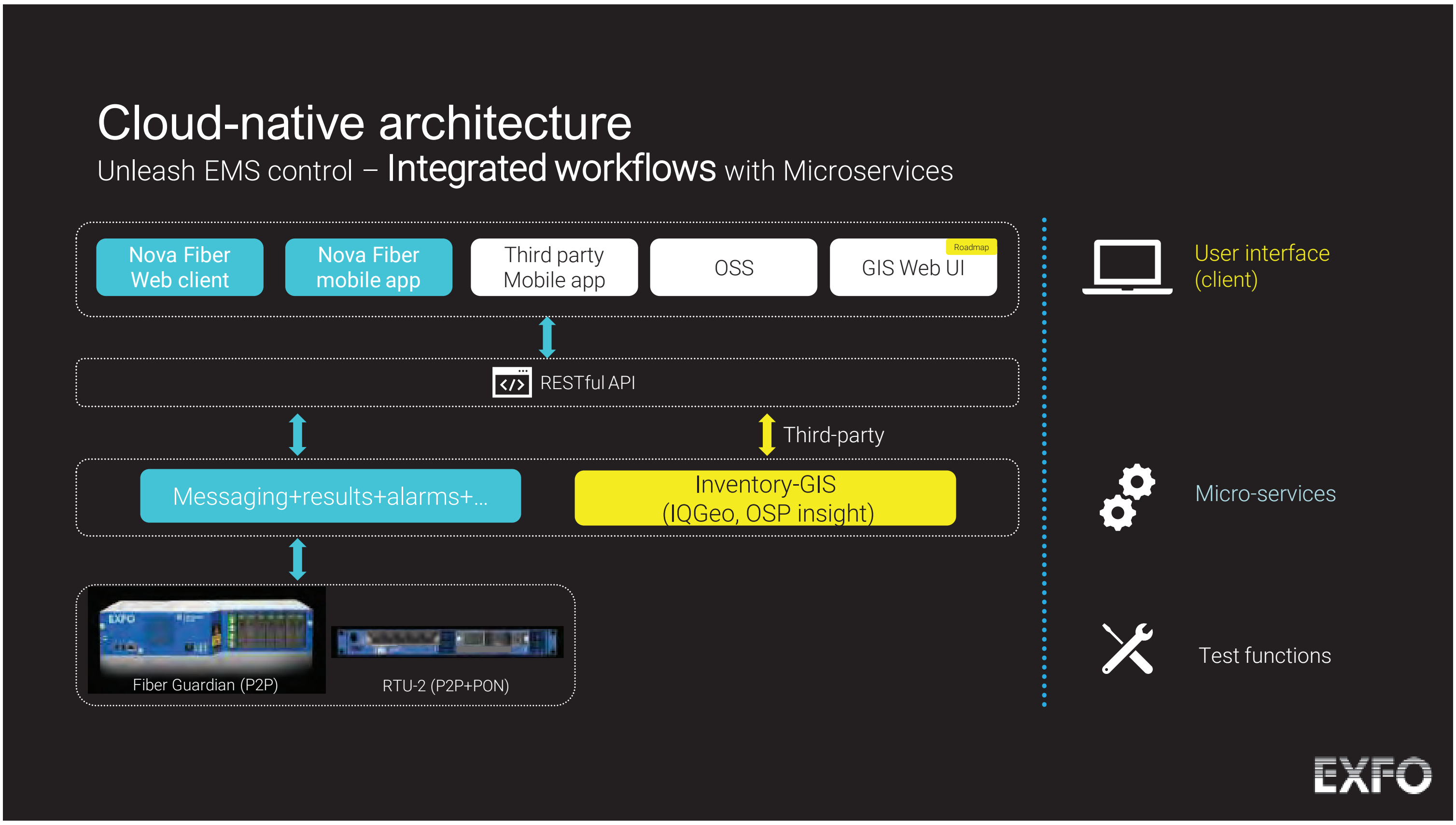
1. **New technologies**
   New adoptions can lead to new problems that require the right experiance

2. **Fiber characterisation and connector inspection lead to a trouble-free deployment**
   Follow industry best practices and standards

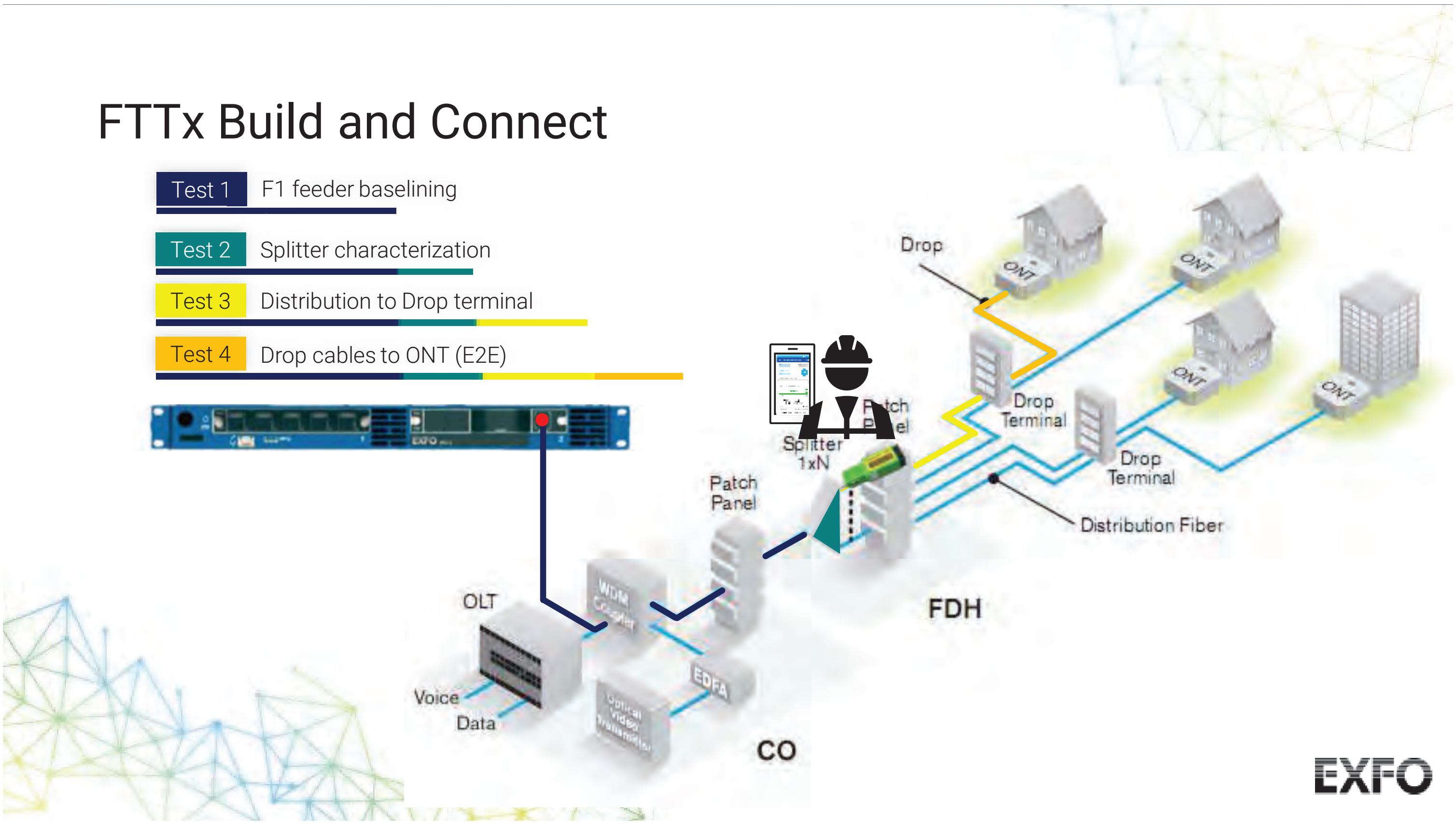
3. **Proper testing tools and MOPs can help in deploying quality FTTH networks with time and cost efficiency**
   Choosing intelligent apps not only accelerates deployment but makes it more reliable for you and most importantly – your customers


RFTS /FMS uses cases
FTTx QUALITY ASSURANCE
• Audit P2P links (F1, F2s)
• Audit PON links (e2e access)
• Birth certificate of network upon contractor handoff
• Flags fraudulent testing
• Compare plan with build
NEW CUSTOMER ACTIVATION
• Birth certificate
• Actual link loss vs budgeted
• Troubleshooting on the spot
• Proof of activation and ties to the service address (when integrated)
SELF-INSTALL READINESS
• Verify link availability and quality from the desk
• Self-install quality assessment
FAULT ISOLATION AND REPAIR
• Enables testing from NOC/SOC
• Ticket issued to the proper resource– based on measurements for intelligent dispatch
• Ad-hoc testing for fiber techs with mobile app
REAL-TIME FIBER MONITORING
• 24/7 proactive monitoring
• Flags issues, degradation and security issues (tapping)
• Proactive Service Assurance for improved customer experience
QA Build
Turn-Up
Monitor & troubleshoot
Network lifecycle
EXFO


RTU-2 related Hardware
1U
2U
1U
Monitor
TAM kit
Couple OTDR testing and live traffic
Scale
RTUe-9120: Optical switches:
Scale testing capacity up to 1024 links (256/switch)
Test
RTU-2 : Remote test unit
Modular platform controlled via cloud-native system (FMS) for PON/P2P links
EXFO



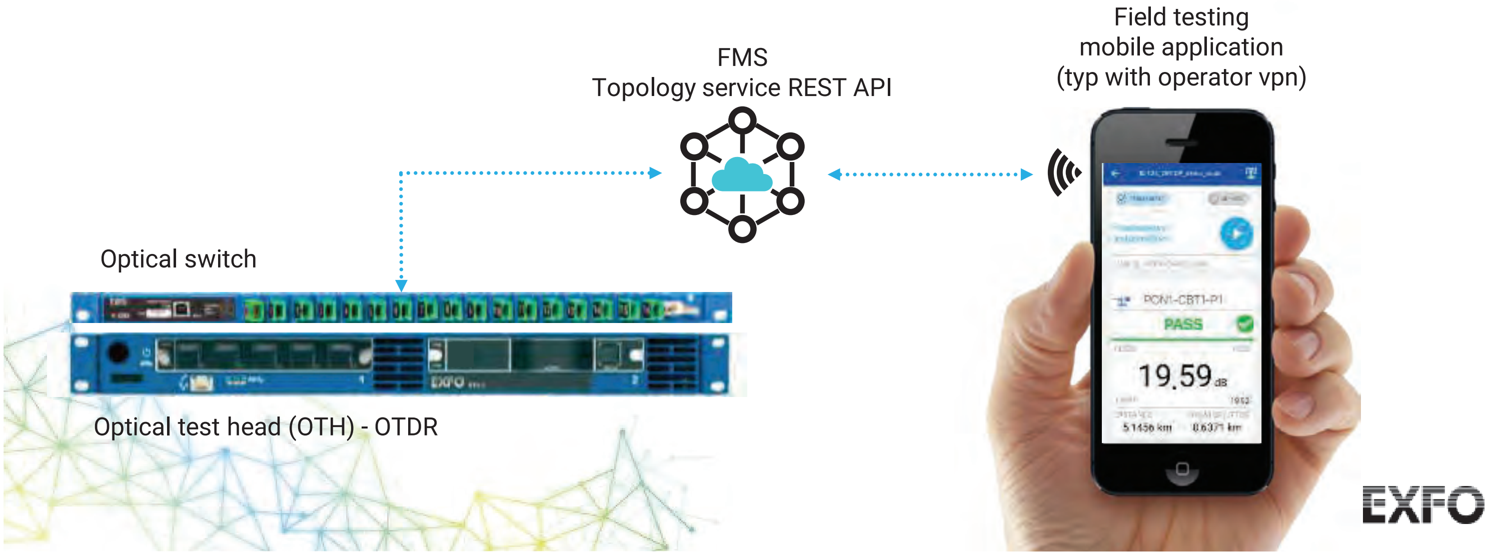
Cloud-native architecture
Unleash EMS control – Integrated workflows with Microservices
Nova Fiber Web client
Nova Fiber mobile app
Third party Mobile app
OSS
Roadmap
GIS Web UI
RESTful API
Third-party
Messaging+results+alarms+...
Inventory-GIS (IQGeo, OSP insight)
Fiber Guardian (P2P)
RTU-2 (P2P+PON)
User interface (client)
Micro-services
Test functions
EXFO



FTTx Build and Connect
Test 1 F1 feeder baselining
Test 2 Splitter characterization
Test 3 Distribution to Drop terminal
Test 4 Drop cables to ONT (E2E)
Drop
ONT
ONT
ONT
ONT
Drop Terminal
Drop Terminal
Distribution Fiber
Splitter 1xN
Patch Panel
FDH
OLT
Voice
Data
CO
EXFO

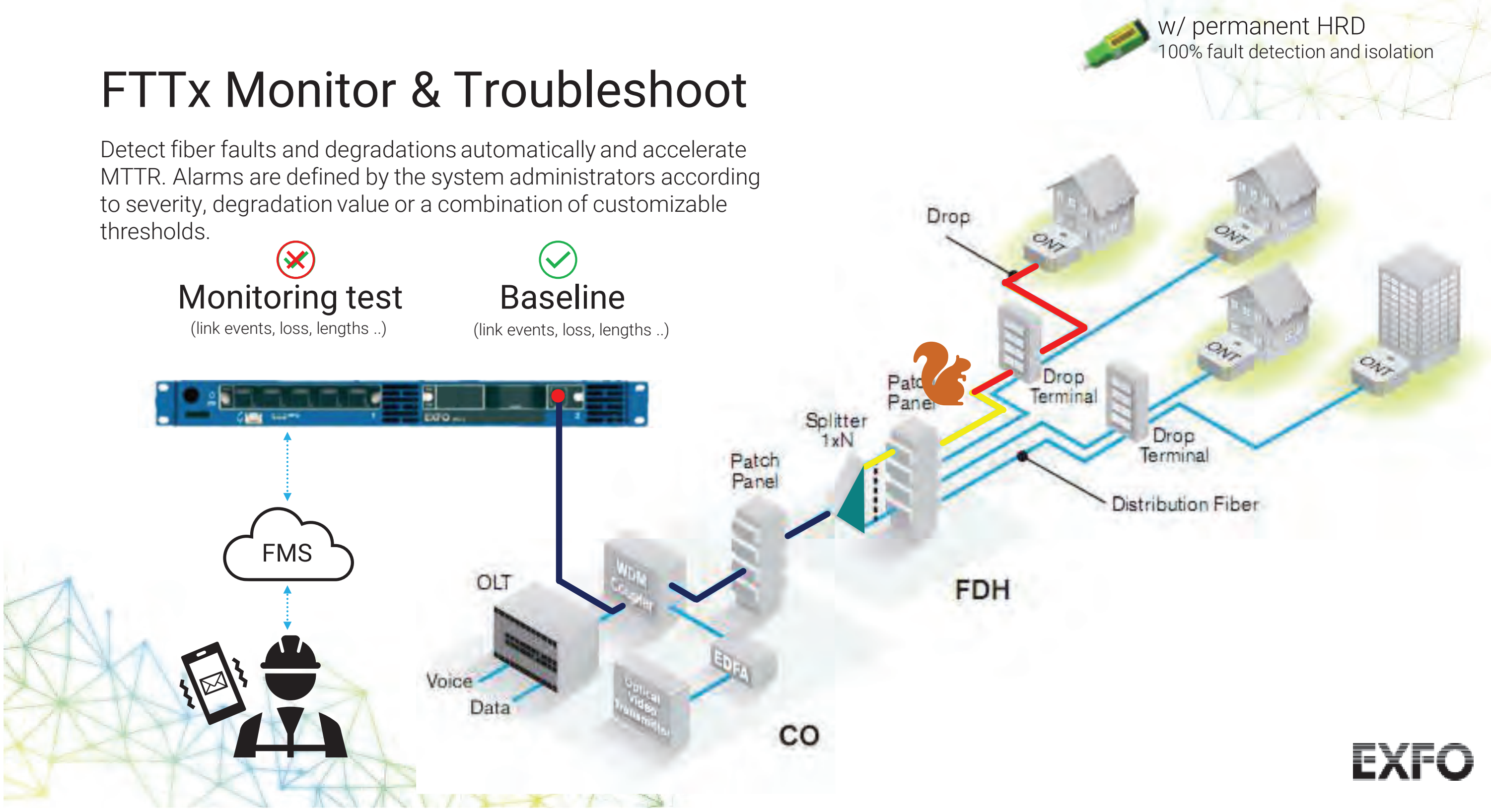
FTTx Build and Connect

The Nova Fiber mobile application enables tech to remotely access OTDR testing capabilities via the cloud-native central controller. The high-reflection demarcation filters leaves a signature on the OTDR trace that allows location of the tester.

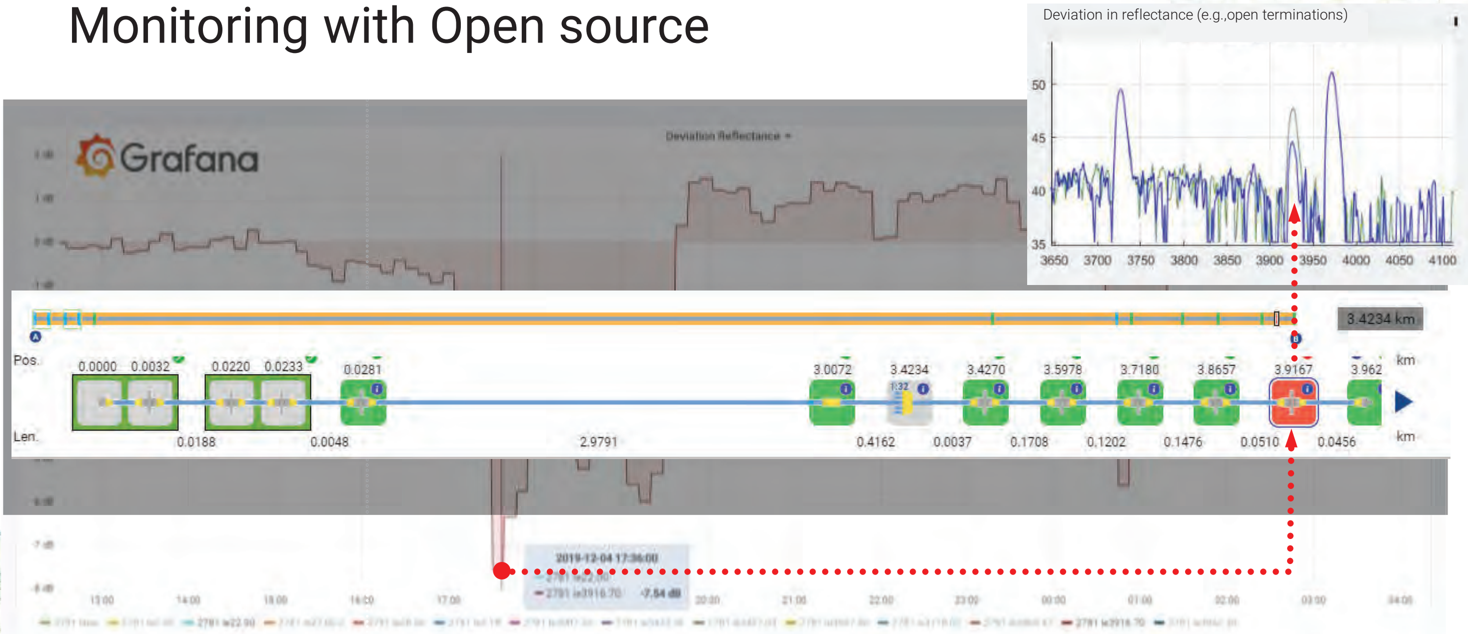


FTTx Monitor & Troubleshoot

Detect fiber faults and degradations automatically and accelerate MTTR. Alarms are defined by the system administrators according to severity, degradation value or a combination of customizable thresholds.



Monitoring with Open source



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Nova Fiber Mobile _1/2

Nova Fiber mobile application

Field technicians remote-testing tool

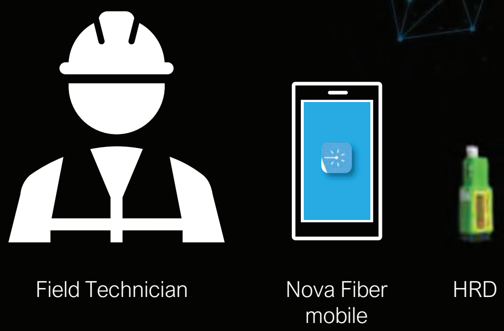
Google Play App Store

Nova Fiber mobile application empowers field technicians to remotely trigger OTDR testing. This is orchestrated via the central server (FMS). From E2E link loss measurements, to link continuity, OTDR link characterization is accessible at the touch of a button with contextual diagnostics available for users on the spot. High-reflection demarcation testing main topic of release 7.6

Toned signal can also be triggered with the mobile app to verify that the technician is working on the right fiber (Live fiber detector needed).

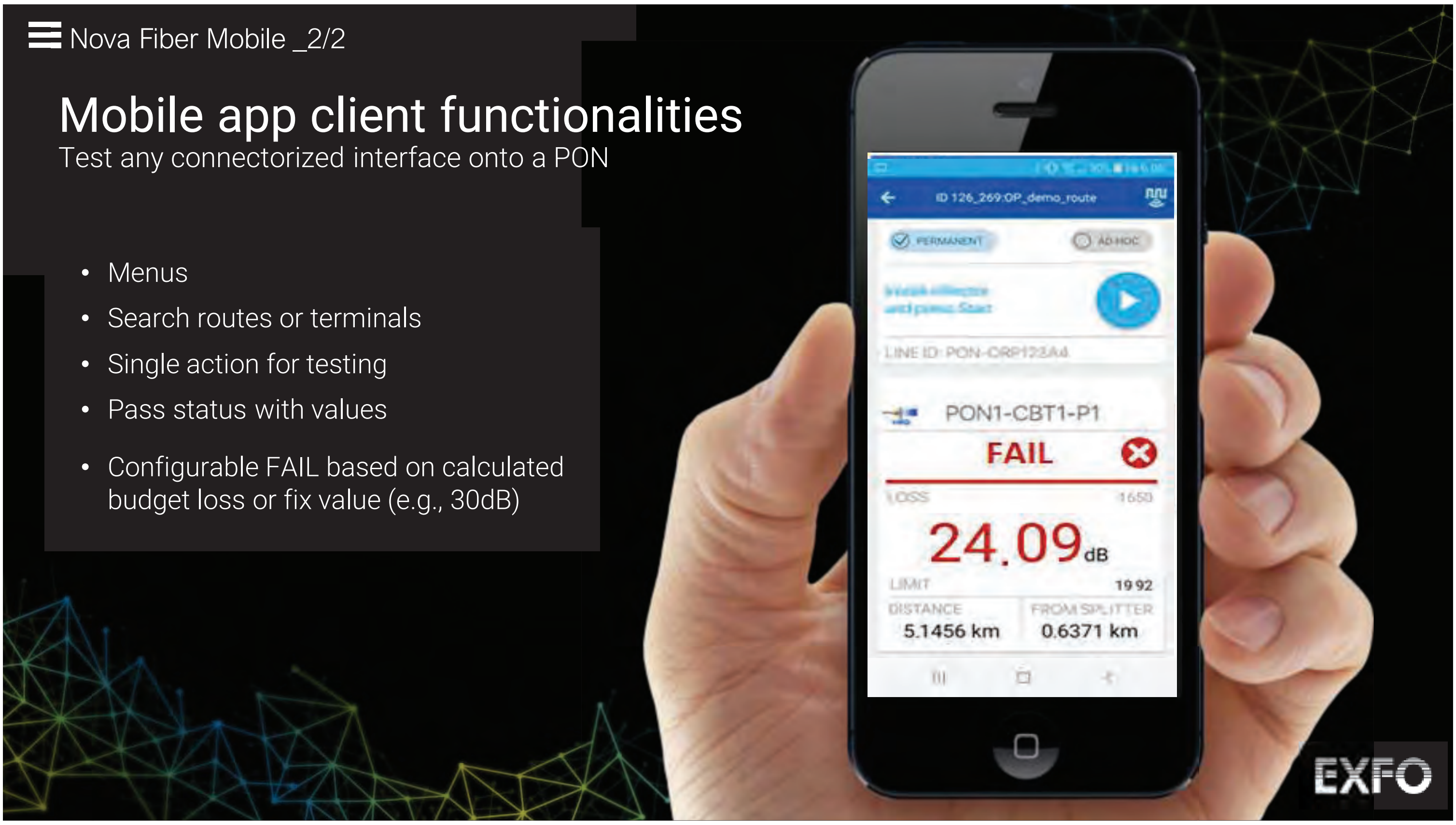
Ideal for managed services

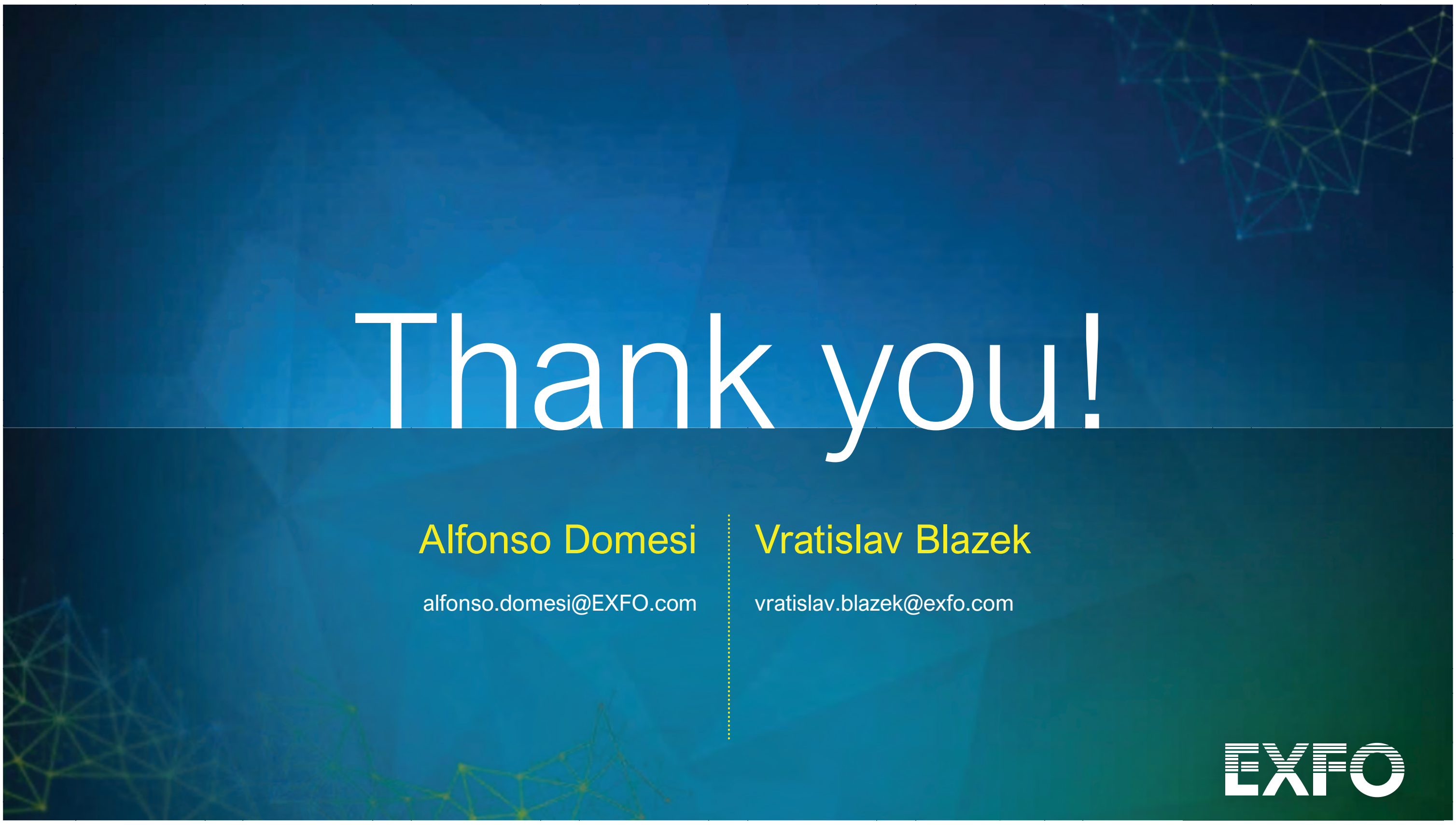
Nova Fiber mobile enables multiple instances of connection and authentication, ideal for managed services



- Link loss (E2E)
- Link length
- Link Pass/Fail status

EXFO


Nova Fiber Mobile _2/2
Mobile app client functionalities
Test any connectorized interface onto a PON
• Menus
• Search routes or terminals
• Single action for testing
• Pass status with values
• Configurable FAIL based on calculated budget loss or fix value (e.g., 30dB)
ID 126_269:OP_demo_route
PON1-CBT1-P1
FAIL
24.09dB
5.1456 km
0.6371 km
EXFO


Thank you!
Alfonso Domesi
alfonso.domesi@EXFO.com
Vratislav Blazek
vratislav.blazek@exfo.com
EXFO

Optično vlakno kot senzor

Optical fibre as a sensor

Uroš Petrič
MI-line, d. o. o.
uros.petric@mi-line.si

Povzetek

Prispevek povzema osnovne lastnosti delovanja in področja uporabe optičnega vlakna kot tipala. Predstavljena je rešitev podjetja Prisma Photonics. Kot primer uporabe je prikazana rešitev za detekcijo padajočega kamenja na Slovenskih železnicah.

Abstract

This paper summarizes the basic performance characteristics and areas of application of optical fiber as a sensor. The Prisma Photonics solution is presented. As an example of use, a solution for the detection of falling stones on the Slovenian Railways is shown.

Biografija avtorja

Uroš Petrič je rojen leta 1971 v Ljubljani. Po diplomi s področja telekomunikacij na Fakulteti za elektrotehniko Univerze v Ljubljani, je začel svojo poklicno kariero na področju analognih in digitalnih PMR sistemih. Sodeloval je pri pilotnem sistemu TETRA (MNZ RS), bil je tudi vodja projekta AIS za potrebe nadzora ladijskega prometa v severnem jadranskem morju (Uprava RS za pomorstvo). Poleg radijskih sistemov se je na svoji poklicni poti ukvarjal tudi z optičnimi prenosnimi sistemi, aplikativnimi rešitvami za mobilne operaterje in z merilno tehnologijo.V prostem času uživa v pohodništvu, popotovanju in poje v pevskem zboru. Trenutno je zaposlen v podjetju MI-line d.o.o., kot vodja projektov.

Author's biography

Uroš Petrič was born in 1971 in Ljubljana. After graduating in the field of telecommunications at the Faculty of Electrical Engineering of the University of Ljubljana, he began his professional career in the field of analog and digital PMR systems. He participated in the TETRA pilot system (MNZ RS), and was also the head of the AIS project for the needs of monitoring shipping traffic in the northern Adriatic Sea (Maritime Administration of the RS). In addition to radio systems, he also worked with optical transmission systems, application solutions for mobile operators and measurement technology during his career. In his spare time, he enjoys hiking, traveling, and singing in a choir. He is currently employed at MI-line d.o.o. as a project manager.

Optično vlakno kot senzor

Januar 2023 Uros.petric@mi-line.com

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Vsebina

- Predstavitev podjetja MI - line d.o.o.
- Predstavitev podjetja Prisma Photonics
- Rešitev Hyper-Scan Fiber-Sensing
  - Tehnologija
  - Področja uporabe
- PoC Detekcija padajočega kamenja na SŽ
- Zaključek

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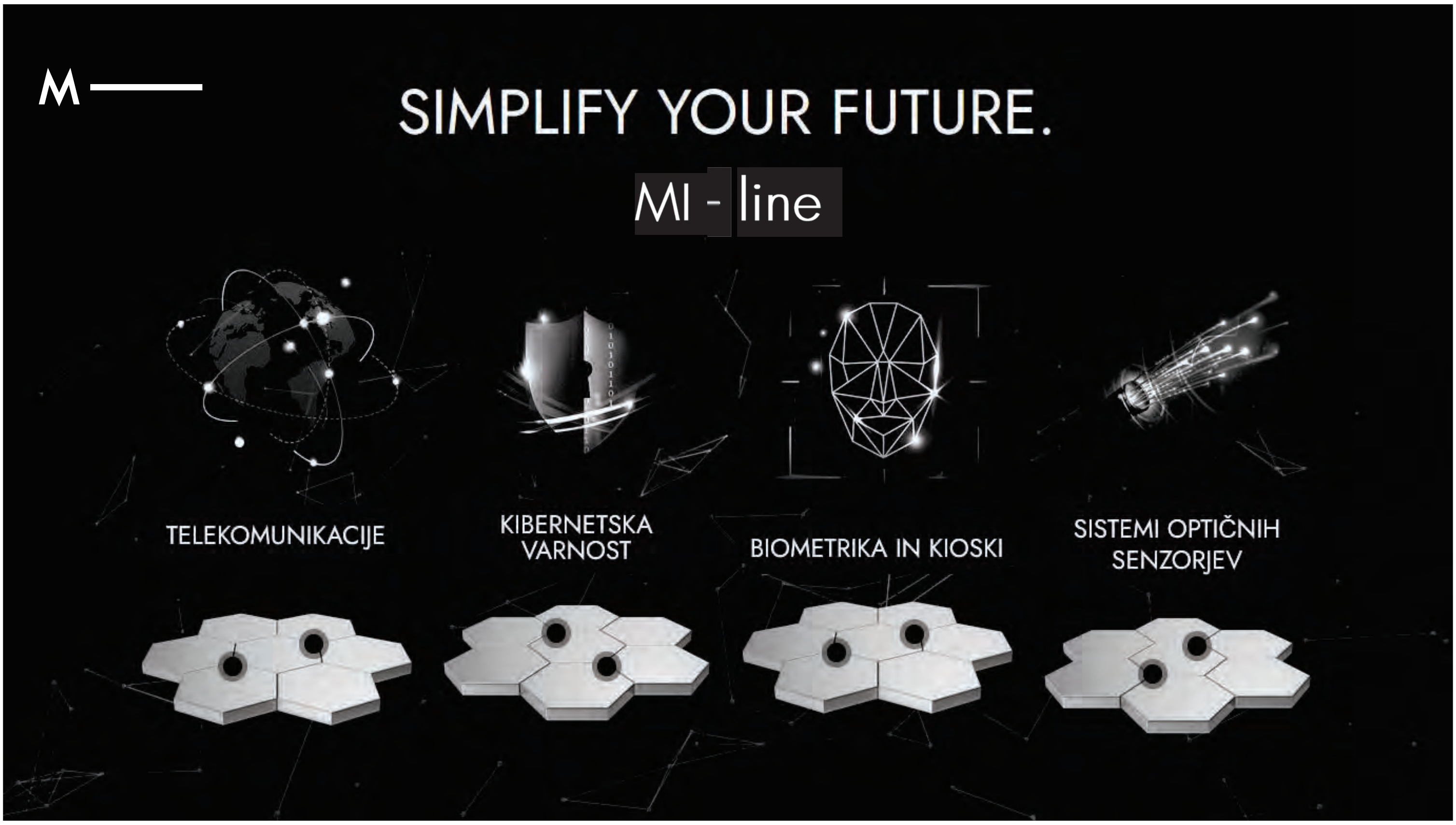
SIMPLIFY YOUR FUTURE.
MI - line
TELEKOMUNIKACIJE
KIBERNETSKA VARNOST
BIOMETRIKA IN KIOSKI
SISTEMI OPTIČNIH SENZORJEV

Prednosti

Eno-rodovno vlakno

Ni potrebe po specialnih optičnih vlaknih.

Porazdeljeno zaznavanje

Meri na vsaki točki vlakna, za razliko od standardnega niza diskretnih senzorjev.

100x večja občutljivost

Tehnološki kvantni preskok, 100-krat bolj občutljiv od senzorjev prve generacije.

Klasifikacija, ki temelji na AI

Rezultat strojnega učenja omogoča natančno klasifikacijo dogodkov, ki jih sicer ni mogoče klasificirati.

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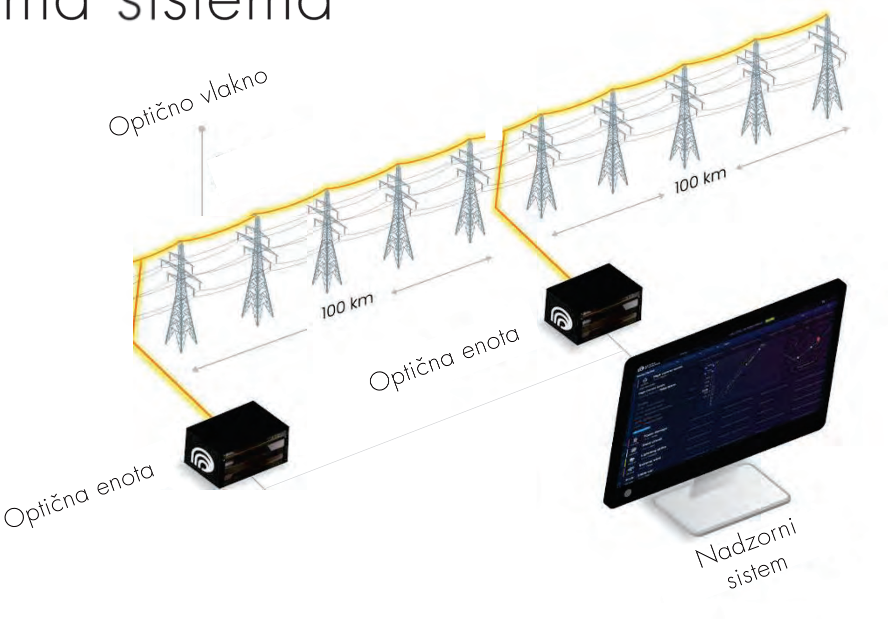
Shema sistema



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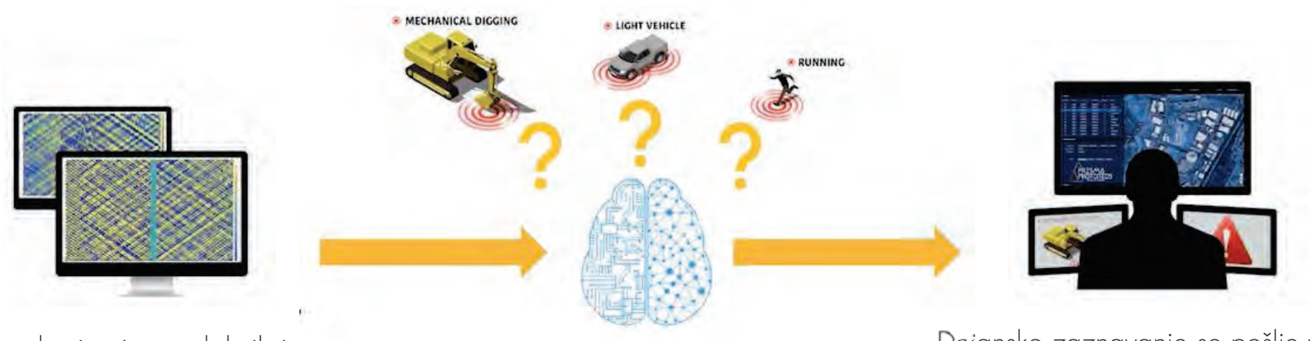
Princip delovanja

HYPER-SCAN™ SMART-CLASSIFICATION™



Hiper skeniranje po vlaknih in posredovanje podatkov AI

Strojno učenje AI razvršča dogodke

Dejansko zaznavanje se pošlje v operacijski center

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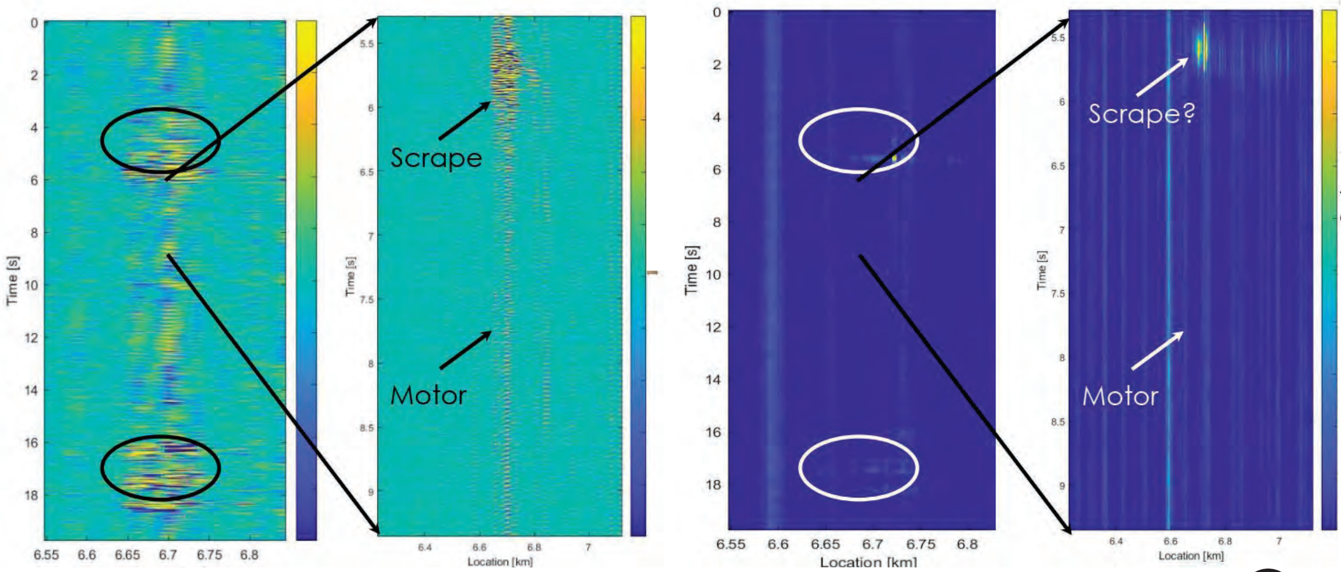
HYPER-SCAN™

Hyper Scan™ Tipični DAS



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Področja uporabe

- Cevovodi
- Daljnovodi
- Varovanje meje/območja
- Podvodna infrastruktura
- Pametne ceste
- Pametne železnice
- Varovanje optične infrastrukture

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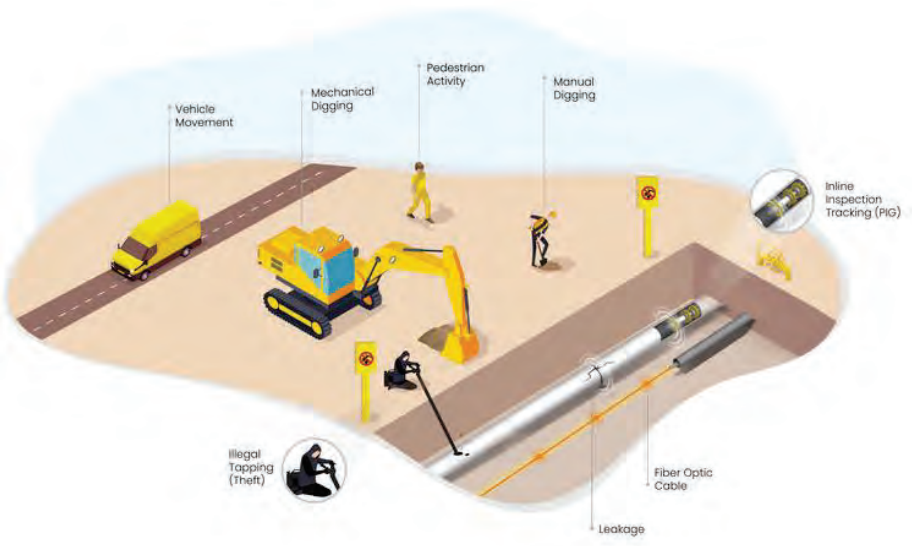
Primer uporabe: Cevovodi

Prisma Flow



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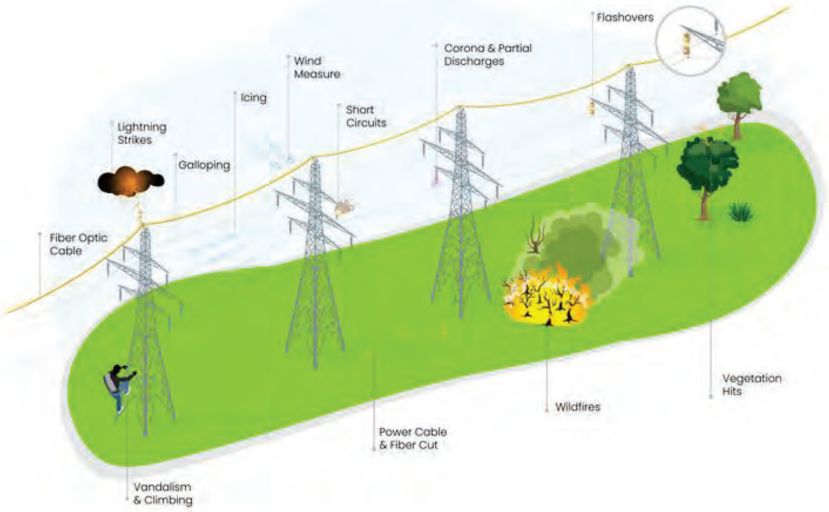
Primer uporabe: Daljnovodi

PrismaPower



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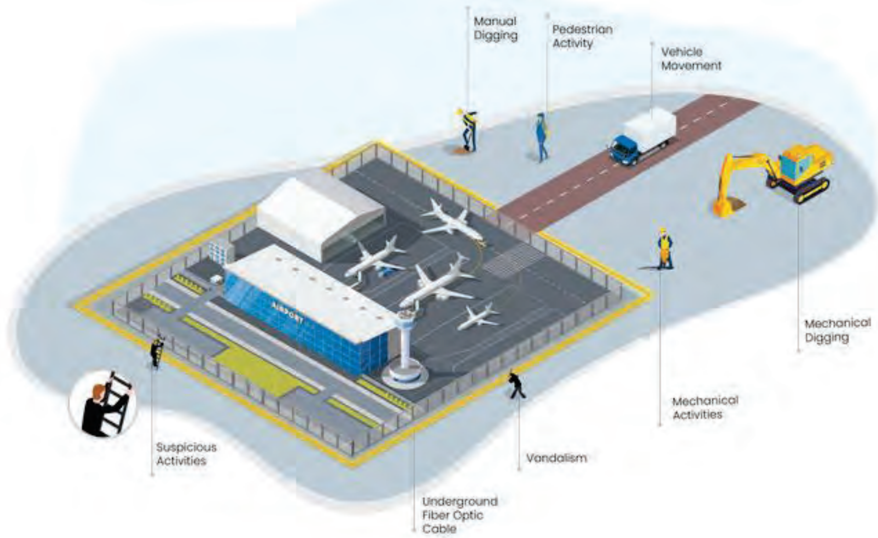
Primer uporabe: Varovanje objektov

PrismaHedge



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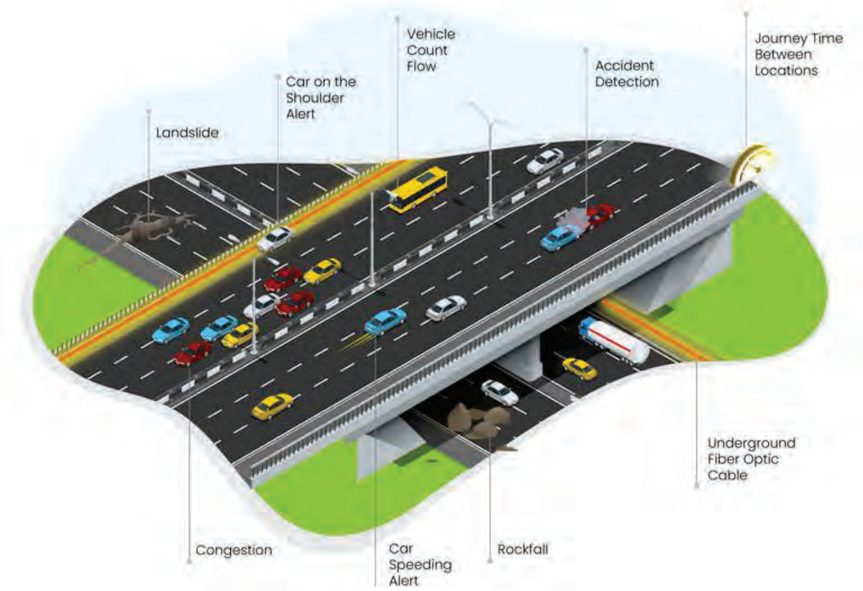
Primer uporabe: Pametne ceste

PrismaRoad



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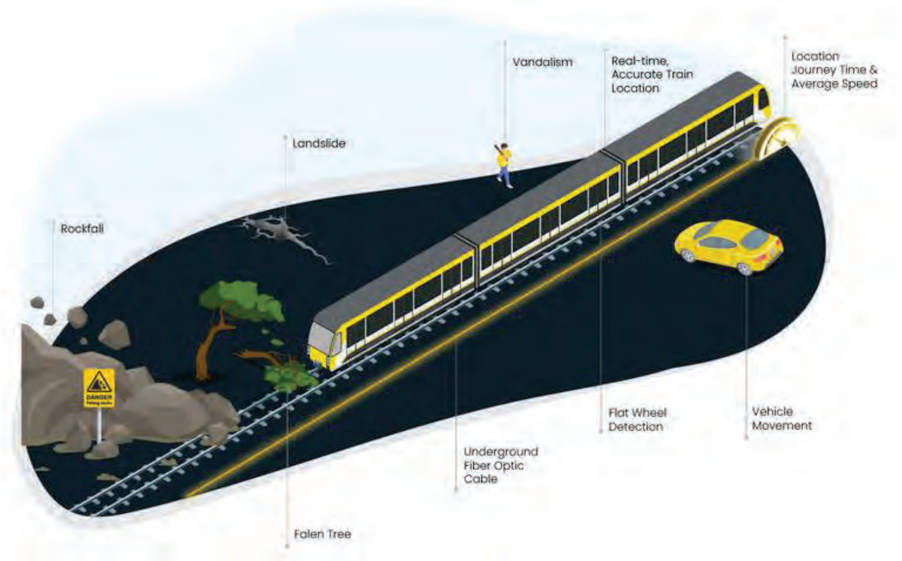
Primer uporabe: Pametne železnice

PrismaRail



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M

PoC zaznavanje dogodkov na SŽ

Splošno:

- Čas trajanja: 19.9 do 20.9. 2022
- Lokacija:NOC Ljubljana, Železniška postaja Laze
- Udeleženci: SŽ infrastruktura, Prisma Photonics, MI – line
- Oprema: obstoječe prosto optično vlakno, žel. derezina, kamenje in pragovi, Prisma Hyper-Scan Fiber-Sensing sistem, VPN povezava.

Cilji:

- Detekcija vlakov na relaciji Ljubljana-Zidani most
- Simulacija in detekcija padajočega kamenja
- Simulacija in detekcija padajočega drevesa
- Simulacija in detekcija "ploščatega kolesa".

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Slovenske železnice

M

PoC Topologija sistema

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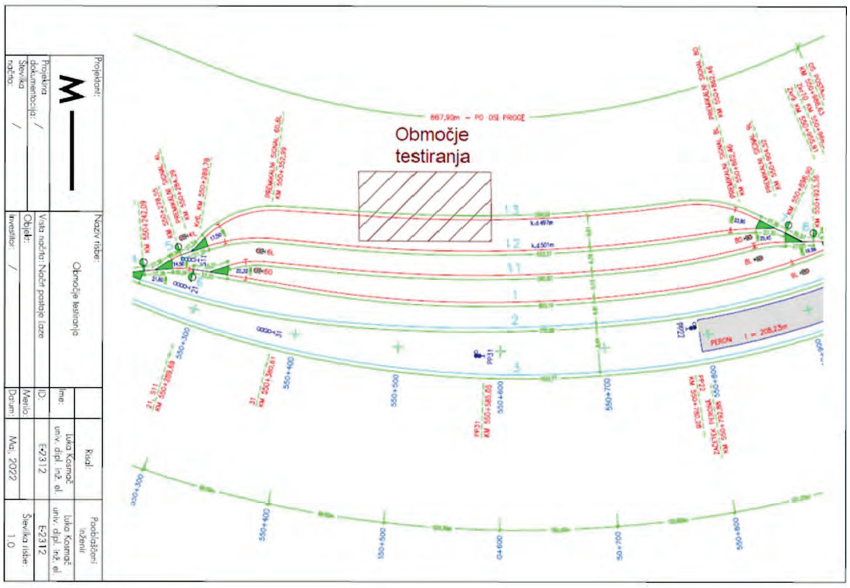
Slovenske železnice

PoC Testno območje



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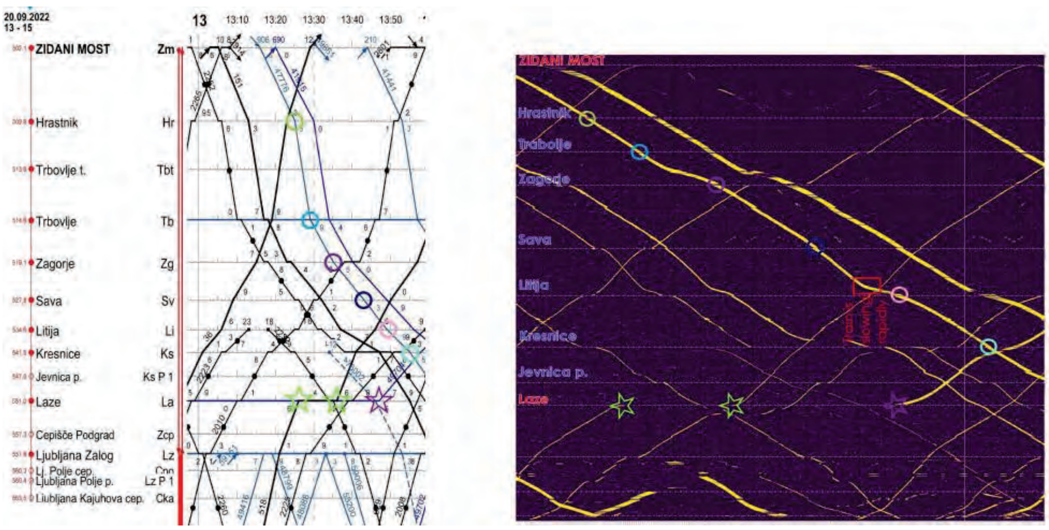
Slovenske železnice

PoC Detekcija vlakov na relaciji Ljubljana-Zidani most



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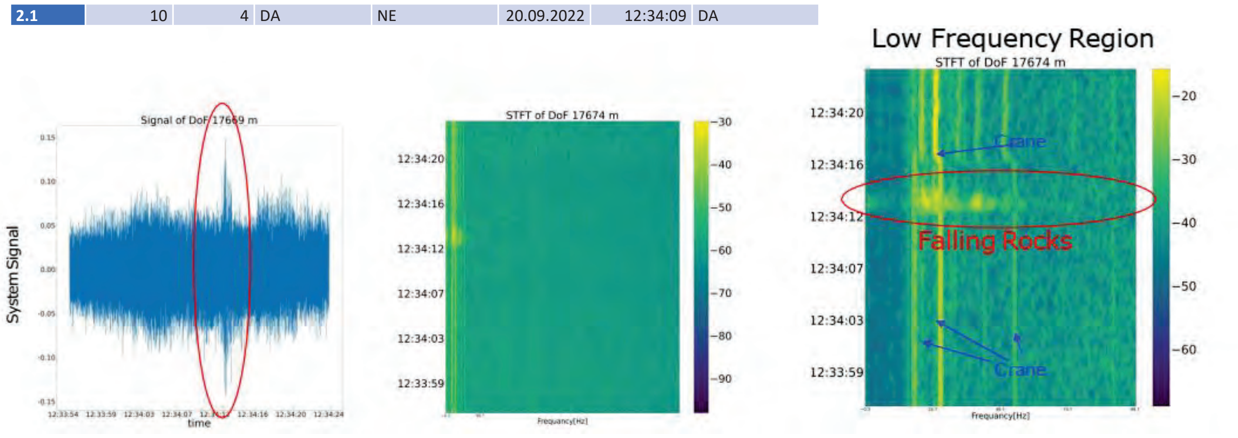
Slovenske železnice

PoC Detekcija padajočega kamenja

Test#	Teža (kg)	Višina (m)	Cestni promet	Železniški promet	Datum	Sistemski čas	Detekcija signala
2.1	10	4	DA	NE	20.09.2022	12:34:09	DA

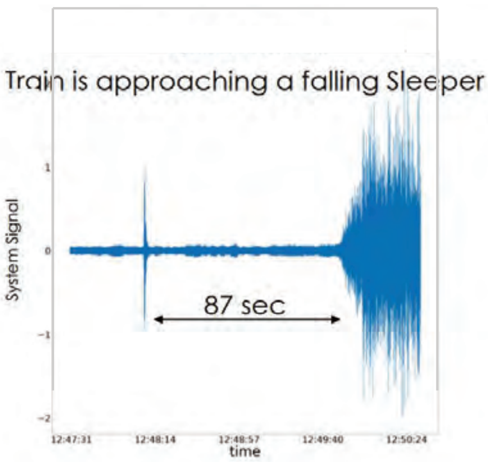


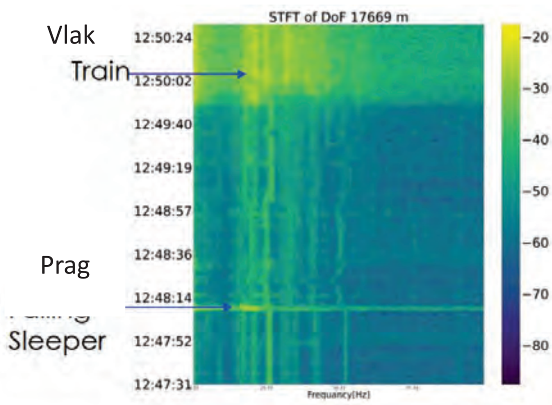
MI - line
www.mi-line.com

Slovenske železnice

PoC Detekcija padajočega drevesa

Test#	Železniški prag	Višina (m)	Cestni promet	Železniški promet	Datum	Sistemski čas	Detekcija signala
2.1	1	4	NE	DA	20.09.2022	12:48:14	DA





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Slovenske železnice

Linijsko merjenje temperature z optičnimi vlakni v industriji

Line temperature measurements with optical fibers in industrial applications

Gorazd Mandelj

GM Projekt, d. o. o.

gorazd@gmprojekt.si

v

Povzetek

V prispevku je prikazan osnovni princip delovanja optičnega vlakna kot senzorja temperature. Prikazano je nekaj najbolj splošnih področij uporabe iz industrije ter implementirana rešitev v avtocestnih predorih v Sloveniji.

Abstract

The lecture shows the basic principle of operation of an optical fiber as a temperature sensor. Some of the most general areas of use from industry are shown, as well as an implemented solution in motorway tunnels in Slovenia.

Biografija avtorja

Gorazd Mandelj je na Fakulteti za elektrotehniko v Ljubljani diplomiral leta 1998 in magistriral leta 2005 s področja biometrije razpoznavanja očesne šarenice. Po vodstvenih pozicijah projektnega vodenja in menedžmenta v gospodarstvu do leta 2014, je sedaj zaposlen v lastnem podjetju GM PROJEKT d.o.o., kjer se, poleg projektnega vodenja, varnostnega inženiringa z ocenjevanjem tveganj in svetovanja, ukvarja tudi z visokotehnološkimi rešitvami s področja biometrije razpoznavanja očesne šarenice in linijskega merjenja temperature. Gorazd Mandelj je certificiran strokovnjak za področje biometrije in linijskega merjenja temperature s strani mednarodnih podjetij, ter liceniran varnostni menedžer in pooblaščeni inženir varnostnih sistemov s strani MNZ in IZS. Na povabilo zbornice ZRSZV je tudi strokovni predavatelj sistemov tehničnega varovanja za različne nacionalne poklicne kvalifikacije varnostnega osebja.

Author's biography

Gorazd Mandelj graduated from the Faculty of Electrical Engineering in Ljubljana in 1998 and received his master's degree in 2005 in the field of iris recognition biometrics. After holding managerial positions in project management and management in different companies until 2014, he is now employed in his own company GM PROJEKT d.o.o., where, in addition to project management, safety engineering with risk assessment and consulting, he also deals with high-tech solutions in the field of iris recognition biometrics and line temperature measurement. Gorazd Mandelj is a certified expert in the field of biometrics and in line temperature measurement by the international companies, and licensed Safety Manager and authorized Safety Systems Engineer by MNZ and IZS. Upon the invitation of the ZRSZV chamber, he is also an expert lecturer on technical security systems for various national professional qualifications of security personnel.

Linijsko merjenje temperature v industriji z optičnimi vlakni

- Linijsko merjenje T – princip delovanja
- Primeri v praksi – predor Markovec

mag. Gorazd Mandelj, u.d.i.e.
Poobl. inženir var. sist., IZS E-1593
Certificirani distributer opreme za fiber-optično detekcijo temperature Luna Innovations Germany
GM PROJEKT d.o.o.
gorazd@gmprojekt.si www.gmprojekt.si

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1. Linijsko merjenje temperature

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Problem – merjenje temperature v agresivnih okoljih ?

Kako uspešno in pravočasno zaznati pogoje za pregrevanje odseka ter izvesti (pred)alarmiranje?

Rešitev:

Uporaba sistema za linijsko merjenje temperature na daljših razdaljah do 70 km ali na večjih površinah z razvodom senzorskega optičnega kabla:

-pravočasno zaznavanje pregrevanja pred izpadom oz. nastankom škode ali nastankom požara (preventivni ukrep NE kurativni)

-zaznavanje temperature na odsekih do 2 m natančno

-poljubno SW definiranje merilnih/alarmnih odsekov

-enostavna integracija v obstoječe SCADA sisteme oz. sisteme javljanja požara ali samostojno oz. neodvisno javljanje (pred)alarmnih stanj.

1. Linijsko merjenje temperature

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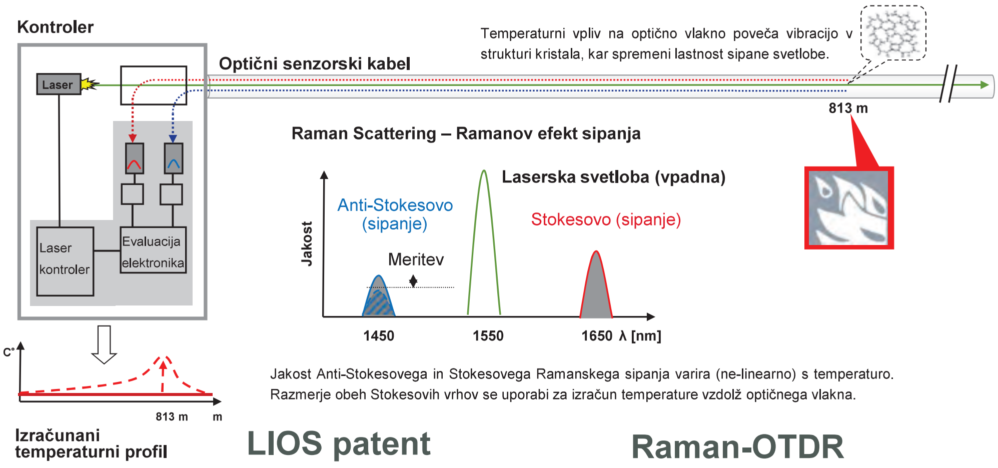
Fizikalni princip – KAKO deluje DTS ?



LIOS patent Raman-OFDR

- Frekvenčno-moduliran cw laser
- High duty cycle / low peak power
- Visok signal
- Konstantna meritev vzdolž kabla

Raman-OTDR

- Pulzni laser
- Low duty cycle / high peak power
- Nizek signal
- Omejeno trajanje laserja
- Napaka meritve narašča z razdaljo

1. Linijsko merjenje temperature

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DTS strojna oprema in FO linijski senzorski kabel – KAKO deluje ?

DTS = Distributed Temperature Sensing

Merjenje temperature vzdolž senzorskega kabla se izvaja v periodičnih ciklih.

Možno izvajanje meritev na več merilnih odsekih (kanalih) hkrati. Vsak senzorski kabel ima dve optični vlakni, kar omogoča izvedbo polno redundančnega sistema.

1. Linijsko merjenje temperature

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Ostale variantne rešitve / fizikalni principi:

- DTS = Ramanov princip: vzorčenje do 0.1m in T resolucija do 0.1K; dolžine do 40 km
- DTS & DSS = Brillouinov princip: vzorčenje do 0.25m in T resolucija do 0.1K; dodatno raztezek z resolucijo 20µm/m; dolžine do 70 km
- DAS = Rayleighov princip: vzorčenje do 10m; dolžine do 50 km

1. Linijsko merjenje temperature

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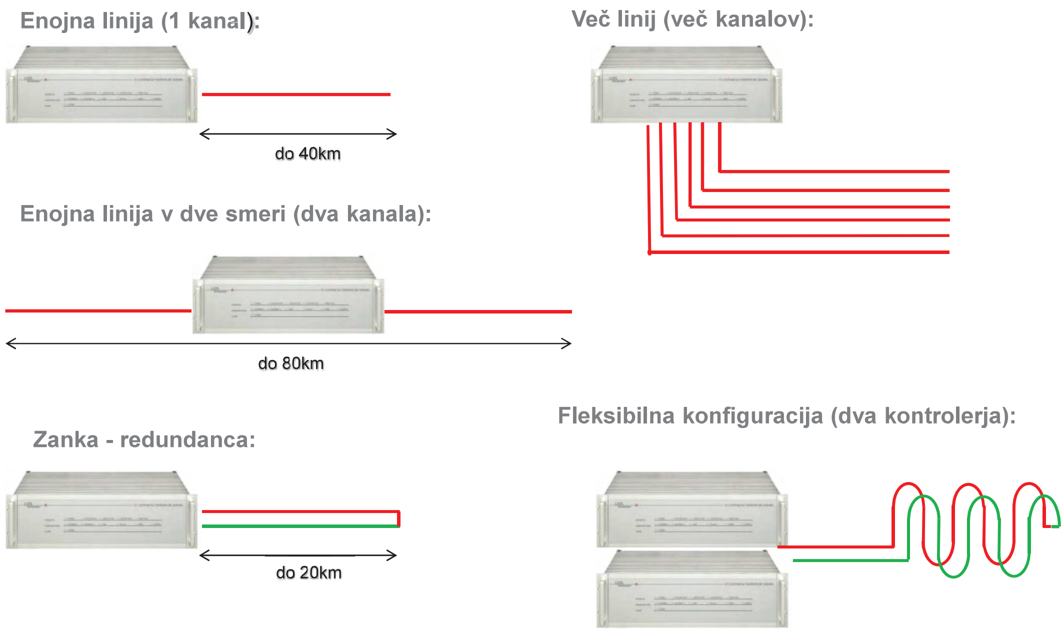
Možne konfiguracije – velika fleksibilnost:



1. Linijsko merjenje temperature

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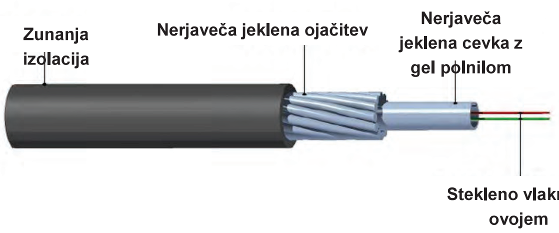
Nastavitev za aplikacijo:

-Definicija (pred)alarmnega kriterija (? Temperatura ?) – termoMAX, TermoDIF, hotspot

-Razteg?

-Ostali (dodatni) kriteriji npr. za dodatno verifikacijo nastanka (pred)alarmnih pogojev: možna interakcija z ostalimi sistemi (3rd party, npr. tehničnega varovanja preko vh / izh vmesnika).



1. Linijsko merjenje temperature

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Prikaz v nadzornem centru (SCADA) – KAKO deluje ?

Informacije o merjeni temperaturi se obdelujejo v realnem času z možnostjo prednastavljenih alarmnih in predalarmnih kriterijev.

1. Linijsko merjenje temperature

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Prednosti za naročnika:

- zaznavanje temperature na razdaljah do 70 km - večja geografska pokritost.
- pravočasno zaznavanje pregrevanja pred izpadom oz. nastankom škode ali nastankom požara
- enostavno vzdrževanje in nižji stroški vzdrževanja sistema v primerjavi s klasičnimi sistemi (npr. točkovno javljanje požara)
- najmanj 20+ let obstojnost senzorskega kabla (velika robustnost)
- poljubno parametriranje sistema: zaznavanje temperature na odsekih do 2 m natančno, poljubno definiranje merilnih/alarmnih odsekov
- enostavna integracija v obstoječi sistem javljanja požara ali samostojno oz. neodvisno javljanje (pred)alarmnih stanj.
- kvalitetna tehnična podpora (lokalni certificirani partner GM projekt)

1. Linijsko merjenje temperature

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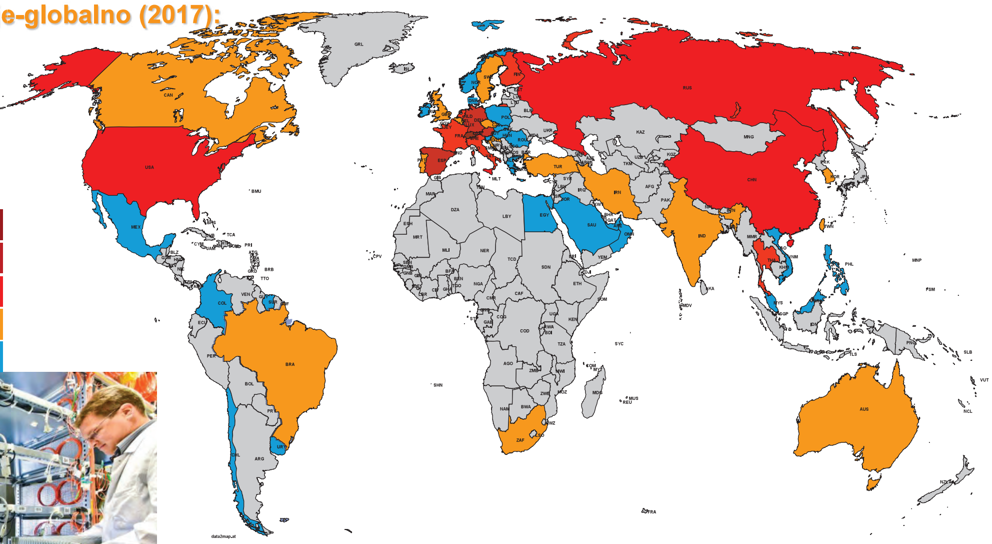
Aplikacije-globalno (2017):



GLOBALNO - Aplikacije na več kot 4.500 vgrajenih sistemih.

1. Linijsko merjenje

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Mednarodna Potrdila in Certifikati:

V skladu z strogimi zahtevami varnostnih standardov in zahtev trga so produkti linijskega merjenja temperature podvrženi certifikacijam v naslednjih neodvisnih inštitucijah:

- VdS	Association of German Property Insurers
- VdS	Quality Management System ISO 9001:2008
- Deloitte	Environmental Management System ISO 14001
- TÜV	ATEX
- FM	USA
- CE	Europe (electromagnetic compliance)
- IBS	Austria
- VKF	Switzerland
- CNBOP	Poland
- CNACL	Chinese State Bureau of Tech Supervision
- KFI	Korea

2. Aplikacije v industriji

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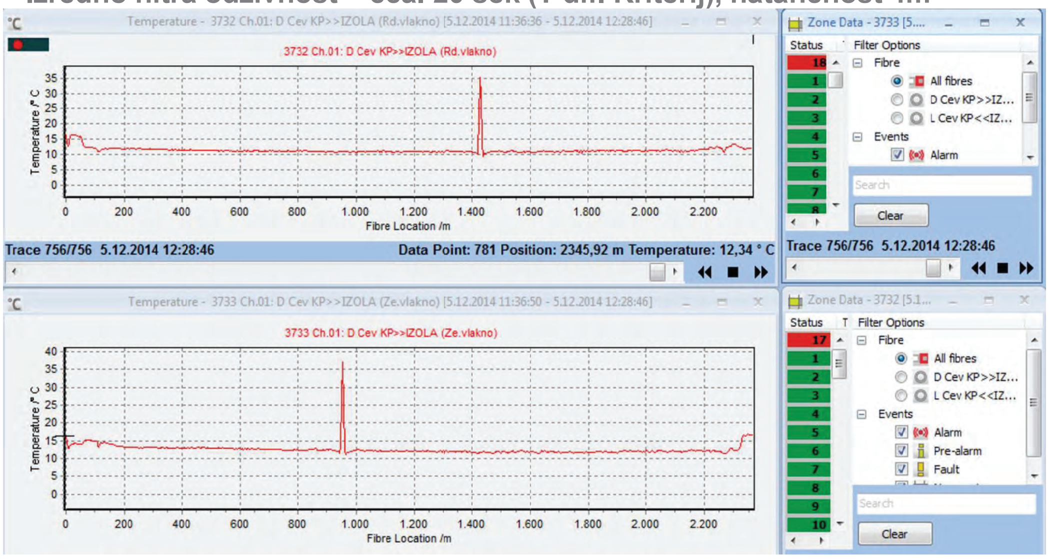
Avtocestni predori (Markovec – SLO)

- Izredno hitra odzivnost – cca. 20 sek (T dif. Kriterij), natančnost 4m



Nastop požarnega alarma v Desni cevi – rdeče in zeleno vlakno iz obeh PogC.

2. Aplikacije v industriji

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Plinovodi, močnostni el. kabli, rafinerije,…

Power Cable Monitoring

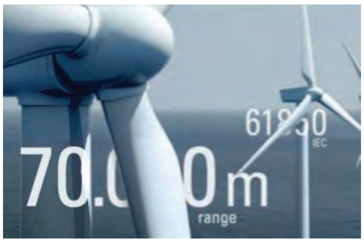
Temperature monitoring & rating solution for the energy transmission and distribution grid

Industrial Monitoring

Monitoring of refineries, reactor vessels / gasifiers, induction furnaces, LNG tanks, pipelines and other industrial infrastructures

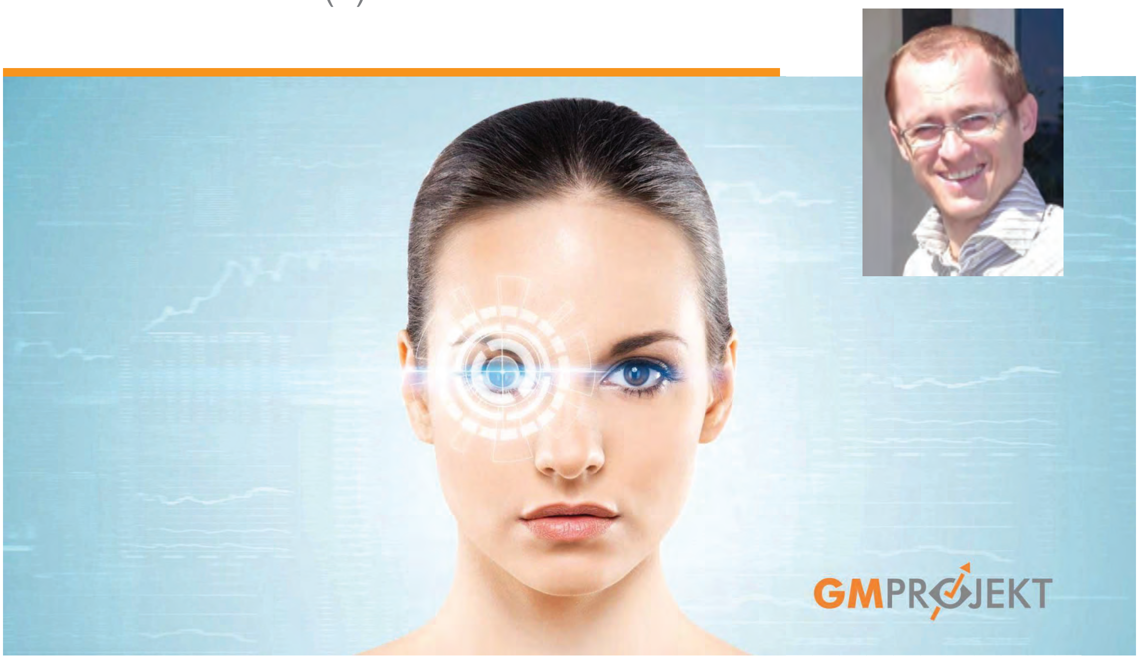
Monitoring for Oil & Gas

Injection & Production monitoring, Fracture monitoring, Well integrity, and CO2 injection well monitoring



Za vse dodatne informacije in predstavitev rešitev smo vam na voljo: info@gmprojekt.si www.gmprojekt.si

Telefon: 00 386 (0)31 393 087



Fiber Sensing technologies for Critical Infrastructure monitoring

Milorad Sarić

IBIS Instruments

milorad.saric@ibis-instruments.com

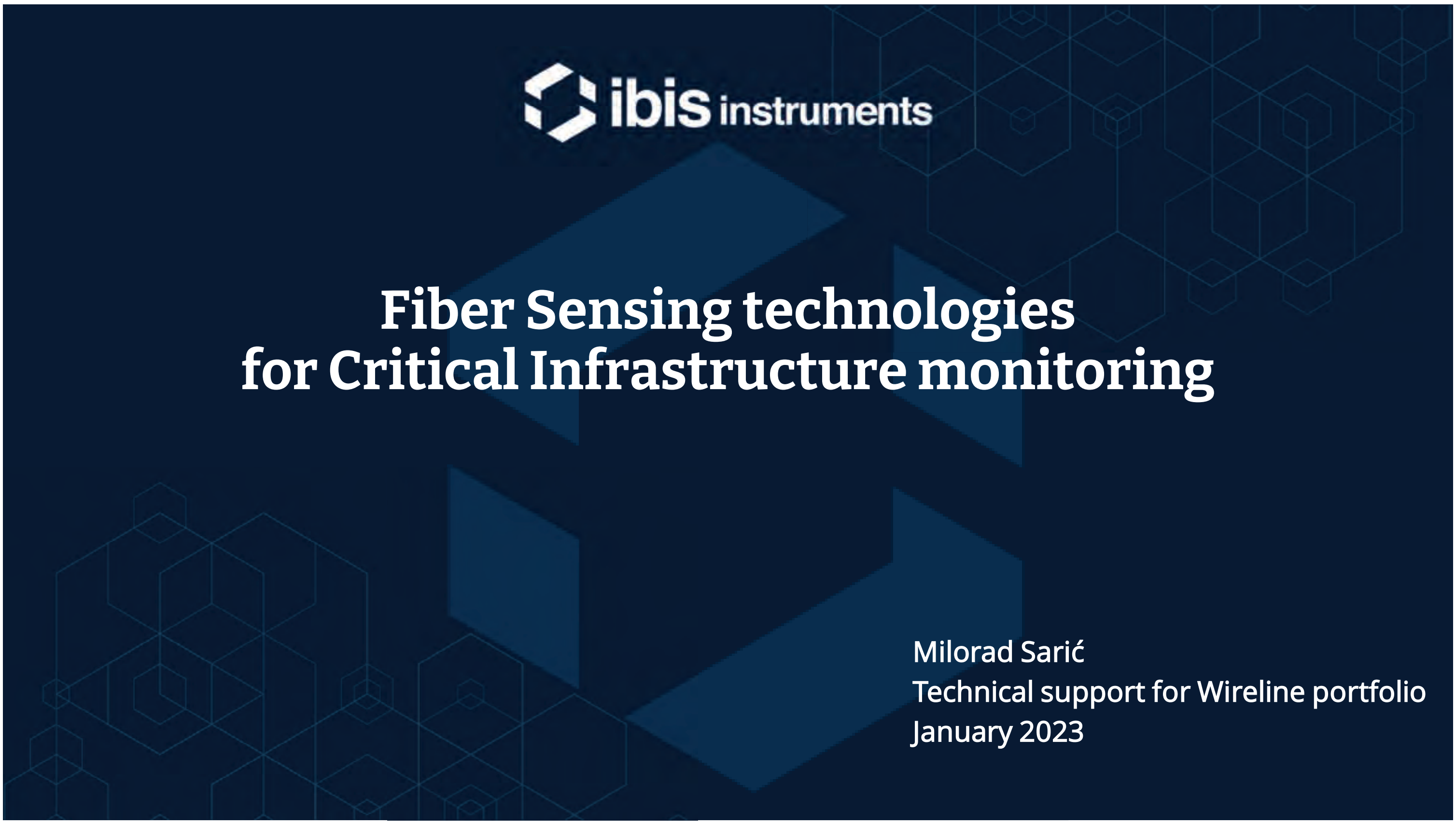
Abstract

Distributed Fiber Optic Sensing presents a different use of optical fiber. Fiber is traditionally used as telecommunication medium, but with this technology it converts into thousands of virtual sensors. The underlying solution leverages specific Optical Time Domain Reflectometer technology to sense subtle changes in the fiber optic cable index of refraction that is a result of changes in the cabling temperature, vibration and/or lateral strain. Numerous applications range across industries and allow early detection and location of fiber aging, overstressed cable detection, pipeline leakage, hotspot/icing, ground movement impact, third party intrusion, electrical arcing or flashover.

Author's biography

Milorad Sarić is technical support engineer with 15 years' experience in presales and postsales support of test and measurement solutions.

He is employed at IBIS Instruments since 2018. He is member of IBIS technical T&M team and responsible for wireline communications solutions (Access Copper, CATV and Optical Networks) and General-Purpose instruments. Milorad graduated in 2007. at the Faculty of Electrical Engineering in Belgrade.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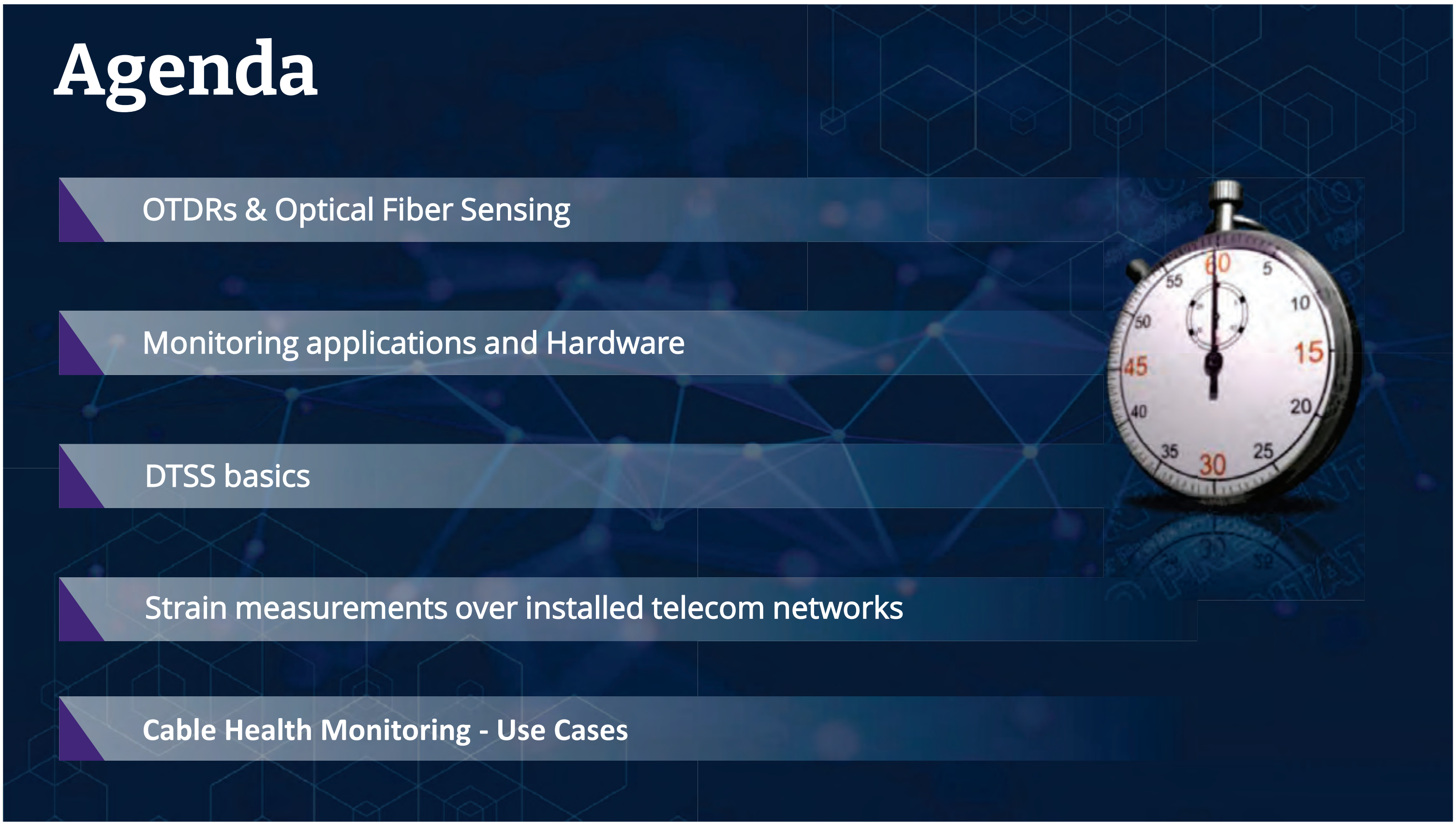
Fiber Sensing technologies
for Critical Infrastructure monitoring
Milorad Sarić
Technical support for Wireline portfolio
January 2023


Agenda
OTDRs & Optical Fiber Sensing
Monitoring applications and Hardware
DTSS basics
Strain measurements over installed telecom networks
Cable Health Monitoring - Use Cases

OTDRs & Optical Fiber Sensing

Distributed Fiber Optic Sensing: A different use of fiber

Optical fiber as an array of thousands virtual sensors

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OTDRs & Optical Fiber Sensing

Using standard Single optical fibre:
Pulses of light are **sent**
Backscattered light is **received**
The backscatter is interrogated
Changes in characteristics
Caused by external stimulus

The **Fibre** is the **Sensor**

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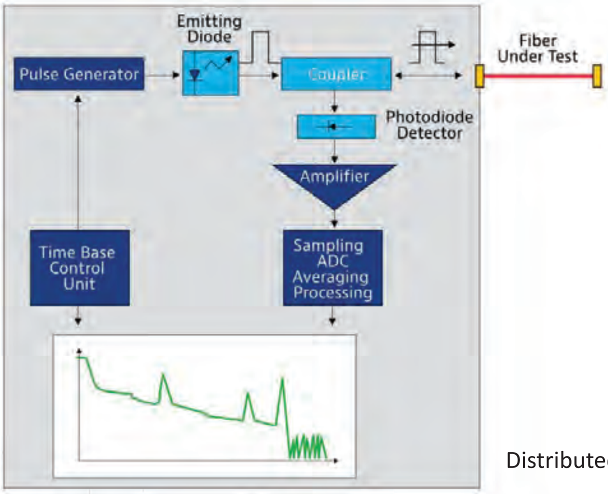
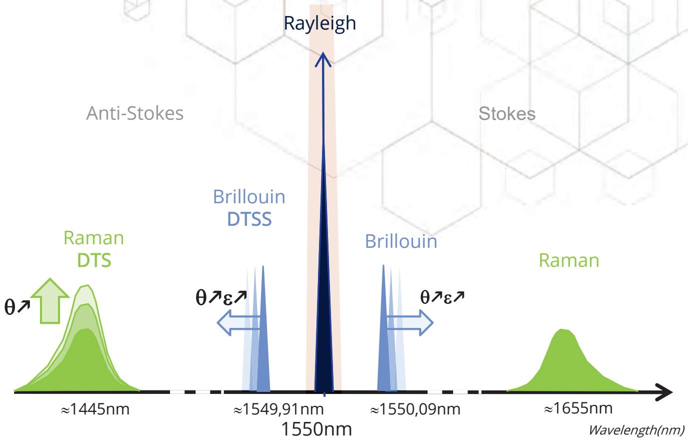
OTDRs & Optical Fiber Sensing





Distributed Fiber Optic Sensing derived from **OTDR** using **Direct or Coherent technologies**

Rayleigh OTDR → Fiber Monitoring - Loss, Reflections & Failures
Raman OTDR → Distributed **Temperature** Sensing (**DTS**)
Brillouin OTDR → Distributed **Temperature & Strain** Sensing (**DTSS**)
Coherent **Rayleigh** OTDR → Distributed **Vibration/Acoustic** Sensing (**DVS/DAS**)

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Monitoring applications and Hardware

Passive sensor : The sensor is just the fiber

- **Advantages**

✓ **Just light sent into the sensing fiber from one side** (interrogator can be at several km from the sensing area. Fiber sensor doesn't need any electrical sources

✓ One fiber cable becomes a sensor , enabling monitoring on **a truly distributed basis**

✓ **Immune to radiation**, EMI , ESD , … (Optical fiber)

✓ Compatible with ATEX zone (ATmospheres Explosives).

✓ Compatible with harsh environments (dust, …)

- **Some examples of applications in Process Productivity & Safety** :

❑ Process temperature monitoring

❑ Pipe & tank monitoring (liquid & gas storage where leakage is not an option)

❑ Structural monitoring, ground movement detection

❑ Early detection of overheating, hot spot or fire

❑ Power cable temperature monitoring

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Monitoring applications and Hardware

Distributed Temperature Sensing (DTS)

Buildings & Infrastructure	Fire Detection
Pipelines	Leak Detection
Power Cables	Hot Spots | Depth of Cover | RTTR/Ampacity | Smart Grid
Oil Wells	Downhaul Process Monitoring | Thermal oil recovery | Reservoir monitoring

Distributed Strain & Temperature Sensing (DTSS)

Buildings, Bridges, Pipelines	Pile Load | Structural Health Monitoring | Seismic areas
Mining & Tailings Dams/Dikes	Landslides Monitoring
Power & Telecom Cables	Asset Health Monitoring |Overstressed fiber identification/Fiber aging/Icing

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Monitoring applications and Hardware

Distributed Acoustic Sensing (DAS)

Power & Telecom Cables	Asset Protection/TPI/Excavation | Electrical arcing/Flashover | Anchor Drag (subsea)
Pipelines	Pipeline Integrity Management | Leak Detection | Hot Tapping | PIG Tracking
Equipment health	Electrical SubStation & Three-phase switch Monitoring | Fan/Conveyor belt Operations
Security	Perimeter Security | Border Security
Smart Cities	Intelligent Transport (Rail, Road, …)

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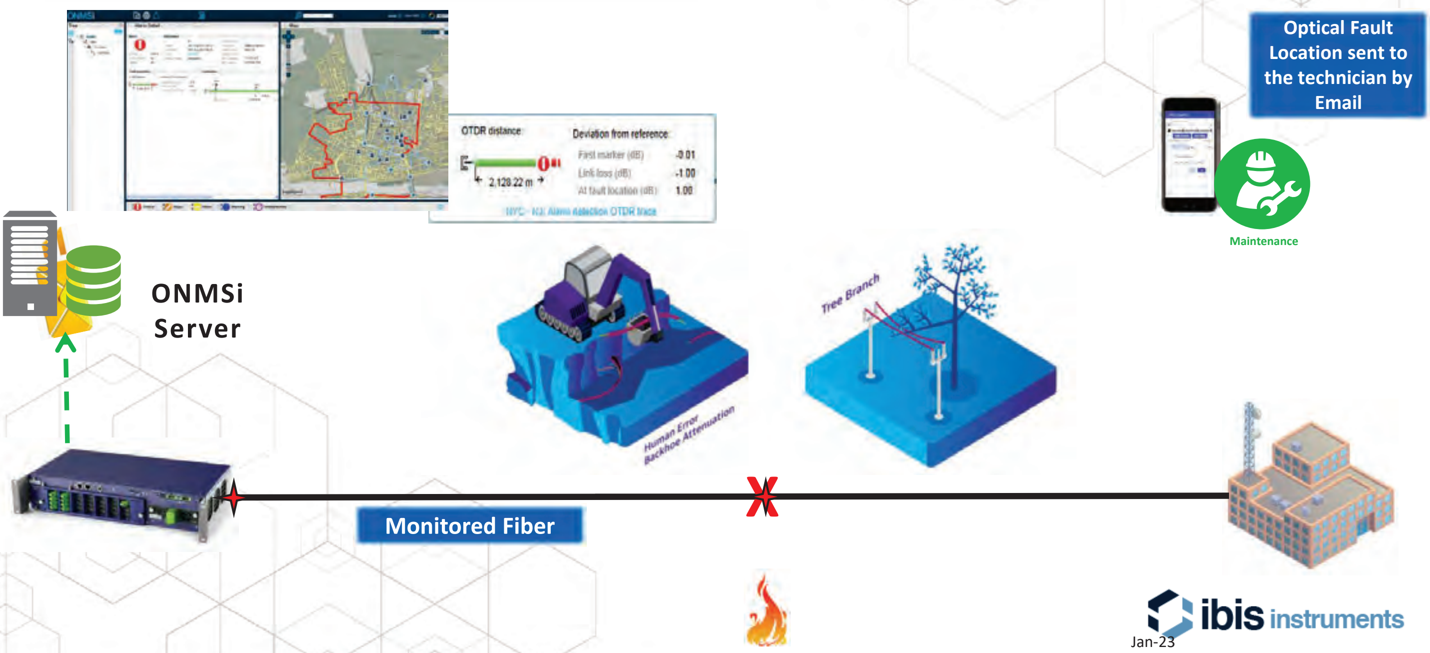
Monitoring Solution

Automatic Monitoring & Alarm Management



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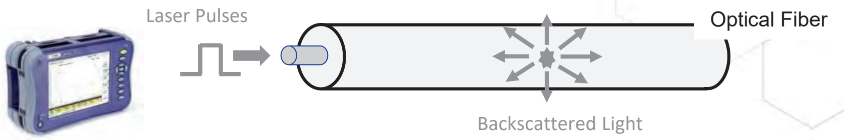
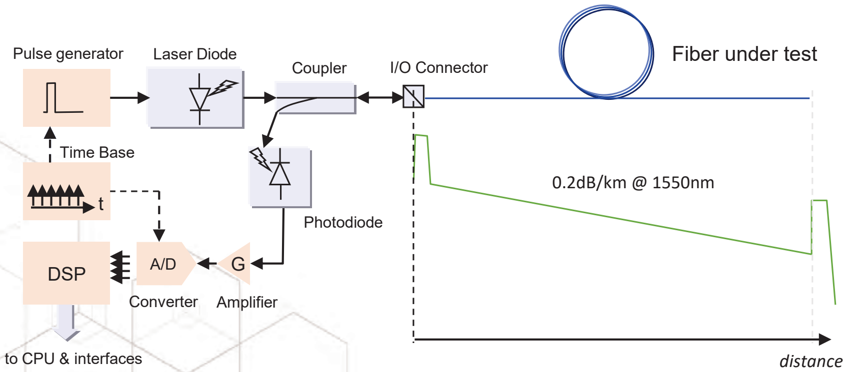
DTSS basics

Optical Time Domain Reflectometer (OTDR)

Regular OTDRs measure all backscattered radiation without filtering the spectrum





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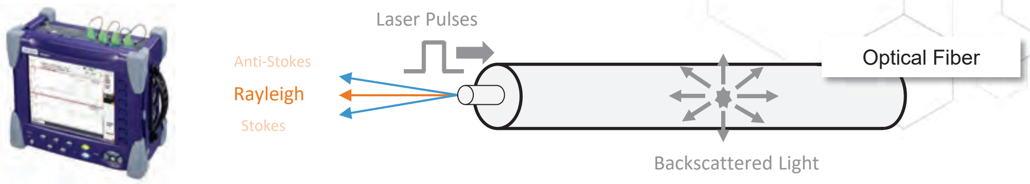
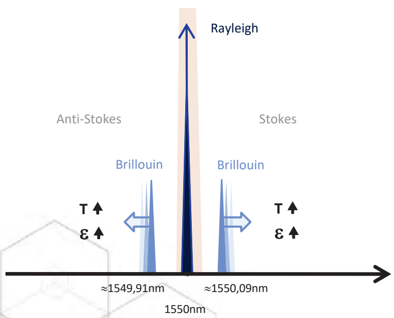
Distributed Temperature & Strain Sensing (DTSS)

Brillouin OTDR (B-OTDR)





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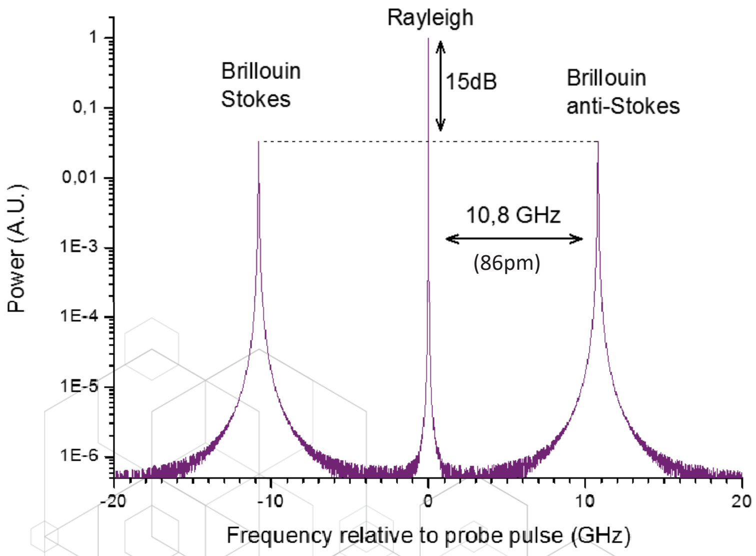
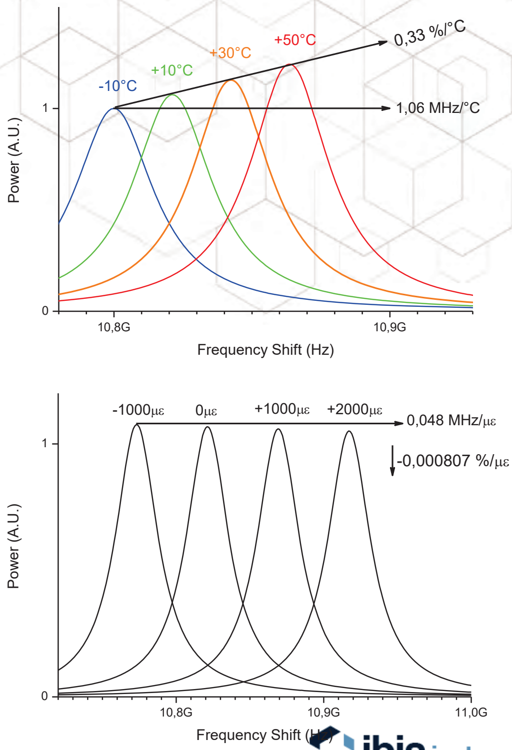
Backscattered Light Spectrum





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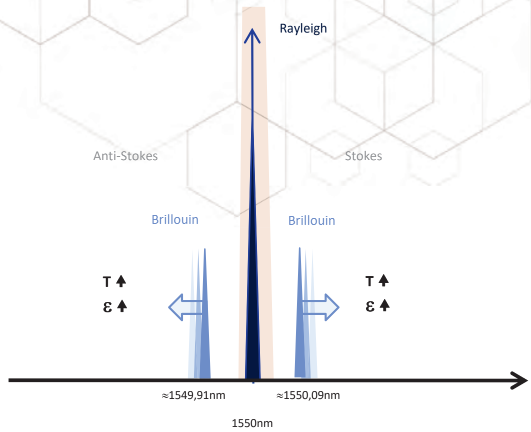
Measurements, Measurands, Coefficients and Offsets

B-OTDR measures

- **Brillouin Frequency Shift** vs **Time** (pulse launched at t=0)
- **Brillouin Power** vs **Time**
- **Rayleigh Power** vs **Time**



Temperature & Strain vs Position

- **Time** → **Distance**
- **Brillouin Frequency** → linearly dependent to **Temperature** & **Strain** (two coefficients, one offset)
- **Brillouin Power** → linearly dependent to **Temperature** & **Strain** (two coefficients, one offset)
- **Rayleigh Power** → **Fiber Losses**

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VIAVI B-OTDR Modes of Operation

Temperature only — Brillouin Frequency Shift and $C_{\vartheta}^{T} = 1,06\ MHz/°C$

Strain only — Brillouin Frequency Shift and $C_{\vartheta}^{\varepsilon} = 0,048\ MHz/\mu\varepsilon$

- Temperature & Strain

$$\begin{pmatrix} \Delta\vartheta_B \\ \Delta P \end{pmatrix} = \begin{bmatrix} C_{\vartheta}^{\varepsilon} & C_{\vartheta}^{T} \\ C_{P}^{\varepsilon} & C_{P}^{T} \end{bmatrix} \begin{pmatrix} \varepsilon \\ \Delta T \end{pmatrix}$$

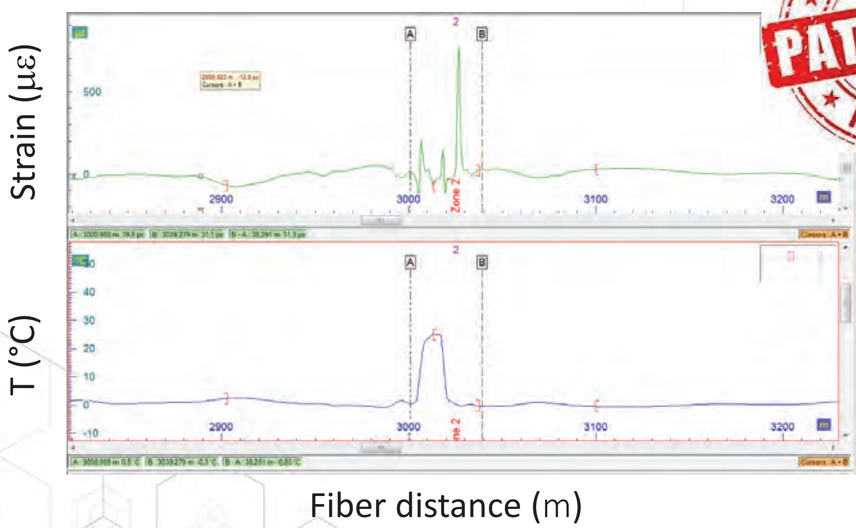
ϑ_B	Brillouin Frequency
P	Brillouin/Rayleigh Power Ratio
ε	Strain
T	Temperature

$C_P^T = 0{,}33\ \%/°C$

$C_P^{\varepsilon} = -0{,}000807\ \%/\mu\varepsilon$

Landau-Placzek Ratio $= \frac{P_{Rayleigh}}{P_{Brillouin}} = \frac{f(attenuation)}{f(\varepsilon,T,attenuation)} = f(\varepsilon, T)$

VIAVI B-OTDR Unique Decorrelation Method



What are the different units?

Measures elongation at every point along the sensing fiber

L ΔL

$$\text{Elongation} = \frac{\Delta L}{L}$$

Temperature & Strain units

- Temperature is given in ° Celsius
- Strain is given in microstrain, µƐ
  - 1 µƐ = it's an elongation or compression of 1µm for a distance of 1 m,
  - also in percentage 1 µƐ = 0,0001%
- Brillouin Shift :
  - 1 MHz= 1°C = 20µƐ = 0,002% for a fiber

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Strain measurements over installed telecom networks

Why measure strain over installed telecom networks?

- Fiber manufactures guarantee a long term operation if fibers are maintained under 0.2% elongation (20% of the production proof test)
- A large number of installation are over 20 years old
- Recent installations are lighter cable structures (ADSS), no metal, low cost, higher fiber counts and bend-insensitive fibers
- Since G652D (<2008), attenuation is no longer a good indicator of strain. In other words the fiber integrity can be threatened while optical transmission still works fine.
- Bend-insensitive fibers indeed, yet still made of glass

	G 652 A	G 652 B	G 652 C	G652 D
Macrobending loss Radius 37.5 mm Number of turns: 100	<0.50 dB @1550 nm	<0.50 dB @1550 nm <0.50 dB@16XX (XX≤25)		< 0.1 dB @1625 nm

- *Safe Stress: 20kpsi=2000με or 0,2%*
- *Rupture Point is 4%*

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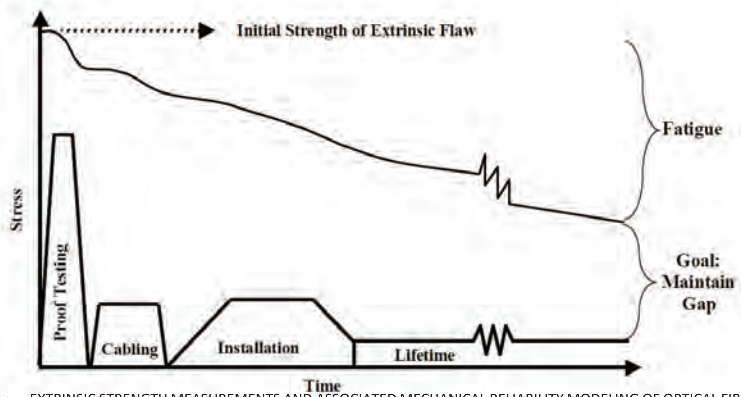
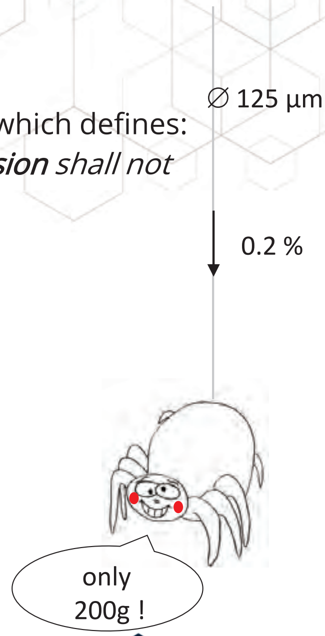
How much strain can be applied on a fiber ?

- Standard fibers are proof-tested at 100kpsi (~1kg, ~1% elongation)
- Fiber will achieve a long life if maintained below 0.2% elongation
- Telecommunications cables are designed as per IEC 60794-3-20 standard which defines:

  «*For 1% proof-tested fibres, the fibre strain **at Maximum Allowable Tension** shall not exceed 20% of this fibre proof strain (equal to absolute 0.2 % strain)*»



EXTRINSIC STRENGTH MEASUREMENTS AND ASSOCIATED MECHANICAL RELIABILITY MODELING OF OPTICAL FIBER, Robert J. Castilone, G. Scott Glaesemann, Thomas A. Hanson, 16th Annual National Fiber Optic Engineers Conference, Denver CO. August 27-30, 2000.



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Strain is an issue, BOTDR measures Strain

- **40 year fiber lifetime <u>only if</u> stress level is maintained below 20% of the proof test** (20% of 100kpsi corresponds to 2000με)- Corning

Total allowable stress design guidelines for any length, resulting in zero failures
Table 2

Duration of Applied Stress	Allowable Safe Stress in Relation to σ_p	Allowable Safe Stress (kpsi) when σ_p = 100 kpsi
40 years	1/5 σ_p	20 kpsi
4 hours	1/3 σ_p	33 kpsi
1 second	1/2 σ_p	50 kpsi

σ_p = proof stress

Strain is measured in microstrain, με

1 με = is the elongation or compression of 1μm for a distance of 1m

or in percentage 1 με = 0,0001%

- **B-OTDR test already becoming a Topic in ITU**
  - Draft revised Recommendation ITU-T L.310 (ex L.53) (for Consent, 26 February 2016). TD 538 Rev. 2 (PLEN/15).

Table 3/L.53 – Suitable test methods for point-to-multipoint access networks

Category	Activity	Item	Methods
Preventative maintenance	Surveillance	Detection of fibre loss increase	OTDR/loss testing
		Detection of signal power loss increase	Power monitoring
		Detection of water penetration	OTDR testing
	Testing	Measurement of fibre fault location	OTDR testing (Note 1)
		Measurement of fibre strain distribution	B-OTDR testing
		Measurement of water location	OTDR testing(Note 1)

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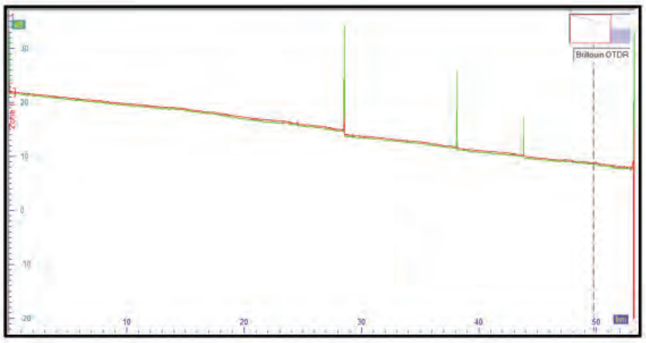
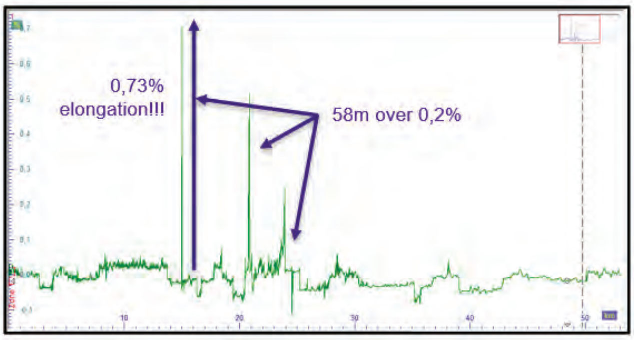
Attenuation vs Elongation

Comparison of OTDR and **B**-OTDR Measurements

Standard OTDR
Attenuation & Reflections



Brillouin OTDR
Strain



Measurements on same 50km long Urban Underground Cable

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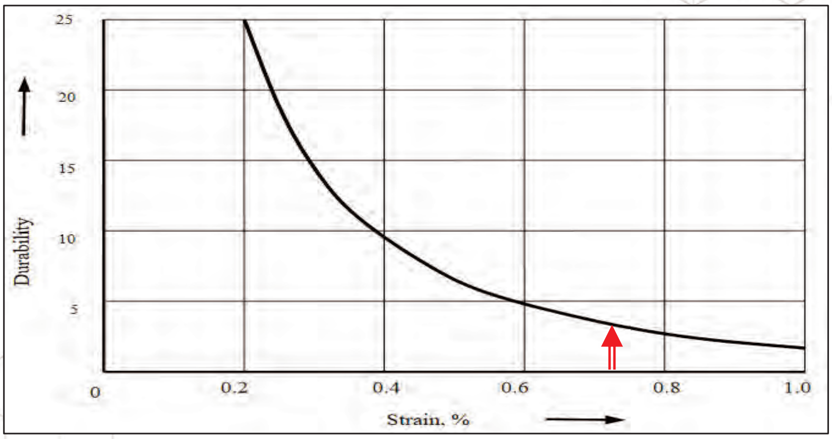
Measuring Strain → Detecting Fiber Aging

Cables under "High" Strain need preventive Maintenance



0.73% tensile strain → probability 3 years life expectancy

Ref. Lutchenko and Bogachkov 2020 J. Phys.: Conf. Ser. 1441 012045

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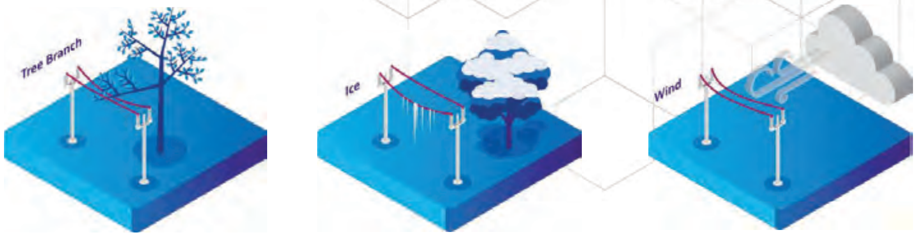
Cable Health Monitoring - Use Cases

Aerial Cables Health Monitoring

OPGW / ADSS cables



Strain
- Installation loads / quality
- Objects on cables
- Ice loads
- Wind loads
- Ground & towers/piles movements
- Seasonal thermal loads

Temperature
- Hot Spots (e.g. OPGW near HV)

OPGW cable

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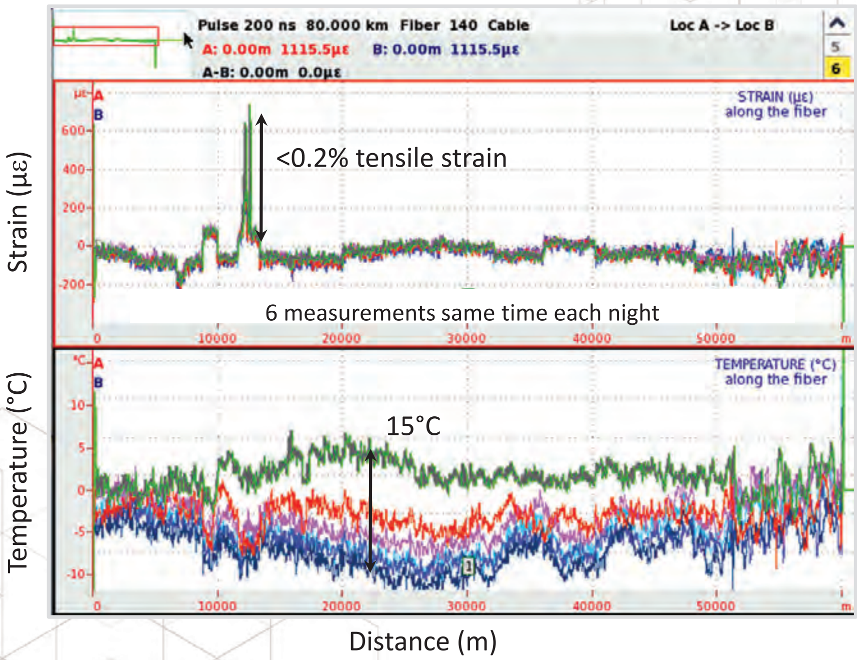
1. 60km Aerial OPGW Cable

Eastern Europe
Mountains
OPGW



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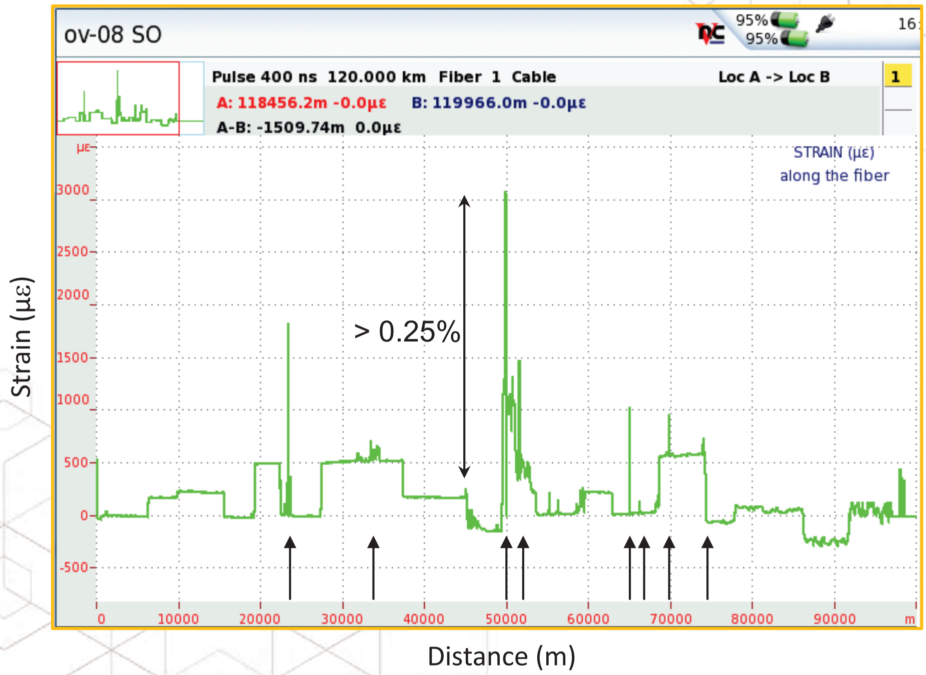
2. 100km Aerial Line

Russia
Extreme Cold Climate
48 OF Cable
One year old



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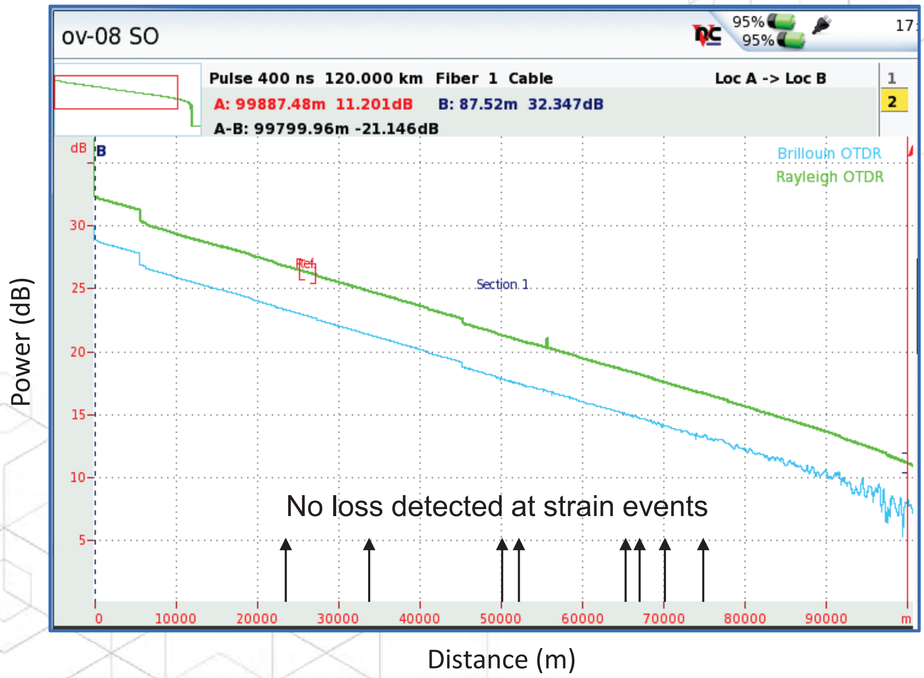
2. 100km Aerial Line OTDR traces

Russia
Extreme Cold Climate
48 OF Cable
One year old



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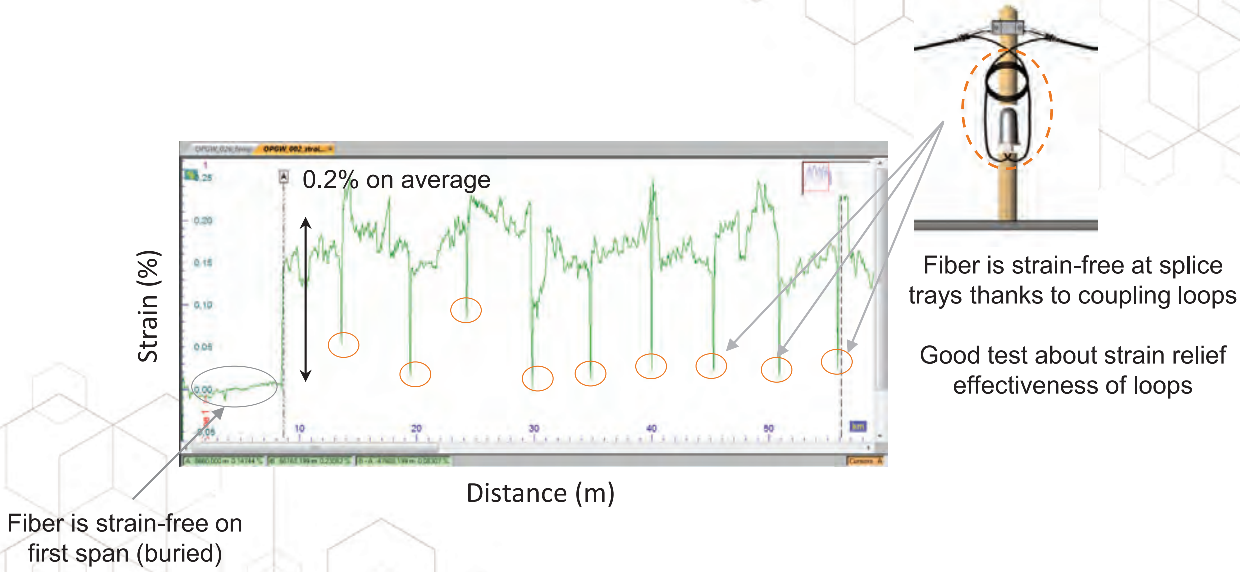
3. 65km Aerial Line

Australia
Extreme Hot Climate
Cable Unknown



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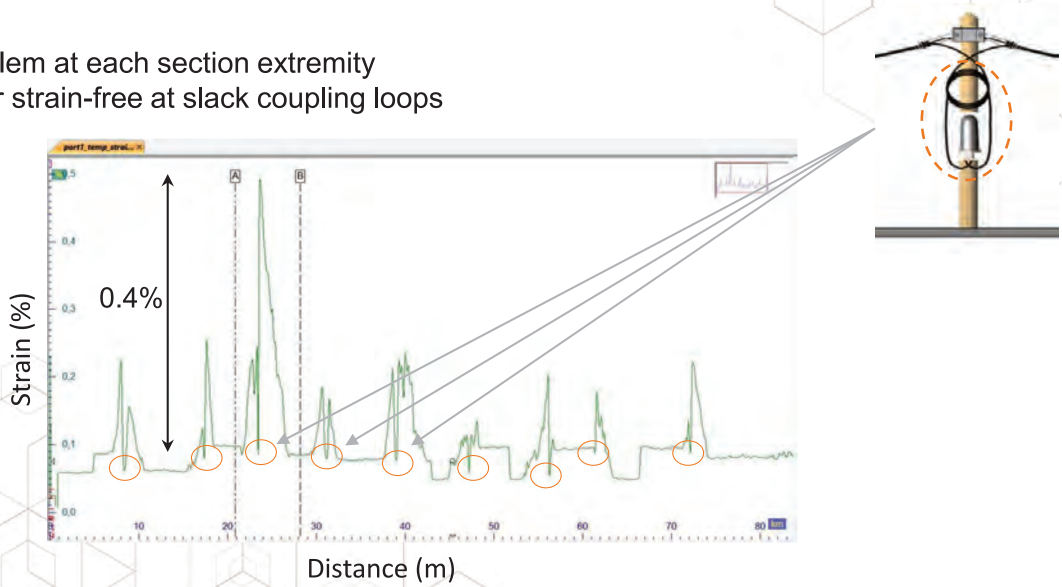
4. 85km Aerial Line

East Europe
Mountains
Cable Unknown

Problem at each section extremity
Fiber strain-free at slack coupling loops



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Over/Underground Cables Health Monitoring

Ducted or Buried Cables

Strain Monitoring

- Installation and commissioning
- Ground movements
- Construction works

Temperature Monitoring

- Burial depth
- Fire detection in ducts
- Leak detection (e.g. water pipes)

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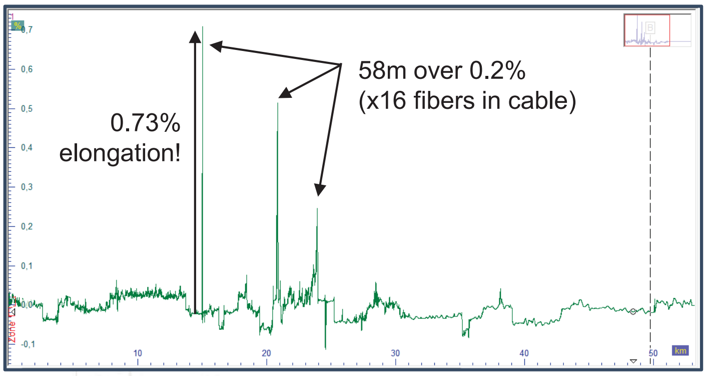
1. 50km Urban Buried Underground Cable

Russia
Buried Urban
16 OF Cable

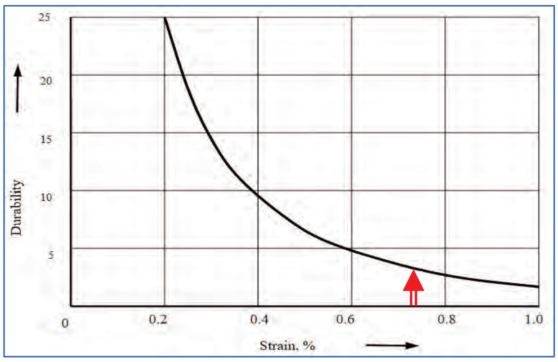
Strain (%)



Distance (m)

No detected loss at strain events

3 years life expectancy for this fiber



Ref. Lutchenko and Bogachkov 2020 J. Phys.: Conf. Ser. 1441 012045

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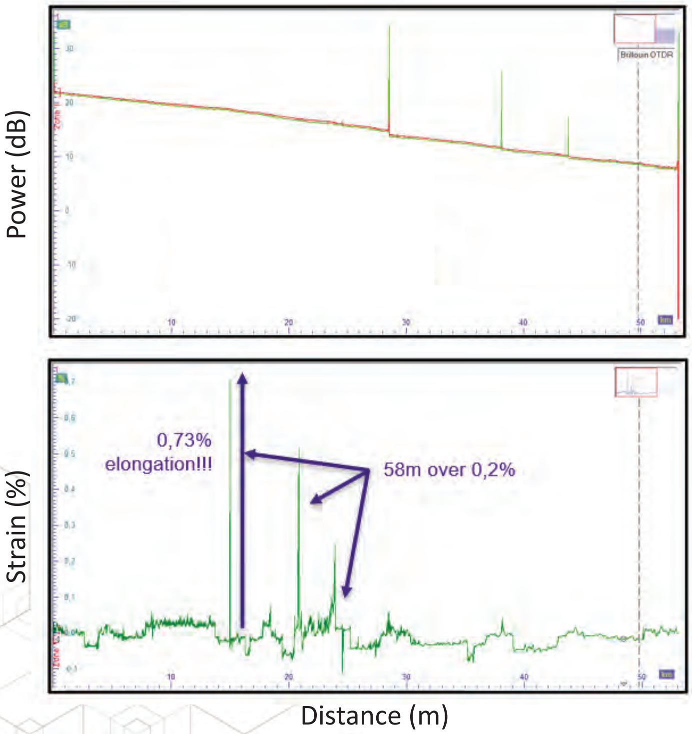
1. 50km Urban Buried Underground Cable

Russia
Buried Urban
16 OF Cable



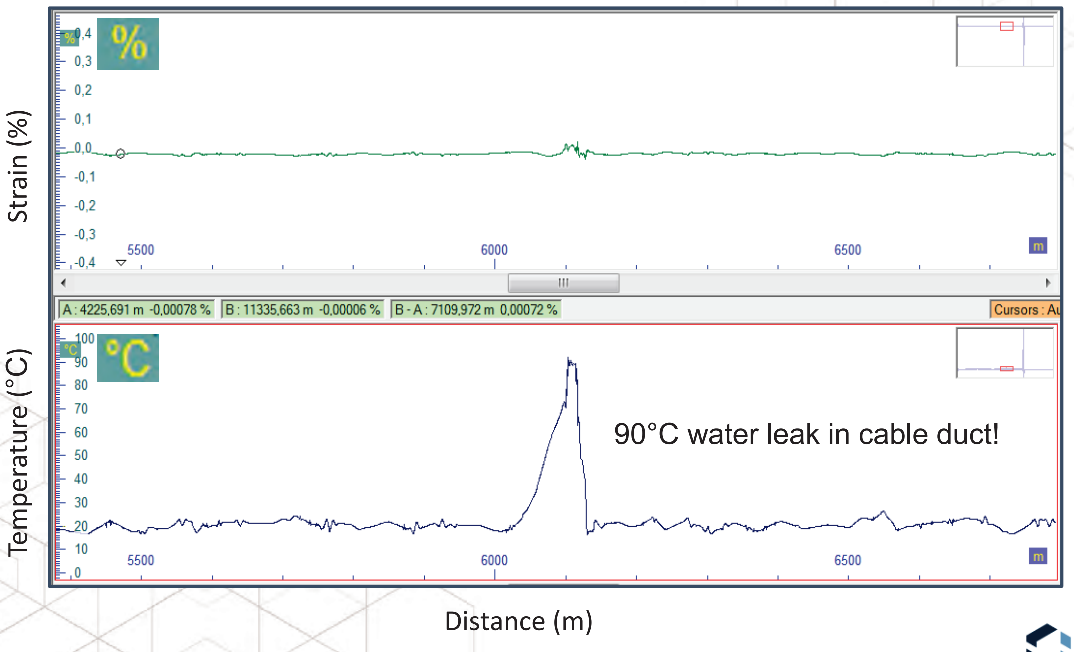
Standard OTDR
Attenuation & Reflections

Brillouin OTDR
Strain

Jan-23

2. 10km Urban Ducted Underground Cable

Russia
Ducted Urban
No Cable Details



New cabling system for Data Centres and cables for military use

Jiří Štefl
OPTOKON, Czech Republic
stefl@optokon.com

Abstract
This article covers the latest standards of fiber-optic cables and connectors in data centers and for military applications. The Vysočina Data Center near Prague, which is built according to the most modern standards, is briefly described. The architecture of the center is designed to withstand the most serious technical incidents, without customers worrying about the availability of services. The basic element of the internal optical structured cabling is a unique concept using pre-connected cables fibed with a new standard of high-density SN connectors and 24-fiber MPO connectors.

Author's biography

Jiří Štefl received the title Ingineer in 1985 from the Czech Technical University in Prague, Faculty of Electrical Engineering with a focus on technology and telecommunications. He worked as a standalone development engineer in the field of fiber optics company Tesla Jihlava for five years. In 1991 he joined the OPTOKON company and worked as a factory manager, and for the next three years as Sales Director. From 1996 he worked as CEO of OPTOKON, responsible for all activities of the group OPTOKON - including accrediated calibration laboratories in Malaysia and a brand new company, OPTOKON KABLE, Co., Ltd, in the Czech Republic. Since 2000 he is a representative of the Czech Republic in the European Committee for Standardization - CENELEC in the field of optical connectors and passive components. From 2021 Mr. Štefl is Chairman of the Board, OPTOKON, a.s. & OPTOKON Group, including the company operating the new VYSOČINA DATA CENTER - OptoNet Communication spol. s.r.o., OPTOKON Pacific SDN. BHD operating OPTOKON calibration laboratories in Malaysia and the production companies OPTOKON Middle East Industries Co. in Kingdom of Saudi Arabia, OPTOKON Elektronik, Limited Şirketi in Turkey and OPTOKON Kable Co., Ltd., s.r.o. in the Czech Republic.

OPTOKON

DATA CENTER

DCS®

CABLE SYSTEM

NEW CABLING SYSTEM FOR DATA CENTRES AND CABLES FOR MILITARY USE

26th Seminar on Optical Communication, Faculty of Electrical Enginering , Ljubljana, Slovenia

Ing. Jiří Štefl, CEO & Chairman

26th January , 2023

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Titulek

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OPTOKON PORTFOLIO, SERVICES & DIVISIONS

- **FIBER OPTIC DIVISION**
  - Connectors, Cable Assemblies
  - Cable Management Systems
  - Splitters, WDM, CWDM and DWDM
  - Data Network Equipment
  - Test Equipment
  - Harsh Environment Optical Network
- **TESTING DIVISION**
  - Calibration laboratory
  - Mechanical and temperature testing
  - EMC semi-anechoic chamber
- **SERVICE DIVISION**

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Calibration laboratory & Testing division

Electromagnetic Compatibility (EMC), climatic and mechanical tests.

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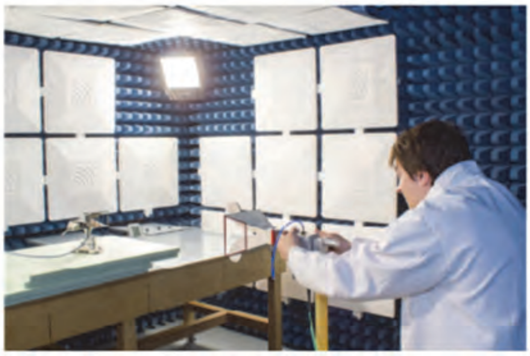
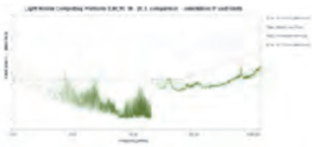
Testing division

- Optical Cables Mechanical Tests
- Optical Cables Environmental Tests
- EMC tests meeting MIL-STD-461G
- Temperature climatic tests





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DATA CENTER

DOS®

CABLE SYSTEM

The **DOS solution is a high-density, modular system** that enables the quick and cost-effective mass installation of pre-terminated cable assemblies.

DOS trunk assemblies allow for pre-terminated cable slack to be stored and secured inside the housings in the majority of scenarios.

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DOS® SOLUTION

The Field of Dreams - Multifiber Connectivity Options!

- With increasing bandwidth demands, you must rise above today's standards.
- **OPTOKON-SENKO 's new DOS solutions** are not built for what you need today, but what you will need tomorrow.
- **The DOS platform is a modular, high-density, rack-mount solution** designed for data centers, central offices, headends and structured cabling networks.
- Whether supporting incremental growth or a full-scale deployment, our DOS solutions deliver optimal fiber management in an easy to use, scalable platform.

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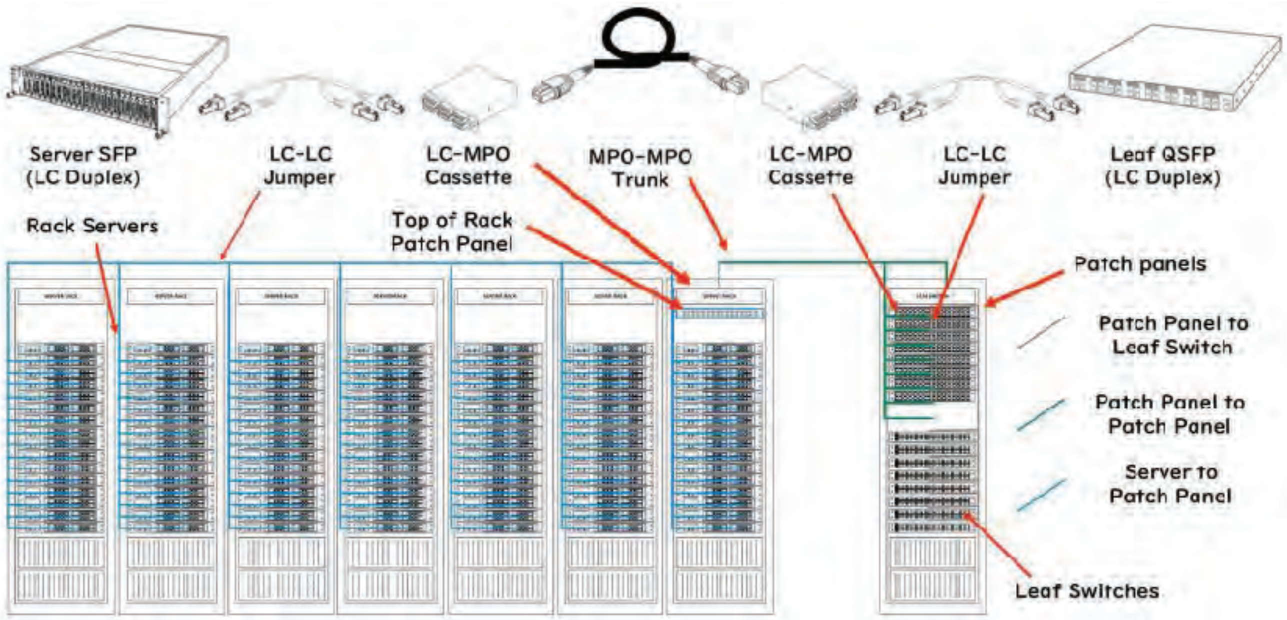
Data Center Structure cabling – LC-MPO Cassette



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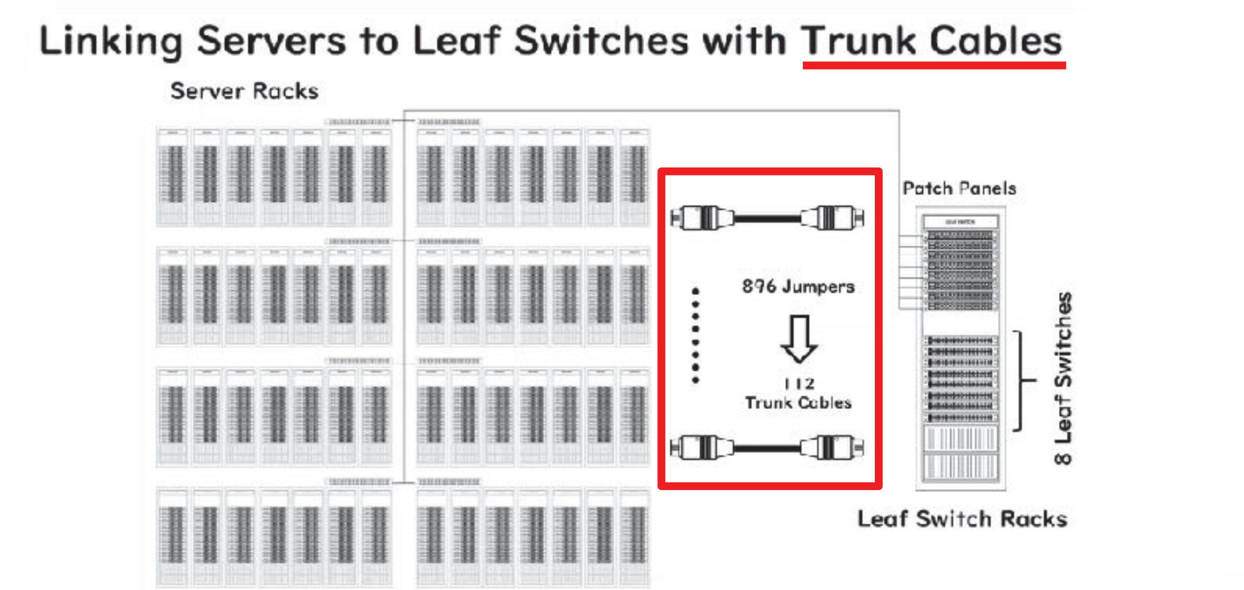
Structured cables – Trunk cables



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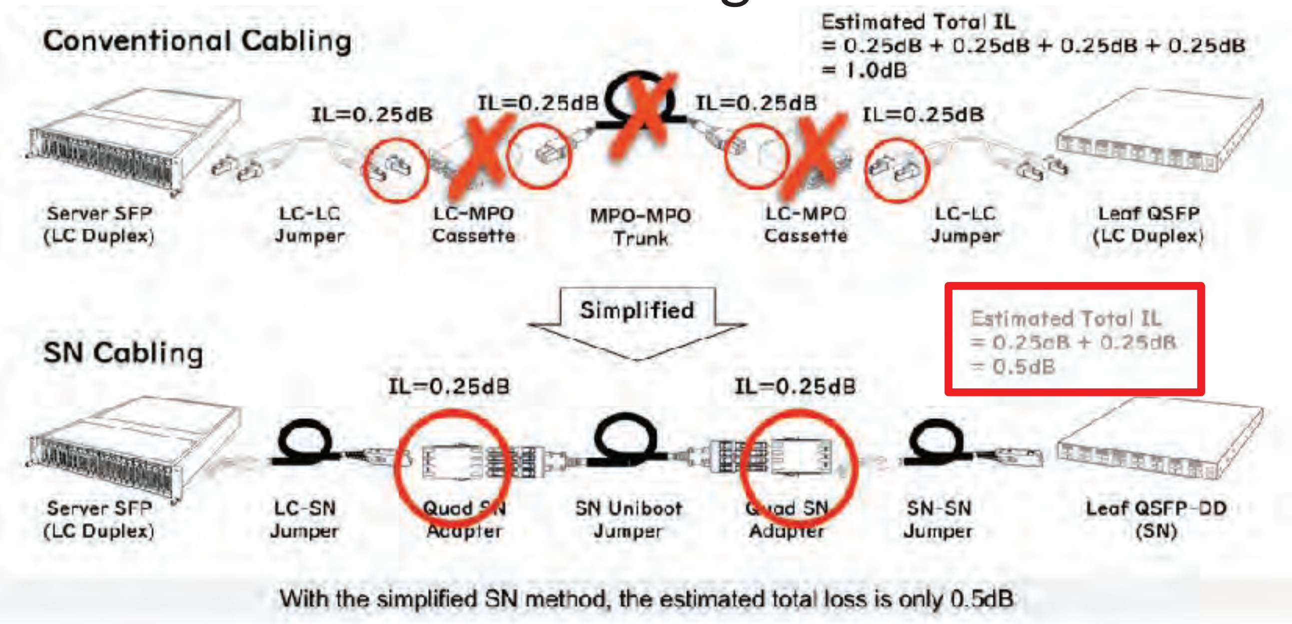
Conventional vs SN cabling



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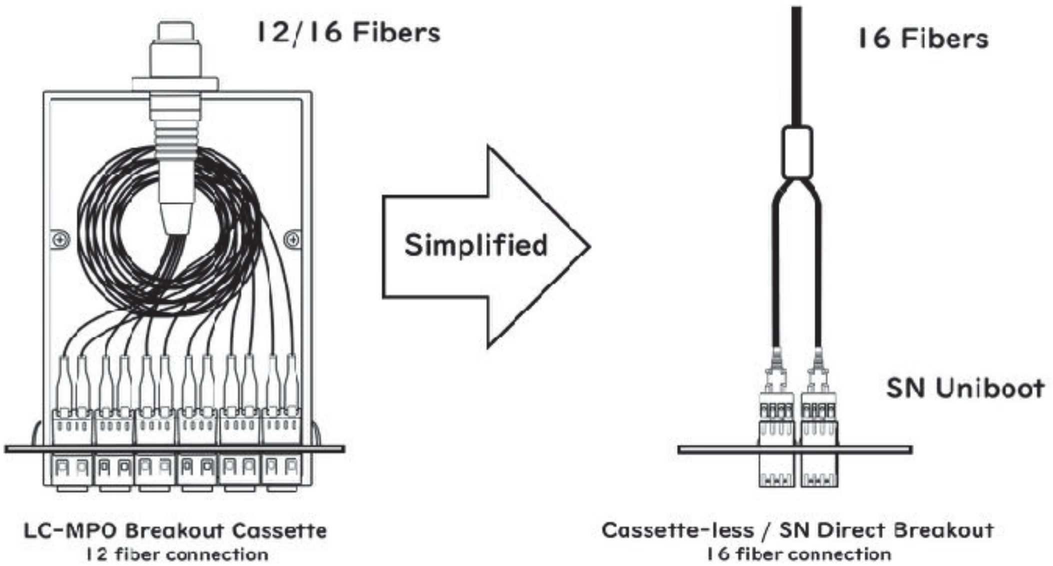
Simplified structure cabling with SN



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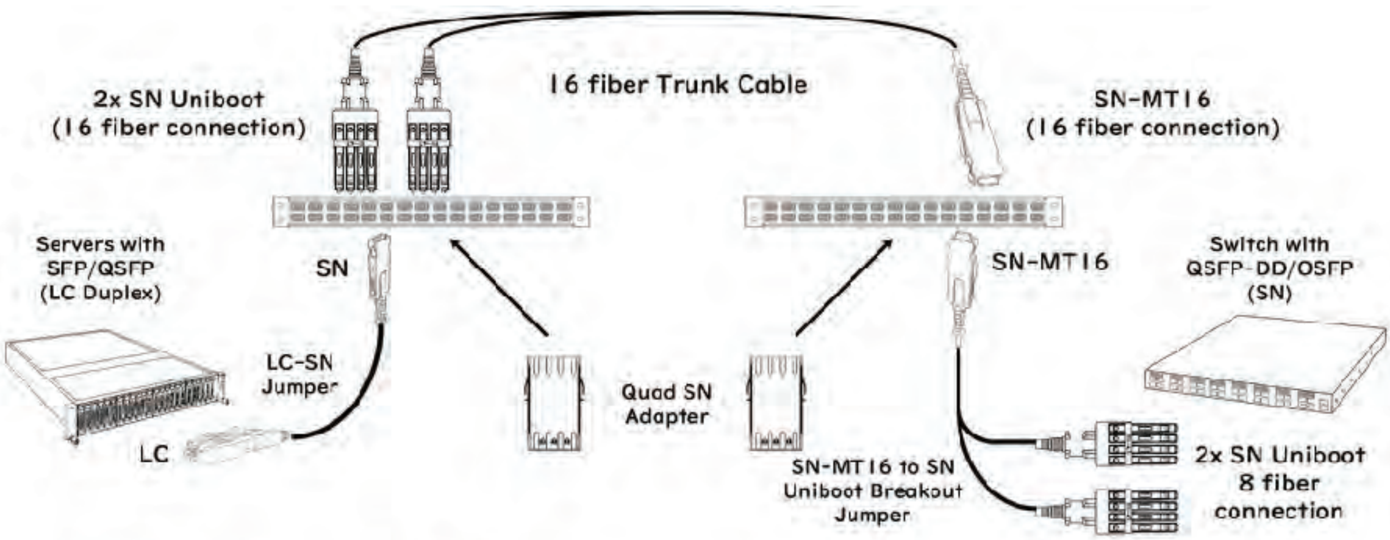
SN-MT16 cabling



The use of SN MT16 connector will allow for a reduced number of trunk cables between the switch and server racks

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OPTOKON®

SN-MT Connector

Simplifying Leaf-Spine Cross-connections

- Up to 16-fibers in a single row
- Same connector footprint as SN connector
- The industry's highest density connector
- 2.7x denser than MPO-16F
- 1.3x denser than MPO-32F
- 200 micron rollable-ribbon compatible
- Insertion loss max.0.35dB max IEC Grade B

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DOS® System can be used with MMC Connectors

- Effective size reduction compared to LC Duplex
- Designed for OSFP/QSFP-DD Break out application
- Proven 1.25 mm ferrule technology
- 4 Duplex connectors (total 8-fibers) in OSFP/QSFP-DD footprint
- 1.6 mm jacketed cable
- IEC random mating Grade B

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OPTOKON

SN - LC Fanout

- Multifiber cables termination
- Parallel optics transmission systems
- Up to 16 fibers termination

MTP - LC Fanout

- Multifiber cables termination
- Parallel optics transmission systems
- Up to 24 fibers termination

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High Density and quick install

- Pre terminated **high density fibre optic system** for high speed networks
- **Removes on-site Termination, massively reducing the time required to install**
- **80% quicker to install** over traditional pre terminated fibre optics
- **DOS system supports future transmissions of 400Gbit and 100Gbit/ second**
- Will provide up to 1 152/ 1536 cores in 1u of rack space (2mm diameter cables- no splice trays, l easier cabinet entry and easier fire-stopping)

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Excelent performace

- DOS offers **preterminated, pre-tested links** that exceed the performance requirements
- Tested at 1310 and 1550nm according IEEE 802.3bs™-2017 and 400GBASE-FR4
- **Pre-labelled by QR code** with the required scheme

OPTOKON's DOS® ULL System includes:

- Singlemode SN/APC-MT-SN/APC-MT (MDC-MDC, MTP-MTP) fiber trunks & jumpers with max **IL of 0.30 dB per connector**
- SN/APC-MT – LC with max **IL of 0.50 dB per module**
- MTP-LC modules with max **IL of 0.50 dB per module**
- MTP adapter plates
- LC Jumpers with max **IL of 0.20 dB per connector**

OPTOKON's SUPERVISOR SYSTEM with LIFE TIME WARRANTY

- Working within an ISO 9001 quality regime DOS controls quality right from the start
- **A unique 100% testing programme**
  - Including 100% interferometer testing
  - Joint OPTOKON & SENKO development I
  - investment in new cable development and accredited testing division in the Czech Republic
- OPTOKON's controls quality all the way through the **OPTOKON's SUPERVISOR SYSTEM with LIFE TIME WARRANTY**
- approved and authorised and qualified facilities (OPTOKON Czech , OPTOKON Elektronik in Turkey, OPTOKON Middle East in KSA and OPTOKON Pacific in Malaysia).

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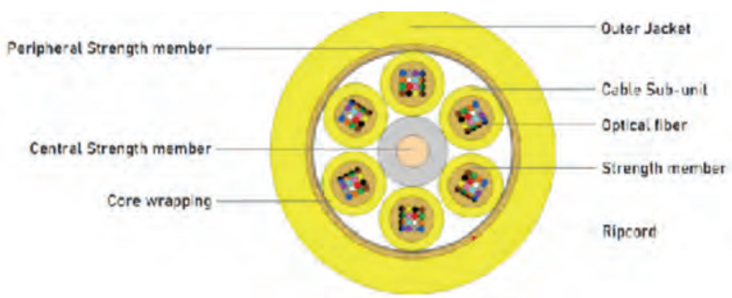
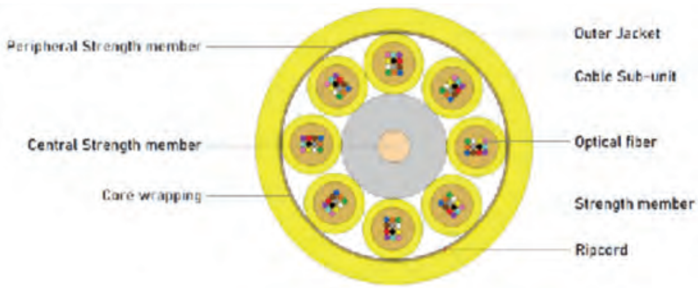
DOS® Data Center Cable

- Indoor Distribution Cable for Data Center Cable Systems

Data Center Cable 96F (8 × 12F)



Data Center Cable 96F (6 × 16F)



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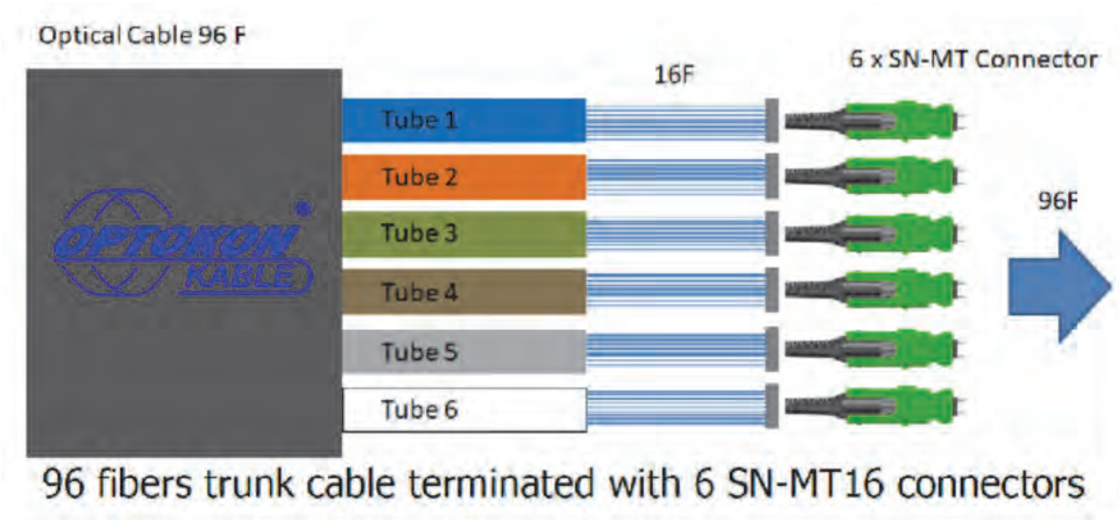
DOS® Data Center Cable



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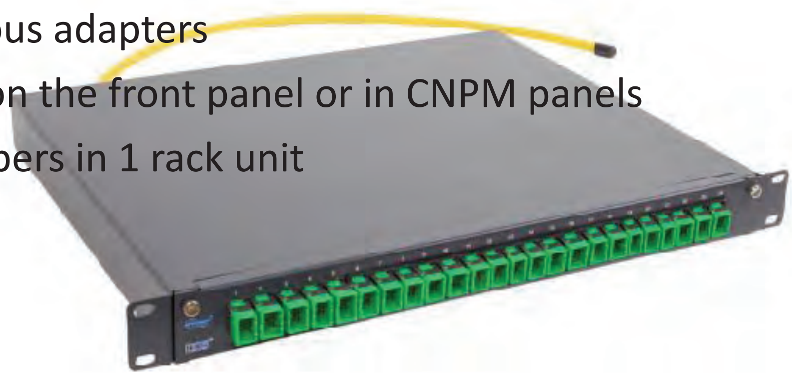
PUDOS

19” Rack mount Optical Distribution Frame for Data Centers

- Designed for cable or microtubes termination
- Compact robust design
- Slide-out shelf provides unrestricted access
- Changeable front panel, various adapters
- Coupling adapters mounted on the front panel or in CNPM panels
- Accommodates up to 1536 fibers in 1 rack unit



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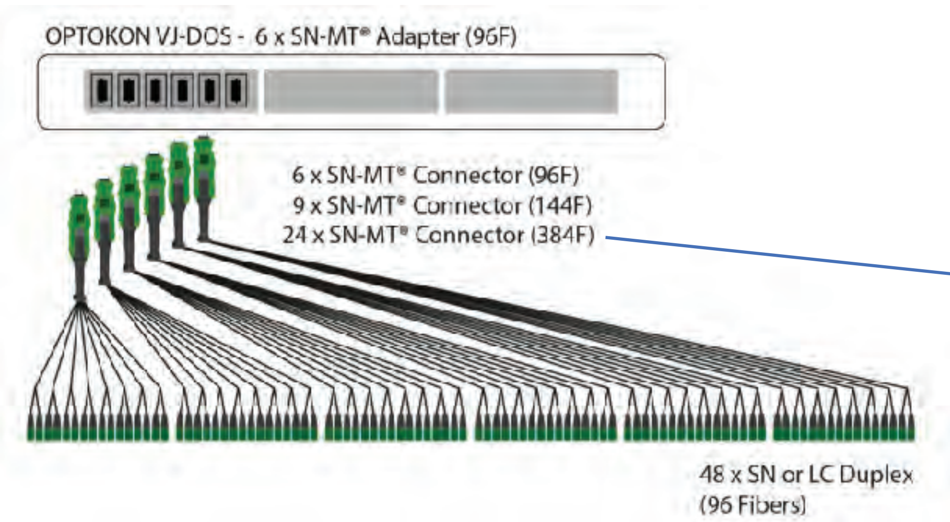
High density with SN-MT (16 fibers per connector)



PUDOS-1E-384-SNMT4
Termination for 384 fibers per panel
- 4 connectors (16 fibers) per adapter
- 6 adapters
384 fibers in one panel

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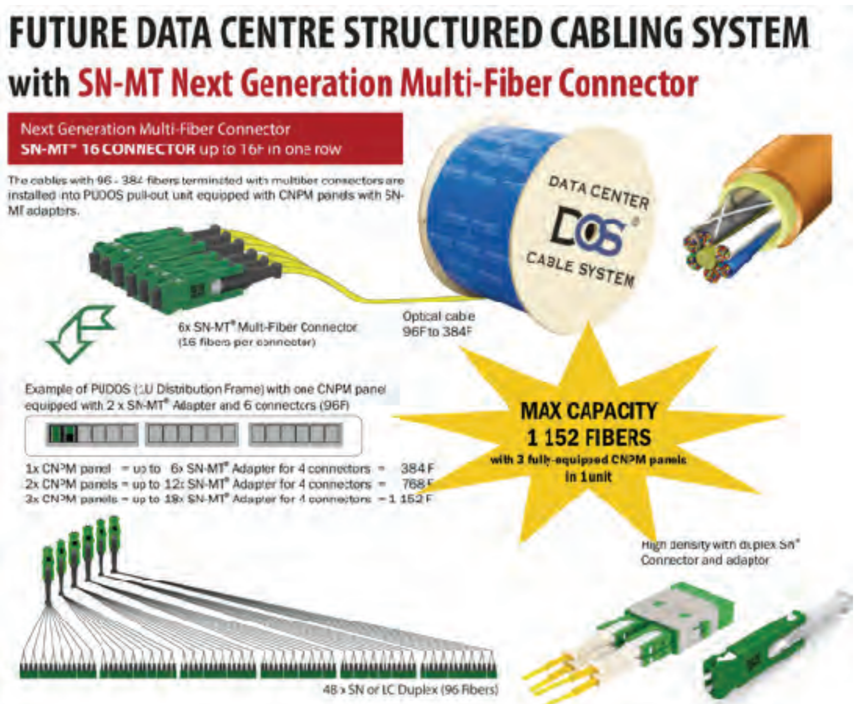
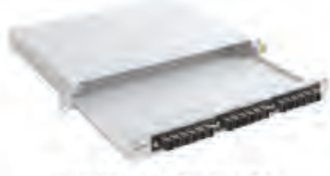


PUDOS-1E-384-SNMT4
Termination for 384 Fibers

PUDOS-1E-768-SNMT4
Termination for 768 Fibers



PUDOS-1E-1152-SNMT4
Termination for 1 152 Fibers

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DOS® SOLUTION

Each component is specifically engineered to work in conjunction with the other components in the platform resulting in a world-class structured fiber cabling system.

Maximum Densities for LC, MPO / MTP and SN-MT connectors:

LC (adapter x connector x fiber)	MPO / MTP (adapter x connector x fiber)	SN/ APC – MT (adapter x connector x fiber)
1RU = 96fiber (24x4x1)	MPO12 1RU = 288-fiber (24x1x12) MPO24 1RU = 576 fiber (24x1x24)	**1RU = 1 152 fiber (18x4x16)** **1RU = 1 536 fiber (24x4x16)**
2RU = 192-fiber (48x4x1)	MPO12 2RU = 576 fiber (48x1x12) MPO24 2RU = 1152 fiber (48x1x24)	**2RU = 2 304 fiber (36 x4x16)** **1RU = 3 072 fiber (48x4x16)**
4RU = 384-fiber (96x4x1)	MPO12 4RU = 1152-fiber (96x1x12) MPO24 4RU = 2304 fiber (96x1x24)	**4RU = 1 152 fiber (72x4x16)** **1RU = 3 072 fiber (96x4x16)**

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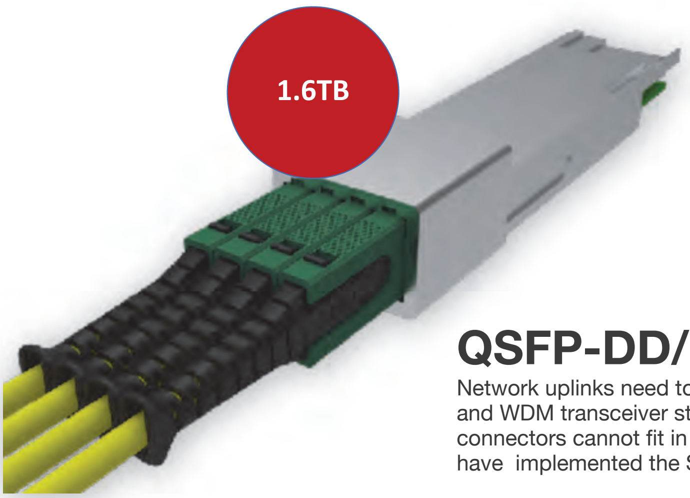
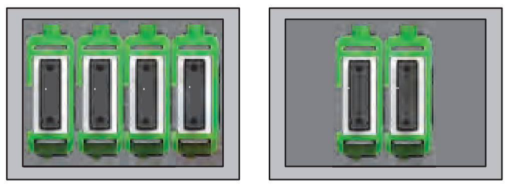
SN-MT8/16 Multi-channel transceivers



4x 400G DR4 2x 800G DR8



QSFP-DD/OSFP Form Factor

Network uplinks need to move to higher speeds to match servers. Currently there are parallel and WDM transceiver structures for 200/400G QSFP-DD/OSFP, but 2X duplex LC connectors cannot fit in the QSFP-DD/OSFP form factor. In response, SENKO & OPTOKON have implemented the SN Connector.

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DATA CENTERS

Growing Bandwidth Capacity

As next-generation data center upgrades turn to 400-Gbps intra-data-center switch fabric and multi-WDM systems, SN Cable Assemblies are a likely choice. They support 400-Gbps QSFP-DD and OSFP transceivers with a reduced ferrule pitch and higher density than LC connectors.

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Typical network topology for data centers

- Dedicated space used for storing and sharing data and applications
- More than 7 million data centers have been built worldwide
- Demand for higher capacity and bandwidth continue increasing

As the demand for more capacity and higher bandwidths continue in an upwards trajectory, so does the technology needed to support it

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Advantages of SN cabling

- Lower link loss by reducing a connection with the absence of the LC-MPO breakout cassette
- Minimize point of failure due to reduction of connection points
- Reduce space & weight required in cable trunking
- Better air flow due to smaller cable and absence of cassette
- Reduce invertory and logistic of heavy cassettes

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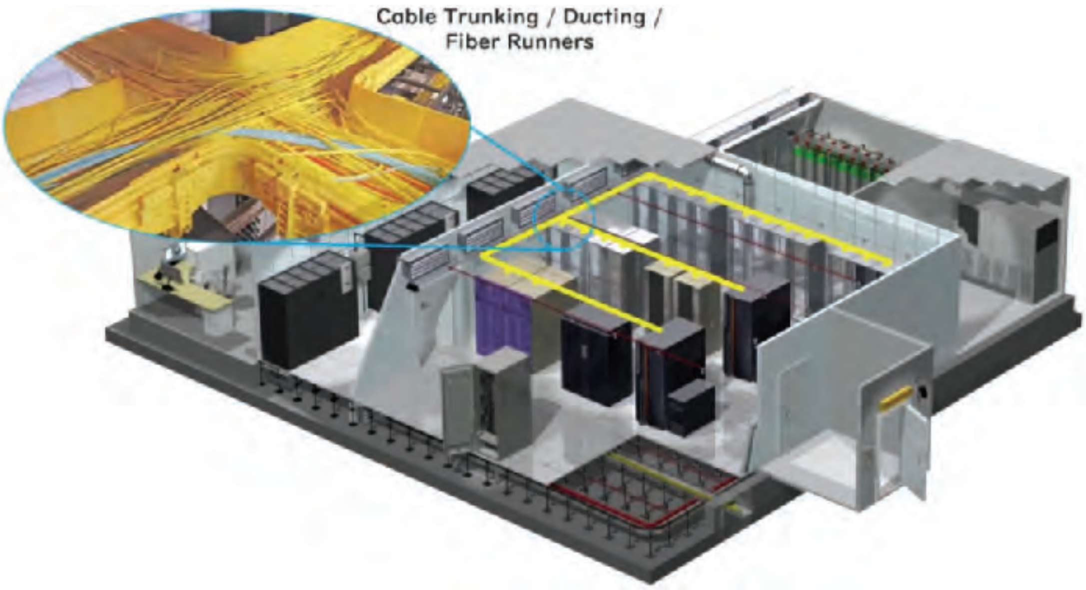
Cable support infrastructure



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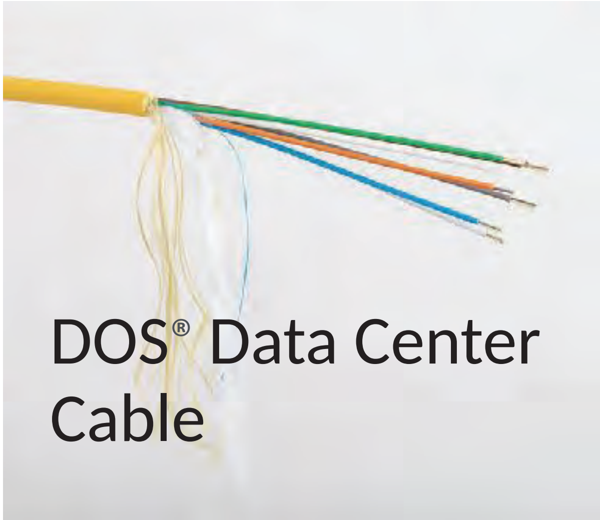
Data Center Cable manufacturing and testing

Micro distribution cable is a construction from the category of cables with high fiber density.



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PM-212-SN-GE Multifiber optical power meter

- Easy measurement of multifiber connectors
- Duples SN input interface
- Portable power meter / USB probe
- Ge large scale photodetector
- Firmware upgrade via USB
- Displayed units: dBm, dB, mW

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LS-240-SNMT & MP-240-SNMT
Multifiber Optical Light Source and Power Meter

- Hand held, light weight
- Multifiber SN-MT connectors testing
- No Fanout patchcords required
- Single or dual wavelength
- Manual switching through all fibers or Cycle mode
- Can be controlled remotely via USB

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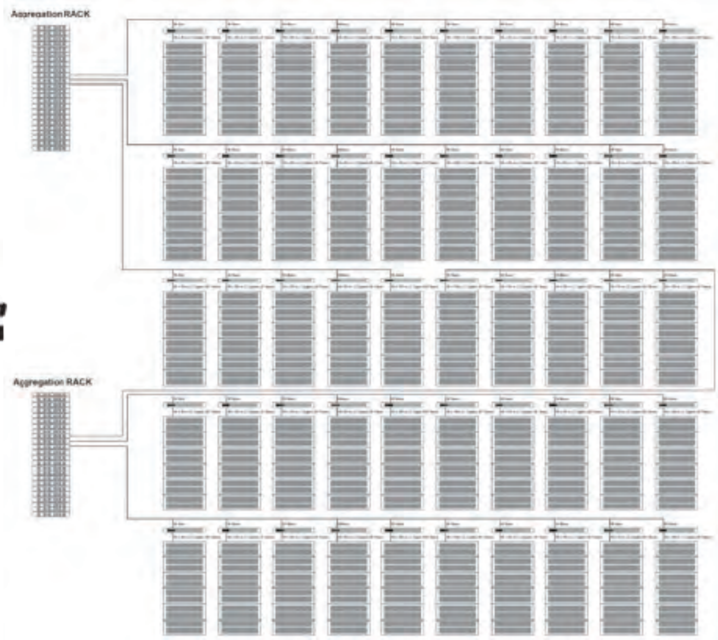
OptoNet
Communication
DATOVÉ CENTRUM VYSOČINA



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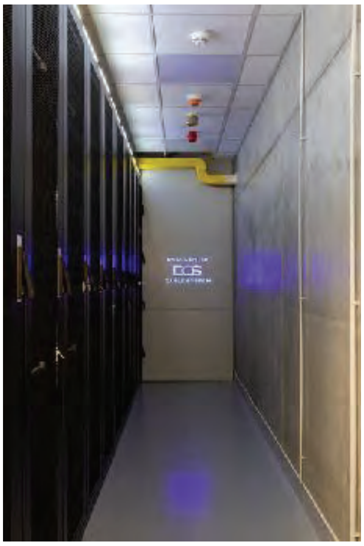
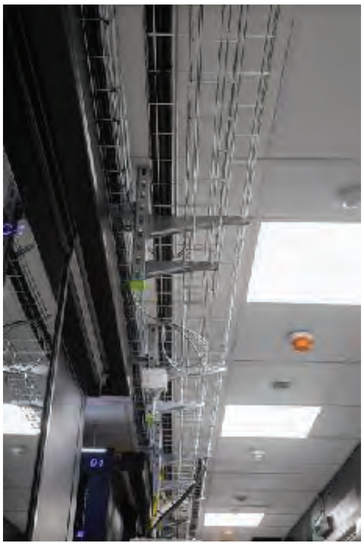
OptoNet Communication
DATOVÉ CENTRUM VYSOČINA





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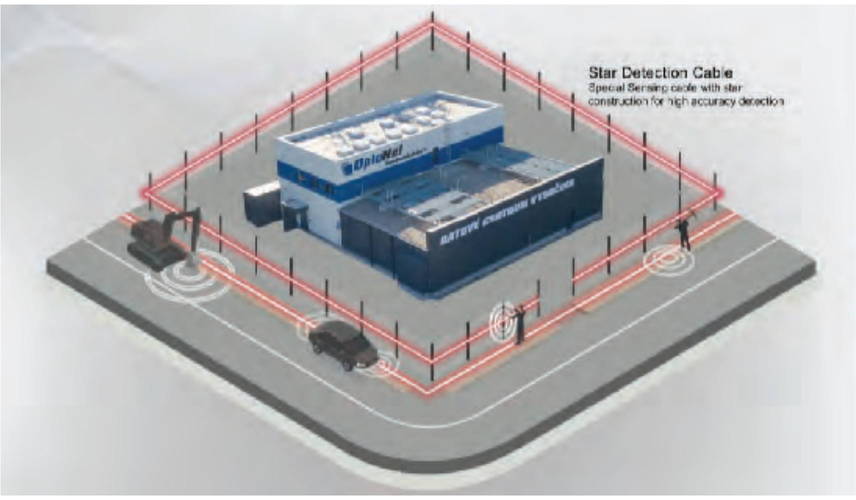
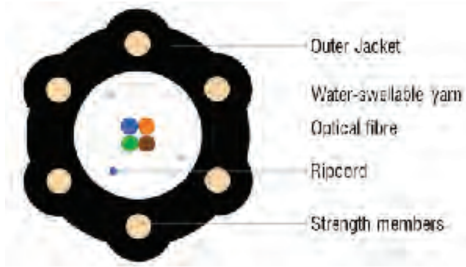
Datacenter security



OPTOKON Sensitive star detection cable

The new FOTAS System uses a unique fiber optic cable for Acoustic Sensing Systems produced by **OPTOKON Kable**. The cable is suitable for installation on the fence and into underground grooves with a silica sand bed.



Tactical fiber optic cables

SUPPLIER OF
NATO ARMED FORCES
FOR MORE THAN 24 YEARS

NATO supplier code: 1583G

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Durability of the tactical cables

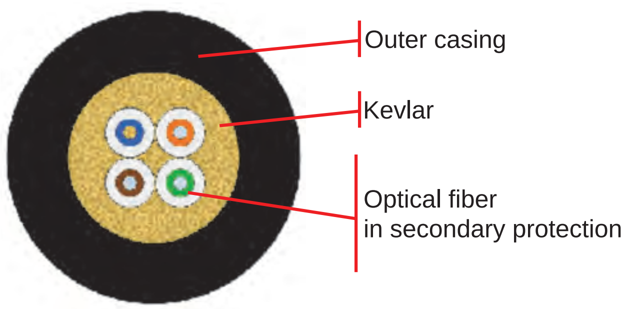
- High resistance to water, UV radiation, chemicals, microorganisms, and mold
- Mechanical resistence, resistant to being cut by a sharp object or punctured.
- High flexibility
- Designed for very low temperatures
- Highly mechanically, chemically, and thermally resistant Polyamide 12, which protects the optical fiber from mechanical damage

	Military cable	Standard cable
Operating temperature range	-55 °C to +85 °C	-20 °C to +60 °C
Compressive strength without change in attenuation	5000 N	~1500 N
Compressive strength with reversible damping	9500 N	~2000 N
Impact resistance	20 Nm	~5 Nm
Flexibility	100 N, >15 000 cycles	20 N, 100 cycles

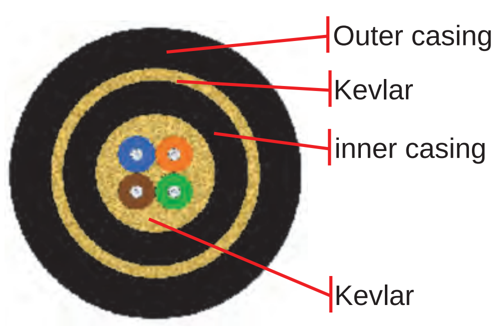
Tactical fiber optic cables

In addition to the standard cable construction, a variant with a second sheath is also available to further increase cable resistance.

Cable variant with one jacket



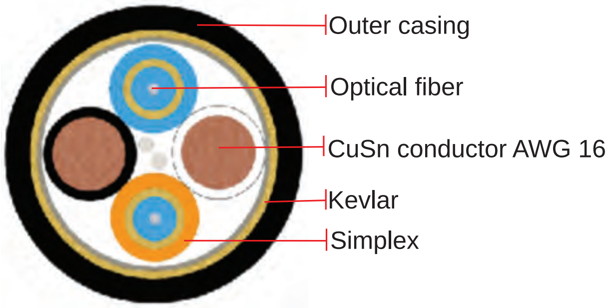
Cable variant with two jackets



Hybrid Tactical cables

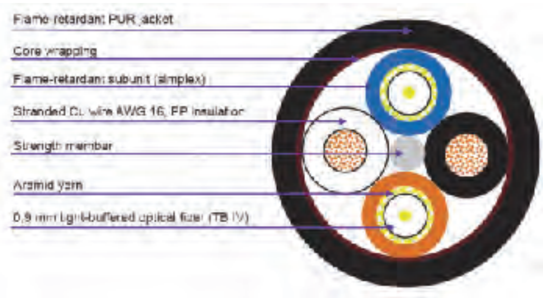
- Two simplexes with SM or MM optical fiber
- Tight secondary shield
- 2 x 16 AWG tinned copper wires with FEP (Fluoroethylene Propylene) insulation.
- Protection against penetration of moisture by water-swelling materials.
- Cable sheath from polyurethane, with high flexibility and mechanical resistance.

Cable tensile strength	500 N
Operating temperature range	-40°C to +70°C
Compressive strength	1500 N/10 cm
Test voltage of conductors underwater	2000 V for 1 hour at 20°C



Optical cables for mobile and tactical use

- Wire DC resistance < 13,7 Ω/km
- Max. Compressive loading 1500 N
- Max. Impact loading 15 N.m
- Min. bend radius 5x OD
- Temperature range 40 to +70°C



OPK-U-SPD-2(4x1,5)A9AHEU

OPTOKON HMA-J connector

- Advanced expanded beam technology
- MIL-DTL-83526 specification
- Hermaphroditic interconnection
  - no adaptors necessary
- Up to 4 fiber channels SM or MM
- Rugged field repairable connector design





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Izzivi pri razvoju vlakenskih laserjev visokih moči

Chellenges in the development of high-power fiber lasers

Peter Lukan
LUMENTUM
peter.lukan@lumentum.com

Povzetek

V zadnjem desetletju so vlakenski laserji zaradi svojih izjemnih lastnosti postali prevladujoč tip laserjev za industrijske aplikacije, ki zahtevajo visoke optične moči. Trend potreb po še višjih močeh se nadaljuje in ta narekuje tudi razvojne zahteve in izzive. Nekateri pomembni parametri, ki jih tovrstni laserji morajo dosegati, so visok optični izkoristek, majhna stopnja fotopotemnitve in dobra kvaliteta svetlobe. Za doseganje teh parametrov sta pomembna tako optična arhitektura, ki mora upoštevati osnovne fizikalne omejitve, kot kvalitetne materialne lastnosti optičnih vlaken, ki izhajajo iz procesa izdelave vlakna. V tej predstavitvi je narejen pregled osrednjih razvojnih izzivov pri razvoju takšnih laserjev s poudarkom na obeh omenjenih vidikih.

Abstract

In the last decade, fiber lasers have become the dominant type of lasers for industrial applications that require high optical powers due to their exceptional properties. The trend of the need for even higher powers continues and this also dictates development requirements and challenges. Some of the important parameters that such lasers must achieve are high optical efficiency, low degree of photodarkening and good quality of light. In order to achieve these parameters, both the optical architecture, which must take into account the basic physical limitations, and the quality material properties of the optical fibers, which result from the fiber manufacturing process, are important. This presentation gives an overview of the development challenges of such lasers, focusing on both aspects mentioned above.

Biografija avtorja

Peter Lukan je mag. fizike, mag. humanistike in doktorat iz filozofije znanosti. Zaposlil se je v slovenskem podjetju Optacore d.o.o., kot vodja merilnega laboratorija. Podjetje je leta 2017 kupilo ameriško podjetje za fotoniko Lumentum, da bi razvijalo laserska vlakna za lastne potrebe. Vodi skupino Specialty Fiber R&D, ki se osredotoča predvsem na razvoj vlaken za laserske in telekomunikacijske aplikacije.

Author's biography

Peter Lukan's background is MSc. in Physics, MSc. in Humanities and PhD. in Philosophy of science. He started his employment working at Slovenian company Optacore d.o.o. as measurement lab lead. The company was acquired by a US owned photonics company Lumentum in 2017 in order to develop laser fibers for internal needs. He is leading the Specialty Fiber R&D group, mainly focusing on development of fibers for laser applications and telecom applications.

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Development challenges of high power fiber lasers

Peter Lukan
January 2023

Overview

- Advantages of fiber lasers
- Fiber laser applications
- Optical architecture of fiber laser
- Triple clad fiber structure
- Important performance parameters
- Some physical limitations
- Areas of development work: waveguide design and glass development
- Fiber fabrication process steps
- Some achievements

Advantages of fiber lasers

- Belong to solid state lasers, but differ from solid state *bulk* lasers
- Efficiencies of > 30% (electrical to optical)
- Laser light already coupled in optical fiber → easy delivery
- High surface-to-volume ratio of active material → easy cooling at very high powers
- Compact, monolithic setup (fiber can be coiled)
- Decreased sensitivity to vibrations, thermal drifts, dust
- Large gain bandwidth → wide wavelength tuning, temperature stabilization of pump diodes not critical
- Diffraction limited beam quality (when using single mode fibers)
- Very high powers (> 3kW) in combination with high beam quality

Fiber laser applications

Aerospace

Battery industry

Dental, medical

Cutting
Drilling
Welding
(dissimilar metals)
Marking
Engraving
Ablation

Electronics

Jewelery

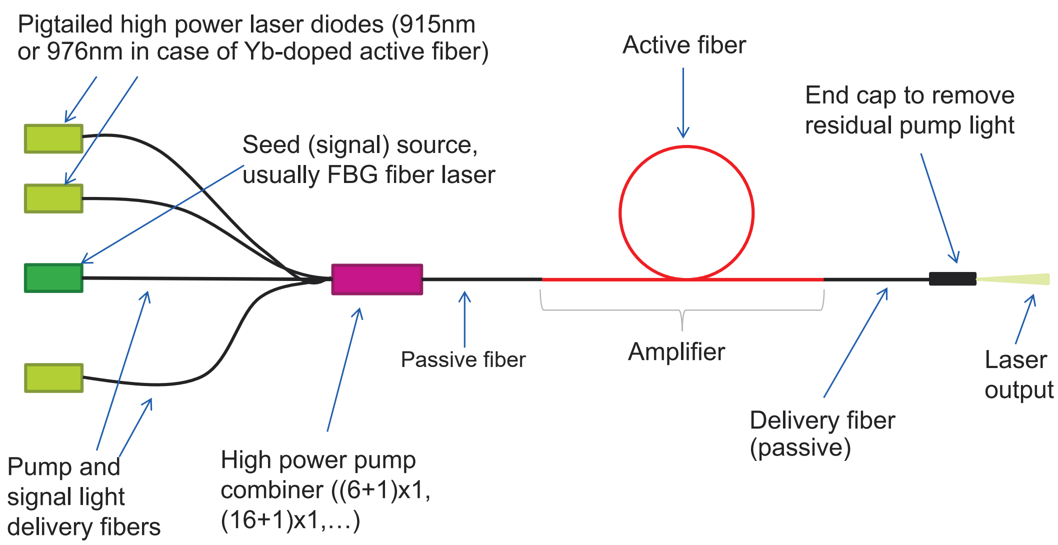
Automotive

Fiber laser applications

- **Continuous wave (CW) lasers, „kilowatt lasers“**
- High power: 4kW from single module
- Industrial precision cutting and welding of sheet metal plates for:
  - automotive,
  - aircrafts,
  - commercial and consumer appliances

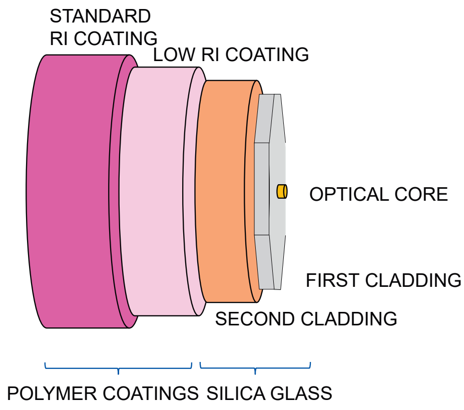
- **Pulsed lasers, „ultrafast lasers“**
- High power: >100W average power
- Micromachining = scribing, cutting, and drilling for production processes of:
  - integrated circuits,
  - LEDs,
  - crystalline Si and thin-film solar cells
  - rigid or flexible PCBs
  - phone glass
- Surface ablation, cleaning

Optical architecture of fiber laser

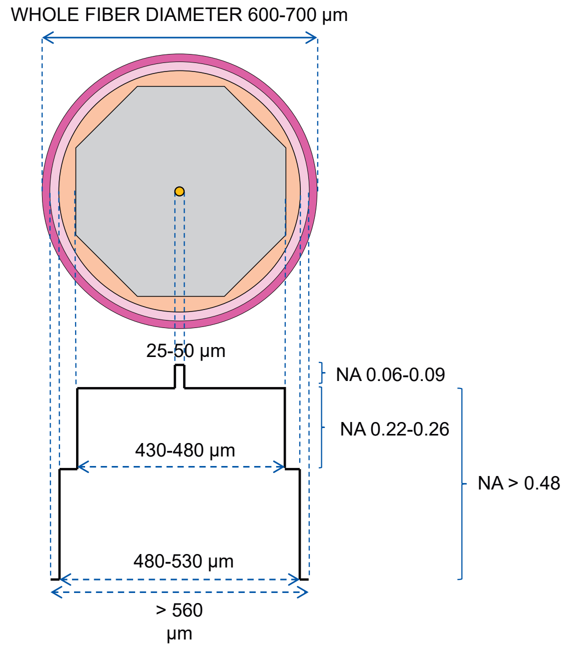


- Overall the optical waveguide consists of many different fibers in a stream
- Matching of refractive index and geometry of fibers is crucial and has to be finely targeted

Triple clad fiber structure



FIBER STRUCTURE



REFRACTIVE INDEX PROFILE

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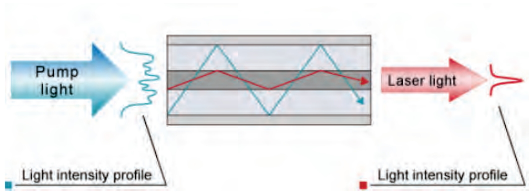
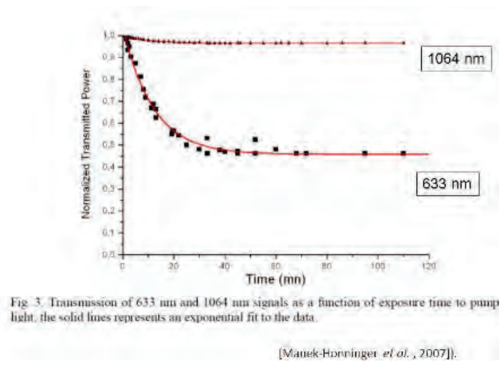
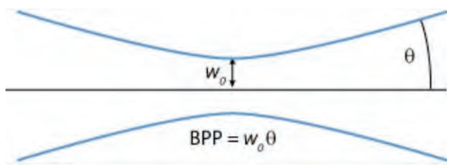
Important performance parameters



Optical to optical efficiency (OOE)
= laser light/pump light
Typical: 70-75% @4kW



Photodarkening (power drop)
Typical: 1,5-3% @ 1080nm



Beam product parameter (BPP)
Typical: ~1.0 mm mrad @ 4kW, 1080nm

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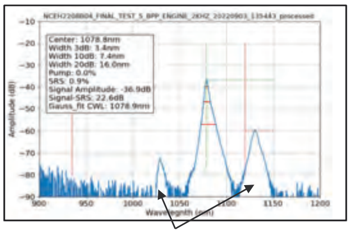
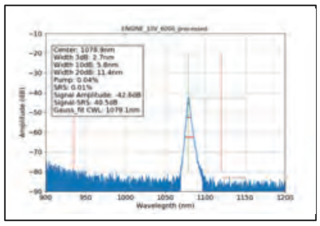
Some physical limitations – non-linear effects

- Photodarkening:
  - Decreases OOE during laser operation
  - Is an optical material related property (→ fiber related)
- Stimulated Raman scattering:
  - Induces a parasitic wavelength → degrades beam quality and OOE
- Heating management
- Transverse mode instabilities
- Pulse distortions (pulsed lasers)

MANY DESIGN COMPROMISES!



Parasitic wavelengths

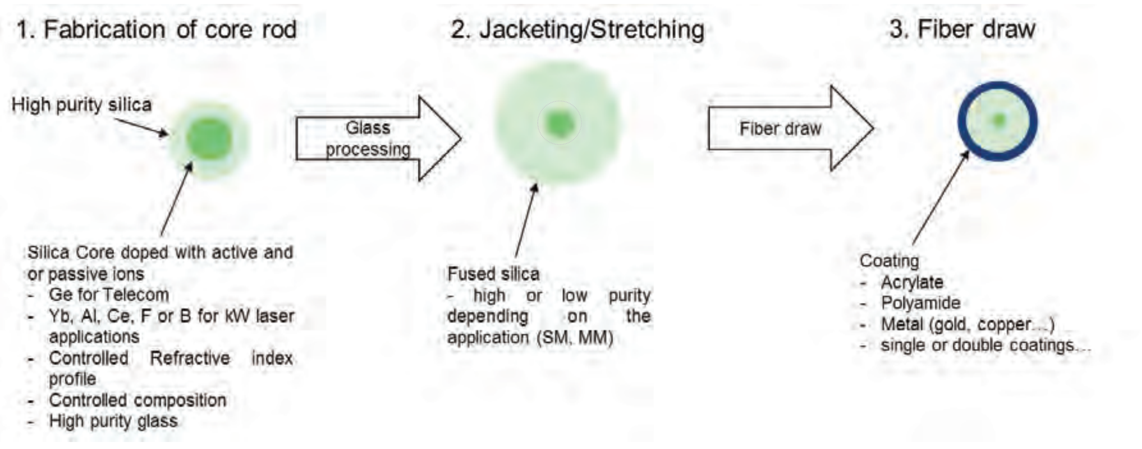


Monochromatic light

Areas of development work

- Waveguide design and glass development:
  - Proper **active glass composition** mitigates photodarkening effect → glass composition recipe development
  - Finely tuned Yb **doping level** of specific fibers guarantees targeted active fiber absorption
  - Finely tuned **refractive index profile** of specific fibers
  - Finely tuned **geometry** of specific fibers (diameter, eccentricity)

Fiber fabrication process steps



Define core NA, material properties (attenuation, absorption, photodarkening..)

Define final clad/core diameter ratio, ensure centricity, other cladding properties.

Target final fiber diameters.

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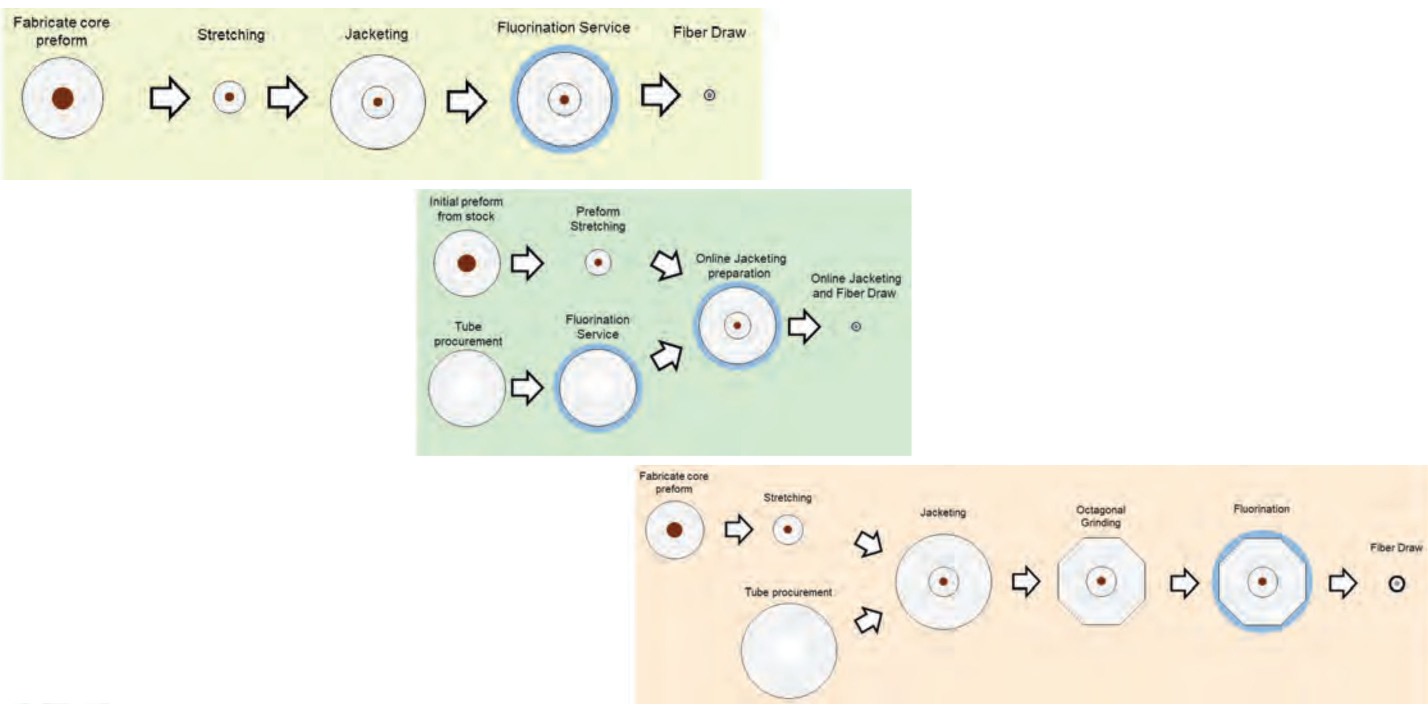
Fiber fabrication process steps – examples



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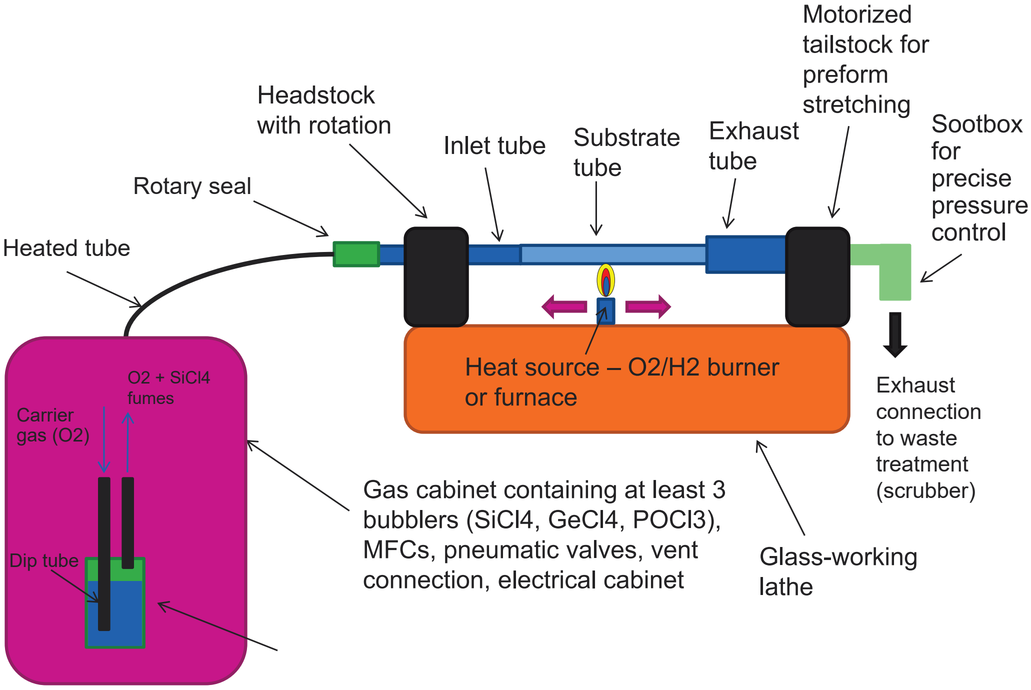
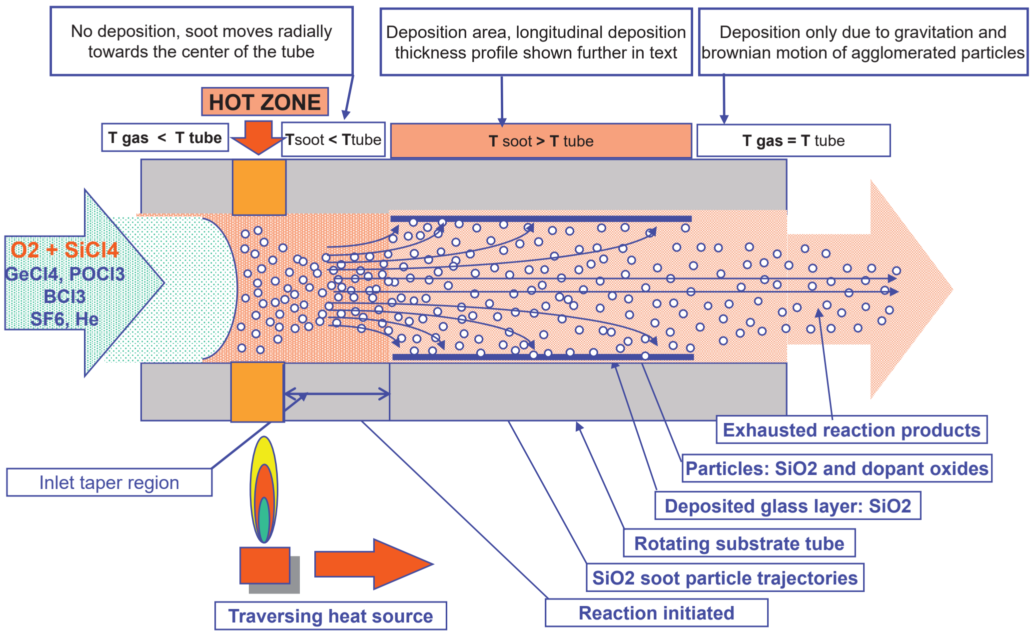
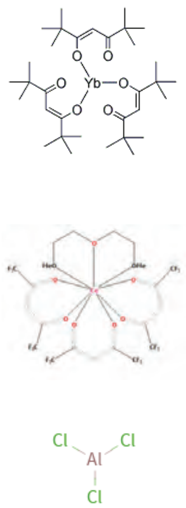
Core rod fabrication (MCVD process)

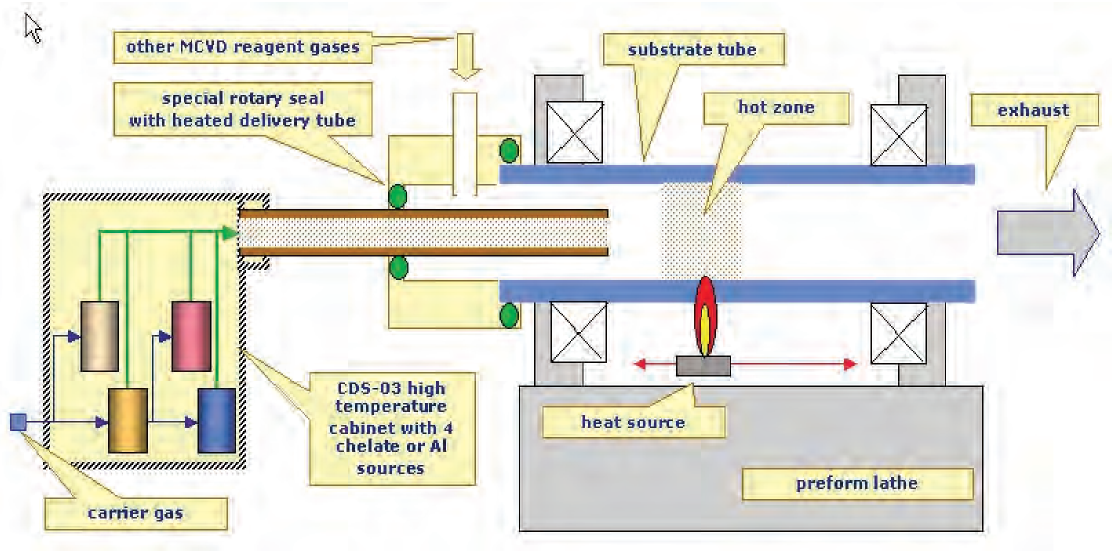


Core rod fabrication (MCVD process)



Rare earth doping – chelate deposition system (CDS)





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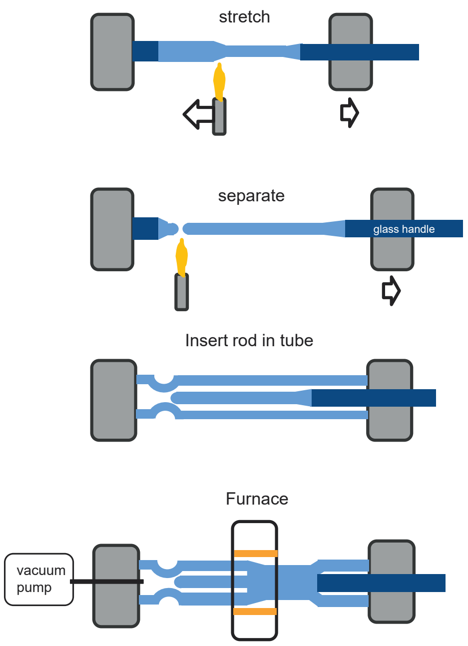
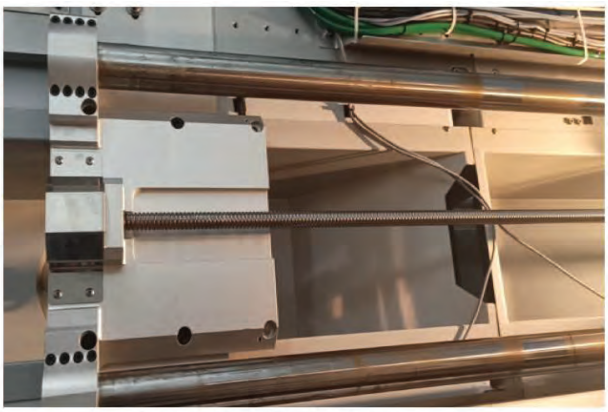
Jacketing/stretching process and fiber draw process



The drop



The draw

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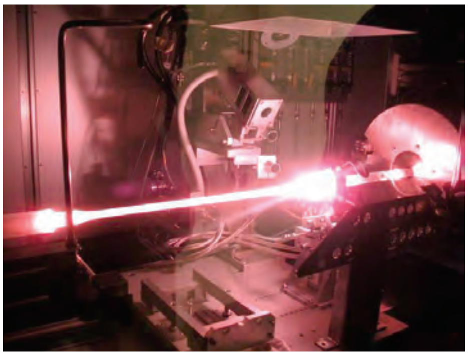
Lumentum Slovenia capabilities


Glass working lathe
(MCVD + CDS)


Measurement lab for fiber characterization


Fiber draw tower

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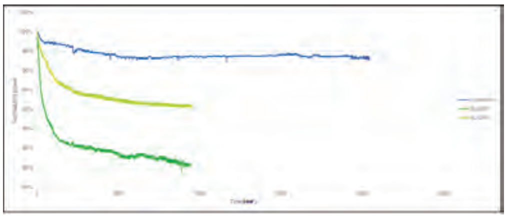
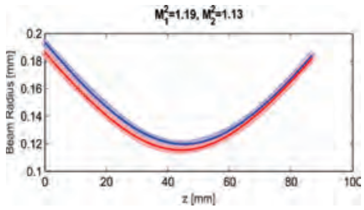
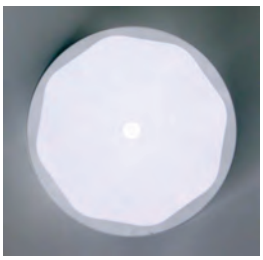
Some achievements

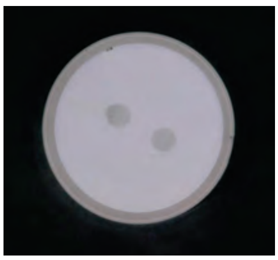

Photodarkening better than
commercially available fibers



Excellent beam quality, M^2 = 1.13 - 1.19

- Low background loss in active fibers: 5-10 dB/km → good optical efficiency, ~75 @ 4kW
- Fiber gallery:





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OPGW - arhitektura in zmogljivosti

OPGW - architecture and performance

Marija Mrzel Ljubič

ELES

mojca.mrzel@eles.si

Povzetek

Elektrodistribucijska in prenosna podjetja uporabljajo za gradnjo komunikacij za potrebe obratovanja in vodenja energetskih omrežij najbolj pogosto kar lastno infrastrukturo. Optične vodnike tako nameščajo na nadzemne daljnovode kot samonosilne kable, jih ovijajo okoli strelovodnih ali faznih vodnikov ter zamenjajo strelovodno vrv ali fazni vodnik s tako, ki ima vgrajena optična vlakna. Najbolj pogost način gradnje optičnega omrežja na visokonapetostnih daljnovodih (110 kV ali več) je v tehnologiji OPGW (Optical Power Ground Wire), kjer so optična vlakna umeščena v strelovodni vrvi daljnovoda.

Abstract

Power distribution and transmission companies most often use their own infrastructure to establishe communications for the needs of operating and managing energy networks. Optical fibers are installed on overhead power lines as self-supporting cables, wrapped around ground wire or phase conductor, or the conductor or ground wire have built-in optical fibers. The most common way of building an optical network on high-voltage transmission lines (of 110kV or more) is OPGW (Optical Power Ground Wire), where optical fibers are placed in the ground wire of the power line.

Biografija avtorja

Marija Mrzel-Ljubič je od leta 1994 zaposlena v podjetju ELES. Šolanje je zaključila na Fakulteti za elektrotehniko Univerze v Ljubljani. V Elesu je sodelovala pri digitalizaciji komunikacijskega omrežja, izgradnji optičnega, SDH, IP in WDM omrežja. Trenutno je zaposlena kot specialist za telekomunikacije. Zadolžena je za izgradnjo in obratovanje optičnega omrežja ter kot nadzorni inženir sodeluje pri izgradnji daljnovodov in razdelilnih postaj.

Author's biography

Marija Mrzel-Ljubič has been employed at ELES since 1994. She completed her education at the Faculty of Electrical Engineering of the University of Ljubljana. At ELES, she participated in the digitization of the communication network, the construction of an optical, SDH, IP and WDM network. She is currently employed as a telecommunications specialist. She is responsible for the construction and operation of the fiber optic network and as a supervising engineer participates in the construction of transmission lines and distribution stations.

ELES

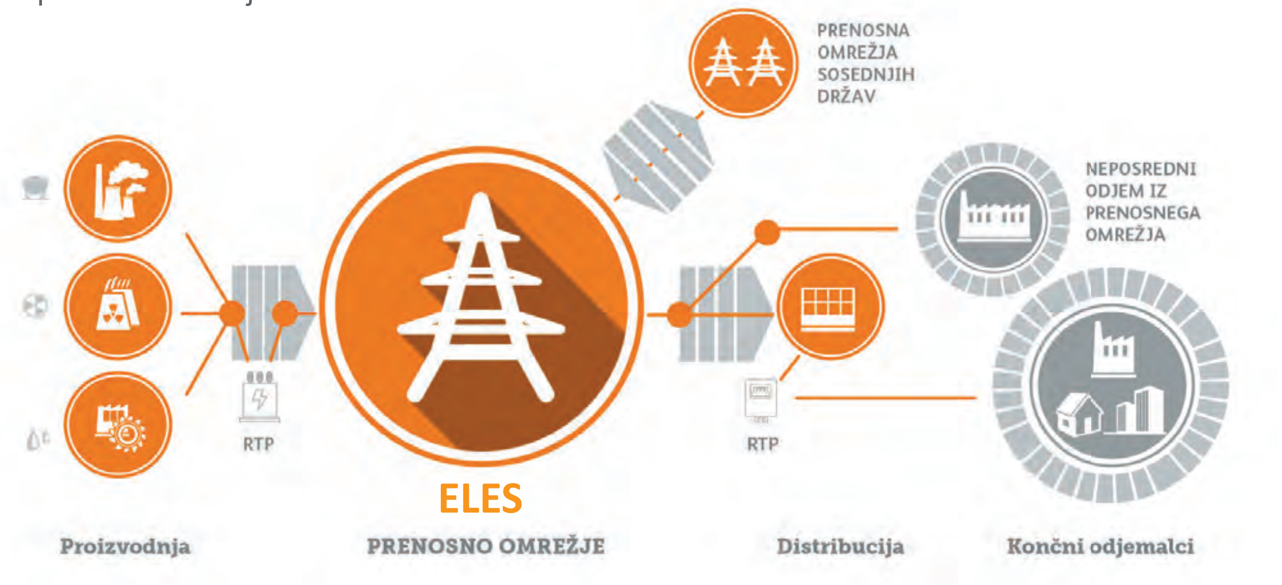
VSEBINA

- KDO SMO
- SHEMA DV IN OPTIČNEGA OMREŽJA ELES
- OPTIKA V ELES
- ZNAČILNOSTI OPGW
- PRIMER OPGW zahteve in izvedba
- PREDNOSTI IN SLABOSTI OPGW
- SOVRAŽNIKI OPGW

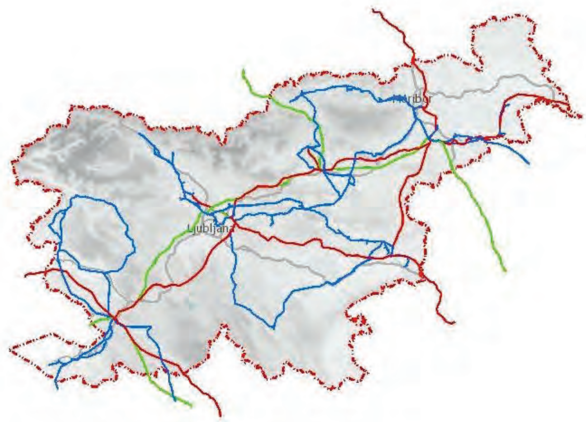
KDO SMO

https://www.eles.si/

ELES je sistemski operater prenosnega elektroenergetskega omrežja Slovenije. Temeljna dejavnost in poslanstvo družbe ELES je varno in zanesljivo obratovanje elektroenergetskega sistema Republike Slovenije.



SHEMA DV IN OPTIČNEGA OMREŽJA ELES

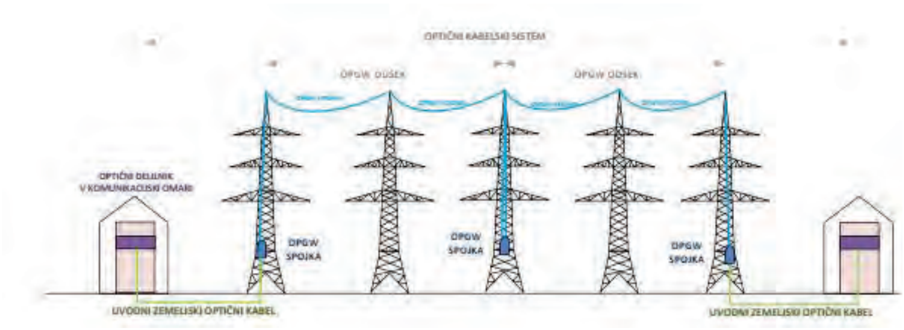


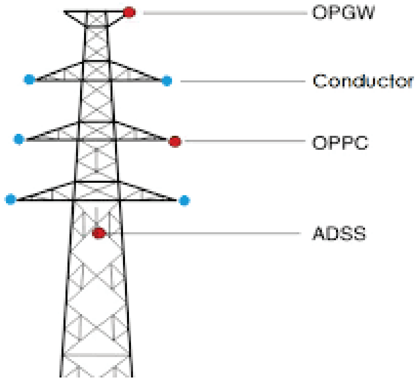
DALJNOVODOV(DV) SKUPAJ: 3113 km
- 828 km na 400 kV
- 328 km na 220 kV
- 1957 km 110 kV (31km kablovodov)

OPTIKA SKUPAJ: NA DV IN ZEMELJSKA 2058,4km
- 1498 km OPGW –zaščitna vrv z vgrajenimi optičnimi vlakni
- 70 km OPPC- fazni vodnik z vgrajenimi optičnimi vlakni
- 14 km OPWR –nekovinski optični kabel ovit okoli žic
- 0,4 km ADSS –nekovinski samonosilni optični kabel
- 476 km ZOK –zemeljski optični kabel

OPTIKA V ELES

- Optična vlakna so na cca 80% Elesovih daljnovodnih trasah
- 77% optičnih kablov je na DV (OPGW, OPWR, OPPC), od tega je 95% OPGW
- Optične povezave s sosednjimi operaterji, distribucijo, ostalimi infrastrukturnimi operaterji (DARS, SŽ) in telekomunikacijskimi operaterji
- Uporaba optičnih vlaken predvsem za lastno TK omrežje za obratovanje energetskega sistema, viški za trg





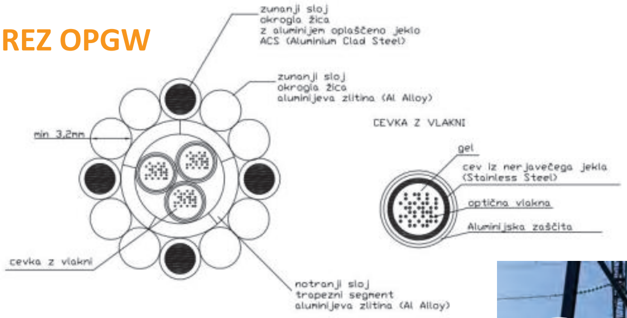
ZNAČILNOSTI OPGW

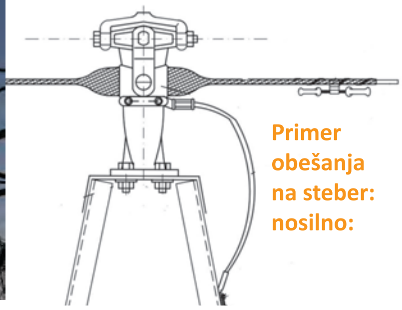
- Po osnovi je to strelovodna vrv daljnovoda in izpolnjuje osnovne konstrukcijske zahteve le-teh
- Sestavljen je iz enega ali več slojev žic iz aluminijeve zlitine ter jekla, žice v slojih so različnih oblik (okrogle, trapez)
- Ena ali več cevk v notranjih slojih so z vlakni z do 5‰ naddolžine vlaken v cevki
- Št. vlaken pogojuje konstrukcija DV (obremenitev vpliva na presek): v Elesu je to od 24 do 108
- Specialna obesna oprema, antivibratorji, specialni stroji za razvlek in način razvleka
- Standardi OPGW: SIST EN 60794-4 in SIST EN 60794-4-10, VLAKNA: ITU.T-652D (in 655C)
- Spojke: lega odvisna od stebrov (na zateznih), od bližine elektro objektov, max. možnega navitja na boben (do 5km); spaja se na tleh in ni potrebnega izklopa DV
- Proizvajalcev OPGW je veliko: NKT, Fujikura, Lumpi…




PRIMER OPGW zahteve in izvedba

PREREZ OPGW

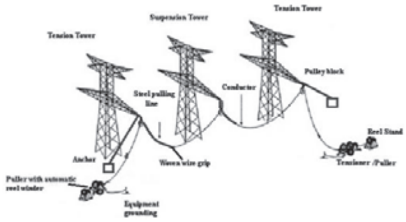




Primer obešanja na steber: nosilno:

KONSTRUKCIJSKE ZAHTEVE

Nosilni presek vrvi	mm²
Premer vrvi (toleranca ±2 %)	mm
Masa na enoto dolžine - maksimalna	kg/km
Računska pretržna sila - minimalna	kN
Nazivni kratkostični tok (20 °C-160 °C) - minimalni	kA, 1 s
Modul elastičnosti (toleranca ±15 %)	kN/mm²
Koeficient temperaturnega raztezka (toleranca ±15 %)	1/K
Enosmerna ohmska upornost pri +20 °C (toleranca ±30 %)	Ω/km
Premer žic ACS v zunanjem sloju	mm



IZVEDBA RAZVLEKA OPGW

PREDNOSTI IN SLABOSTI OPGW

PREDNOSTI V PRIMERJAVI Z ZEMELJSKIM KABLOM

- Cenejša in hitrejša izvedba: ni kopanja, služnosti, hitreje se izvede
- Manj poškodb: ni glodavcev, ni gradbenih poškodb pri kopanju
- Krajše trase in manjše slabljenje: DV imajo običajno ravne linije

SLABOSTI V PRIMERJAVI Z ZEMELJSKIM KABLOM

- Dražji material: kabel je dražji, dodatni obesni material
- Sanacija poškodb je daljša: zahteva izklop DV, zamenjava vrvi, zamenjava stebrov – več dni
- Manjša fleksibilnost pri dodatnih vzankanjih: ni možno dodajati dodatnih spojk, brez zamenjave dela OPGW

PREDNOSTI IN SLABOSTI OPGW

PREDNOSTI V PRIMERJAVI Z OPPC, OPWR, ADSS

- Manj poškodb v primerjavi z ADSS, OPWR (odpornost materiala)
- Lažje spajanje OPGW kot OPPC: OPGW spojka se spusti na tla, ni izklopa DV, pri OPPC je spajanje v izolatorju
- Več rezerve kabla za ponovna spajanja je na OPGW kot na OPPC

SLABOSTI V PRIMERJAVI Z OPPC, OPWR, ADSS

- OPGW kabel je dražji kot ADSS in OPWR
- Sanacija poškodb je daljša kot pri ADSS (v obeh primerih je izklop DV)
- Za razvlek in sanacijo OPGW ali ADSS je potreben izklop vseh DV sistemov na stebru, pri OPWR ali OPPC pa samo tistega na katerem je OPPC ali OPWR

SOVRAŽNIKI OPGW

Hitri vtični moduli (100 - 800 Gbit/s)
Fast plug-in modules (100 - 800 Gbps)

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Povzetek

Predavanje obsega prestavitev novih tehnologij, standardov in industrijskih dogovorov, ki omogočajo izvedbo kompaktnih vtičnih modulov (QSFP,QSFP-DD and OSFP), ki podpirajo prenosne hitrosti nad 100 Gb/s. Obravnavane so novosti glede upravljanja modulov (CMIS, C-CMIS) in glavne optične lastnosti nekaterih tipov modulov, ki so namenjeni za vzpostavitev povezav na večje razdalje. Glavni poudarek je na pregledu lastnosti koherentnih modulov 400G ZR in 400G ZR+. Predstavljene so zahtevane lastnosti optičnih transportnih sistemov, ki omogočajo izvedbo povezav s temi moduli, ter diagnostika teh povezav. Opisana je zasnova paketnega transportnega sistema, ki uporablja te povezave. V zaključku so omenjene še predvidene lastnosti bodočih tipov (hitrejših) modulov, ki bodo podpirali prenosne hitrosti vse do 3,2 Tb/s.

Abstract

In this paper an overview of technologies, standards and industrial agreements that enabled design and production of high speed compact pluggable modules (QSFP,QSFP-DD and OSFP) is given. This includes design concepts and management of these modules including CMIS and C-CMIS. An overview of main optical properties is discussed with emphasis on properties of modules using coherent transmission - 400G ZR and 400GZR+. Requirements of optical transport networks that allow efficient use of these modules are presented together with diagnostics procedures that enable establishing fast connections on long distances. There are discussed future trends and types of modules which cover devices that will support communications speeds of up to 3.2Tbps. A short description of packet transport system that uses these high speed connections is also covered.

Biografija avtorja

Peter Reinhardt je veteran na področju elektronike in računalništva, s 25 leti razvojno raziskovalnega dela na Institutu Jožef Stefan, in za tem prek 20 let v podjetju Xenya d.o.o. Z mrežami se ukvarja še iz časov DECNet-a. Z IP omrežji ima že več kot 30 letne izkušnje ter več kot 20 letne izkušnje z optičnimi komunikacijami. Sodeloval je pri zasnovah in postavitvi vrste javnih in poslovnih omrežij, optičnih povezav ter računskih centrov v Sloveniji. Ukvarja se s transportnimi optičnimi omrežji, IP omrežji, z arhitekturo omrežij in podatkovnih centrov, ter z načrtovanjem naprav in optičnih sistemov ter meritvami na področju optičnih komunikacij in v podatkovnih omrežjih..

Author's biography

Peter Reinhardt is a veteran in the field of electronics and computing, with 25 years of development and research work at the J. Stefan Institute, followed by over

20 years at Xenya d.o.o. He has been working with networks since the DECNet days. He has more than 30 years of experience with IP networks and more than 20 years of experience with optical communications. He participated in the design and installation of a number of public and business networks, optical connections and computer centers in Slovenia. He deals with transport optical networks, IP networks, the architecture of networks and data centers, as well as the planning of devices and optical systems, as well as measurements in the field of optical communications and data networks.

XenOpt

Hitri vtični moduli – 100Gb do 800Gb in hitreje

Pregled stanja tehnologije in novosti pri vtičnih modulih visokih hitrosti

Jan. 2023

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XENYA

Poudarki predstavitve

- Tehnologije, ki omogočajo izvedbo hitrih vtičnih modulov
- Spremembe pri upravljanju modulov CMIS, C-CMIS
- Pregled osnovnih tipov najbolj pogosto uporabljenih modulov za lokalne povezave
- Pregled glavnih lastnosti modulov za dolge povezave (400G-ZR in 400G-ZR+)
- Pregled zahtev, ki jih morajo izpolnjevati optični transportni sistemi, za uspešno delo na dolge razdalje
- Diagnostika dolgih povezav, Paketni transportni sistemi
- Novosti glede vtičnih modulov

Slike ozadja generirane z AI programom DALL-E

XenOpt

FEC – korekcija napak

- Bistvena funkcija za izvedbo uporabnih hitrih vtičnih modulov
  - Cenovno najbolj ugodna rešitev za povečanje zanesljivosti hitrih prenosov

- FEC na linijski strani je FEC nujen
  - Efektivno izboljša dinamiko prenosa za 4-11,6 dB
  - Standarni BER brez FECa se gibljejo med 2.0E-5 do 2.0E-2
  - Prva generacija: G.709, LL-FEC
  - Druga generacija ST-FEC, SD-FEC, CFEC,
  - Tretja generacija: oFEC, RS-BCH
  - oFEC, nepogrešljiv za 400Gb in hitrejše prenose na večje razdalje
    - FEC algoritm, ki bazira na korekciji (PCS) blokov podatkov z dodatno tro-stopensko SD (Soft Decision) korekcijo
    - 11.6dB efektivnega ojačanja (za DP-16QAM)
    - Korigira BER 2.0E-2 pred FEC na BER 10E-12 ali boljšo
    - Latenca prehoda prek obeh strani <3us
    - Za 400Gb prenosa zahteva DSP najnovejše generacije (7nm geometrija, visoka poraba)

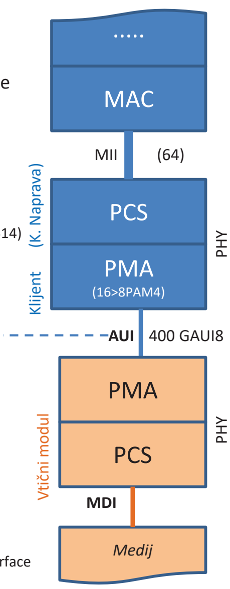
- FEC na električni strani
  - Visoke hitrosti povzročijo visoka dušenja na kratkih poteh (28-30dB), kar zniža SNR
  - Zaradi uporabe PAM4 se SNR na električni strani še dodatno zniža in BER poveča – potrebna korekcija
  - 25Gb: Brez ali z RS-KR-FEC [RS(528,514,t=7, N10)],
  - 50Gb: RS-KP-FEC [RS(544, 514, t=15, N10)]
  - IEEE 802.3 Clause 91

Vmesniki in modulacije na

klientni strani

- Na klientni (električni) strani morajo biti prenosi izvedeni prek več vzporednih poti 1,2,4,8,16 ker so hitrosti podatkov previsoke, da bi bilo mogoče prenašati te signale povsem serijsko
- Zaradi paralelnih prenosov in velikih hitrosti so potrebni dodatni protokolni nivoji
  - **PCS (Physical Coding Sublayer)**
    - Pretvorba iz 64/66 kodiranja na MII nivoju v bolj učinkovito 256/257 kodiranje v PCS nivoju, GMP (gearbox funkcije), ki omogočajo kompatibilnost s počasnejšimi kodiranji in sinhronizacijo pri različno hitrih urah na obeh straneh
    - vstavljanje OH, AM[1], ki omogočajo sinhronizaciji med potmi in identifikacijo začetka PCS bloka,
    - FEC korekcijo (), ki je potrebna zaradi znižanega SNR zaradi uporabe PAM4 enkodiranja RS(544,514)
    - Za 400Gb IEEE802.3bs c. 119,
  - **PMA (Physical Medium Attachment)**
    - Pretvorba 16 NRZI kanalov v 8 PAM4
    - Za 400Gb IEEE802.3bs c.120
- Pri izvedbi hitrejših protokolov se kombinira in ponovno uporablja protokole nižjih hitrosti s čim manj dodatki
  - 2x GMP100 za prenos 200Gb, 2x 200Gb za prenos 400Gb, 2x400Gb PCS za prenos 800Gb ...
  - To omogoča lažjo implementacijo, ponovno uporabo že razvitih in preizkušenih komponent in kompatibilnost s počasnejšimi protokoli

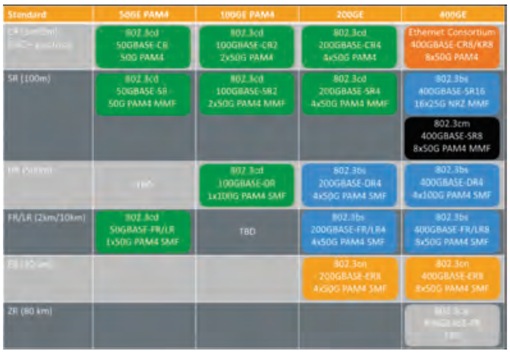
- Vtični modul in komunikacijska naprava sta na PMA nivoju povezana prek AUI vmesnika (Attachement Unit Interface). Za Ethrnet signale:
  - do 28Gbit je to CAUI vmesnik: 25Gb/pot; prim.: **100 CAUI-4** -100Gb NRI, FEC RS-(528,514, T=7, N=10) kot opcija (RS-KR FEC)
  - do 56Gbit je to GAUI vmesnik: 50Gb/pot; prim: **400 GAUI-8** – 400Gb PAM4, obvezen FEC RS(544,514, T=15, N=10) (RS-KP FEC)
  - Do 112Gb: do56Gbaud+ PAM4 -**OIF-CEI-112G-MR** Meadium reach ali **OIF-CEI-112G-LR** Long Reach Interface + PAM4 z ES-KP FEC
  - Do 224Gb: do 112Gb + PAM4 so specifikacije še v pripravi



1 OH-overhead bits, AM-Alignments Marker

Standardi in dogovori

- IEEE v okviru 802.3 grupe zagotavlja standarde, ki določajo lastnosti raznih tipov komunikacijskih vmesnikov.
- Žal standardi večinoma zaostajajo za dejanskimi produkti, ki so že na voljo in se uporabljajo v praksi
- OIF dopolnjuje te standarde z implementacijskimi dogovori, ki so običajno izdani hitreje



Standard	50GE PAM4	100GE PAM4	200GE	400GE
[illegible]	802.3cd 50GBASE-CR 50G PAM4	802.3cd 100GBASE-CR2 2x50G PAM4	802.3cd 200GBASE-CR4 4x50G PAM4	Ethernet Consortium 400GBASE-CR8/KR8 8x50G PAM4
SR (100m)	802.3cd 50GBASE-SR 50G PAM4 MMF	802.3cd 100GBASE-SR2 2x50G PAM4 MMF	802.3cd 200GBASE-SR4 4x50G PAM4 MMF	802.3bs 400GBASE-SR16 16x25G NRZ MMF; 802.3cm 400GBASE-SR8 8x50G PAM4 MMF
[illegible]	[illegible]	802.3cd 100GBASE-DR 1x100G PAM4 SMF	802.3bs 200GBASE-DR4 4x50G PAM4 SMF	802.3bs 400GBASE-DR4 4x100G PAM4 SMF
FR/LR (2km/10km)	802.3cd 50GBASE-FR/LR 1x50G PAM4 SMF	TBD	802.3bs 200GBASE-FR/LR4 4x50G PAM4 SMF	802.3bs 400GBASE-FR/LR8 8x50G PAM4 SMF
[illegible]			802.3cn 200GBASE-ER8 4x50G PAM4 SMF	802.3cn 400GBASE-ER8 8x50G PAM4 SMF
ZR (80 km)				[illegible]

IEEE 802.3 standardi, ki regulirajo 50-400GE vmesnike

- Nekateri novejši pomembni Standardi in dogovorjena pravila (MSA) za hitre vtične module
  - OIF[1]-400ZR-Implementation agreement, OIF CMIS Common Management Interface V5.5, Coherent extension C-CMIS V1.2, OIF-CEI – Common Electrical I-O
  - OpenZR+ MSA Specifications, v2.0
  - QSFP-DD-Hardware-Rev6.3-final, SNIA SFF Specifications (SFF-8636 ….), SFP-DD Specification V5.1
  - IEEE: Za 100-400Gb **IEEE802.3bs**, za 800Gb in 1.6Tb **IEEE 802.3df**

Ethernet aliance

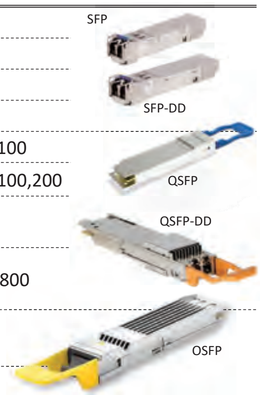
1 IOF – Optical Internetworking Forum

Pakiranje vtičnih modulov

in glavne lastnosti

Ime pakiranja	Št. par. poti (lanes)	Max s. h./pot [Gbaud]	Tipi vmesnika na strani klienta	Max. Disipacija [W][2]	Podprte Ethernet hitrosti [Gb]
SFP28	1	28	CAUI-1	5.5	1, 10, 25
SFP112	1	112[1]	112LR-1	5.5	100
SFP-DD	2	56	CAUI-2, GAUI-2	5.5	50, 100
SFP-DD112	2	112	GAUI-2, 112LR-2	5.5	100, 200
QSFP28	4	28	CAUI-4	6	4x1,4x10,4x25,2x50,50,100
QSFP56	4	56	CAUI-4, 2xGAUI-2, GAUI-4	6	4x1,4x10,4x25,2x50,50,100,200
QSFP-DD	8	28	4x CAUI-2, 2x CAUI-4, CAUI-8	14, 24	8x25,4x50,100,200
QSFP-DD800	8	56	4x CAUI-2, 2x CAUI-4, CAUI-8 4x GAUI-2, 2x GAUI-4, GAUI-8	14, 24	8x25,4x50,100,200,400,800
OSFP(800)	8	56	4x CAUI-2, 2x CAUI-4, CAUI-8 4x GAUI-2, 2x GAUI-4, GAUI-8	30	100, 200, 400, 800
OSFP1600 **OSFP-XD**	16	112	GAUI-16, 112LR-16, 224LR-8	40	100, 200, 400, 800, 1600, 3200

Slika

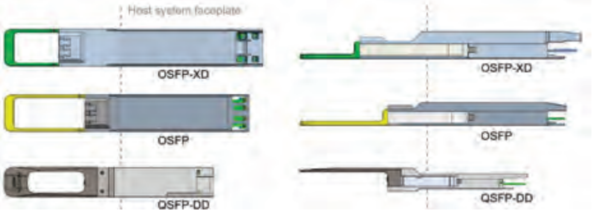


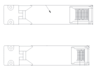
1 Hitrejši moduli podpirajo tudi vse počasnejše prenose

2 Poraba je določena v 4 do 8 razredih porabe, tu je naveden najvišji fiksni razred in najvišja poraba, ki jo lahko specificira modul v variabilnem razredu

Glavne lastnosti novih tipov pakiranja

- Primerjava velikosti: QSFO-DD OSFP OSFP1600 OSFP-XD SFP-DD SFP





SFP-DD

SFP

xSFP-DD konektor

- OSFP:
  - Večja dovoljena disipacija (30W)
  - Boljše vodenje hitrih signalov, hitrejši vmesniki do 224Gb
  - Dvo funkcijski (3 nivijski) počasni signali
  - Še vedno podpira vgradnjo 32 modulov v 1U stikalu
  - Možen Adapter QSFP-DD v OSFP
- OSFP-XD
  - 16 vzporednih poti
  - Večja dovoljena disipacija (40W)

- SFP-DD, SFP-DD112 :
  - Večja dovoljena disipacija (5.5W)
  - Hitrejši klijentni vmesniki (28, 56, 112 Gb)
  - Vtično mesto podpira vgradnjo SFP28, SFP+ in SFP modulov
  - Uporabljen predvsem v deljenih AOCin bakrenih kabih
  - Omogoča izvedbo 48 200Gb priključkov v 1U napravi

- SFP112:
  - Večja dovoljena disipacija (5.5W)
  - Vtično mesto podpira vgradnjo vseh počasejšh SFPx modulov
  - Uporabljen predvsem v deljenih AOC in bakrenih kabih

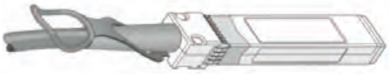
- Primerjava velikosti: QSFO-DD QSFP28 in SFP-DD

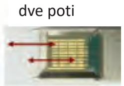
SFP-DD 2 poti

Deljeni 100Gb priključki – 4x 25Gb, 2x50Gb

- Pakiranja SFP/SFP+/SFP28
  - 1 sled, do 25Gb/s
  - SFP prenos do 100Mb/s- 4Gb/s
  - SFP+ prenos 8Gb/s, 10Gb/s, 16Gb/s
  - SFP28 – prenos do 25Gb/s
  - SFP112 – prenos do 100Gb/s
- SFP-DD : SFP56-DD, SFP112-DD
  - 2 sledi, 2x25Gb/s ali 2x 50Gb/s ali 2x 100 Gb/s izvedene z dvojnim konektorjem razporejenim po globini
  - prenos 50,100,200 Gb/s
  - Poraba do 3.5W
  - Predvsem uporabljen za deljene povezave 200Gb/s QSFP28 na 2x 100Gb SFP-DD, večinoma kot DAC kabel
- Priključek stikala je lahko kompatibilen s starejšimi vtičnimi moduli
  - QSFP28 priključek z
    - SFP: 1-4G, (1,2,4 FC)
    - SFP+:, 10G, (8G,16G FC),
    - SFP28: 25G
  - SFP-DD priključek z
    - SFP/SFP+QSFP28: z vsemi zgoraj naštetimi in
    - SFP-DD: 50Gb (2x25Gb, 1x50Gb) in 100Gb (2x50Gb)

SFP-DD
dve poti





Upravljanje vtičnih modulov

- Stari tipi modulov: SFP, SFP+, QSFP+, QSFP28, QSFP56
  - Upravljanje prek spominsko mapiranih registrov v emuliranem I2C eepromu, 256 znaakov razdeljenih na 2 strani
    - spodnja za identifikacijo, pomembne parametre, nadzorujejo delovanje modula in del diagnostike, vedno dostopna, zgornja mapira več (prek page registra) strani za razširjene funkcije, diagnostiko...
    - diagnostika se prikauje kot registri za branje v istem pomnilniku
    - Zaščita je večinoma le geslo, ki dovoljujejo pisanje/branje določenih delov pomnilnika
  - Večina parametrov opisanih v SNIA dokumentih (npr. SFF-8636 ....)
- Novi tipi modulov: SFP-DD, QSFP-DD, OSFP, OSFP-XD
  - Upravljanje prek **CMIS** protokola (Common Management Interface Specification)[1]
  - CMIS protokol za komunikacijo z modulom še vedno uporablja I2C protokol, in emuliran spominski vmesnik (256 znakov, 2 strani...)
  - Lokacije diagnostičnih registrov so različne kot registri z isto funkcionalnostjo v starih tipih modulov
  - Zadnja verzija je V5.2. Izvedbe z verzijo V3.0 in nižje niso skladne z V4.0 in višjimi. Nekatere funkcije med glavnimi verzijami prav tako niso skladne

1 OIF-CMIS-05.2 – Common Management Interface Specification (CMIS) Revision 5.2 (April 2022)

CMIS

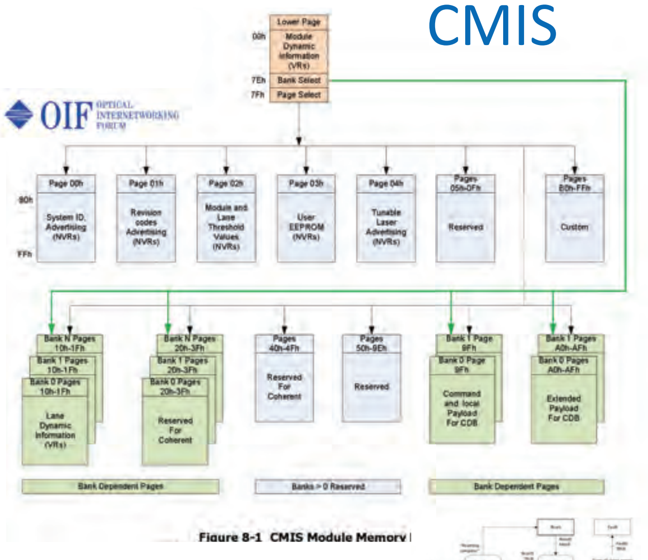


Figure 8-1 CMIS Module Memory

- Modul predstavi svoje sposobnosti napravi prek Advertising funkcij
- Isti Modul lahko podpira več različnih načinov dela (t.i. Aplikacij)
- V opisu Aplikacije se lahko ločeno določa način dela na klientni strani in način dela na linijski strani
- Odvisno od modula je lahko hkrati aktivnih več aplikacij
- Podpira izvedbo CDB ukazov, ki lahko prenašajo parametre in izvajajo kompleksne funkcije. Nekaj standardnih CDB ukazov:
  - Nadgradnja FW modula
  - Več nivojev detaljne diagnostike
  - BERT testi ....
  - Specifične funkcije za posameznega proizvajalca

Modul ima stanje spanja in aktivno stanje med katerimi prehaja v skladu s končnim avtomatom modula (MSM) prikazanim levo. Nekatere funkcije so podprte le v določenih stanjih modula.

CMIS Koherentnih modulov

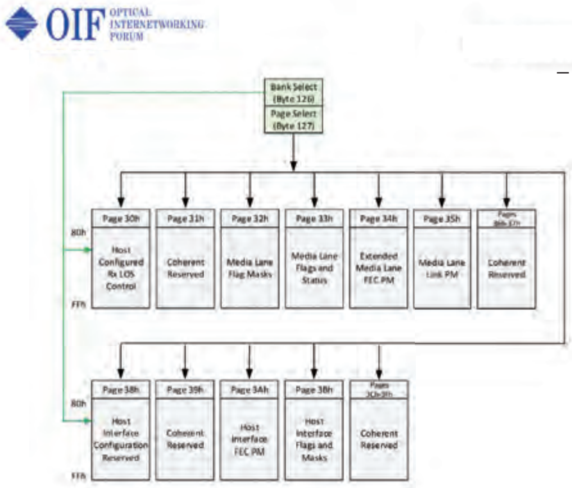


Figure 1: Diagram of Coherent Pages Extending CMIS Memory Map

- Koherentni moduli podpirajo dodatne nastavitve in diagnostične funkcije, ki se jih krmili prek ukazov specificiranih v C-CMIS[1] specifikaciji.
  Trenutno veljavna verzija C-CMIS je V1.2
- Dodatni Ukazi podpirajo:
  - Nastavitve parametrov koherentne modulacije
  - Nastavitve pragov optičnih nivojev za alarmiranje
  - Izbor FEC algoritmov tako na strani klijenta kot na strani linije
  - Detaljni diagnostični parametri linije (za vsako pot ločeno) med njimi:
    - Prikaz Optičnih moči oddajnih in sprejemnih signalov, prage za alarme ....
    - Prikaz Izmerjene CD linije in DGD signla
    - Odstopanje dejanske valovne dolžine od standardne vrednosti kanala
    - Izmerjeno Pol. Odv. duš. (PDL) linije
    - Izmerjen OSNR linije
    - Izmerjen SNR na električni strani (ESNR)
    - Prikaz SNR za posamezne poti na klijentni (električni) strani
    - Statistiko napak FEC vključno z številom popravljenih napak, in BER pred FECom na linijski in klientni strani[2]
    - Hitrost rotacije polarizacije signala
  - ....

1 OIF-C-CMIS-01.2 – Implementation Agreement for Coherent CMIS (March 2022)
2 Po intervalih, v 64bitnih števcih, k.naprava računa skupno statistiko

Kompatibilnost modulov in kablov

- Poleg parametrov, ki vplivajo na delovanje modula je v krmilnem lahko delu zapisna še dodatna vsebina ki jo proizvajalec preverja :
  - Proizvajalec
  - Oznaka modula
  - Serijska številka
  - Specifični parametri
  - Dodatna vsebina specifična za proizvajalca komunikacijske opreme
- V redkih primerih je modul spremenjen tudi na strojnem nivoju
- Vsi zgoraj našteti parametri in vsebine moraj biti pravi, da komunikacijska naprava zazna modul kot lasten (kompatibilen) modul. Če ga ne, ne deluje v opremi ali deluje z omejeno funkcionalnostjo ali ne zagotavlja tehnične podpore za opremo (tudi če delovanje modula ni sporno)
- Pri standardnih generičnih modulih je mogoče vsebino modula spreminjati z ustreznim programatorjem (tudi na terenu), tako da se vsebino enega generičnega modula lahko prilagodi zahtevam različnih proizvajalcev
- Pri modulih velikih hitrostih so nekateri proizvajalci opreme ločili kompatibilnost modula od licenc za pasovno širino in dovoljujejo uporabo vseh skladnih modulov
- Drugi proizvajalci napovedujejo da bodo pričeli vpisovati digitalne certifikate v module – kar zahteva vgradnjo dodatnega identifikacijskega čipa v sam modul (Brocade)

Generične IEEE oznake tipov vtičnih modulov

- Modulacija (NRZ), PAM4, Koherentni
- Pakiranje (SFP, SFP28,SFP-DD,SFP56-DD, QSFP28-DD, QSFP56-DD, OSFP,OSFP112)
- Hitrost prenosa (25, 50, 100, 200, 300, 400, 800 Gb, 1.6T, 3.2T)
- Standardni tipi modulov z IEEE oznako tipa (beli del):

<Pakiranje> <d>G-<x><y>

<d> Hitrost			<x> Doseg			<y> Število kanalov
10	100		SR , PMM	100m	P (MM)	Število nosilcev: Parov (P) optičnih vlaken ali Število valovnih dolžin (V) (1),2,4,8,16
25	200		DR, PSM	500m	P (SM)	
50	400		FR	2 km	V	
	800		LR	10 km	V	
			ER	40 km	V	
			ZR	80 km +	V	

Pregled tipov hitrih modulov

del standardnih **nekoherntnih** modulov

- Kabli
  - Bakreni (DAC): pasivni, aktivni (uporaba zaradi: cene, zakasnitve)
    - Direktni priključek–priključek : 100Gb (CAUI) do 3m, 200Gb (GAUI) do 2m, 200Gb (112LR) do 1m, če stikalo podpira AN & LT[1]
    - Deljeni Y - En priključek na več delnih priključkov
  - Aktivni optični kabli AOC
    - Direktni razdalje do 100m in več
    - Deljeni Y - En priključek na več delnih priključkov,
    - Deljeni H - Več delnih se križno vežejo na več delnih priključkov (uporaba v RC Spine/Leaf povezavah)
- Širokopasovni Moduli
  - Vtični moduli za kratke povezave (<40km, ena povezava /par ali več parov)
    - 100g: SR4 (100m), PSM4 (500m), FR4 (2km), LR4 (10km), CWDM4 (2,10km)
    - 200g: SR4 (100m), SR8 (100m), PSM8 (2km,10km), FR4 (2km), LR8 (10km,20km)
    - 400g, 800g: SR8 (100m), PSM8 (500m,2km,10km), FR8 (2km), LR8 (10km,20km,)
  - Široko pasovni vtični moduli za daljše povezave (≥40km, ena povezava/par)
    - 100Gb: CWDM4 (40km), ER4 (40km), ZR4 (80km), 4WDM-10 (120km)
- Moduli, ki z eno od WDM tehnologij omogočajo prenos večjega števila povezav prek ene fizične povezave (optičnega vlakna ali para)
  - WDM (NRZ),
    - 25Gb DWDM (15km)
  - PAM4 DWDM (80km),
  - O Band DWDM (80km) ,
  - Koherentni moduli v nadaljevanju

1 Line Training –Protokol, ki prilagodi parametre premphasis karakteristokam medija. Je nujen Za 112 Gbaud prenos na večje razdalje. (IEE802.3 clause 162 za 112G SerDes)

Standardne oznake prikazane v tabeli

	Backplane	Twinax Cable	15-40m(OT) Single Twisted Pair	>100m (OT) Single Twisted Pair	100m (IT) Twisted Pair (2/4 Pair)	MMF	500m PSM4	2km SMF	10km SMF	20km SMF	40km SMF	80km SMF	Electrical Interface	Pluggable Module
10BASE–	T1S		T1S	T1L	T									
100BASE–			T1	T1L*	T									
1000BASE–			T1		T									
2.5GBASE–	KX		T1		T									
5GBASE–	KR		T1		T									
10GBASE–			T1		T				BIDI Access	BIDI Access	BIDI Access			
25GBASE–	KR1 KR	CR1 CR/CR-S	T1		T (30m)	SR			LR EPON BIDI Access	EPON BIDI Access	ER BIDI Access		25GAUI	SFP
40GBASE–	KR4	CR4			T (30m)	SR4/eSR4	PSM4	FR	LR4				XLAUI XLPPI	QSFP
50GBASE–	KR2 KR	CR2 CR	T2			SR		FR	EPON BIDI Access LxR	EPON BIDI Access	BIDI Access ER		LAUI-2/50GAUI-2 50GAUI-1	SFP/QSFP
100GBASE–	KR4 KR2 KR1	CR10 CR4 CR2 CR1	T4			SR10 SR4 SR2 VR1 SR1	PSM4 DR	CWDM4 FR1	LR4 4WDM-10 LR1	4WDM-20	ER4 4WDM-40	ZR	CAUI-10 CPPI CAUI-4/100GAUI-4 100GAUI-2 100GAUI-1	SFP QSFP/QSFP-DD OSFP
200GBASE–	KR4 KR2	CR4 CR2 CR1*				SR4 VR2 SR2	DR4 1pair*	FR4 1 pair*	LR4		ER4		200GAUI-4 200GAUI-2 200GAUI-1*	QSFP/QSFP-DD SFP-DD
400GBASE–	KR4*	CR4 CR2*				SR16 SR8/SR4.2 VR4 SR4	DR4 2 pair*	FR8 FR4 400G-FR4	LR8 LR4-6 400G-LR4-10		ER8	ZR	400GAUI-16 400GAUI-8 400GAUI-4 400GAUI-2*	QSFP/QSFP-DD OSFP
800GBASE-	ETC-KR8 KR8*	ETC-KR8 CR8* CR4*				VR8* SR8*	8 pair* 4 pair*	8 pair* 4 pair* 4 lambda*	TBD*		TBD*		800GAUI-8* 800GAUI-4*	
1.6TBASE-		CR8*					8 pair*	8 pair*					1.6TAUI-16* 1.6TAUI-8*	QSFP/QSFP-DD OSFP/OSFP-XD

Gray Text = IEEE Standard Red Text = In Task Force Green Text = In Study Group
Blue Text = Non-IEEE standard but complies to IEEE electrical interfaces * Note: As of publication, subject to change

Primeri: QSFP, QSFP28, QSFP56 NRZ

Primeri nekaterih širikopasovnih 100Gb, 200Gb vtičnih modulov

- Nadgradnja QSFP+ 4x10Gb/s
- QSFP28 – 4x25Gb/s -100Gb
- QSFP56 – 4x25Gb/s -200Gb
  - MM -100m, brezbarvni LX, 2, 10Km
  - CWDM (okoli 1310nm) – 2km do 10km

Tip in hitrost	Doseg	Ohišje	Konektor	Vlakno
100G SR4	100 m	QSFP28	MPO	MMF
100G MM Duplex	100 - 300 m	QSFP28	MPO	MMF
100G eSR4	300 m	QSFP28	MPO	MMF
100G PSM4	500 m	QSFP28	LC	SMF
100G DR/DR+	500m, 2km	QSFP28	LC	SMF
100G CWDM4	2 km	QSFP28	LC	SMF
100G FR1	2 km	QSFP28	MPO	SMF
100G LR4 and LR1	10 km	QSFP28	LC	SMF
100G 4WDM10	10 km	QSFP28	LC	SMF
100G 4WDM20	20 km	QSFP28	LC	SMF
100G ER4-Lite	30 km	QSFP28	LC	SMF
100G ER4	40 km	QSFP28	LC	SMF
100G ZR4	80 km	QSFP28	LC	SMF
200G SR4	100 m	QSFP56	MPO	MMF
200G FR4	3 km	QSFP56	MPO	SMF

- Paralelne Valovne dolžine:
  - SR4 100m-2km,
  - LR4 (2-10)km, ER4 (20-40km)
  - FR4, ZR4 4 val. dolžine v bližini 1310nm CWDM, NWDM (60-100km, 100Gb)
- paralelne parice 1-8
  - PMM večrodne (100m)
  - PSM enorodne (500m)

- O-Band DWDM 200GHz, 150GHz razmik do 12 kanalov (do 3 povezave prek ene parice)

QSFP28, 100G ZR4, NRZ

Primer parametrov modula za povezave do 80km: XQSLN9-80LY-QSFP28

Parameter	Enote	Min	Typ	Max
Signaling Speed per Lane	Gb/s	25.78125 ± 100 ppm		
Wavelengths	nm	1294.53		1296.59
		1299.02		1301.09
		1303.54		1305.63
		1308.09		1310.19
Oddajnik				
Total Average Launch Power	dBm	8		12.5
Average launch power, each lane	dBm	2	4	6.5
Difference in launch power between any two lanes (Average and OMA)	dBm			3
Extinction Ratio (ER)	dB	6		
RIN OMA (~ TX OSNR)	dB/Hz			-130
Sprejemnik				
Average receiver power, each lane	dBm	-28		-7
Receiver power, each lane (OMA)	dBm			-7
Receiver sensitivity Average[1], each lane	dBm			-28
Max Power consumption	W		5	5.5

1 Rx Občutljivost pri BER@5E-5 kar nam z uporabo RS-FEC zagotovi BER<10E-12

- Brezbarvni (~1290-1310 nm)
- Dinamika >30dB, Doseg 80Km
- P_d<5.5W
- QSFP28

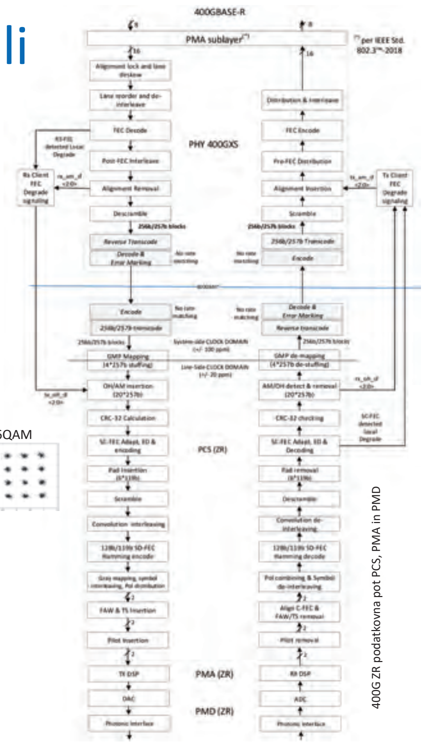
QSFP28 100G - PAM4 (Inphy ColorZ)

- PAM4: 100Gb DWDM:
  - Dva nosilca znotraj standardnega 100GHz pasu (λ_c±25GHz)
  - Oddajni nivo -10dBm na nosilec, Sprejemni nivo -2dB na nosilec
  - Ne deluje brez zunanjega optičnega ojačanja
  - Zahteva precizno kompenzacijo kromatske disperzije. Preostala disperzija max +-100ps.
  - Zahteva OSNR > 31dB
  - Uporablja PAM4 prenos in dva optična nosilca znotraj standardnega 100GHz DWDM kanala
  - Omogoča cenovne ugodne izvedbe sistemov ki prenašajo od 3 do 40 povezav po 100Gb med lokacijama oddaljenima do 80km
  - Pakiran v QSFP28 ohišje s porabo med 3.5 do 5W, kar omogoča delovanje v večini standardnih stikalih

Koherentni vtični moduli

- Edina resna alternativa za WDM prenos na večje razdalje na valovnih dolžinah izven O pasu (1310nm)
- Prvotno so bile koherentne rešitve na voljo le v CFP pakiranjih predvsem zaradi visoke porabe (do30W) in nizke integracije.
- V začetku 2020 so se pojavile prve izvedbe Koherentnih modulov v QSF-DD pakiranju. Te danes prevladujejo. Nove instalacije uporabljajo v več kot 90% prav koherentne 400G ZR ali 400G ZR+ QSFP-DD vmesnike. CFP moduli so sedaj smiselni le za posebne aplikacije (OTN prenos).
- Sedaj sta dobavljiva Dva glavna tipa QSFP-DD koherentnih modulov:
  - **400Gb ZR** prva verzija specificirana v OIF Implementation agreement 400ZR (marec 2020), deluje samo v 400Gb načinu z CFEC z DP-16QAM modulacijo
  - **400Gb ZR+** združuje iniciative OpenROADM in definiran v OpenZR+ MSA Spec. V2.0, prvič objavljena verzija V1 Sept. 2020
- **Skupne Lastnosti vseh koherentnih modulov**
  - Uporaba nastavljivega laserja kot lokalnega oscilatorja – omogoča nastavljanje kanala na keterem deluje sprejem in oddaja
  - Uporaba kompleksnih modulacij, ki prenašajo več bitov (3,4,..) v simbolu in tako bolj učinkovito izkorišča pasovno širino vlakna
  - Prenos samo Ethernt protokolov, opuščeni so OTN protokoli
  - Implemntacija večine podatkovnih protokolov zvedena v DSP, izven je le je optični del v obliki photonskeg IC, ki implementira laser in quad. modulatorje/demodulatorje in optično mutipleksiranje.
  - Sposobni kompenzirati visoke nivoje kromatske disperzije, PDL, SOP in drugih deformacij signala, ki se zgodijo v optičnem vlaknu, zato lahko delujejo v sistemih brez zunanjih kompenzaciskih naprav n adolge razdalje
  - Moduli večinoma še vedno zahtevajo zunanje optično ojačanje
  - V večini je degradacija OSNR tista, ki omejuje doseg teh modulov

16QAM



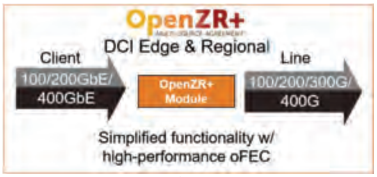
400G ZR podatkovna pot PCS, PMA in PMD

Koherentni 400G ZR - glavne lastnosti

Parameter	Vrednost	Komentar
Valovne dolžine delovanja	50 GHz Mreža / 75 GHz Pas. Širina	100 GHz in 75GHz mreža podprti
Modulacija Liniska stran , Baud Rate	DP-16QAM 59.84375 Gbaud/s	
TX OSNR znotraj pasu	34 dB	Za 0.1nm pasovne širine (12.5 GHz)
TX OSNR izven pasu	23 dB	Znotraj celotnega frekvenčnega področja
Line side Lane, FEC	SC-FEC	OSNR (B-B) = 26 dB
Tx Output Power, Typ	-9 dBm	-10 dBm min
Vmesnik klijenta	400 GAUI8	53.125 Gbps, PAM4 KP4 RS FEC (OIF CEI 56-MR)
Rx OSNR Toleranca	26 dB	
Rx Občutljivost	-12dBm TYP	-18 dBm razširjen obseg, s slabšo OSNR toleranco, omejen s šumom
CD toleranca	2400 ps/nm	do 120 km G.652 cable
Frekvenčni pas	191.3 to 196.1 THz	75 or 100 GHz raster
Temperatura ohišja	0 to 75°C	
Total Power Consumption	≤ 19 W	Temp. ohišja 75°C
Napajanje	3.135 V to 3.465 V	

- Deluje le v enem načinu dela: z modulacijo DP-16QAM za prenos 400Gb/s
- Vmesnik proti stikalu podpira tudi en sam način dela 400G GAUI-8
- OSNR toleranca 8dB > majhno število ojačevalnih stopenj predno je OSNR toleranca omejitev dosega
- Dodatno znižanje OSNR tolerance za do 2.8dB možno zaradi mejne vrednost CD<2400, mejne vrednosti PMD<10ps, velike razlike dušenja odvisne od polarizacije (PDL<3.5dB), velike hitrosti vrtenja polarizacijskih ravnin (SOP<50Krad)
- Odpornost na CD omejuje doseg na največ 120km
- Sprejemna občutljivost -12dBm, da ohrani OSNR toleranco
- Brez optičnega ojačanja lahko dosega le okoli 20-km dosega, zato to ni smiselna uporaba
- Visok šum izven delovnega pasu – koristno uporabiti pasovno filtriranje
- Na voljo je tudi HiPower verzija 400G ZR, lahko oddaja z 0DBm moči, ostaleparametre pa ima enake ta ima doseg brez optičnega ojačanja od 60-80km

400G ZR+



- Združene izbrane funkcije iz dveh preverjenih projektov: OpenROADM in 400ZR
- Dobimo modul, ki je sposoben prenašati Ethernet protokole s hitrostmi od 100, 200, 300 in 400Gb in to bolj zanesljivo zaradi uporabe bolj učinkovitih posopkov korekcije napak
- Sodobni koherentni moduli (OpenZR+) uporabljajo bolj kompleksne modulacije in oFEC korekcijo
  - za linijsko hitrost 100Gb in 200Gb tipično DP-QPSK, DP-8QAM
  - za linijsko hitrost 300 Gb tipično DP-8QAM
  - za linijsko hitrost 400 Gb tipično DP-16QAM

400G ZR+ glavne lastnosti

primerjava Specifikacije Standardega OpenZR+ in specifikacij dejanske izvedbe 400G ZR+ (Xenopt XKDT84-J0LY)

- Djanske izvedbe OpenZR+ kot 400G ZR+ lahko presegajo predpisane mejne vrednoti v OpenZR MSA, poleg tega pa lahko izvajajo še dodatne funkcije kot so npr. Skadnost z 400G ZR in optično ojačanje TX signala ...

Skupne lastnosti:

Parameter	Vrednost po OpenZR+	Vrednost (Xenopt Hi power)	Komentar
Frekvenčni obseg	C-Band: 191.3 to 196.1 THz		
Val. dolžina	Flex grid 6.25 GHz resolution		Podprt 75 in100 GHz spacing
Min pasovna širina kanala	75 GHz		Minimalna razmik kanalov 75 GHz
Podprti načini delana linijski strani	400Gb-CFEC-16QAM (400G 16QAM ZR) (samo Xenopt), 400Gb-OFEC-16QAM (400G 16QAM ZR+), 300Gb-OFEC-8QAM (400G 8QAM ZR+), 200Gb-OFEC-QPSK (200G QPSK ZR+), 100Gb-OFEC-QPSK (100G QPSK ZR+)		Deluje z drugimi OIF ZR in Open ZR+ skladnimi moduli
Linijski FEC	oFEC, cFEC		
Načini dela vmesnika klijenta	400GE: 400 GAUI-8, 4x100GE: 4x100GAUI-2, 3x 100GE: 3x100GAUI-2, 2x200GE: 2x GAUI-4, 100GE: 100GAUI-2,100GE: CAUI-4		Po IEEE Std 802.3 [5], Annex 83E, Table 83E–7

- DWDM C-Band delovanje z nastavljivim kanali
- Vsak ZR+ modul lahko deluje v naslednjih načinih:
  - 400G – 400G GAUI8
  - 400G – 4x100G GAUI2
  - 400G – 2x 200G
  - 300G – 3x 100G GAUI2
  - 200G – 1x 200G GAUI4
  - 200G – 2x 100G GAUI4 ali CAUI4
  - 100G – 1x 100G GAUI4 ali CAUI4
- OpenZR+ specifikacija ne zahteva skladnosti z 400G ZR, ker ne zahteva podpore CFEC, kljub temu je večina izvedb 400G ZR+ skladna tudi z 400G ZR

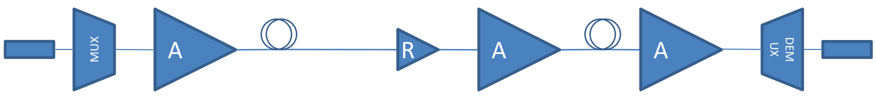
400G ZR+ glavne lastnosti (nadaljevanje)

Parameter	Vrednost po OpenZR+	Vrednost (Xenopt Hi power)	Komentar
Linijski FEC	oFEC, cFEC		
TX Moč	-13 to -9 dBm	-6 to 1 dBm	+-1db tolerance
TX Moč typ	-10dBm	0dBm	
TX OSNR (in band)	34dB/0.1nm	40dB/0.1nm	
TX OSNR izven kanala	23 dBm	35 dBm	
RX občutljivost, 400G, 300G, 200G, 100G ne ojačan signal	-12, -15, -18, -18 dBm (OpenZR+ ne določa verjetno je višja)	-23, -26, -30, -32 dBm	OSNR >35dB/0.1nm, 400G 16QAM
RX občutljivost 400G, 300G, 200G, 100G ojačan signal	-12, -15, -18, -18 dBm	-18 to 0 dBm	Za OSNR znotraj spodnjih meja
RX OSNR toleranca 400G, 300G, 200G, 100G ojačan signal	24, 21, 16, 12,5 dB/0.1nm	25.0, 23.5, 15.0, 12.0 dB/0.1nm	Za standardne RX vhodne nivoje,
CD Tolerance (ZR)	+-2400 ps/nm	+-2400 ps/nm	Do 120 km prek G.652 v ZR načinu
CD Tolerance (ZR+) 400G, 300G, 200G, 100G	20000,40000, 50000,100000 ps/nm	12000,18000, 24000,48000 ps/nm	Xenopt do 650 km prek G.652 OpenZR+ do 1100 km za 400G 16QAM, prek G.652 na nižjih hitrostih več
Poraba	Ni določena	22W (19W Typ)	

- OSNR toleranca 8dB > majhno število ojačevalnih stopenj predno je OSNR toleranca omejitev dosega
- OSNR toleranca je boljša pri 400Gb ZR+ kot pri nižjih hitrostih in znaša 10 / 15 dB
- OpenZR+ MSA predvideva nizkek OSNR izven kanala, ki znaša le 23 dB (11dB manjši kot v kanalu zato je za standardne module še bolj pomembni zagotoviti filtriranje tudi za neojačane povezave
- Dodatno znižanje OSNR tolerance za do 2.8dB možno zaradi mejne vrednost CD<2400, mejne vrednosti PMD<10ps, velike razlike dušenja odvisne od polarizacije (PDL<3.5dB), velike hitrosti vrtenja polarizacijskih ravnin (SOP<50Krad)
- Odpornost na CD v v obeh primerih velika, tako da bo domet običajno omejen z OSNR dinamiko
- Brez optičnega ojačanja lahko standardni ZR+ dosega le okoli okoli 30km dosega, zato to ni smiselna uporaba za direktne povezave. Specifikacija OpenZR+ ne specificira bolše občutljivosti ob najboljšem možnem OSNR, zato je ta razdalja le ocena.
- Hi power ZR+ omogoča 23 dB dinamike v neojačanem načinu dela, kar omogoča delo na razdalje od 80 do 100km brez ojačanja.

Ukrepi za prilagoditev optičnega sitema

za uspešno izvedbo ZR+ povezav



- Optično ojačanje je potrebno zagotoviti z nizkim dodanim šumom
  - Izračunati vpliv optičnih ojačevalcev na OSNR Če je ta pod OSNR toleranco modulov je potrebno Zmanjšati vpliv ojačevalcev na OSNR z naslednjimi ukrepi
    - Povišati nivoje signalov na vhodih
      - Povečati moč na oddaji
      - Zmanjšati število kanalov
    - če to ni mogoče skrajšati trase, oz dodati vmesne lokacije za optično ojačanje
    - če to ni ogoče je potrebno na kritičnih mestih uporabiti kombinacijo RAMAN in EDFA ojačevalcev
- Upoštevati je potrebno dejanski vpliv CD, PDL, PMD na poslabšanje OSNR
  - Dovoljene Mejne vrednosti vsakega od teh parametrov znižujejo OSNR odpornost za 0.5 do 2.3dB
- Odstraniti je potrebno vse komponente, ki ne zagotavljajo vsaj 75GHz pasovne širine kanala (kanalizirane Bgagg DCM module, 50GHz filtre, interleaverje ...)
- Poskrbeti, da ne prihaja do presluhov iz drugih kanalov
- Poskrbeti da ne prihaja do nelinearnih pojavov (Briulin, Raman, intermodulacija)
- Tudi v neojačanih sistemih je koristno uporabiti 100GHz filtre, da izločimo motnje izven pasu.

Diagnostika povezav

- Diagnostiko lahko izvajamo direktno na komunikacijski opremi, ki jo 400G ZR/ZR+ povezuje
  - CLI ukazi, ki prikažejo parametre, ki kažejo na kvaliteto optične povezave
  - SNMP, orkestracija
  - Na večini stikal dostopna tudi programsko kot json ali Netconf/Yang ...
- Različen postopek za aktiviranje in za nadzor
- Prioritetni vrstni red indikatorjev
  - Error rate (post FEC)
  - Pre FEC error rate
  - OSNR na liniji
  - OSNR na klientni strani

Primer dela izpisa statistike priključka:

```
PCS statistics                              Seconds
   Bit errors                                     0
   Errored blocks                                12
 Ethernet FEC Mode  :                    FEC91-RS544
 Ethernet FEC statistics                      Errors
   FEC Corrected Errors                         179
   FEC Uncorrected Errors                        12
   FEC Corrected Errors Rate                      0
   FEC Uncorrected Errors Rate                    0
 Optic FEC Mode  :                             CFEC
 Optic FEC statistics:
   Corrected Errors                                        20548530872257
   Uncorrected Words                                                    0
   Corrected Error rate                                         490045240
   Uncorrected Error rate                                               0
   Corrected Error Ratio     (46063 seconds average)  9.99e-04
 PRBS Mode : Disabled
 Interface transmit statistics: Disabled
 Link Degrade :
   Link Monitoring            :  Disable
```

Del izpisa optičnih parametrov koherentnega modula

```
Lane 0
    Laser bias current           :  251.496 mA
    Laser output power           :  0.169 mW / -7.71 dBm
    Laser temperature            :  65 degrees C / 149 degrees F
    Laser receiver power         :  0.048 mW / -13.14 dBm
    Lane chromatic dispersion                :  0.0 ps/nm
    Lane differential group delay            :  3.0 ps
    Lane carrier frequency offset            :  -54.0 MHz
    Lane polarization dependent loss         :  0.3 dB
    Lane snr                                 :  17.7 dB
    Lane Optical signal-to-noise ratio       :  36.4 dB
```

Diagnostika povezav (2)

- Nekatera stikala podpirajo ukaze, ki (prek CMIS MDB ukazov) podpirajo generiraje testnih (PRBS) tokove prometa pri polni hitrosti medija
- Iz diagnostičnih izpisov lahko vidimo dejanske vrednosti parametrov linije, ki vplivajo na znižanje OSNR tolerance in na osnovi tega bolj natančno izračunamo rezervo pri OSNR.
- Glede na nivoje optične moči signalov, nivoje OSNR ter pogostost napak lahko sklepamo na vzrok.
- Če prihaja do napak preverimo da so:
  - optični nivoji znotraj meja
  - temperature modula znotraj dovoljenih
  - modul spoznan in označen kot delujoč (da na moduli ni aktivnega alarma)
  - OSNR nad minimalno zahtevanim
  - Pre FEC rate pod pragom sposobnosti FEC algoritma
  - Pri spremembah na liniji prvo opazujemo spremembo FEC statistike, Potem OSNR
  - Zelo majhne spremebe OSNR lahko povzročijo velike spremebe v naraščanju ali padanju števila napak (popravljivih in nepopravljivih)
- Pri delujoči liniji imamo več stopenj zgodnjih opozoril, ki kažejo na slabšanje kvalitete povezave veliko prej, predno lahko to vpliva na samo komunikacijo.

Del izpisa detaljnega izpisa optičnih parametrov

```
Tunable param init:            true
    Wavelength Tunable:            true
    Tunable(fc contrl):            false
    Tunable(wl contrl):            false
    Tunable(First 100 Freq[THz]):  191.3
    Tunable(Last 100 Freq[THz]):   196.1
    Tunable(First 100 ch):         -18
    Tunable(Last 100 ch):          30
    Tunable(First 75 freq[THz]):   191.3
    Tunable(Last 75 freq[THz]):    196.1
    Tunable(First 75 ch):          -72
    Tunable(Last 75 ch):           120
    Tunable(First 6.25 freq[THz]): 191.275
    Tunable(Last 6.25 freq[THz]):  196.125
    Tunable(First 6.25 ch):        -292
    Tunable(Last 6.25 ch):         484
    Grid Spacing[Ghz]:             100
    Encoded Range:                 0
    Tuned Frequency[THz]:          193
    Tuned Wavelength[nm]:          1553.33
    Pending Wavelength[nm]:        1553.33
    Wavelength Is Pending?:        0
    Tuned Channel Raw:             -1
    Config Channel 2s Compl:       1
    Chromatic Dispersion[ps/nm]:   4
    SOPMD[ps^2]:                   31
    Pdl[dB]:                       0.3
    Carrier Frequency Offset[MHz]: -312
    Diff Group Delay[ps]:          1
    Electrical SNR[dB]:            17.3
    Optical SNR[dB]:               36.4
    Rx Power[mW]:                  0.042
    Tx Power[mW]:                  0.1674

root@acx-test:pfe>
```

IPoDWDM paketni transportni sistemi

- Trend izgradnje paketnih transportnih sistemov, ki prenašajo le IP promet in nadomeščajo klasične L1 transportne sisteme
- Povezave Točka-Točka z DWDM hitrimi vtičnimi moduli (Nx 100 do Nx400Gb/s ...)
- Moduli vtaknjeni direktno v komunikacijska stikala, brez transponderjev.
- Dodan le optični del transportnega sistema (mux/demux, ojačevalniki) in pasivni optični sistem, ki zagotavlja premoščanje sosednjih usmerjevalnikov z nekaj povezavami, klahko zagotovijo dodatno stopnjo redundantnosti
- Stikala poganjajo usmerjevalni protokol (tipično BGP in/ali OSPF), ki zagotavlja redundantnost povezav
- Uporabniške povezave zagotovljene ali s tuneliranjem L2 ali L3 tunelov prek L3 omrežja (VXLAN, EVPN) ali z MPLS EVPN povezavami.
- Orkestracija omrežja zagotavlja hitro samodejno vzpostavitev logično ločenih L2 in L3 povezav
- Nadgradnja pasovne širine s postopnim dodajanjem dodatnih DWDM povezav, brez motenj delovanja transportnega sistema
- Možna uporaba cenovno ugodnih stikal namenjenih uporabi v podatkovnih centrih z določenimi omejitvami glede strukture prometa, ki omogočajo izogibanje ozkim nastanku ozkih grl. Ta stikala zagotavljajo ugodno ceno glede na prenosno hitrost in nizke zakasnitve

Zaključek

- Hitri vtični moduli, posebno koherentni, so kompleksne naprave, ki jih je potrebno uporabiti pravilno, da delajo dobro in zanesljivo prenašajo promet brez napak. Pri pravi uporabi lahko opozorimo na slabšanje linije preden to povzroči prekinitev komunikacije

- Sedaj so klasični transportni sistemi postali manj relevantni, še posebno če rabimo le paketne prenose podatkov

- Izgradnja paketnih transpornih sistemov s popolno diagnostiko in je postala bistveno cenejša in bolj enostavna. Taki sistemi so lahko bolj robustni in bolj zanesljivi od klasičnih. Pasovna širina je z novimi moduli postala bistveno cenejša, postopno prilagajanje naraščanju potreb pa lažje.

- Razvoj teh modulov se je šele dobro začel (<2 leti) in trenutno smo še v začetni fazi zelo hitrega razvoja, ki ga spodbujajo največji porabniki (cloud providerji), in nove aplikacije v podatkovnih centrih (AI). Trenutno so ozko grlo prej ponudniki hitrih stikal kot kapaciteta prenosa. Na vidiku pa so rešitve za vmesnike za dolge linije s hitrostmi 800 Gb, 1600 Gb in 3200Gb, ki so videti rešljive že s sedanjo tehnologijo hitrih vtičnih modulov.

The use of telecom fiber optics in sensor applications

Edvin Škaljo

University of Sarajevo, Department of Physics, BiH

sklajo@hotmail.com

Abstract

This SMM and MM fibers are the two most common varieties of fiber in use in telecommunications. Because the cost of fiber and associated equipment is continually falling, it is now available for laboratory research outside of telecom. In this articel there is explained three types of sensor applications:

1) sensor applications with direct light passages,

2) sensor applications based on reflected light,

3) sensor application in combinations of MM and SM fibers.

Mathematical models and experimental setups are also discussed.

Author's biography

Edvin Skaljo, has more than 20 years of experience in telecommunications. He received his Ph.D. from the University of Tuzla, Bosnia and Herzegovina. Dr. Skaljo has held several management positions at BH Telecom, the leading telecom operator in Bosnia and Herzegovina. He has pioneered the implementation of numerous projects and new services in the field of fiber optics communications and related broadband technologies. He is the author of many international presentations in this field. Dr. Skaljo is also an associate professor at the University of Sarajevo, and an Associate Editor of the international journal Fiber and Integrated Optics. He is a president of Professional association of electronic, automatics and telecommunications engineers and vice-chairman of Engineer chamber of engineers of the Federation of Bosnia and Herzegovina. He is a senior member of IEEE, Optica and SPIE. In addition, he has served as chairman of the International Workshop on Fiber Optics in Access Networks (FOAN), since its founding.

The use of telecom fiber optics in sensor applications

Edvin Skaljo,
University of Sarajevo, Department of Physics
Bosnia and Herzegovina

Agenda

ĀMotivation and focus of presentation;

ĀFour mechanism for sensing

4 Reflection
4 Transmission
4 Absorption
4 Scattering

ĀFew examples and experiments

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About me

Ā Education::
  Ā University of Banjaluka/University of Sarajevo undergraduate programs; University of Sarajevo master's programs; University of Tuzla doctoral programs

Ā Since 1996, I have worked for BH Telecom in various capacities, including fiber optics, broadband networks, Ethernet, IP, IPTV, SIP, etc.

Ā an Associate Professor in the Physics Department of the Faculty of Science at the University of Sarajevo.
  Ā an adjunct professor at UNSA who teaches courses in electronics, fiber optics, and electrical measurements of non-electric quantities.

Ā Vice President of the Federation of Bosnia and Herzegovina's Chamber of Engineers and President of the Association of Electronics, Automation, and Telecommunications Engineers (EAT)

Ā an assistant editor-in-chief for Taylor&Francis' "Fiber and Integrated Optics" magazine.

Ā Founder and president of the FOAN series of international workshops on fiber optics in access networks;

Ā The creator of over 40 papers in reputable databases

Ā SPIE, OSA, and IEEE senior members;

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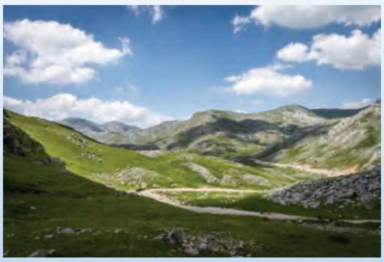
Fibers can be found everywhere.

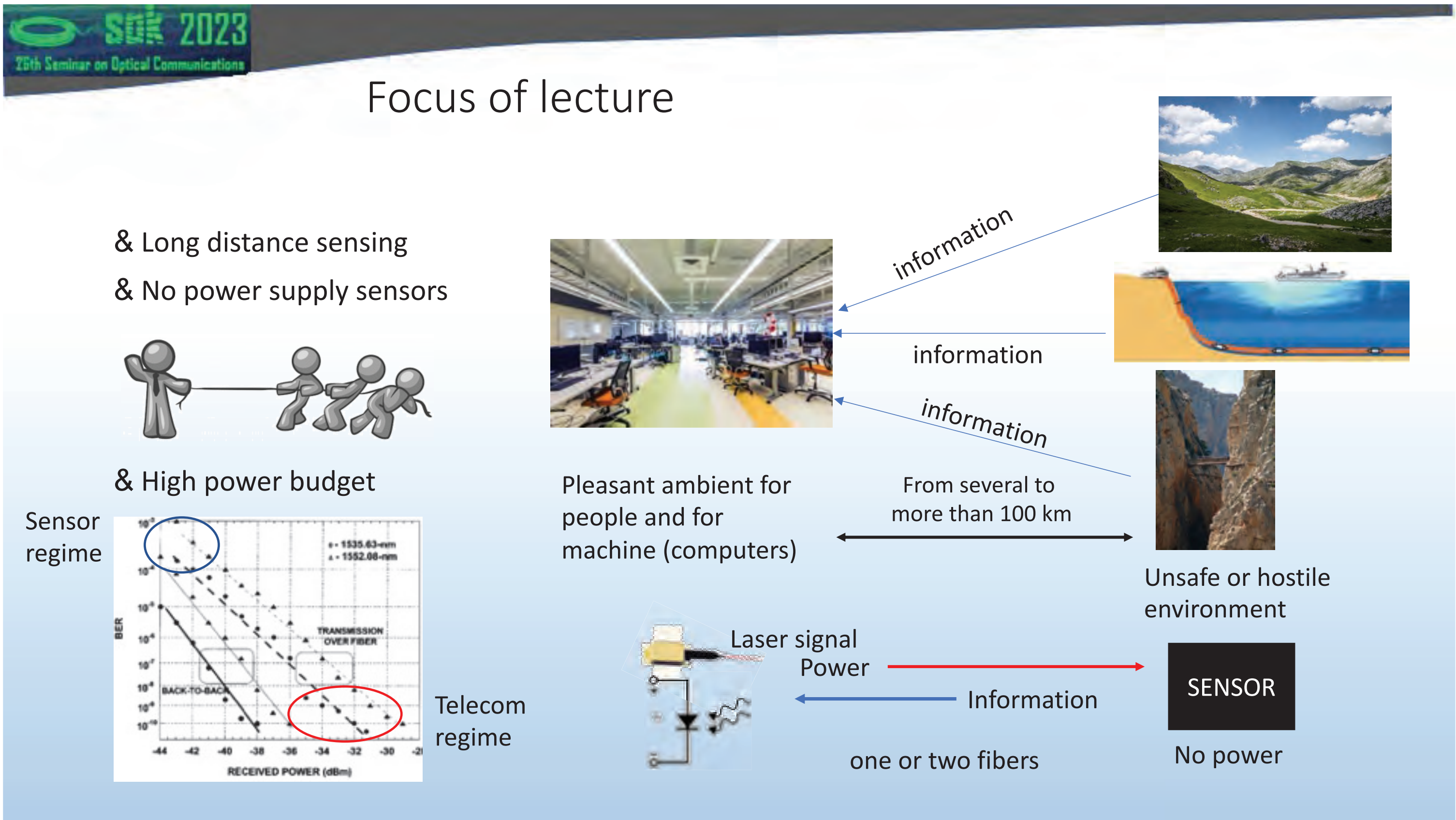
YELLOWSTONE NATIONAL PARK TO GET 187 MILES OF FIBER OPTIC CABLE, FEBRUARY 16, 2022, HTTPS://MYBIGHORNBASIN.COM/

&,9>=Ā#$Ā57<Ā80",%Ā
*+.'#Ā#!"(%- @/;/Ā6+3.Ā+<Ā
:+;=Ā90Ā=2/Ā:;94/-= Ā
*;94/-=Ā3<Ā$(Ā98Ā)98=Ā
'?/;/<=



Bosnian mountain Visočica,
Optical cable installed 10 years ago

Ā The main advantages of fiber optics is possibility of long-distance transmission of high amount of information;
  Ā Fiber optics is around us: Between cities, in neighbored, over mountain, under ocean or river, access deserts
  Ā There is almost no competition on long distance and high-speed applications: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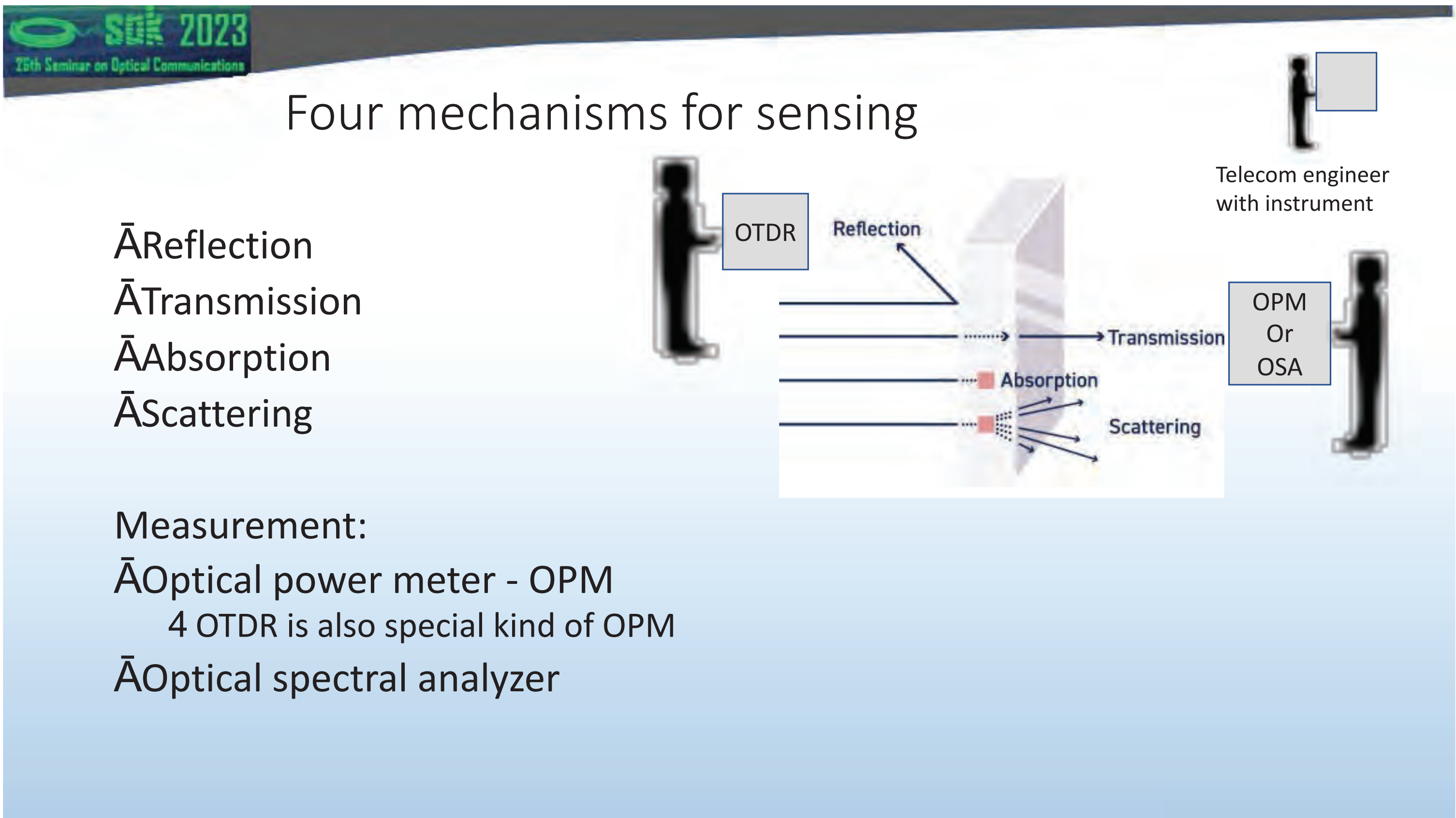
Focus of lecture
& Long distance sensing
& No power supply sensors
& High power budget
Sensor regime
Telecom regime
BACK-TO-BACK
TRANSMISSION OVER FIBER
RECEIVED POWER (dBm)
BER
information
information
information
Pleasant ambient for people and for machine (computers)
From several to more than 100 km
Unsafe or hostile environment
Laser signal
Power
Information
SENSOR
one or two fibers
No power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Four mechanisms for sensing
ĀReflection
ĀTransmission
ĀAbsorption
ĀScattering
Measurement:
ĀOptical power meter - OPM
4 OTDR is also special kind of OPM
ĀOptical spectral analyzer
Telecom engineer with instrument
OTDR
Reflection
Transmission
Absorption
Scattering
OPM
Or
OSA

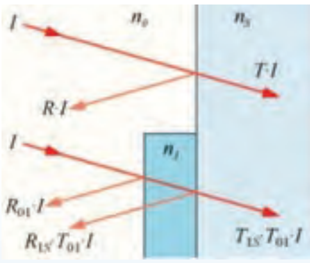
Reflection

& The difference in refractive indexes determines reflection – R;

& If light exits the fiber (I1) and enters another medium, the signal is reduced by R.

$$R = \frac{(n1 - n2)}{(n1 + n2)^2}^2$$

T1 = I – RI = I(1-R)



& In telecom we it see as attenuation or loss, instead I we use P_0, and P_1 instead T1,

$$L_R = 10log\left(\frac{I(1-R)}{I}\right) = 10log(1 - R) \qquad L_R = 10log\left(1 - \left(\frac{n1-n2}{n1+n2}\right)^2\right)$$

Ā ORL – optical return loss

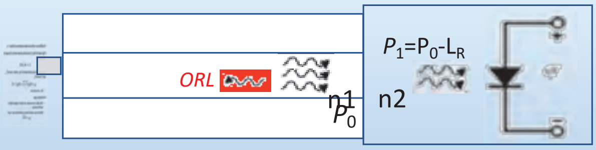
$$ORL = 10log\left(\frac{n1 - n2}{n1 + n2}\right)^2$$

& Antireflective layer

C Fiber optical communication can hardly be imagined without antireflection layer

C Reflection loss is reduced when an antireflective layer is used.

$$n_{AR} = \sqrt{n1n2}$$



The first idea for sensing:
If the refractive index (n2) changes due to some natural phenomenon, (as temperature, ..
it can be measured using an instrument as OPM (or OTDR)

NOTE: n2 – is not index of cladding, so we will use n_m as m -media

Refractive index of fiber (core or cladding) depends on wavelength

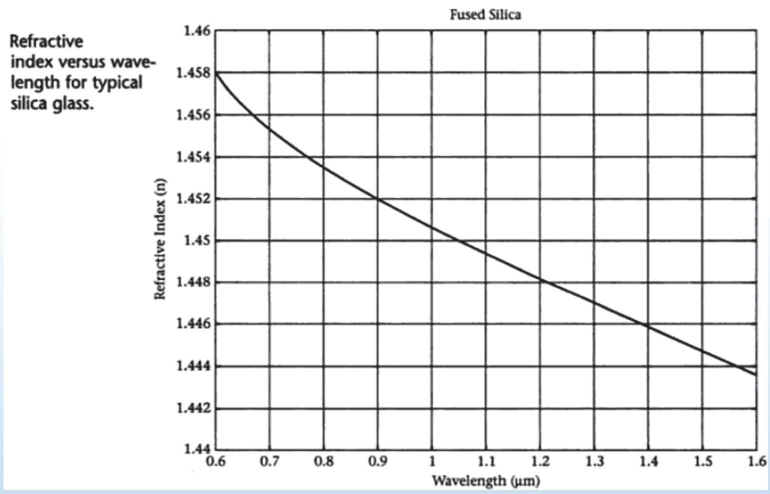
& Typical difference in refractive index in core and cladding is in 3 to 5 decimals;

& For example (source: www.refractiveindex.info):

650 nm	1.45650
850 nm	1.45250
1310 nm	1.44680
1550 nm	1.44400

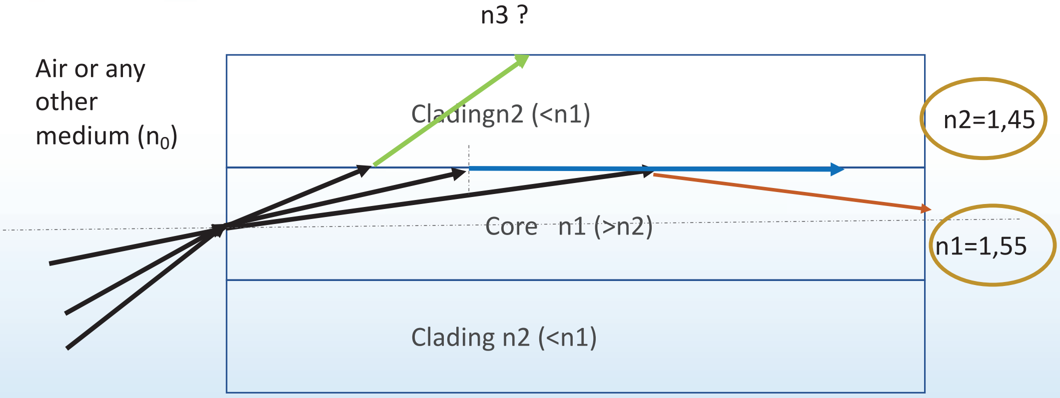
C As n1 depend on wavelength, it means that ORL also depend on wavelength:

$$ORL(\lambda, media) = 10log\left(\frac{n1 - n_m}{n1 + n_m}\right)^2$$



S

Transmission: is based Snell law (or Ibn Sahl) and transparency of some wavelength window

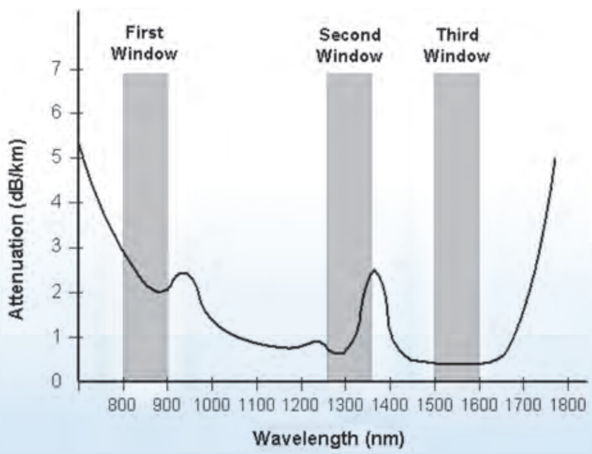


- & If difference is changed than the amount of light that go out is changed:
  - & Small difference will produce that more light go out;
  - & Larger difference – more light stay in the core
- 4 How about cladding and air (n3)?

Snell's law discovered by '((%",/,$ À)%((- 1621
But it was described by Ibn Shal – 984.

Transmission: Fiber optics wavelength window

- & In telecom we are speaking about three window:
  - Ā 850 nm, 1310 and 1550 nm
  - Ā Most used are 1310 and 1550 nm
  - Ā Left of 1280 nm is almost forgotten. Why.
- & In sensing application :
  - Ā 650 nm to 1800 nm is acceptable
- & 1310 and 1550 nm allow us a long-distance communication a long-distance sensing application



The first idea for sensing:

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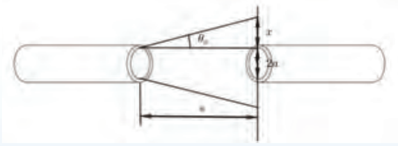
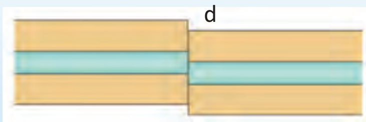
Transmission: fiber misalignments

ĀThere are three misalignments:



$$A = -20log(\frac{a}{a + sNA})$$



$$A= -10lpg_{10}\left(\frac{1}{\pi}\left(2arccos\frac{d}{2a} - \frac{d}{a}\sqrt{1-\left(\frac{d}{2a}\right)^2}\right)\right)$$

The first idea for sensing:
Mechanical force or pressure can move fibers

$$A = -10\log(cos\theta)$$

$$A\ is\ \infty, for\ \theta > \theta_c$$

NA –numerical aperture
a - diametre of core

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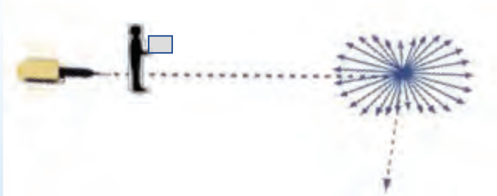
Scattering

- & There are several scatterings,
- & The scattering from molecules and very tiny particles (< 1 /10 wavelength) is predominantly Rayleigh scattering.
  - & No change of wavelength;
  - & Happening when wavelength is less than molecule or particle
  - & Rayleigh scattering is wavelength dependent:

$$I \sim \frac{1}{\lambda^4} \qquad x = \frac{2\pi}{\lambda}$$

  - & ĀÀ%$ #!"scattering x<1, the best x around 0,1
- & The scattering at 1310 nm is 2 x as great as that at 1550 nm
- & Scattering in which the scattered photons have either a higher or lower photon energy is called Raman scattering.

In fiber optics everybody knows *Rayleigh scattering*



The first idea for sensing:
If there are some particles (as pollution, blood components,) out of fiber than *ORL* and *IL* will depend on the number of particles if diameter of particles is several times less than wavelength;

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Absorption

ĀAbsorption will be occurred if particles of matter are larger than wavelength

4 but also, if /&#Ā2 1#(#*%/&ĀĀ+$Ā/&#Ā('%
2 1#Ā) /"&#.Ā/&#Ā$-#,0#*"3Ā /Ā2&'"&
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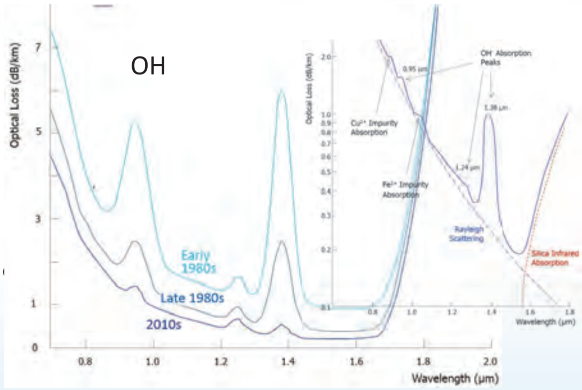
1'!- /#Ȁ

4 The most well-known absorption in fiber optics is that of OH- ions



The first idea for sensing:
Absorption as a sensor mechanism can be used for detection of pollutions for particles larger than ~0,01 mm
For detection in human blood, 9AB2+/79169,38Ȁ%$!Ā=9Ā"!!!

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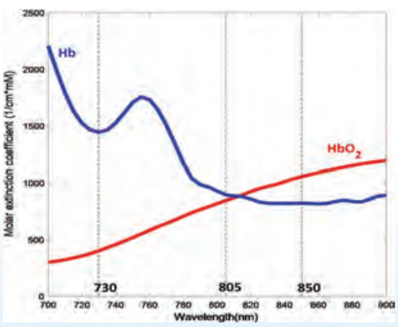
Fiber sensing in hemoglobin detection

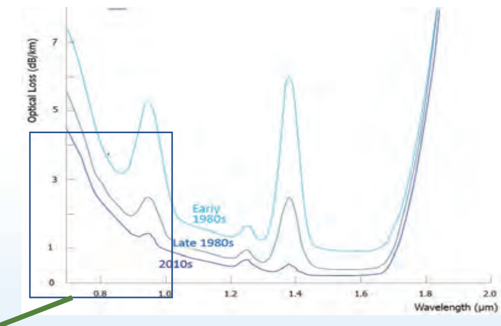
Ā There are two types of hemoglobins:
  Ā Deoxyhemoglobin Hb
  Ā Oxyhemoglobin HbO2

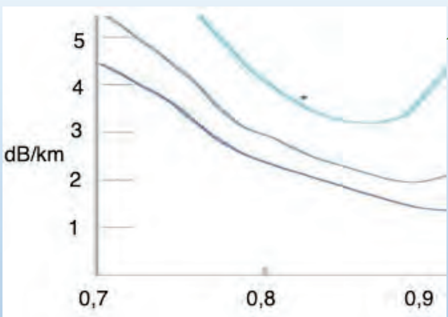
Ā Measurements at two wavelengths:
  Ā 805 and 700 nm

Ā 805 will detect how much hemoglobin particles is for both

Ā 700 nm will dedicate which one is



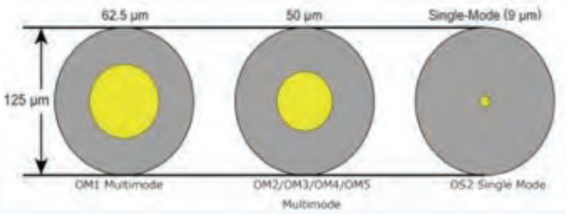




For long distance sensing:
the patient may be about 5 km away.
This example has no practical value, tha aim of thos slide is to shoe how sensoig by fibr should looks

Which type of fiber?

Standard fibers:
Multimode - MMF
C 50/125 or 62,5/125 µm
C NA – 0.2 – 0.3

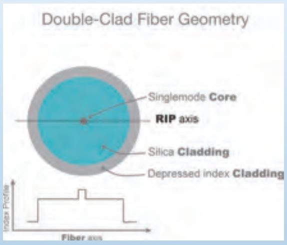


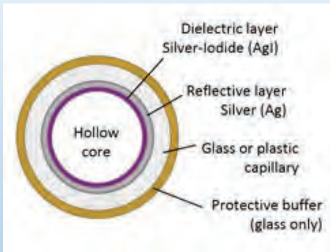
Issues:

& Standard or non-standard fiber types;

& If standard, use SMF or MMF.

& If MMF , step or gradient?



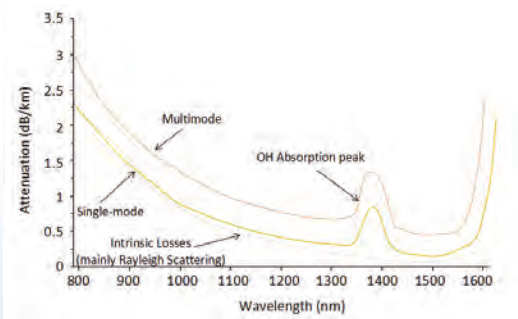


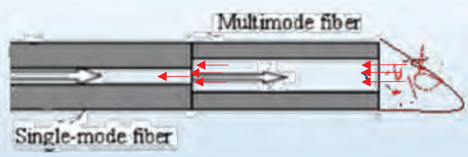
MMF or SMF

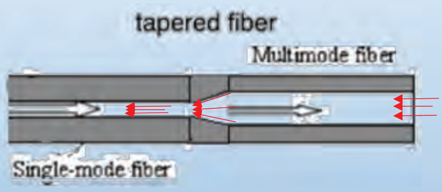
& Attenuation is on side of SMF

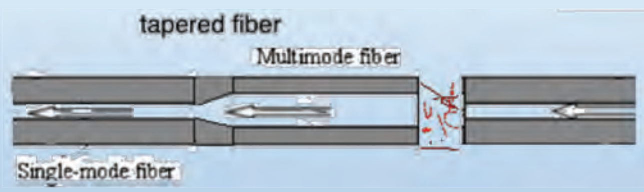
& About 0.7 dB/km at 850 nm

& Large core of MMF can collect more light, so on sensor side the advanced is on MM



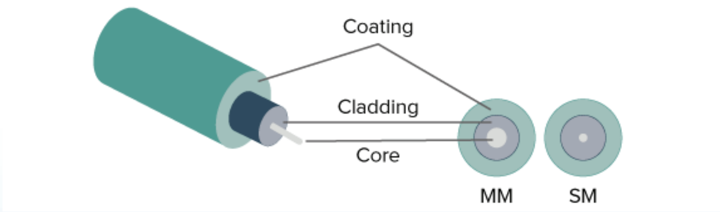


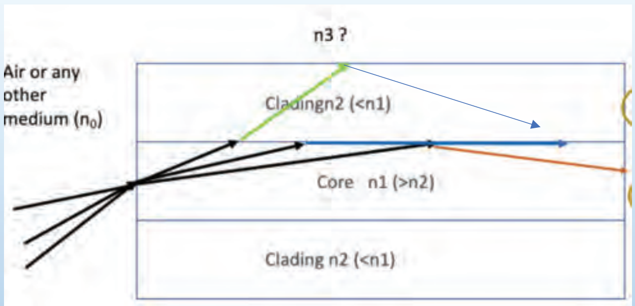




Cladding as a sensor

In telecom fiber:
If light going
Each fiber has primary coating. Its role is to make fiber stronger, however there is one mor role:
Put out light form cladding

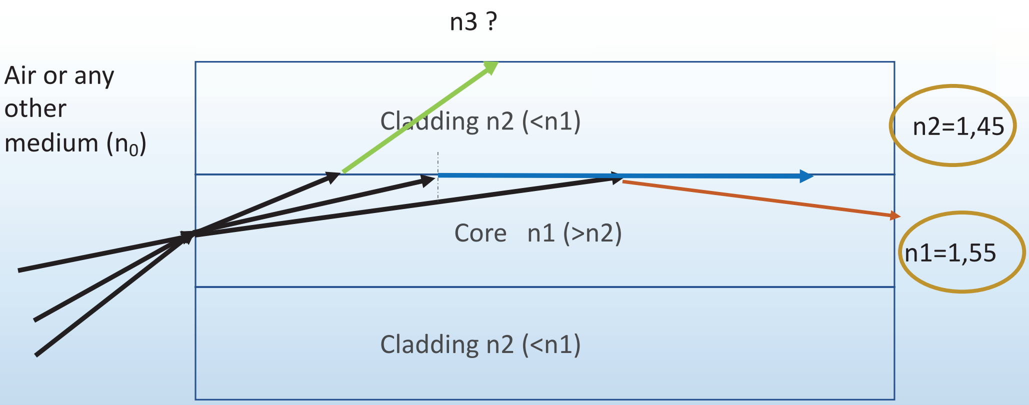




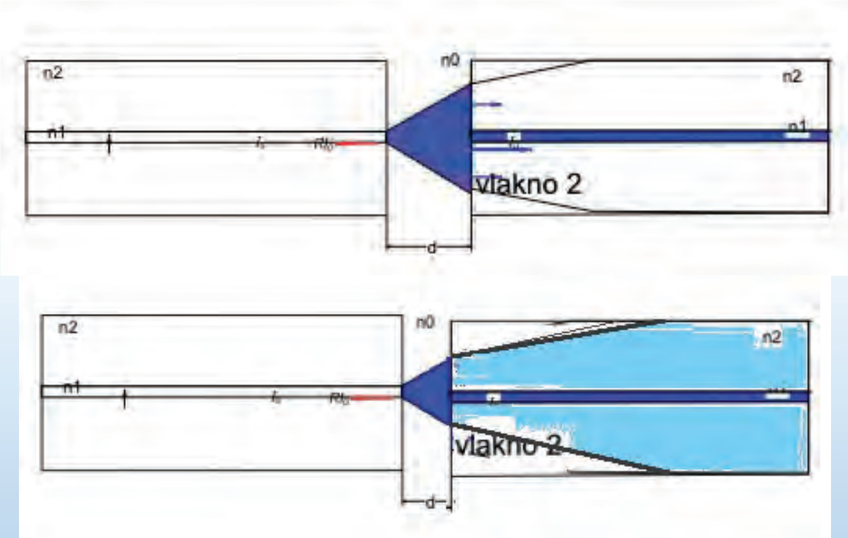
If n3<n2
Than total reflection will bi occured

Refractive index water temperature

- Promjena temeratrue od 1 0C donisi promjenu ide



$$A = -20log(\frac{a}{a + sNA})$$



- In according with attenuation of longitudinal separation,
  - half of power will go in the core if s = 15,5 μm
  - 1:10 cladding :core if s=81 m

Small d – small amount of light in clding

On off detection of water appearing

$$R = \frac{(n1 - n2)}{(n1 + n2)^2}^2$$

-5 dB

970 m SSM

pream plifier

PLC spliter

3,6 dB

-27,58 dBm – no water
-40,09 dBm - water

	ORL (dB)
fiber -air	-14,782432
fiber-watar	-27,297271

- We performed the test in laboratory and got:
- -20,7
- -34,95

Difference of 5 to 7 dB was occurred because 3 additional connectors joint was between laser and water tank.

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The measurement of various liquid levels

Ā In previous experiments, not only water but also the presence of any liquid could be detected;

Ā More levels can be detected:

Ā Each end of cable will send one of two ORL value:

  Ā fiber - air, or

  Ā fiber – liquid

Ā The liquid tank will send $ORL_{collected}$ reduced for attenuation of splitter

$$ORL_{ollected} = ORL_1 + ORL_2 + ORL_3 + ORL_4 - IL_{spliter}$$

Ā on central office side, OPM will measure:

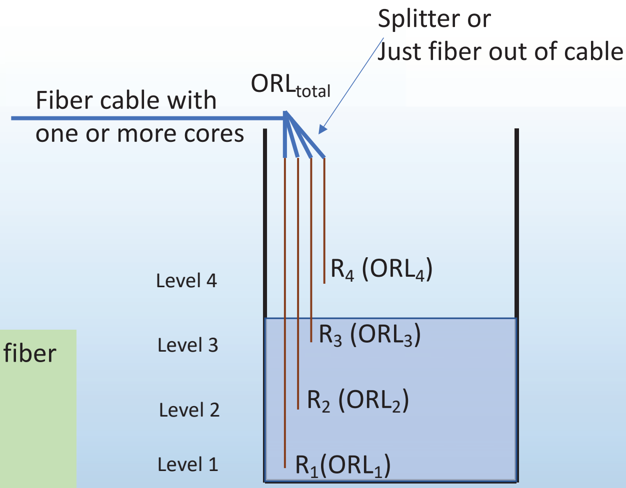
$$ORL_{OPM} = ORL_{ollected} \text{ - Attenuation of fiber path}$$

We conducted the experiment with two water tanks using only a fiber and a splitter 1:2, and it worked:

Ā no water - ORL about -30dBm ,

Ā one tank with water, one no water about – 36 dBm

Ā both tanks with water, about - 42. dBm



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What can be measured?

Contrast between wine and water
Initial research indicates that expensive wine is more similar to water than inexpensive wine.

Coffee quality can be identified very precisely.

Many substances were found, including

Ā olive and sunflower oils

Ā the standard of honey

Ā water salinity

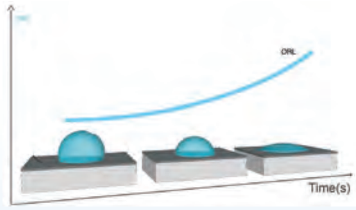
Ā Water temperature

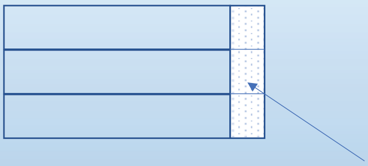
Ā ..

Sensing based on reflection: advantages and disadvantages

& Advantages
- Ā Very efficiency system
- Ā Low mathematical calculation

& Practical realization:
- Ā The fiber must be cut sharply, and smooth.
- Ā Liquid can remain on the fibers for a long time after the liquid level has decreased;
- Ā Does the liquid wet the walls or not?





Request: low interaction with liquid,
Refractive index the same or like glass

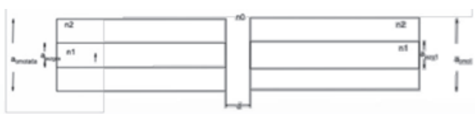
Direct light transmission

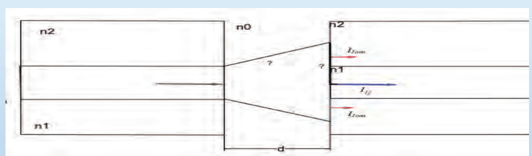
4 All four sensing mechanisms must be calculated;

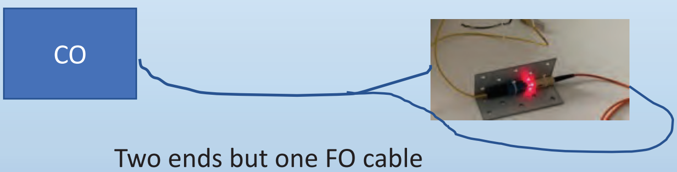
4 Separation loss are greater than reflection loss

4 Absorption can limit distance

4 Very highly sensitive on small inaccuracies in separation







Two ends but one FO cable

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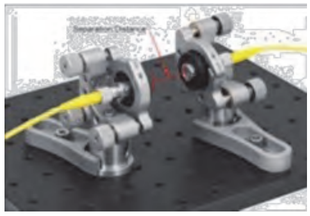
Fiber collimators

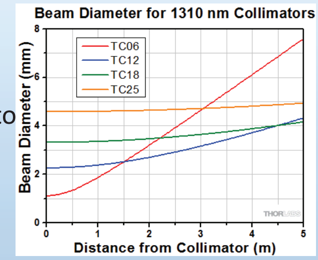
4 The main disadvantages of measurement with separation of the ends of fiber is strongly sensitive by small inaccuracy in distance;

4 The main characteristic:
- & operating wavelengths and antireflective coating
- & Beam diameter and waist distance
- & Fiber type : SM or MM

4 Two main application:
- & Speed and counter measurement
- & Scattering and absorption in the air



Attenuation will increase along with distance as it grows to more than 2x waist distance .



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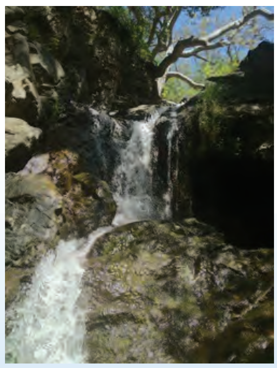
Conclusions

ĀNew possibilities for monitoring processes and natural phenomena;
- Ā long-distance measurement
- Ā wavelengths from 650 to 1650 nm
- Ā no power sup lay on sensor side

ĀThe mathematical computations are practical and widely used;

ĀLong-distance sensing based on fiber should be constructed for a long lifespan.



x from FTTx can now be:
- Fiber to the coffee machine -
- Fiber to the wine barrel;
- Fiber to the beehives
- ...

Software-defined passive optical network evolution

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Boštjan Batagelj

Univerza v Ljubljani, Fakulteta za elektrotehniko

Abstract

The need for a sustainable, flexible, and future-proof network has become a must for telecoms and cable industry. Passive optical networks (PON) have become a technology of choice as future proof solution, however traditional PON with proprietary active solution still poses some challenges in providing flexibility and scalability. This reinforces the idea of using open software and white-box hardware converged with software-defined networking and network function virtualization (NVF) to add flexibility and scalability to the passive optical network. With the advent of 5G mobile and the role that PON must play in the x-haul of 5G networks, this scalability and flexibility becomes even more important. Looking at the mobile network, where the trend toward flexibility and simplicity also appeared in the radio access network (RAN) as an open radio access network (Open RAN) a few years ago, these trends are also evident in the optical access network. In the Open RAN of the 5G network, there are two primary technological requirements that provide flexibility and simplicity to the network. First, network function virtualization (NFV) abstracts the legacy, purpose-built network hardware functions used in previous generations (2G, 3G, and 4G) into virtualized, software-based network functions (VNFs). The VNF architecture is hardware independent and can be hosted on any hypervisor and hardware. This enables fast and dynamic deployment, less complex hardware lifecycle management, and lower costs. Second, Software Defined Networking (SDN) is used to decouple the user plane from the control plane and enable centralized management and programmability of network resources through SDN controllers. The convergence of the fixed and mobile network will be possible will the help of SDN and NFV.

Author's biography

Jakup Ratkoceri was born in Pristna, Kosovo, in 1983. He received BSc and MSc from the University of Prishtina, Faculty of Electrical and Computer Engineering. He received PhD from University of Ljubljana, Faculty of Electrical Engineering, under supervision of associate. professor dr. Bostjan Batagelj. Currently he is with Technetix in Netherlands, as director of FTTx products and assistant professor at UBT Colleague, in Pristina, Kosovo.

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Software-defined passive optical network evolution

UBT

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Technetix, The Netherlands
UBT-Higher Education Institute, Republic of Kosovo

Bostjan Batagelj
University of Ljubljana, Faculty of Electrical Engineering, Slovenia

Univerza *v Ljubljani*
Fakulteta *za elektrotehniko*

1

Motivation

- Dissagregation the software from the access node hardware, eliminating specific hardware platform monopoly
- Flexible and scalable infrastructure for rapid growth in traffic demand
- Access network that goes beyond broadband to support fixed-mobile convergence applications

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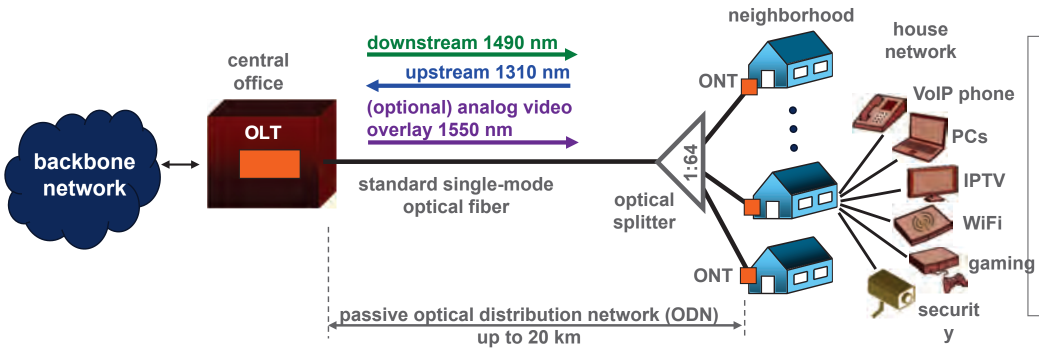
Passive optical networks (PON)

3

PON Technology

- Passive Optical Network (PON) is well-known and standardized optical fiber communication technology in optical access networks.
- PON enables point-to-multi-point connections (P2MP) to end-users in fiber-to-the-home (FTTH) installations, where optical fiber is used from a central office directly to individual households.



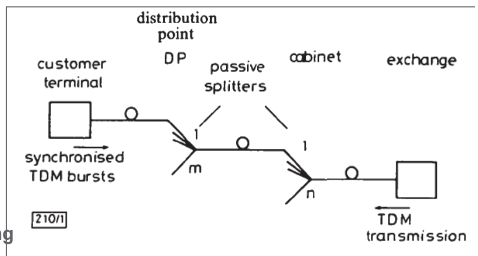


Fig. 1 *Basic TPON network*

J. R. Stern, et. al. (British Telecom), PASSIVE OPTICAL LOCAL NETWORKS FOR TELEPHONY APPLICATIONS AND BEYOND, Electronics Letters, November 1987

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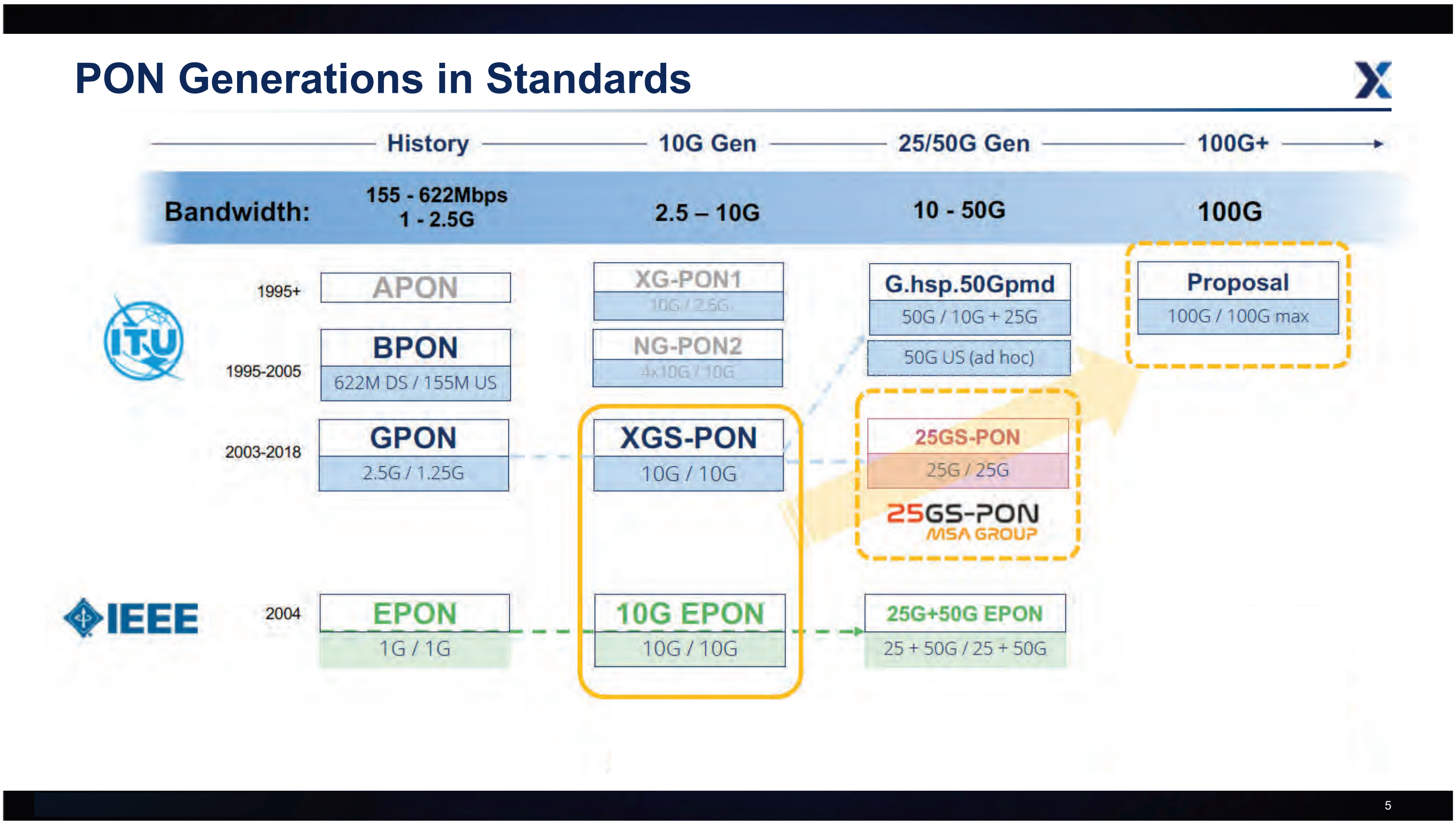

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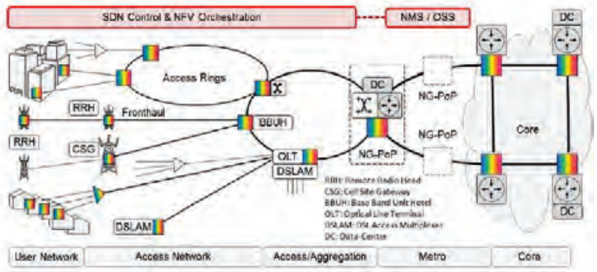
Software Defined Networks (SDN)

6

SDN

- The increasing capability and availability of cloud infrastructure is being leveraged to remove control plane functions from network elements.
- Software Defined Networking (SDN) virtualizes configuration and control of network elements (NE), generally with a controller located in the cloud or data center communicating with network elements via a protocol such as OpenFlow.
- There are many control and management functions required for broadband access, which, similar to SDN, can migrate from embedded firmware in dedicated network equipment into software controllers running on commodity hardware in a private or public cloud, saving costs while increasing capabilities.



K. Kerpez and G. Ginis, "Software-Defined Access Network (SDAN)," 2014 48th Annual Conference on Information Sciences and Systems (CISS), Princeton, NJ, USA, 2014, pp. 1-6, doi: 10.1109/CISS.2014.6814134.

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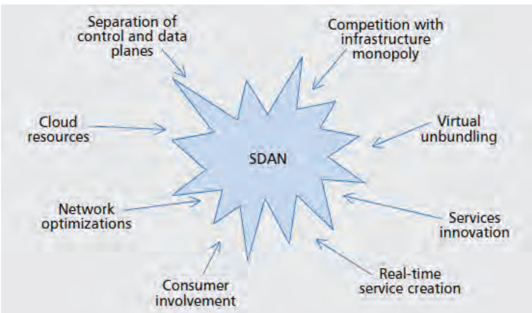
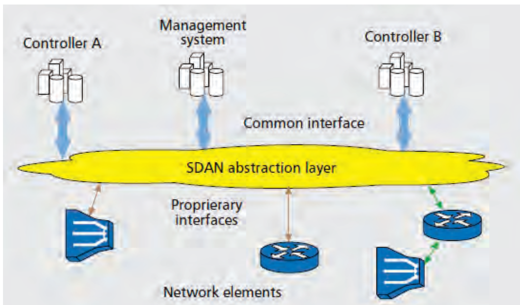
Software-Defined Access Networks (SDAN)

- The SDAN is built on a common control plane that virtualizes the infrastructure, separating the control plane from the data plane.
- The SDAN provides a common interface and a unified touch point for policy, control, and management.
- A number of trends are converging to drive the development of the SDAN

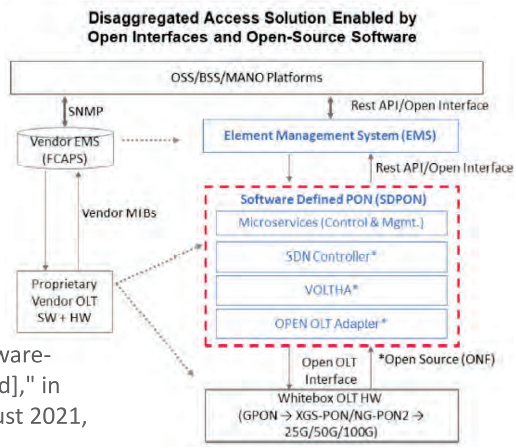




8

Industrial view of the importance of open access netowrks

- Digitalization and ubiquitous connectivity with everything and everyone define this era. It is driven by:
  - **A huge increase in data traffic:** Potentially up to 100x more capacity will be required.
  - **New services and users' demands:** Consumers demand new types of mobile services to enjoy anywhere: virtual or augmented Reality, video 360º, 4K or 8K , connected cars or smart cities.
  - **IoT explosion:** A vast array of networked machines that will digitize our world.
  - **Digitalization:** Consumers are demanding services that they can provision in real-time to enjoy faster personalized services.
- **Open Access architecture:** This is a necessary evolution in order to deploy 5G, XGS-PON networks and CPEs in a sustainable way. Our access network will be transformed into an open and standard based access network. Natively built as a software-based solution with multivendor components integrated in a whitebox node. (Telefonica)



J. Montalvo, J. Torrijos, D. Cortes, R. Chundury and M. St. Peter, "Journey toward software-defined passive optical networks with multi-PON technology: an industry view [Invited]," in Journal of Optical Communications and Networking, vol. 13, no. 8, pp. D22-D31, August 2021, doi: 10.1364/JOCN.423034.

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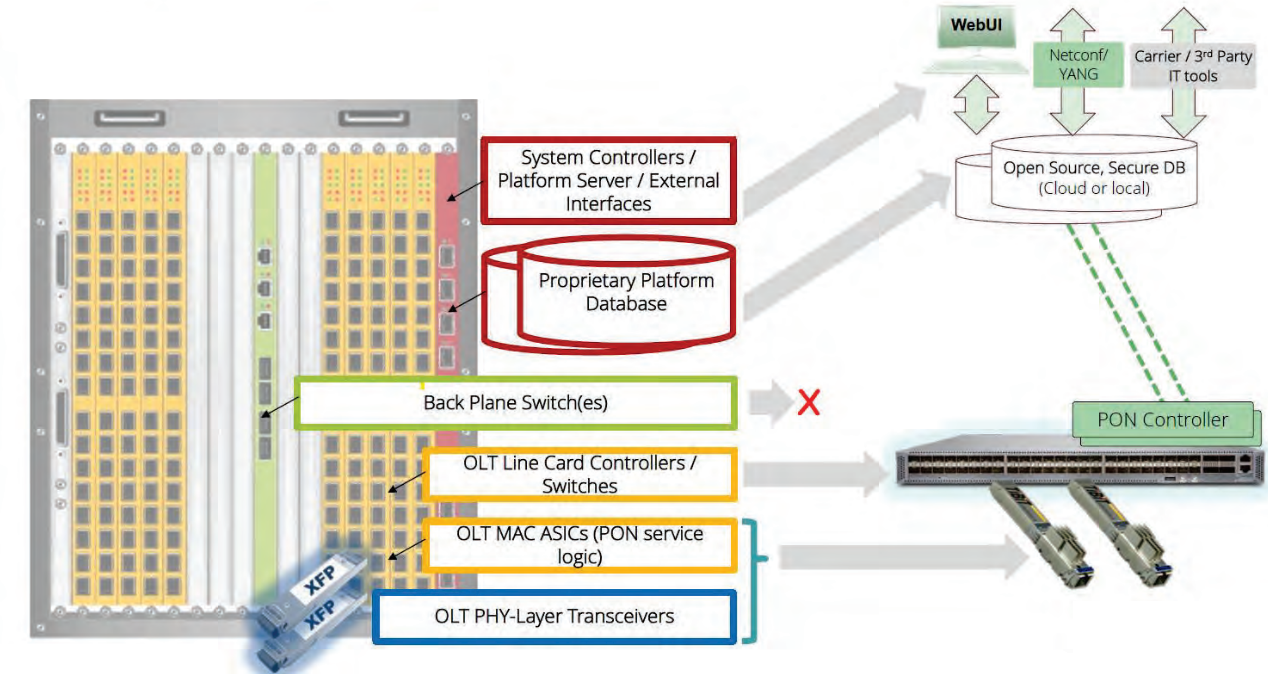
Technetix MicroOLT ecosystem

10

Moving towards open architecture



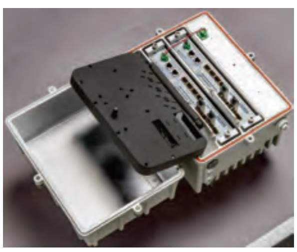
11

Next generation PON

Traditional PON chassis

MicroPlug OLT solution

Now any switch can be an OLT!

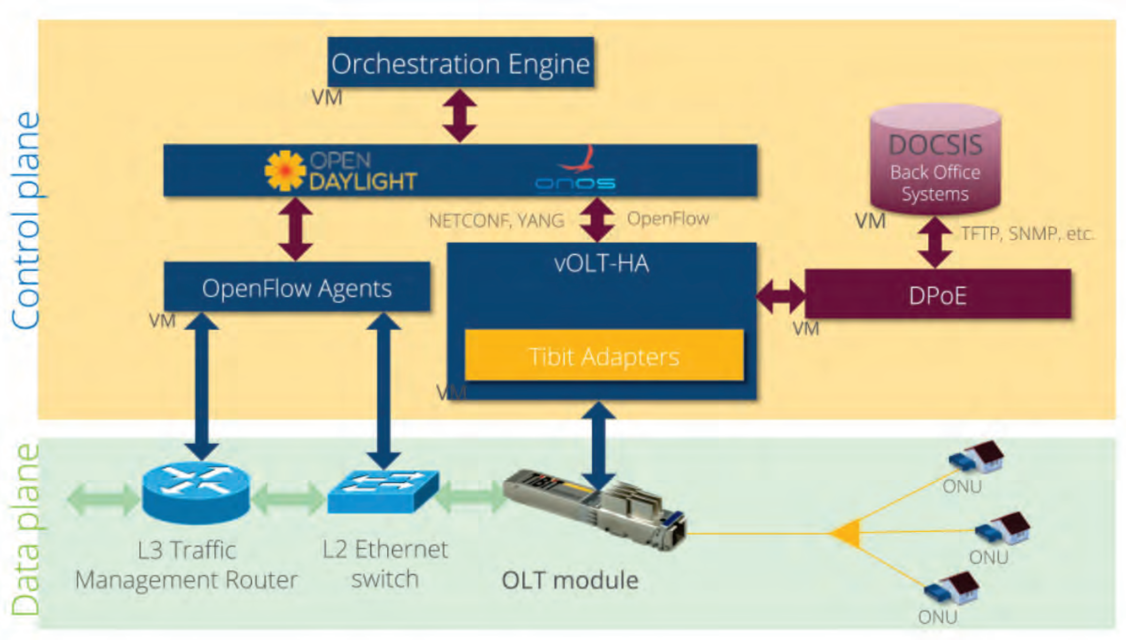


"Old school" proprietary fixed access

Open, disaggregated, scalable xPON access

12

Virtual OLT



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Simplifying PON

- Clearly Separate PON & Switch Domains
  - Micro OLT integrates all 10G PON MAC and PHY capabilities into a standards based, SFP+ pluggable transceiver module.
- Remove Proprietary Switching Layers
  - In creating an Ethernet-pluggable OLT device, MicroOLT connects directly into commercially available 10G Ethernet switches.
- Enable Modular Scalability:
  - port, switch host, management needs
- Implement Virtualized, Cloud-based Management
  - By concentrating all PON-specific MAC & PHY hardware functionality within the MicroPlug OLT itself, it allows PON management to exist as a true cloud-based solution – implemented only in software, hosted on commercially available servers, SDN-ready, and flexibly located anywhere in a carrier network.
- Implement ‘Interoperability by Design’
  - OLT-to- ONT/ONU interoperability should be part of the core design of OLT solutions. This often has the single largest impact on per-line cost for carriers, and yet is extremely difficult to implement on legacy OLT solutions that bury OMCI engines deep inside complex architectures

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Technetix FTTx software solution

- FTTx management
- BISDN system integration partner
  - pOLTA – Pluggable OLT Abstraction
- Pre integrated with Technetix FTTx systems
- Symphonica and UMBOSS for Orchestration and Service Assurance

pOLTA controls pluggable XGS-PON OLTs and switch hardware as a conventional “chassis/frame/port” OLT system

Symphonica - Multi-service orchestration & activation
- Zero/minimal touch provisioning
- Life cycle management
- Cloud native
- Residential, business and network services
- FTTx end to end service configuration.

UMBOSS - network management and service assurance utility.
- Fault Management
- Performance Management
- Resource Inventory Management
- Service Quality Management
- Reporting

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pOLTA – Pluggable OLT Abstraction System

- pOLTA software stack for an easy and cloud-based management of pluggable XGS-PON OLTs.
- pOLTA can be integrated with third-party switch hardware.
- It creates a topology abstraction into a single virtual multi-port OLT exposing a BBF TR 383/385 NETCONF/YANG interface
- Can be used with externally managed switches such as rOLT and Modular OLT or with fully integrated whitebox switches (virtual multi-port, multi-frame OLT).
- pOLTA is a flexible, scalable software stack that controls pluggable XGS-PON OLTs and switch hardware and exposes this as a conventional “chassis/frame/port” OLT system.
- The entire stack can be run on the switch as an integrated OLT solution or, alternatively, the pOLTA stack can be deployed in a public or private cloud and manage the OLTs remotely

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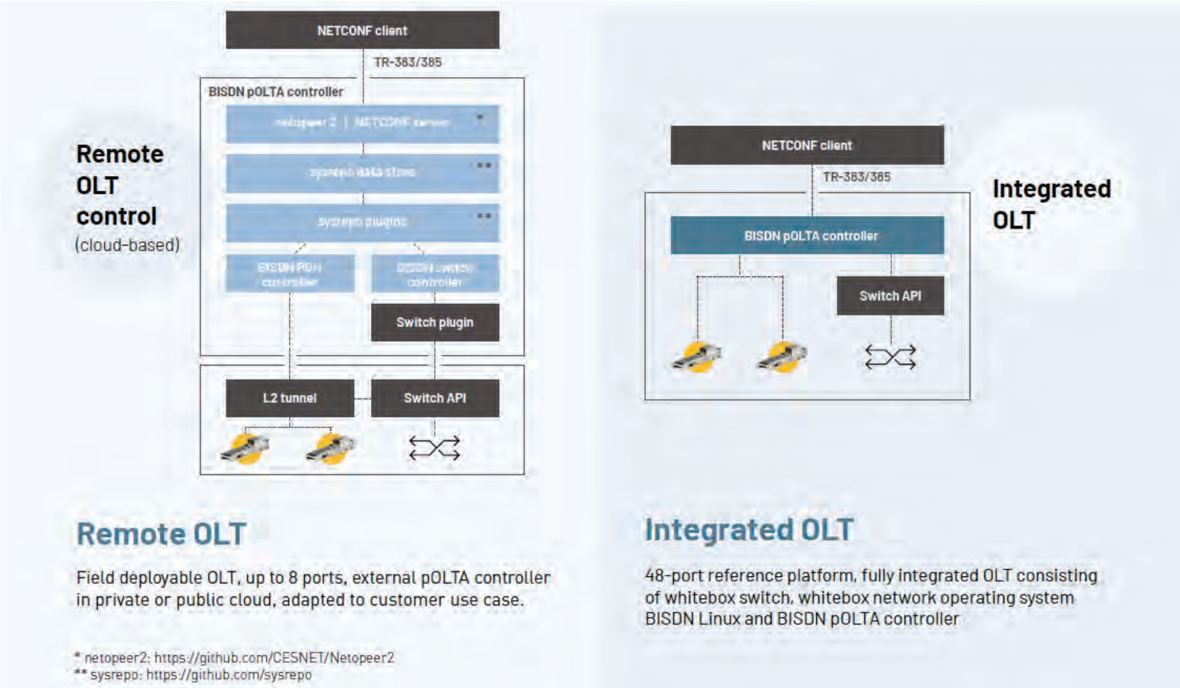
Deployment and integration options



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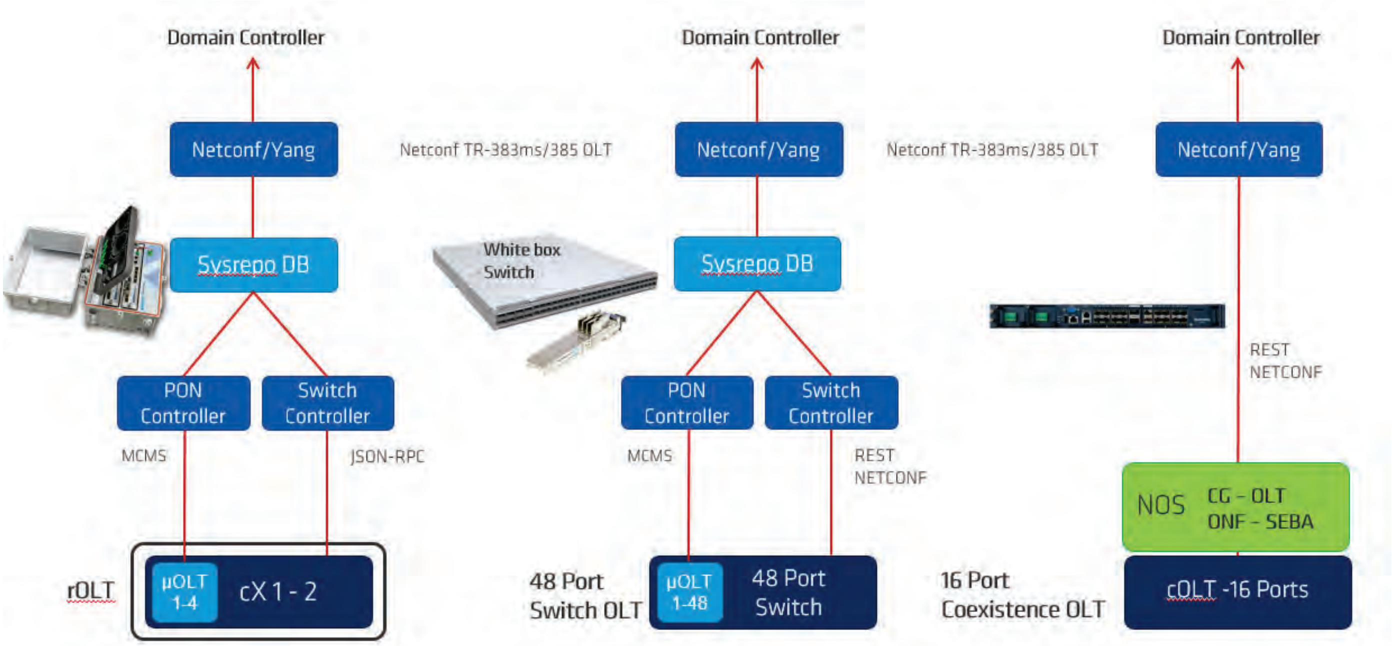
Control & Management



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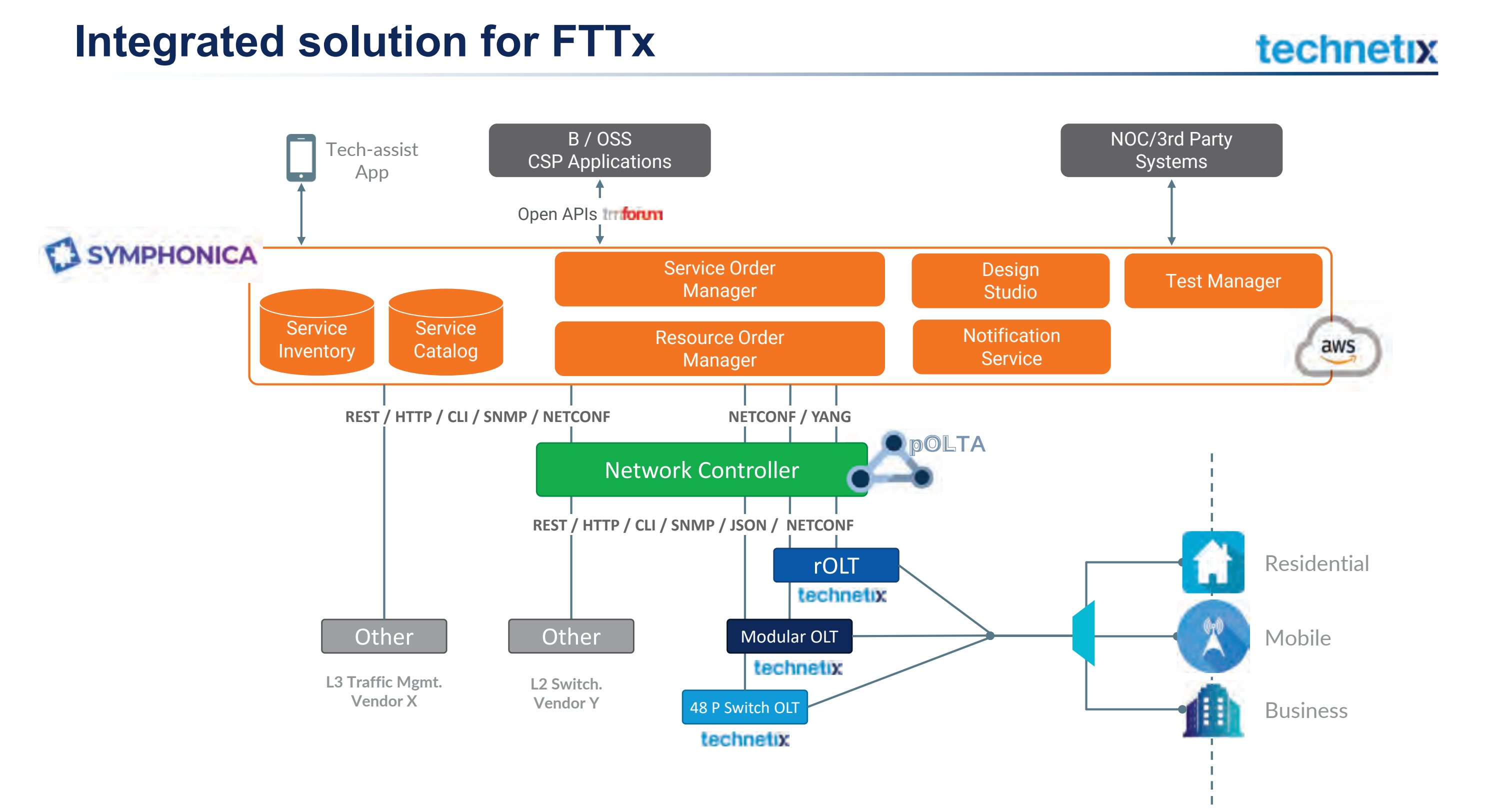
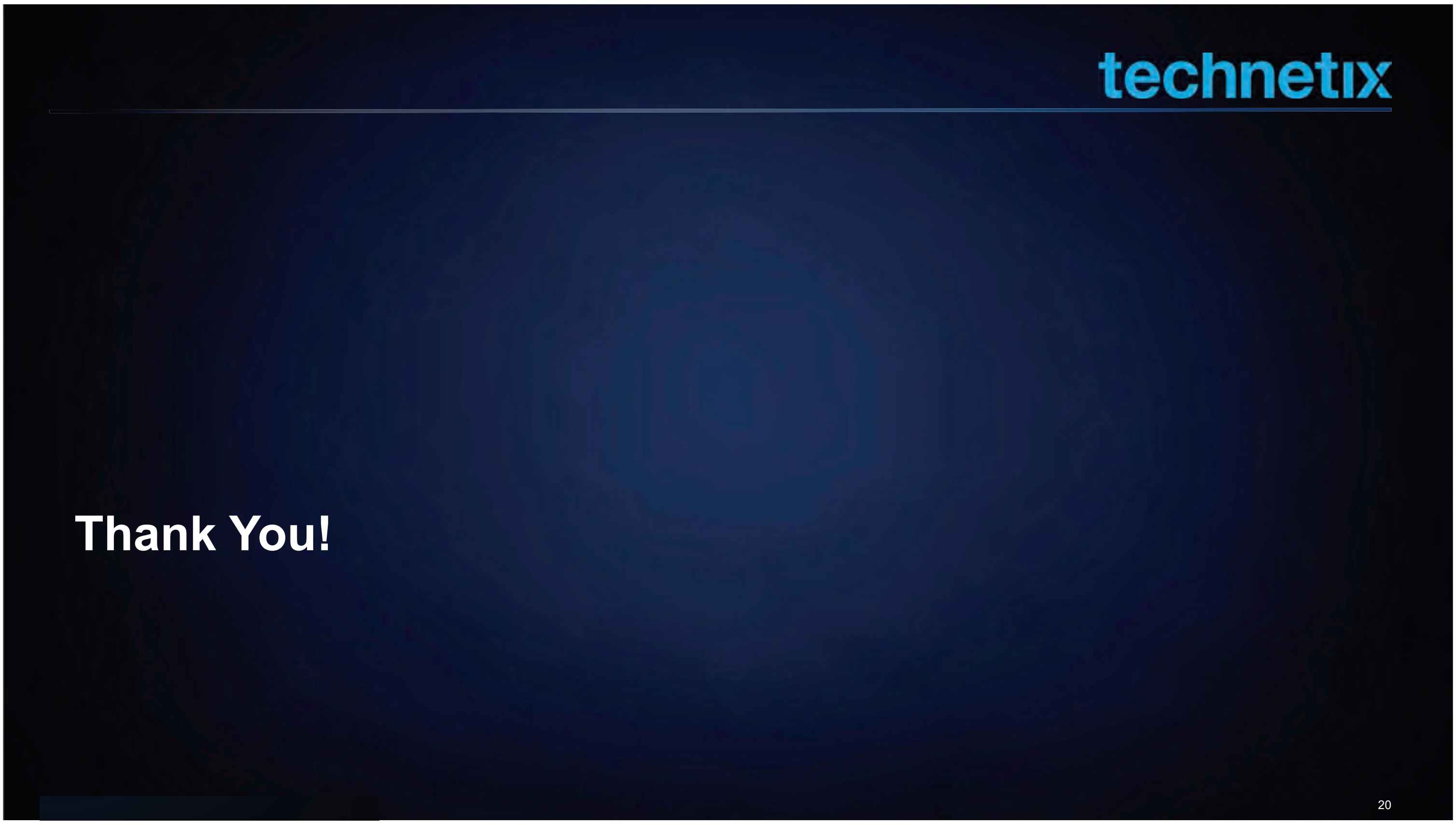

Integrated solution for FTTx
technetix
Tech-assist App
B / OSS CSP Applications
NOC/3rd Party Systems
Open APIs tmforum
SYMPHONICA
Service Inventory
Service Catalog
Service Order Manager
Resource Order Manager
Design Studio
Notification Service
Test Manager
aws
REST / HTTP / CLI / SNMP / NETCONF
NETCONF / YANG
Network Controller
pOLTA
REST / HTTP / CLI / SNMP / JSON / NETCONF
rOLT
technetix
Modular OLT
technetix
48 P Switch OLT
technetix
Other
L3 Traffic Mgmt. Vendor X
Other
L2 Switch. Vendor Y
Residential
Mobile
Business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Thank You!
20

Stride to F5.5G

Igor Milojević

Huawei CEE & Nordics

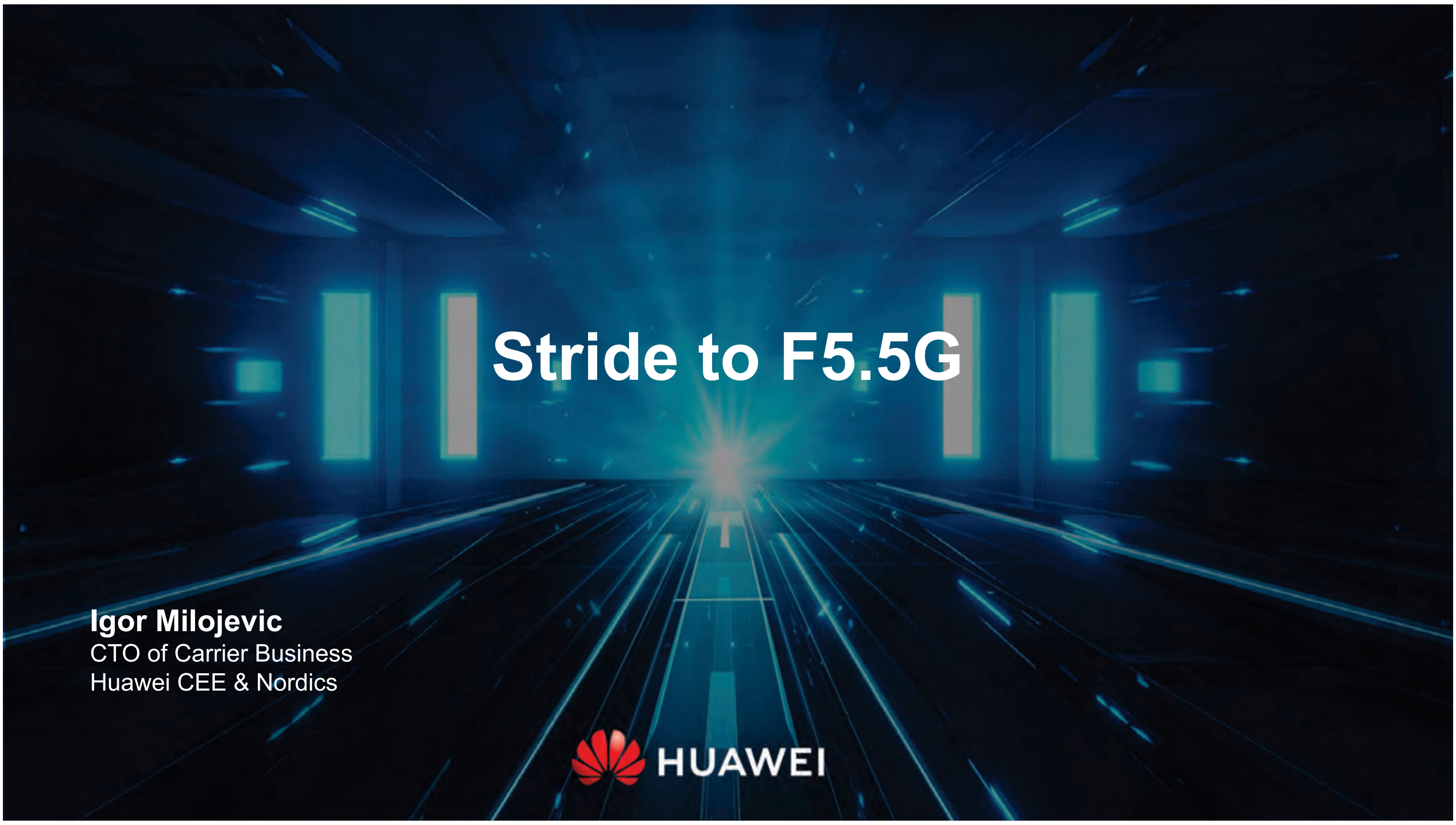
igor.milojevic@huawei.com

Abstract

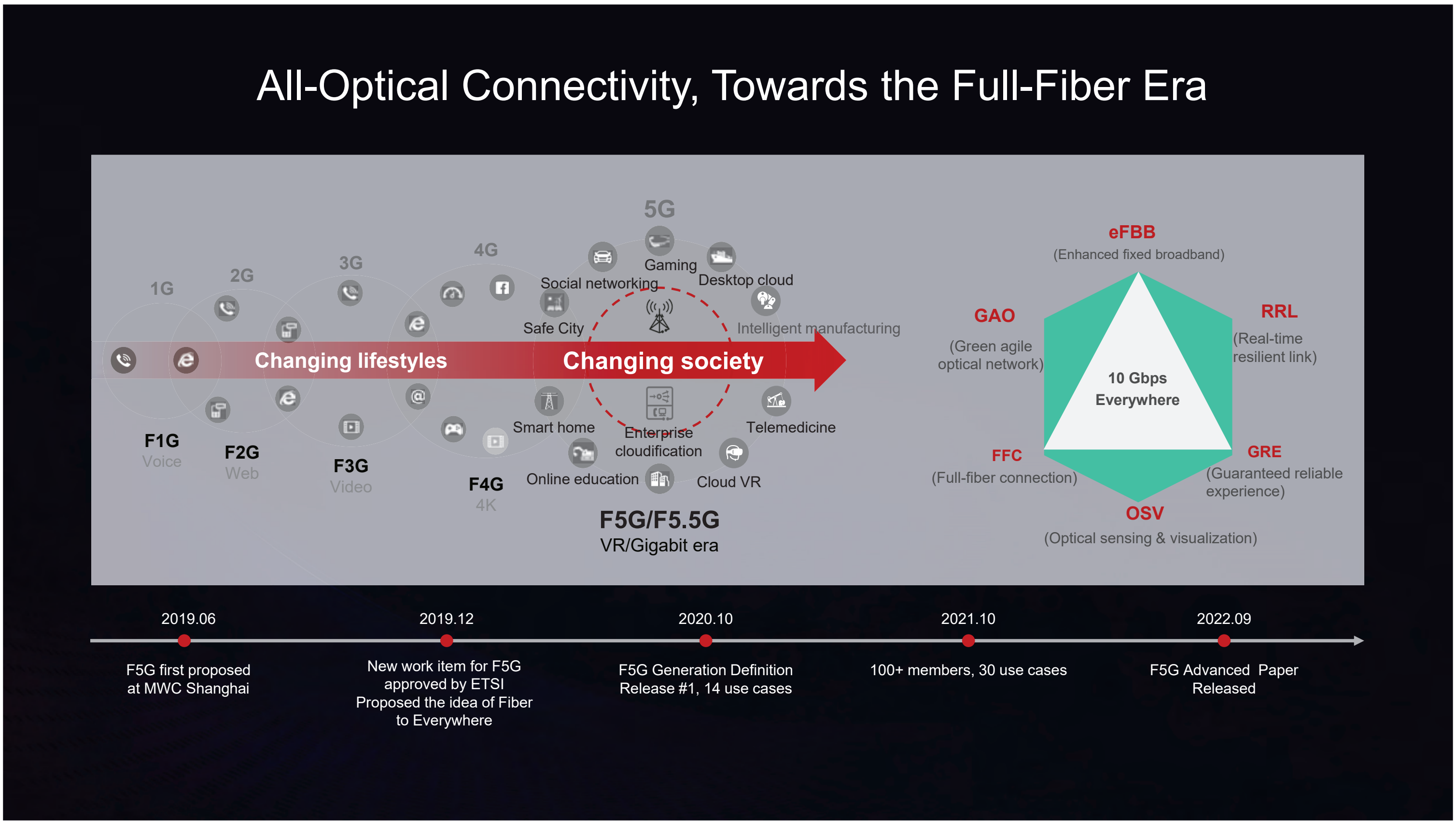
In this article technologies and architectures enabling the F5.5G era are presented. The emphasis is given to innovation and breakthroughs in all optical networking. The objective is to bring 10 Gbps everywhere with F5.5G. F5.5G will speed up the digital upgrade of industries, for example in digital power grids for production control or in smart factory for precision manufacturing.

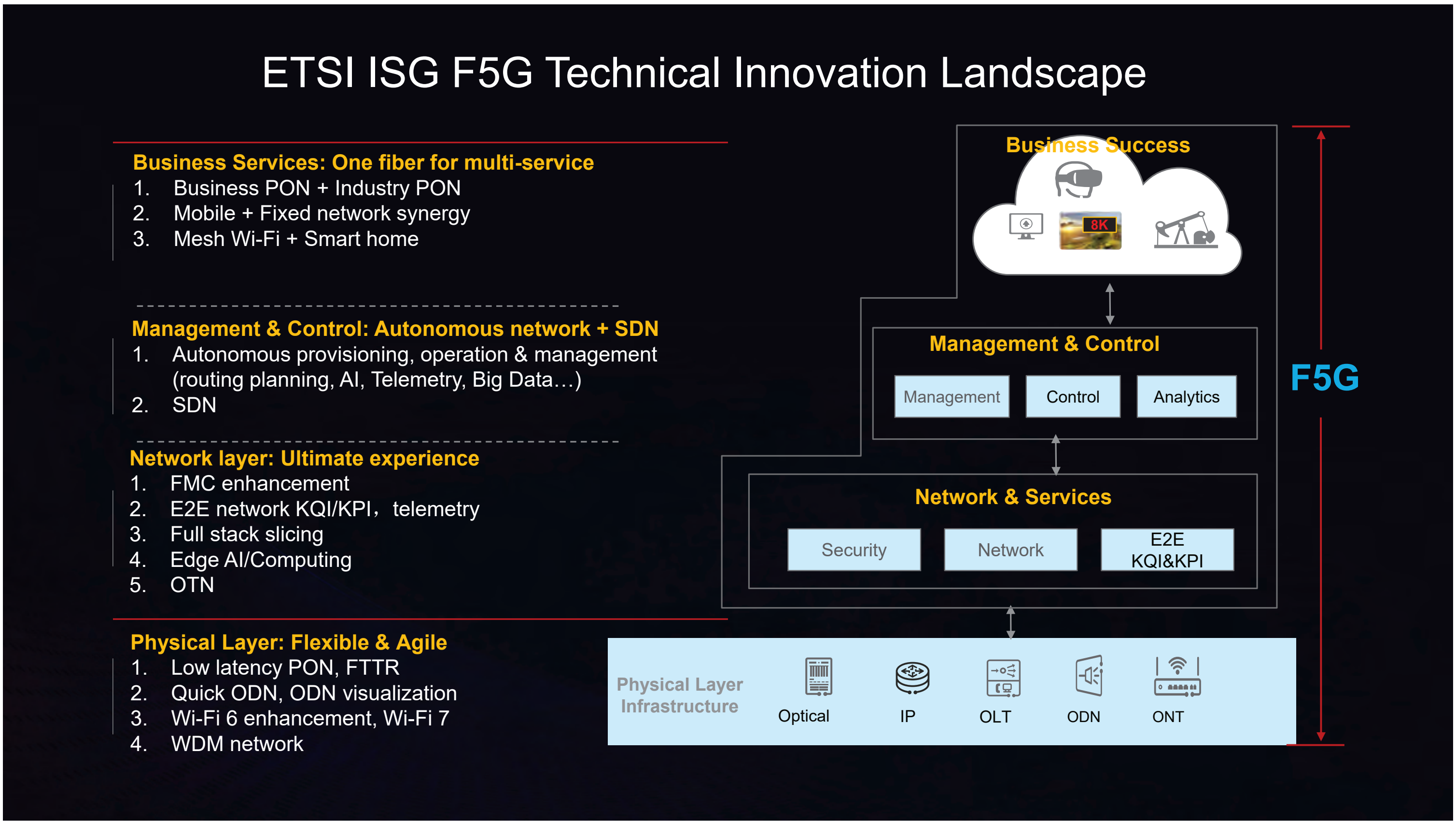
Author's biography

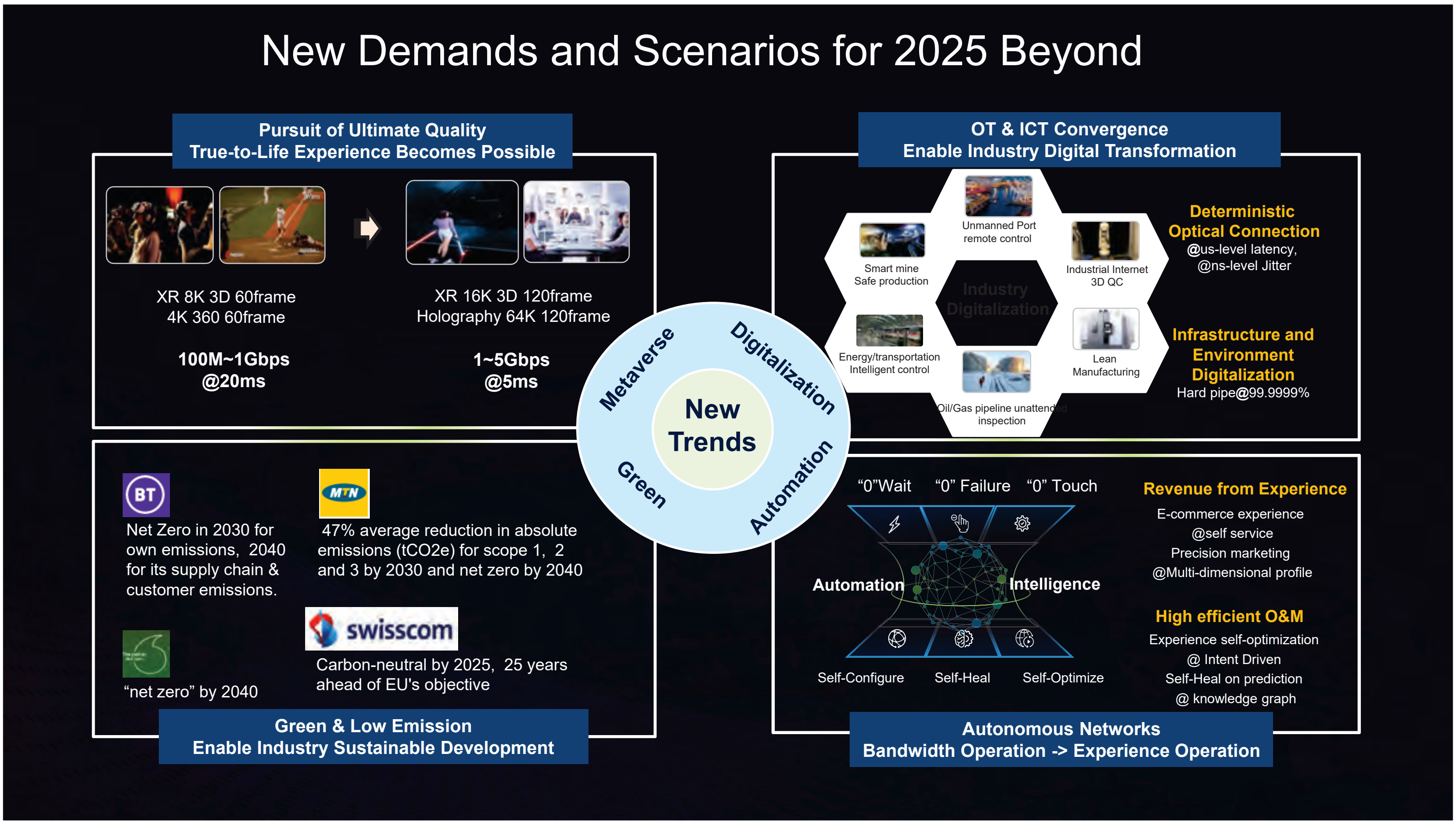
Igor Milojevic is the CTO of Huawei CEE & Nordics Carrier Business driving ICT solution programs and projects with leading operators in 28 countries of CEE & Nordics, addressing technology, architecture transformation and service innovation. He is responsible for Huawei's regional competence across fixed, mobile, cloud and digital. Igor is also a consultant to Huawei's R&D and global ICT organization in technology, market, product strategy and development. He is an active contributor to industry, European and national initiatives in 5G, networking technology standardization and AI. He is currently focused on helping operators in target architectures, digital transformation and developing 5G capabilities and ecosystem.


Stride to F5.5G
Igor Milojevic
CTO of Carrier Business
Huawei CEE & Nordics
HUAWEI

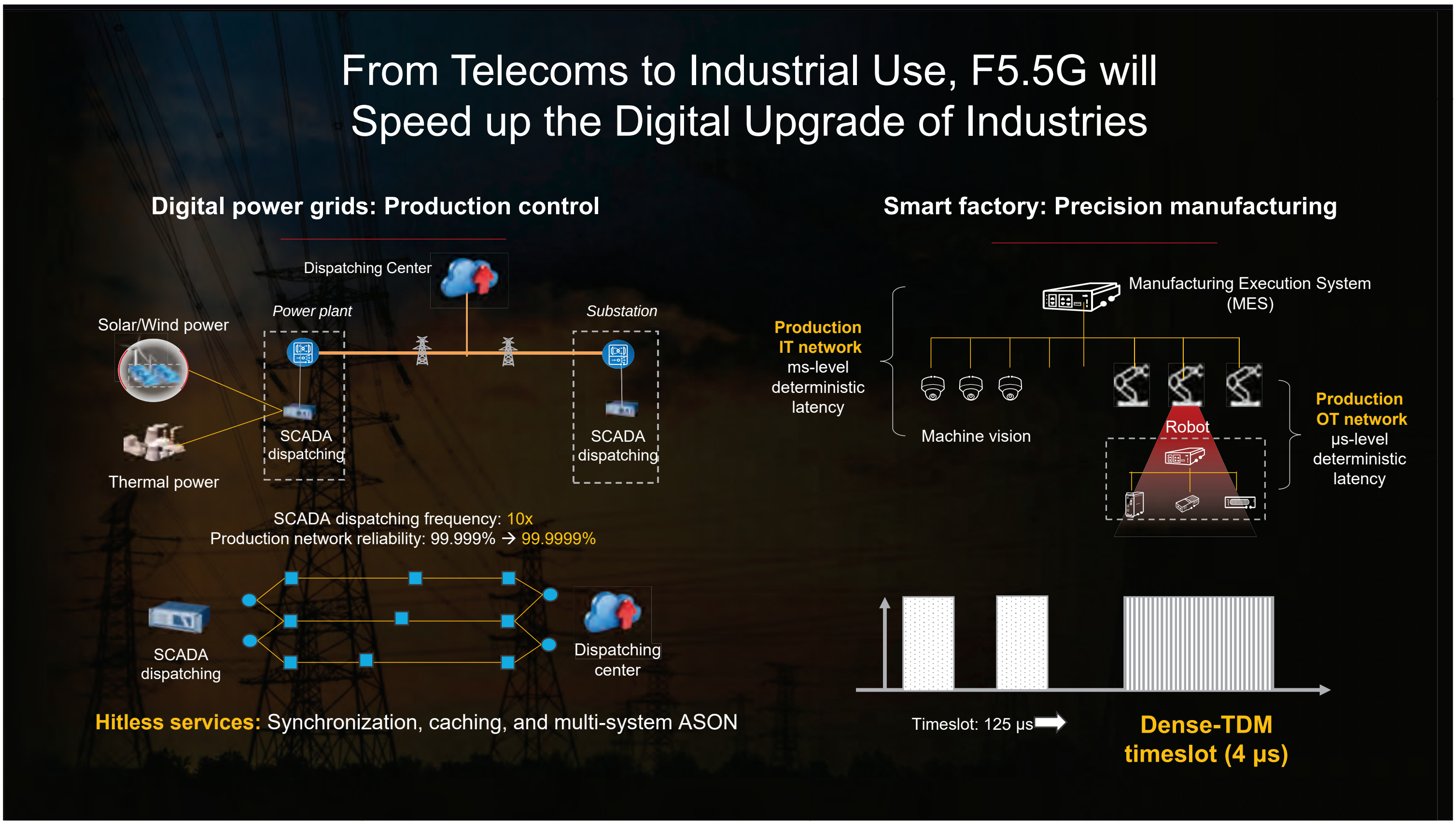

Gigabit has Arrived, Moving Towards 10Gps
Gigabit Era, 3 Years Ahead
Bringing New Businesses
Government Driving
Gigabit era @2022
49% Carriers Gigabit Service
6% Carriers 10Gigabit Service
3 years ahead
Gigabit Era @ 2025
Gigabit Era @ 2022
2019 forecast
Now
Gigabit means >= 500Mbps
Source: Omdia, Aug/2022
Diversified Home Services
40% digital economy accounts for GDP in 47 countries
Source: CAICT
Very High Capacity Networks (Fiber & 5G)
Project Gigabit
Infrastructure Investment and Jobs Act
Dual-Gigabit Networks Action Plan
Source: Internet

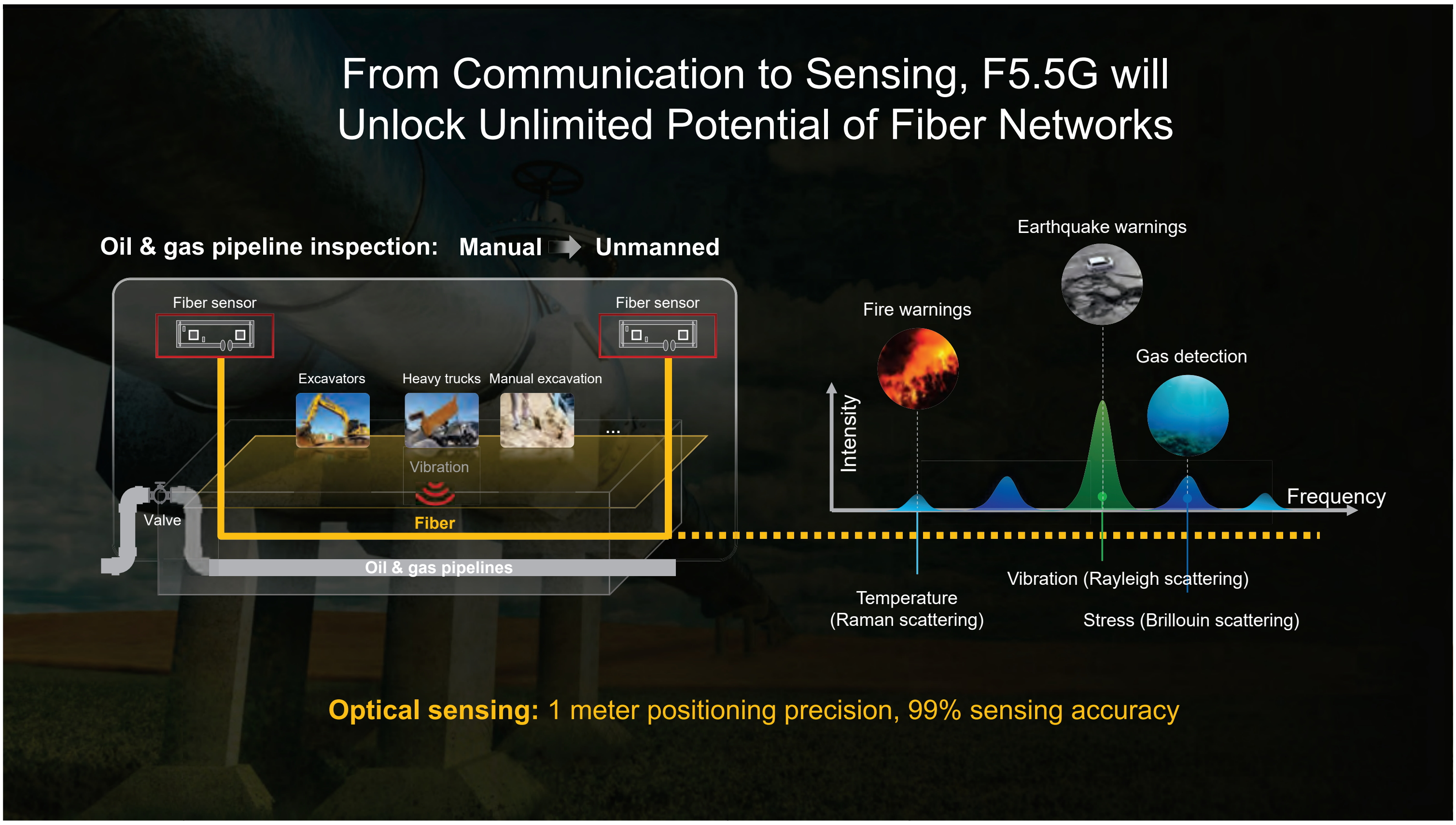

All-Optical Connectivity, Towards the Full-Fiber Era
1G
2G
3G
4G
5G
Changing lifestyles
Changing society
Gaming
Social networking
Desktop cloud
Safe City
Intelligent manufacturing
Smart home
Enterprise cloudification
Telemedicine
Online education
Cloud VR
F1G
Voice
F2G
Web
F3G
Video
F4G
4K
F5G/F5.5G
VR/Gigabit era
eFBB
(Enhanced fixed broadband)
GAO
(Green agile optical network)
RRL
(Real-time resilient link)
10 Gbps Everywhere
FFC
(Full-fiber connection)
GRE
(Guaranteed reliable experience)
OSV
(Optical sensing & visualization)
2019.06
F5G first proposed at MWC Shanghai
2019.12
New work item for F5G approved by ETSI
Proposed the idea of Fiber to Everywhere
2020.10
F5G Generation Definition Release #1, 14 use cases
2021.10
100+ members, 30 use cases
2022.09
F5G Advanced Paper Released


ETSI ISG F5G Technical Innovation Landscape
Business Services: One fiber for multi-service
1. Business PON + Industry PON
2. Mobile + Fixed network synergy
3. Mesh Wi-Fi + Smart home
Management & Control: Autonomous network + SDN
1. Autonomous provisioning, operation & management (routing planning, AI, Telemetry, Big Data…)
2. SDN
Network layer: Ultimate experience
1. FMC enhancement
2. E2E network KQI/KPI，telemetry
3. Full stack slicing
4. Edge AI/Computing
5. OTN
Physical Layer: Flexible & Agile
1. Low latency PON, FTTR
2. Quick ODN, ODN visualization
3. Wi-Fi 6 enhancement, Wi-Fi 7
4. WDM network
Business Success
8K
Management & Control
Management
Control
Analytics
Network & Services
Security
Network
E2E KQI&KPI
Physical Layer Infrastructure
Optical
IP
OLT
ODN
ONT
F5G


New Demands and Scenarios for 2025 Beyond
Pursuit of Ultimate Quality
True-to-Life Experience Becomes Possible
XR 8K 3D 60frame
4K 360 60frame
100M~1Gbps
@20ms
XR 16K 3D 120frame
Holography 64K 120frame
1~5Gbps
@5ms
OT & ICT Convergence
Enable Industry Digital Transformation
Unmanned Port
remote control
Smart mine
Safe production
Industrial Internet
3D QC
Industry
Digitalization
Energy/transportation
Intelligent control
Lean
Manufacturing
Oil/Gas pipeline unattended
inspection
Deterministic
Optical Connection
@us-level latency,
@ns-level Jitter
Infrastructure and
Environment
Digitalization
Hard pipe@99.9999%
Metaverse
Digitalization
New
Trends
Green
Automation
BT
Net Zero in 2030 for
own emissions, 2040
for its supply chain &
customer emissions.
MTN
47% average reduction in absolute
emissions (tCO2e) for scope 1, 2
and 3 by 2030 and net zero by 2040
swisscom
Carbon-neutral by 2025, 25 years
ahead of EU's objective
"net zero" by 2040
Green & Low Emission
Enable Industry Sustainable Development
"0"Wait
"0" Failure
"0" Touch
Automation
Intelligence
Self-Configure
Self-Heal
Self-Optimize
Revenue from Experience
E-commerce experience
@self service
Precision marketing
@Multi-dimensional profile
High efficient O&M
Experience self-optimization
@ Intent Driven
Self-Heal on prediction
@ knowledge graph
Autonomous Networks
Bandwidth Operation -> Experience Operation

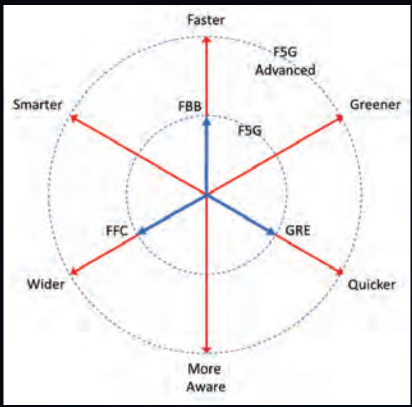

Bringing 10 Gbps Everywhere with F5.5G
eFBB
10x higher bandwidth, 10 Gbps everywhere
GAO
Green Agile Optical Network
10x energy efficiency, 0.03W/Gbps per site
RRL
Real-time Resilient Link
µs-level deterministic latency, 99.9999% reliability
F5.5G
Fiber to
Everywhere
FFC
10x connections, 1 mn/km2
GRE
Level 4 ADN, from diagnosable to self-optimization
OSV
Optical Sensing & Visualization
1 meter positioning precision, 99% sensing accuracy


From Telecoms to Industrial Use, F5.5G will Speed up the Digital Upgrade of Industries
Digital power grids: Production control
Smart factory: Precision manufacturing
Dispatching Center
Solar/Wind power
Power plant
Substation
SCADA dispatching
SCADA dispatching
Thermal power
SCADA dispatching frequency: 10x
Production network reliability: 99.999% → 99.9999%
SCADA dispatching
Dispatching center
Hitless services: Synchronization, caching, and multi-system ASON
Manufacturing Execution System (MES)
Production IT network
ms-level deterministic latency
Machine vision
Robot
Production OT network
μs-level deterministic latency
Timeslot: 125 μs
Dense-TDM timeslot (4 μs)


From Communication to Sensing, F5.5G will Unlock Unlimited Potential of Fiber Networks
Oil & gas pipeline inspection: Manual Unmanned
Fiber sensor
Fiber sensor
Excavators
Heavy trucks
Manual excavation
...
Vibration
Valve
Fiber
Oil & gas pipelines
Earthquake warnings
Fire warnings
Gas detection
Intensity
Frequency
Temperature (Raman scattering)
Vibration (Rayleigh scattering)
Stress (Brillouin scattering)
Optical sensing: 1 meter positioning precision, 99% sensing accuracy

ETSI “F5G Advanced and Beyond” WP Published in September

Main features for F5G Advanced (6)



- **Faster:** Increasing bandwidth
- **Quicker:** Reducing latency
- **Wider:** Increasing the number of endpoints
- **Greener:** Enhancing energy efficiency
- **More Aware:** Integrating computing
- **Smarter:** Improving network operations

Key technologies for F5G Advanced (7 areas)

Network Technologies
- 800G OTN
- 50G-PON
- Wi-Fi 6e/7

Fiber to everywhere
- FTTRoom
- FTTOffice
- FTTMachine (manufacturing)

Distributed computing technologies
- Elastic resource scaling
- Latency aware process dispatching
- Network and processing optimization

Autonomous network
- Intent-based service modelling
- Knowledge graph for fault management
- Improved network information gathering

Latency control technologies
- Deterministic networking
- End to end slicing

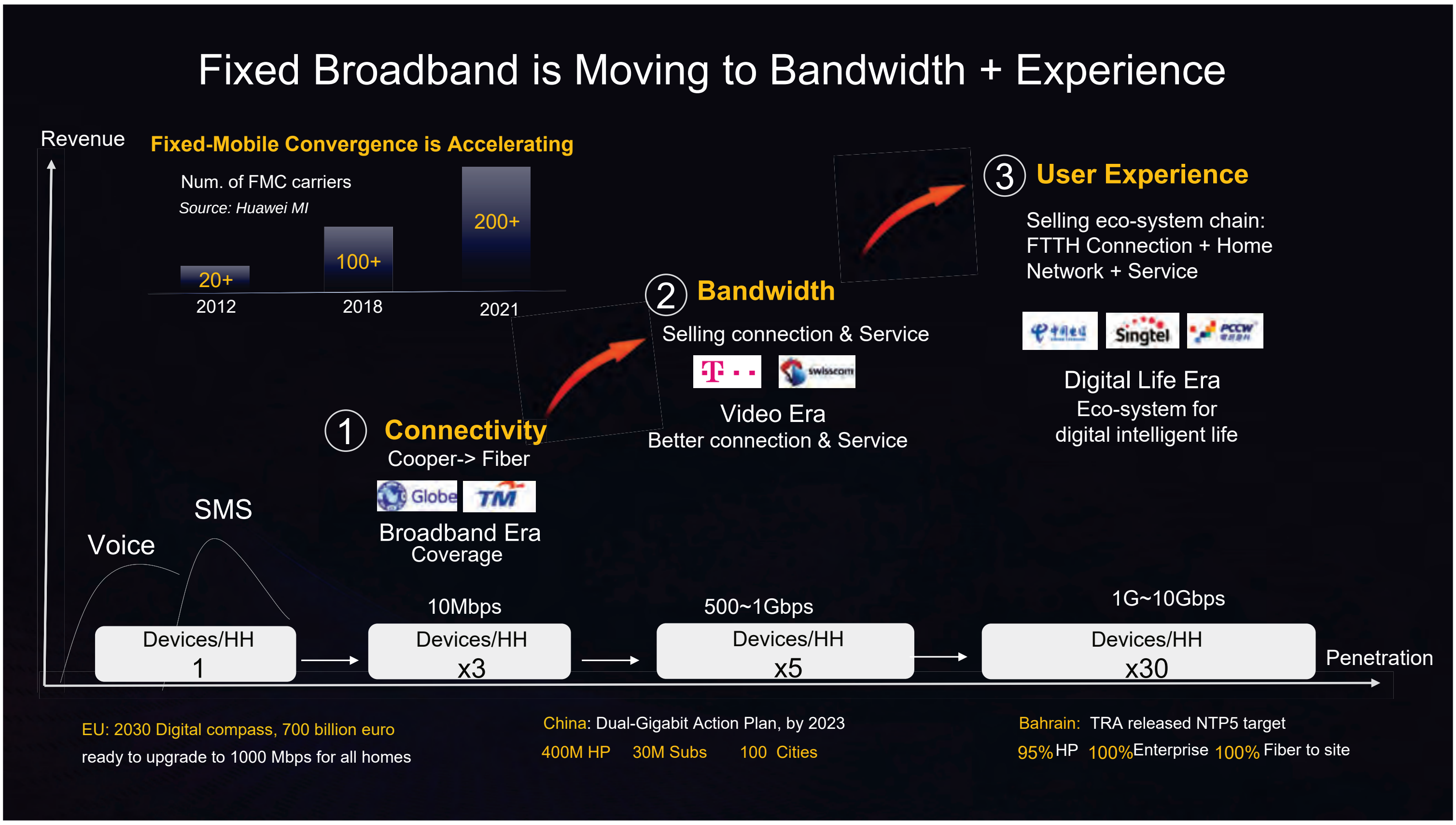
Energy efficiency technologies
- Energy aware switching/routing
- Power saving operation modes
- Dynamic load shifting

Network-based sensing
- Fiber cable digitization
- Distributed optical fiber sensing
- Wi-Fi sensing

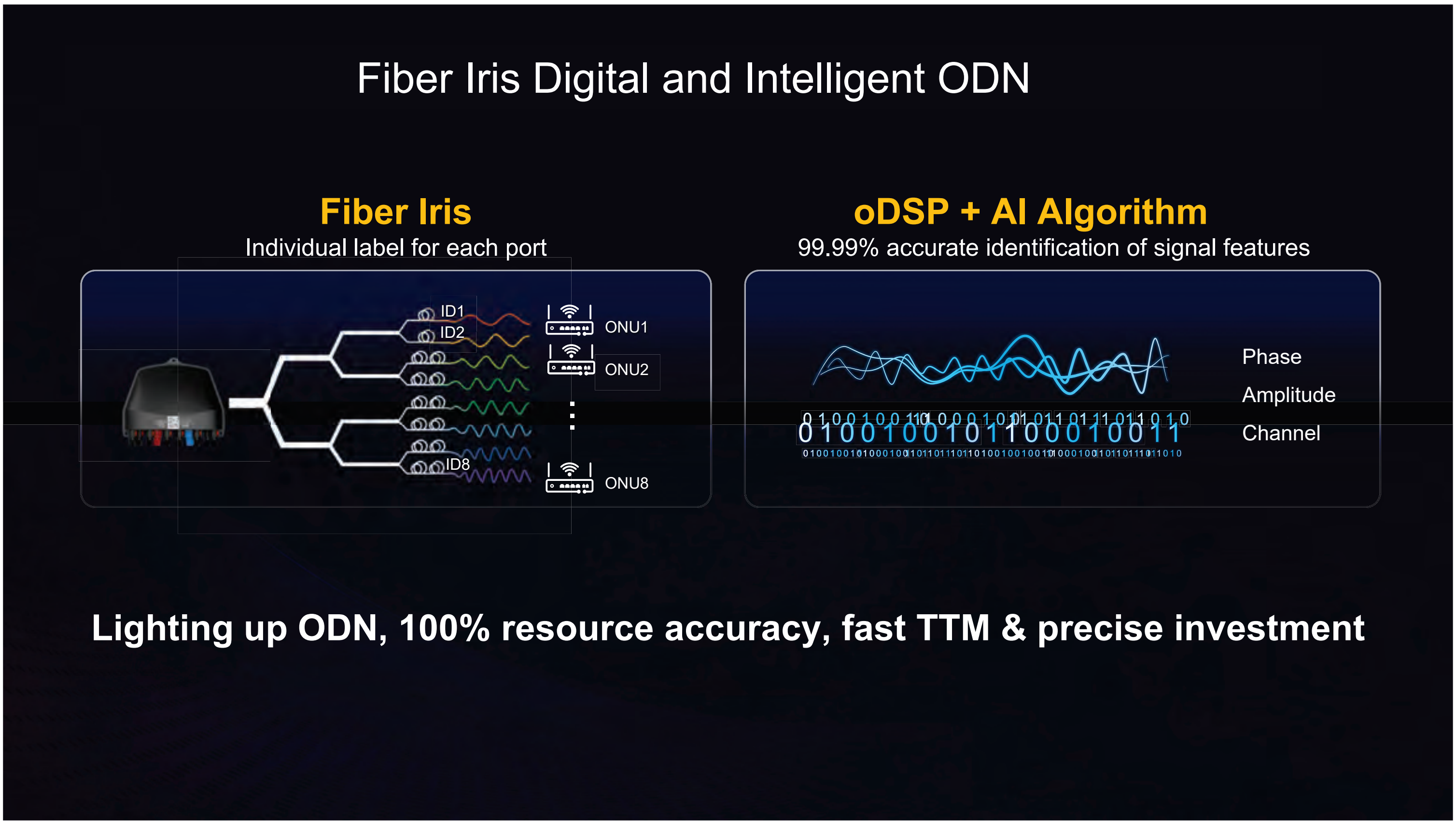
ETSI

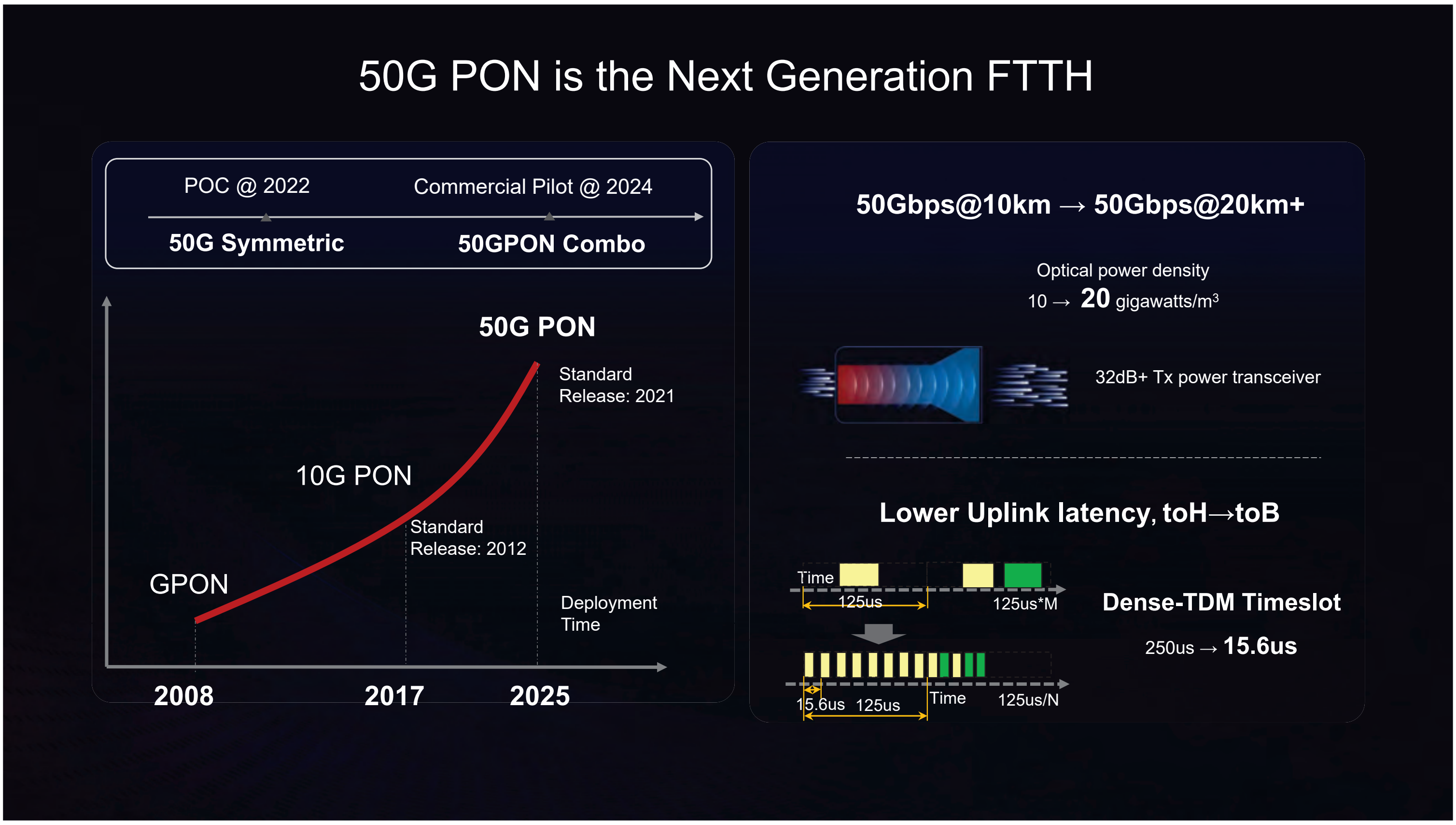
F5.5G-Oriented All-Optical Network in Practice

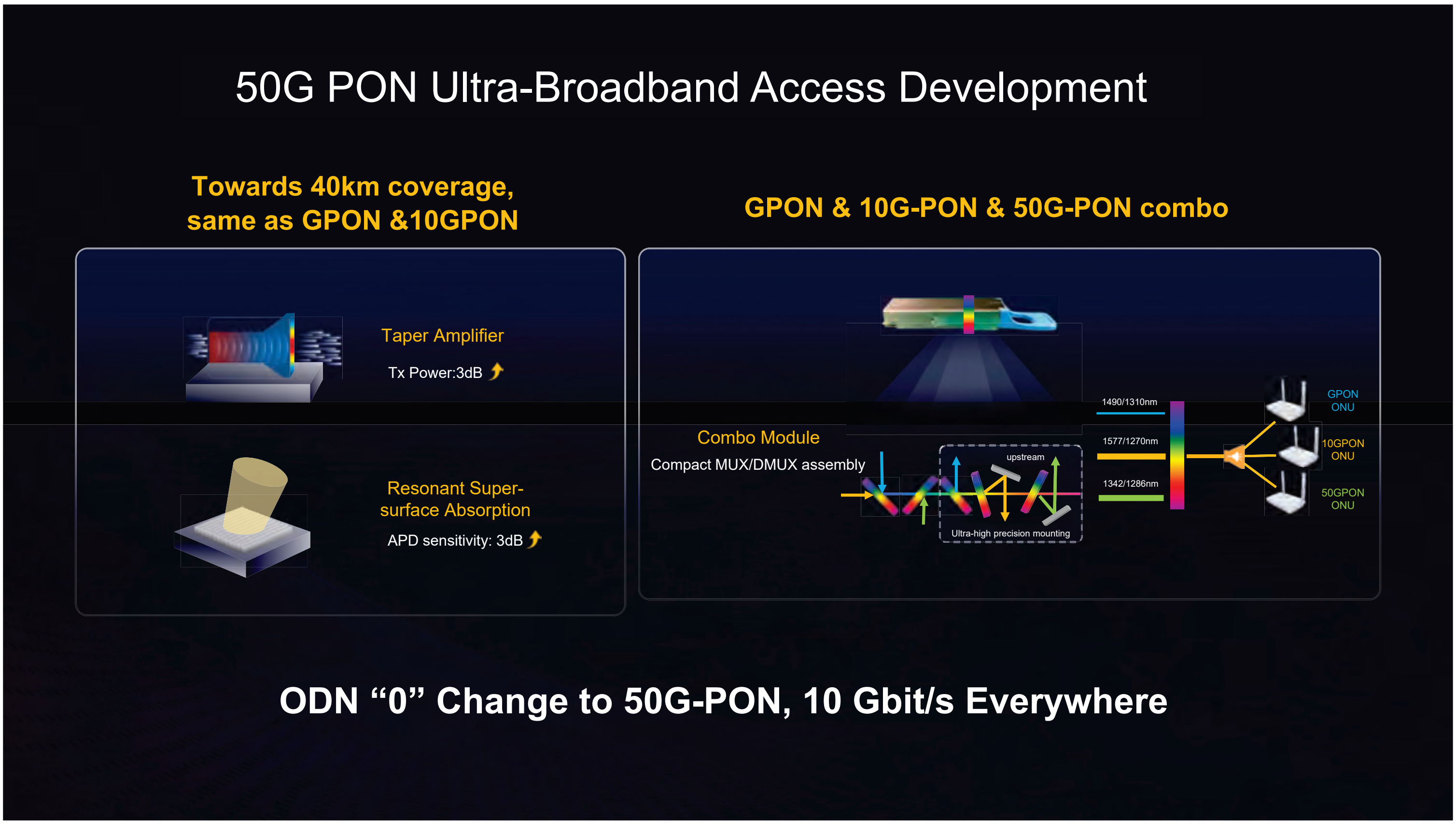
- Home Broadband Coverage Improvement
- Premium Home-Broadband
- Premium Enterprise Private Line
- Innovative Metro & Access Network
- DC-Centric All-Optical Network

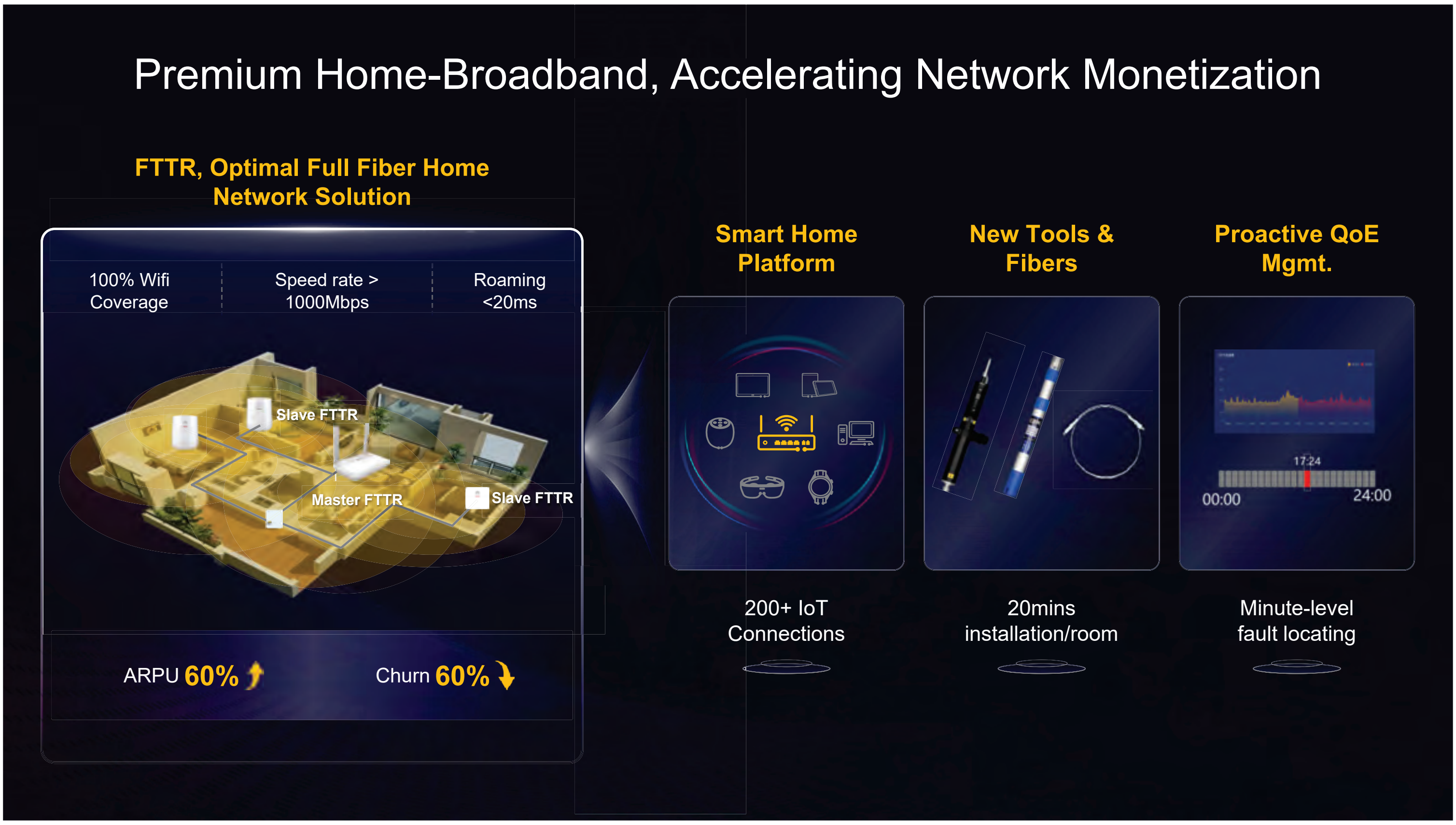

Fixed Broadband is Moving to Bandwidth + Experience
Revenue
Fixed-Mobile Convergence is Accelerating
Num. of FMC carriers
Source: Huawei MI
20+
2012
100+
2018
200+
2021
③ User Experience
Selling eco-system chain: FTTH Connection + Home Network + Service
Digital Life Era
Eco-system for digital intelligent life
② Bandwidth
Selling connection & Service
Video Era
Better connection & Service
① Connectivity
Cooper-> Fiber
Broadband Era
Coverage
SMS
Voice
Devices/HH 1
10Mbps
Devices/HH x3
500~1Gbps
Devices/HH x5
1G~10Gbps
Devices/HH x30
Penetration
EU: 2030 Digital compass, 700 billion euro
ready to upgrade to 1000 Mbps for all homes
China: Dual-Gigabit Action Plan, by 2023
400M HP 30M Subs 100 Cities
Bahrain: TRA released NTP5 target
95% HP 100% Enterprise 100% Fiber to site

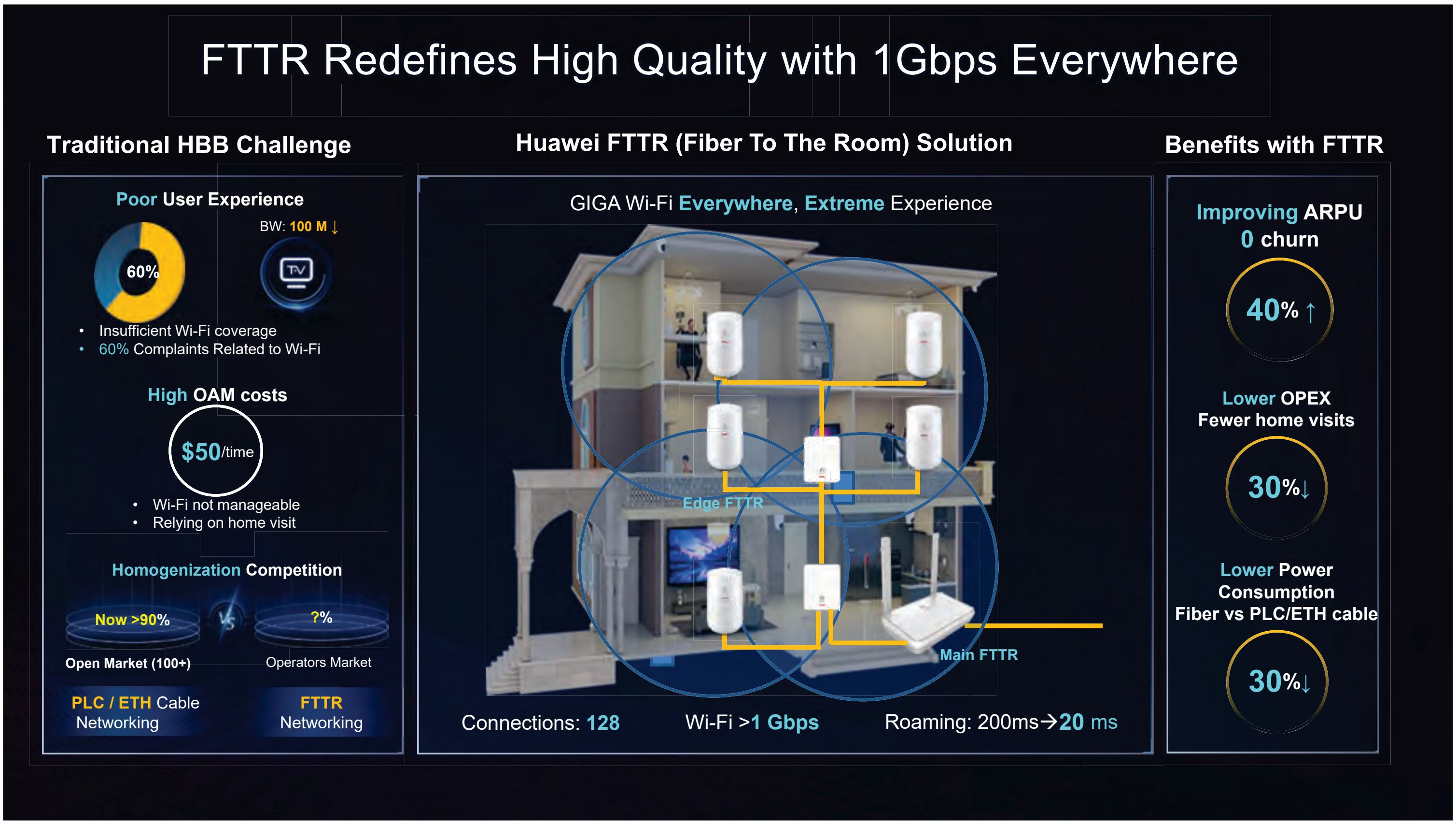

Fast Construction with DQ ODN: High Quality and Visible Management
Fast Construction
One Push Connection
No Reopening
Insert & rotate 45°
Splicing free
connect in 10 seconds
30% TTM Saving
Operator P Practice
Fast Provisioning
One Scan Management
Digital acquisition
Intelligent identification
Image Recognition
Big data modeling
Resource
Real-time auto-synchronization
100% Accurate Resource
Operator C Practice
Fast Troubleshooting
One Click Maintenance
ODN Visualizer
Remote fault demarcation
Auto-root cause analysis
Real-time optical detection
Demarcation
Minute and Meter Level
↓ 40% Truck Roll
Operator E Practice


Fiber Iris Digital and Intelligent ODN
Fiber Iris
Individual label for each port
ID1
ID2
ID8
ONU1
ONU2
ONU8
oDSP + AI Algorithm
99.99% accurate identification of signal features
Phase
Amplitude
Channel
Lighting up ODN, 100% resource accuracy, fast TTM & precise investment

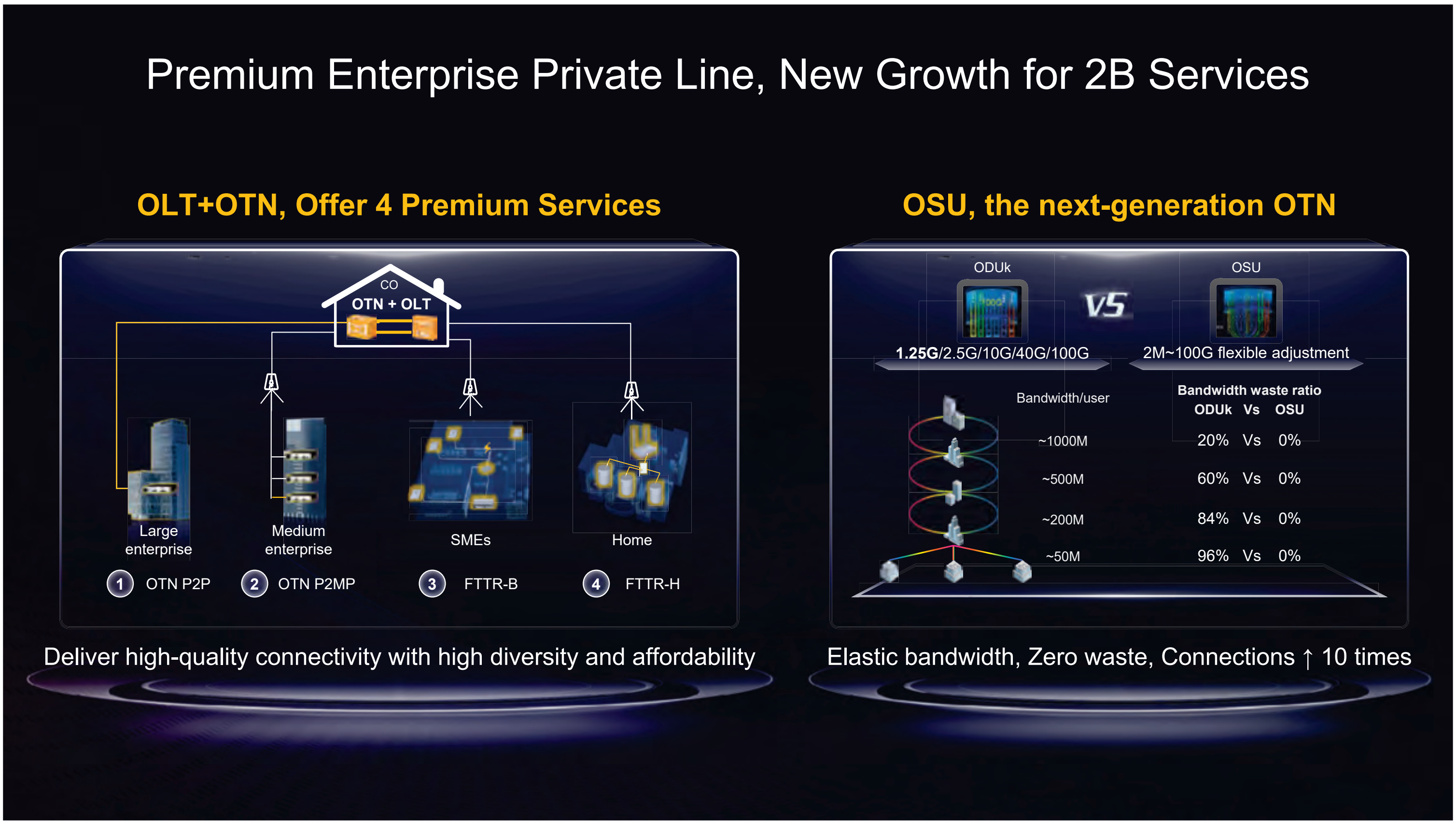

50G PON is the Next Generation FTTH
POC @ 2022
Commercial Pilot @ 2024
50G Symmetric
50GPON Combo
50G PON
Standard Release: 2021
10G PON
Standard Release: 2012
GPON
Deployment Time
2008
2017
2025
50Gbps@10km → 50Gbps@20km+
Optical power density
10 → 20 gigawatts/m³
32dB+ Tx power transceiver
Lower Uplink latency, toH→toB
Time
125us
125us*M
15.6us
125us
125us/N
Dense-TDM Timeslot
250us → 15.6us

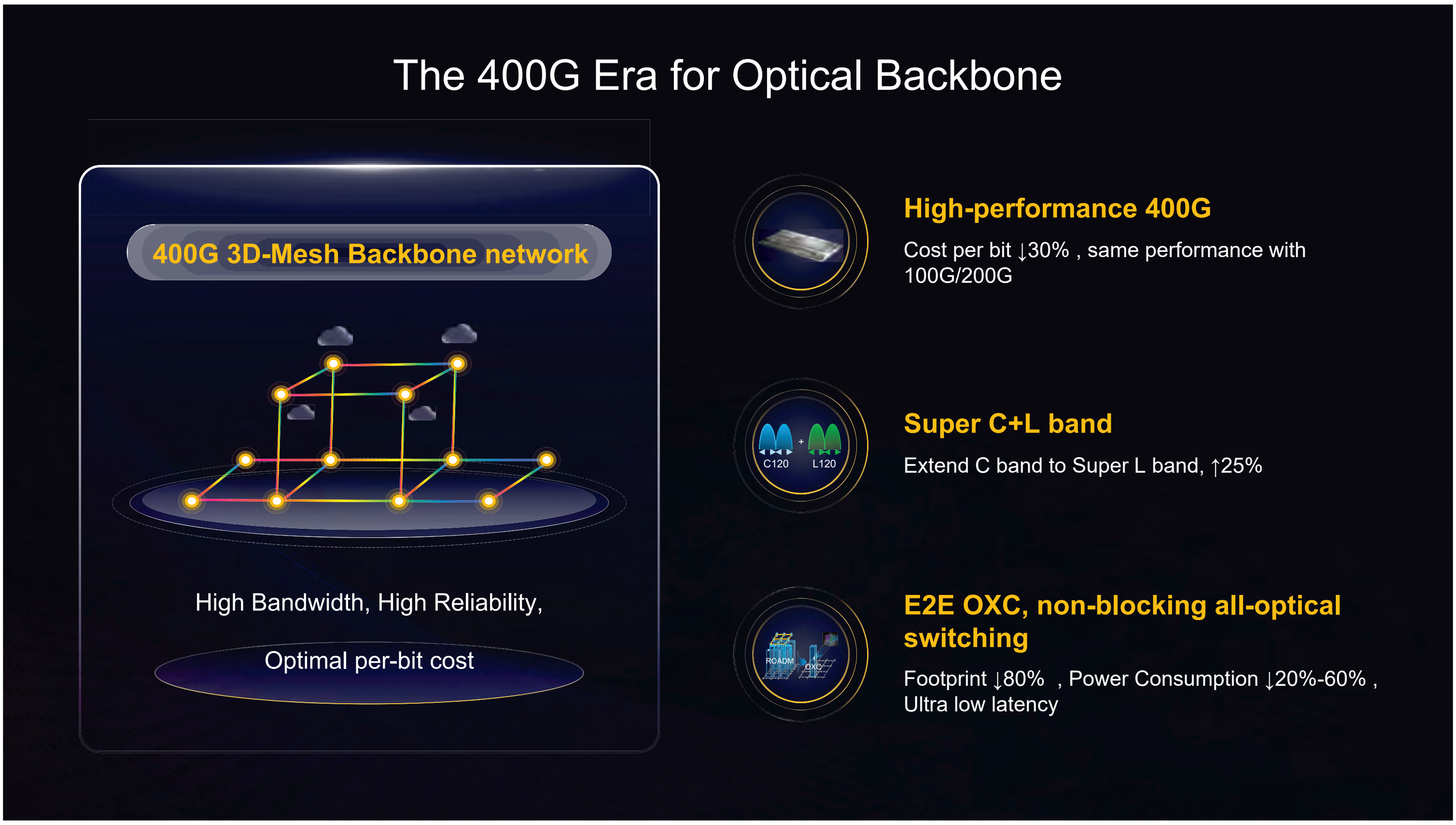

50G PON Ultra-Broadband Access Development
Towards 40km coverage, same as GPON &10GPON
Taper Amplifier
Tx Power:3dB
Resonant Super-surface Absorption
APD sensitivity: 3dB
GPON & 10G-PON & 50G-PON combo
Combo Module
Compact MUX/DMUX assembly
upstream
Ultra-high precision mounting
1490/1310nm
1577/1270nm
1342/1286nm
GPON ONU
10GPON ONU
50GPON ONU
ODN "0" Change to 50G-PON, 10 Gbit/s Everywhere

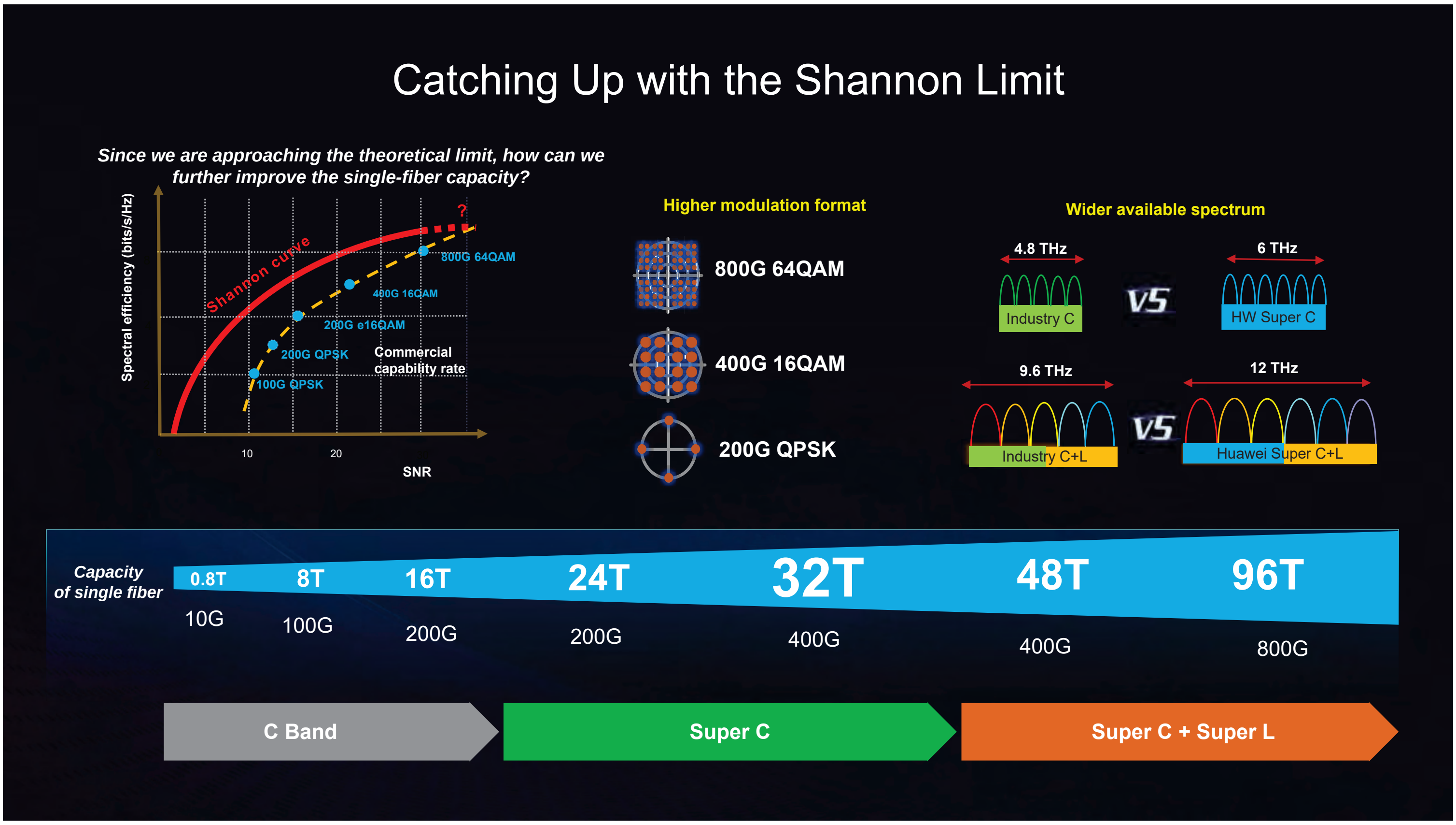

Premium Home-Broadband, Accelerating Network Monetization
FTTR, Optimal Full Fiber Home Network Solution
100% Wifi Coverage
Speed rate > 1000Mbps
Roaming <20ms
Slave FTTR
Master FTTR
Slave FTTR
ARPU 60%
Churn 60%
Smart Home Platform
New Tools & Fibers
Proactive QoE Mgmt.
17:24
00:00
24:00
200+ IoT Connections
20mins installation/room
Minute-level fault locating

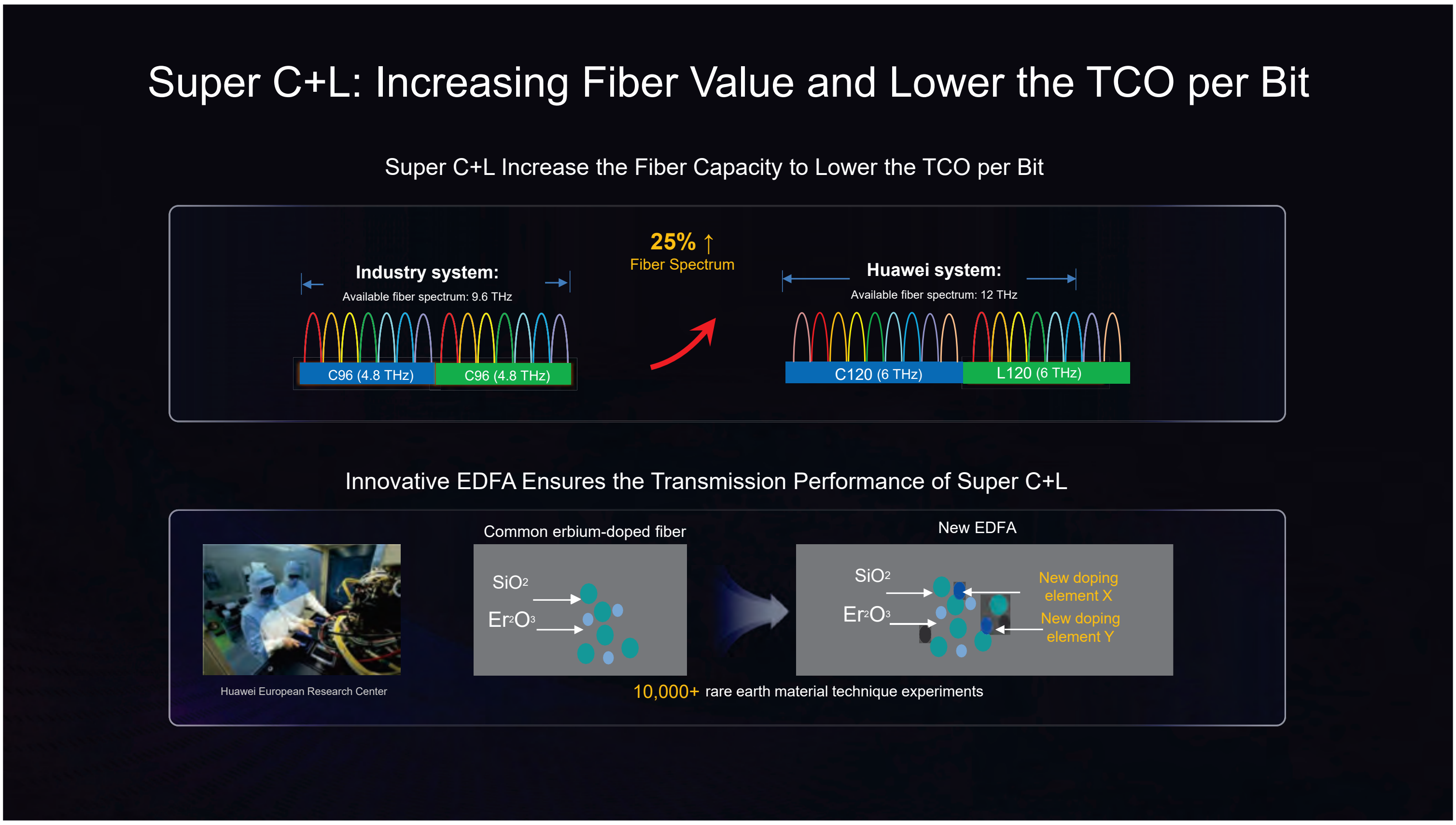

FTTR Redefines High Quality with 1Gbps Everywhere
Traditional HBB Challenge
Huawei FTTR (Fiber To The Room) Solution
Benefits with FTTR
Poor User Experience
BW: 100 M ↓
60%
Insufficient Wi-Fi coverage
60% Complaints Related to Wi-Fi
High OAM costs
$50/time
Wi-Fi not manageable
Relying on home visit
Homogenization Competition
Now >90%
?%
Open Market (100+)
Operators Market
PLC / ETH Cable Networking
FTTR Networking
GIGA Wi-Fi Everywhere, Extreme Experience
Edge FTTR
Main FTTR
Connections: 128
Wi-Fi >1 Gbps
Roaming: 200ms→20 ms
Improving ARPU
0 churn
40% ↑
Lower OPEX
Fewer home visits
30%↓
Lower Power Consumption
Fiber vs PLC/ETH cable
30%↓

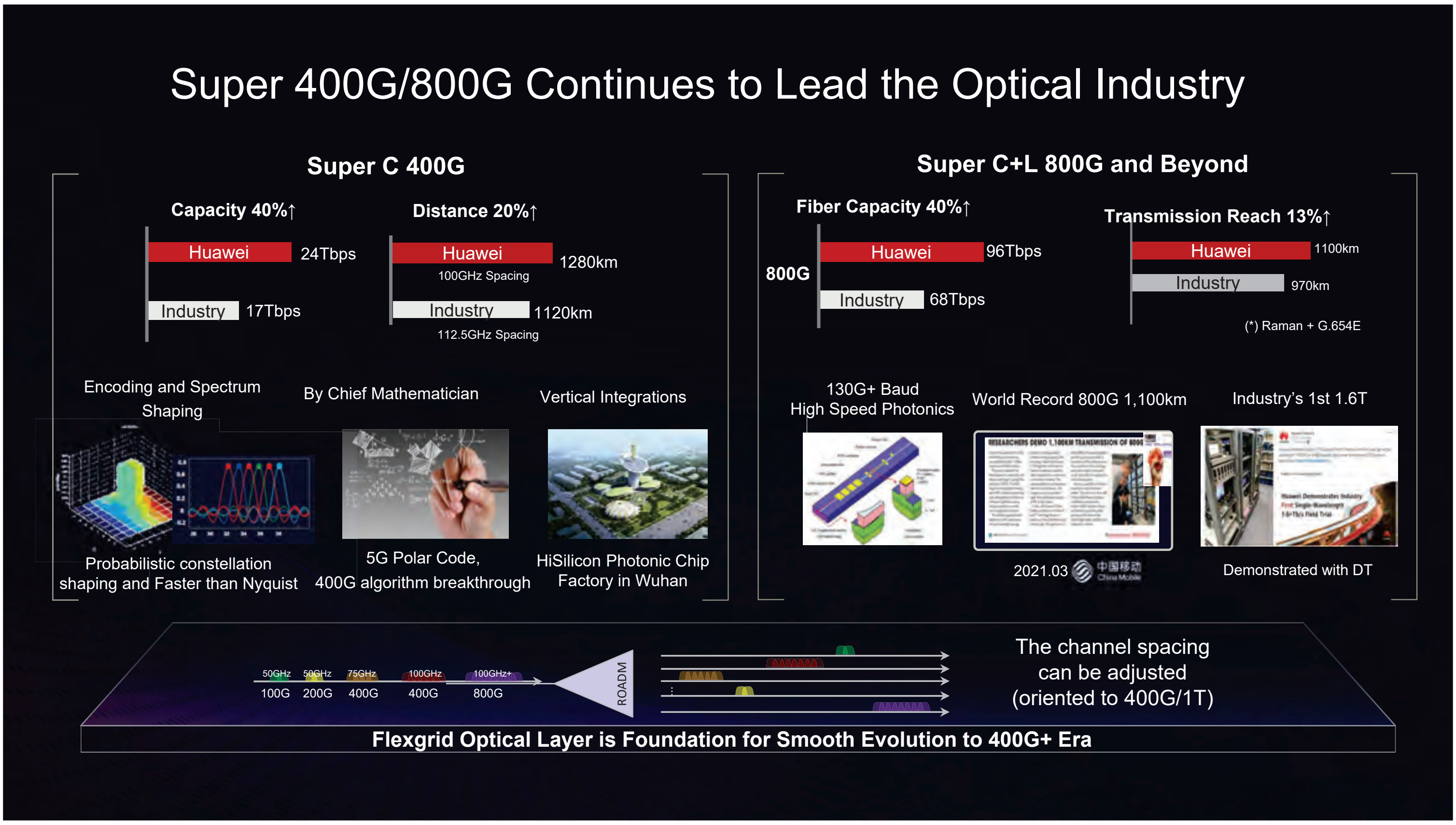

FTTR Centralized Wi-Fi Access Network (C-WAN)
C-WAN provides premium & consistent Wi-Fi experience
Conventional Wi-Fi Network
C-WAN
DWM Algorithm
Throughput: 50%
DWM: Dynamic Wi-Fi Management
Intelligent FBA Algorithm
Multiple concurrency : 4x
FBA: Frequency Band Adjustment
SRCN Technology
Seamless roaming: <20ms
SRCN: Seamless Roaming Coordinate Network
Seamless Roaming

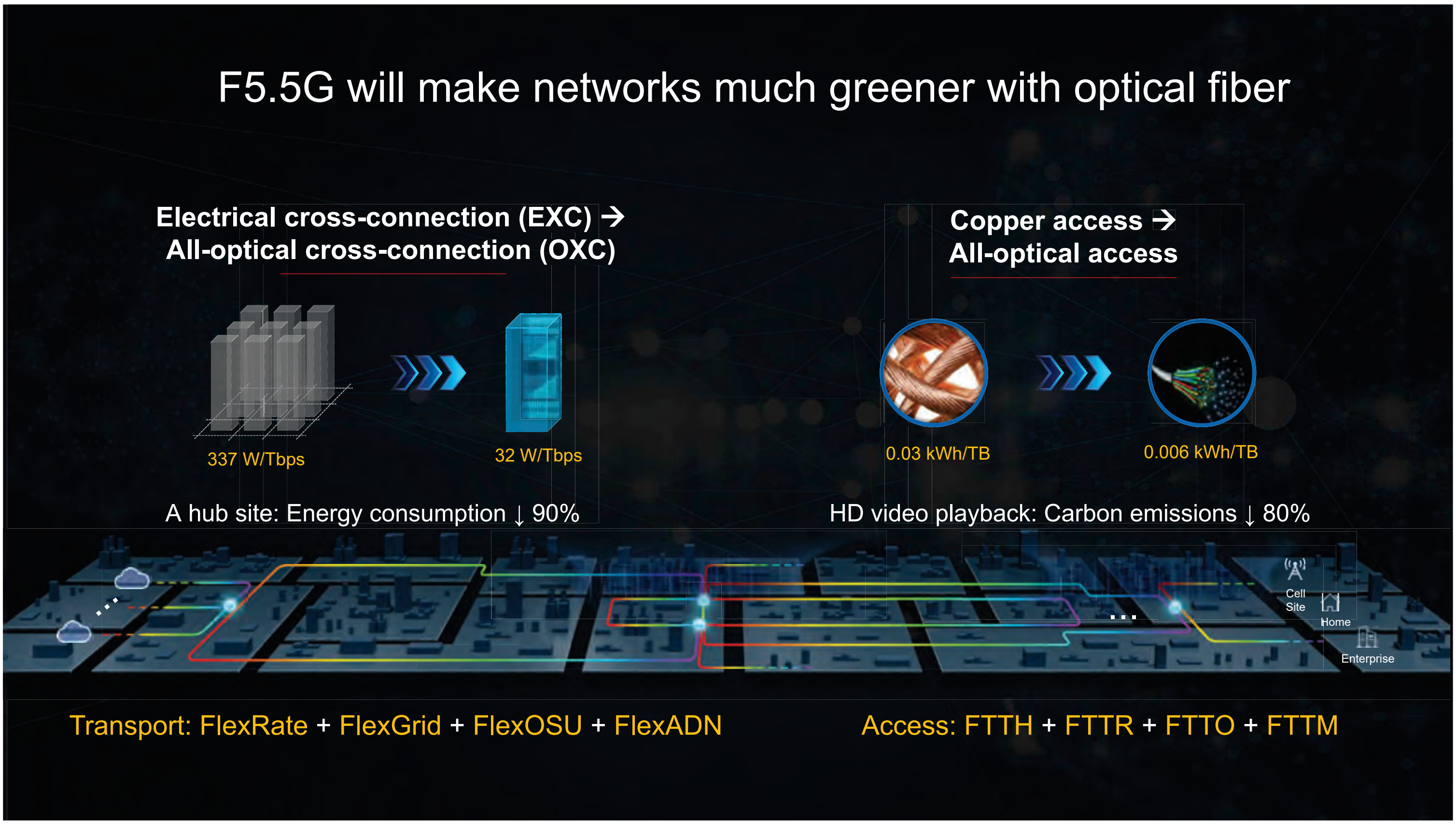

Premium Enterprise Private Line, New Growth for 2B Services
OLT+OTN, Offer 4 Premium Services
CO
OTN + OLT
Large enterprise
Medium enterprise
SMEs
Home
1 OTN P2P
2 OTN P2MP
3 FTTR-B
4 FTTR-H
Deliver high-quality connectivity with high diversity and affordability
OSU, the next-generation OTN
ODUk
VS
OSU
1.25G/2.5G/10G/40G/100G
2M~100G flexible adjustment
Bandwidth/user
Bandwidth waste ratio
ODUk Vs OSU
~1000M 20% Vs 0%
~500M 60% Vs 0%
~200M 84% Vs 0%
~50M 96% Vs 0%
Elastic bandwidth, Zero waste, Connections ↑ 10 times

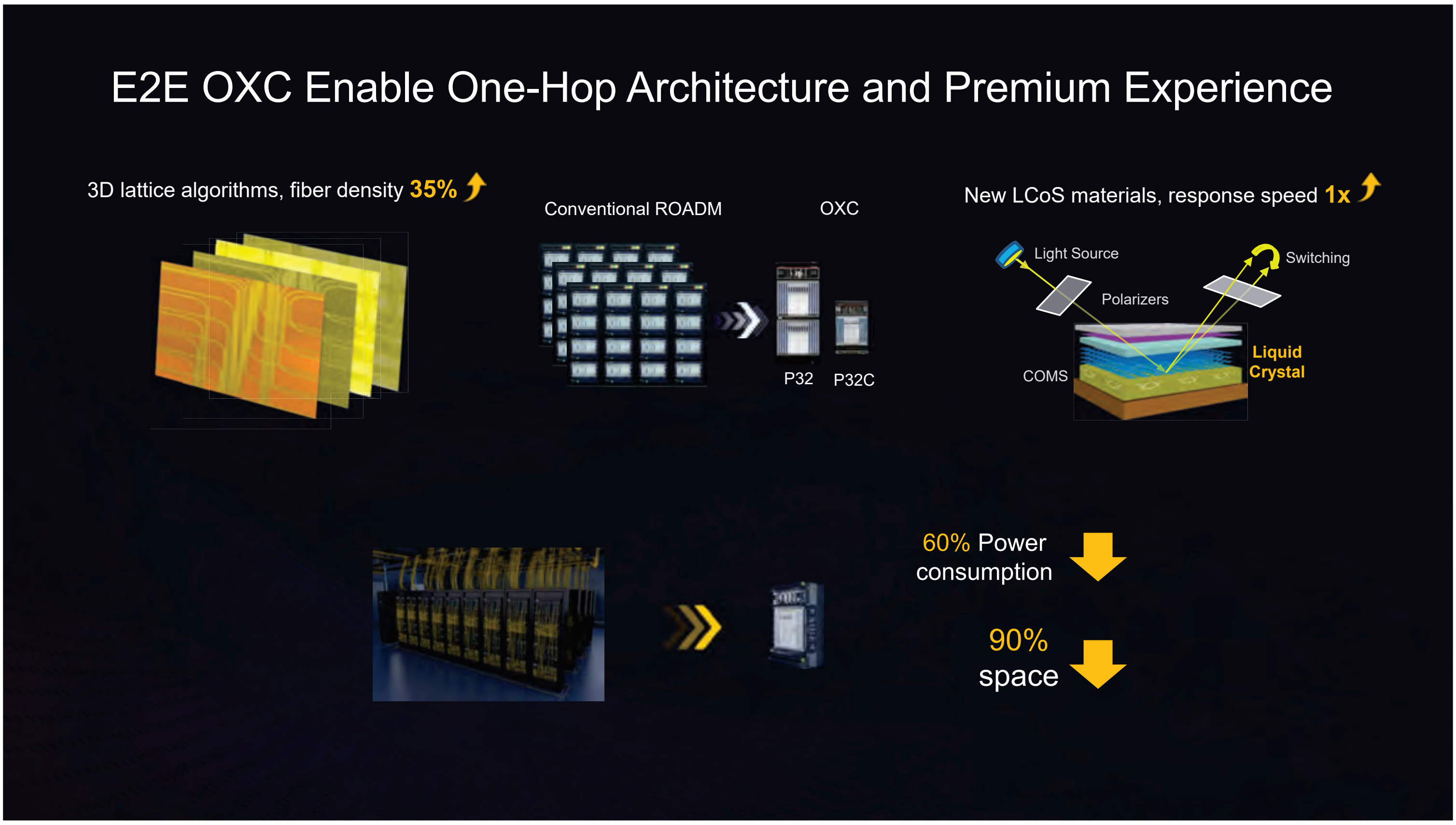

The 400G Era for Optical Backbone
400G 3D-Mesh Backbone network
High Bandwidth, High Reliability,
Optimal per-bit cost
High-performance 400G
Cost per bit ↓30% , same performance with 100G/200G
C120
L120
Super C+L band
Extend C band to Super L band, ↑25%
ROADM
OXC
E2E OXC, non-blocking all-optical switching
Footprint ↓80% , Power Consumption ↓20%-60% , Ultra low latency

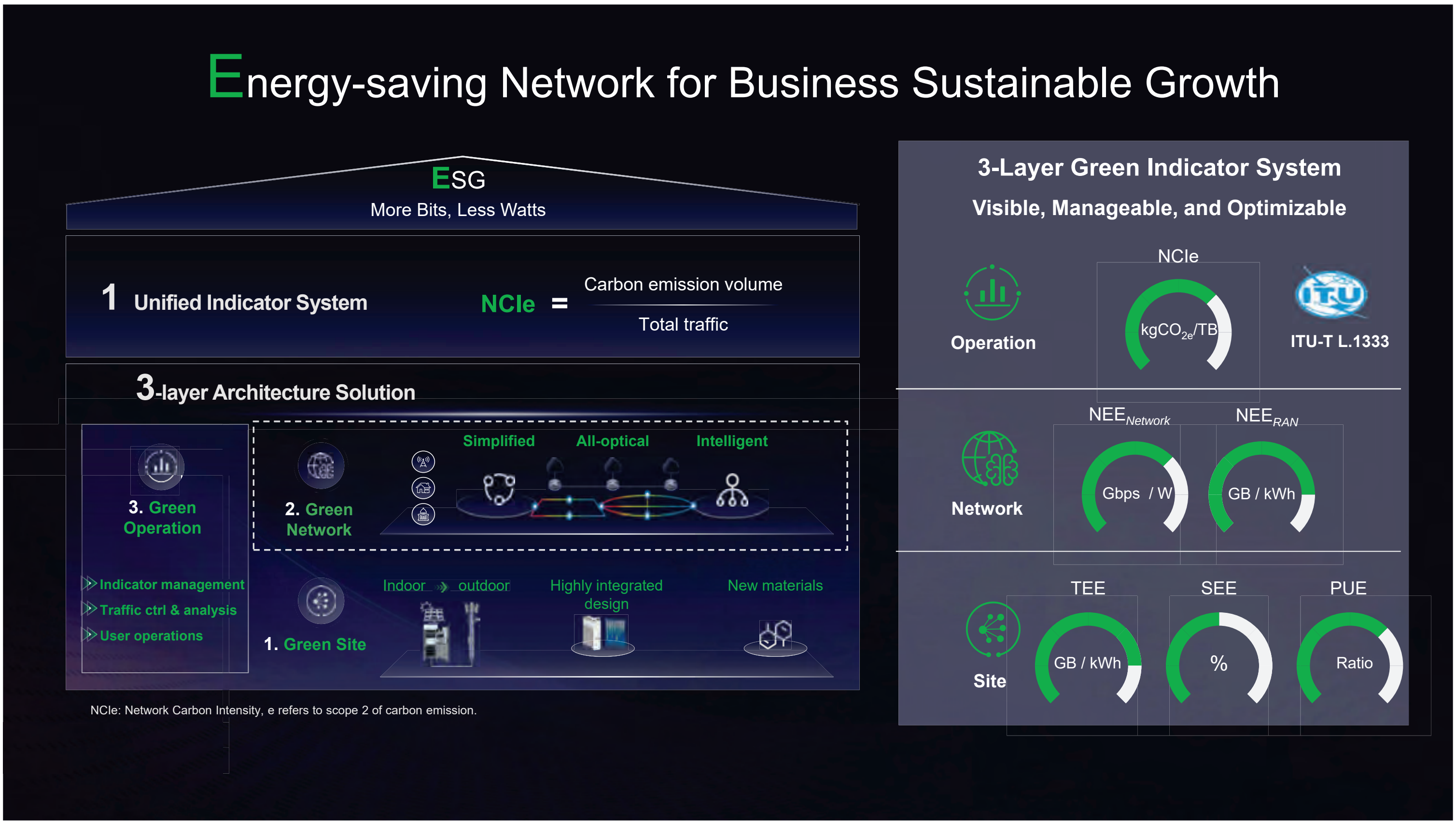

Catching Up with the Shannon Limit
Since we are approaching the theoretical limit, how can we further improve the single-fiber capacity?
Spectral efficiency (bits/s/Hz)
Shannon curve
800G 64QAM
400G 16QAM
200G e16QAM
200G QPSK
100G QPSK
Commercial capability rate
10
20
SNR
Higher modulation format
800G 64QAM
400G 16QAM
200G QPSK
Wider available spectrum
4.8 THz
Industry C
VS
6 THz
HW Super C
9.6 THz
Industry C+L
VS
12 THz
Huawei Super C+L
Capacity of single fiber
0.8T
8T
16T
24T
32T
48T
96T
10G
100G
200G
200G
400G
400G
800G
C Band
Super C
Super C + Super L


Super C+L: Increasing Fiber Value and Lower the TCO per Bit
Super C+L Increase the Fiber Capacity to Lower the TCO per Bit
25% ↑
Fiber Spectrum
Industry system:
Available fiber spectrum: 9.6 THz
C96 (4.8 THz)
C96 (4.8 THz)
Huawei system:
Available fiber spectrum: 12 THz
C120 (6 THz)
L120 (6 THz)
Innovative EDFA Ensures the Transmission Performance of Super C+L
Huawei European Research Center
Common erbium-doped fiber
SiO2
Er2O3
New EDFA
SiO2
Er2O3
New doping element X
New doping element Y
10,000+ rare earth material technique experiments


Super 400G/800G Continues to Lead the Optical Industry
Super C 400G
Capacity 40%↑
Huawei 24Tbps
Industry 17Tbps
Distance 20%↑
Huawei 1280km
100GHz Spacing
Industry 1120km
112.5GHz Spacing
Encoding and Spectrum Shaping
By Chief Mathematician
Vertical Integrations
Probabilistic constellation shaping and Faster than Nyquist
5G Polar Code, 400G algorithm breakthrough
HiSilicon Photonic Chip Factory in Wuhan
Super C+L 800G and Beyond
Fiber Capacity 40%↑
800G
Huawei 96Tbps
Industry 68Tbps
Transmission Reach 13%↑
Huawei 1100km
Industry 970km
(*) Raman + G.654E
130G+ Baud High Speed Photonics
World Record 800G 1,100km
Industry's 1st 1.6T
2021.03
Demonstrated with DT
50GHz 50GHz 75GHz 100GHz 100GHz+
100G 200G 400G 400G 800G
ROADM
The channel spacing can be adjusted (oriented to 400G/1T)
Flexgrid Optical Layer is Foundation for Smooth Evolution to 400G+ Era


F5.5G will make networks much greener with optical fiber
Electrical cross-connection (EXC) → All-optical cross-connection (OXC)
337 W/Tbps
32 W/Tbps
A hub site: Energy consumption ↓ 90%
Copper access → All-optical access
0.03 kWh/TB
0.006 kWh/TB
HD video playback: Carbon emissions ↓ 80%
Cell Site
Home
Enterprise
Transport: FlexRate + FlexGrid + FlexOSU + FlexADN
Access: FTTH + FTTR + FTTO + FTTM


E2E OXC Enable One-Hop Architecture and Premium Experience
3D lattice algorithms, fiber density 35%
Conventional ROADM
OXC
P32
P32C
New LCoS materials, response speed 1x
Light Source
Switching
Polarizers
COMS
Liquid Crystal
60% Power consumption
90% space


Energy-saving Network for Business Sustainable Growth
ESG
More Bits, Less Watts
1 Unified Indicator System
NCIe = Carbon emission volume / Total traffic
3-layer Architecture Solution
3. Green Operation
Indicator management
Traffic ctrl & analysis
User operations
2. Green Network
Simplified
All-optical
Intelligent
1. Green Site
Indoor outdoor
Highly integrated design
New materials
NCIe: Network Carbon Intensity, e refers to scope 2 of carbon emission.
3-Layer Green Indicator System
Visible, Manageable, and Optimizable
NCIe
Operation
kgCO2e/TB
ITU-T L.1333
NEE Network
NEE RAN
Network
Gbps / W
GB / kWh
TEE
SEE
PUE
Site
GB / kWh
%
Ratio


Together, We Stride to
F5.5G
1
50G PON
2
Super C+L
3
OXC
4
Super C+L
5
OSU
6
FTTR
7
Fiber Iris
8
ADN

Tutorial on machine learning

Darko Zibar

DTU - Technical University of Denmark

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Abstract

In this tutorial article, basic concepts with machine learning such as learning data-driven models for regression and classification are covered. Moreover, key concepts within machine learning such as overfitting, underfitting and generalization are explained and demonstrated using numerical examples.

Author's biography

Darko Zibar is Professor at the Department of Photonics Engineering, Technical University of Denmark and the group leader of Machine Learning in Photonics Systems (M-LiPS) group. He received M.Sc. degree in telecommunication and the Ph.D. degree in optical communications from the Technical University of Denmark, in 2004 and 2007, respectively. His research efforts are currently focused on the application of machine learning techniques to advance classical and quantum optical communication and measurement systems. Some of his major scientific contributions include: record capacity hybrid optical-wireless link (2011), record sensitive optical phase noise measurement technique that approaches the quantum limit (2019) and design of programmable ultrawide band arbitrary gain Raman amplifier (2020). He is a recipient of European Research Council (ERC) Consolidator Grant (2017) and Alexander von Humboldt Bessel Research Award (2022). Finally, he was a part of the team that won the HORIZON 2020 prize for breaking the optical transmission barriers (2016).

Introduction to machine learning and regression models

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Today's agenda

- Part I – Linear models for classification (~60 min)
  - What is machine learning?
  - Applications of machine learning
  - Types of machine learning
  - Learning the linear model
  - Learning the nonlinear model
  - What is a neural network
  - The simplest neural network (Rosenblatt perceptron)
  - Learning logical gates (AND, OR and XOR)
  - Break (~15 min)
- Part II – Problem solving session 1 (~120 min)
- Part III – Solution to exercises (~40 min)

Material

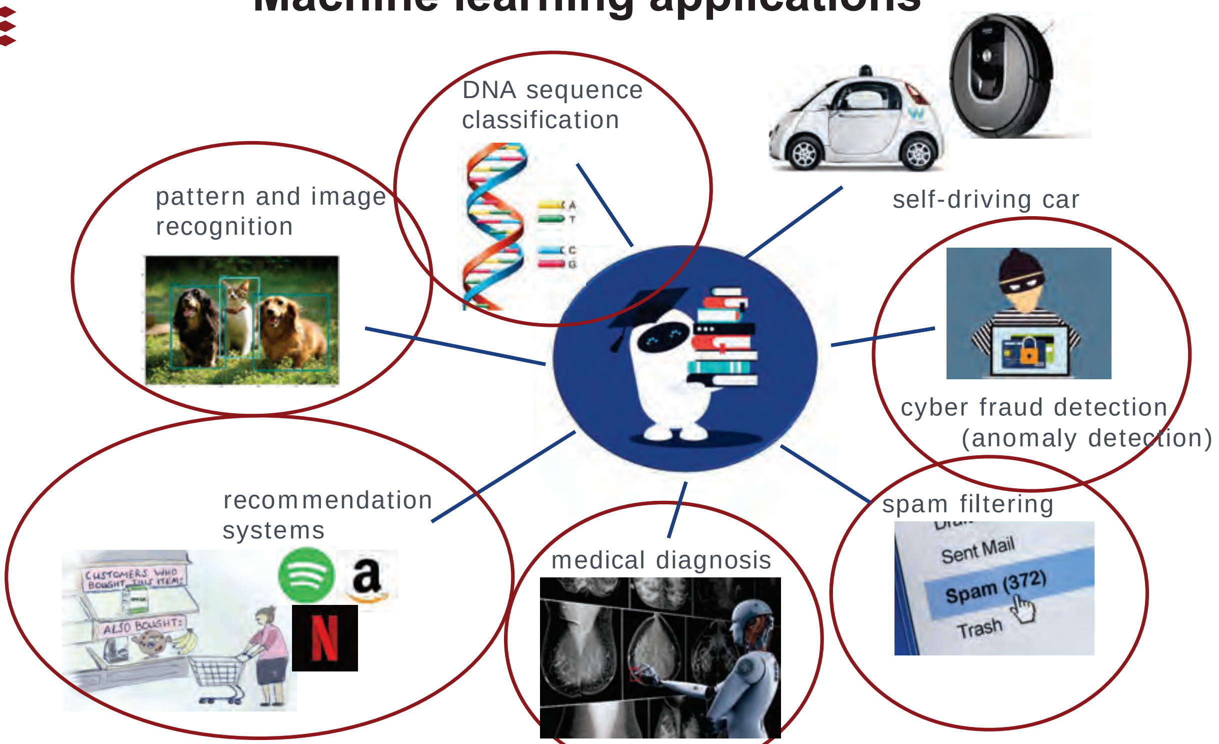
1. Simon Haykin, Neural Networks and Learning Machines
   - Introduction 1,
   - Chapter 1

2. Christopher M. Bishop, Pattern Recognition and Machine Learning, Springer 2006
   - Introduction (pp. 1-12)
   - Chapter 3 (pp. 137-144)

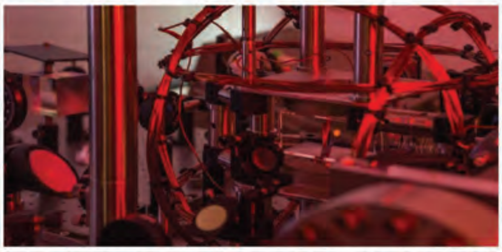
http://dai.fmph.uniba.sk/courses/NN/haykin.neural-networks.3ed.2009.pdf

https://www.academia.edu/34757446/Neural_Networks_and_Learning_Machines_3rd_Edition

Machine learning applications



AI learns and recreates Nobel-winning experiment



Australian physicists, perhaps searching for a way to shorten the work week, have created an AI that can run and even improve a complex physics experiment with little oversight. The research could eventually allow human scientists to focus on high-level problems and research design, leaving the nuts and bolts to a robotic lab assistant.

nature physics

Thesis | Published: 02 December 2019

The power of machine learning

Mark Buchanan

Nature Physics **15**, 1208(2019) | Cite this article

nature photonics

News & Views | Published: 30 November 2017

VIEW FROM... ECOC 2017

Machine learning under the spotlight

Darko Zibar, Henk Wymeersch & Ilya Lyubomirsky

Nature Photonics **11**, 749–751(2017) | Cite this article

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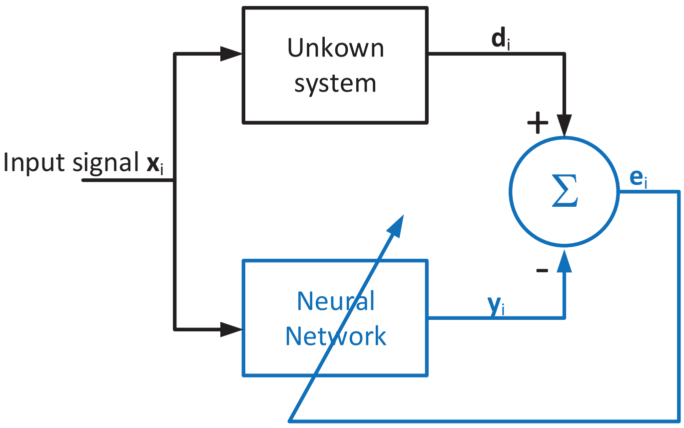
System identification



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What is machine learning according to definitions?

"Field of study that gives computers the ability to learn without being explicitly programmed" (A. Samuel, 1959)

Learn from data

"A computer program is said to learn from experience **E** with respect to some task **T** and some performance measure **P**, if its performance on **T**, as measured by **P**, improves with experience **E**." (T. Mitchell, 1998)

Learning from experience improves task's performance

A.L. Samuel, "Some Studies in Machine Learning Using the Game of Checkers," in *IBM Journal of Research and Development*, vol. 3, no. 3, pp. 210-229, July 1959.

T.M. Mitchell, "Machine Learning," McGraw-Hill International Editions Computer Science Series) 1st Edition, 1998

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When should we use ML?

Take 10min to discuss it with your neighbour.

Please remember to respect social-distancing!

When it is difficult or infeasible to develop a conventional algorithm for effectively performing the task

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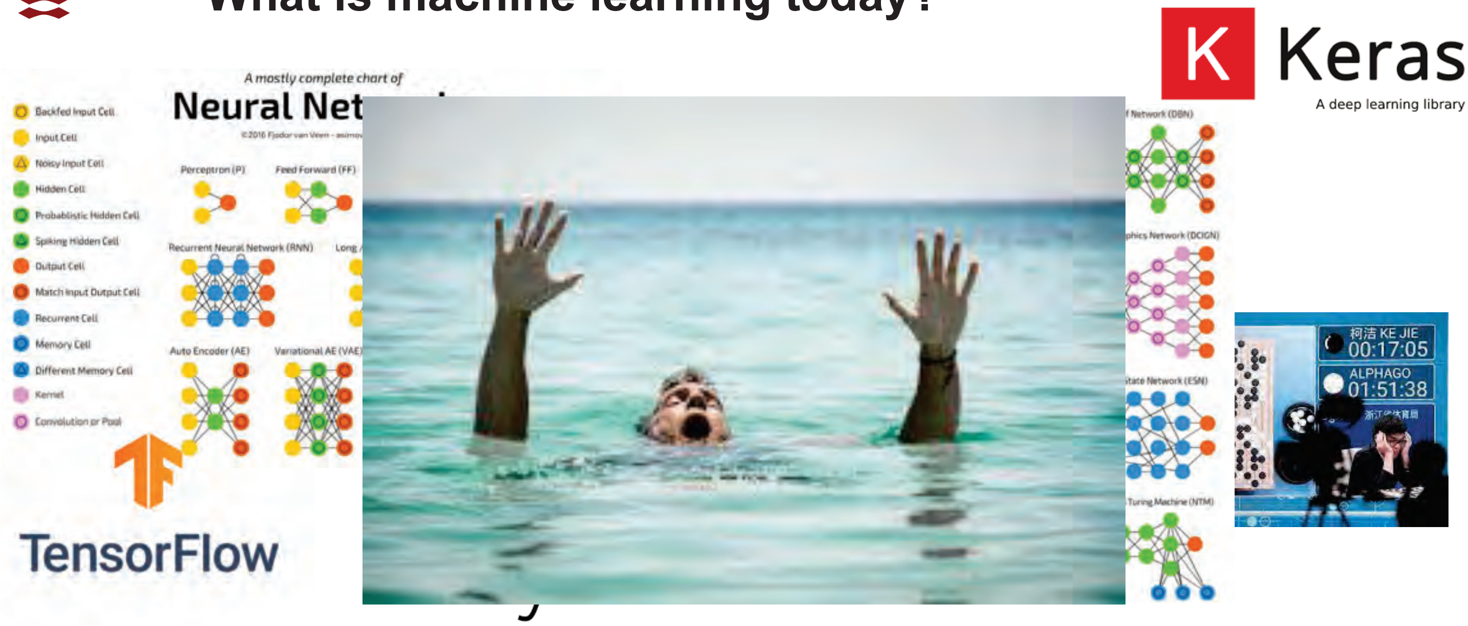
What is machine learning today?



https://becominghuman.ai/cheat-sheets-for-ai-neural-networks-machine-learning-deep-learning-big-data-678c51b4b463

29 October 2020 DTU Fotonik 34366 - Intro to ML 9

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Let’s go back to the beginning…

“A computer program is said to <u>learn</u> from <u>experience</u> **E** with respect to some <u>task</u> **T** and some performance measure **P**, if its performance on **T**, as measured by **P**, improves with experience **E**.” (T. Mitchell, 1998)

Example:

You want to apply machine learning to improve your spam filter

- What is T?
- What is E?
- What is P?

T.M. Mitchell, “Machine Learning,” McGraw-Hill International Editions Computer Science Series) 1st Edition, 1998

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An example of ML problem

Handwritten Digit Recognition

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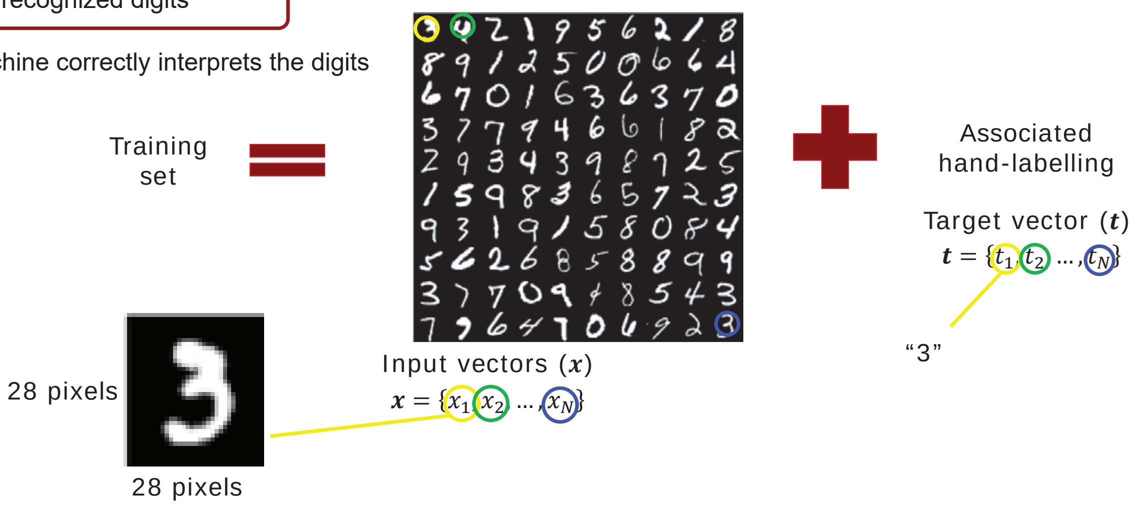
Task, experience, performance…

Task: correctly recognize the hand-written digits

Experience: manually recognized digits

Performance: the machine correctly interprets the digits

Training



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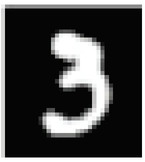
Training a model

Tuning the adaptive model



$\boldsymbol{x} = \{x_1, x_2, \dots, x_N\}$ → **Adaptive model** → $\boldsymbol{t} = \{t_1, t_2, \dots, t_N\}$ "3"

Training or learning phase

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Testing a model

Fixed parameter

$\boldsymbol{x} = \{x_1, x_2, \dots, x_N\}$ → **Final model** $y(x)$ → $\hat{\boldsymbol{t}}$ ***Prediction***

Testing phase: how well does the model generalize?

Generalization: the ability to correctly categorize a new example

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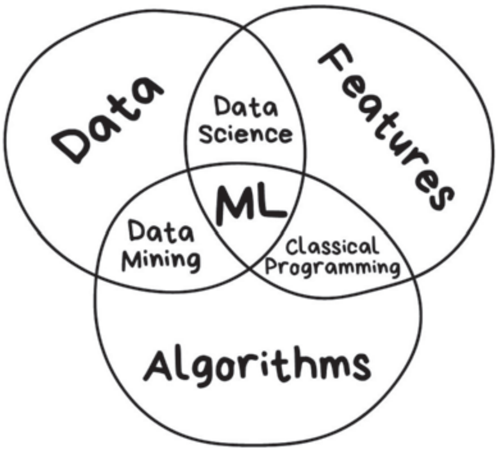
The three key components of ML



- **Data → Your experience used to train your model**
- **Feature → The important parameters/variables in your data. These can be known in advance or may need to be extracted.**
- **Algorithms → The specific method you apply to solve a given problem.**

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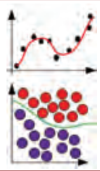
Machine learning algorithms

Supervised learning
Given data x and associated value y, learn y = f(x) or p(y|x)

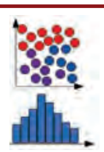
→ Regression / Classification



Predict outcomes

Unsupervised learning
Given data x learn useful properties: p(x)

→ Clustering / Density estimation



Describe data

Reinforcement learning
Feedback based optimization with interaction reward

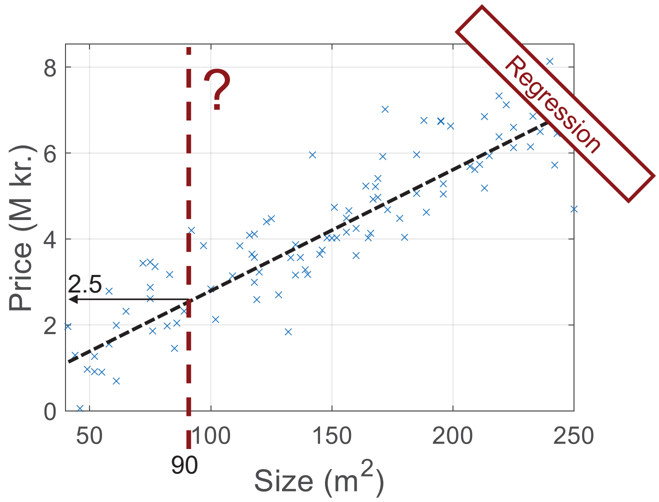
reward — Learning system / Environment — action

Improve

Supervised learning

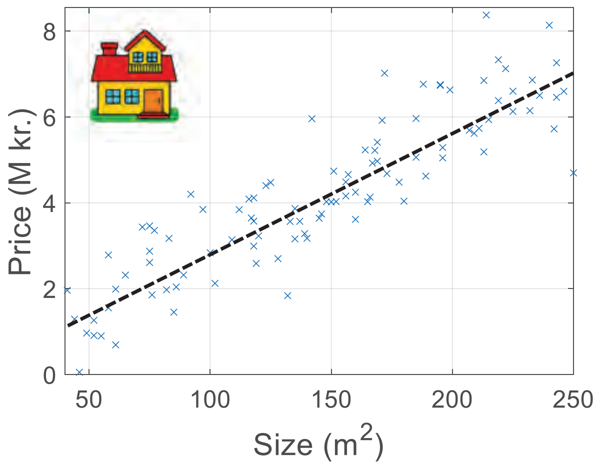
In supervised learning, the “right answers” (e.g. “labels” for training) are known.

Example: house pricing / square meter

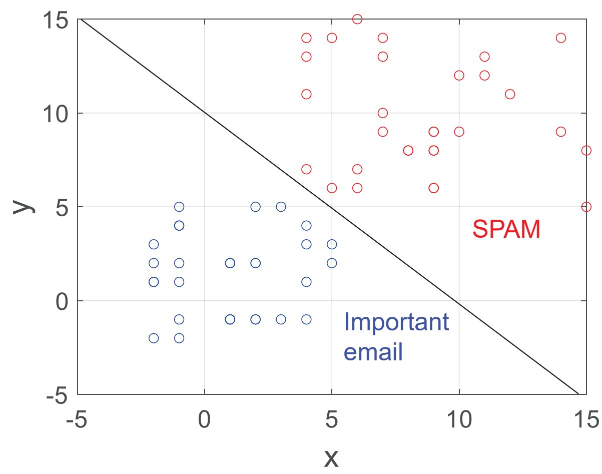


Regression vs. classification

House pricing prediction



Spam filter



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Regression vs. classification – checking…

Regression problems predict **continuous** valued outputs

Classification problems predict **discrete** valued outputs

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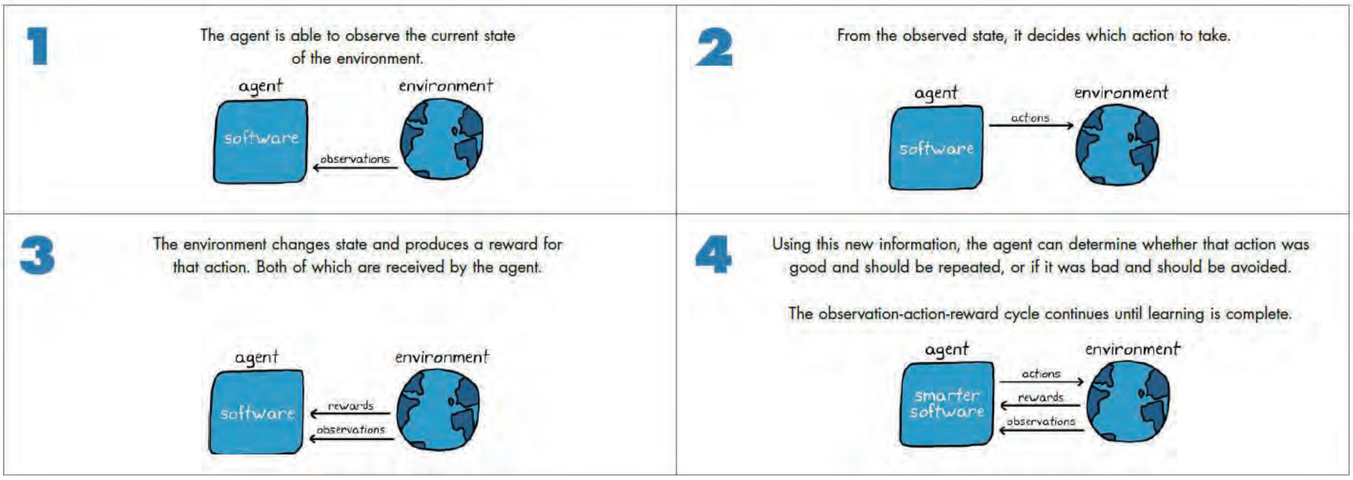
Reinforcement learning (RL)



MATLAB Reinforcement learning e-book

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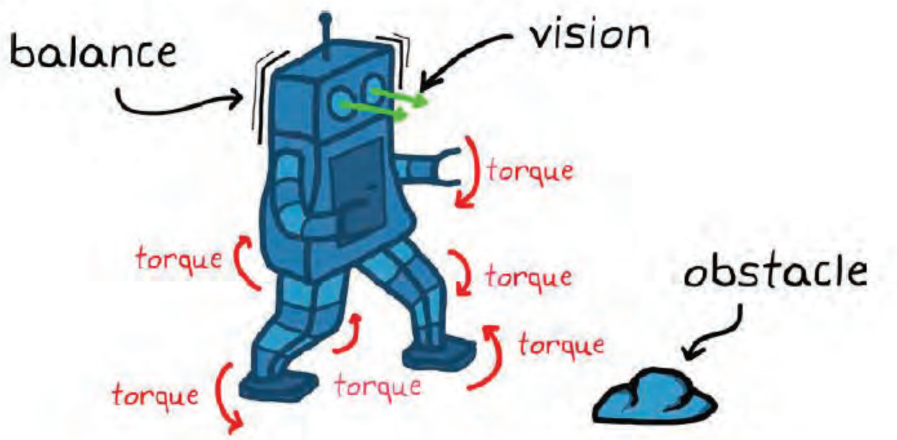
RL for controlling robot motion



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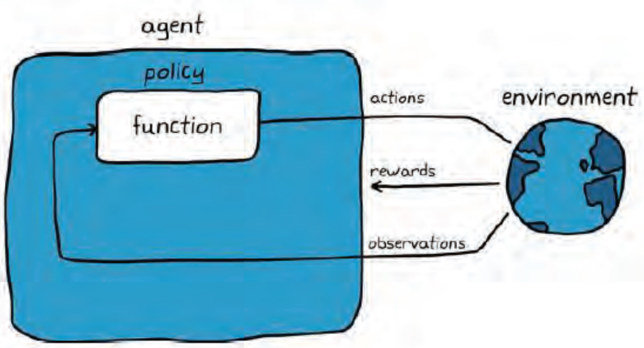
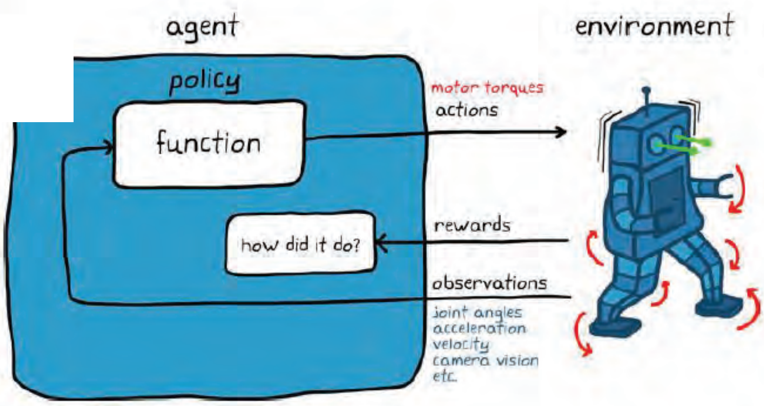
RL for controlling robot motion





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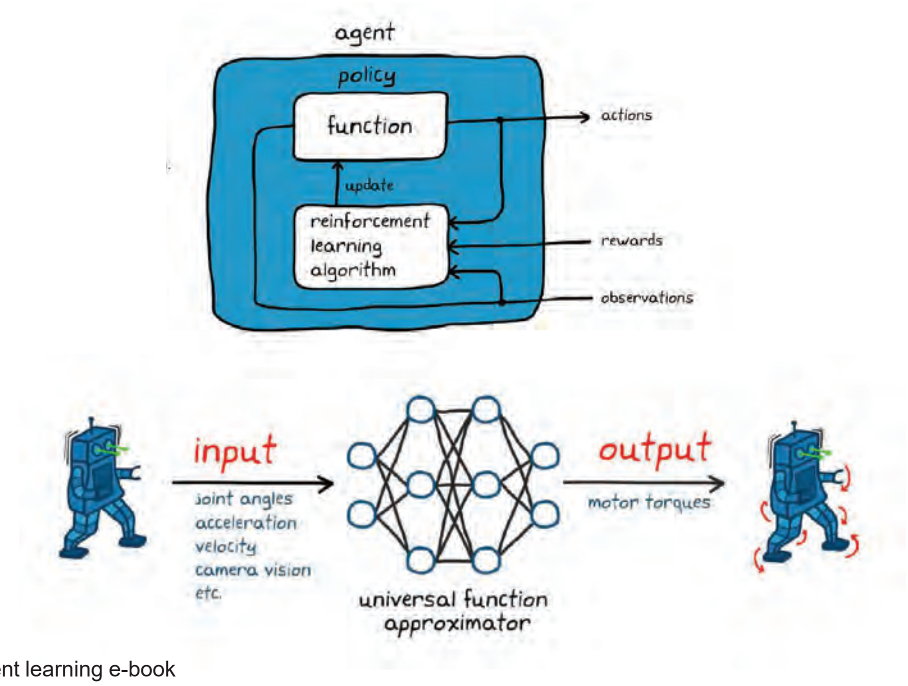
Actions represented by neural-network



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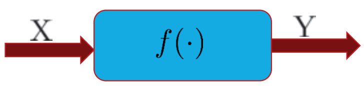
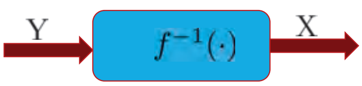
Where does machine learning excel?

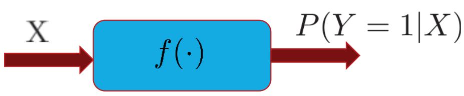
- Learning complex **direct** mappings:



- Learning complex **inverse** mappings:



- Learning **decision rules** for complex mappings:



Use neural networks to learn $f(\cdot)$ and $f^{-1}(\cdot)$

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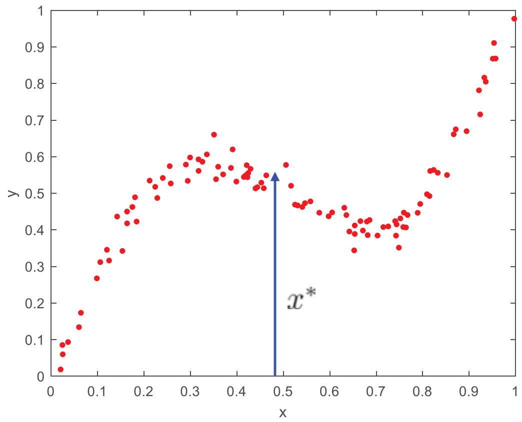
Learning complex functions



1. Given a training data-set (input and output values): $\mathcal{D} = \{x(k), y(k)\}_{k=1}^{K}$
2. For new input $x^*(k) \notin \mathcal{D}$ compute $y^*(k)$
3. Analytical expression *unknown,* must be learned from: $\mathcal{D} = \{x(k), y(k)\}_{k=1}^{K}$

Use *machine learning* to build a model that represents the data set

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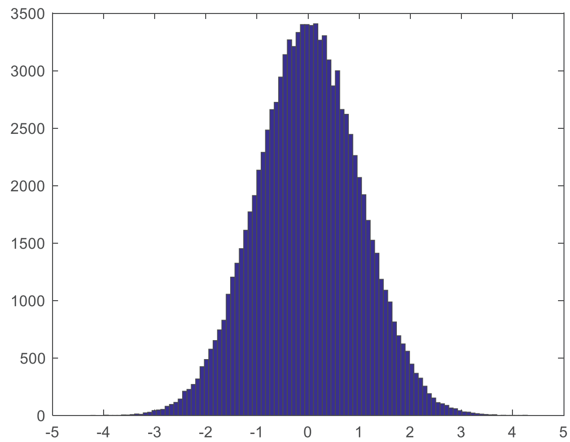
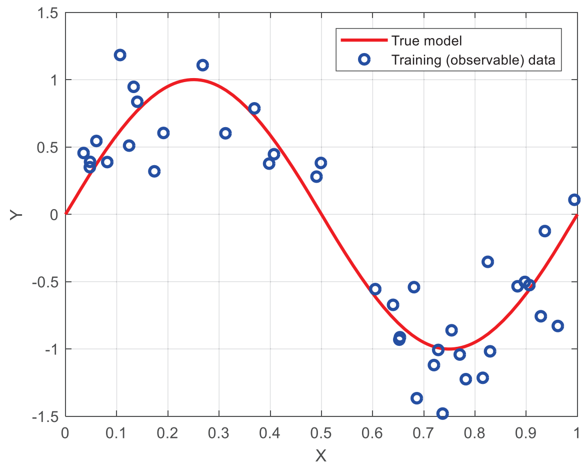
True model and observable data

Typically, a "true" model is given by *continuous* function: $y^{true} = f(x) = \sin(2\pi x)$

The measured (observed) data is *discrete* and corrupted by *noise*: $y_k = f(x_k) + n_k = \sin(2\pi x) + n_k$

Noise assumed to be Gaussian: $n_k \sim N(0, \sigma^2)$





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Learning the (linear) model

Our assumptions (guesses) on the model :

$$\hat{y}(x_k, \mathbf{w}) = w_0 + w_1 x_k + w_2 x^2 + ... + w_M x^M = \sum_{j=0}^{M} w_j x_k^j$$

Or

$$\hat{y}(x_k, \mathbf{w}) = w_0 + w_1 \sin(2\pi x_k) + w_2 \sin(2\pi x^2) + ... + w_M \sin(2\pi x^M) = \sum_{j=0}^{M} w_j \sin(2\pi x_k^j)$$

Or

$$\hat{y}(x_k, \mathbf{w}) = w_0 + w_1 \sin(2\pi x_k) + w_2 \sin^2(2\pi x) + ... + w_M \sin^M(2\pi x) = \sum_{j=0}^{M} w_j \sin^j(2\pi x_k)$$

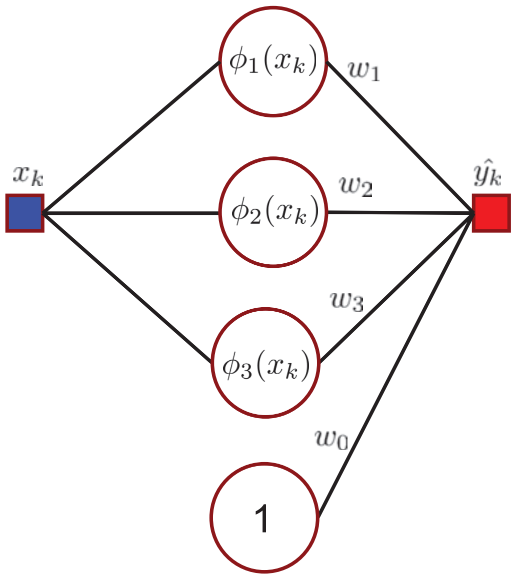
General linear model:

$$\hat{y}(x_k, \mathbf{W}) = w_0 + \sum_{j=1}^{M} w_j \phi_j(x_k)$$

Once we have chosen the model the task is to determine the weights: $\mathbf{W} = [w_0, w_1, ..., w_M]$

Procedure: choose a model then determine the weights

Topology of the linear model



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$$\hat{y}(x_k, \mathbf{W}) = w_0 + \sum_{j=1}^{3} w_j \phi_j(x_k)$$

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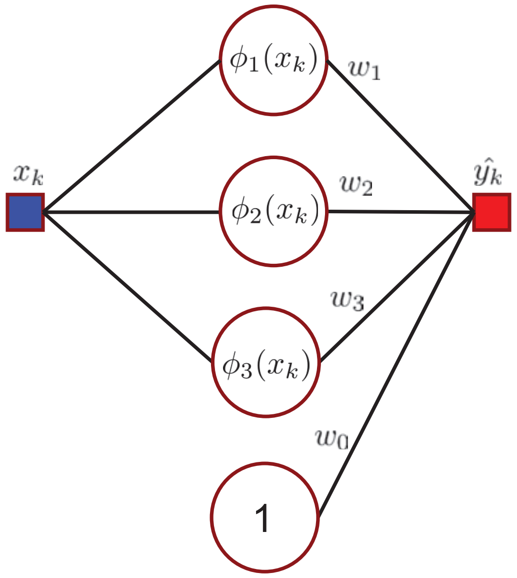
Determining the weights

Gradient descent for weights update: $\mathbf{W}_{(k+1)} = \mathbf{W}_k - \eta \nabla \frac{\partial e_k}{\partial \mathbf{W}_k}$



Defining the mean square error:

$$e_k = \frac{1}{2}[y_k - \hat{y}(x_k, \mathbf{W}_k)]^2 = \frac{1}{2}[y_k - w_0 - \sum_{j=1}^{M} w_j \phi_j(x_k)]^2$$

$$= \frac{1}{2}[y_k - \mathbf{W}_k^T \mathbf{\Phi}_k]^2$$

Computing the gradient: $\frac{\partial e_k}{\partial \mathbf{W}_k} = -[y_k - \mathbf{W}_k^T \mathbf{\Phi}_k]\mathbf{\Phi}_k$

```
for i = 1 : L_iter
    for k = 1 : L_train
        grad = de(k)dw;
        W = W + eta*grad;
    end
    e(i) = mean(e.^2);
end
```

$$\mathbf{W} = [w_0, w_1, ..., w_M]^T \quad \mathbf{\Phi}_k = [1, \phi_1(x_k), ..., \phi_M(x_k)]^T$$

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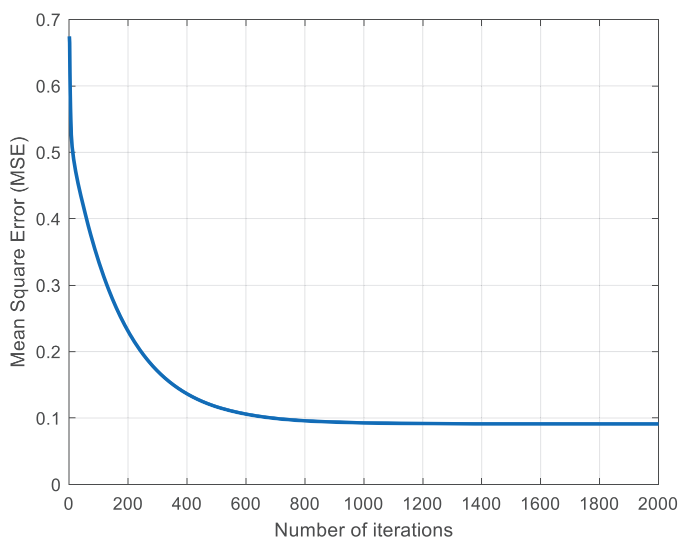
Performance evaluation on training data-set



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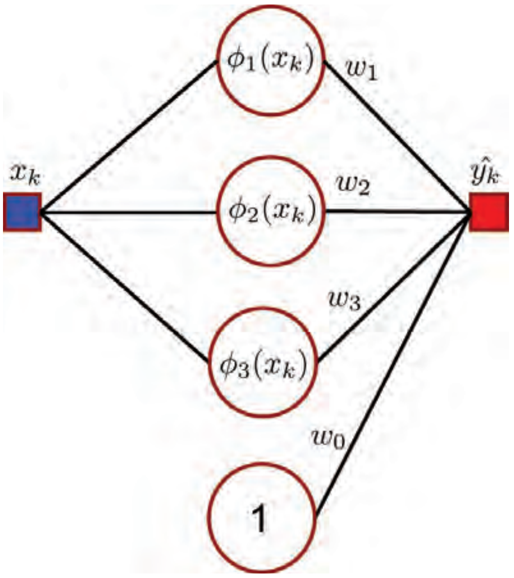
Determining the weights in one step



The output is expressed as:

$$\begin{bmatrix} \hat{y}_1 \\ \hat{y}_2 \\ \cdot \\ \hat{y}_N \end{bmatrix} = \begin{bmatrix} 1 & \phi_1(x_1) & \phi_2(x_1) & \phi_3(x_1) \\ 1 & \phi_1(x_2) & \phi_2(x_2) & \phi_3(x_2) \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \phi_1(x_N) & \phi_2(x_N) & \phi_3(x_N) \end{bmatrix} \begin{bmatrix} w_0 \\ w_1 \\ w_2 \\ w_3 \end{bmatrix}$$

$$\mathbf{Y} = \mathbf{\Phi W}$$

The weights are computed as Moore-Penrose pseudo inverse:

$$\mathbf{W} = \left(\mathbf{\Phi}^T\mathbf{\Phi}\right)^{-1}\mathbf{\Phi}^T\mathbf{Y}$$

If $\mathbf{\Phi}$ is square and invertible:

$$\left(\mathbf{\Phi}^T\mathbf{\Phi}\right)^{-1}\mathbf{\Phi}^T = \mathbf{\Phi}^{-1}$$

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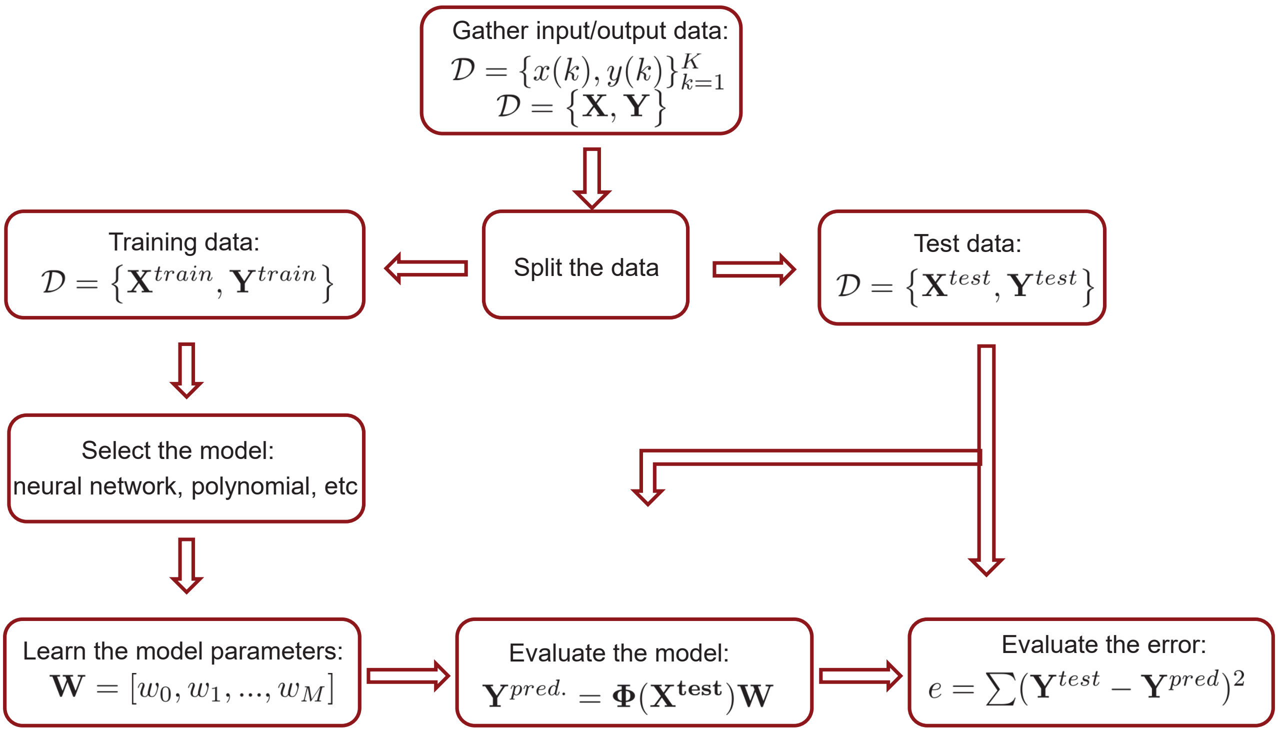

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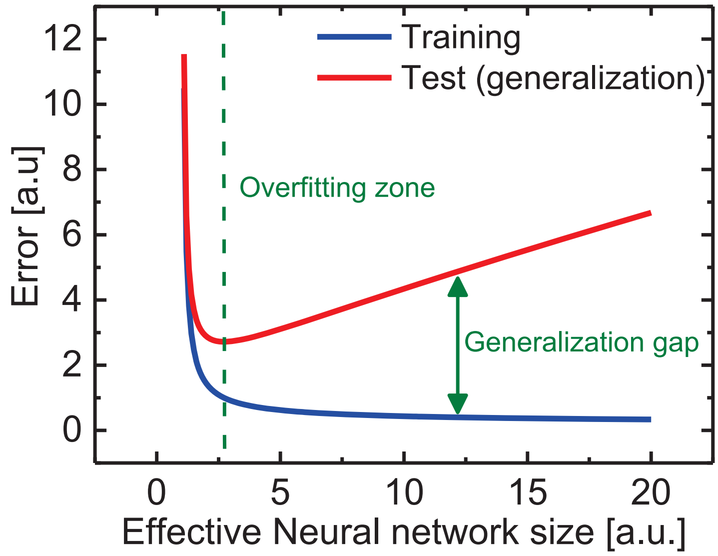
Key performance metric: generalization



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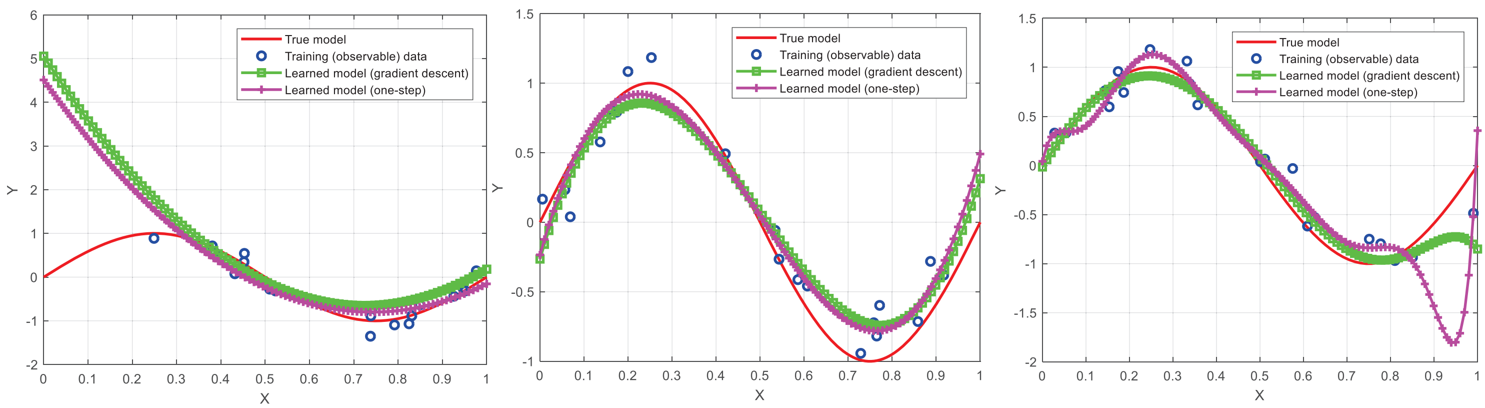
Evaluating the learned the model



Assumed polynomial model order M=2 (too simple model: underfitting)

Assumed polynomial model order M=3 (the right model)

Assumed polynomial model order M=9 (too complex model: overrfitting)

Use learned weights to compute: $\mathbf{Y} = \mathbf{\Phi W}$ where $x \in \{0:1\}$

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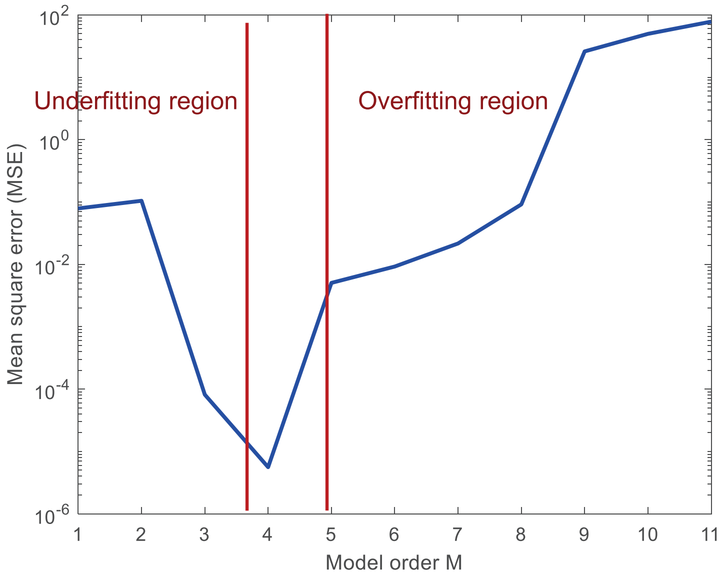
Evaluating different models on test data



$$MSE = \frac{1}{2}\sum_{k=0}^{N}[y_k^{true} - \mathbf{\Phi}(x_k)\mathbf{W}]^2$$

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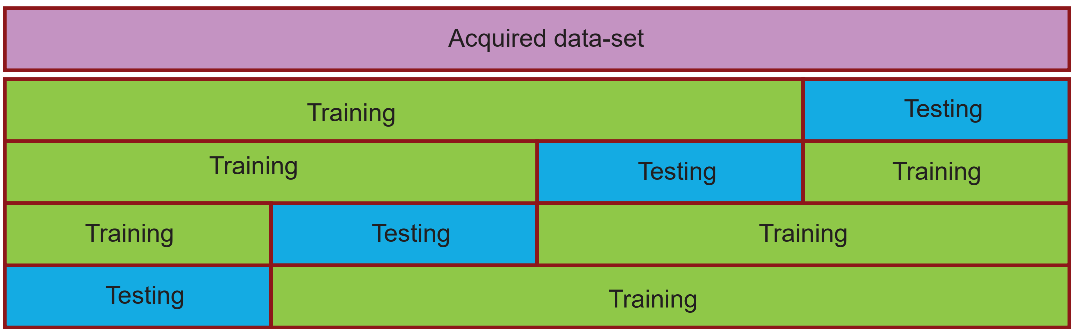
Cross-validation

- Typically, the true mode is unknown
- We only have access to noisy observable data (data set)
- Observable data needs to be used for training and test
- Split the observable data into folds for training and test
- Perform weights estimation (learning) and testing for each fold
- Compute average test error as a function of model size



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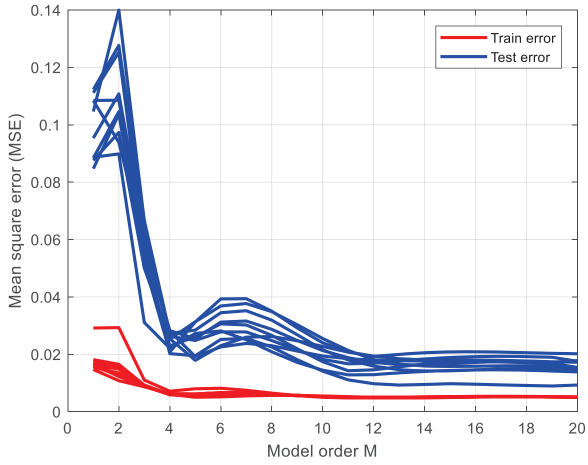
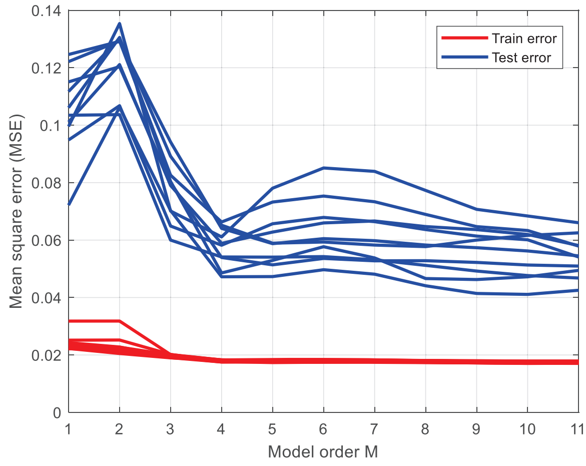
10-fold cross validation



Noise variance 0.0001



Noise variance 0.09

Employ averaging over different test sets to find the model order

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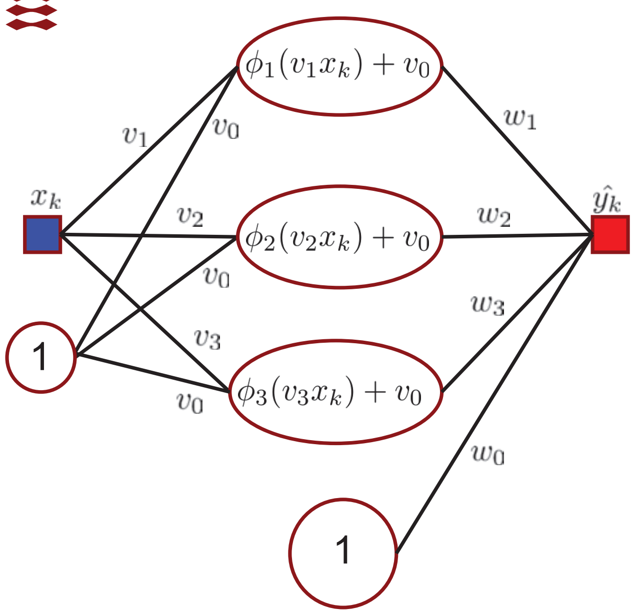
Nonlinear model (neural-network)



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$$\hat{y}(x_k, \mathbf{w}) = w_0 + \sum_{j=1}^{3} w_j \phi_j(v_j x_k + v_0)$$

Weights that need to be learned:

$$\mathbf{W} = [w_0, w_1, ..., w_3]^T$$
$$\mathbf{V} = [v_0, v_1, ..., v_3]^T$$

The problem of determining the weights becomes nonlinear:

$$\mathbf{Y} = \mathbf{\Phi}(\mathbf{V})\mathbf{W}$$

We can no longer perform matrix inversion to find the weights!

Random weight initialization trick

$$\begin{bmatrix} \hat{y}_1 \\ \hat{y}_2 \\ \cdot \\ \hat{y}_N \end{bmatrix} = \begin{bmatrix} 1 & \phi_1(v_1 x_1 + v_0) & \phi_2(v_2 x_1 + v_0) & \phi_3(v_3 x_1 + v_0) \\ 1 & \phi_1(v_1 x_2 + v_0) & \phi_2(v_2 x_2 + v_0) & \phi_3(v_3 x_2 + v_0) \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \phi_1(v_1 x_N + v_0) & \phi_2(v_2 x_N + v_0) & \phi_3(v_3 x_N + v_0) \end{bmatrix} \begin{bmatrix} w_0 \\ w_1 \\ w_2 \\ w_3 \end{bmatrix}$$

Assign random weights to $\mathbf{V} = [v_0, v_1, v_2, v_3]$ by sampling from a normal distribution with variance:

$$\mathbf{V} \sim \mathcal{N}(0, \sigma \mathbf{I})$$

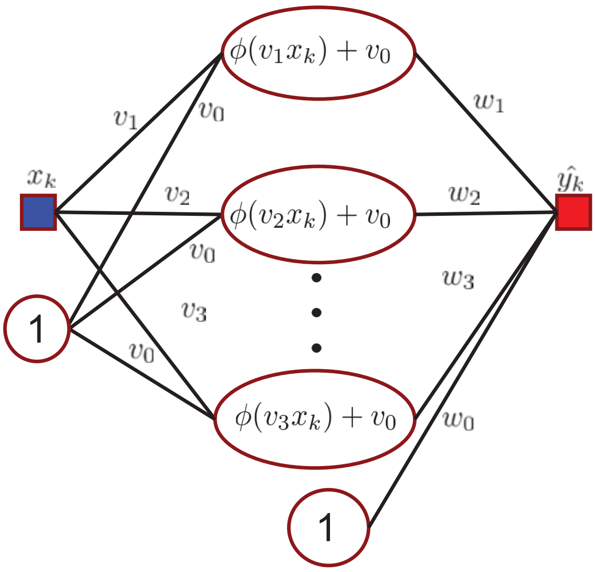
$\mathbf{I} : 3 \times 3$ identity matrix

σ : standard deviation of the weights (tuning parameter)

Finally, we use Moore-Penrose pseudo inverse to compute the outer weights:

$$\mathbf{W} = \left(\mathbf{\Phi}^T \mathbf{\Phi}\right)^{-1} \mathbf{\Phi}^T \mathbf{Y}$$

Typical one-layer neural network architecture



Common approach is to use single type basis function and very their number

Examples of common basis/activation functions

Threshold function:

$$\psi(v_k) = \begin{cases} 1 & : v_k \geq 0 \\ 0 & : v_k < 0 \end{cases}$$

Sign function:

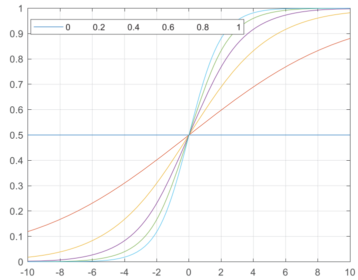
$$\psi(v_k) = \begin{cases} 1 & : v_k \geq 0 \\ -1 & : v_k < 0 \end{cases}$$

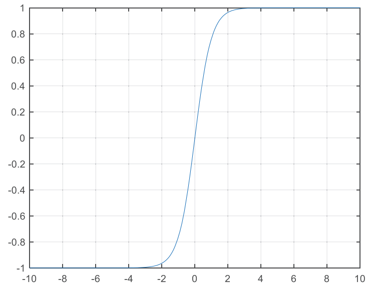
Sigmoid function:

$$\psi(v_k) = \frac{1}{1+\exp(-av_k)}$$

Tangents function:

$$\psi(v_k) = \tanh(v_k)$$





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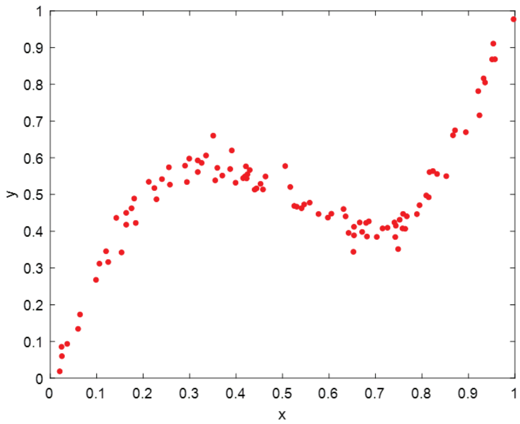
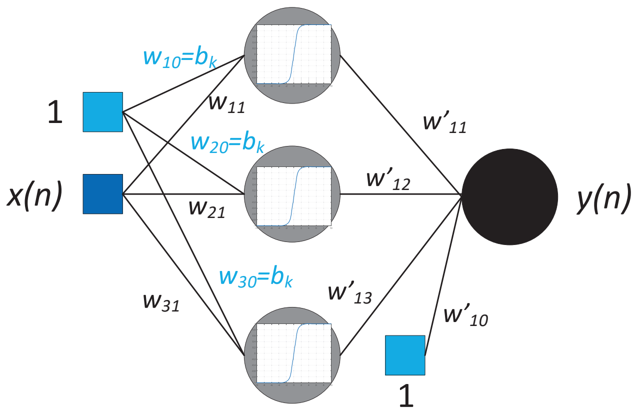
Learn the mapping using neural-network





Objective: learn the coefficients *(central problem in machine learning):*

$$\mathbf{W} = \begin{bmatrix} w_{10} & w_{11} & w'_{10} \\ w_{20} & w_{21} & w'_{11} \\ w_{30} & w_{31} & w'_{12} \\ - & - & w'_{13} \end{bmatrix}$$

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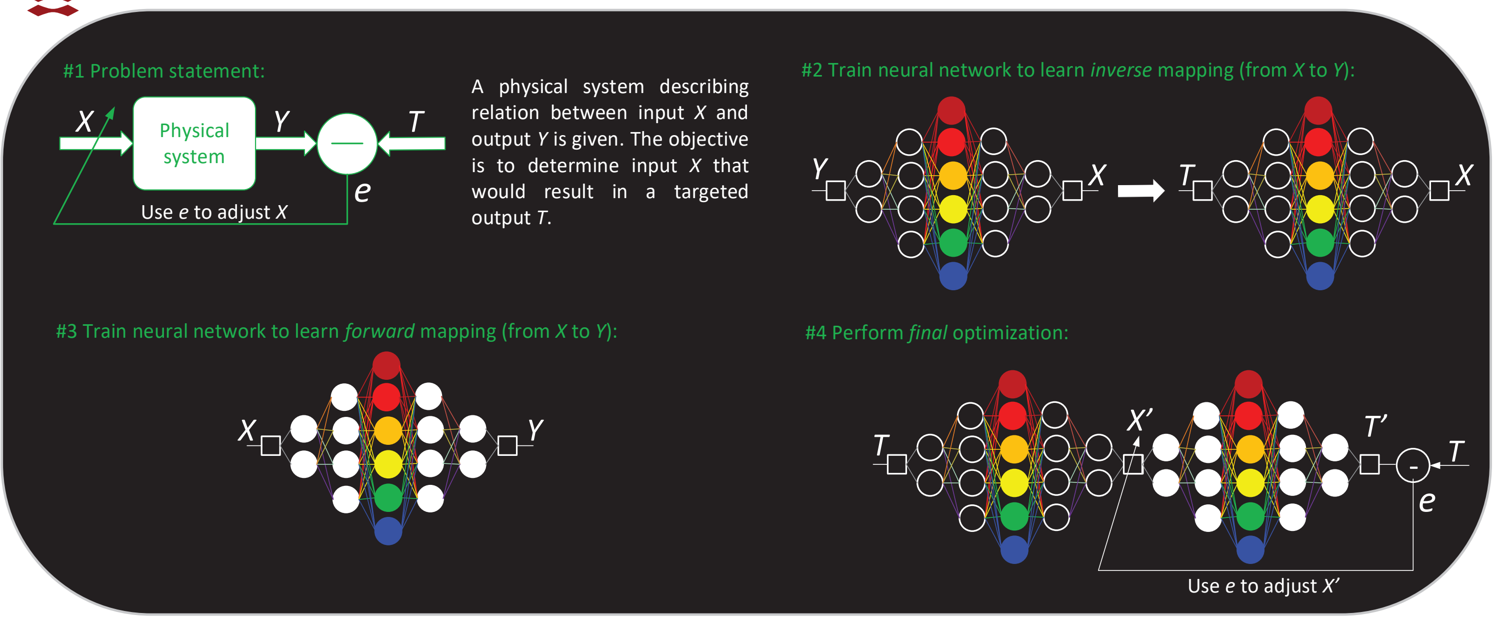
Inverse system learning



[1] D. Zibar et al., "Inverse system design using machine learning: the Raman amplifier case," Journal of Lightwave technology, 2019

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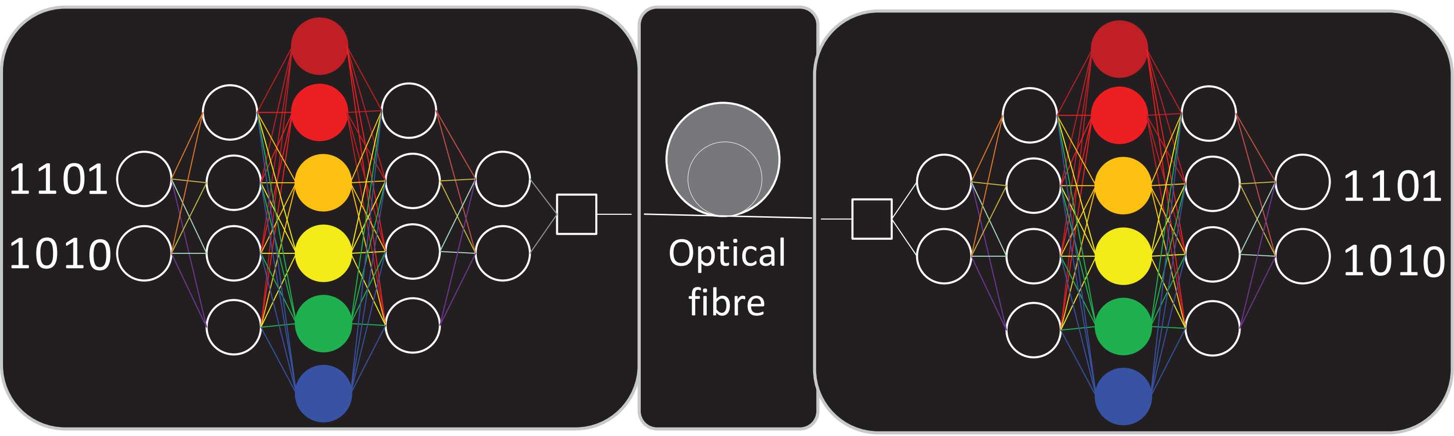
Learning to transmit and receive data over complex channels

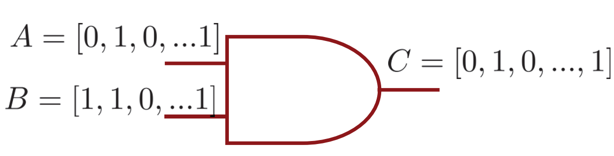


[1] R.Jones, M. Yankov, D. Zibar et al., "End-to-end learning of GMI optimized constellation shapes," ECOC 2019

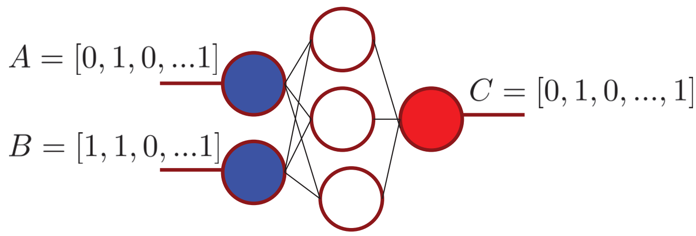
Can we learn mappings between categorical variables?

A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

AND gate

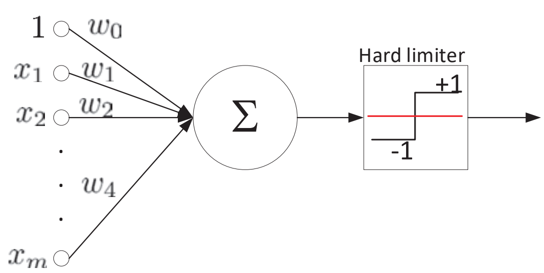


True model



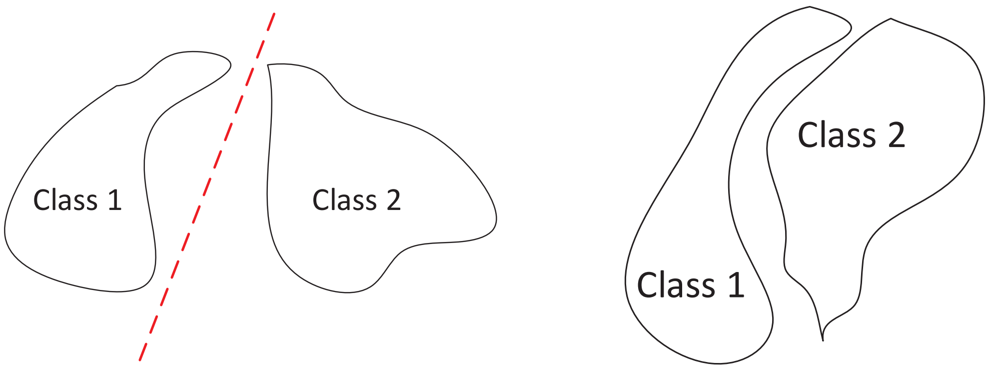
Learned model

Rossenblatt perceptron (simplest neural network)



$$v_k = \sum_{j=0}^{m} w_j x_j = \mathbf{W}^T\mathbf{X}$$

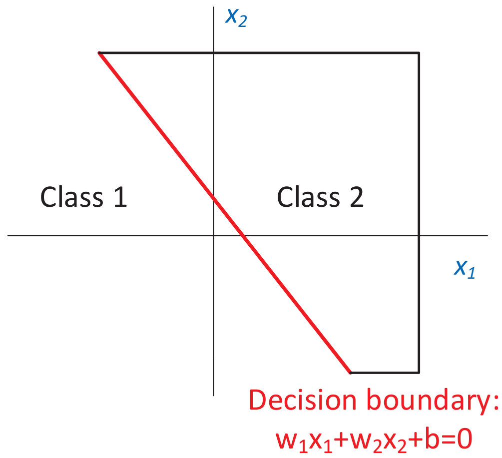
Linearly separable classes



(a) Linearly separable classes (b) Linearly non-separable classes

The perceptron only works for linearly separable classes

Decision boundary



$$v_k = \sum_{j=0}^{m} w_j x_j = \mathbf{w}^T\mathbf{x} = 0$$

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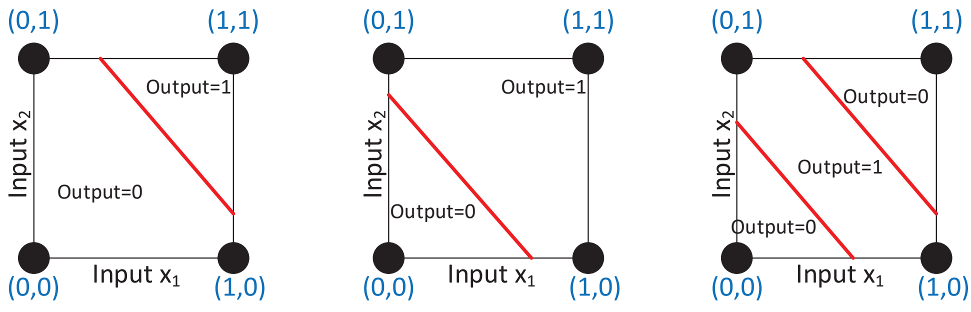
Decision Boundaries (DB)



AND gate *(Linear DB)*

OR gate *(Linear DB)*

XOR gate *(Nonlinear DB)*

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Perceptron learning algorithm

TABLE 1.1 Summary of the Perceptron Convergence Algorithm

Variables and Parameters:

$\mathbf{x}(n)$ = $(m+1)$-by-1 input vector
= $[+1, x_1(n), x_2(n), \ldots, x_m(n)]^T$
$\mathbf{w}(n)$ = $(m+1)$-by-1 weight vector
= $[b, w_1(n), w_2(n), \ldots, w_m(n)]^T$
b = bias
$y(n)$ = actual response (quantized)
$d(n)$ = desired response
η = learning-rate parameter, a positive constant less than unity

1. *Initialization.* Set $\mathbf{w}(0) = \mathbf{0}$. Then perform the following computations for time-step $n = 1, 2, \ldots$.
2. *Activation.* At time-step n, activate the perceptron by applying continuous-valued input vector $\mathbf{x}(n)$ and desired response $d(n)$.
3. *Computation of Actual Response.* Compute the actual response of the perceptron as
$$y(n) = \mathrm{sgn}[\mathbf{w}^T(n)\mathbf{x}(n)]$$
where sgn(·) is the signum function.
4. *Adaptation of Weight Vector.* Update the weight vector of the perceptron to obtain
$$\mathbf{w}(n+1) = \mathbf{w}(n) + \eta[d(n) - y(n)]\mathbf{x}(n)$$
where
$$d(n) = \begin{cases} +1 & \text{if } \mathbf{x}(n) \text{ belongs to class } \mathscr{C}_1 \\ -1 & \text{if } \mathbf{x}(n) \text{ belongs to class } \mathscr{C}_2 \end{cases}$$
5. *Continuation.* Increment time step n by one and go back to step 2.

[1] Simon Haykin, Neural Networks and Learning Machines, pp. 54

Categorical functions learning

A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

AND gate

A	B	C
0	0	0
0	1	1
1	0	1
1	1	1

OR gate

A	B	C
0	0	0
0	1	1
1	0	1
1	1	0

Exclusive OR gate

1. *Specify the length of the training and test data set*
2. *Generate data sets by uniform sampling from one of the tables*
3. *Run the perceptron learning algorithm and learn the weights*
4. *Run the validation on the test data*

In this lecture we have learned….

- What machine learning is
- How to build linear and nonlinear models from data
- Difference between training and test set
- How to estimate the weights for linear and nonlinear models
  – Gradient descent
  – Matrix inversion
- How to evaluate learned model
- Rosenblatt perceptron
- How to learn logical gates

Application of machine learning techniques to optical communications

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Abstract

In this article, applications of machine learning to programmable ultra-wideband optical amplifier design, geometrical shaping and laser phase noise measurement are introduced and demonstrated. The focus of the lecture is on deep neural networks and Bayesian estimation.

Author's biography

Darko Zibar is Professor at the Department of Photonics Engineering, Technical University of Denmark and the group leader of Machine Learning in Photonics Systems (M-LiPS) group. He received M.Sc. degree in telecommunication and the Ph.D. degree in optical communications from the Technical University of Denmark, in 2004 and 2007, respectively. His research efforts are currently focused on the application of machine learning techniques to advance classical and quantum optical communication and measurement systems. Some of his major scientific contributions include: record capacity hybrid optical-wireless link (2011), record sensitive optical phase noise measurement technique that approaches the quantum limit (2019) and design of programmable ultrawide band arbitrary gain Raman amplifier (2020). He is a recipient of European Research Council (ERC) Consolidator Grant (2017) and Alexander von Humboldt Bessel Research Award (2022). Finally, he was a part of the team that won the HORIZON 2020 prize for breaking the optical transmission barriers (2016).

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Application of machine learning in optical communication systems

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John E. Bowers

Nokia Bell Labs, Germany
Henning Bülow, Vahid Aref, Roman Dischler

Aston University, UK
Sergei Turitsyn, Wladek Forysiak, Md Asif Iqbal, Morteza Kamalian, Lukasz Krzczanowicz

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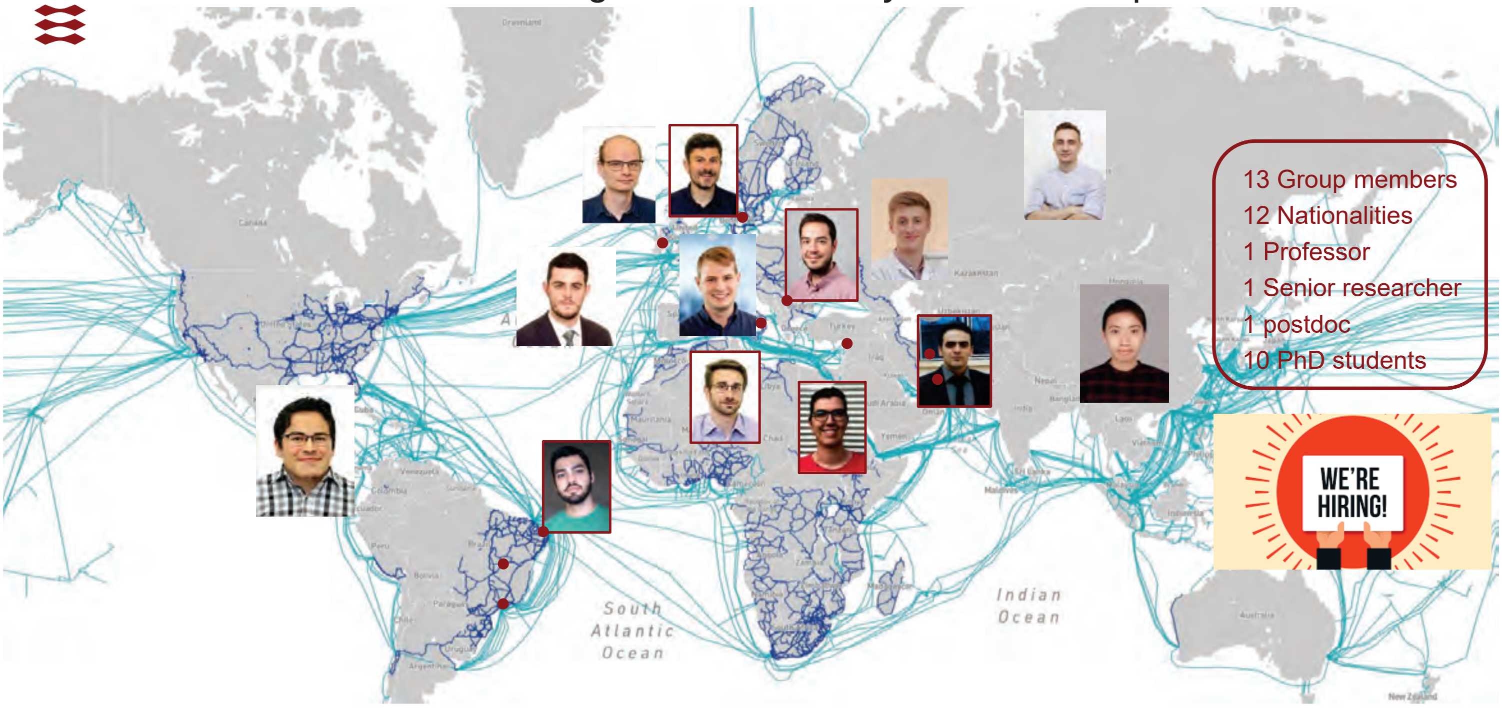
Machine Learning in Photonic Systems Group



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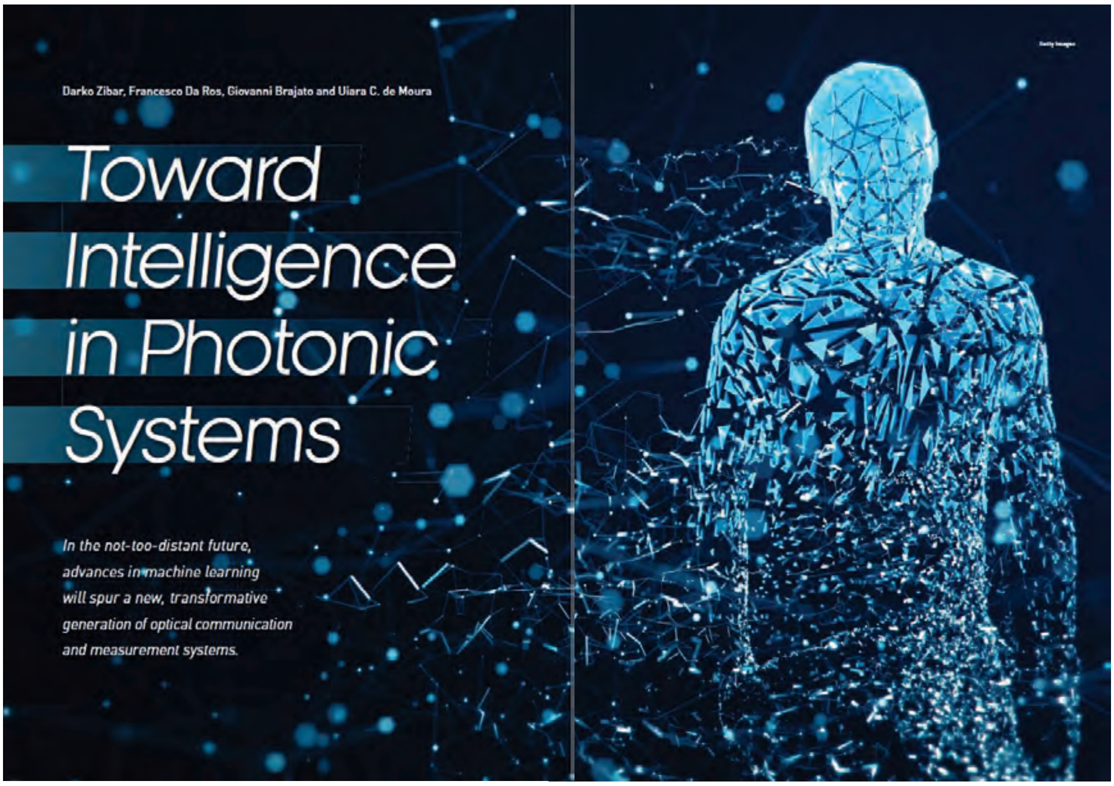

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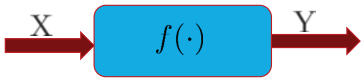
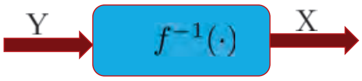
Where does machine learning excel?

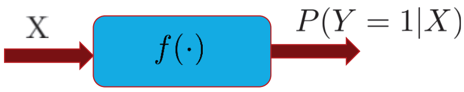
- Learning complex **direct** mappings:



- Learning complex **inverse** mappings:



- Learning **decision rules** for complex mappings:



Use neural networks to learn $f(\cdot)$ and $f^{-1}(\cdot)$

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Problems that could benefit from ML

- Communication over the nonlinear fiber-optic channel:
  - Channel highly complex
  - Capacity **unknown**?
  - Optimum receiver architecture **unknown**
  - Optimum modulation and pulse-shapes **unknown**
- Optical amplifiers for multiband-wavelength and SDM systems:
  - Complex relation between pumps and gain
  - Optimization of pump powers and wavelengths for target gain profiles
  - Optimization of pump powers and wavelengths for target mode dependent
- Design of optical components (inverse system design):
  - Given laser bandwidth and noise find the physical parameters
  - Given modulator BW find the physical parameters
  - Instead of running time-consuming simulation build fast ML based models
- Noise characterization of lasers and frequency combs:
  - Amplitude and phase tracking at the quantum limit
  - Extraction of noise correlation matrices, e.e amplitude, phase, amplitude-phase
  - Macroscopic comb parameters, i.e. timing jitter, amplitude jitter, carrier envelope offset

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Research topics and collaborations

- Machine learning enabled ultra-wideband amplifier design
- Unifying framework for lasers and frequency combs noise characterization
- Machine learning techniques for communicate over complex channels
- Optical technologies to accelerate AI
- Quantum phase tracking and communication
- Highly-sensitive fiber based sensing systems

CHALMERS

Technische Universität München

POLITECNICO DI TORINO

MenloSystems

Infinera

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

NKT Photonics the power of light

Aston University Engineering & Applied Science

NICT National Institute of Information and Communications Technology

NOKIA Bell Labs

DTU Compute Institut for Matematik og Computer Science

DTU Physics Department of Physics

Friedrich-Alexander-Universität Erlangen-Nürnberg

MAX PLANCK INSTITUTE for the science of light

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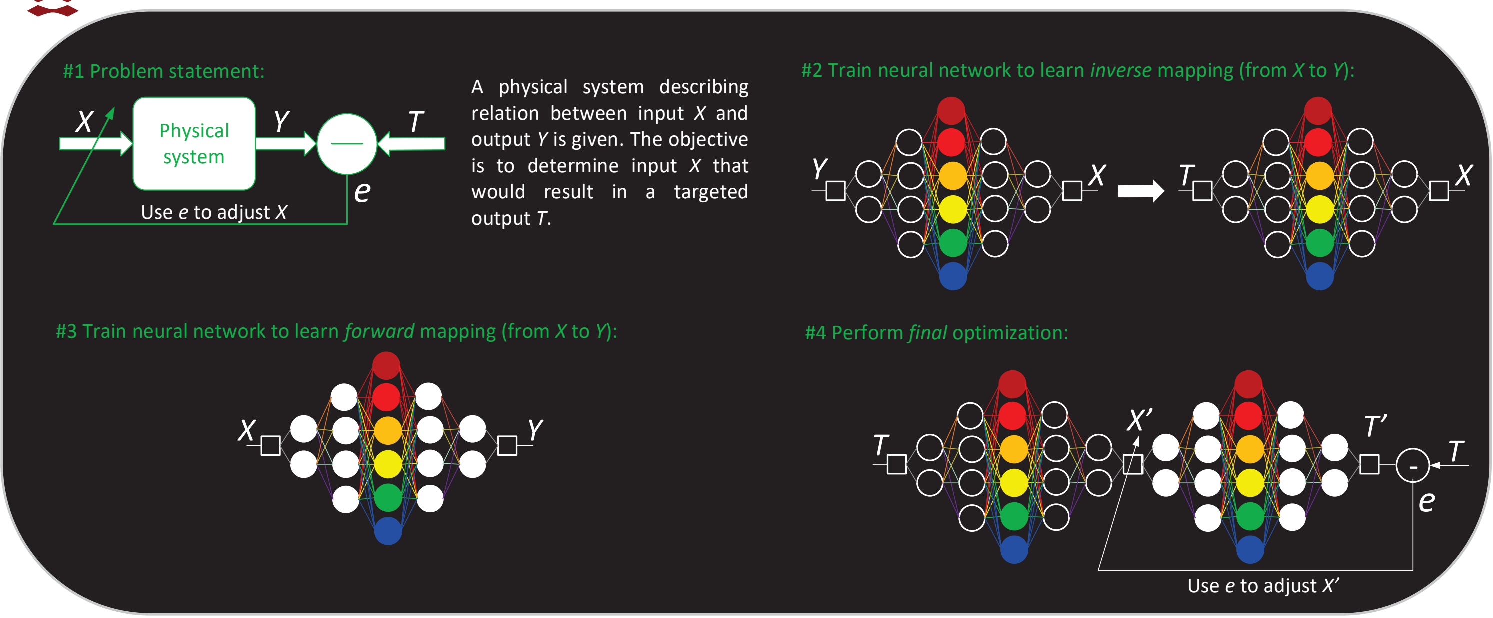
Inverse system learning



[1] D. Zibar et al., "Inverse system design using machine learning: the Raman amplifier case," Journal of Lightwave technology, 2019

[2] U. C. de Moura et al., "Multi-band programmable Raman amplifier," Journal of Lightwave technology, 2020

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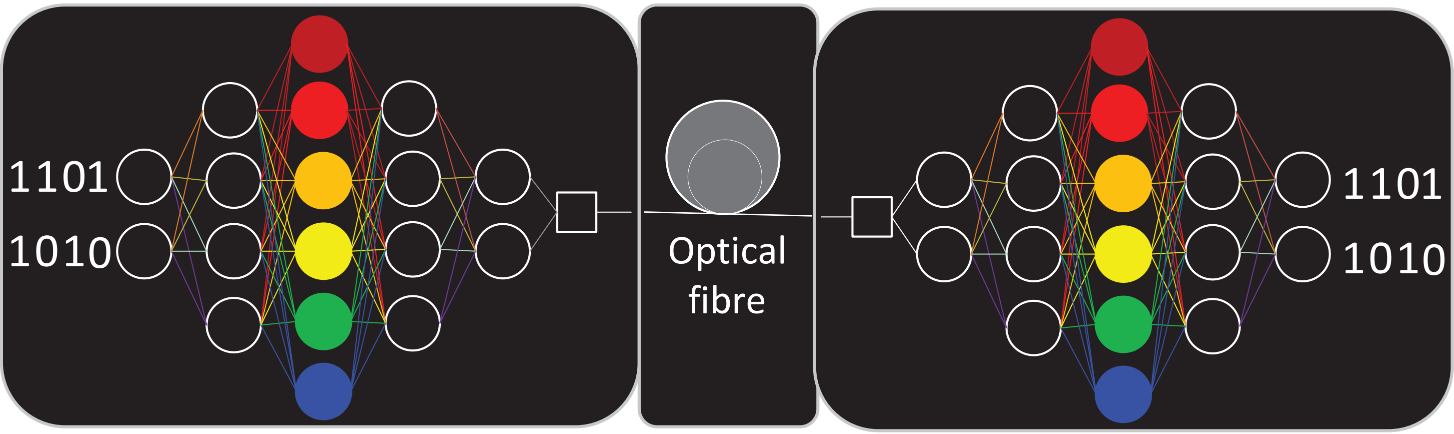
Learning to communicate over complex channels



[1] R. Jones, et al., ECOC 2018
[2] R. Jones, et al., ECOC 2019
[3] S. Gaiarin et al., JLT, 2020
[4] O. Jovanovic et al., et al, JLT 2021

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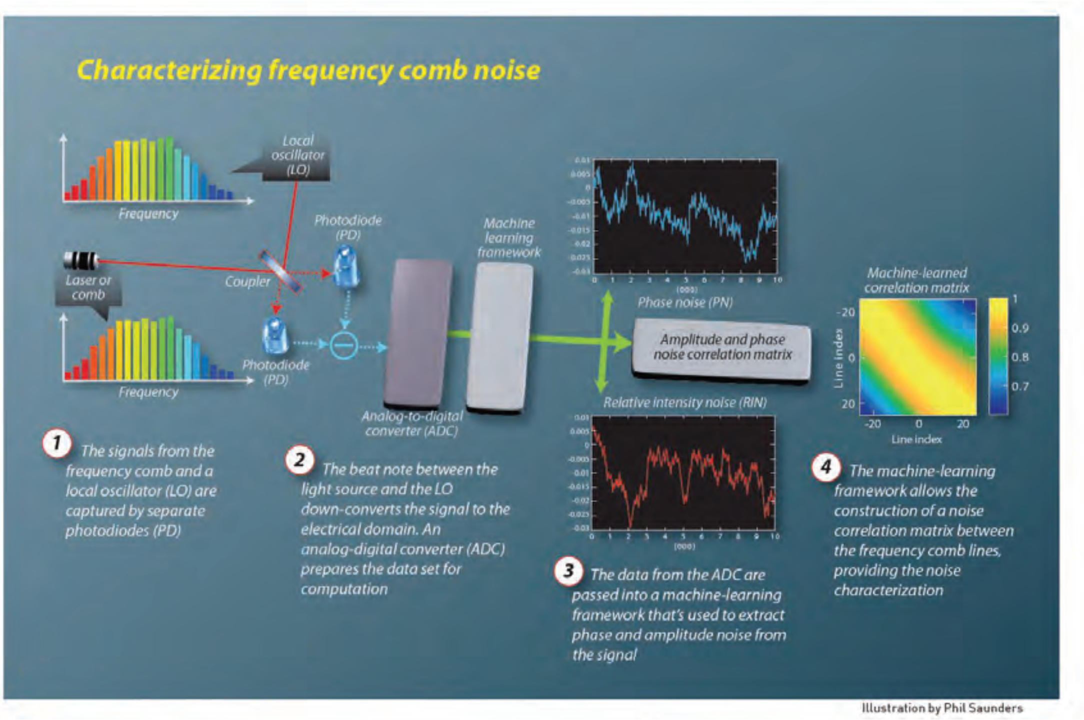

[1] D. Zibar et al., PTL 2019
[2] G. Brajatto et al, Optics Express, 2020

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State-of-the-art

D. Zibar et al., Nature Photonics, (11) 749-751, 2017

New topics anno 2020-2021:

- Photonic reservoir computing[1]
- Optical amplifier and laser design[2-3]
- End-to-end learning[4]
- Back-propagation learning[5]
- Optical network optimization[6-7]
- Frequency comb noise characetrization[8]
- Photonic component design

[1] S. Ranzini, "Tuneable optoelectronic..." JSTQE 2020
[2] D. Zibar, "Inverse system design...," JLT 2019
[3] Z. Ma, "Paremeter extraction and inverse," Optics Express 2020
[3] Karanov, "End-to-end deep learning...", JLT 2018
[4] C. Hager, "Revisiting multi-step...," ECOC 19
[5] F. Musemechi, "An overview on...," IEEE Comm. survey, 2019
[6] F. N. Khan, "An optical communication persp...," JLT 2019
[7] G. Brajato, "Bayesian filtering...," Optics Express, 2020
[8] U. C. de Moura, "Multi-band optical program. Amplifier," JLT 2020
[9] K. Kojima, "Inverse Design of Nanophotonic Devices...", OFC 2020
[10] G. Genty, "Machine learning in ultrafast photonics," Nat. Phot., 2020

Will machine learning be a *game changer*?

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Research Highlights (2019-2021)

- **Record -sensitive and -accurate optical phase measurement[1,2] (quantum limited operation)**
  – Identification of fundamental laser linewidth
  – Identification of frequency comb noise sources
  – Optimum phase measurement in the presence of amplifier noise

- **Machine learning enabled ultra-wideband Raman amplifiers[3,4,5,6]**
  – Arbitrary gain profiles in S-C-L band
  – *Gain and power profile shaping in distance and frequency*
  – Noise figure prediction of Raman amplifiers

- **Learning optimum transmitter and receivers architectures[7,8,9]**
  – Channel tailored constellation
  – SNR and linewidth robust constellation
  – Equalization of IM/DD using reservoir computing

1. *D. Zibar et al., Optica, 2021*
2. *G. Brajato et al. Opt. Express, 2020*
3. *D. Zibar, J. Ligtwave Technol., 2020 (top cited JLT paper in 2020)*
4. *M. Soltani, Optics Letters, 2021*
5. *U. de Moura, J. Lightwave Technol., 2020*
6. *U. de Moura, Optics Letters, 2021*
7. *R. Jones et al, ECOC 2019*
8. *O. Jovanovic et al., sub to JLT, 2021*
9. *F. Da Ros, IEEE J. Select. Topics Quant. El. 2020*

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Challenges to be addressed

- Fields focuses on the experimental demonstrations
- ML benefits on experimental data should be ideally shown
- Noise in experimental set-ups (non Gaussian, non additive)
- Experimental-set ups are prone drifts and fluctuations
- Automatizing experimental-set ups for training data acquisition (noise, drift,)
- Training of NNs using gradients computation - challenging in experimental environments
- Deep understanding of statistics, linear algebra, optimization and experimental set-up debugging necessary not to end in pitfalls

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Application of multi-layer neural networks for design of Raman amplifiers

[1] D. Zibar, A. M. Rosa Brusin, U. C. de Moura, F. Da Ros, V. Curri, Andrea Carena, "Inverse system design using machine learning: The Raman amplifier case," Journal of Lightwave Technology, vol. 38, no. 4, 2020

[2] M. Soltani, F. Da Ros, A. Carena, D. Zibar, "Inverse design of a Raman amplifier in frequency and distance domains using convolutional neural networks," Optics Letters, vol. 46, no. 11, 2021

[3] A. M. Rosa Brusin, V. Curri, D. Zibar, and A. Carena, "An ultrafast method for gain and noise prediction of Raman amplifiers," in proceedings of European Conference on Optical Communication, ECOC, 2019

[4] U. C. de Moura, F. Da Ros, A. M. Rosa Brusin, A. Carena, and D. Zibar, "Experimental demonstration of arbitrary Raman gain–profile designs using machine learning, " in Optical Fiber Communication Conference (OFC) 2019, OSA Technical Digest (Optical Society of America), 2020

[5] U. C. de Moura, Md A. Iqbal, M. Kamalian, L. Krzczanowicz, F. Da Ros, A. M. Rosa Brusin, A. Carena, W. Forysiak, S. Turitsyn and D. Zibar, "Multi–band programmable gain Raman amplifier," Journal of Lightwave Technology, 2020

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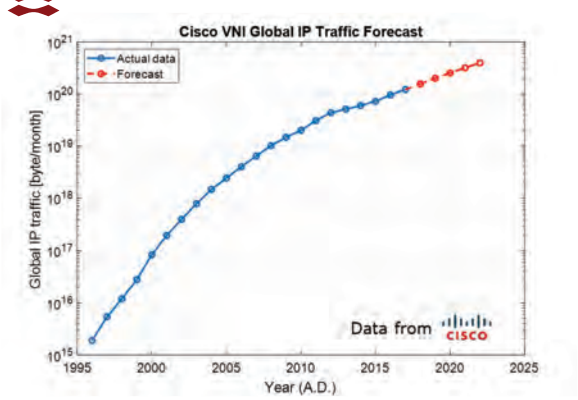
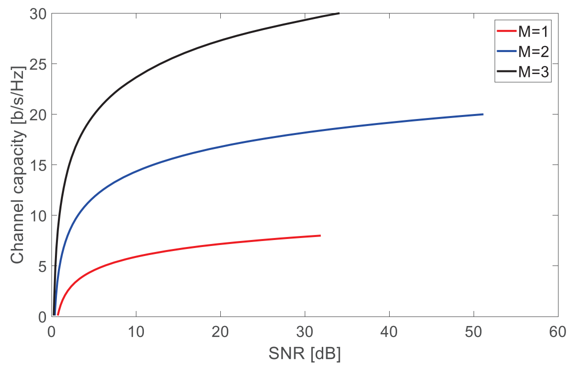
Increasing the bandwidth of optical systems



(a) Future data projection



(b) Channel capacity

$$\frac{C}{B} = M \log\left(1 + \frac{E_b}{N_0}\frac{C}{B}\right)$$ [b/s/Hz]

C : capacity
M : spatial paths
B : bandwidth
$\frac{E_b}{N_0}$: signal-to-noise ratio

Significantly higher gains by increasing spatial paths than SNR

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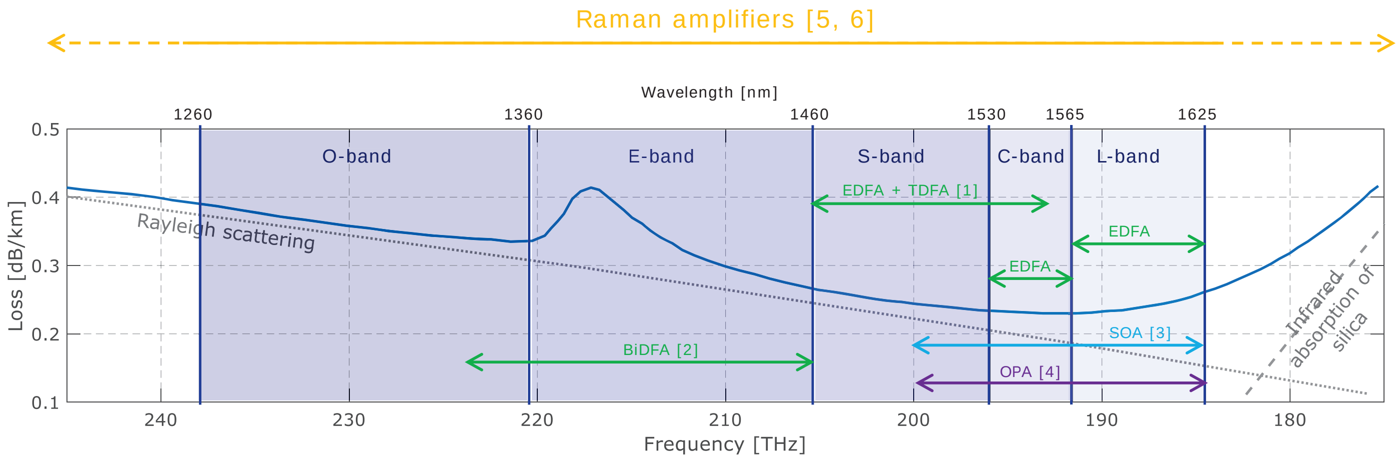
Ultra-wideband optical amplification



xDFA: doped fiber amplifier

SOA: semiconductor optical amplifier

OPA: optical parametric amplifier

[1] T. Sakamoto, JLT, vol. 24, no. 6, 2006
[2] Y. Wang, OFC 2020, Th4B.1
[3] J. Renaudier, ECOC, 2018
[4] T. Kobayashi, OFC 2020, Th4C.7
[5] J. Chen, IEEE Photonics Journal, vol. 10, 2018
[6] M. A. Iqbal, OFC 2020, W3E.4

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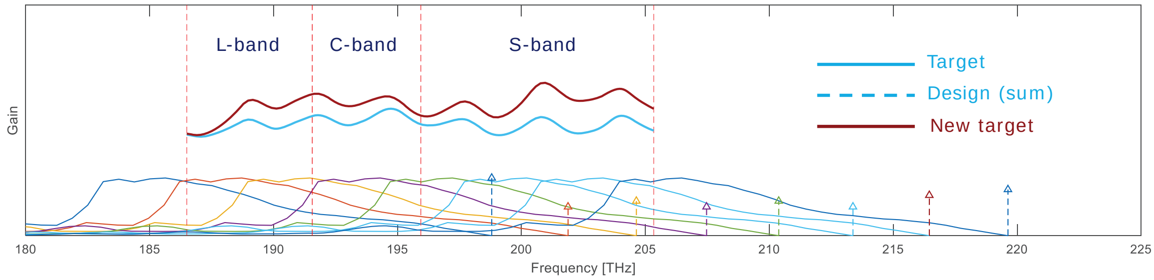
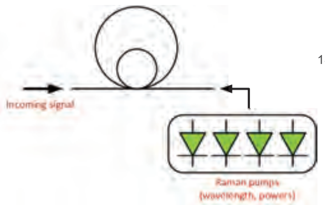
Arbitrary gain Raman amplifiers

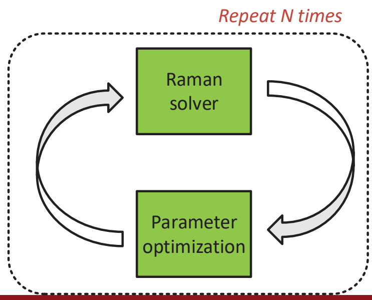




$$\frac{dP_s}{dz} = -\alpha_s P_s + C_R(\lambda_s, \lambda_p)\left[P_p^+ + P_p^-\right] P_s \quad (1)$$

$$\pm\frac{dP_p^\pm}{dz} = -\alpha_p P_p^\pm - \left(\frac{\lambda_s}{\lambda_p}\right) C_R(\lambda_s, \lambda_p)\, P_s\, P_p^\pm \quad (2)$$

$$\pm\frac{dP_A^\pm}{dz} = -\alpha_A P_A^\pm + C_R(\lambda_A, \lambda_p) P_p P_A^\pm + C_R(\lambda_A, \lambda_p)[1+\eta(T)] h\nu_A B_{ref} P_p \quad (3)$$



- High complexity due to Raman solver
- Long convergence time
- Restart optimization for new gain profile
- Rely on evolutional algorithms

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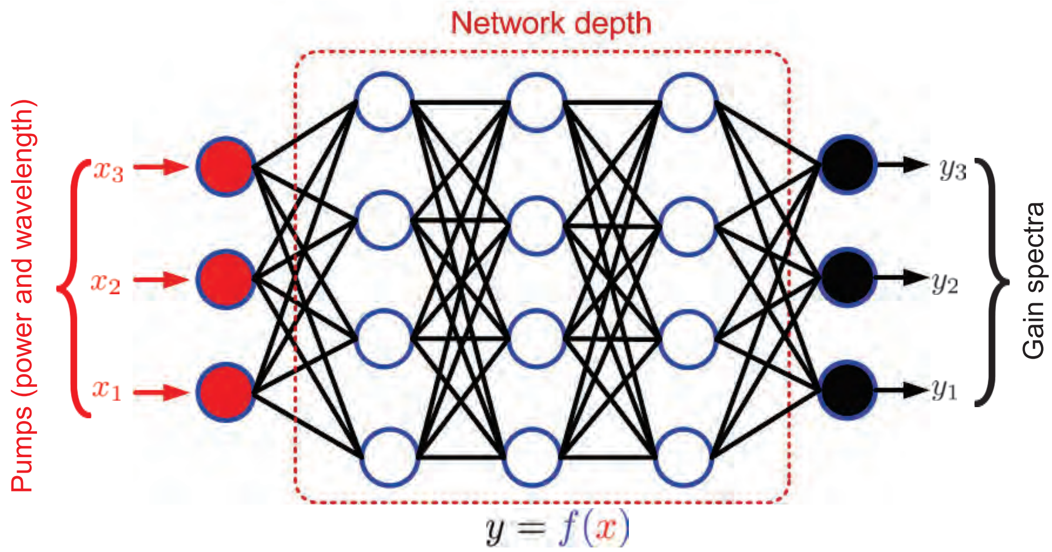
Approximating Raman amplifier with NN



Neural network learns forward mapping, $f(\cdot)$, using training data and perform predictions for *new input* data: $y_{new} = f(x_{new})$

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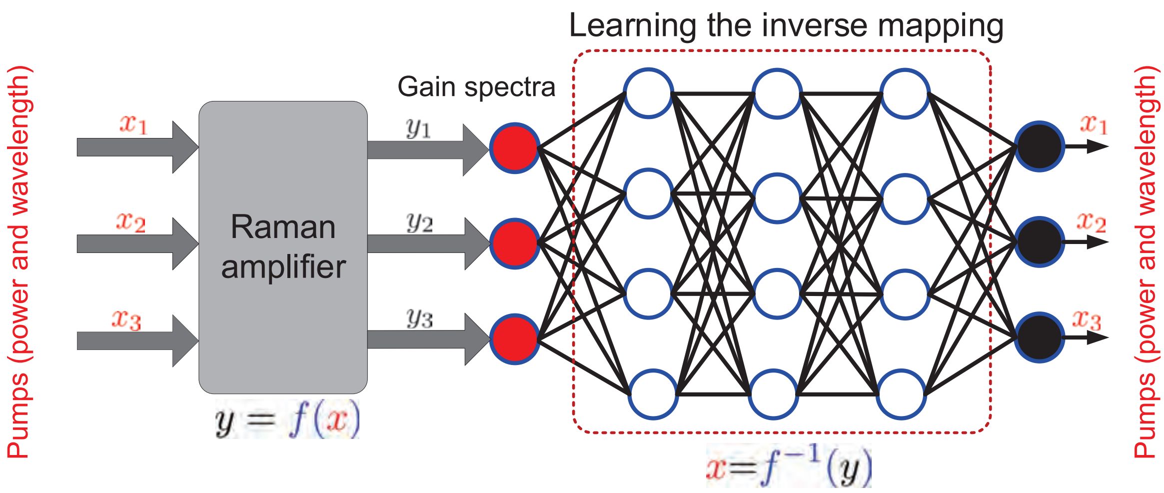
Learning inverse mapping



Learning the inverse mapping allows for designing arbitrary gain profile

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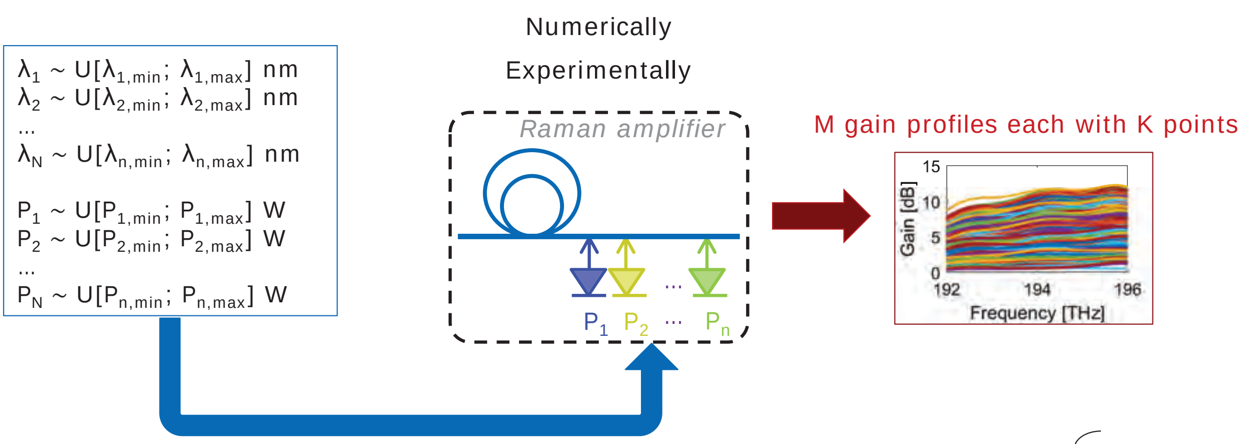
Building the model from the data

Given N pumps generate M gain profiles



Data-set ⇨ $\mathcal{D} = \{(\lambda_1^i, \lambda_2^i, \dots, \lambda_N^i, P_1^i, P_2^i, \dots, P_N^i, G_1^i, G_2^i, \dots, G_K^i) | i = 1, \dots, M\}$ Training / Validation

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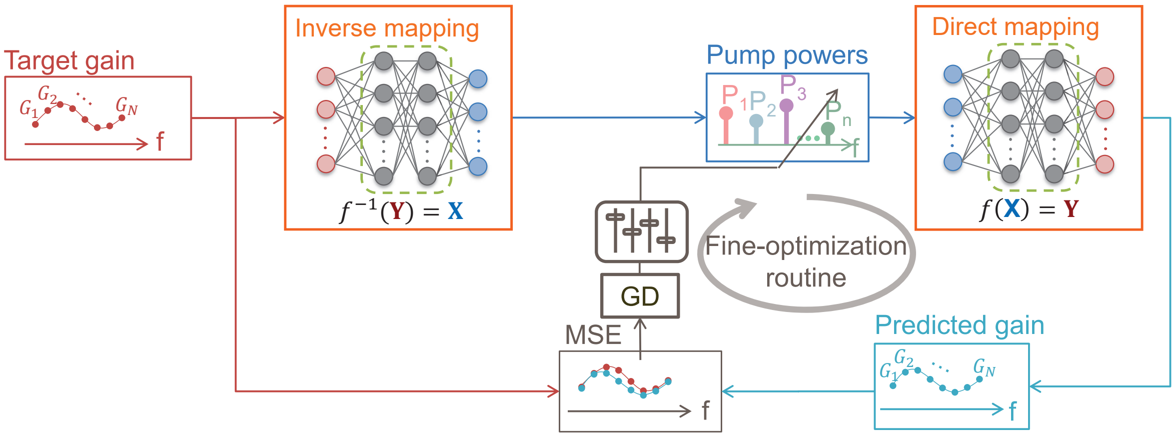
The machine learning framework



MSE: mean squared error

GD: gradient descent

D. Zibar, J. Lightwave Technol. **38**(4), 736–753 (2019)

U. de Moura, J. Lightwave Technol. **39**(4),1162–1170 (2021)

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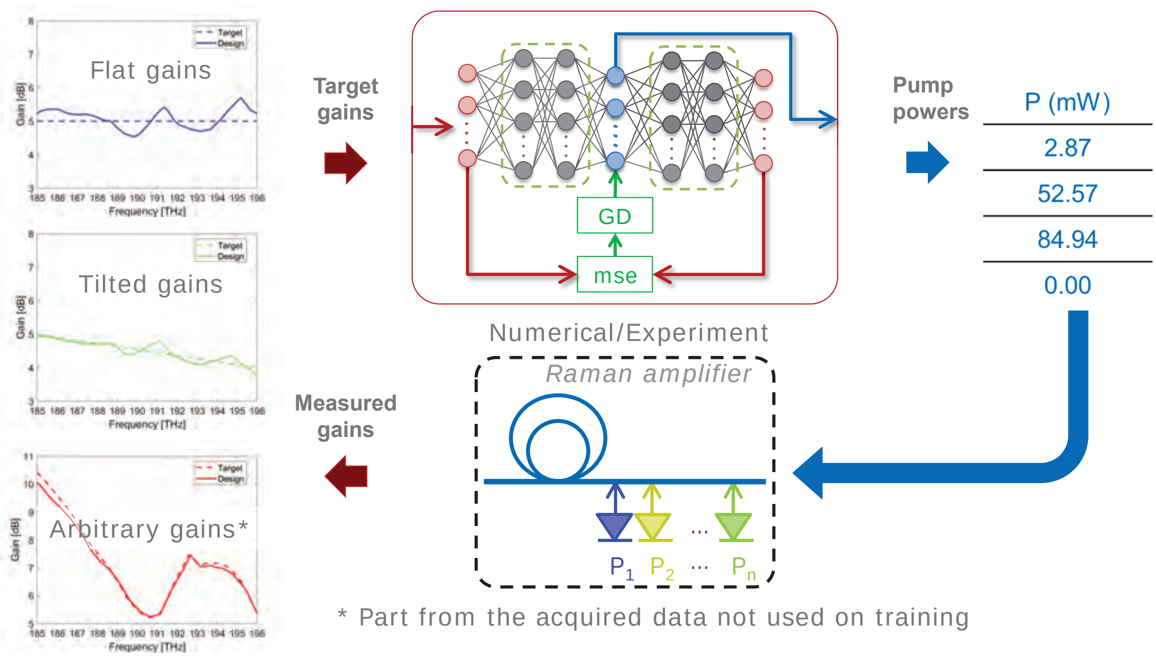
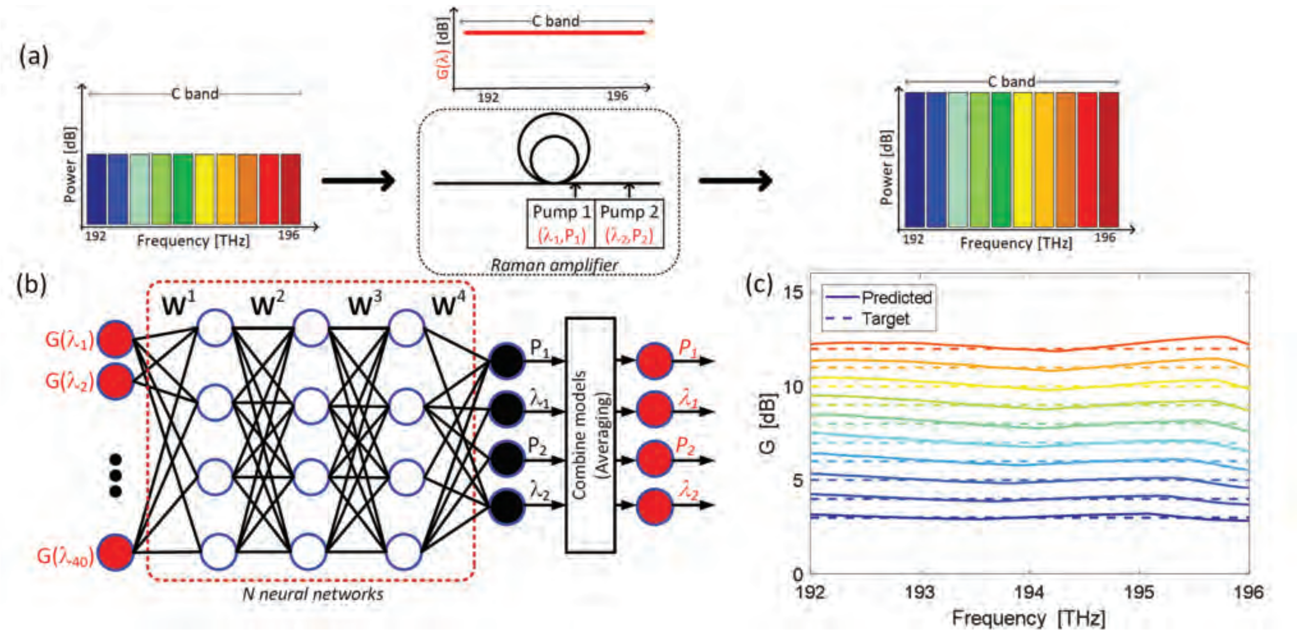
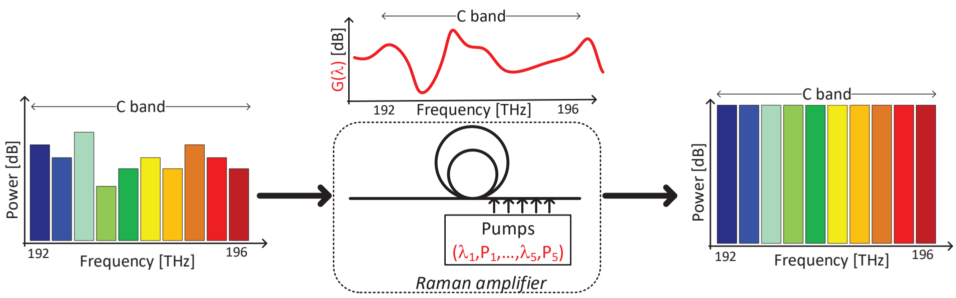
Experimental validation of the learned model

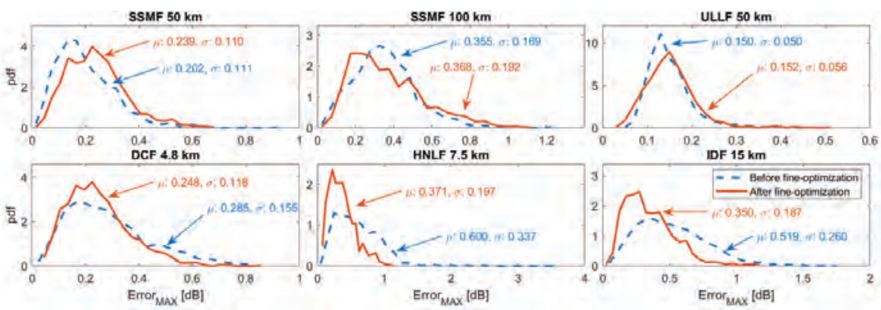


Flat gain profile design (C band)



Arbitrary gain profile design (C band)





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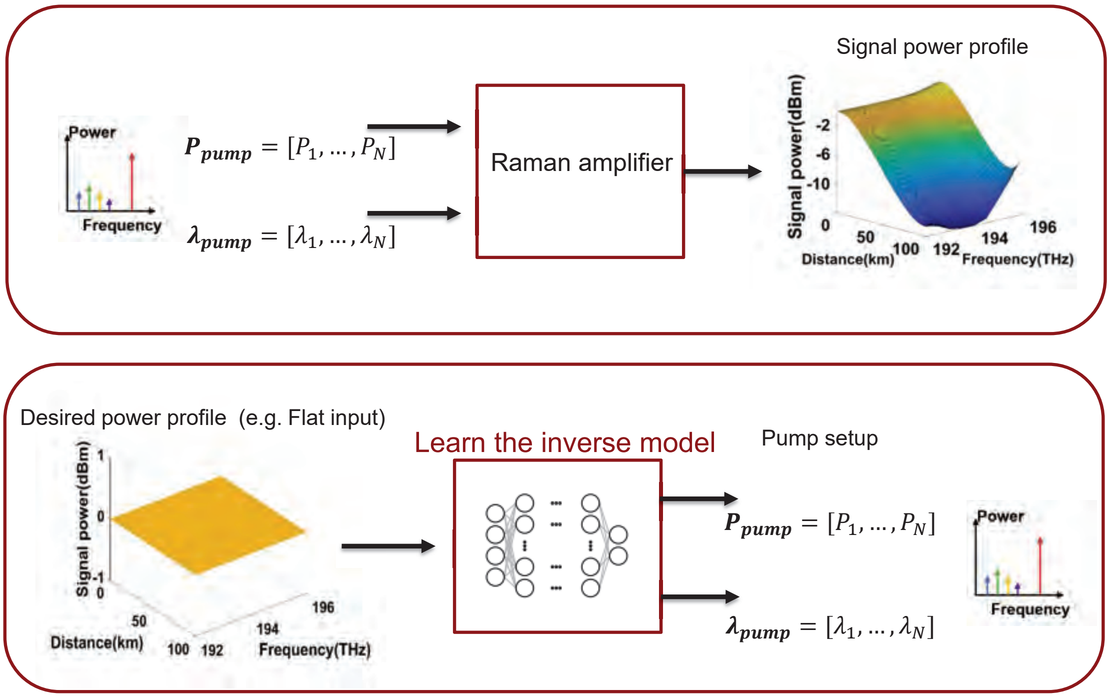
Arbitrary distance and gain profile



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Power profile and gain shaping

Quasi-lossless transmission with uniform distribution of power resulting in:

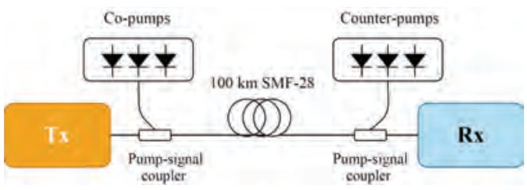
- Minimizing the amplified spontaneous emission (ASE) noise level
- Requirement for Nonlinear Fourier Transform (NFT) - NFT assumes lossless transmission

Symmetric power distribution:

- A requirement for nonlinearity mitigation using optical phase conjugation (OPC)

Bi-directional Raman amplifier

Direct model (Raman Solver)
Computationally demanding

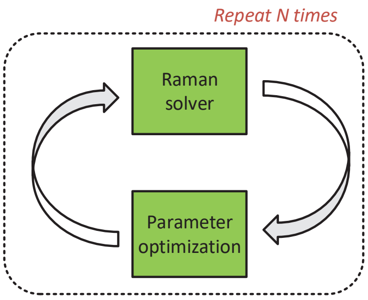


$$\frac{dP_s}{dz} = g_R P_p P_s - \alpha_s P_s,$$

$$\pm\frac{dP_p}{dz} = -\frac{\omega_p}{\omega_s} g_R P_p P_s - \alpha_p P_p,$$

Inverse model

No closed-form solution!



- Long convergence time
- Restart optimization for new gain profile
- Usually based on evolutional algorithms

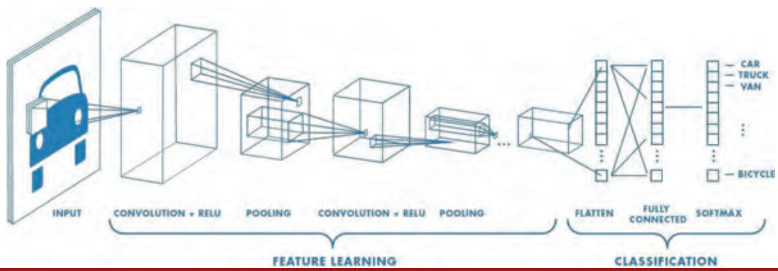
Network architecture?

Using State-of-the-art networks :

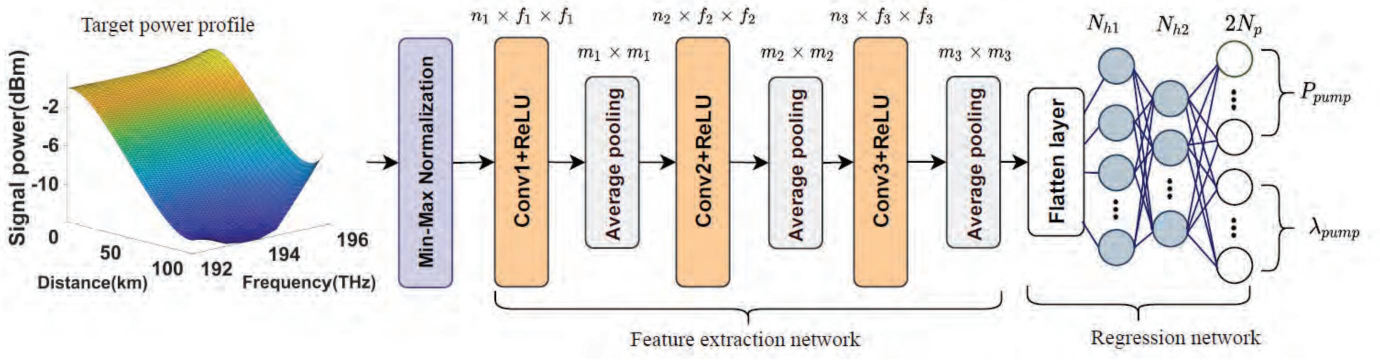
- Requires vectorising the input without removing the spatial relevancy
- Number of training parameters goes extremely high
- High training time
- Overfitting

Using Convolutional Neural Networks (CNNs)

- 2D power profile is resembled as an image
- Extracts the spatial information and decrease the redundancy
- Higher training speed and Extremely lower number of parameters

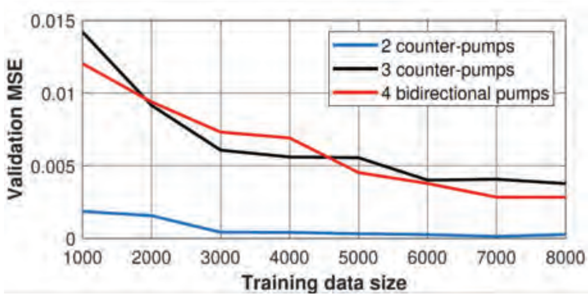


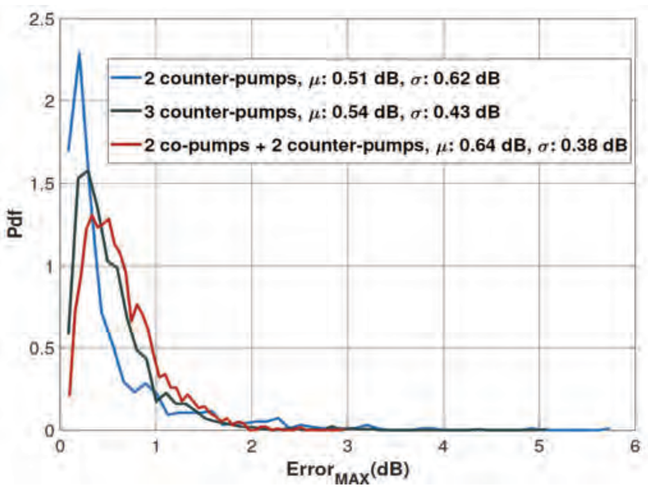
Proposed network for inverse design



M. Soltani, Opt. Lett. 46, 2650-2653 (2021).

Simulation results - 1st order pumping test results

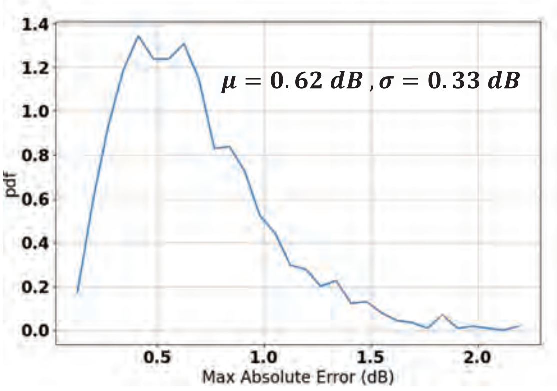




Simulation results – 2nd order pumping test results

Pump parameters for 8 pumps case

Pumps	Power range	Wavelengths (fixed)
2nd order co-pump	0.2 – 1.2 W	1366 nm
2nd order counter-pump	0.2 – 1.2 W	1366 nm
3 1st co-pumps	5 – 150 mW	[1425, 1455, 1475]
3 1st counter-pumps	5 – 150 mW	[1425, 1455, 1475]



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Conclusion and outlook

- Multi-layer and convolutional neural networks can learn Raman amplifier direct and inverse mappings
- Learned mappings useful for optimization of pump powers and wavelengths for:
  - *Generation of arbitrary gain profiles*
  - *Generation of arbitrary power and gain profiles*
- Maximization of information rate for ultra-wideband optical networks requires *power* and *gain* optimization
- The framework brings significant advantages for *complex* experimental optimization procedures
- Machine-learning enabled inverse system design relevant for a variety of problems in photonics

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Unifying framework for noise characterization of lasers and frequency combs

[1] D. Zibar et al., "Ultra-sensitive phase and frequency noise measurement technique using Bayesian filtering," Photonics Technology Letters, 2019 (invited paper)

[2] D. Zibar et al., "Towards intelligence in photonic systems," Optics & Photonics News, 2020

[3] G. Brajato et al., "Bayesian filtering framework for noise characterization of frequency combs," Optics Express 2020

[4] H. M. Chin et al. "Machine learning aided carrier recovery in quantum key distribution," npj Qunatum Inf. 2020

[5] N. Von Bandel et al., "Time-dependent laser linewidth: beat-note digital acquisition," Optics Express, 2016

[6] X. Xie et al., "Phase noise characterization of sub-hertz linewidth lasers via digital cross correlation," Opt. Lett. 2017

[7] D. Zibar et al., "Optimum phase measurement in the presence of amplifier noise," Optica 2021 (https://arxiv.org/abs/2106.03577)

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Research question to be answered

What is the impact of amplifier noise on signal phase?

- Relevant for building high-power ultra-narrow linewidth lasers
- Relevant for generation of optical frequency combs
- Relevant for transmission of frequency standards
- Relevant for noise characterization of lasers and frequency combs

Surprisingly few works on the topic and no common agreement

SPECTRAL BROADENING DUE TO FIBRE AMPLIFIER PHASE NOISE
ELECTRONICS LETTERS 29th March 1990 Vol. 26 No. 7
G. J. COWLE†
P. R. MORKEL
R. I. LAMING
D. N. PAYNE

IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 34, NO. 9, SEPTEMBER 1998

Novel Aspects of Spectral Broadening Due to Fiber Amplifier Phase Noise
Lothar Möller

IEEE JOURNAL ON SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 7, NO. 1, JANUARY/FEBRUARY 2001

New Investigations on the Effect of Fiber Amplifier Phase Noise
Etienne Rochat and René Dändliker

2610 Vol. 59, No. 8 / 10 March 2020 / Applied Optics Research Article

applied optics

Influence of amplified spontaneous emission on laser linewidth in a fiber amplifier
MINGYUAN XUE,[1,2] CUNXIAO GAO,[1,*] LINQUAN NIU,[1] SHAOLAN ZHU,[1] AND CHUANDONG SUN[1]

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1604 PROCEEDINGS OF THE IRE July

The Fundamental Noise Limit of Linear Amplifiers*

H. HEFFNER†, FELLOW, IRE

* Received January 8, 1962; revised manuscript received, April 30, 1962.

PHYSICAL REVIEW VOLUME 128, NUMBER 5 DECEMBER 1, 1962

Quantum Noise in Linear Amplifiers

H. A. HAUS
Electrical Engineering Department and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts

AND

J. A. MULLEN
Research Division, Raytheon Company, Waltham, Massachusetts
(Received May 10, 1962; revised manuscript received August 23, 1962)

Both papers derive that *power* and *phase fluctuation* due to amplifier noise are given by:

$$\Delta P = (G-1)h\nu B$$

$$\Delta \phi = \frac{(G-1)h\nu B}{2P}$$

Heffner and Haus assume input to the amplifier contains single frequency
(Lasers have amplitude and phase noise)

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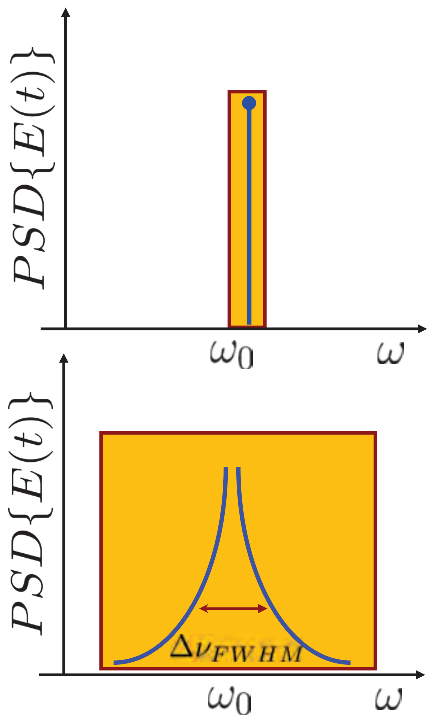
Assumptions by Heffner and Haus

Constant phase signal:

$$E(t) = \sqrt{P_0}\sin[\omega_0 t + \phi_0]$$



In practice amplitude and phase are (randomly) time-varying :

$$E(t) = \sqrt{P_0(1+\alpha(t))}\sin[\omega_0 t + \phi_0(t)]$$

The implication of time-varying amplitude and phase:
Measurement bandwidth needs to be carefully chosen

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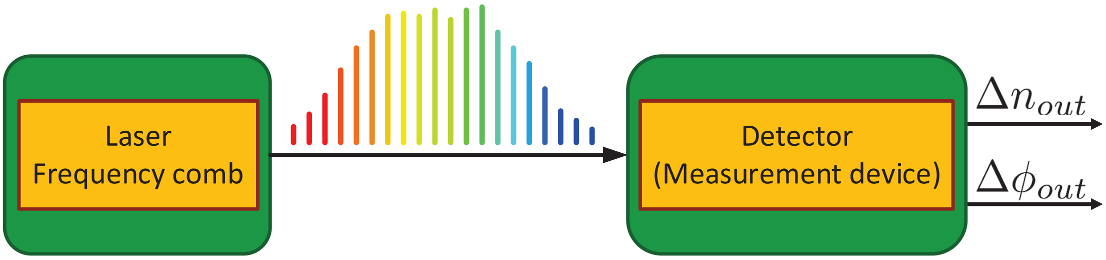
Ultimate laser stability conditioned by measurement precision



Heisenberg uncertainty sets limit on how accurately *photon number* and *phase* can be measured:

$$\Delta n_{out} \Delta \phi_{out} \geq \frac{1}{2}$$

In spectral domain *Heisenberg uncertainty* translates to:

$$S_{RIN}(f) S_{\phi}(f) \geq \left(\frac{h\nu}{2P}\right)^2$$

A. Yariv, SPIE 1995

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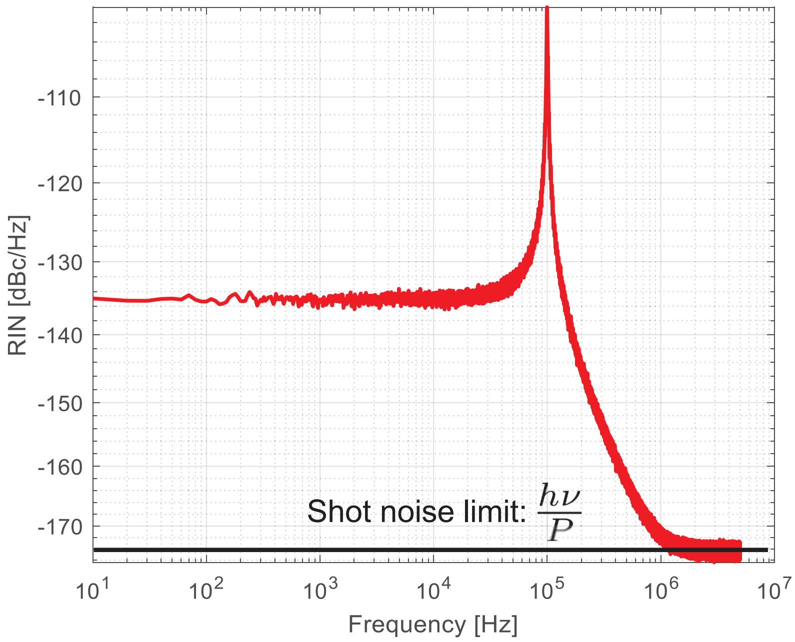
Limit on measuring Relative Intensity Noise (RIN)



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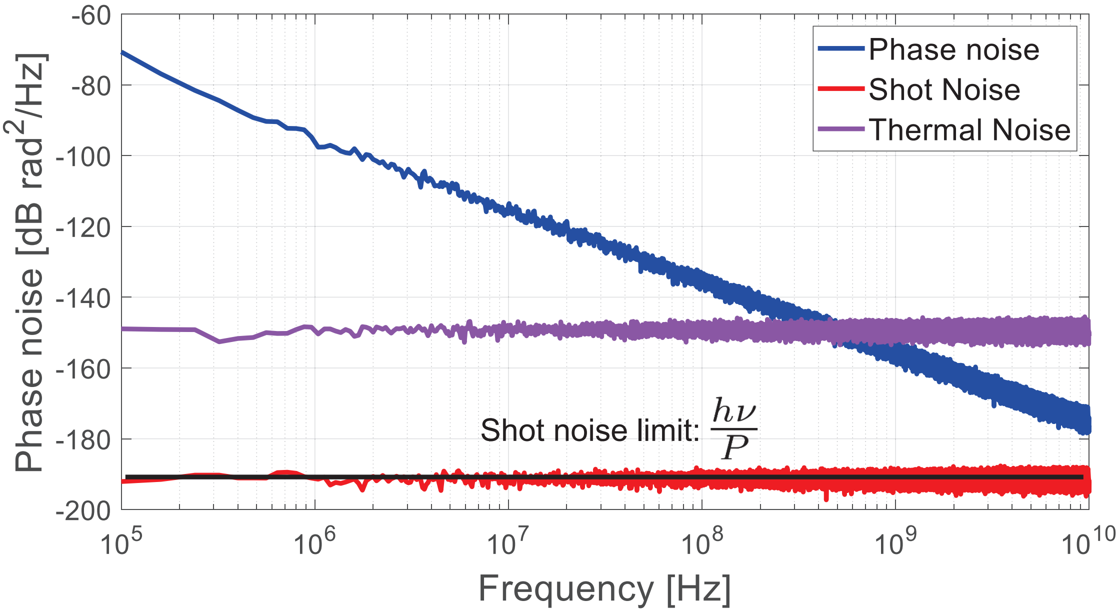
Limit on measuring phase noise



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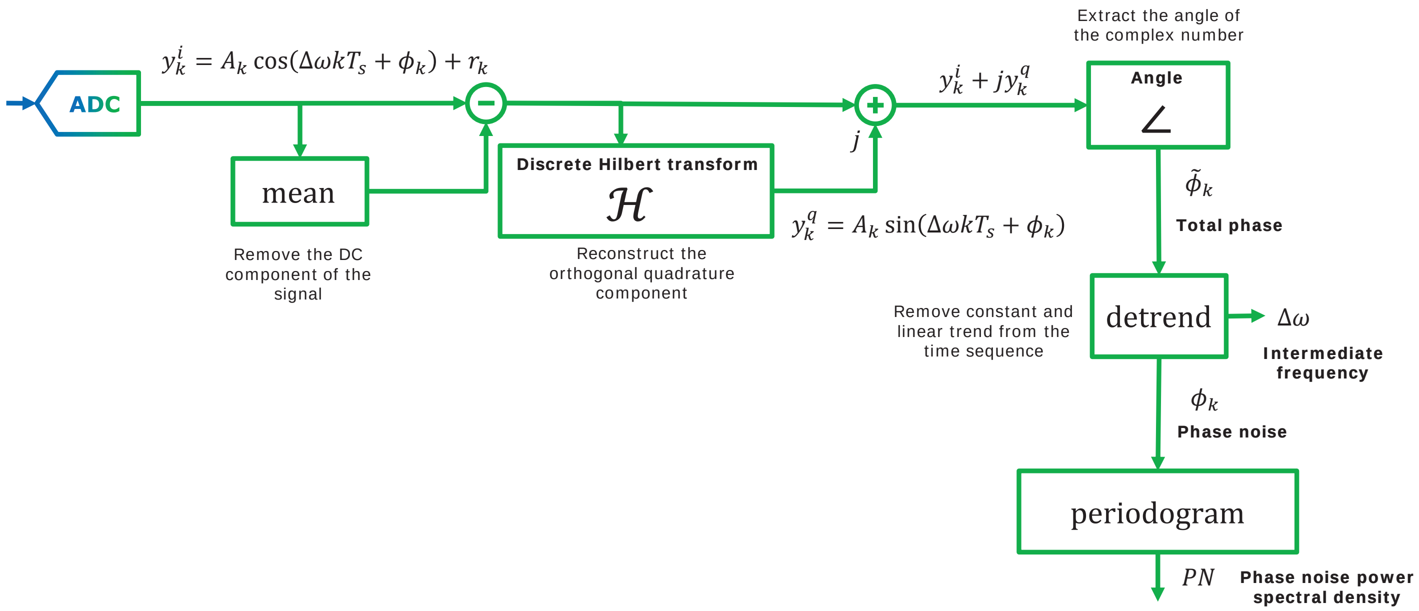
Conventional phase measurement



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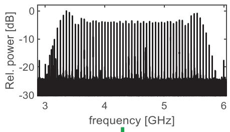
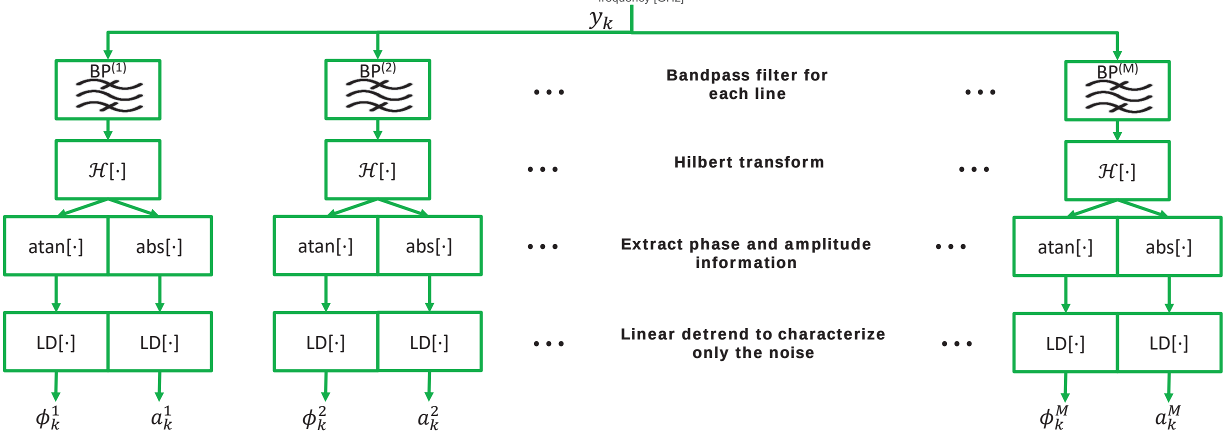
Conventional phase noise extraction

From the downconverted comb, extraction of amplitude and phase noise



Parallel processing of all the frequency lines (generalization of a single line)



Problem! Measurement noise affect the comb noise estimation

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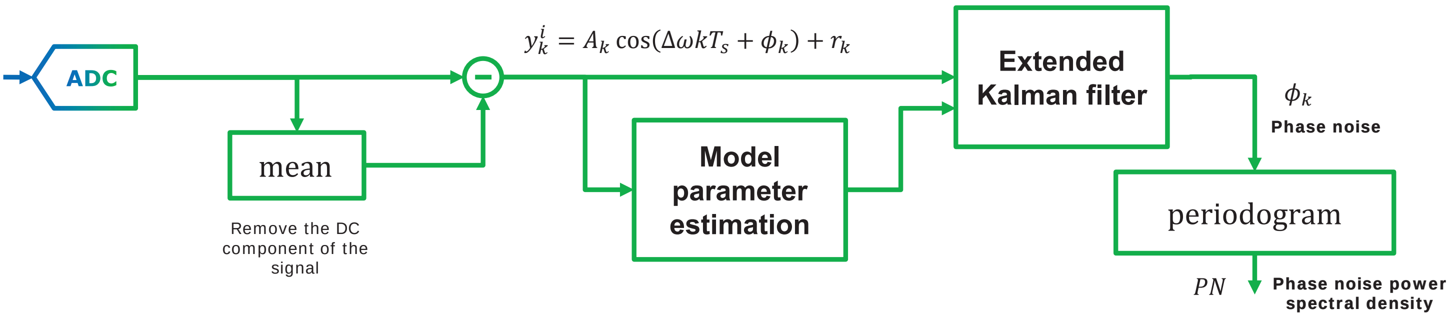
Bayesian filtering based phase extraction



The model we are using

$$\phi_k = \phi_{k-1} + q_k^\phi \qquad q_k^\phi \sim \mathcal{N}(0, \sigma_\phi^2)$$

$$y_k^i = A\cos(\Delta\omega k T_s + \phi_k) + r_k \qquad r_k \sim \mathcal{N}(0, \sigma_r^2)$$

The parameters:

σ_ϕ^2 **Phase noise variance**

σ_r^2 **Measurement noise variance**

$\Delta\omega$ **Intermediate angular frequency**

A **Average signal amplitude**

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Bayesian filtering for joint amplitude and phase noise estimation

Hidden state: phase and amplitude noise of all lines

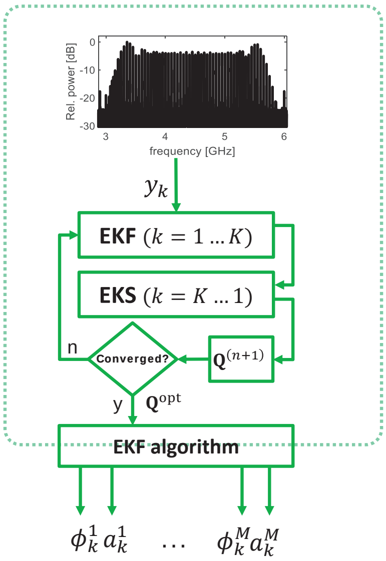
Phase and amplitude model: **Multidimensional Gaussian random walk**

$$\boldsymbol{\phi}_k = \begin{bmatrix} \phi_k^1 \\ \phi_k^2 \\ \vdots \\ \phi_k^M \end{bmatrix} \qquad \delta \boldsymbol{A}_k = \begin{bmatrix} \delta A_k^1 \\ \delta A_k^2 \\ \vdots \\ \delta A_k^M \end{bmatrix}$$

With M lines, we have M phase noise sequences and M amplitude noise sequences

$$\begin{bmatrix} \boldsymbol{\phi}_k \\ \delta \boldsymbol{A}_k \end{bmatrix} = \begin{bmatrix} \boldsymbol{\phi}_{k-1} \\ \delta \boldsymbol{A}_{k-1} \end{bmatrix} + \boldsymbol{q}_{k-1}, \qquad \text{with } \boldsymbol{q}_{k-1} \sim \mathcal{N}(0, \mathbf{Q}), \ \mathbf{Q} = \begin{bmatrix} \mathbf{Q}_\phi & \mathbf{Q}_{\phi A} \\ \mathbf{Q}_{A\phi} & \mathbf{Q}_A \end{bmatrix}$$

$$y_k = \sum_{m=1}^{M} \bar{A}^m (1 + \delta A_k^m) \cos(\Delta\omega_m k T_S + \phi_k^m) + n_k$$



[1] G. Brajato et al, Optics Express 2020

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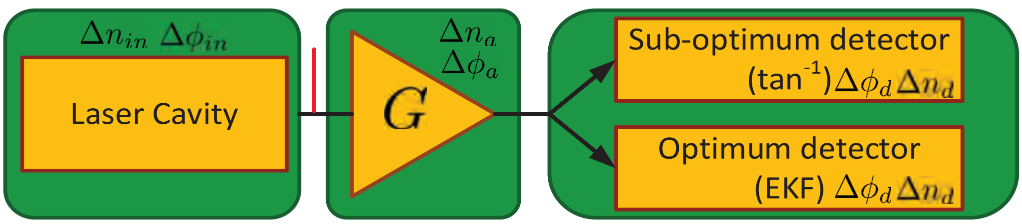
The concept of optimum detector



$$\Delta n_{out}^2 = \Delta n_a^2 + \Delta n_d^2$$

$$\Delta \phi_{out}^2 = \Delta \phi_a^2 + \Delta \phi_d^2$$

Ultimate performance limit governed by:

$$\Delta n_{out} \Delta \phi_{out} \geq \frac{1}{2}$$

Heisenberg uncertainty limit reached when:

$$\frac{\Delta n_d}{\Delta \phi_d} = \frac{\Delta n_a}{\Delta \phi_a}$$

Detector uncertainty needs to be *matched* to amplifier uncertainty (optimum detector)

H. Heffner, 1962

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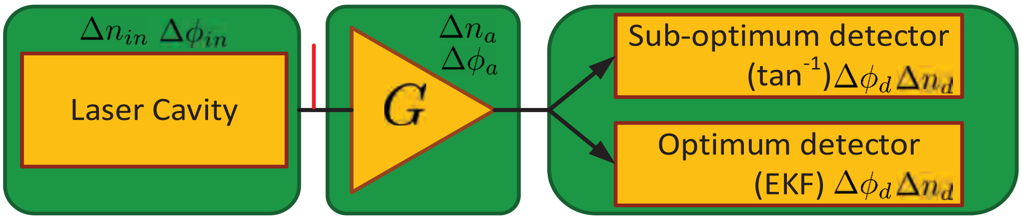
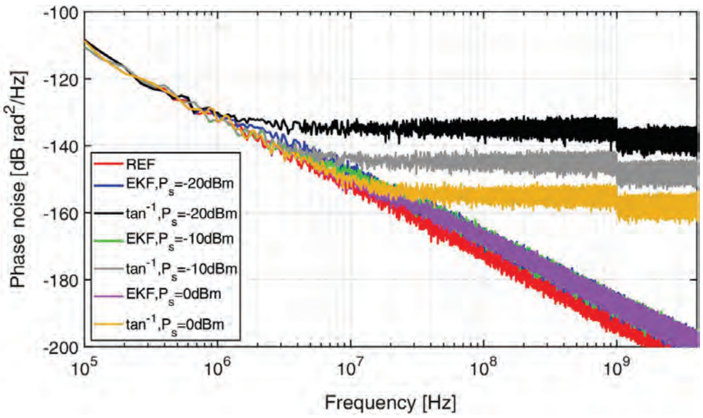
The importance of optimum detector





Darko Zibar, Jens E. Pedersen, Poul Varming, Giovanni Brajato, Francesco Da Ros, "Approaching optimum phase measurement in the presence of amplifier noise," Optica **8,** 1262-1267 (2021);

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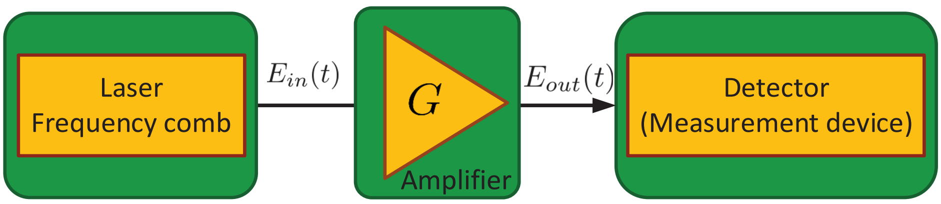
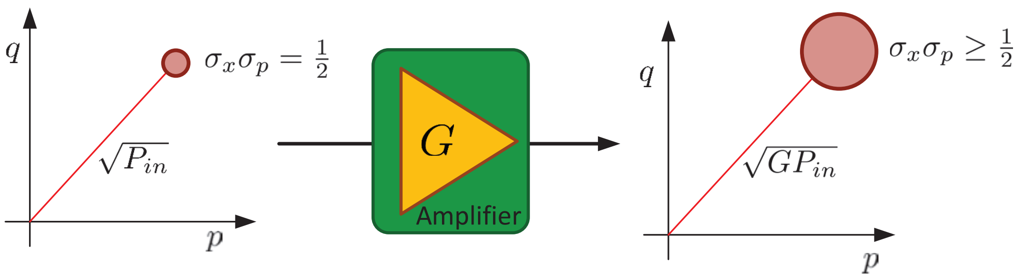
Minimum noise added by the amplifier



$$E_{in}(t) = \sqrt{P_{in}}\sin[\omega t + \phi_0] \qquad E_{out}(t) = \sqrt{GP_{in}}\sin[\omega t + \phi_0] + N(t)$$

$N(t)$: Gaussian noise with zero mean and standard deviation $\Delta P = (G-1)h\nu B$



E. Desurvire, 1994

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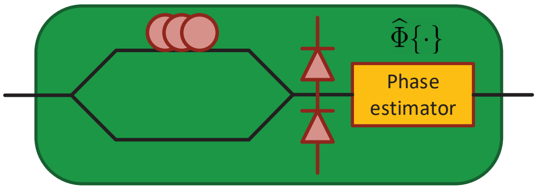
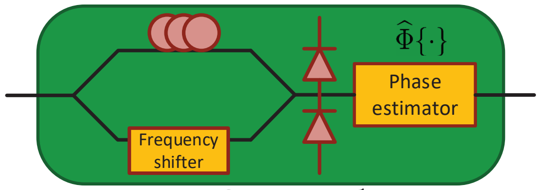
Quantum limited phase detection (the best we can do)

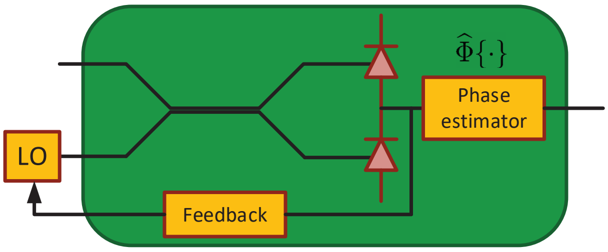


$$\Delta\phi_{ql}^2 = \frac{1}{\sqrt{N_p}}$$

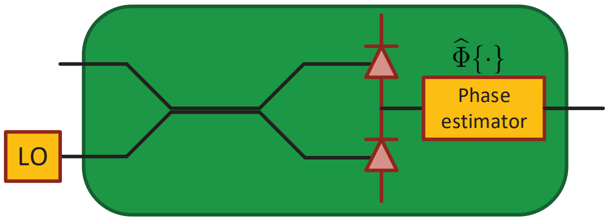


$$\Delta\phi_{ql}^2 = \frac{1}{\sqrt{N_p/2}}$$

$$N_p = \frac{P_{in}}{h\nu\pi\Delta\nu_{FWHM}}$$



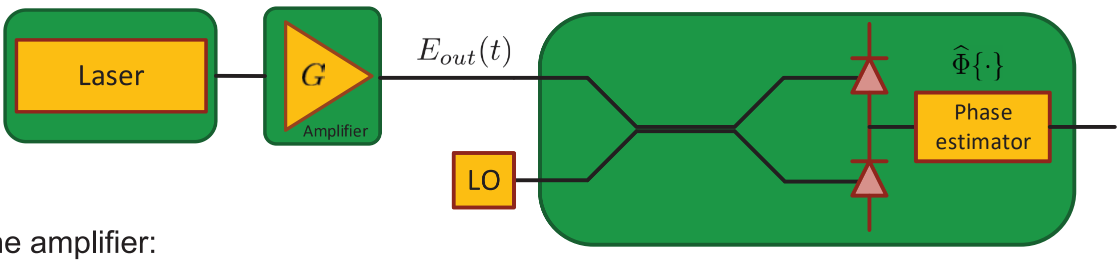
$$\Delta\phi_{ql}^2 = \frac{1}{2\sqrt{N_p}}$$



$$\Delta\phi_{ql}^2 = \frac{1}{2\sqrt{N_p/2}}$$

H. M . Wiseman, 2002

Minimum phase fluctuation due to amplifier noise



Output of the amplifier:

$$E_{out}(t) = \sqrt{GP_{in}}\sin[\omega_0 t + \phi(t)] + n_a(t)$$

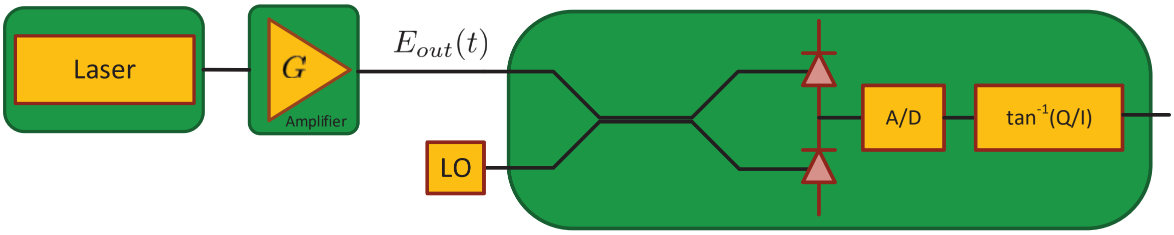
$n_a(t)$: Gaussian noise term added by the amplifier with variance :

$$\sigma_N^2 = P_N = h\nu(G-1)B$$

Quantum limited (minimum) phase fluctuation due to amplifier noise $(B = \Delta\nu_{FWHM})$:

$$\Delta\phi_a^{MAP} = \frac{1}{2\sqrt{\sqrt{N_p/2}}} = \frac{1}{\sqrt{2\sqrt{GP_{in}/2h\nu(G-1)\pi\Delta\nu_{FWHM}}}}$$

Optimum phase measurement for *high* SNR



Discrete-time signal after analogue-to-digital converter (A/D):

$$y[k] = 2R\sqrt{GP_{in}P_{LO}}\cos(\Delta\omega k T_s + \phi[k]) + n^{sh}[k] + n^{b}[k]$$

Phase estimation method: $\phi_{\tan^{-1}} = \arg[(y[k] + j\mathcal{H}\{y[k]\})e^{-j\Delta\omega t}] = \arg[(I + jQ)e^{-j\omega t}] = \tan^{-1}(Q/I)$

Quantum limited (minimum) phase fluctuation due to amplifier noise:

$$\Delta\phi_a = \frac{1}{2\sqrt{N_p/2}} = \frac{1}{2\sqrt{GP_{in}/2h\nu(G-1)B}} = \frac{1}{2\sqrt{SNR/2}}$$

Measuring at low and medium SNR is important

- Technical noise dominates laser phase noise at low frequencies
- Determining fundamental laser linewidth (quantum noise limited) requires measuring beyond MHz
- Laser power may be low (output of the cavity)
- Frequency comb lines may have low power
- Several stages of amplification may reduce SNR

Signal-to-noise ratio of beat signal after heterodyne detection:

$$SNR = \frac{2RP_sP_{LO}}{\sigma_{shot}^2 + \sigma_b^2} = \frac{2RP_sP_{LO}}{2qRP_{LO}B + 4P_{LO}N_Ah\nu(G-1)B}$$

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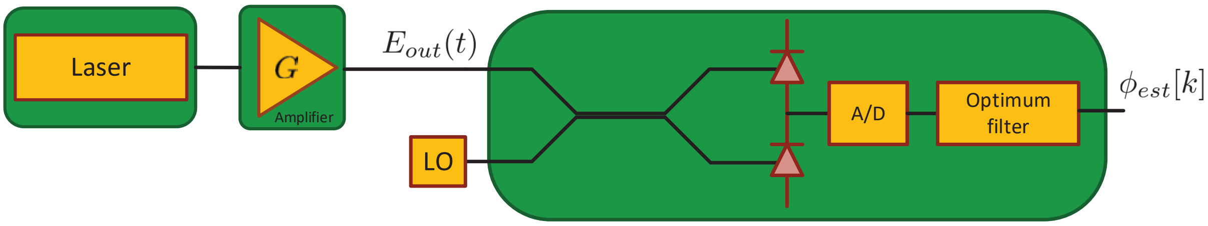
Optimum filtering for *wide-range* of SNRs



Given discrete-time signal after analogue-to-digital converter (A/D):

$$y[k] = 2R\sqrt{GP_{in}P_{LO}}\cos(\Delta\omega kT_s + \phi[k]) + n^{sh}[k] + n^b[k]$$

Optimum filter finds phase that is closest to $\phi[k]$ for a given SNR

For extracting signal from noise Bayesian filter is theoretically optimum filter
Kalman filter is an approximation of Bayesian filter

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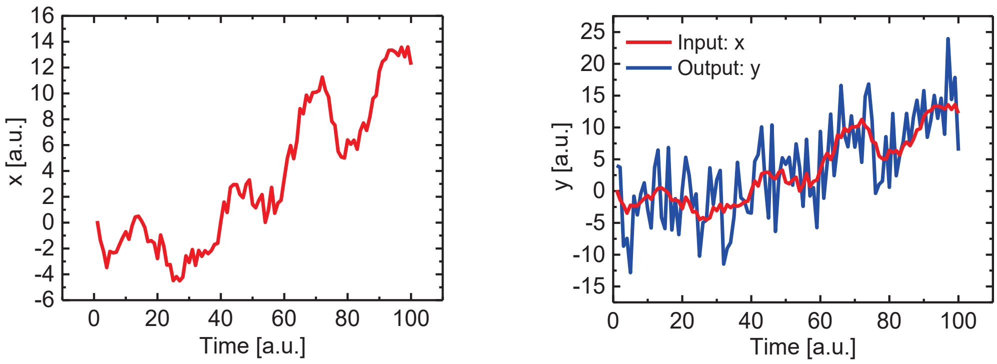
Bayesian filtering: infer *input x* from *noisy output y*



$x_t = g(x_{t-1}, w_{t-1})$

$y_t = f(x_t, n_t)$

States: amp., phase noise, PMD x_t

Mapping function: $g(\cdot)$

Process noise: w_{t-1}

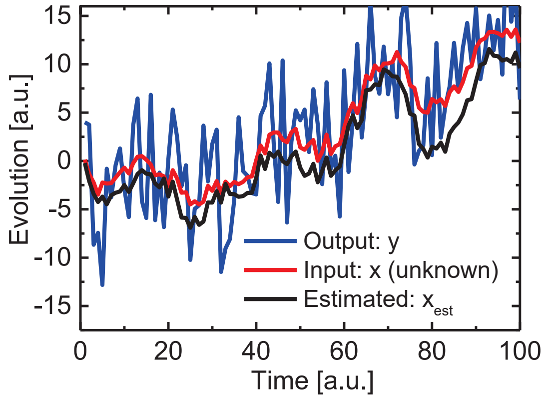
Observations: y_t

Mapping function: $f(\cdot)$

Measurement noise: n_t

S. Sarka, 2013

Bayesian filtering: infer *input x* from *noisy output y*



Given a measurement:

$$y = x + n$$

Compute:

$$\overbrace{p(x|y)}^{posterior} = \frac{p(y|x)\overbrace{p(x)}^{prior}}{p(y)} \longrightarrow x_{est} = E[x] = \int xp(x|y)dx$$

Bayesian filtering equations

Deterministic state space model:

$$x_t = g(x_{t-1}, w_{t-1})$$
$$y_t = f(x_t, n_t)$$

Probabilistic state space model:

$$\theta \sim p(\theta)$$
$$x_t \sim p(x_t|x_{t-1}, \theta)$$
$$y_t \sim p(y_t|x_t, \theta)$$

Use Kalman or particle filtering to solve:

for t=1:T

1. Compute prior: $p(x_t|y_{1:t-1}) = \int p(x_t|x_t - 1)p(x_{t-1}|y_{1:t-1})dx_{t-1}$

2. Compute posterior: $p(x_t|y_{1:t}) = \frac{p(y_t|x_t, \theta)p(x_t|y_{1:t-1}, \theta)}{p(y_{1:k}|\theta)}$

end

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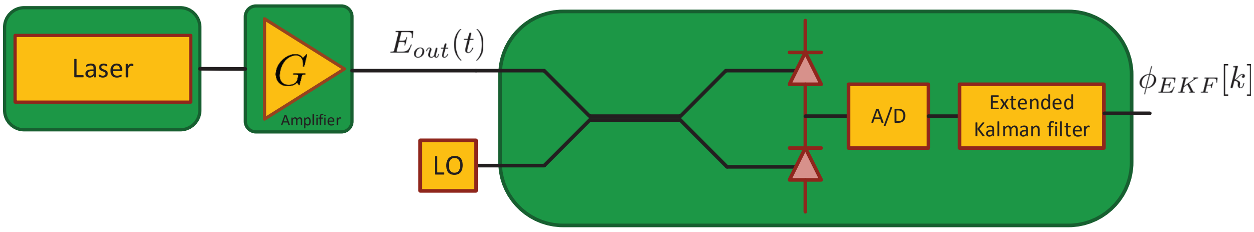
Approaching optimum filtering with Kalman filter



EKF based phase estimation approaches quantum limit:

$$\sigma_{EKF} = \sqrt{\frac{1}{K}\sum_{k=1}^{K}(\phi^{true}[k] - \phi_{EKF}[k])^2} \rightarrow \Delta\phi^{MAP} = \frac{1}{\sqrt{2\sqrt{N_p/2}}}$$

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Practical implication of random phase fluctuations

Given a observation time *T*, laser phase noise variance is expressed as:

$$\Delta\phi^2(T) = 2\pi\Delta\nu T$$

The corresponding *spectral broadening* expressed as:

$$\Delta\nu = \frac{\Delta\phi^2(T)}{2\pi T}$$

The quantum limited spectral broadening due to amplifier noise :

$$\Delta\nu_a^{MAP} = \frac{\Delta\phi_a^{MAP}}{2\pi T}$$

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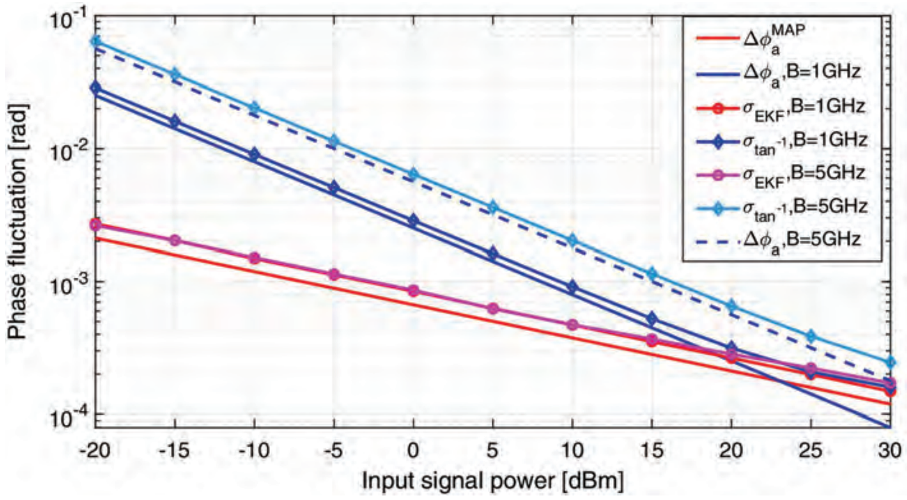
Numerical results: phase fluctuation



$\Delta\nu_{FWHM} = 1$ kHz

$$\Delta\phi_a^{MAP} = \frac{1}{2\sqrt{\sqrt{N_p/2}}} = \frac{1}{\sqrt{2\sqrt{GP_{in}/2h\nu(G-1)\pi\Delta\nu_{FWHM}}}}$$

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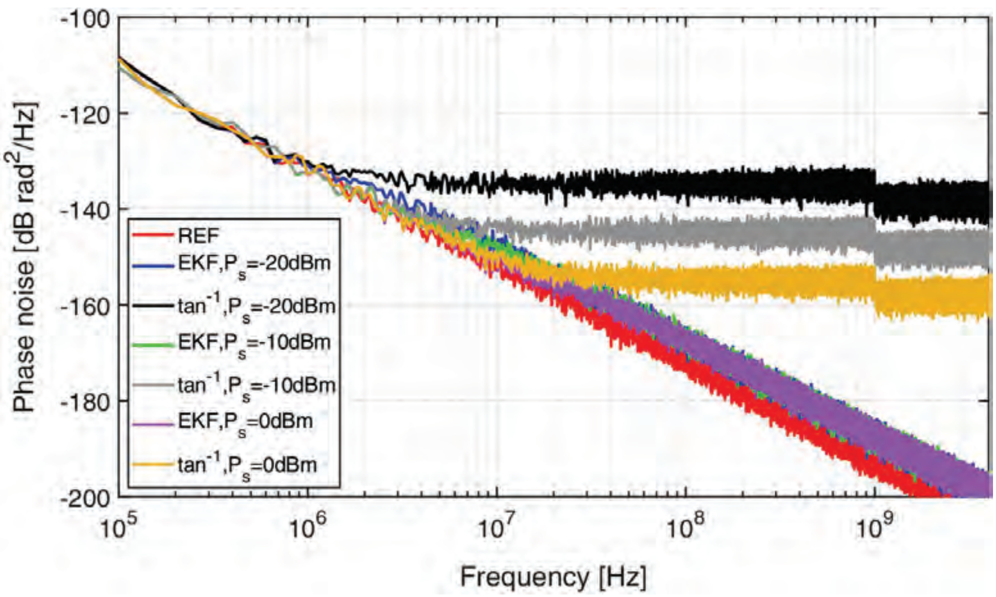
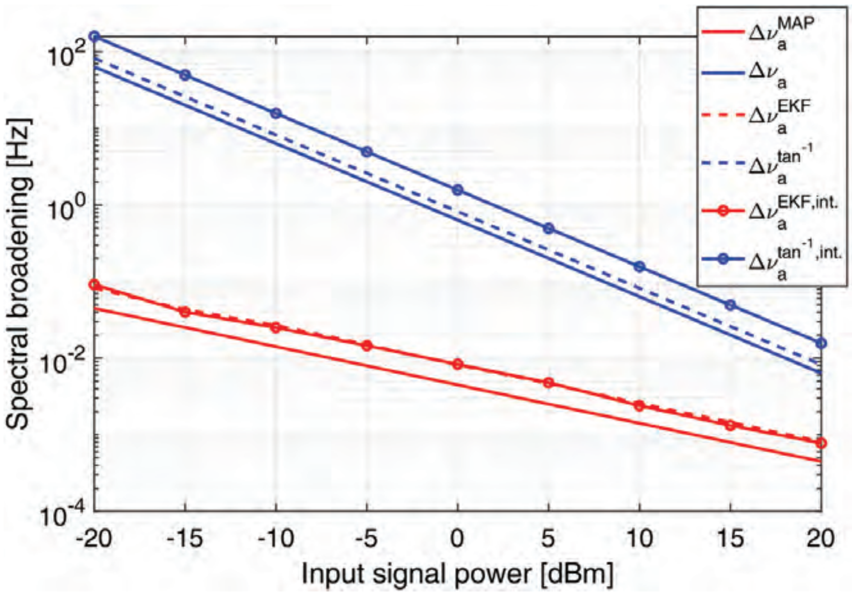
Numerical results: phase PSD



Numerical results: spectral broadening



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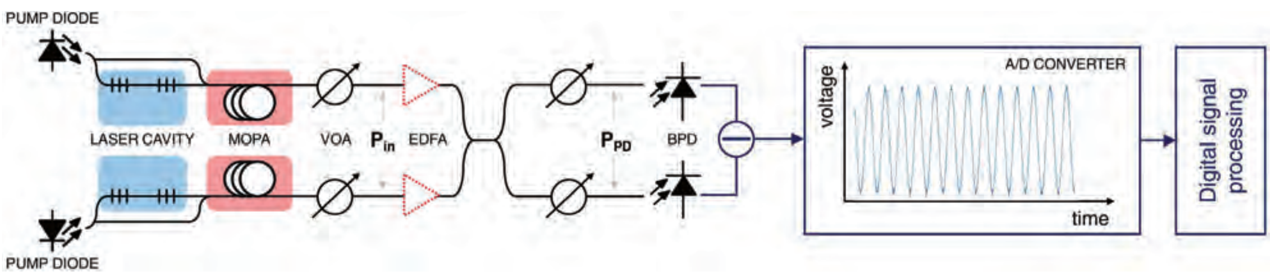
Experimental set-up



Darko Zibar, Jens E. Pedersen, Poul Varming, Giovanni Brajato, Francesco Da Ros, "Approaching optimum phase measurement in the presence of amplifier noise," Optica **8,** 1262-1267 (2021);

https://www.osapublishing.org/optica/abstract.cfm?uri=optica-8-10-1262

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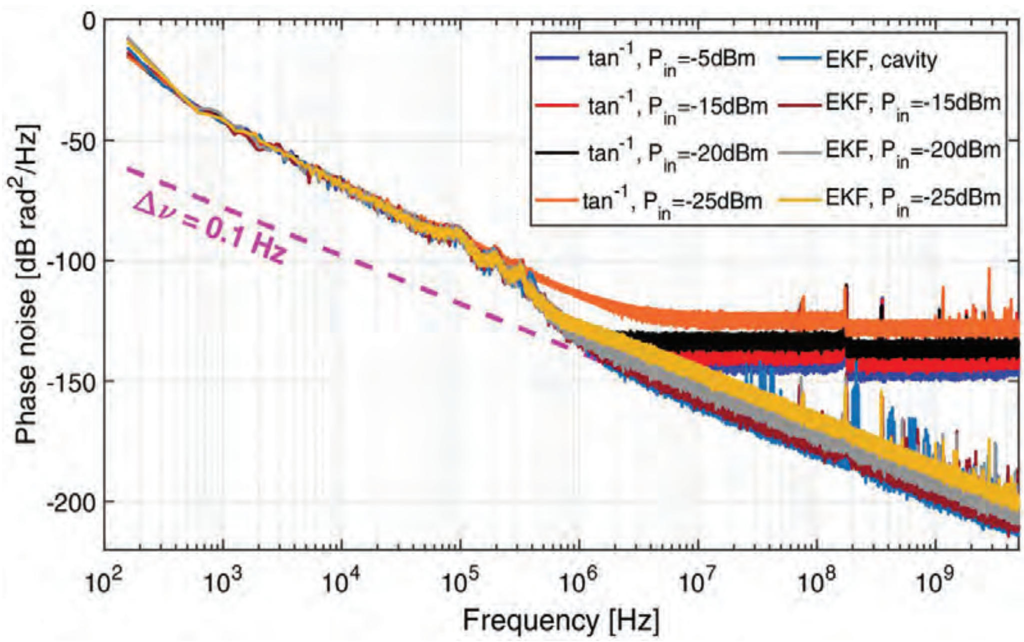
Experimental: phase-noise measurement



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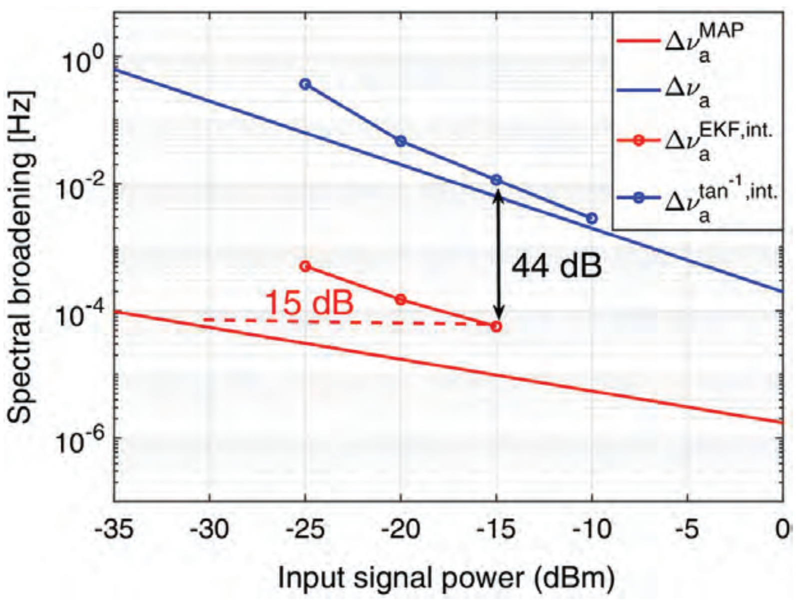
Experimental: spectral broadening



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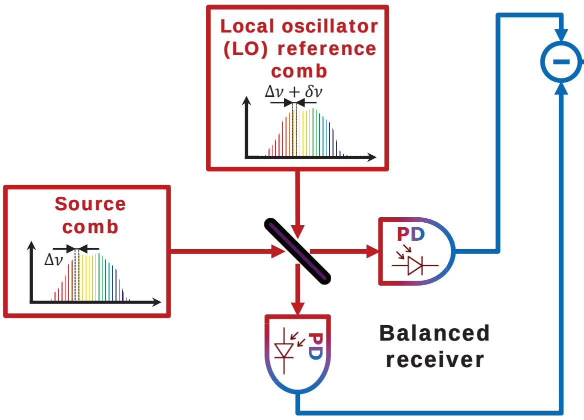
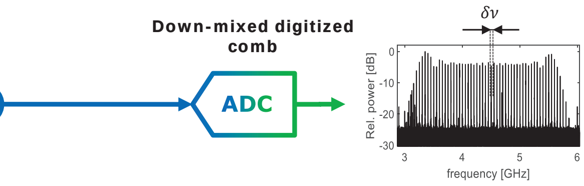
Characterization of frequency combs

Dual comb multiheterodyne set-up





The noise of the down-mixed comb is given by the **contribution** of the reference comb and the source comb

It is possible to characterize the source comb when the reference contribution can be neglected or they equally contribute

The **k-th sample of the down-digitized comb** can be described in time domain as a summation of beating tones

$$y_k = \sum_{m=1}^{M} \bar{A}^m (1 + a_k^m) \cos(\Delta\omega_m k T_S + \phi_k^m) + n_k$$

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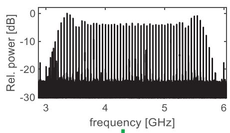
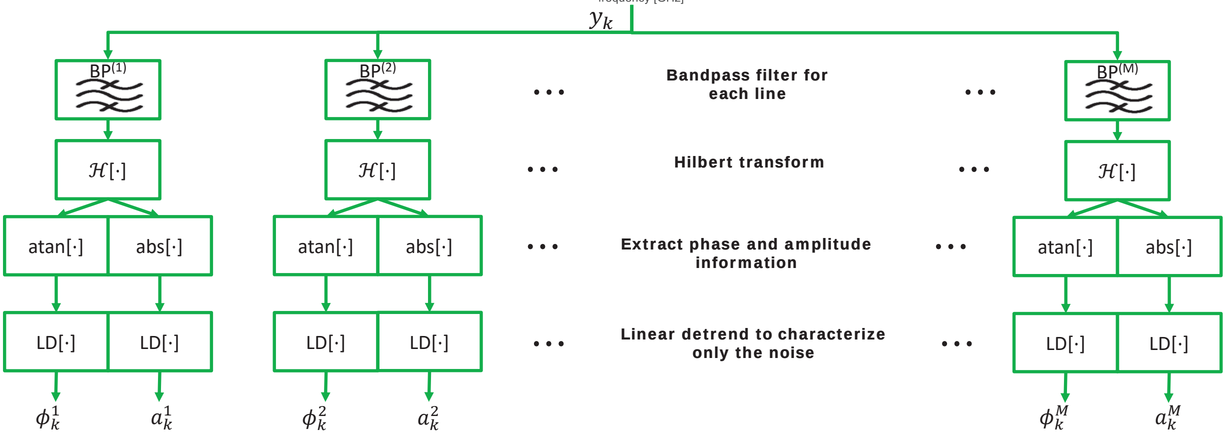
Conventional phase noise extraction

From the downconverted comb, extraction of amplitude and phase noise



Parallel processing of all the frequency lines (generalization of a single line)



Problem! Measurement noise affect the comb noise estimation

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Bayesian filtering for joint amplitude and phase noise estimation

Hidden state: phase and amplitude noise of all lines

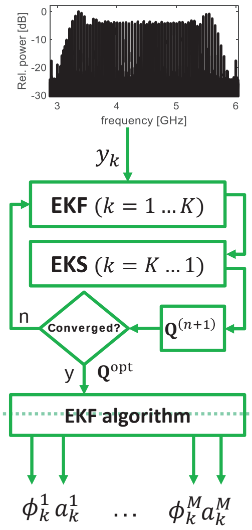
Phase and amplitude model: **Multidimensional Gaussian random walk**

$$\boldsymbol{\phi}_k = \begin{bmatrix} \phi_k^1 \\ \phi_k^2 \\ \vdots \\ \phi_k^M \end{bmatrix} \qquad \delta\boldsymbol{A}_k = \begin{bmatrix} \delta A_k^1 \\ \delta A_k^2 \\ \vdots \\ \delta A_k^M \end{bmatrix}$$

With M lines, we have M phase noise sequences and M amplitude noise sequences

$$\begin{bmatrix} \boldsymbol{\phi}_k \\ \delta\boldsymbol{A}_k \end{bmatrix} = \begin{bmatrix} \boldsymbol{\phi}_{k-1} \\ \delta\boldsymbol{A}_{k-1} \end{bmatrix} + \boldsymbol{q}_{k-1}, \qquad \text{with } \boldsymbol{q}_{k-1} \sim \mathcal{N}(0, \mathbf{Q}) \ , \mathbf{Q} = \begin{bmatrix} \mathbf{Q}_\phi & \mathbf{Q}_{\phi A} \\ \mathbf{Q}_{A\phi} & \mathbf{Q}_A \end{bmatrix}$$

$$y_k = \sum_{m=1}^{M} \bar{A}^m (1 + \delta A_k^m) \cos(\Delta\omega_m k T_S + \phi_k^m) + n_k$$



[1] G. Brajato et al, Optics Express 2020

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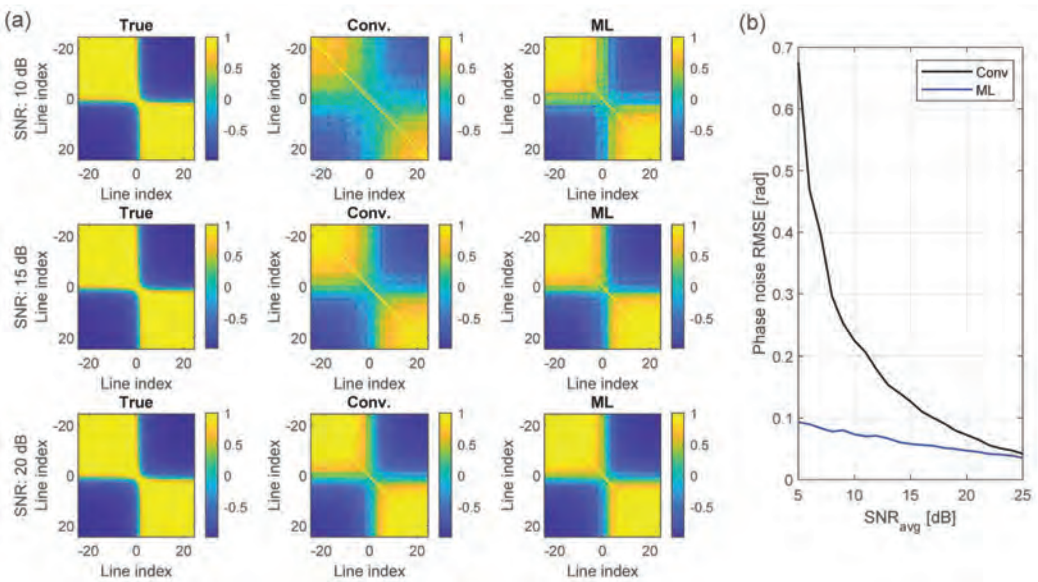
Frequency comb phase noise correlation matrix



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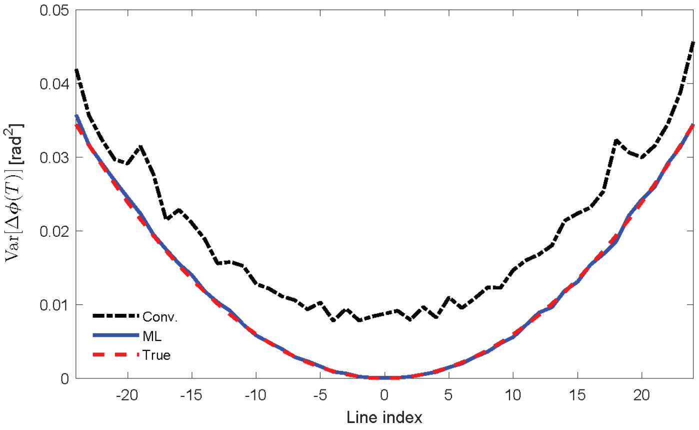
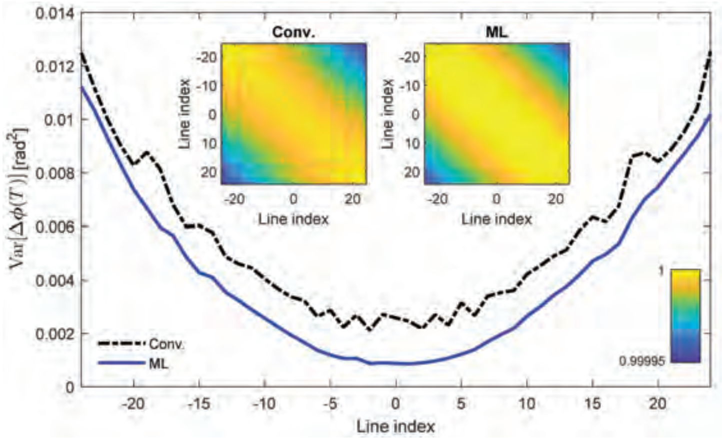
Combs lines phase variance



(a) Simulations



(b) Experimental

Machine learning methods provides more accurate estimations

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Conclusion and outlook

- Machine learning toolbox brings significant advantages to photonics
- Machine learning effective in learning complex mappings
  - Optical amplifier design
  - Communication over fiber-optic channel
  - Noise characterization of lasers and frequency combs
  - Quantum noise limited tracking
- Many other problems could benefit from ML (e.g. component design, power allocation etc)
- A lot of room for interesting research problems
- ML toolbox part of electrical and photonics engineering curriculum
- Lack of researchers that understand ML and optics to advance the field

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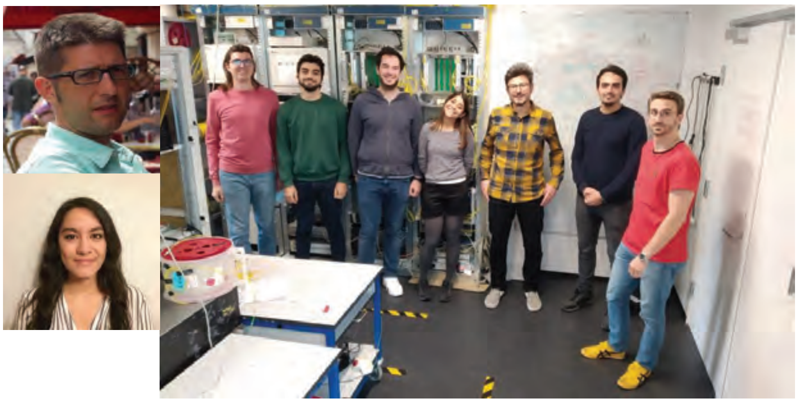

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Villum Foundations (VYI grant OPTIC-AI no.29344),

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Quantum random number generation based on the times of photon detections

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BME - Budapest University of Technology and Economics, Hungary

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Abstract

Quantum random number generation (QRNG) has become an increasingly important field in the recent years, since it can provide uniformly distributed, completely unpredictable bits by exploiting the entropy of quantum measurements. Optical phenomena are especially promising, as the emission and detection of photons is technologically well established. Several optical QRNG methods are discussed, focusing mainly on those that measure the times elapsed between photon detections to obtain random numbers. The importance of mathematical modelling and randomness testing is also outlined via examples, comparing slower but more robust schemes to faster ones, which are more sensitive towards changes in ambient factors.

Author's biography

Ágoston Schranz received the B.Sc., M.Sc. and Ph. D. degrees in electrical engineering from the Budapest University of Technology and Economics (BME), Budapest, Hungary, in 2015, 2017, and 2022, respectively. He is currently an associate professor at the Department of Networked Systems and Services, and he is involved in several research projects and teaching activities as a member of the Mobile Communications and Quantum Technologies Laboratory. His research interests include optical communications, quantum key distribution, and quantum random number generation.

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QUANTUM RANDOM NUMBER GENERATION BASED ON THE TIMES OF PHOTON DETECTIONS

26th Seminar on Optical Communications

Ljubljana
January 27, 2023

Dr. Ágoston Schranz

BME Department of Networked Systems and Services
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Random numbers

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  - Symmetric-key cryptography
  - Monte Carlo simulations
  - Gambling
- What kind of randomness?
- Range of numbers?
- For the present discussion: *sequences of uniformly distributed, independent bits*

...0111010101101101000101101011001011010010 00...

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PRNGs and TRNGs

- For many applications, true randomness is not necessary, just the desired statistical properties
  - Pseudorandom RNGs (PRNGs): algorithmic, deterministic methods, e.g. linear feedback shift registers
  - Starting from a seed, their operation is periodic
  - Unsuitable for cryptography
- True RNGs
  - Sampling physical processes

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Quantum random number generation

- A subgroup of TRNGs operate based on quantum physical principles
- Utilizing the uncertainty of quantum measurements
- If tuned well, the resulting bits are uniformly distributed
- Quantum and classical noise components need to be analyzed and separated

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Randomness testing

- Main question: **was a given bit sequence produced by a perfect RNG?**
  - Impossible to decide with certainty!
- Two-way approach
  1. Mathematical modelling, calculations involving probabilities, entropy estimation + experimental validation
  2. Statistical hypothesis testing of the output bits
- Testing
  - Infinitely many aspects of randomness (relative frequency, number of runs, lack of periodic components, etc.)
  - Specially designed test suites with a multitude of tests (NIST STS, DieHarder, TestU01. . .)

Optical QRNGs

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Why optics?

- Early research (1970) targeted radioactive decay as a source of randomness
  - Low rates
  - Depleting source
  - Health concerns
- Advanced technology for creation, manipulation and detection of light
  - Simple and affordable hardware (telecom-grade devices)
  - Measurement technology
  - No health hazards (unless someone tries really hard. . .)
- Methods can utilize the dual nature of light (wave–particle duality)

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Optical principles

- Branching path
- Photon number
- Time-of-arrival
- Amplified spontaneous emission
- Phase noise of lasers
- Vacuum fluctuations
- Raman scattering
- . . .

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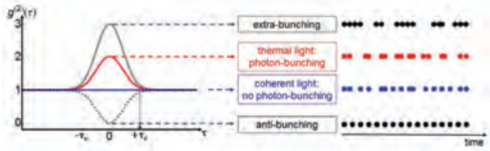
Time-of-Arrival generators

- Coherent light: low-power quasi-monochromatic laser
- Poisson point process
  - Number of photons per unit time: Poisson distributed
  - Time elapsed between photon detections: exponentially distributed
- Attenuation and dead time of detectors push thermal statistics toward Poissonian



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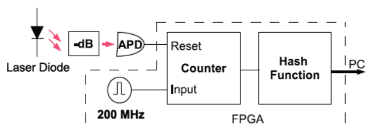
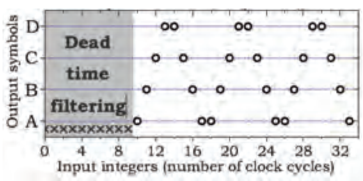
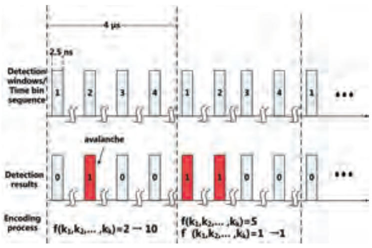
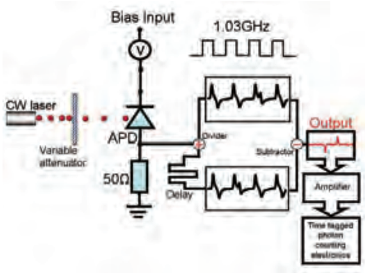
ToA generators: examples









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- F. -X. Wang et al., "Robust Quantum Random Number Generator Based on Avalanche Photodiodes," Journal of Lightwave Technology, vol. 33, no. 15, pp. 3319-3326 (2015)

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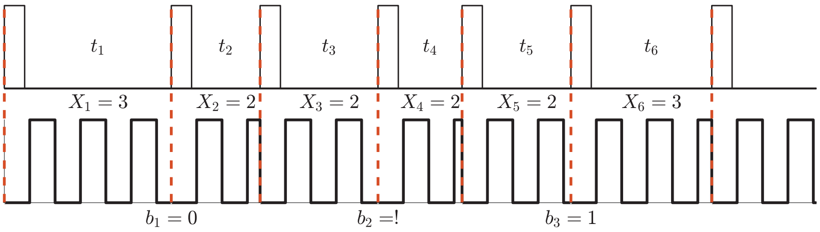
Method of interest

- M. Stipčević and B. Medved Rogina , "Quantum random number generator based on photonic emission in semiconductors", Review of Scientific Instruments 78, 045104 (2007)
- Compare two successive interarrival times
  - Bit assigned based on which is longer, equalities: discarded
- Robust against ambient fluctuations due to symmetry
- Main model parameters: photon rate λ, measurement precision τ, dead time τ_{d}



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Notation, figures of merit

- Random variables (i.i.d. within a group)
  - T_j: j^{th} exponentially distributed time between two detections
  - X_j: j^{th} discretized time (no dead time – geometrical distribution)
  - W_i: sign of the difference $X_{2i} - X_{2i-1}$, uniformly distributed after discarding each $W_i = 0$
- Bit generation efficiency η_{R}: average number of bits assigned per random event
- Bit generation rate R: average number of bits generated per unit time

$$\eta_{\mathrm{R}} = \frac{1 - P\left[X_{2i} = X_{2i-1}\right]}{2} = \frac{1 - \sum_{n=0}^{\infty} P\left[X_j = n\right]^2}{2} \qquad R = \frac{\eta_{\mathrm{R}}}{\mathbb{E}\left[T_j\right]}$$

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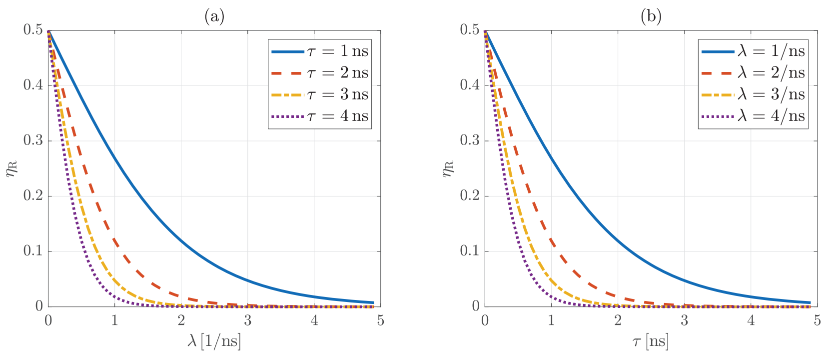
Bit generation efficiency



η_R is maximal as either λ or $\tau \to 0$

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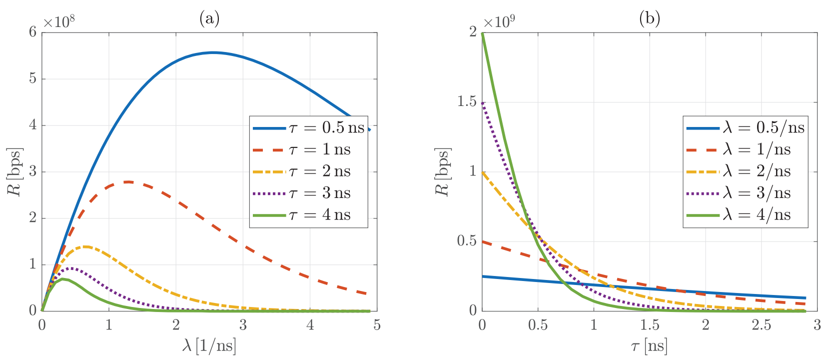
Bit generation rate



R is zero as $\lambda \to 0$

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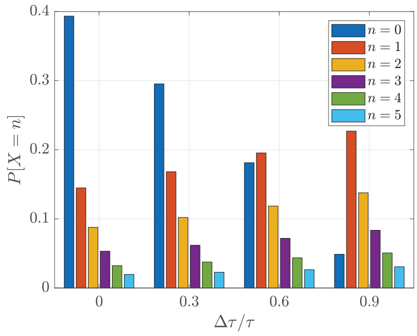
Distorted distributions

- Introduce a dead time $\tau_\text{d} = k\tau + \Delta\tau = \left(k + \frac{\Delta\tau}{\tau}\right)\tau, \quad k \in \mathbb{Z}^+$
- PMF $P[X=n]$ shifted to $P[X=n+k] \Rightarrow \eta_\text{R}$ is unchanged (left-padding with zeros means invariance under infinite summation)



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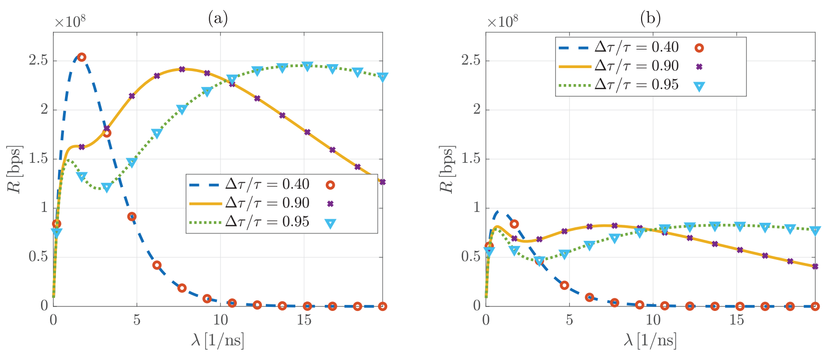
Formula and simulations

- Bit generation rate depends on the whole dead time, as it reduces the output count rate
- $R(\lambda,\tau,\tau_\text{d} = k\tau+\Delta\tau) = \frac{1}{2}\cdot\frac{\lambda}{1+\lambda\tau_\text{d}}\cdot\left\{1-\left[1-\mathrm{e}^{-\lambda(\tau-\Delta\tau)}\right]^2 - \frac{\mathrm{e}^{2\lambda\Delta\tau}\left(1-\mathrm{e}^{-\lambda\tau}\right)^2}{\mathrm{e}^{2\lambda\tau}-1}\right\}$



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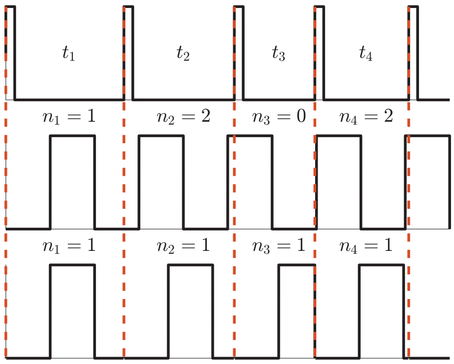
Continuously running clocks



- Restarting the clock is not always feasible
- Continuous clock: random phase at detections introduces correlations between measurements and bits

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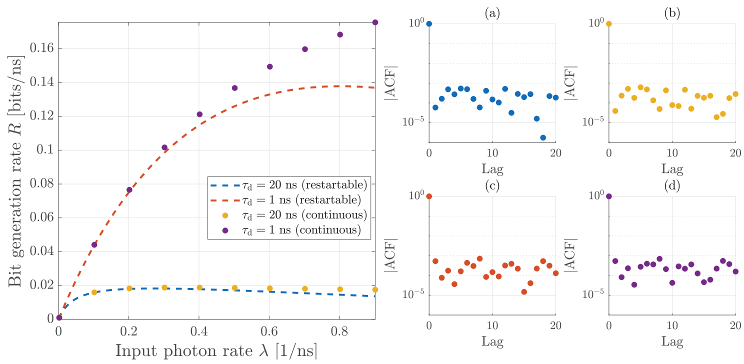
Correlations and dependence



- At small $\lambda\tau$ values the rates are close
- In the high-precision regime $\lambda\tau \ll 1$: autocorrelation between successive bits remains negligible

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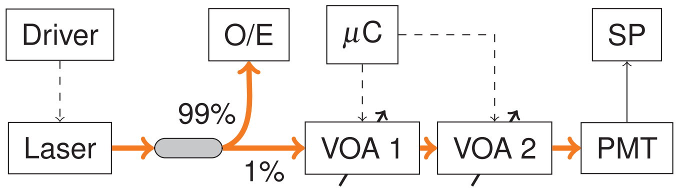
Experimental setup



- Laser wavelength: 520 nm
- Time-to-Digital Converter (SP): dead time ~2 ns, resolution 250 ps, continuous clock!
- Photomultiplier tube (PMT): max count rate 5 million/s, quantum efficiency @520 nm ~22%, dark count rate: <50 cps, output pulse width 1.5 ns FWHM

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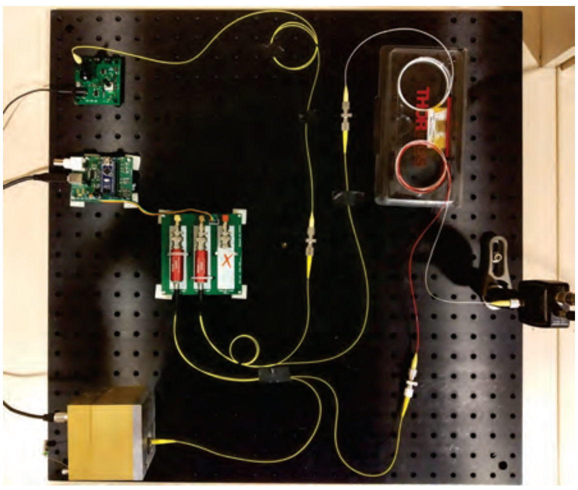
Experimental setup



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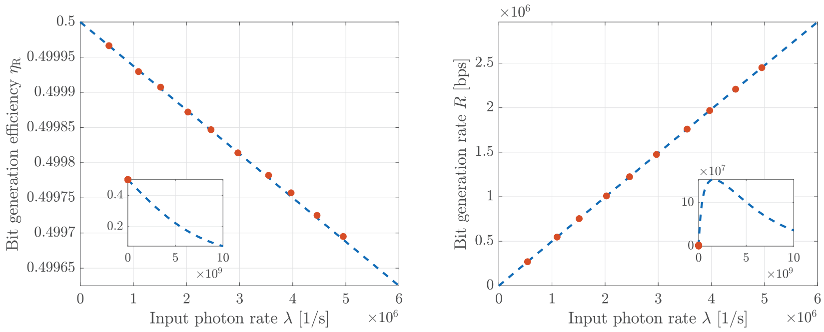
Validation of theoretical results



- Measurements between 0.5 and 5 million output counts per second
- Excellent agreement, but restricted to the initial section of the graphs
- Up until 3 million cps: 188/188 randomness tests of the NIST STS passed; at 4 and 5 million, 187 and 186

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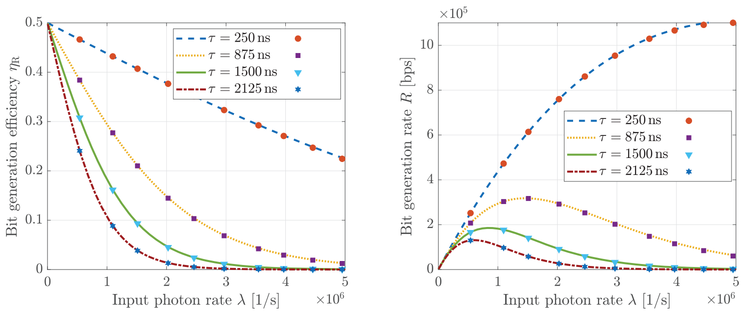
Extended validity check



- For a more thorough check: software-based clock period adjustment
- Treating originally measured time differences as analog values; counting rising edges of a cruder, restartable clock signal within these intervals

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Work in progress

- Extended model based on discretized Markov chains: calculating the effects of the random clock phase at the detection
- Solving the problem of dependence and correlations: eliminating the effects of phase and unknown dead time at a price of a slightly reduced final bit rate

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Increase the efficiency!

- Robustness is great
- Efficiency and rate is quite limited
- Can we increase them by minor adjustments?
  - Yes, if we can maintain a specific value of λ very precisely!
  - No need for directly discarding values measured to be equal

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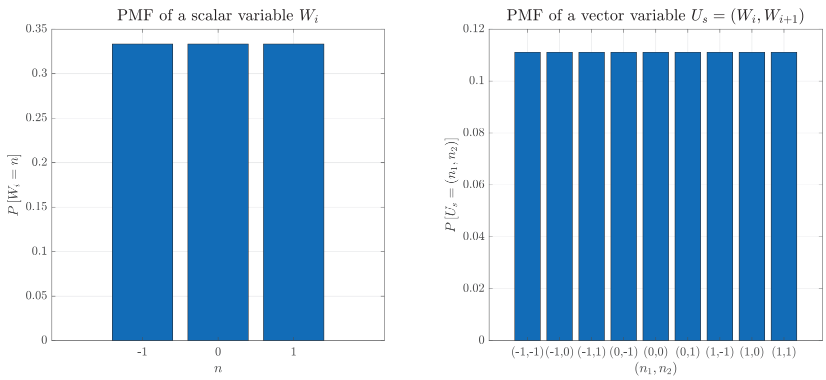
Grouping events: vector-valued RVs



By forming groups of $m = 2$, the new distribution is still uniform, but on a sample space with $3^m = 9$ elements $\Rightarrow$ discard one outcome, keep 8. The **available min-entropy** $\lfloor H_\infty \rfloor < H_\infty$ is increased!

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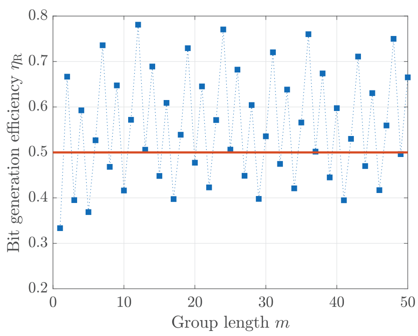
Which group length to choose?

- Bit generation efficiency: function of m
- $$\eta_{\mathrm{R}}(m) = \underbrace{\frac{\lfloor m \cdot \log_2(3) \rfloor}{2m}}_{\eta_{\mathrm{R,A}}(m)} \cdot \underbrace{\frac{2^{\lfloor m \cdot \log_2(3) \rfloor}}{3^m}}_{\eta_{\mathrm{R,B}}(m)}$$ $\eta_{\mathrm{R}}(2) = 0.667, \eta_{\mathrm{R}}(7) = 0.736$



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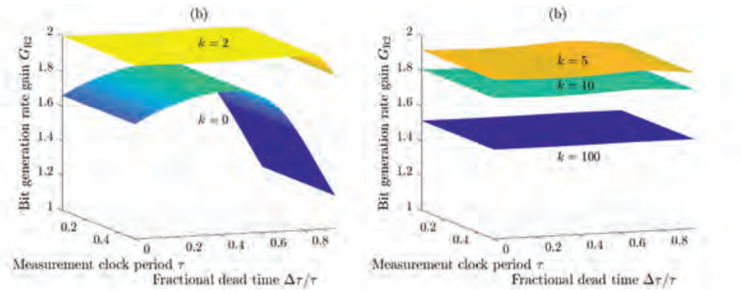
Bit generation gain



- Bit generation gain: comparing the respective maxima of methods (with different parameter sets; shown for $m = 2$)
- Both methods in the new settings: new is more efficient and faster
- Both methods on the same hardware: new is more efficient and faster

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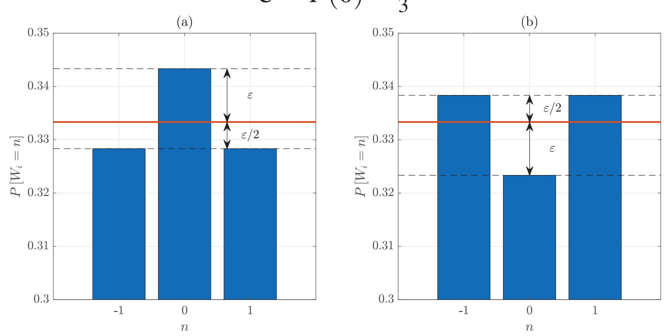
Error model: base distribution

$$\varepsilon = P(0) - \frac{1}{3}$$



- Symmetric, as successive times of arrival are still i.i.d.
- Non-uniformity depends on λ, τ and τ_d

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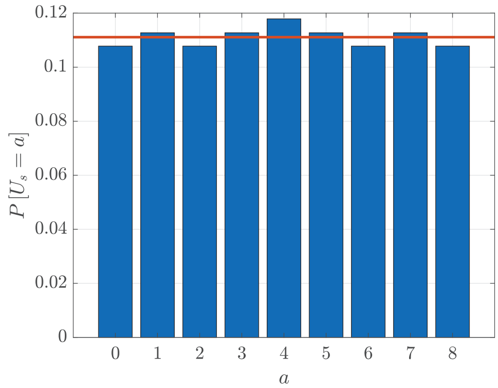
Error dispersion by grouping



Grouping disperses the deviations from uniformity ($m = 2$ shown here)

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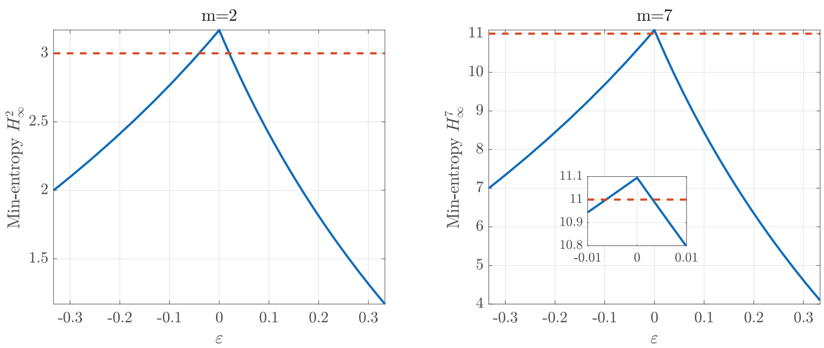
Boundaries for the min-entropy



Error bounds to keep the required min-entropy

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Bias-free coding

$\mathscr{B}_2 = \{0,1,2,3,5,6,7,8\}$

a	W_{2i-1}	W_{2i}	$p(a) = P[W_{2i-1}, W_{2i}]$	Bits	Weight w_a
0	-1	-1	$p_{0,2}$	000	0
1	-1	0	$p_{1,2}$	001	1
2	-1	1	$p_{0,2}$	010	1
3	0	-1	$p_{1,2}$	011	2
4	0	0	$p_{2,2}$	-	-
5	0	1	$p_{1,2}$	100	1
6	1	-1	$p_{0,2}$	101	2
7	1	0	$p_{1,2}$	110	2
8	1	1	$p_{0,2}$	111	3

A bias-free coding function for m=2

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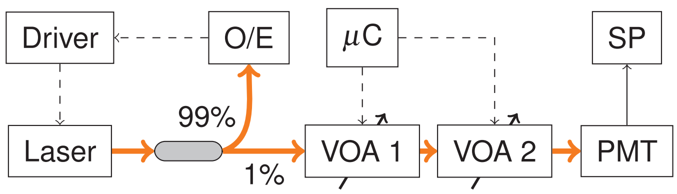
Experimental results



- Optical power control to maintain the desired λ
- Software-defined measurement clock, periodically updated
- Measured error ε well within min-entropy bounds
- Passing 188/188 NIST STS tests @$m = 7$ // at least 187/188 @$m = 2$
- On the given hardware, the generation rate showed a 47.25% increase compared to the old method.

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Future plans

- Different ToA generation schemes
- Improvement over previous models
  - In a figure of merit (efficiency, rate)
  - In robustness
  - In inherent uniformity
- New, extended mathematical analysis techniques
- Refinements of the hardware, potential extensions

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Thank you for your attention!

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Libera Sync

Reference clock transfer system with fs phase stability

Sebastjan Zorzut, Dejan Tinta and Manuel Cargnelutti

Introduction

– Modern technologically advanced and spatially distributed systems, such as particle accelerators or parabolic antenna arrays are, require time synchronization of individual subsystems at the femtosecond level. In addition to the long-term stability of such synchronization, exceptional spectral purity and low added jitter of the clock used for synchronization are also required.

Figure 1: Libera Sync existing and potential users.

System requirements

- Long-term stability: <100 fs/day at 3GHz
- Added jitter : < 10 fs at 3GHz
- Imunity to disturbances from the environment
- The ability to transmit the clock over distances in the order of a kilometer
- The ability to compensate drifts in the optical transmission path of up to 500 ps
- The ability to be integrated into the user control system
- System reliability and robustness, easy to use

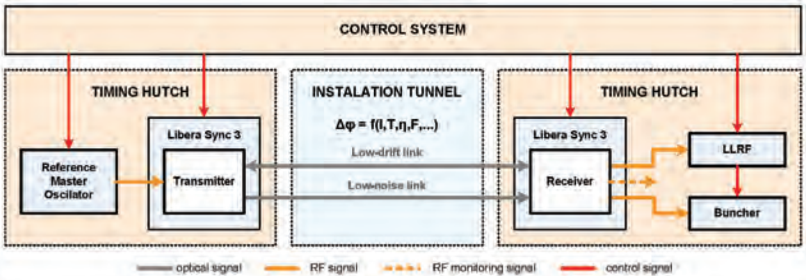

Figure 2: Libera Sync instalation and integration with user control system.

System architecture

– The Libera Sync system consists of a transmitter and receiver unit. Optical fiber is used for the transmission line due to its low loss, capability to implement active phase drift compensation and the maturity as well as availability of technology. The Libera Sync uses 3 control loops to compensate phase drifts in the electronics and in the optical transmission line. Electronic circuits and optical components are temperature stabilized to 0.01°C. Large phase drifts in the optical link are compensated with temperature-regulated optical spool that acts as delay line. Low added jitter is achieved by careful selection of ultra low-noise electronic components and appropriate design of electronic circuits as well as by use of low-noise optical link. System is self tuned and ofers abundant diagnostic data.

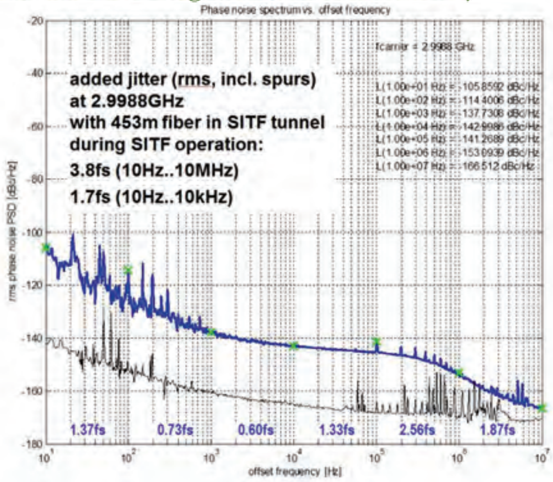

Figure 3: Libera Sync added jitter.

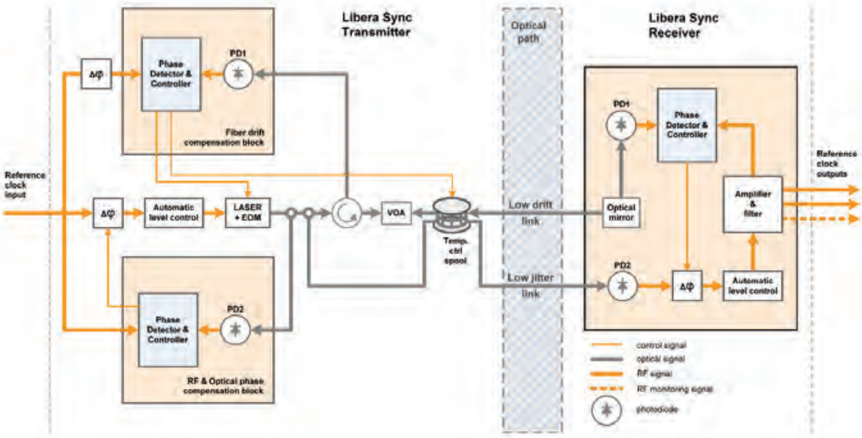

Figure 4: Libera Sync architecture.

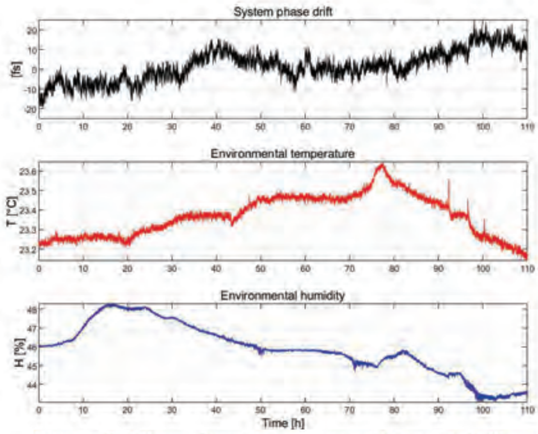

Figure 5: Libera Sync long-term phase stability.

Results

– Over 60 systems have been built and installed worldwide.

In case the transmitter and receiver units are installed in stable environment the long-term phase stability is of the order of several tens of fs/day otherwise an additional influence of environment conditions on performance can be observed. We have learned a lot through the development, testing and production of such a complex and precise system and we continue to use the acquired knowledge daily in the development of new products.

Literature

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[3] P. Orel, S. Zorzut et al.,"Test Results of the Libera Sync 3 CW Reference Clock Transfer System", IPAC (2014).
[4] S. Zorzut, M. Cargnelutti et al.,"Influence of environment changes on Libera Sync 3 long-term stability", FEL(2015).

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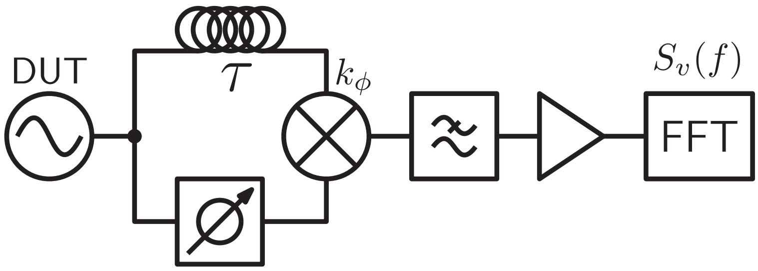
Analogna optična zveza za merjenje faznega šuma

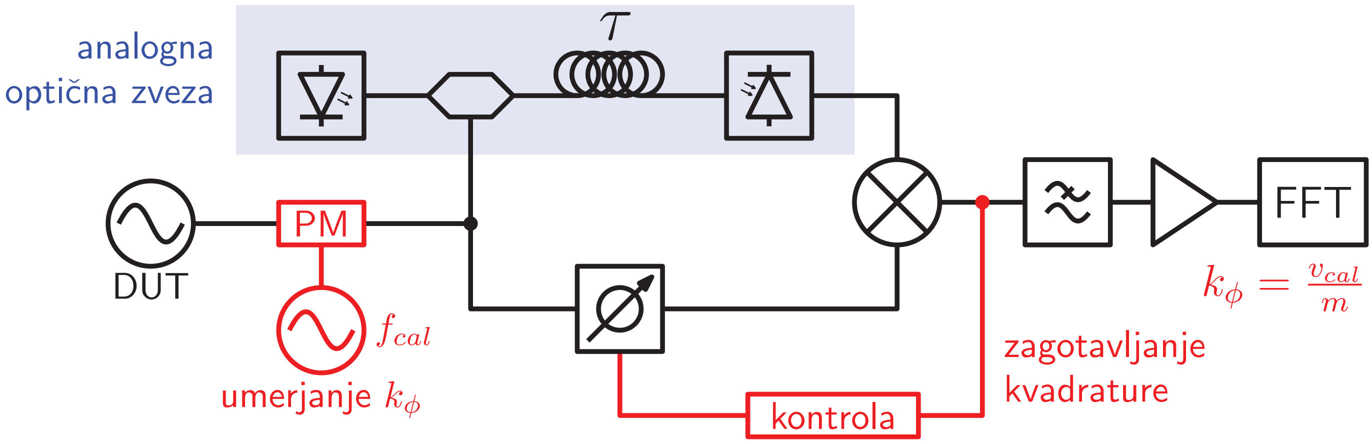
Andrej Lavrič, Boštjan Batagelj, Matjaž Vidmar

Merjenje faznega šuma spada med zahtevnejše meritve sodobnega inženirja elektrotehnike. [1] Postopek s kasnilnim vodom omogoča meritev brez kakovostne reference. Z mešanjem signala z lastno zakasnjeno kopijo preslikamo fazni šum v osnovni pas, kjer dolžina zakasnitve določa občutljivost za ceno manjše pasovne širine spektra šuma.



$$S_\phi(f) = \frac{S_v(f)}{4k_\phi^2|\sin\pi\tau f|^2} \qquad \mathscr{L}(f) = \frac{1}{2}S_\phi(f)$$

Klasični električni prenosni vodi so s svojimi izgubami dolgo omejevali uporabnost postopka s kasnilnim vodom. S pojavom optičnega vlakna in razvojem mikrovalovne fotonike je postopek ponovno postal privlačen. [2] Optično vlakno s svojimi majhnimi izgubami omogoča dovolj dolgo zakasnitev za uporabne občutljivosti merilnega sistema.



Poleg zadostne zakasnitve sta za dobro meritev potrebna tudi pravilni režim delovanja in umerjanje. [3] Kvadratura na vhodu mešalnika zagotavlja, da ta deluje kot fazni detektor. Z umerjanjem pa določimo konstanto detektorja k_ϕ.

Samodejno nastavljanje in umerjanje merilnika z optičnim kasnilnim vodom je enostavno in cenovno dostopno. Z enosmernim signalom iz izhoda mešalnika preko povratne vezave krmilimo fazni sukalnik, tako da sta vhoda mešalnika v kvadraturi. Konstanto detektorja k_ϕ določimo s fazno modulacijo merjenca z znanim modulacijskim indeksom m.

[1] U. L. Rohde, A. K. Poddar and A. M. Apte, "Getting Its Measure: Oscillator Phase Noise Measurement Techniques and Limitations,"in IEEE Microwave Magazine, vol. 14, no. 6, pp. 73-86, Sept.-Oct. 2013, doi: 10.1109/MMM.2013.2269860
[2] E. Rubiola, E. Salik, S. Huang, N. Yu, and L. Maleki, "Photonic-delay technique for phase-noise measurement of microwave oscillators,"J. Opt. Soc. Am. B 22, 987-997 (2005). https://doi.org/10.1364/JOSAB.22.000987
[3] Lavrič, A.; Batagelj, B.; Vidmar, M. Calibration of an RF/Microwave Phase Noise Meter with a Photonic Delay Line. Photonics 2022, 9, 533. https://doi.org/10.3390/photonics9080533

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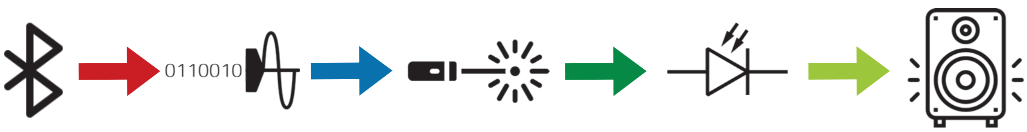
Laserski prenos zvočnega signala

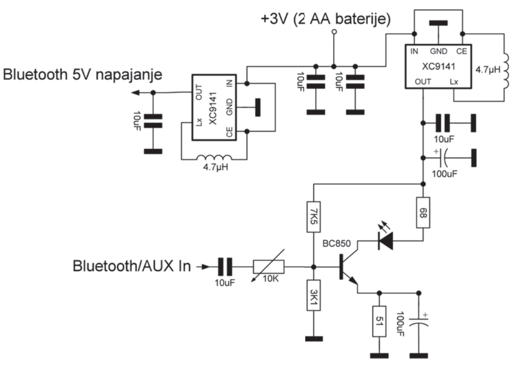
Luka Podbregar, Luka Zmrzlak, Aljaž Blatnik

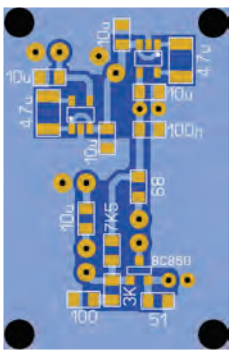
Uvod – Prenos signala na dolge razdalje najatraktivneje prikažemo z uporabo svetlobe. Poizkus postane še bolj zanimiv, če v prenosno pot dodajamo motnje. Najpreprosteje to naredimo kar z odrsko meglo! Predstavljen poizkus prikazuje izgradnjo enostavnega vezja, ki služi kot prikaz načina komuniciranja z uporabo prostozračne optične povezave. Na voljo je tudi kot kit komplet, ki ga je mogoče sestaviti v osnovni šoli z zelo osnovno elektrotehniško opremo. Služi kot promocija elektrotehnike mlajšim generacijam.

Prostozračna optična povezava – Optično povezavo je mogoče vzpostaviti tudi v praznem prostoru brez uporabe optičnega vlakna. Najstarejši zgled za takšno zvezo so dimni signali, ki hkrati razkrivajo slabosti takšnih komunikacij, to sta majhna zmogljivost zveze ter občutljivost za motnje in omejitve razširjanja svetlobe v ozračju. Domet prostozračne optične zveze je zato precej boljši sredi jasne noči kot podnevi v megli. Z uporabe umetne megle lahko na poizkusu opazujemo vpliv vremenskih pojavov na prostozračne optične povezave.

Signalna pot – Poizkus prikazuje prenos zvočnega signala, ki svojo pot začne v digitalni obliki na poljubnem predvajalniku glasbe. Zaradi odsotnosti analognih priključkov mobilnih naprav, je zvok do laserskega oddajnika prenesen preko povezave Bluetooth. Zvočni zapis najprej pretvorimo v amplitudno modulacijo laserskega žarka, tega pa usmerimo v sprejemno fotodiodo, ki optični signal zopet pretvori v električnega, predvajano glasbo pa lahko poslušamo na zvočniku.

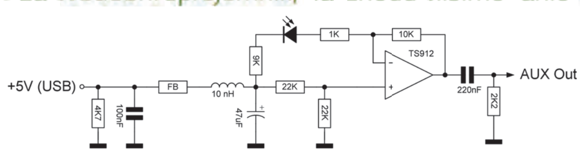


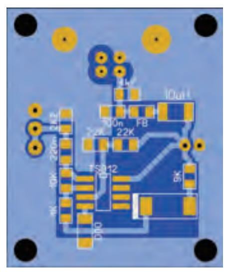




Oddajnik – Bluetooth sprejemnik za svoje delovanje potrebuje 5 V napetosti. Ker so AA baterije veliko cenejše od 9 V baterij, v vezje vključimo preprost stikalni napajalnik, ki zagotavlja stabilno napetost kljub praznjenju dveh AA baterij. Tok skozi lasersko diodo spreminjamo z NPN tranzistorjem, z ustrezno enosmerno delovno točko in preprostim spreminjanjem ojačenja avdio signala preko vrtljivega potenciometra. Tega nastavimo tako, da dosežemo čim večjo amplitudno modulacijo brez slišnega popačenja zvočnega signala. Ker Bluetooth sprejemnik proizvaja precej motenj na svojih priključkih, moramo napetost zanj proizvesti z ločenim stikalnim napajalnikom.

Sprejemnik – 5 V napetost za sprejemnik dobimo kar preko USB polnilnika za telefon, zato na vezje namestimo ustrezen priključek. Moduliran laserski signal s fotodiodo pretvorimo v električnega, ki ga ojačamo z operacijskim ojačevalnikom. Ker gre za svetlobni sprejemnik, na izhodu slišimo rahlo brnenje, ki je sicer odvisno od uporabljenih luči v prostoru. Pojav precej omilimo že z namestitvijo preprostega visokoprepustnega sita na izhodu in z izvajanjem poizkusa v temi.





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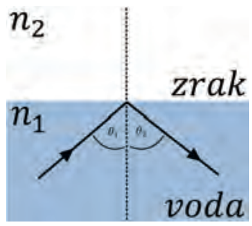
Žarek ujet v vodnem curku

Luka Zmrzlak, Luka Podbregar, Aljaž Blatnik

Uvod – Vas navdušuje ideja, da svetloba potuje po majhnem steklenem ali plastičnem vodniku na dolge razdalje, s tem pa dosega izjemno zanesljivo komunikacijo? Kako je to sploh mogoče? Odgovor se skriva v popolnem odboju.

Leta 1621 je nizozemski matematik Willebrord Snellius odkril zakonitost popolnega odboja, ki ga danes imenujemo Snellov lomni zakon. Gre za pojav, pri katerem se vpadni žarek na meji med optično gostejšo in optično redkejšo snovjo v celoti odbije, če je le vpadni kot večji od mejnega. V optičnem vlaknu jedro s svojo oblogo ustvarja ustrezne pogoje za popolni odboj svetlobe in s tem navidezno ujetje žarka v drobno stekleno strukturo. Pojav lahko z malo iznajdljivosti prikažemo tudi z vodnim curkom, kjer laserski žarek potuje po celotni ukrivljeni poti vse do zbiralnega bazena. Vsak vodni curek iz vrtne cevi žal ne bo primeren, saj njegova povsem neravna površina slej kot prej povzroči vpadni kot manjši od mejnega in žarek iz curka uide. Kako umetno ustvariti gladek curek (za katerega se zdi, da je zamrznil v prostoru), vanj pa ujeti laserski žarek, je svojevrsteni tehnični izziv.

Laminarni tok - Vrsto pretoka tekočine, pri katerem se voda giblje v vzporednih plasteh brez turbulence ali mešanja med plastmi, imenujemo laminarni tok. Običajno je vzorec toka opisan s "tokovnicami", to so črte, ki povezujejo točke iste smeri. Pri laminarnem toku so te vzporedne in se ne križajo, kar prinaša gladek in enakomeren izhodni curek. Nasprotno je za turbulentni tok značilno kaotično, nepredvidljivo gibanje in s tem mešanje med različnimi plastmi tekočine. To pogosto opazimo v odprtih kanalih, kot so rečne struge, drenaže meteornih voda in v večjih vodnih virih (oceanih). Doseganje kakovostnega laminarnega toka, je ključnega pomenza za uspešno izvedbo predstavljenega optičnega poskusa. Zelo gladek prehod med vodo in zrakom ohranja enak prostorski kot vpadnega žarka svetlobe, kar omogoča opazovanje popolnega odboja v skoraj celotnem delu curka povsem do izliva v zbiralni bazen. V primeru črpanja vode s propelersko črpalko, je za doseganje laminarnega toka potrebno izdelati namensko šobo.



$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

Zgradba – Pri načrtovanju nastavka (šobe) za ustvarjanje laminarnega toka vode je potrebno zmanjšati tlak znotraj cevi, umiriti pulzirajoč učinek črpanja z akvarijsko črpalko in obrniti tokovnice vode v isto smer. Strukturno najlažje zgradimo z uporabo plastičnih odtočnih cevi za katere je še mogoče dobiti zaključne čepe. Po začetnem votlem prostoru sledijo plasti drobne abrazivne gobice za brušenje, odrezane na notranji presek cevi. Te zelo učinkovito poskrbijo za dušenje nenadnih sprememb tlaka vodne črpalke. Sledi več sto plastičnih slamic dolžine 190 mm in premerom 6 mm (gostinske slamice za večkratno uporabo), ki jih v skupek drži tanka mreža za komarje. Ta je vpeta v plastični obroč, ki se vstavi v notranjost odtočne cevi. Na sredini je nameščen zelen laser zaprt v aluminijasto ohišje, ki se hladi z okoliško vodo. Po nekoliko daljšem praznem prostoru (preostanek odtočne cevi) je v zaključni čep zvrtana luknja, šoba pa je izdelana iz tanke aluminijaste pločevine, katere robovi so natančno in gladko brušeni v lep krog. Prav natančno brušenje šobe je tisto, ki pri izdelavi uporabnega prototipa določa kakovosten laminarni tok, saj bo najmanjša izboklina zopet povzročila turbolentni tok, zelen laserski žarek pa bo iz takšnega curka „pobegnil". Premer kroga določa debelino izhodnega curka čigar doseg je odvisen od pretoka črpalke.

Prototip nastavka za ustvarjanje laminarnega toka s priklopom za vrtno cev in USB priključkom za napajanje laserja. Pogled od znotraj, prikaz šobe, stranski in bočni prerez.

O seminarju
The seminar

Strokovni seminar Optične komunikacije se je razvil iz izobraževalne dejavnosti, ki jo je pod okriljem projekta TEMPUS JEN-04202 v letih 1993 do 1997 izvajala Fakulteta za elektrotehniko Univerze v Ljubljani. Seminar je namenjen strokovnemu izpopolnjevanju strokovnjakov optičnih komunikacij in drugih, ki jih to področje zanima. Vključen je v program izvajanja vseživljenjskega izobraževanja na Fakulteti za elektrotehniko v Ljubljani. Njegov namen je osveževanje, razširjanje izpopolnjevanje in poglabljanje znanja ter dvig strokovnosti zaposlenih strokovnjakov na področju optičnih komunikacij. Seminar obsega uvodni del, namenjen obnavljanju in razširjanju znanja, ter strokovni del, namenjen seznanjanju in poglabljanju v strokovna vprašanja o sistemih in njihovih sestavnih delih. Izvedenski del seminarja, ki ga izvajajo priznani vabljeni strokovnjaki, obsega nekatera pomembnejša razvojna vprašanja.

Seminar on Optical Communications evolved from the activities running at the Faculty of Electrical Engineering University of Ljubljana, during the period from 1993 to 1997 under the auspices of the European project TEMPUS JEN-04202 granted for the same period. The seminar si intended to communication professionals and other involved into the field of optical communications. It is part of the continuing education programme at the Faculty of Electrical Engineering in Ljubljana. Its primer porpuse is to enhance the expertise of professionals in the field of optical communications. The seminar consists of two parts: one part is dedicated to basic technical topics aiming to refresh fundamental knowledge in optical communications, and the second part is intended to the latest research and development achievements and trends from spectrum regulation, standardization, systems and solutions, all from international and national experts.

Ključna gesla
Keywords

10G-EPON, DWDM, EPON, F5.5G, Fabry-Periot laserska dioda, fazni šum, FTTH točka-točka, FTTH točka-več točk, generiranje kvantnih naključnih števil, GPON, hitri vtični moduli, integriran polarizacijski razcepnik, integrirana fotonska vezja, integrirana optika, kvantna distribucija ključev, kvantni ključi, kvantno fotonsko integrirano vezje, kvantno šifriranje, mikroobročni resonator, NG-PON2, OLT, ONU, OPGW, optična omrežja, optične modulacije, programirljivi PON, ROADM, sinhronizacija, strojno učenje, umetna inteligenca, večdimenzionalni modulacijski formati, vlakenski laserji, vlakenski oddajnik, XGS-PON, xPON, zaznavanje z optičnimi vlakni

10G-EPON, artificial inteligence, DWDM, EPON, F5.5G, Fabry-Periot laser diode, fast plug-in modules, fiber lasers, fiber optic transmitter, fiber sensing, GPON, integrated optics, integrated polarization splitter, machine learning, micro-ring resonator, multidimensional modulation formats, NG-PON2, OLT, ONU, OPGW, optical modulations, optical networks, P2MP FTTH, P2P FTTH, phase noise, photonic integrated circuits, quantum encryption, quantum key distribution, quantum keys, quantum photonic integrated circuit, quantum random number generation, ROADM, software defined PON, synchronization, XGS-PON, xPON

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