TERANETS: ULTRA-BROADBAND COMMUNICATION NETWORKS IN THE TERAHERTZ BAND

IAN F. AKYILDIZ, JOSEP MIQUEL JORNET, AND CHONG HAN

ABSTRACT

Terahertz Band communication is envisioned as a key technology to satisfy the data rate requirements of future wireless communication networks, and enable new applications both in classical networking domains as well as in novel nanoscale communication paradigms. Major recent advancements in THz Band technologies are helping to finally close the so called THz Gap and bring practical THz Band communication networks one step closer. This paper surveys the state of the art in THz Band device technologies, and highlights the challenges and potential solutions from the communication and networking perspective as well as in terms of experimental testbeds. Ultimately, a roadmap is defined for the development of THz Band systems as the new frontier in wireless communications.

INTRODUCTION

Over the last few years wireless data traffic has drastically increased due to a change in the way today's society creates, shares, and consumes information. This change has been accompanied by an increasing demand for higher speed wireless communication anywhere, anytime. Following this trend, wireless Terabit-per-second (Tb/s) links are expected to become a reality within the next five to 10 years. Several alternatives are being considered to meet this demand.

Millimeter wave (mm-Wave) communication systems, such as those at 60 GHz, have gained a lot of attention in the last few years due to their ability to support much higher data rates than communication systems below 5 GHz, in the order of 10 Gb/s, at the cost of a lower transmission distance [1]. While this is definitely the path to follow, this data rate is still two orders of magnitude below the expected demand. The path to improve these data rates involves the development of more complex transceiver architectures able to implement physical layer solutions with much higher spectral efficiency. However, ultimately the usable bandwidth is limited to less than 7 GHz, which effectively poses an upper bound on data rates.

Free Space Optical (FSO) communication systems, which operate at infrared (IR) frequencies and above, are similarly being explored as a way to improve the achievable data rates in wireless networks. The intrinsically very large available bandwidth at such very high frequency plays to their advantage. However, low transmission power budget due to eye-safety limits, the impact of several atmospheric effects on signal propagation (e.g. fog, rain, dust, or pollution), and the size and need of strict alignment between transmitter and receiver, limit the achievable data rates and practicality of FSO systems for mobile and personal wireless networks [2].

Instead of the aforementioned frequency regions, Terahertz Band communication is envisioned as a key technology to satisfy the need for Tb/s links in wireless networks [3, 4]. In this article the term THz Band refers to the broad spectrum between 0.1 and 10 THz, but alternative definitions that span only a sub-set of these frequencies have been utilized in the related literature. For many years the lack of compact and efficient methods to generate and detect THz Band signals has limited the feasibility of THz Band communication networks. However, the refinement of existing architectures and the utilization of new technologies bring this paradigm one step closer. Still many challenges arise, especially regarding the very high propagation loss in THz Band communication. Therefore, it is the right time for the telecommunications community to jointly define and pave the way for the future of this novel communication paradigm. In this direction, the IEEE 802.15 Wireless Personal Area Networks (WPAN) Study Group 100 Gb/s Wireless (SG100G) [5] has been established, which aims to work toward the first standard for THz Band communication that supports multi-Gb/s and Tb/s links.

The use of this still-unregulated frequency band will alleviate the spectrum scarcity and capacity limitations of current wireless systems and enable a plethora of applications, both in classical domains at the macroscale as well as in novel nanoscale communication paradigms. On the one hand, at the macroscale THz Band communication can contribute to the development of ultra-high-speed small cell systems, provide ultra-high-speed data transfers among nearby devices, and create secure wireless communication for military and defense applications. On the other hand, state-of-the-art nanoscale transceivers and antennas point the THz Band

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This work was supported by the U.S. National Science Foundation (NSF) under Grant No. CCF-1349828.

 1536-1284/14/$25.00 © 2014 IEEE

as their frequency range of operation. Applications that are enabled by the nanomachines range from advanced health monitoring systems to chemical attack prevention systems, wireless networks on chip to the Internet of Nano-things.

In this article we review the state of the art in THz Band communications networks and provide an in-depth view of this novel networking paradigm both from the device perspective as well as from the communication and information theoretic point of view.

We revise the state of the art and highlight the major challenges and possible solutions for THz Band transceivers and antennas in the next section. Following that, we outline the communication challenges in terms of channel modeling, physical layer and up to transport layer functionalities. Then we review the state of the art in terms of experimental platforms and identify the main challenges in their realization. Finally, we conclude the article in the final section.

Challenges in Terahertz Band Device Technologies

In this section we review the state of the art and research challenges for THz Band transceiver and antenna design.

Terahertz Band Transceivers

Within the last five years outstanding progress has been achieved toward the development of compact THz Band transceivers. These transceivers should be able to exploit the very large available bandwidth at THz Band frequencies, while providing high transmission power, high detection sensitivity, and low noise figures needed to overcome the very high path-loss at THz Band frequencies. Currently, different technologies are being considered.

Silicon Germanium (SiGe) technology is commonly the first choice for many performance-constrained high-frequency systems. SiGe-based Heterojunction Bipolar Transistors (HBTs) have been utilized to build radio-frequency (RF) front-ends able to operate up to 820 GHz [6]. Standard **Silicon (Si) Complementary Metal-Oxide-Semiconductor (CMOS)** technology has also been utilized to build oscillators at 870 GHz and sub-harmonic detectors between 790 and 960 GHz [7]. However, intrinsic material properties limit the use of SiGe and Si technologies above 1 THz.

Compound semiconductor technologies such as Gallium Nitride (GaN) and Indium Phosphide (InP) as well as **metamorphic devices** are being utilized to develop high power amplifiers which can be used to overcome the distance limitations of THz Band communication. For example, InP-based High-Electron-Mobility Transistors (HEMTs) have been used to build amplifiers with more than 10 dB gain at 640 GHz [8]. Still, technology limitations constrain the performance of these devices above 1 THz.

Photonic devices, such as Quantum Cascade Lasers (QCLs) and bolometric detectors, are at the basis of many classical THz Band transmission and reception systems. The need for an external laser for optical electron pumping in QCLs, and eventually their size, limit the use of these traditional approaches in the envisioned applications. **Plasma wave emitters and detectors**, enabled by electrical charge resonances at the channel of HEMT device with nanometric length, have also been proposed for THz Band systems [9]. However, while providing good sensitivity in reception, only very low powers can be generated in transmission.

Finally, one of the most recent alternatives to develop THz Band transceivers is based on the utilization of **graphene**, a novel nanomaterial with outstanding physical, electrical, and optical properties. Among others, the propagation properties of electrons in graphene enable the development of very high frequency devices that can intrinsically operate between 1 and 10 THz and above. While this technology is not as mature as the aforementioned technologies and part of its potential remains unknown, its unique properties and preliminary results motivate its further development. For example, graphene can be used to enhance the emission and detection of THz radiation from plasma wave devices.

Terahertz Band Antennas

In addition to an ultra-high-speed transceiver, ultra-broadband antennas are needed for THz Band communication. Moreover, very large antenna arrays will be necessary to overcome the very high path loss in the THz Band. We summarize next the advancements in this realm.

Ultra-Broadband and Multi-Band Antennas — Terahertz Band antennas need to support bandwidths ranging from tens of GHz up to a few THz. Existing experimental wireless data transmission systems at 300 GHz make use of classical antennas such as horn antennas or paraboloid antennas, which can provide a radiation bandwidth in the order of 10 percent of their center frequency. However, the geometry of these antennas makes them not suitable for mobile and personal devices. Sinuous antennas have proven to be attractive for THz Band circuits such as broadband detectors. However, a systematic analysis of the performance of these antennas is missing. Furthermore, the potential of novel antennas based on **nanomaterials and metamaterials** needs to be investigated. For example, it has been shown that graphene can be used to build plasmonic nano-antennas (Fig. 1), which exploit the behavior of global oscillations of surface charges to radiate in the THz Band. The response of graphene-based nano-antennas can be easily dynamically tuned by means of material doping, that is, dynamically changing the electrical properties [10] by means of electrostatic bias, for example, and their very small size enables their integration in virtually everything.

Very Large Antenna Arrays — The expectedly very low gain and effective area of individual THz Band antennas motivates the investigation of very large antenna arrays. The very small size of a THz Band antenna allows the integration of a very large number of antennas with a very small footprint. An open challenge is to characterize and account for the interaction and coupling effects among nearby antennas. This analysis

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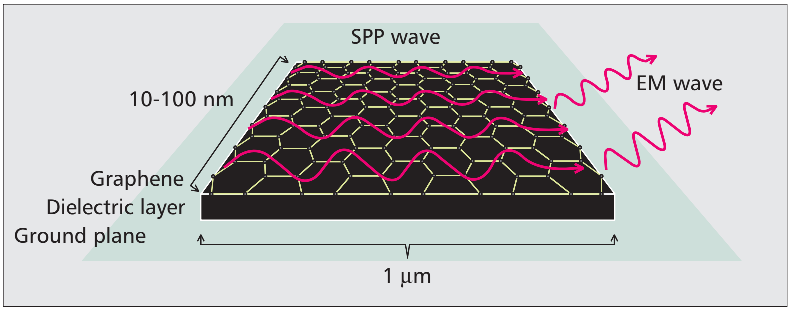

Figure 1. A graphene-based plasmonic THz Band antenna [10].

depends on the specific antenna technology. Another challenge is to develop new ultra-broadband approaches for antenna arrays pattern synthesis. Classical phased arrays might not be able to support the very large bandwidth needed to achieve multi-Gb/s or Tb/s links. New techniques should be developed by leveraging the opportunities brought by new antenna technologies. For example, we envision a new antenna pattern synthesis approach based on **dynamic material doping of graphene-based antennas**. These very large antenna arrays will then enable Massive MIMO schemes.

Challenges in Terahertz Band Communication Networks

We describe next the challenges from the communication perspective by following a bottom-up approach, starting from the THz Band channel modeling up to the development of transport layer solutions. The discussion in this section might also contribute to the development of mm-Wave systems.

Channel Modeling

The propagation peculiarities of the THz Band require the development of new channel models. Current channel characterization efforts are focused on the 300 GHz transmission window [3], as experimental measurements are readily available. However, a higher-frequency transmission window, or even more than one window at the same time over the entire THz Band, will be needed to provide stable Tb/s links. We summarize next the progress in terms of THz Band channel modeling for different propagation conditions.

Line-of-Sight (LOS) Propagation — The free-space propagation properties of EM waves at THz Band frequencies is determined by the spreading loss and mainly the molecular absorption loss [11]. The resulting path loss is highly frequency-selective and can easily go above 100 dB for distances just above a few meters. In addition, molecular absorption by water vapor molecules defines several transmission windows, whose position and width depend on the distance and molecular composition of the medium. For distances much below one meter, molecular absorption loss is almost negligible, and thus the THz Band behaves almost as a 10 THz wide transmission window. For distances over one meter, many resonances become significant and the transmission windows (e.g. w_i in Fig. 2) become narrower. This very strong distance-dependent behavior impacts the design of the physical and link layers.

Non-Line-of-Sight (NLOS) Propagation — Line-of-Sight transmissions might not always be possible due to the presence of obstacles. Non-Line-of-Sight transmissions can be categorized into *specular reflected propagation*, *diffusely scattered propagation,* and *diffracted propagation*. To account for NLOS propagation, it is necessary to characterize the coefficients for reflection, scattering, and diffraction of EM waves at THz Band frequencies. The experimental characterization of such coefficients for common materials in the envisioned application scenarios, that is, from silicon chips to plaster in indoor environments, remains an open challenge. Another research challenge is to investigate NLOS communication in the presence of directed reflection on dielectric mirrors.

Multi-Path Channel — Each frequency component in an ultra-broadband signal experiences different attenuation and delay. This frequency-dispersion effect, or equivalent distortion in the time domain, needs to be characterized in THz Band multi-path channel models. One possible approach to analyze multi-path propagation is to study individual arrival rays at the receiver, by using ray tracing techniques. However, this requires prior knowledge of the environment geometry. Alternatively, a statistical model to characterize the multi-path channel efficiently can be developed. This requires a probabilistic analysis of the frequency-sensitive parameters that affect the received multi-path signals, such as the probability of the presence of LOS propagation, the number of NLOS components, delays, and gains.

Noise Sources in the Terahertz Band — There are several noise sources that affect the performance of THz Band communication. First, the ambient noise in the THz Band channel is mainly contributed by the *molecular absorption noise*. The absorption from molecules present in the medium does not only attenuate the transmitted signal, but also introduces noise. Moreover, two major noise sources appear at the receiver, namely, thermal noise and shot noise, which need to be studied for the different device technologies. Furthermore, the phase noise in THz Band oscillators, which results in fast random fluctuations in the phase of the transmitted signal, needs to be taken into account. Phase noise can significantly challenge the synchronization and the demodulation processes at the receiver. The joint end-to-end analysis of the transmitter, channel, and receiver will allow the computation of realistic figures for the true capacity of the THz Band.

Physical Layer

Modulation — Classical modulations cannot fully benefit from the properties of the THz Band. In particular, the very strong distance-dependent behavior of the available bandwidth requires the development of different modulations for different applications based on the targeted transmis-

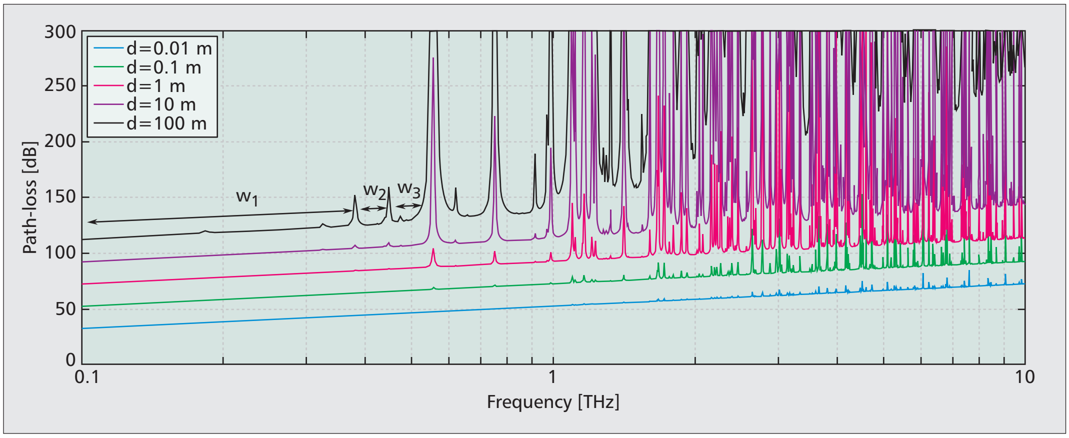

Figure 2. Path loss in the THz Band for different transmission distances.

The very large antenna arrays needed at THz Band frequencies enable novel Massive MIMO transmission schemes. In one extreme case, all the active elements in the antenna array can be used to create a single razor-sharp beam between one transmitter and one receiver. In the other extreme, each antenna could be utilized to create a separate independent link.

sion distance. For distances below one meter, modulations based on the exchange of **one-hundred-femtosecond-long pulses** can be utilized. These very short pulses, whose power spectral density lies in the THz Band, can be easily generated and detected with photonic and plasma wave devices. For longer distances, modulations that take advantage of **distance-dependent transmission bandwidth** appear as an interesting path to explore. For example, we can think of a new communication scheme in which a node dynamically adapts the transmitted waveform based on the transmission distance in order to match the window shape. Moreover, new opportunities will arise by new transceiver device technologies, such as doping-enabled modulations with graphene-based transceivers.

Coding — New coding schemes are needed to overcome the channel errors in the THz Band. The first step toward developing effective error control policies is to characterize the nature of such errors by developing stochastic models of noise, multi-path fading, and interference. After understanding the error sources at THz Band frequencies, new types of ultra-low-complexity channel coding schemes can be developed. For example, in the case of short range communications, **low-weight coding schemes** combined with femtosecond-long pulse-based modulations could be utilized to prevent channel errors from happening rather than trying to correct them afterward.

Massive MIMO — The very large antenna arrays needed at THz Band frequencies enable novel Massive MIMO transmission schemes. In one extreme case, all the active elements in the antenna array can be used to create a single **razor-sharp beam** between one transmitter and one receiver. In the other extreme, each antenna could be utilized to create a separate independent link. Any intermediate option is also possible. For example, the array could be divided into four sub-sets of elements, and each sub-set can be utilized either to create a single beam or multiple beams. Control algorithms able to quickly switch between different operation modes are required. This can only be done if very fast antenna array synthesis techniques are available.

Synchronization — The challenges in sampling the received signal at the Nyquist rate and performing sophisticated digital signal processing tasks at Tb/s data rates require the development of new solutions for synchronization. For example, for distances below one meter, pulse-based modulation schemes permit the use of low-complexity non-coherent analog detectors, for example, energy detector and auto-correlation receivers. For longer distances, robust and accurate synchronization mechanisms for time, carrier frequency, and phase are needed. Additional open challenges include the investigation of mechanisms to reduce the acquisition time at the receiver and the investigation of the potential of joint modulation and synchronization solutions.

Additional Challenges at the Physical Layer — Equalization plays a key role in the performance of the proposed physical layer solutions. The very high data rates at which signals are transmitted and received requires the development of simple yet efficient equalization schemes, which can effectively balance the computational load between the transmitter and the receiver. **Physical layer security** is another opportunity for THz Band communication networks. The very large available bandwidth enables efficient ultra-spread spectrum transmission techniques. In addition, the transmission at very high data rates results in very short signals. The utilization of razor-sharp beams makes the interception of the transmitted information even more challenging. Moreover, concepts such as **the electromagnetic signature of materials and devices at THz Band frequencies** could be leveraged for authentication methods at the physical layer.

Link Layer

Medium Access Control — Novel MAC protocols are required for THz Band communication networks, since classical solutions do not capture the peculiarities of the THz Band. The very large available bandwidth and the use of narrow directional beams almost eliminates the need for nodes to contend for the channel. The transmission of very short signals also minimizes the chances for collisions. All these come at the cost of more complex synchronization schemes between devices. Ideas to be explored for new

The THz Band (0.1–10 THz) is envisioned as a key player to satisfy the need for ultra-high data-rates in the next five to 10 years. Major advancements in the development of advanced transceiver architectures and sophisticated antenna systems are rapidly closing the so called THz gap.

MAC protocols include, among others, the development of **receiver-initiated transmission schemes** to guarantee alignment between the transmitter and the receiver, by combining different antenna modes and synchronized beam-steering patterns, or the exploitation of ultra-fast steerable beams and NLOS propagation to create parallel interleaved channels among different users.

Additional Challenges at the Link Layer — Existing studies on **optimal error control policies** need to be revised in light of the channel effects and physical layer peculiarities in THz Band communication. For example, on the one hand the packet time when transmitting at Tb/s might be even several orders of magnitude lower than the processing time needed to code the packet, depending on the transmission and coding schemes. Similarly, the energy consumption in computation and communication depend on the transceiver front-end and signal processing technologies. The ratio between these four magnitudes will determine the use of different forms of error control, ranging from simple automatic repeat request to forward error correction or a combination of both. Additional aspects to be addressed are the systematic analysis of **optimal packet size** for different applications in the THz Band, as well as the investigation of **flow control policies** to prevent link layer congestion and buffer overflow.

Network and Transport Layers

New challenges also arise at the higher layers of the protocol stack in THz Band communication networks. For example, at the network layer, new **routing mechanisms** could be developed that take into account the availability of both classical active relaying nodes as well as novel passive dielectric mirrors, which can direct the signal toward its final destination. In addition, new routing metrics that take into account the channel molecular composition and its impact on the available distance-dependent bandwidth need to be explored. When it comes to addressing, we expect IPv6 to be sufficient for classical macroscale communications, but **different addressing paradigms** might be explored for nanoscale applications of THz Band. In parallel, as wireless multi-Gb/s and Tb/s links become a reality, the aggregated traffic flowing through the network will dramatically increase. These will introduce many challenges at the transport layer regarding **congestion control as well as end-to-end reliable transport**. For example, we expect that a revision of the TCP congestion control window mechanism will be necessary to cope with the traffic dynamics of THz Band communication networks.

Experimental Testbeds

New experimental testbeds are needed to validate the developed solutions. Several platforms have been successfully utilized at frequencies between 200 and 300 GHz. In [12] a setup based on a Schottky diode subharmonic mixer is utilized for 1080p digital video transmission over 52 m. In [13] an InP-based front-end is used for wireless data transmission at 220 GHz, which can support data rates up to 25 Gb/s over 10 m. In [14] a photodiode emitter in transmission and a Schottky barrier diode detector in reception are used to experimentally create a stable wireless link at 300 GHz able to support 24 Gb/s data transmission over 0.5 m. More recently, in [15] a hybrid photonic-electronic system is used to create a stable 100 Gb/s over 20 m. More advanced physical testbeds will be developed with the advancement of the technologies earlier.

Conclusions

The THz Band (0.1–10 THz) is envisioned as a key player to satisfy the need for ultra-high data-rates in the next five to 10 years. Major advancements in the development of advanced transceiver architectures and sophisticated antenna systems are rapidly closing the so called THz gap. In this article we have surveyed the state of the art in THz Band technology from the device perspective, and highlighted the challenges and potential solutions in terms of communication and experimental testbeds, thus defining a roadmap for the realization of this new frontier for wireless communications.

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