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Towards THz Communications - Status in Research, Standardization and Regulation

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Abstract In the most recent years, wireless communication networks have been facing a rapidly increasing demand for mobile traffic along with the evolvement of applications that require data rates of several 10s of Gbit/s. In order to enable the transmission of such high data rates, two approaches are possible in principle. The first one is aiming at systems operating with moderate bandwidths at 60 GHz, for example, where 7 GHz spectrum is dedicated to mobile services worldwide. However, in order to reach the targeted date rates, systems with high spectral efficiencies beyond 10 bit/s/Hz have to be developed, which will be very challenging. A second approach adopts moderate spectral efficiencies and requires ultra high bandwidths beyond 20 GHz. Such an amount of unregulated spectrum can be identified only in the THz frequency range, i.e. beyond 300 GHz. Systems operated at those frequencies are referred to as THz communication systems. The technology enabling small integrated transceivers with highly directive, steerable antennas becomes the key challenges at THz frequencies in face of the very high path losses. This paper gives an overview over THz communications, summarizing current research projects, spectrum regulations and ongoing standardization activities.

Keywords THz communications · THz channel modeling · regulation · standardization

1 Introduction

The emergence of applications requiring wireless data rates of several 10s of Gbit/s [1] in combination with the general trend of a fast increasing demand of mobile traffic [2] motivates the need for either more spectrum-efficient transmission technologies or for more spectrum - or even both. A depiction of the evolution of data rates achieved by wireless system – known as Edholm's law of data rates - has been published first in [3] and updated in [4], see Figure 1. Under the assumption that the same trend will be observed in the future, it is obvious that around the year 2020 wireles data rates of around 100 Gbit/s will be achieved. Within the spectrum currently allocated to mobile services, the largest connected band can be found around 60 GHz, where a bandwidth of 7 GHz is globally available. There,

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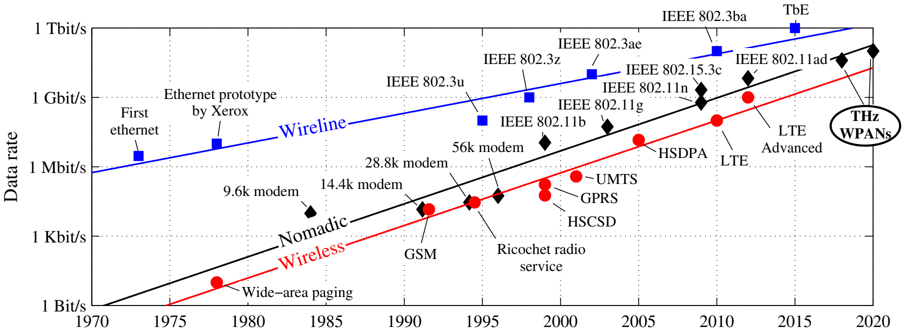

Figure 1 Development of data rates in wireline, nomadic and wireless systems (from [3])

data rates in the order of 100 Gbit/s can only be achieved with transmission schemes having a spectral efficiency of at least 14 bit/s/Hz, which is extremely challenging. An alternative approach to achieve 100 Gbit/s targets systems with moderate, realistic spectral efficiencies of a few bit/s/Hz and requires ultra high bandwidths far beyond 10 GHz. Sufficient unregulated spectrum can be found only in the THz frequency range, i. e. from 300 GHz to 3 THz. First ideas on concepts for communication systems operated in this frequency band have been published recently by various research groups from all over the world [5–8]. Making THz communications happen requires big efforts in fundamental and conceptual research, spectrum regulations and standardization. The intention of this tutorial paper is to provide a brief overview of the current status in all three areas. As those fields are developing rapidly, the paper provides an extension and update of a plenary key note presented at the FTT 2012 in Nara [9]. It is organized as follows. At first, Chapter II introduces exemplary potential applications for THz communications. Chapter III gives an overview of research activities dealing with the THz wave propagation and radio channel modeling, with system concepts as well as with technology.

2 Potential Applications for THZ Communications

Whereas the extrapolation of Edholm's law provides a justification for wireless data rates of 100 Gbit/s until 2020 purely based on the past and without an analysis of future demands, seven potential applications actually requiring such high throughputs are described in this section. The information is composed from [1, 10, 11].

- ***Wireless local area networks (WLAN):*** This application means ultra-high speed connections to access points with mostly nomadic users. Typical operations will be mainly indoors with coverage ranges in the order of 10 m. Although the deployment will assume line-of-sight connections, shadowing by moving people may cause non-line-of-sight conditions, which have to be mitigated by utilizing indirect transmission paths via reflections or scattering from walls by fully automatic beam steering.
- ***Wireless personal area networks (WPAN):*** This application means ultra-high speed ad-hoc connections between devices over short distances, for example between a camera and a notebook or between an external harddisk and a laptop. The typical deployment will be indoors, for example on a desktop. The alignment of high gain antennas should be ideally done by automatic beam steering, but rough manual alignment may be thinkable in case of less directive antennas also.

- ***Kiosk downloading:*** This is a special type of a WPAN, where one device is connected to a fixed kiosk download station offering ultra-high downloads of multimedia-content, e.g. a movie, to a mobile device. The capabilities of such a solution are displayed in Table 1. Typical transmission ranges are in the order of a few cm under rather known channel conditions, facilitating less directive antennas with manual antenna alignment. Multiple reflections between the Tx and Rx may still limit the achievable data rates.
- ***Wireless conncetions in data centers:*** For the optimization of capacity within data centers, a frequent and dynamic reconfiguration of the architecture is required, which is extremely difficult to achieve with fully wired systems. The introduction of ultra-high data rate wireless hops, see Fig. 2, is considered as an attractive alternative currently explored for 60 GHz [11–13]. THz communication enables far higher data rates with comparable prerequisites and under the same conditions. Flexible reconfiguration necessiates beam steering capabilities. However, these are required only during reconfiguration in an otherwise static environment with known antenna positions, so that beam switching with a predefined subset of weight vectors suffices.
- ***Chip-to-chip communications:*** This application means wireless links inside computers or any other electronic devices. It is of high relevance because wired connectors and micro strip lines on printed circuit boards potentially become a bottleneck of upcoming bus systems and inter chip connections. Transmission ranges are a few cm with both LOS and NLOS situations. Potentially strong multi paths have to be considered. The fully static environment allows for a fixed alignment during design process with automatic beam steering as an option for sequential multipoint operation between more than just two chips.
- ***Wireless backhauling:*** Fixed links with ultra high data rates can be utilized for the wireless extension of backbone networks, for the aggregation of multiple backhaul links with lower data rates as well as for the wireless backhaul of future cellular base stations with very high overall throughputs. The deployment will be outdoors with transmission ranges of several 100 m up to a few kilometers. Very directive antennas will be used. The static deployment allows antenna alignment during the installation process by radio engineers. However, small automatic corrections may be required during operation to counteract effects such as pole swing.
- ***Nano cells:*** Nano cells consist of ultra-high data rate "pipes" within a cellular network and can be envisioned just alike today's WLAN hotspots. Deployment can be outdoors and indoors. The overall concept will be similar as for the WLAN case. However, dynamic effects will be more severe than in the WLAN application and the environment can be more versatile and is less predictable, so that the complexity for this application is highest among those introduced here.

Table 1 Size of data transferable within 1 second (from [1])

Data rate	Size of Data	Run time of a 1080p video stored on a Blu-Ray disc
10 Gbps	1.25 GByte	4 min
40 Gbps	5.0 GByte	17 min
100 Gbps	12.5 Gbyte	42 min
1 Tbps	125 Gbyte	7 hours

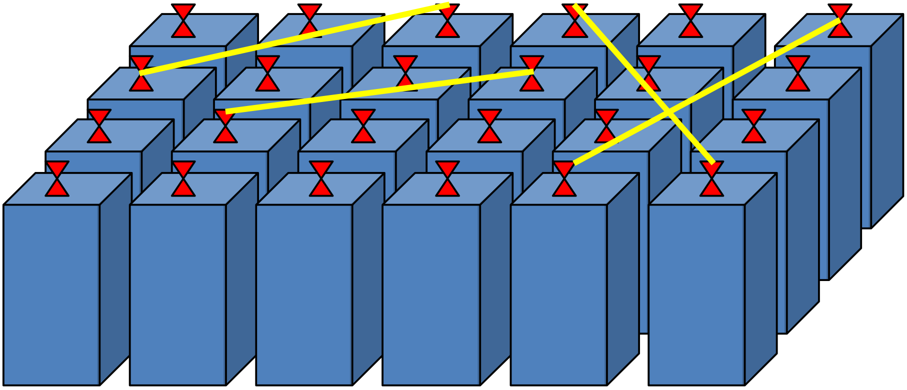

Figure 2 Wireless hops in a data center (from [11]). Computers are equipped with highly directive steerable antennas on top of the racks. Connections between different computers are realized by aligning the beams of the corresponding antennas

3 Research

Research in the field of THz communications has focused on three main areas so far: THz radio wave propagation as well as radio channel modeling, system concepts and technology. Each will be detailed separately in the following.

3.1 A. Propagation and Channel Modeling

Investigations on a new wireless communication system always start with studies of the radio channel. This preliminary step has to preceed the radio system conception and prototyping in order to identify specialties and challenges of the radio channel behavior, which heavily impact the appropriate radio system design. According to the use cases mentioned in Sec. 2, the corresponding channels can be segmented into three types: intra device, indoor and outdoor. To the best knowledge of the authors, intra device channels have not even subject to any published studies yet. On the other hand, the latter two channel types have been understood well. Among the two, indoor environments have the by far much more complex propagation conditions and will be discussed first.

1.) ***Indoor environments:*** early publications by Piesiewicz et al. [14, 15] have dealt with the characterization of typical building materials in the THz frequency range. In subsequent steps, basic propagation phenomena like scattering and diffraction have been subject to detailed experimental and theoretical investigations [16–20]. First ultra broadband indoor channel measurements in a more complex office environment have been performed by Priebe et al. at 300 GHz in 2011 [20]. Theoretical models have been validated for the individual propagation phenomena with the outcome of all these experiments. For the simulation of the overall channel conditions, the various models have then been incorporated into a ray tracing propagation simulator. Because of the very short wavelength in the THz band, THz waves propagate quasi-optically and can be modeled highly accurate with a ray optical approach. Ray tracing has already enabled very good prediction capabilities at 60 GHz and can be expected to the more so in the THz range, which has been proven in [21]. There, the ray tracer had additionally been extended to channel simulations in the frequency domain as necessary for ultra broadband channels. After the validation and calibration with measurements in [21], it has been used study important characteristics of the THz indoor propagation channel. The following key aspects have been found:

- ***Reflections:*** Specular reflection attenuations from smooth surfaces can be modeled with the well known Fresnel equations given that they are sufficiently thick with respect to the wavelength. Otherwise, reflections within the material or multiple reflections at the interfaces of layered media have to be taken into account, causing a highly frequency-dependent reflection behavior.
- ***Scattering:*** For the reason of the wavelength ranging in the order magnitude of typical building material surface height deviations, diffuse scattering from walls covered with rough materials such as ingrain wallpaper or plaster becomes highly relevant [16, 17]. The scattering of a considerable amount of power out of the specular reflection direction can cause additional reflection attenuations of several 10 dB and induce multipath propagation through the diffuse components. Such effects can be described analytically with the Kirchhoff theory [17] and have additionally been modeled stochastically in [22].
- ***Diffraction:*** Very high diffraction attenuations of easily 30 dB and more make diffraction effects in the shadowing region behind objects at furniture etc. negligible. Diffraction could still be proven suitable and helpful to model dynamic ray shadowing effects caused by human movement, where the body itself is approximated as a diffracting object [19].
- ***Frequency dispersion:*** Under consideration of the huge bandwidths beyond 10 GHz, the propagation phenomena themselves have to be treated as frequency-dependent. This frequency dispersion of the channel necessitates the broadband channel simulation in frequency domain and can cause a certain distortion of transmitted pulse shapes [21].

  Channel aspects not addressed by research so far are channel dynamics introduced by moving objects and /or persons as well as by moved devices. Dynamic ray shadowing has already been considered in [19] as discussed above, which just causes a temporal variation of the path losses. However, reflections at the persons may additionally be subject to Doppler shifts and entire Doppler spectra may result. The same holds should the transceiver units be moved relative to each other. Non-negligible impairments of the data transmission can be expected especially because of the very high carrier frequencies and the corresponding high Doppler shifts. This will have to be studied in detail in the future.

2.) ***Outdoor conditions:*** Radio channels in outdoor environments may in principle feature comparable propagation phenomena like indoors such as reflections at the ground or at the outer walls of buildings. However, because the primary outdoor use case is backhauling, utilizing extremely focusing antennas, none of the multipath phenomena mentioned above for indoor environments becomes effectively relevant there. An exception where reflections etc. may still occur is a THz nanocell, which will be difficult to realize and have hence not been studied in detail nor are they in the immediate scope of this paper. On the other hand, further effects like scintillation and fog may have to be taken into consideration for fixed links as investigated by Moeller et al. [23]. Moreover, the atmospheric attenuation must not be neglected over longer ranges, which has been discussed in Schneider et al. [24]. Another secondary effect, being specific for fixed links and reaching beyond the mere propagation, is a certain antenna mispointing due to pole swing caused by wind.

All considerations on the THz wave propagation and the radio channels lead to the immediate conclusion that versatile, novel and innovative system concepts will be required to tackle the resulting challenges, which will be subject in the next subsection.

3.2 B. System Concepts

Basic system concepts have been developed and investigated by means of simulations and transmission experiments for both indoor and outdoor environments. Various transmission demonstrations have been carried out by different groups with different kinds of technology (cf. next subsection), proving that wireless communication links are feasible at 300 GHz and beyond [25–30]. For indoor environments, basic link budget calculations [5] have revealed the necessity of highly directive antennas to overcome the high path loss of easily 100 dB and more at THz frequencies in face of the fairly limited output powers. The differences in path loss and possible output powers between THz communications channels and conventional WLAN radio channels at 2.4, 5 and 60 GHz are illustrated in Table 2 including the resulting implications on the antennas. An advantage of high-gain antennas beyond the mere gain is the effect of spatial filtering, i.e. multipath signals are suppressed, reducing the RMS delay spread and hence enabling higher data rates [3]. A more detailed study of the antenna impact on the THz propagation channel characteristics is described in [32].

On the downside, two problems are induced with increasing antenna directivity, namely a higher sensitivity against antenna mispointing and a significant link affection by ray shadowing. The higher the antenna gain the higher is the sensitivity with respect to mispointing becomes. A quantitative investigation is presented in [33] revealing that the beamwidth should exceed the expected standard deviation of the random antenna misalignment in degrees by a factor of 1.6. Regarding the second aspect, the feasibility study in [31] reveals that multipath signals coming from scattering or reflections are suitable to overcome the blockage of the direct line-of-sight path caused by objects or moving people, for example. To exploit this possibility, the directive antennas will have to be aimed in direction of the strongest reflection, which necessitates automatic beam steering with precise antenna alignment. This concept is called directed NLOS transmission.

For backhaul links operated in outdoor environments, a detailed link budget analysis is described in [24, 34]. In [34] it is shown that solutions with required antenna gains up to 2x40 dBi are subject to a loss of connectivity due to antenna pole sway and twist for mispointing angles larger than 0.04°, which must be mitigated by automatic (optical) alignment tracking and a closed loop pointing control.

Table 2 Comparison of conventional and THz communication channels

	2.4 GHz, 5 GHz	60 GHz	300 GHz
Path loss at 10 m	≈ 60 dB	≈ 88 dB	≈ 101 dB
Output powers	Limited by regulations ≈ 22 dBm	Limited by technology and regulations; typically ≈ 10 dBm	Currently limited by technology <<10 dBm
Antennas	Omnidirectional (≈ 3 dBi)	Medium directivities (15…25 dBi)	High directivities (20…40 dBi)
Bandwidths	40 MHz	≈ 2 GHz	10…100 GHz
Data rates	600 Mbit/s	≈ 4 Gbit/s	100 Gbit/s and beyond

3.3 Technology-Related Research

For the generation of signals in the THz frequency range, approaches can be based either on photonics or on electronics. Nagatsuma et al [32, 33, 35] have introduced a hybrid setup consisting of a photonics-based transmitter using a Uni-Travelling-Carrier photodiode and an electronics-based receiver employing a Schottky-barrier diode. With this principle, a data transmission of 24 Gbit/s was successfully demonstrated at 300 GHz. Monolithically integrated components (so-called monolithic millimeter-wave integrated circuits - MMICs) have been reported for both the transmitting and receiving end of the link by Kallfass et al. [36, 37]. Their solution is based on InP and GaAs MMIC technology, which allows for multi-functional and ultra compact components. With such MMIC chips, a data rate of 25 Gbit/s has been achieved over a distance of 10 m at 220 GHz.

Regarding market readiness, especially the MMIC integration of multiplier chains and mixers is highly promising in terms of form factor as well as cost and makes them favorable over optics. However, the InP and GaAs processing remains costly compared to CMOS and makes those materials attractive for performance-demanding, less cost-sensitive markets such as professional applications like backhauls or data center links. Mass market applications can be addressed more appropriately with CMOS technology, reducing costs significantly for large quantities. Although CMOS for THz frequencies is not available yet, a contribution to IEEE 802.15 on THz-CMOS [38] gives clear hints that CMOS technology may be an option in the future.

4 Spectrum Regulation

In the Radio Regulations [39], spectrum beyond 275 GHz has not been assigned to any specific service yet. However, this does not mean that the completely free use of spectrum is allowed in the THz frequency range. Footnote 5.565 of the Radio-Rregulations defines dedicated frequency bands beyond 275 GHz, where so-called passive services like radio astronomy and satellite-based Earth-monitoring have to be protected from harmful interference by active services like THz communications. Both services do not transmit actively but receive extremely low signals using highly sensitive receivers. The THz communications community has already started an active dialogue with the Earth exploration and remote sensing societies in the framework of the IEEE 802.15 Terahertz Interest Group [40, 41]. The study described in [40] shows that the radio astronomy is not to critical in terms of interference from THz communications due to the fact that the radio telescopes are operated at a few high-altitude observatories on high-altitude platforms. [41] shows thata potential affectionof Earth-exploration satellite services (EESS) by THz communications has to be taken into account. Utilizing only those frequency bands not employed by the EESS would leave a fragmented spectrum for THz communications with contiguous spectrum parts of less than 10 GHz only [1]. As a consequence, the use of bandwidths larger than 10 GHz in the THz range is only possible by developing and applying spectrum sharing concepts with the EESS. A first comprehensive study on potential interference scenarios and first ideas on interference avoidance is presented by Priebe et al. [42]. The key findings of these investigations are that interference may be observed under very worst case conditions, whereas transmit power limitations become an appropriate mitigation technique not severely restricting transmission ranges of THz WLANs or fixed backhaul links, for instance.

5 Standardisation

Already in 2008, the Interest Group THz has been established within IEEE 802.15, having the goal to explore the potential of the THz frequencies and to create one or various standards for THz communication systems [43]. In the past years, the tasks of this group have been to identify potential application scenarios, to follow the technological progress of semiconductor technology, to work on radio channel models and to attend and influence the spectrum discussions with respect to the Word Radio Conference (WRC) 2012. A couple of possible applications and usage scenarios for THz wireless data transmission have been defined in [10, 44], where the specific propagation conditions and the requirements in terms of antenna alignment are given with the implication of significantly varying complexities of the appropriate system concepts. As a consequence, the need for more than one standard is likely under consideration of the diverse requirements for the different applications. As soon as technology matures sufficiently for one of those applications, a corresponding study group is likely to be established and then to be followed by a task group, eventually developing a concrete standard.

6 Conclusion

The paper has presented the current status in research, spectrum regulations and standardization activities in the field of THz communications. On the way to the wireless transmission of 100 Gbit/s, promising results have been achieved over the last couple of years in all three areas. These findings will form the basis for the development, standardization and finally for the implementation of ultra fast THz communication systems. From the recent progress, the commercial introduction of THz communications can be expected in the not too distant future and will help coping with the ongoing tremendously increasing demand for wireless data rates.

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