Invited Paper

Towards Future THz Communications Systems

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(Received February 14, 2012)

Abstract: Carrier frequencies beyond 300 *GHz*, belonging to the so-called THz range, have received attention for considering this frequency band for future multi-gigabit short-range communication systems. This review paper gives an overview of current issues in the emerging field of THz communications targeting to deliver wireless 100 *Gbps* over short distances. The paper will start by introducing scenarios and applications requiring such high data rates followed by a discussion on the radio channel characteristics. In the 300 *GHz* frequency band, the path loss is even more significant than at 60 *GHz* and appropriate measures to mitigate effects in none-line-of-sight (NLOS) cases, caused e. g. by the influence of moving people, are required. Advanced antenna techniques like beam forming or beam switching are a pre-requisite to guarantee seamless service. In order to consider such techniques in the standards development, the propagation channel operating at these mm- and sub-mm wave bands in realistic environments must be well understood. Therefore, intensive channel measurement and modeling activities have been done at 300 *GHz*, which started a couple of years ago at Terahertz Communications Lab (TCL). Due to the short wave length, the influence of surface roughness of typical building materials plays an important role. Hence, the modeling of rough surface scattering has been one of the main areas in these investigations. In this contribution, the main results of the propagation research activities at TCL are summarized. In the last part of the paper, an overview of the state-of-the-art in technology development and successful demonstrations of data transmission will be given together with a report on the status quo of ongoing activities in standardization at IEEE 802.15 IG *THz* and the regulation of the spectrum beyond 300 *GHz*.

Keywords: THz Communications, Multi-gigabit wireless data rates, Channel characterization, Regulation and standardization

doi: 10.11906/TST.011-017.2012.03.02

1. Introduction

The extremely fast growing demand for mobile data traffic [1] and the trends towards higher data rates predicted to be multiple tens of Gbit/s around the year 2020 [2-3] raise the question of spectrum availability to fulfill these demands. Apart from designing wireless communication systems with spectral efficiencies of tens of bit/s/Hz, which are difficult to achieve under practical realizable constraints, the only possibility is to increase the available bandwidth to several tens of GHz. However, in the fully regulated part of frequency bands below 300 *GHz*, identifying such amount of spectrum is not feasible at all. Hence, the spectrum beyond 300 *GHz*, which has not been allocated yet to any other radio service, is a prosperous candidate to provide enough spectrums. In the past years, a couple of research groups all around the world have started to investigate wireless communication systems to be operated beyond 300 *GHz*, the so-called

THz communications systems [2-4]. This paper gives a short overview of the results achieved so far. More details on these results can be found in the references at the end of this paper. The remaining part of the paper is organized as follows: Chapter 2 gives a brief overview of possible scenarios and applications followed by a description of the specific channel characteristics at frequencies beyond 300 *GHz*. An overview of achievements in developing technology and demonstrators is given in chapter 4. Ongoing activities in standardization and regulation are presented in chapter 5. Chapter 6 provides some conclusions and an outlook to future research required in this area.

2. Scenarios and applications

Within the IEEE 802.15 Interest Group THz, various proposals for applications of THz communication systems have been made. Tab. I summarizes these applications and scenarios, which have been presented in [5]. For each application also the specific propagation conditions and the requirements in terms of antenna alignment are given. These requirements will yield different levels of complexity when designing the systems and as a consequence the development of different standards may be necessary.

Tab. I Applications and Scenarios for THz Communication Systems.

Application	Operational Environment	Typical Range	Specific Propagation Conditions	Requirements for Antenna Alignment
Fixed Wireless Links	Links of the backbone network; static use; outdoor	A few hundred meters up to several kilometers	LOS; Atmospheric attenuation becomes important	Highly directive antennas; alignment during the installation process by radio engineers
THz Nano Cells	Part of a hierarchical cellular network; potentially mobile users; indoor as well as outdoor	< 100m	LOS/NLOS; dynamically changing conditions	automatic beam steering required
WLAN/WPAN	Connection to access points; nomadic users; mainly indoor	< 100m (mostly < 10m)	LOS/NLOS; dynamically changing conditions	automatic beam steering required
Connecting Devices on Short Ranges	indoor (typically on a desktop), nomadic use	a few cm	LOS, multipaths from nearby objects and multiple reflections from Tx and Rx	ideally by automatic beam steering, but manual alignment may be possible
Kiosk Downloading	indoor, nomadic use	a few cm	LOS, multiple reflections from Tx and Rx	automatic beam steering (manual alignment may be very difficult)
Board-to-Board Communication	inside computers, fixed use	a few cm	LOS/NLOS, potentially strong multipaths	fixed alignment during design process possible (automatic beam steering as an option)

One of the first applications of THz communications which may become reality is a fixed wireless link which enables the increase of the capacity of the backbone of wireless networks, for example. Such an application will be operated in outdoor environments. Another more outdoor oriented applications are THz nano cells that are part of a hierarchical cellular network providing high capacity in hot spots. However, such an application will be very demanding in terms of technical requirements. The same holds for WLAN/WPAN (wireless local area networks/wireless personal area networks) type applications, which are targeting mostly nomadic indoor users with communication distances of up to several tens of meters. THz communication also offers perspectives for providing high capacity wireless links of computer peripherals located on a desktop, e. g. connecting a hard disk drive with a computer. A similar application is kiosk downloading, which enables the transfer of the content of a DVD, e. g., to a mobile device within a few seconds from a dedicated kiosk in a shop or a mall. With these two applications the specific propagation conditions are less demanding. The last application listed in tab. I is board-to-board communication, where the ultra-high speed communication between different components inside a computer, e. g., is realized by THz communication.

3. Channel characterization at 300 *GHz*

In the 300 *GHz* frequency band, the path loss is even more significant than at 60 *GHz* requiring high gain antennas even for freespace conditions at both ends of the wireless link [2]. When operating in long-distance outdoor environments, significant additional attenuation caused by atmospheric absorption has to be taken into account [2], [4]. In indoor environments, the development of 60 *GHz* systems has shown that appropriate measures to mitigate effects in none-line-of-sight (NLOS) cases caused, e. g., by the influence of moving people [6-7] are required. Possible solutions to this problem are advanced antenna techniques like beam forming or beam switching, which have proven to be a pre-requisite to guarantee seamless service already at 60 *GHz* [8]. For most of the applications mentioned in table I, similar solutions will be required for systems operating beyond 300 *GHz*. Consequently, detailed knowledge of the channel characteristics is required. Therefore, Terahertz Communications Lab (TCL) has concentrated on systematically investigating the propagation conditions beyond 300 *GHz* in indoor environments by measuring and modeling the basic propagation phenomena. A reasonable approach to derive propagation characteristics beyond 300 *GHz* are ray-tracing techniques, which work very well already at 60 *GHz*. Since the ratio between the sizes of objects interacting with the electromagnetic waves and wave length becomes even larger at higher frequencies this technique is even better suitable at THz frequencies. However, a proper modeling of reflection and scattering processes for typical building materials is required. For this reason extensive measurement campaigns to derive the dielectric properties of typical building materials have been made [9-10]. Due to the short wave length, considering surface roughness becomes important. The surface roughness causes an additional attenuation even in the specular direction of reflection [11]. Measurements and models for diffuse scattering are described in [12]. A wallpaper or a thick paint on top of a concrete wall, e. g., make it necessary to take into account reflection on multilayer objects [13]. Finally, in order to be able to properly model the impact of shadowing by moving humans, thorough investigation of diffraction effects taking into account different materials, realistic antennas as well as transmission through the objects at 60 and 300 *GHz* is described in [14]. A first measurement of the propagation characteristics of a small office room is presented in [15], where the ray tracing method is verified by comparing its channel impulse response with the measured channel impulse response determined by a vector network analyzer. Ray tracing can be used to simulate complete scenarios and evaluate the potential of THz communication [16] and to derive stochastic channel models [17]. The need for the use of extremely high-gain antennas with a 3 *dB* width of only a few degrees puts high requirements on the alignment of the transmit and receive antennas. Investigations of this effect by means of measurements and ray tracing simulations are presented in [18-19].

4. Technology trends and demonstrators

Apart from investigations of the basic propagation phenomena described in the previous chapters, a couple of demonstrators have been set up by various research groups. A first transmission of a video using an analog television signal was demonstrated by TCL already in 2008 [20]. Transmitter and receiver were based on a Schottky mixer operating on its second harmonic. In this experiment, a transmission range of 10 *m* was achieved using antennas of 40 *dB* at both ends of the link. This antenna gain was achieved using a combination of a horn antenna (26 *dB* gain) with a polyethylene lens (14 *dB* gain). The same transmission principle was used to demonstrate the feasibility of wireless data transmission, where an error-free transmission of a DVB-S2 signal over a distance of 52 *m* with a data rate of 96 *Mbit/s* was achieved [21]. Nagatsuma et al. [22], [3] successfully demonstrated an error-free data transmission of 12.5 *Gbit/s* at 300 *GHz* over a distance of 0.5 *m*. In this case, the photonics-based transmitter using a Uni-Travelling-Carrier photodiode and an electronics-based receiver using a Schottky-Barrier diode was applied. Moeller et al. [23] demonstrated 2.5 *Gbit/s* error-free transmission at 625 *GHz* carrier frequency over lab distance. At the transmitter, a frequency multiplier chain combined with advanced modulation formats for compressing its spectral bandwidth was used, whereas at the receiver direct detection by means of a Schottky diode was applied. A first integrated solution using transmit and receive frontends consisting of active multi-functional millimeter-wave microwave integrated circuits (MMICs) was presented by Kallfass et al. [24]. With this transmission system, a wireless data link operating at a carrier frequency of 220 *GHz* at a data rate of up to 25 *Gbit/s* was demonstrated.

5. Standardization and regulation

Standardization and regulation activities for THz communication started already in 2008 when the IEEE 802.15 Interest Group THz [25] was established to explore wireless systems operating at 300 *GHz* and beyond. The current tasks of the Interest Group are to follow and survey the technological developments, prepare channel models that can be used in the further standardization process and provide input to the discussion on spectrum issues, especially related to the agenda item 1.6 of the World Radio Conference WRC 2012 [26]. One of the outcomes of WRC 2012 is that the use of large continuous frequency bands for THz communications requires the development of sharing concepts between THz communication and the so-called passive services like radio astronomy and satellite-based earth monitoring [27]. A dialogue with representatives of these services already started during the preparation of WRC 2012 [28-29].

6. Conclusions and future challenges

In this paper, a review on the current status of the development of future THz communications has been presented. The basic propagation characteristics in this frequency band for the most likely applications and scenarios are well understood. Most recent developments of semiconductor technologies have enabled to set up demonstrators showing the clear potential to achieve data rates of multiple tens of *Gbit/s*. One of the most important challenges for future tasks is the development of intelligent antenna concepts to overcome the high path loss in conjunction with dynamic shadowing events caused, for example, by moving humans. In order to enable the application of several tens of *GHz*, spectrum sharing concepts with passive services will have to be developed.

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