CONVERGENCE OF FIXED AND MOBILE NETWORKS BY RADIO OVER FIBRE TECHNOLOGY

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Key words: Radio over Fibre, remote antenna unit, cellular architecture, fibre access, fixed and mobile convergence

Abstract: This article presents a solution for the convergence of mobile and fixed access networks on the physical level that allows different service providers to share the same mobile infrastructure. A mobile cell solution is presented which features a fibre optic access infrastructure that is independent of the standard and allows the transmission of different types of broadband telecommunication traffic. For an efficient broadband network frequencies in the millimetre-wave range need to be used (30 – 300 GHz) and the cell size needs to be reduced to a pico (100 m) or even femto (10 m) of a cell.

The network presented is based on the transmission of a radio signal over optic fibre, namely 'Radio over Fibre' (RoF). The goal is to transfer complex signal processing functions from the base station to the central station. This decreases the costs of remote antenna units in the base station, making a larger number of picocells a viable solution. Uneconomical radiofrequency signal processing functions such as (de)modulation, synchronisation, multiplexing, frequency hopping, spread spectrum technology and other technologies are now located in the central station. The RF signal created in the central station is distributed through remote base station antenna units which cover the picocells used by mobile users. This article also presents the key building blocks of the RoF system, such as a photodiode with an integrated antenna, an electro absorption modulator, an optic millimetre-wave generator with a phase-locked loop and an optic-controllable antenna.

Zlivanje mobilnih in fiksnih omrežij s tehnologijo prenosa radijskega signala preko optičnega vlakna

Kjučne besede: prenos radiofrekvenčnega signala prek optičnega vlakna, oddaljena antenska enota, celična arhitektura, vlakenski dostop, fiksno in mobilno zlivanje

Izvleček: V članku je predstavljena rešitev za zlitje mobilnih in fiksnih dostopovnih omrežij na fizičnem nivoju, kar omogoča različnim ponudnikom storitev souporabo iste prenosne infrastrukture. Predstavljena je mobilno-celična rešitev z optično vlakensko dostopovno infrastrukturo, ki je neodvisna od standarda in omogoča prenos raznovrstnega širokopasovnega telekomunikacijskega prometa. Za učinkovito širokopasovno omrežje je potrebno uporabiti frekvence v milimeterskem valovnem področju (30 – 300 GHz) in zmanjšati velikost celice na piko (100 m) ali celo femto (10 m) celice.

Osnova predstavljenega omrežja je prenos radijskega signala preko optičnega vlakna (angl. Radio over Fiber – RoF), katerega cilj je premestitev kompliciranih funkcij za obdelavo signalov iz bazne postaje na centralizirano postajo. S tem se zmanjšajo stroški oddaljene antenske enote v bazni postaji, tako da je večje število pikocelic smotrna rešitev. Potratne radiofrekvenčne signalno procesne funkcije, kot so (de)modulacija, sinhronizacija, razvrščanje, frekvenčno skakanje, tehnike razširjenega spektra in ostale morebitne so izvedene v centralni postaji. V centralni postaji pripravljen RF signal je razdeljen med oddaljenimi antenskimi enotami baznih postaj, ki pokrivajo pikocelice, kjer se nahajajo mobilni uporabniki. V članku so predstavljeni tudi ključni gradniki RoF sistema, kot so fotodioda z integrirano anteno, elektroabsorpcijski modulator, optični generator milimeterskih valov s fazno sklenjeno zanko in optično vodljiva antena.

1. Introduction

The main representatives of today's and future /1/ wireless radio communications are mobile communications and nomadic communications where the user is somewhat less mobile. There are also fixed directional radio connections and fixed one-to-multiple point radio connections, however fibre connections are the most suitable for the stationary user. This renders fixed radio connections obsolete except in cases where optic fibre lines have not yet been laid, or where telecommunication network redundancy needs to be ensured.

A fibre optic link is superior to a radio connection in both parameters of significance which determine the value of telecommunication lines /2/. The first is the range of the telecommunication line measured in units of length, where optic fibre is the absolute winner with the attenuation of 0.2 dB/km. The second parameter is link capacity which measures the amount of information transmitted in units of time, where the optic fibre's broadband properties make it a practically bandwidth unlimited medium.

Fixed-mobile convergence is a phenomenon which involve services, applications, devices and networks. Meanwhile the service and application convergence have started already /3/, device and network convergence are still on hold since fixed and mobile industry are not ready to merge and to build an integrated radio-optical platform for efficient end-to-end service delivery with guaranteed performance. Although network convergence seems far away from nowadays techno-economical reality, this paper presents technical solutions for the convergence of mobile and fixed access network. Since the end user want to have wireless broadband access, the access network is main convergence point of interest.

Today, most base stations are connected to central stations via fibre optics, using the Plesiochronous Digital Hierarchy (PDH), Asynchronous Transfer Mode (ATM) or IP transfer systems. The base station is where conversion to radio frequency occurs, bringing a broadband signal to the user's mobile station, as illustrated in Figure 1. Across greater distances, transmission from the central station to the base stations is achieved via fibre optics. Across smaller distances within the cell area transmission from the base station equipped with an antenna unit to the user is achieved wirelessly using radio waves.

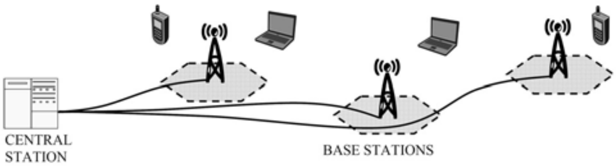

Fig. 1: Network segmentation by picocells.

For short-range communications, the frequency range of around 60 GHz has been identified, which is the absorption peak of oxygen molecules. Since atmospheric attenuation for millimetre waves is high, radio propagation is limited to small area. For an efficient broadband network frequencies in the millimetre-wave range need to be used (30-300 GHz) and the cell size needs to be reduced to a pico (100 m) or even femto (10 m) radius of a cell.

In the new radio frequency plan prepared by Electronic Communications Committee (ECC) within the European Conference of Postal and Telecommunications Administrations (CEPT) /4/, it is clearly evident that frequency bands from 57 GHz to 66 GHz are used for broadband data transmission. The 62 GHz to 63 GHz band is reserved for land mobile broadband connections. The 60 GHz band is highly suitable for use in home communication /5/ where we can already see the first examples of its commercial use.

2. Radio over Fibre

The basic idea of technology which allows the transmission of a radio frequency (RF) signal over fibre (Radio over Fibre - RoF) is a simple combination of fixed fibre and mobile RF transmission. The transmission of an RF signal over fibre using optical media /6/ is viable where the network is accessible to the end-user wirelessly using the cellular network.

The common principle, which has been in use for a number of years and can be seen in most currently available commercial cellular networks, is illustrated in Figure 2. Optical fibre is used as an effective substitute for a twisted pair or coaxial cable. Through an optical line, comprising an emitting laser diode (LD) and photodiode (PD) transmission is achieved with PDH or ATM, which in recent times are being replaced by IP. With this type of solution the transition from wired to wireless transmission requires a complex signal conversion at each base station. Frequency mixers and a reference RF oscillator are used to up-convert the baseband signal into the modulated carrier needed for the wireless transmission. This network architecture is complex and uneconomical due to its large number of cells.

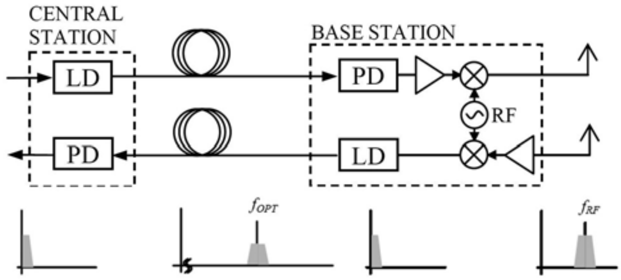

Fig. 2: Transmission over fibre in the baseband and signal processing at the base station.

A fibre optical line with a large bandwidth allows the transmission of data signals directly over the RF carrier. In this way complex signal conversions at the base station side can be avoided. The complex signal processing functions are transferred from base stations to the central station. Thus, radiofrequency signal processing functions such as (de)modulation, synchronisation, multiplexing, frequency hopping, spread spectrum technology etc are now carried out at the central control station. The transmission of broadband signal above described is illustrated in Figure 3. In a practical network with a large number of terminal base stations and a small number of central stations, the above type of RoF transmission brings a significant economical advantage.

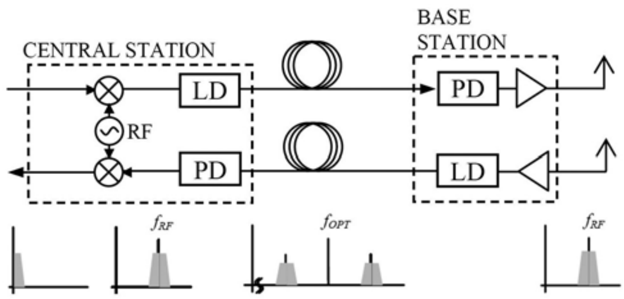

Fig. 3: RF signal transmission over fibre and signal processing at the central station.

A transmission from the central station to individual base stations can be made also over a single optic fibre using wavelength-division multiplexing (WDM), as shown in Figure 4. However, from a practical standpoint the dual-fibre concept is easier to implement.

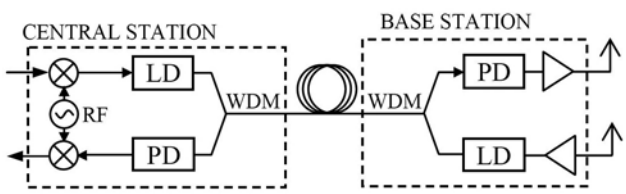

Fig. 4: RF signal transmission via an optic WDM connection.

It makes sense to use the same antenna for signal transmission and reception at the base station where the transmission and reception signals are joined/divided via a micro-wave circulator (Figure 5). In this case, the base station contains a laser, photodiode, circulator, RF amplifiers, control unit and power circuitry. Although it is all packed into a small casing, the unit is still quite complex.

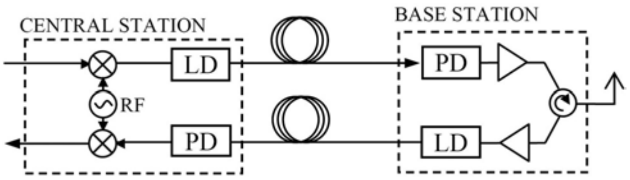

Fig. 5: RF signal transmission via fibre optic and transmission and reception via a single antenna.

In order to reduce the number of elements, it was proposed to replace the laser, photodiode and circulator with a single semiconductor electroabsorption modulator (EAM) /7/. This device can act as both a receiver and transmitter. The advantage of such a solution is that a laser source is no longer necessary at the base station. This makes a remote antenna unit much less complex and costly /8/.

A remote antenna unit can be further simplified (Figure 6) if radio coverage is limited to a small area. This eliminates the need for RF amplifiers and the electroabsorption modulator can operate without any biasing. In this case, the base station consists only of an electroabsorption modulator and antenna /9/.

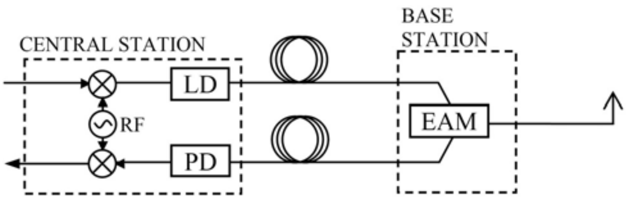

Fig. 6: RF signal transfer via fibre optic and the use of an electroabsorption modulator.

The use of carrier re-modulation at the base station rather than a local light source is promising technique. Avoiding stabilisation and provisioning issues associated with a laser at base station is a good way of reducing installation and maintenance costs. An electroabsorption modulator integrated with a reflective semiconductor optical amplifier (R-SOA) can provide optical amplification and optical modulation in a single device /10/. As shown in Figure 7, the implementation of R-SOA with EAM into RoF system is replacing dual fibre link by only one single

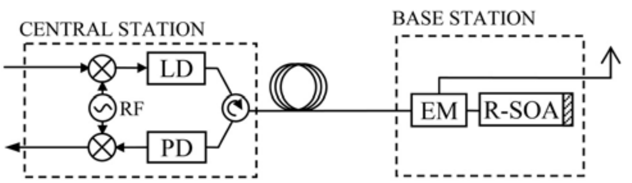

Fig. 7: RF signal transfer via fibre optic and the use of an electroabsorption modulator and R-SOA.

It should be noted that there are certain disadvantages of processing the RF signal at the central station. Due to the broadband nature of the RF signal, it is often impossible to directly modulate the laser and therefore an external Mach-Zehnder modulator (MZM) is required. Furthermore, the amplitude modulation is highly sensitive to chromatic dispersion of the optical fibre which accumulates with the length of fibre /11/. As the optical signal is transferred across the fibre with the carrier and double sidebands, the chromatic dispersion causes a different phase delay on each of the spectral components, as shown in Figure 8.

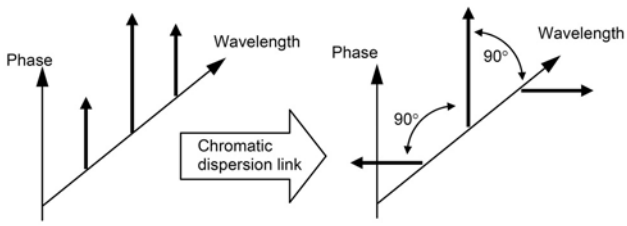

Fig. 8: Chromatic dispersion changes the phase relationship between the optical carrier and upper and lower sideband.

The phase delay depends on the fibre length, modulation frequency and dispersion coefficient. The power of detected signal is length dependent /12/

$$P(L, f_{\text{mod}}) \propto \cos\left(\pi LcD\left(\frac{f_{\text{mod}}}{f_0}\right)^2\right),$$

where L is the fibre length, c is the speed of light in free space, D is the fibre dispersion coefficient, f_0 is the optical carrier frequency, and f_{mod} is the frequency of subcarrier.

If the phase delay between the sidebands at the end of the fibre line is 180°, the destructive mixing on the photodiode will negate the entire RF signal, as shown in Figure 9. For an example of the standard single-mode optical fibre with a 17 ps/(nm km) dispersion at 1550 nm, a 3 dB RF signal degradation for double sideband modulation occurs at 6 km, at a 20 GHz modulation frequency. At a 60 GHz

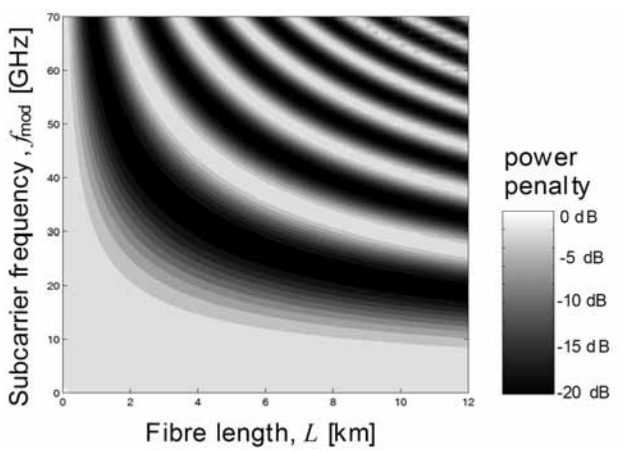

Fig. 9: Power penalty of the RF signal depending on the fibre length and modulation frequency.

modulation frequency a 3 dB degradation already occurs at 0.7 km /13/.

Direct modulation is only applicable for frequencies up to 10 GHz. For higher frequencies the limiting dispersion occurrence can be reduced by using a single sideband modulation /14, 15/ with an optic filtration or specially controlled MZM.

With detailed knowledge of the dispersion characteristics of the RoF system, the disruptive phenomenon can be used to one's advantage. In the special case of the optical regulation of an antenna array, the phenomenon is welcome as it enables control over the antenna array beam /16/.

In cases where a high level of resistance to dispersion is desired on the connection between the central and base station, the final signal processing must once again be transferred to the base station. Another reason for this is the limiting direct modulation of the laser source. Simultaneity, warless systems which are based on orthogonal frequency-division multiplexing (OFDM) are requiring RF signal source with high stability located in temperature regulated enviroment. Because greater complexity of the base station is undesirable, the optic generation of the carrier RF signal is recommended, as shown in Figure 10. The RF signal generation through optical photomixing eliminates the need for frequency stabilisation of the local oscillator due to the thermal dependence of the oscillation frequencies. Unfortunately, in case of presence of PMD in the transmission fibre, efficiency of RF signal is reduced or even equal to zero in the worst case. Consequently, low PMD fibre is required.

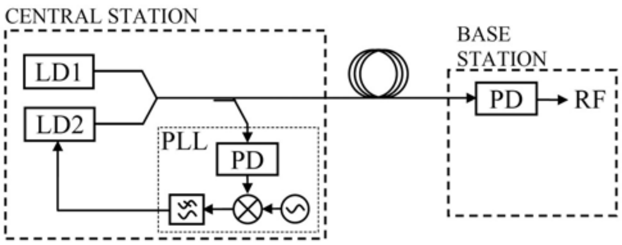

Fig. 10: Illustrations of RF signal generation through photomixing.

With separate optic carriers, the signal is transmitted from the central station over the baseband frequency. At the remote base station, the optical signals are mixed on the photodiode, creating a RF signal suitable for frequency conversion of the data signal in the mixer. The technology which uses separate optic lines for the data signal and for mixing signal is displayed in Figure 11. All optical lines can also be joined in a single optic fibre using WDM technology.

Unfortunately, power supply for amplifier and RF mixers is needed in base station location. Complication with electric power delivery can be avoided by using photonic power delivery /17/. In this case, the base station can be readily energized by high-power laser which illuminate optical energy and photovoltaic converter, as shown on Figure 12.

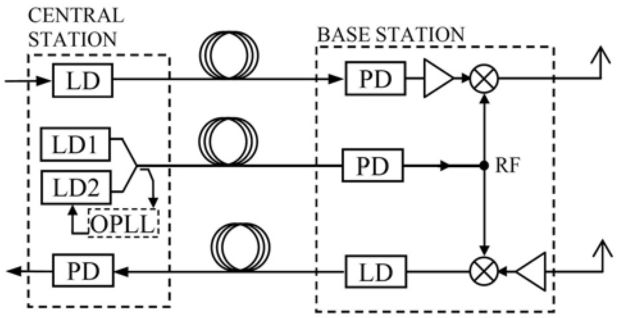

Fig. 11: Transmission by RF signal generation.

Photovoltaic cells can convert up to 50% of the incident light into electrical energy. If the wavelength of low fibre attenuation is used optical power can be transmitted up to 10 km. This approach offers total electrical isolation and independence of base station.

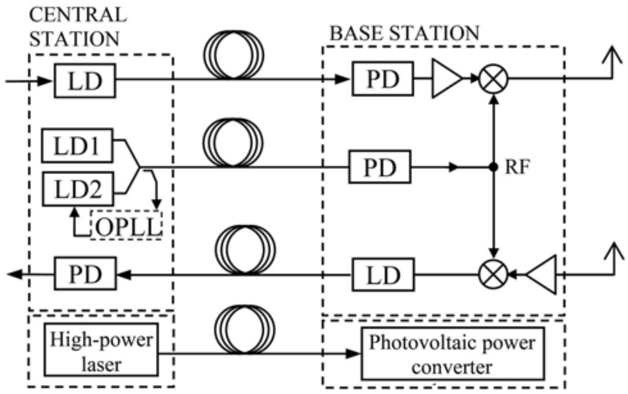

Fig. 12: Photonic power conversion delivers electric power to base station.

3. Key elements for Radio over Fibre technology

If we wish to create an RF signal through photomixing, the used photodetector needs a sufficient bandwidth for the relevant frequency area. Travelling wave photodiodes are currently the most suitable option for this /18/.

The optical carriers for photomixing can be obtained from two separate lasers where the signals are joined into a single optical fibre using an optical coupler. A dual-line laser can be used, which oscillates on two wavelengths simultaneously.

A heterodyne OPLL (Figure 13) allows the slave laser to be phase-locked to the master laser by a frequency deference equal to the frequency of the microwave reference. The offset frequency can in principle be arbitrary, but in practice is restricted by the bandwidth of the photodetector or microwave components. When the used optic sources are phase-locked there is no error signal at the phase detector output and the obtained RF signal is clear in terms of the spectrum and the phase noise. An electro-optical phase-locked loop /19/ is used for the phase locking of separate laser sources. Even when using very narrow linewidth solid-state lasers, the complete loop delay has to be kept very small to avoid cycle slips. An electro-optic phase-locked loop is not necessary if a dual-line laser is used as the laser's structure itself ensures phase harmonisation.

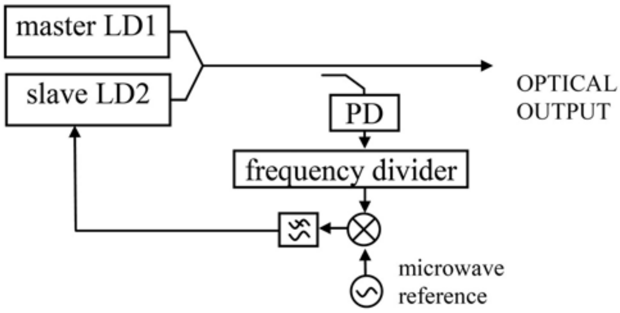

Fig. 13: Heterodyne optical phase-locked loop with frequency divider.

At the output of the photodetector, the issue of choosing a suitable waveguide arises due to the great bandwidth. In order to avoid the waveguide from the photodetector to the antenna, the photodiode can be placed on the antenna itself. As the antenna is much larger than the photodetector, the photodiode can be placed directly on the antenna's supply junction (Figure 14).

The antenna's working frequency range needs to cover the frequency area of the RF signal coming from the photodetector. As we are dealing with a broad frequency spectrum from several GHz to several THz, the antenna needs to be broadband to accommodate this.

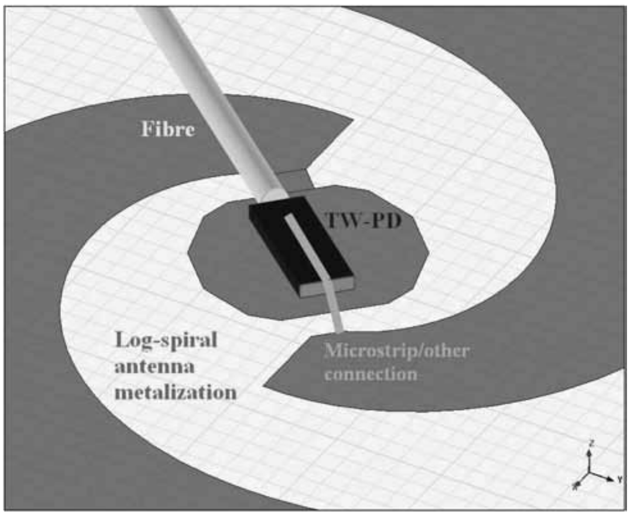

Fig. 14: Layout of the photodetector integrated with the planar antenna.

At the moment, the most appropriate option has proven to be the planar spiral antenna as it has a well-defined radiation pattern and relatively constant impedance over a broad frequency range. The spiral antenna rests on a hemispherical silicone lens (Figure 15). If the diameter of the spiral antenna is about 2 mm on a lens with the diameter of 4 – 8 mm the usable operating frequency range is above approximately 70 GHz. The calculated radiation pattern of this structure at 100 GHz is illustrated in Figure 16.

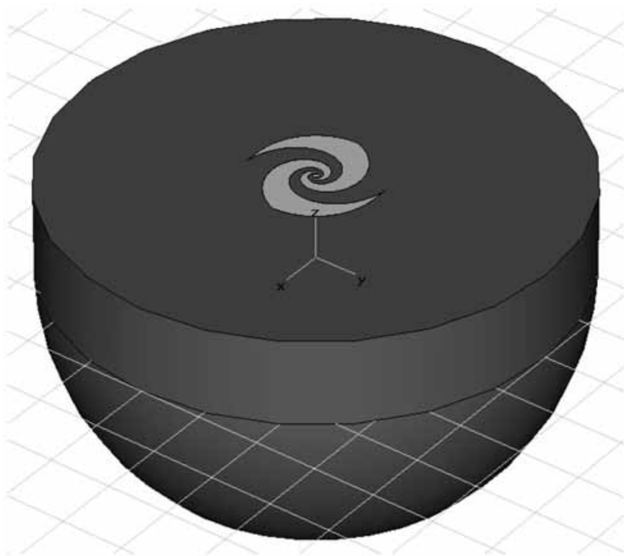

Fig. 15: Planar spiral antenna on a dielectric lens.

The antenna emits the main beam in the direction of the lens axis through the substrate and the lens. Side beams are relatively low. The gain is around 7 dBi at 100 GHz. The antenna's impedance is relatively constant and changes between 20 Ω and 80 Ω, which fits well to the impedance of the travelling wave photodetector.

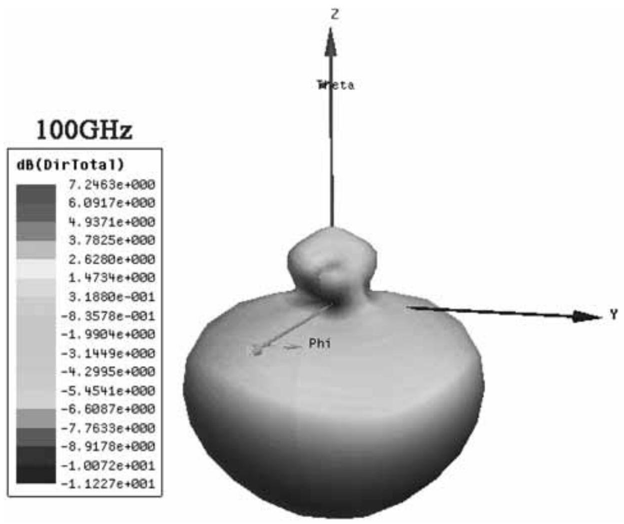

Fig. 16: Simulated radiation pattern of the spiral antenna on a hemispherical silicon lens at 100 GHz.

4. Conclusion

This article presents the convergence of mobile and fixed access network on the physical level. It describes a mobile solution based on a fibre optic access infrastructure which is standard independent. Presented convergent network architectures are able to transfer any telecommunication protocol.

With the aim of reducing the costs of a remote antenna unit of a picocell network, the solution is based on RoF technology. The RoF system transfers complex radio frequency signal processing functions from the base station to the centralised control station. However, all signal processing concentrated at central station brings some limitations manly due to fibre chromatic dispersion.

Among the presented uses of fibre optical lines for the distribution of radio frequency signal from the central location to the remote antenna units, the most attractive solution involves the large-scale integration of electro optical components. A simple base station consisting only of an electroabsorption modulator integrated with reflective SOA and antenna is certainly the best solution and supports different types of traffic. The use of carrier re-modulation at the base station rather than a local light source has been suggested as a way of reducing installation and maintenance costs. I the case when RF signal is generated by optical mixing in base station, power supply can be delivered as photonic power what further reduce implementation costs.

The presented key building blocks of the RoF system, such as the photodiode with an integrated antenna, electroabsorption modulator, optic millimetre-wave generator with a phase-locked loop and an optic-controllable antenna have been developed as prototypes and are ready for industrialization and use in both system solutions and networks.

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