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Terahertz band: Next frontier for wireless communications

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ABSTRACT

This paper provides an in-depth view of Terahertz Band (0.1–10 THz) communication, which is envisioned as a key technology to satisfy the increasing demand for higher speed wireless communication. THz Band communication will alleviate the spectrum scarcity and capacity limitations of current wireless systems, and enable new applications both in classical networking domains as well as in novel nanoscale communication paradigms. In this paper, the device design and development challenges for THz Band are surveyed first. The limitations and possible solutions for high-speed transceiver architectures are highlighted. The challenges for the development of new ultra-broadband antennas and very large antenna arrays are explained. When the devices are finally developed, then they need to communicate in the THz band. There exist many novel communication challenges such as propagation modeling, capacity analysis, modulation schemes, and other physical and link layer solutions, in the THz band which can be seen as a new frontier in the communication research. These challenges are treated in depth in this paper explaining the existing plethora of work and what still needs to be tackled.

1. 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 much higher speed wireless communication anywhere, anytime. In particular, wireless data rates have doubled every eighteen months over the last three decades and are quickly approaching the capacity of wired communication systems [1]. Following this trend, wireless Terabit-per-second (Tbps) links are expected to become a reality within the next five to ten years. Advanced physical layer solutions and, more importantly, new spectral bands will be required to support these extremely high data rates.

In this context, Terahertz Band communication [2–8] is envisioned as a key wireless technology to satisfy this demand, by alleviating the spectrum scarcity and capacity limitations of current wireless systems, and enabling a plethora of long-awaited applications in diverse fields (Section 2). The THz Band is the spectral band that spans the frequencies between 0.1 THz and 10 THz. While the frequency regions immediately below and above this band (the microwaves and the far infrared, respectively) have been extensively investigated, this is still one of the least-explored frequency bands for communication.

There are several reasons that motivate the use of the THz Band for ultra-broadband communication networks:

- *Wireless technologies below* 0.1 THz *are not able to support* Tbps *links.* On the one hand, advanced digital modulations, e.g., Orthogonal Frequency Division Multiplexing (OFDM), and sophisticated communication schemes, e.g., very large scale Multiple Input Multiple Output (MIMO) systems, are being used to achieve

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a very high spectral efficiency at frequencies below 5 GHz. However, the scarcity of the available bandwidth limits the achievable data rates. For example, in Long-Term Evolution Advanced (LTE-A) networks, peak data rates in the order of 1 Gbps are possible when using a four-by-four MIMO scheme over a 100 MHz aggregated bandwidth [9]. These data rates are three orders of magnitude below the targeted 1 Tbps. On the other hand, millimeter wave (mm-Wave) communication systems, such as those at 60 GHz, can support data rates in the order of 10 Gbps within one meter [10]. 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 the data rate involves the development of more complex transceiver architectures able to implement physical layer solutions with much higher spectral efficiency. However, the usable bandwidth is limited to less than 7 GHz, which effectively imposes an upper bound on the data rates.

- *Compact wireless technologies above* 10 THz *are not able to support* Tbps *links.* Despite the very large available bandwidth in Free Space Optical (FSO) communication systems, which operate at infrared (IR) frequencies and above, there are several issues that limit the practicality of these schemes for personal wireless communications. Low transmission power budget due to eye-safety limits, the impact of several atmospheric effects on the signal propagation (e.g., fog, rain, dust or pollution), high diffuse reflection losses, and the impact of misalignment between transmitter and receiver, limit both the achievable data rates and transmission range of FSO communication systems [2]. For example, a IR FSO communication system able to support 10 Gbps wireless links in case of Line-of-Sight (LOS) propagation has been proposed for Wireless Local Area Networks (WLANs) in [11]. However, only much lower data rates are supported in the case of diffused Non-Line-of-Sight (NLOS) communication, as analytically demonstrated in [12]. Similarly, in [13], an indoor FSO communication system able to support a 1-Gbps link at visible light frequencies was reported. By following a totally different approach, a long-distance FSO system able to support 1.28 Tbps link was demonstrated in [14]. Typical fiber communication equipment was used to generate and detect high capacity optical signals, which are then injected into an optical front-end. Only the optical front-end is 12 cm × 12 cm × 20 cm and almost 1 kg in weight, and does not include the signal generation/detection and modulation/demodulation blocks. All these constraints limit the feasibility of this large-scale optical approach for personal and mobile wireless communications.

On its turn, *the* THz *Band offers a much larger bandwidth*, which ranges from tens of GHz up to several THz depending on the transmission distance. The available bandwidth is more than one order of magnitude above state-of-art mm-Wave systems, while the frequency of operation is at least one order of magnitude below that of FSO systems. In addition, the technology required to make THz Band communication a reality is rapidly advancing, and the development of new transceiver architectures and antennas built upon novel materials with unprecedented properties are finally overcoming one of the major challenges in the so-called THz gap (Section 3).

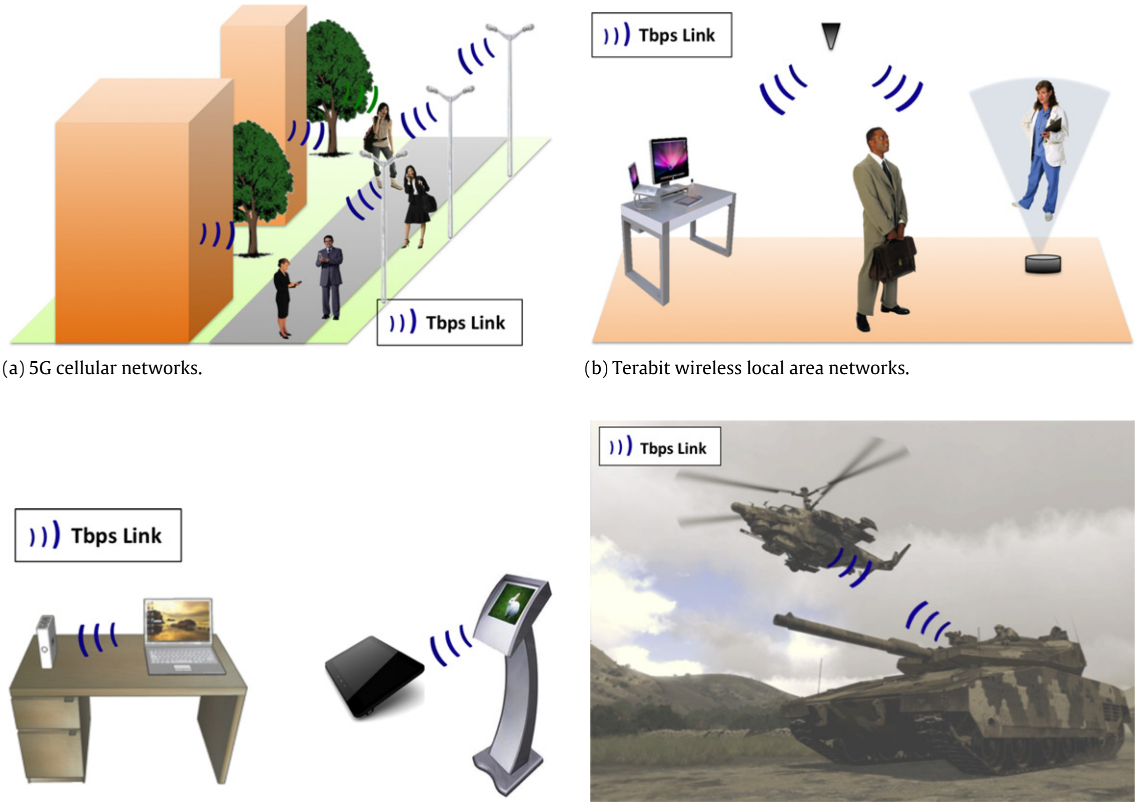
However, there still exist several research challenges both from the device and the communication perspectives that require innovative solutions and even the revision of well-established concepts in wireless communications. One of the main challenges is imposed by the very high path loss at THz Band frequencies, which poses a *major constraint on the communication distance*. Additional challenges range from the implementation of compact high-power THz Band transceivers, the development of efficient ultra-broadband antennas at THz Band frequencies, and the characterization of the frequency-selective path loss of the THz Band channel, to the development of novel modulations, transmission schemes and communication protocols tailored to the peculiarities of this paradigm. Many of these challenges are common to mm-Wave communication systems and, as a result, the solutions proposed in this paper can also benefit those systems.

In addition to all these challenges, *the* THz *Band is not yet regulated.* 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 Gbit/s Wireless (SG100G) [15], formerly known as the IEEE 802.15 WPAN Terahertz Interest Group (IGThz), has been recently established. The ultimate goal of the SC100G is to work towards the first standard for THz Band communication able to support multi-Gbps and Tbps links.

In this paper, 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. In Section 2, we describe many potential applications of ultra-broadband communications in the THz Band. In Section 3, we state the challenges in device technologies, which include transceiver and antenna designs in the THz Band. In Section 4, we outline the communication challenges in terms of channel modeling, physical, link, network and transport layers functionalities for THz Band communication networks. In Section 5, we review the state of the art in terms of experimental and simulation platforms and identify the main challenges in their realization. Finally, we conclude the paper in Section 6.

2. Applications of terahertz band communication

The very large bandwidth provided by the THz Band opens the door to a variety of applications which demand ultra-high data rates and allows the development of a plethora of novel applications in classical networking scenarios as well as in new nanoscale communication paradigms. Some of these applications can already be foreseen and others will undoubtedly emerge as technology progresses.



(a) 5G cellular networks.

(b) Terabit wireless local area networks.

(c) Terabit wireless personal area networks.

(d) Secure wireless communication for military applications.

Fig. 1. Terahertz Band applications at the macroscale.

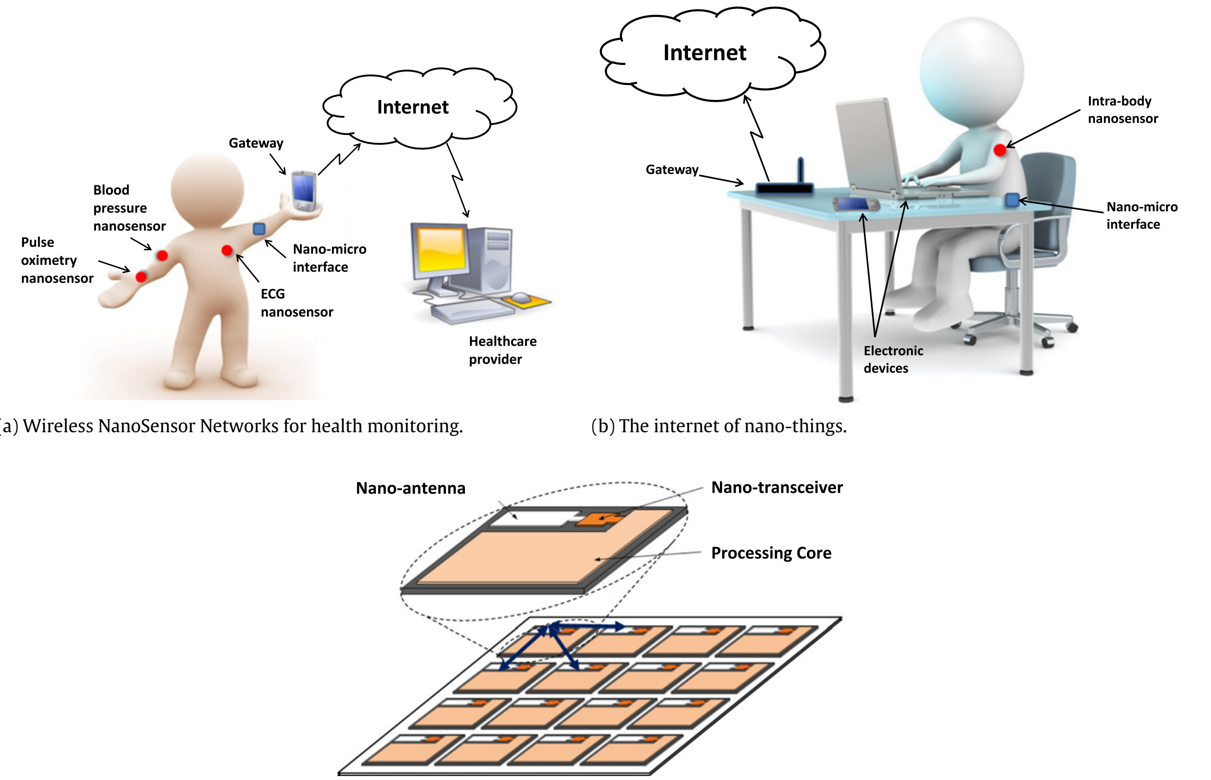
2.1. *Terahertz band communication at the macroscale*

The envisioned applications of THz Band communication at the macroscale are, among others:

- *5G Cellular Networks:* THz Band communication can be used in next generation small cells, i.e., as a part of hierarchical cellular networks or heterogeneous networks [9]. The THz Band will provide small cells with ultra-high-speed data communication within coverage areas of up to 10 m. The operational environment of these small cells includes static and mobile users, both in indoor and outdoor scenarios. Specific applications are ultra-high-definition multimedia streaming to smartphones, or ultra-high-definition video conferencing (Fig. 1(a)). In addition, directional THz Band links can be used to provide an ultra-high-speed wireless backhaul to the small cells.
- *Terabit Wireless Local Area Networks (T-WLAN):* THz Band communication enables the seamless interconnection between ultra-high-speed wired networks, e.g., fiber optical links, and personal wireless devices such as laptops and tablet-like devices (no speed difference between wireless and wired links). This will facilitate the use of bandwidth-intensive applications across static and mobile users, mainly in indoor scenarios. Some specific applications are high-definition holographic video conferencing (Fig. 1(b)) or ultra-high-speed wireless data distribution in data centers [16,17].
- *Terabit Wireless Personal Area Networks (T-WPAN):* Tbps links among devices in close proximity are possible with THz Band communication. The operational environment is mainly indoor and usually on a desk. Specific applications include multimedia kiosks and ultra-high-speed data transfer between personal devices (Fig. 1(c)). For example, to transfer the equivalent content of a blue-ray disk to a tablet-like device could take less than one second with a 1 Tbps link, boosting the data-rates of existing technologies such as WiFi Direct, Apple Airplay or Miracast.
- *Secure Terabit Wireless Communication:* The THz Band can also enable ultra-broadband secure communication links in the military and defense fields (Fig. 1(d)). The very high atmospheric attenuation at THz Band frequencies and the use of very large antenna arrays to overcome the limited communication distance result in very narrow, almost razor-sharp, beams, which drastically limit the eavesdropping probability. Spread spectrum techniques can also be used over the ultra-broad channel bandwidth to prevent and overcome common jamming attacks.

2.2. *Terahertz band communication at the micro/nanoscale*

The THz Band will also enable wireless communication among nanoscale machines or nanomachines, i.e., very small functional devices which are able to perform simple



(a) Wireless NanoSensor Networks for health monitoring.

(b) The internet of nano-things.

(c) Wireless on-chip communication.

Fig. 2. Terahertz Band applications at the nanoscale.

tasks at the nanoscale, such as computing, data storage, actuation or sensing. Each component of a nanomachine is up to a few hundred cubic nanometers in size, and the size of the entire device is in the order of a few cubic micrometers at most. The state of the art in nanoscale transceivers and antennas points to the THz Band as their frequency range of operation [18–23]. It is not that nanomachines are purposely developed to communicate in the Terahertz Band, but the very small size and unique properties of nano-antennas and nano-transceivers enable nanomachines to communicate at this very high frequency. Some specific applications are:

- *Health Monitoring Systems:* Sodium, glucose and other ions in blood [24], cholesterol [25], cancer biomarkers [26] or the presence of different infectious agents [27] can be monitored by means of nanoscale sensors or nanosensors. Several nanosensors distributed around the body, defining a human body nanosensor network (Fig. 2(a)), could be used to collect relevant data about the patient's health. A wireless interface between these nanosensors and a micro-device such as a cellphone or specialized medical equipment could be used to collect all these data and forward them to the healthcare provider.
- *Nuclear, Biological and Chemical Defenses:* Chemical and biological nanosensors can be used to detect harmful chemicals and biological weapons in a distributed manner. One of the main benefits of using nanosensors rather than classical chemical sensors is that the presence of a chemical composite can be detected in a concentration as low as one molecule and much faster than classical microscale sensors [18]. However, taking into account that these sensors need direct contact with the molecules, having a network with a very large number of nanosensor nodes becomes necessary. By means of *distributed spectroscopy*, a wireless nanosensor network will be able to converge the information of the molecular composition of the air in a specific location to a macro-device in a very short time.
- *The Internet of Nano-things:* The interconnection of nanoscale machines with existing communication networks and ultimately Internet defines a truly cyber–physical system which known as the Internet of Nano-Things (IoNT) [28]. The IoNT enables new interesting applications that will impact also in the way we work. For example, in an interconnected office (Fig. 2(b)), a nano-transceiver and nano-antenna can be embedded in every single object to allow them to be permanently connected to the Internet. As a result, a user can keep track of all its professional and personal item in an effortless fashion.
- *Ultra-high-speed On-chip Communication:* The THz Band can provide efficient and scalable means of inter-core communication in wireless on-chip networks [29], by using planar nano-antennas to create ultra-high-speed links (Fig. 2(c)). This novel approach will expectedly fulfill the stringent requirements of the

area-constraint and communication-intensive on-chip scenario by virtue of both its high bandwidth and extremely low area overhead. More importantly, the use of graphene-based THz Band communication [21] would deliver inherent multicast and broadcast communication capabilities at the core level.

3. Challenges in terahertz band device technologies

In this section, the device design and development challenges for THz Band are surveyed. The limitations and possible solutions for ultra-high-speed transceiver architectures are highlighted, and the challenges in the development of ultra-broadband antennas and antenna arrays are explained.

3.1. Terahertz band transceivers

There is a need to develop new transceiver architectures that are able to operate at THz Band frequencies and, more importantly, able to exploit the very large available bandwidth. High power, high sensitivity and low noise figure are additional transceiver features, which are required to overcome the very high path-loss at THz Band frequencies. Currently, different technologies are considered, which we review next.

3.1.1. Silicon germanium BiCMOS and CMOS technologies

Silicon Germanium (SiGe) technology is usually the first choice for many performance-constrained high-frequency radio-frequency (RF) systems. SiGe technology offers designers the many performance virtues of SiGe Heterojunction Bipolar Transistors (HBTs), i.e., high gain, low noise, good linearity, and good power handling, among others, within a low-cost, highly-integrated, silicon-compatible technology platform [30]. SiGe also provides on-die silicon Complementary Metal–Oxide–Semiconductor (CMOS) multi-level metallization with low-loss transmission lines, and a suite of integrated passive elements, such as antennas [31], for a true system-on-a-chip technology platform.

The performance of SiGe technology has improved dramatically in recent years and has been used to develop HBTs with a transistor cut-off frequency f_T (i.e., the highest frequency at which the transistor current gain is equal to one) and a maximum oscillation frequency $f_{\max}$ (i.e., the highest frequency for which the transistor power gain is equal to one) up to $f_T > 300$ GHz and $f_{\max} > 500$ GHz, respectively [32], and 3-dB bandwidth of up to 27 GHz [33]. High-performance SiGe-based front-ends for radar and communication systems have been demonstrated at millimeter-wave frequencies (e.g., 60 GHz) [34,35]. First attempts to realize SiGe-based front-ends in the THz Band have already been demonstrated at 200 to 300 GHz [36] and even up to 840 GHz [37]. However, these implementations consist of up- and down-converters, and their application scenarios are limited to THz Band imaging, in which a large bandwidth is not needed. As a result, *the development of SiGe-based transceivers for true* THz *Band operation is still an open research challenge*.

Another technology that is currently gaining momentum for THz Band applications is standard silicon CMOS technology. For example, in [38], a CMOS-based oscillator able to operate at a fundamental frequency of 220 GHz is demonstrated. The fourth order harmonic of the oscillator is boosted and radiated through a patch antenna at 870 GHz. From the reception perspective, in [39], CMOS technology with cut-off frequency $f_T > 160$ GHz and maximum oscillation frequency $f_{\max} > 200$ GHz is used to build a sub-harmonic direct detector with maximum responsivity between 790 and 960 GHz, i.e., almost a 170 GHz band. Still, however, in these two technologies, major challenges that need to be addressed are *to overcome the intrinsic device speed limitation that limit f_T and $f_{\max}$ at about* 200–300 GHz *and, in particular in the case of* CMOS *technology, overcome the parasitics and other losses.*

3.1.2. Gallium nitride, indium phosphide and metamorphic technologies

Although SiGe-based and CMOS-based transceivers can be used for the lower part of the THz Band, the limited power gain and insufficient transistor breakdown voltage of SiGe HBTs hamper their utilization in high-power applications at frequencies above 500 GHz. Therefore, high-gain power amplifiers are needed to overcome the very high path loss in the THz Band, which will be discussed in detail in Section 4.1.

Among others, Gallium Nitride (GaN) technology is usually considered for high-power applications. State-of-the-art GaN-based High-Electron-Mobility Transistors (HEMTs) have been shown with a cut-off frequency $f_T > 450$ GHz, maximum oscillation frequency $f_{\max} > 600$ GHz, and a breakdown voltage up to $V_T > 13$ V [40]. Compared to SiGe-based and CMOS devices, the high breakdown voltage in GaN-based transistors is highly appreciated for power amplification in millimeter-wave and sub-millimeter-wave circuits. For example, at a relatively early-stage development phase, GaN-based Microwave Monolithic Integrated Circuits (MMICs) have already demonstrated an output power $P_{out} > 2.1$ W [41,42] at 100 GHz over a 4 GHz bandwidth. However, to the best of our knowledge, no GaN-based amplifier exists above this frequency for the time being.

Besides GaN, another very relevant player for high-power high-frequency applications is Indium Phosphide (InP) technology. State-of-the-art InP-based HEMTs have been reported with a cut-off frequency $f_T > 600$ GHz and maximum oscillation frequency $f_{\max} > 1.2$ THz [43]. This technology has been utilized to build a Terahertz Monolithic Integrated Circuit (TMIC) amplifier, able to provide a peak output power of 3 mW at 650 GHz and small signal gain above 10 dB from 625 to 640 GHz. This transistor technology has already been demonstrated in wireless links at 220–300 GHz able to support data-rates up to 25 Gbps at 10 m [44,45], and even up to 100 Gbps at 20 m when combined with an optical transmission system [46].

Another technology is based on the utilization of metamorphic HEMTs (mHEMTS) for TMICs. State-of-the-art mHEMTS based on hybrid structures built with Indium (In), Aluminum (Al) and Gallium Arsenide (GaAs) layers have been developed with a cut-off frequency $f_T > 500$ GHz and a maximum oscillation frequency $f_{\max} > 1$ THz [47]. This technology has been used to built TMIC amplifiers with a linear gain of 20.3 dB at 610 GHz and more than 18 dB over the bandwidth from 557 to 616 GHz, almost a 60-GHz-wide band. *Further refinement of these technologies is needed to ultimately enable fully-electronic* THz *Band transceivers able to support wireless* Tbps *links.*

3.1.3. Photonic and plasma wave technologies

Classical ways to generate and detect THz Band radiation includes the utilization of photonic devices. For example, from the signal generation perspective, photodiodes and Quantum Cascade Lasers (QCLs) [48,49] have been proposed as high-power THz Band sources, which can be used as local oscillators (LO) in heterodyne transceiver architectures. QCLs based on different combinations of III–V semiconductors (e.g., GaN, GaAs) can operate at frequencies above a few THz and can generate an average power in the order of a few mW when operating at very low (almost cryogenic) temperatures. However, the need of an external laser for optical electron pumping, their limited performance at room temperature, and their size might limit their use in some of the envisioned applications.

From the signal detection point of view, among others, Schottky diodes and bolometric detectors [50,51] have been investigated for direct detection of Terahertz Band radiation. These devices are able to detect very low power signals and have a high modulation bandwidth (up to a few GHz). However, their performance is usually reduced when operating at room temperature and their size poses a major constraint for the nano-devices. Other classical ways to generate and detect THz Band radiation in a photonic approach include the utilization of nonlinear optical phenomena such as optical rectification and the linear electro-optic effect, which have been mainly used for THz Band spectroscopy applications [52]. Their size and power consumption limit their use in the aforementioned applications.

More recently, compact signal generators and detectors are being developed by using a single HEMT based on III–V semiconductors [53,22,23,54]. In particular, it has been recently shown that plasma waves at THz Band frequencies can be excited in the channel of a HEMT with nanometric gate length by means of either electrical or optical pumping. At cryogenic temperatures, the periodic excitation of the electrons can result in well-defined resonant plasma waves created through the Dyakonov–Shur instability [55]. At room temperature, plasma waves are overdamped and the performance as a source and as a detector drastically decreases. Therefore, there is a need *to improve the performance of solid-state plasma-wave transceivers by developing innovative designs*. This could for example be achieved by combining these structures with novel materials such as graphene, as we describe next.

3.1.4. Graphene technology

One of the most recent alternatives to develop THz Band compact transceivers is based on the utilization of graphene, i.e., a one-atom-thick nanomaterial which was experimentally obtained for the first time in 2004 [56,57]. Graphene has outstanding physical, electrical and optical properties, and it is often termed as "the wonder material" of the 21st century [58]. The carrier mobility measured in graphene devices is extremely high, in the order of 8000–10,000 $cm^2\ V^{-1}\ s^{-1}$ at room temperature, but speeds up to 200,000 $cm^2\ V^{-1}\ s^{-1}$ have been measured at room temperature in suspended ex-foliated graphene. This value is several order of magnitude above those of the previous materials. Moreover, the mean-free path for ballistic carrier transport is 300–500 nm and can even reach more than 1 μm at special cases at room temperature.

Graphene and its derivatives, namely, carbon nanotubes (CNTs) and graphene nanoribbons (GNRs), have been used to fabricate optical detectors for visible and infrared radiation which exhibit very fast response. However, detection of THz Band radiation is a field which is only now emerging. So far, semiconducting CNTs have been successfully used to produce an RF rectifier. In this approach, a high frequency diode is formed between the CNT and a metal electrode. This will lead to rectification and thus a DC response exactly as is the case for semiconductor diodes [59]. However, these devices face several issues: first of all, the yield reported is extremely low since most devices were shorted by conducting CNTs, furthermore, the response in terms of speed was limited by the poor ohmic performance of the second metallic electrode. Placing in parallel many CNTs could potentially improve the situation.

Graphene technology is still much less mature than the aforementioned technologies and, as a result, many challenges arise. For example, *innovate designs for graphene-based signal emitters and detectors for* THz *Band frequencies need to be developed.* For example, instead of trying to realize graphene-based FETs and, thus, creating active electronics that can handle the required speed, it might be more efficient to take advantage of the properties of graphene and GNRs as nanomaterials. At the transmitting side, emitters can be created by realizing nano-sized oscillators that produce the required very high frequency RF radiation. Accordingly, at the receiving end, the detector can demodulate the received signal. This approach might limit the very high frequency components and provide the missing link to achieve true THz Band carrier frequency. In a similar direction, i.e., by taking advantage of the new properties of graphene, novel signal modulators for THz Band communications have been recently proposed in [60].

An additional challenge is *to investigate hybrid architectures that benefit from these technologies*. For example, hybrid SiGe and GaN-based devices could be enhanced with graphene to improve their response at THz Band frequencies. Among others, graphene supports the propagation of Surface Plasmon Polariton (SPP) waves at THz Band frequencies [61–65]. SPP waves are confined EM waves coupled to the surface electric charges at the interface between a metal and a dielectric material. From this, one option is to use graphene to improve the efficiency of current solid-state THz Band sources based on HEMTs built with III–V semiconductor materials [66] (Fig. 3). *While the graphene technology is not as mature as the aforementioned technologies and part of its potential remains unknown, its unique properties and the preliminary results motivate its further development.*

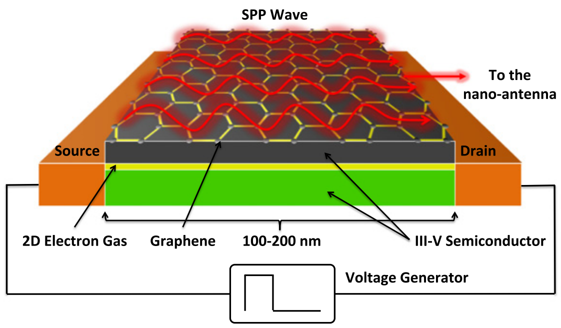


Fig. 3. A graphene-based plasmonic transceiver for THz Band communication [66].

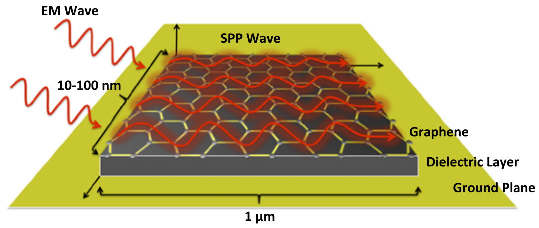


Fig. 4. A graphene-based plasmonic antenna for THz Band communication [21].

3.2. Terahertz band antennas

In addition to the transceivers, ultra-broadband and multi-band antennas are needed to enable multi-Gbps and Tbps links in the THz Band. Moreover, new advanced antenna systems, such as very large antenna arrays, will be required overcome the very high path loss of the THz Band channel (Section 4.1). Next, we discuss the challenges and opportunities in this realm.

3.2.1. Ultra-broadband and multi-band antennas

Similarly to the transceiver, the antennas in a THz Band communication system need to support a very large transmission bandwidth, which ranges from several tens of GHz up to a few THz (Section 4.1). The efficiency of classical ultra-broadband antennas when operating at THz Band frequencies remains unknown. For example, on the one hand, existing practical THz Band communication 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% of their center frequency, i.e., in the order of 30 GHz. On the other hand, sinuous antennas have proven to be attractive for THz Band circuits such as broadband detectors [67]. This particular type of log-periodic antennas were first proposed and studied by DuHamel and then applied to many circuits and components primarily in the microwave frequency range [68]. Sinuous antennas can support much larger bandwidths than other classical antenna designs. However, in any case, evaluation of the critical performance characteristics of different types of antennas, including bandwidth, impedance and polarization has not yet been systematically performed in the THz Band.

Besides the very large bandwidth, omnidirectional antennas will be needed to enable some of the aforementioned applications, whereas highly directional antennas will be required in some others. All these requirements result in many challenges in the design of THz Band antennas, such as:

- *To investigate the performance of classical ultra-broadband antennas when operating at* THz *Band frequencies.* In addition to the aforementioned paraboloid, horn and sinuous antennas, simpler multi-band and sub-band radiating structures need to be evaluated, such as embedded coil antennas, in order to test their usability for individual band data handling capabilities. This requires both analytical modeling as well as experimental characterization of different antenna designs.
- *To explore the potential of novel nano-antennas based on graphene and its derivatives.* As proposed in [69,19,20,70,21], graphene can be used to build novel plasmonic nano-antennas (Fig. 4), which exploit the behavior of SPP waves in GNRs to efficiently radiate in the THz Band. The size of these nano-antennas is in the order of one micrometer by tens to hundreds of nanometers, i.e., almost two orders of magnitude smaller than conventional THz Band antennas. This small size enables both, the integration of individual nano-antennas into nanomachines (Section 2) as well as the development of very large antenna arrays, as discussed in the next section. In addition, the response of graphene-based nano-antennas can be easily tuned by means of material doping. Nevertheless, many challenges need to be addressed. Optimal antenna designs with maximal efficiency need to be investigated. The ways to improve the efficiency of the nano-antenna are twofold. On the one hand, there is a need to develop efficient ways to feed the antenna. The use of graphene for the antenna and for the transceiver should help in the achievement of this task. On the other hand, new broadband antenna designs need to be explored, which ultimately depend on the new techniques to manufacture and tailor graphene.

3.2.2. Very large antenna arrays

In order to overcome the very small gain and effective area of individual THz Band antennas, it is necessary to *investigate the performance of novel very large antenna arrays.* Indeed, the very small size of a THz Band antenna allows for the integration of a very large number of antennas with very small footprint. The major research challenges are as follows:

- *To model the interaction and coupling effects among nearby antennas.* This analysis is needed to guide the deployment of a very large number of antennas in a compact footprint. This analysis needs to be tailored to the different antenna technologies developed in the previous section as, for example, the coupling among graphene-based nano-antennas is remains largely unknown for the time being.
- *To develop radically new approaches for antenna arrays pattern synthesis.* Classical phase arrays might not be able to support the very large bandwidth needed to achieve multi-Gbps or Tbps links. On the contrary, we believe that new techniques should be developed by levering the opportunities brought by graphene, among

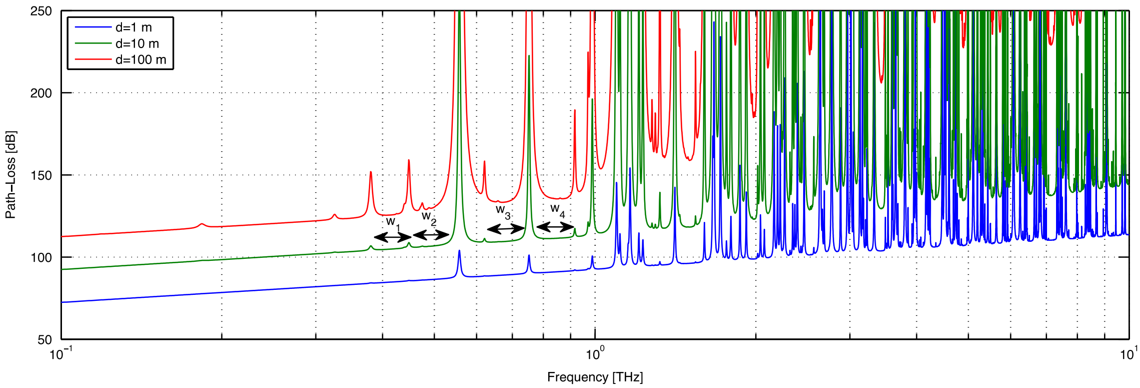


Fig. 5. Path loss in the THz Band for different transmission distances.

others. Indeed, as we mentioned above, the response of an individual graphene-based plasmonic antenna can be easily tuned by means of electrostatic material doping. Therefore, we envision a new antenna pattern synthesis approach based on dynamic doping of different antennas.

As we will discuss in Section 4.2.3, these very large antenna arrays enable unique physical layer solutions, such as novel Massive MIMO schemes.

4. Challenges in terahertz band communication networks

There are many challenges in the realization of efficient and practical THz Band communication networks, which require the development of innovative solutions at the different layers of the protocol stack. In the following, the main challenges are discussed in a bottom-up approach, by starting from the THz Band channel modeling, up to the development of transport layers solutions for ultra-broadband communication networks in the THz Band. As we mentioned in the introduction of this paper, many of the challenges in the THz Band are common to those of mm-Wave systems. In the many cases, the solutions proposed in this section can also be utilized to overcome the challenges in mm-Wave systems.

4.1. Channel modeling

Existing channel models for lower frequency bands cannot be used in the THz Band, because they do not capture the behavior of this spectrum band, e.g., the very high molecular absorption loss or the very high reflection loss [4–6]. For the time being, current channel characterization efforts are focused on the 300 GHz transmission window [71–76], 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 Tbps links. In addition, besides LOS communication, NLOS propagation needs to be considered. Ultimately, a complete multi-path channel model accounting for the statistical varying environment is needed.

In this section, we discuss the state of art and open challenges in terms of THz Band channel modeling for different propagation conditions.

4.1.1. Line-of-sight propagation

The first step towards understanding of the THz Band channel is the characterization of the propagation phenomena affecting the free space propagation of THz Band radiation. In this direction, we have recently developed a LOS propagation model for the entire THz Band (0.1–10 THz) [77]. In particular, we used radiative transfer theory and the information in the HITRAN database [78] to analyze the impact of molecular absorption on the path-loss and noise.

The path loss for a traveling wave in the THz Band is defined as the addition of the spreading loss and the molecular absorption loss. The spreading loss accounts for the attenuation due to the expansion of the wave as it propagates through the medium. The absorption loss accounts for the attenuation that a propagating wave suffers because of molecular absorption and depends on the concentration and the particular mixture of molecules encountered along the path. As a result, the channel in the THz Band is very frequency selective.

The properties of the LOS propagation channel in the THz Band are illustrated in Fig. 5. These results are numerically obtained from [77] for the case of using an ideal isotropic antenna with unity gain in transmission and in reception. For a given transmission distance, the total path loss increases with frequency due to the spreading loss. The path loss can easily go above 100 dB for transmission distances in the order of just a few meters. In addition, the molecular absorption defines several transmission windows, whose position and width depend on the transmission distance. For distances much below 1 m, molecular absorption loss is almost negligible and, thus, the THz Band behaves almost as a 10 THz wide transmission window. However, for transmission distances over 1 m, many resonances become significant and the transmission windows become narrower. Several transmission windows, w_1 = [0.38–0.44 THz], w_2 = [0.45–0.52 THz], w_3 = [0.62–0.72 THz] and w_4 = [0.77–0.92 THz], have been marked in Fig. 5. Within each transmission window, the impact of molecular absorption loss is minimal, well below 10 dB/km. Still, however, due to the spreading loss, the total path-loss is very high, and motivates the utilization of highly directional/high gain antennas, as well as new Massive MIMO schemes, which will be described in Section 4.2.3.

Based on this behavior, there is a need to *identify the center frequency, the bandwidth and the total path loss for the different available transmission windows* as functions of the transmission distance. The entire THz Band needs to be explored to locate the best transmission windows in light of information capacity. For example, as we mentioned before, current efforts are focused on 0.35 THz with the bandwidth of 51.1 GHz. By contrast, the bandwidth increases up to 142.7 GHz for the transmission window centered at 0.84 THz.

4.1.2. Non-line-of-sight propagation

LOS transmissions might not be always possible due to the presence of obstacles. In particular, NLOS 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. These coefficients depend on the material and geometry of the surface, as well as on the frequency and angle of the incident EM wave.

There are additional research challenges in terms of NLOS propagation modeling, as follows:

- *To characterize the reflection, scattering and diffraction coefficients for common materials at* THz *Band frequencies*. The properties of building materials have been measured up to 1 THz [79]. However, the reflection, scattering and diffraction coefficients for common materials found in our envisioned applications (from indoor environments to on-chip communications) need to be studied analytically and validated with experimental measurements for the entire THz Band.
- *To investigate NLOS communication deployed with directed reflection on dielectric mirrors* [80]. This NLOS propagation acts as supplementary for the case when LOS is unavailable. Particularly in the indoor environment, LOS propagation is likely unavailable. Instead, NLOS propagation can be designed by strategically placing mounted dielectric mirrors to reflect the beam to the receiver. The resulting path loss is acceptable owing to the low reflection loss on dielectric mirrors.

4.1.3. Multi-path channel

With ultra-broad bandwidth, each frequency component in the transmitted signal experiences different attenuation and delay. This frequency-dispersion effect, or equivalent distortion in the time domain, are not captured in existing multi-path channel models. Hence, new multi-path channel models need to be developed for THz Band communication.

One possible approach to analyze multi-path propagation is to *study individual arrival rays at the receiver, by using ray tracing techniques*. When LOS is available, only LOS and reflected rays need to be investigated in the multi-path channel model. By contrast, under NLOS conditions, scattering effects need to be incorporated in the multi-path model in addition to reflected components. In particular, higher portion of the power is contained in diffusely scattered rays other than the reflected ray, as the surface roughness increases. In both cases, diffraction effects can be ignored, only except when the receiver is very closed to the incident shadow boundary.

Alternatively, because the study of the channel model in terms of individual arrival signal requires prior knowledge of the environment geometry, *a statistical model to characterize the multi-path channel efficiently* can be developed. A research challenge is to stochastically analyze the different frequency-sensitive parameters that affect the received multi-path signals, which may include the probability of the presence of LOS propagation, the number of resolvable NLOS components, propagation delays, and path gains. Furthermore, it is also relevant to include *the impact of antenna directivity on the multi-path channel path loss*.

An additional research challenge is to investigate the polarization effects in the THz Band channel. Depolarization can occur as a result of two factors. One factor arises from the transmitter/receiver antenna orientation and gain pattern, which causes power loss of the received signal for both LOS and reflected NLOS components, since the receiver antenna cannot remain co-polarized with the transmitter antenna polarization owing to the mobility and orientation of transmitter/receiver antennas. The other factor that causes depolarization is the reflection in different types of materials that NLOS propagation experiences. *The development of an ultra-broadband multi-polarized fading channel model that captures the these depolarization effects remains as an unresolved challenge.*

4.1.4. Noise sources in the terahertz band

There are several noise sources in the THz Band. On the one hand, *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 it also introduces noise [81]. The equivalent noise temperature at the receiver is determined by the number and the particular mixture of molecules found along the path. The molecular absorption noise is not white. Indeed, because of the different resonant frequencies of each type of molecules, the power spectral density of noise is not flat, but has several peaks. In addition, this type of noise is mainly present when transmitting, i.e., there will be only background noise if the channel is not being used. This peculiarity can be exploited in the design of novel modulations and channel codes, as we will explain in Section 4.2.

On the other hand, besides the ambient noise originated in the channel, a major noise sources comes from the receiver. The receiver noise, which is commonly characterized by the noise figure, depends on the device technology in use (Section 3.1). For example, in the case of SiGe-based transceivers at frequencies below 1 THz, *the noise figure of the* HBT *in the first amplifying stage after the antenna needs to be characterized. Similar analyses need to be conducted for* GaN *and* InP HEMTs *and* mHEMTS *in* THz *Band receivers.* More interestingly, new noise models for graphene devices need to be developed. For the time being, contradictory statements on the noise figure of graphene devices have been made [82–86]. On the one hand, the very high contact resistance of nano-sized structures was believed to result in a very high thermal noise. However, on the other hand, the fact that graphene-based nano-structures allow the ballistic transport of electrons results in very low thermal noise in the device. *A unified noise model for graphene needs to be developed.*

4.2. Physical layer

By exploiting the capabilities of the THz Band transceivers and antennas as well as the channel behaviors, we describe next the challenges and opportunities at the physical layer, including modulation, coding, massive MIMO, synchronization, equalization and security.

4.2.1. Modulation

Classical modulation schemes can be used for THz Band communication, but they will not be able to fully benefit from THz Band channel properties. As discussed in the previous section, the ultra-broadband bandwidth associated to each transmission window in the THz Band drastically changes with small variations in the distance. For example, for distances much below 1 m, the THz Band channel behaves as almost a 10-THz-wide window. However, the bandwidth of several transmission windows is reduced by more than 10% when increasing the transmission distance from 1 to 10 m (Fig. 5). This requires the development of different modulations for different applications, based on the targeted distance.

For short-range communication, consistently with the trends of ultra-low power, compact-size and ultra-low complexity design in broadband communications [87], we have recently proposed a novel *pulse-based communication scheme for short range* THz Band communication [88]. This scheme is based on the asynchronous exchange of one-hundred-femtosecond-long pulses by following an on–off modulation spread in time (TSOOK). The main components of the power spectral density of these pulses are within the THz Band. Despite their very short duration, these pulses can be detected and analogically demodulated with the plasma wave transceivers reviewed in Section 3.1.3 and hybrid plasmonic transceivers in Section 3.1.4. This modulation is mainly valid for short distances, in which molecular absorption does not drastically impact the channel.

For distances longer than 1 m, molecular absorption defines multiple transmission windows, in which each window has a strongly distance-dependent bandwidth. *New distance-aware modulations* that take advantage of this peculiar behavior appear as an interesting path to explore. In this direction, we have developed a new scheme that allows nodes to intelligently share the channel by adapting the modulation scheme according to the transmission distance [89]. In particular, a node can adaptively choose modulations based on the transmission distance in order to occupy either (i) the entire transmission bandwidth, (ii) the central part of the transmission window (this information reaches both close and far nodes), or (iii) the sides of the transmission window (the information only reaches nearby devices).

New modulation challenges and opportunities also appear in relation to novel transceiver device technologies (Section 3.1). For example, the modulation of a carrier signal by changing the *material doping of graphene-based devices* has been recently proposed [60,90]. By changing the number of available holes and electrons in the material, the response of a graphene-based signal generator, mixer or amplifier, drastically changes. Starting from these results, new ultra-broadband modulations suitable for THz Band communication need to be investigated, such as femtosecond-long pulse-shaping and pulse-shifting by means of material doping. Moreover, antennas can be tuned to filter the transmitted pulses for a desired shape in accordance with the aforementioned distance-dependent channel behavior.

4.2.2. Coding

The channel peculiarities and the expected capabilities of transceivers require the development of novel channel codes for THz Band communication. The classical capacity-approaching channel codes are designed to maximize the data rate for a given transmit power or equivalently to minimize the transmit power for a target data rate. However, in addition to transmit power, decoding power is another fundamental source of power consumption [91]. Indeed, for distance smaller than ten meters, the decoding power required by most state-of-the-art decoders is often comparable to, or even larger than, the transmit power. Uncoded transmission is commonly used in 60 GHz systems [92] to reduce the decoding power, despite increasing the transmission power. Hence, for THz Band communication, decoding power and decoding time need to be carefully considered while designing and choosing channel codes due to the ultra-wide bandwidth and very high bit-rates.

The research challenges in terms of coding are:

- *To characterize the error sources at* THz *Band frequencies.* The THz Band channel peculiarities and, in particular, the molecular absorption noise and the multi-path fading, determine the probability of having channel bit errors as well as the characteristics of these errors. The nature of channel errors should be analyzed by starting from a stochastic analysis of both noise (Section 4.1.4) and multi-path propagation (Section 4.1.3).
- *To develop new types of ultra-low-complexity channel coding schemes*. It is important to investigate the tradeoff between transmission power and decoding time, and design channel codes to minimize the overall transmit and decoding powers. For example, we have recently proposed the use of low-weight coding schemes to prevent channel errors from happening rather than trying to correct them afterwards [93]. In particular, we showed how the reduction of the coding weight results in lower noise and multi-user interference power at THz Band frequencies. Efficient ways to generate low-weight codes need to be investigated. In addition, dynamic mechanisms to determine and set the optimal coding weight in light of the network conditions need to be investigated.

4.2.3. Dynamic massive MIMO

As we discussed in Section 3.2.2, very large antenna arrays can be developed to overcome the very high path loss of the channel and the power limitations of the

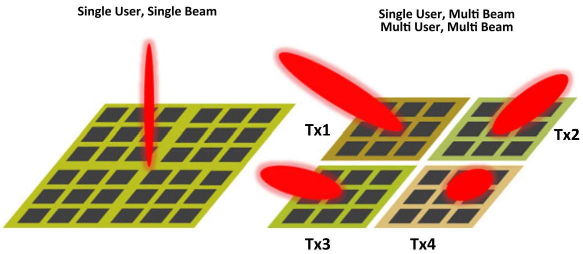


Fig. 6. Two massive MIMO modes.

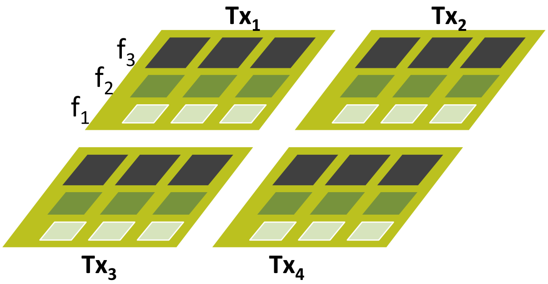


Fig. 7. Multi-band massive MIMO.

transceivers in the THz Band. This opens many new opportunities for the development of very large scale Massive MIMO systems.

By properly feeding the antenna array elements, different array modes can be generated (Fig. 6), such as:

- *Single User, Single Beam (SUSB):* the array is programmed to create a single very highly directional beam, as in conventional beamforming. This is used to reach the most distant users, once at a time. Very high-gain links come at the cost of very narrow beam widths (specially with this very large element density), which requires accurate pointing and automatic beam steering techniques.
- *Single User, Multiple Beams (SUMB):* the array is programmed to create multiple directional beams, which are used by a single user to exploit spatial diversity in order to increase capacity. For example, a 100 by 100 array can be seen as four individual 50×50 arrays. A user can take advantage of this by treating it as a four MIMO system, in which each unit is an array.
- *Multiple Users, Single Beam (MUSB):* the array is programmed to create multiple directional beams, which are individually used by different users. In this case, the four 50×50 arrays can be seen as a four multi-user MIMO (MU-MIMO) system, in which each unit is an array.
- *Multiple Users, Multiple Beams (MUMB):* the array is programmed to create many multiple beams, which are used by different users. In order to guarantee that the channel seen by each sub-array is uncorrelated, the antenna elements are alternated for the different users.

The research challenges in implementing and controlling these modes are as follows:

- *To develop algorithms to dynamically combine different antenna array working modes to accommodate different users with different needs at different distances.* In these algorithms, it is important to take into account the current channel and network status, and be able to reprogram the antenna array elements intelligently.
- *To analyze multi-band massive* MIMO *communication.* The huge bandwidth for THz Band communication can exceed the bandwidth provided by a single antenna. Hence, by using different length antennas in the same array, multiple transmission windows and even the entire 10-THz Band can be simultaneously utilized (Fig. 7).
- *To efficiently estimate channel information of thousands of channels.* The performance of MIMO systems depends on the accuracy of the channel estimation information, which resides a challenging task with massive active entries in the channel matrix.

In addition, if antenna arrays are not available to an individual transmitter, *cooperative communication can be exploited to emulate virtual massive* MIMO *among a group of transmitters*, by enabling multiple sources to simultaneously transmit a common message collaboratively. This technique is specially suited for high node density networks (e.g., nanoscale networks). The idea is to control the phase of the transmissions, so that the signals are constructively received at an intended receiver. The transmission range of individual devices can be enhanced at the expense of tight synchronization and coordination requirements among nodes, which are still open challenges.

4.2.4. Synchronization

Synchronization is a critical task at the receiver as well as among different transmitters for cooperative communication, and it becomes more challenging in ultra-broadband communication networks for the following reasons. First, at Tbps data rates, it is extremely challenging to sample the signal at the Nyquist rate and to perform sophisticated signal processing tasks. Second, different users have independent local oscillators to generate carrier frequencies, resulting in significant frequency offsets across devices.

For short-range communication, pulse-based modulation schemes permit the use of low-complexity non-coherent analog detectors, e.g., energy detector and auto-correlation receiver [94]. In this direction, in [95], we presented a more advanced non-coherent receiver architecture based on a Continuous-time Moving Average symbol detection scheme. This symbol detection scheme outperforms previous detection schemes for pulse-based modulations in terms of the symbol error rate and relaxes the synchronization requirements. However, for longer communication distances, robust and accurate synchronization mechanisms are needed for ultra-broadband communication in the THz Band.

The research challenges associated with the two aspects of synchronization are as follows:

- *To develop new mechanisms for frequency synchronization.* Carrier frequencies require accurate synchronization to eliminate the frequency offset among different users. One approach is to employ a master–slave architecture [96], where a "slave" user makes use of a phase-locked loop to lock to a reference carrier signal which is broadcasted by a "master" user. Alternatively, frequency estimation can be obtained by using a very short preamble of femtosecond-long pulses, so that the "slave" user can learn the "master" user's clock from the time difference between pulses in the preamble.

- *To develop new schemes for time synchronization*. Time synchronization requires the two steps: *frame timing recovery*, which is to estimate the beginning of the individual frame, and *symbol timing recovery*, which is to identify the first frame of a symbol in the incoming frame stream [97]. One approach is to design femtosecond-long-pulse-based burst wake-up signals, which can be used to start the receiver "at the right time".
- In any case, independently of the adopted time and frequency synchronization technique, additional challenges include the investigation of mechanisms to reduce the acquisition time at the receiver, the analysis of the impact of multi-path effects on synchronization and the investigation of joint modulation and synchronization solutions.

4.2.5. Additional challenges at the physical layer

Whether just for a single channel between two nanoscale machines or for hundreds of parallel channels in a massive MIMO transmission, *equalization is needed*. Ultimately, the performance of the physical layer solutions presented in this section rely on having accurate channel information, to then be able to either pre-process the modulated signals or post-process the received waveforms. The very high data rates at which signals can be transmitted and received enforces the use of *simple and efficient pre- and post-processing schemes, which balance the complexity between the transmitter and the receiver.*

Physical layer security is another challenge and opportunity in THz Band systems. The transmission of very short signals, e.g., a thousand bits could be ideally transmitted in 1 ns, and the utilization of razor-sharp beams, makes the interception of the transmitted information very challenging. In addition, orthogonal frequency hoping or spread spectrum schemes over the entire THz Band will become feasible too, as the transceiver technologies evolve. 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.*

4.3. Link layer

The capabilities of ultra-high-speed transceivers, the behavior of very large antenna arrays and the expected functionalities of new physical layer solutions require the development of novel link layer solutions. In this section, we describe the research challenges in the link layer, in terms of Medium Access Control (MAC) mechanisms, error control policy and packet size design for THz Band communication networks.

4.3.1. Medium access control

Novel MAC protocols are required for THz Band communication networks, since classical solutions are inadequate to capture the following characteristics. First, the THz Band provides devices with a very large bandwidth, ranging from several multi-GHz-wide windows to almost a 10 THz range. Therefore, devices do not need to aggressively contend for the channel. In addition, this very large bandwidth results in very high bit-rates and, thus, very short transmission times. This results into a very low collision probability. Moreover, the use of very large arrays and very narrow directional beams can also clearly reduce the multi-user interference. However, high-bit-rates and razor-sharp beams increase the synchronization requirements.

Some preliminary ideas to develop new MAC protocols for THz Band communication networks are summarized next:

- *To develop receiver-initiated transmission schemes to guarantee alignment between the transmitter and the receiver.* For example, a device can periodically switch between three operation modes: sleeping mode, transmitting mode and receiving mode. A device in *transmitting mode*, just waits for its intended receiver or relaying candidate to be available. A device in *receiving mode* scans its neighborhood by steering its antenna beam at a fixed speed and in a predefined pattern. During this process, the receiver announces its availability to receive a packet. Then, the transmitter can choose the best physical layer parameters by accounting for the communication distance and estimated channel conditions.
- *To exploit fast-steerable narrow beams for network-wide objectives*. The fast steering and pattern control capabilities of very large antenna arrays enable new functionalities that can be exploited to control interference. For example, in the downlink, a transmitter can simultaneously send information to two receivers in NLOS channels, by transmitting time-interleaved pulses in different directions so that the pulses intended for each user add coherently at the desired receiver, with no interference. There exists a tradeoff between user acquisition complexity and communication robustness, in terms of beam-width choice. A possible scheme to fully harness the huge antenna array is to adapt wider beamwidth during scanning phase for fast user acquisition, and intelligently steer focused thin beam for the subsequent data communication.
- *To develop a stochastic model for the multi-user interference*. Multi-user interference occurs when symbols from different transmitters reach the receiver at the same time and overlap. In order to capture this effect, a stochastic model of the interference is needed, which takes into account the modulation scheme and the relative position and orientation of interfering nodes in the network. The resulting probability density function of the interference power can assist the design of new MAC protocols, and be used in the studies of capacity and achievable data rates.

4.3.2. Additional challenges at the link layer

Existing studies on optimal error control mechanisms are not valid for communication networks in the THz Band because they do not capture the peculiarities of the channel. Therefore, there is a need *to develop new algorithms to* *dynamically choose among error control schemes*. As a result of the transmission at very high data rates and the utilization of razor-sharp antenna beams, the energy and time consumed in transmitting a packet can be expectedly several orders of magnitude lower than in classical wireless networks. As a result, depending on the transceiver capabilities and the type of channel coding scheme, the time and energy consumed in encoding a packet before transmission can be much higher than the time and energy consumption of retransmitting the packet. The relation between these magnitudes will motivate the use of different forms of error control, ranging from simple automatic repeat request to forward error correction or a combination of both.

Another aspect to be discussed at the link layer is *the definition of the optimal packet size.* When transmitting at multiple Gbps or Tbps, even very long packets occupy the channel for extremely short periods of time. For example, the transmission of 1-megabit-long packet would require approximately 1 μs when transmitting at 1 Tbps. Therefore, the chances of having a collision with another packet within such short time frame are minimal, specially when massive MIMO schemes are used at the same time. However, for the same bit error probability, longer packets will expectedly suffer from a larger number of channel errors, thus, increasing the requirements on the error detection and correction schemes. In addition, the transmission of very long packets could also lead to buffering problems at the receiver. This motivates both 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.*

4.4. Network layer

Neighbor discovery and routing becomes more challenging in THz Band communication networks due to both the limited communication distance as well as the utilization of highly directional antenna systems. In addition, in case of mobile devices in small cells systems, handovers become frequent and, thus, the right mechanisms need to be in place to maintain the network functionalities.

These are several open challenges to be addressed:

- *To explore the opportunities of multi-hop communication with both passive and active relays*. The benefits of using intermediate relays between a transmitter and a receiver at THz Band frequencies are several. As in any wireless communication system, the transmission power, and thus the energy consumption, can be reduced, by having several intermediate hops between the transmitter and the receiver. In addition, due to the unique distance-dependent behavior of the available bandwidth, the reduction of the transmission distance results into the availability of much wider bands, and, thus, the transmission at much higher bit-rates. These can contribute, once again, to major energy savings [98]. In addition, besides conventional relaying nodes, dielectric reflective mirrors can be utilized to enhance the signal propagation [80]. Optimal deployment topologies which take into account the location and orientation of such mirrors, their reflection coefficient, and their cost, need to be developed.
- *To develop new routing algorithms tailored to the physical and link layers of* THz *Band networks.* New routing metrics need be explored. Given that the available bandwidth depends on the molecular composition of the channel, it seems reasonable to incorporate such information into the routing decision process. For example, routes through lower-humidity areas should be prioritized. Currently, several cellphones incorporate humidity sensors with different applications. The information collected by that sensor could be incorporated in the routing decision process as part of the channel conditions. Of course, this is just an addition to more classical metrics which take into account the transmission distance, physical and link layers resources, and energy savings, among many others [99]. Once the route has been chosen, the link layer will ensure the data transmission to the next hop.
- *To design novel handover algorithms and supporting network architectures*. In the presence of mobile devices, the very limited communication distance of individual nodes as well as reduced coverage of a single small cell (Section 2.1) result into frequent handovers. When transmitting at very high data rates, the speed of the handover process becomes crucial. Intelligent handoff algorithms, which use additional information such as velocity, direction, and traffic information and advanced techniques like fuzzy logic [100], need to be developed in THz Band communication networks. Moreover, more appropriate small cell network architectures can be designed to reduce the number of handovers and the probability of handover drop, such as virtual cell [101] or extended cell [102].

An additional research challenge in network layer is posed by addressing. It seems reasonable to think that the addressing problem can be overcome by the use of IPv6 addresses, which are 128-bit long. However for nanoscale applications such as IoNT (Section 2.2), assigning a different address to every nano-node is not a simple task, mainly due to the fact that this would require the use of very long addresses for every nanomachine, and complex coordination among nanomachines. Instead of using classical approaches, more feasible alternatives can be explored, which take into account the hierarchical network architecture to only force those nano-nodes coordinated by the same nano-router to have different addresses [28].

4.5. Transport layer

As wireless multi-Gbps and Tbps links become a reality, the aggregated traffic flowing through the network and ultimately the Internet will dramatically increase. While flow control at the link layer is needed to prevent data losses in a single link (Section 4.3.2), it will be necessary to revise the functioning of well-established transport layer protocols such as TCP and to develop new transport layer solutions able to prevent, limit, control and recover from network congestion issues. In addition, the overhead of existing transport protocols needs to be minimized, to avoid additional performance constraints.

Among others, the following are open challenges that need to be addressed:

- *To adapt the* TCP *congestion operation to the new requirements of* THz *Band networks*. It is a fact that the majority of traffic over the Internet is transported by TCP. Therefore, it seems reasonable to modify and improve the performance of TCP while keeping backwards compatibility, rather than directly proposing radically new protocols. In particular, new algorithms to control the behavior of the congestion window size need to be explored. For example, as proposed in [103] for Gbps optical links, the congestion window size can be designed to be intelligently increased using available link capacity and measured source–receiver delays as parameters, in a cross-layer approach [104].

- *To develop radically new mechanisms for reliable transport and congestion control.* In the applications in which the use of classical transport layer solutions is not required, fundamentally different protocols can be developed. For example, in nanoscale applications (Section 2.2), robust transport layer solutions are necessary to deal with frequent device failures, disconnections due to energy fluctuations, or molecular channel composition transient effects [28]. For macroscale applications, a cross-layer optimization framework can be developed, which takes into account the THz Band channel and the physical, link, network and transport layers functionalities into account. Throughput, energy consumption and transmission delay can be then jointly optimized.

5. Experimental and simulation testbeds

The validation of the developed solutions requires the development of experimental platforms. Ideally, these platforms should be integrated by at least one transceiver and one receiver, and should be able to support stable THz Band links. For the time being, several platforms at frequencies below 1 THz have been built and successfully utilized for data transmission, channel measurements and propagation studies. In [105], a setup based on a Schottky diode sub-harmonic mixer combined with a commercial signal generator in transmission and a spectrum analyzer in reception is utilized for channel measurement and propagation studies. An analog video stream is transmitted over distances up to 22 m. In [106], the same platform is revised and utilized for 1080p digital video transmission over 52 m.

InP MMIC technologies (Section 3.1.2) are at the basis of several experimental wireless links at tens of Gbps. In [107], data rates up to 10 Gbps at 2 m and 25 Gbps at 0.5 m are shown, when operating at 220 GHz. An improved platform is used in [44] to demonstrate wireless data transmission at 25 Gbps over 10 m, still at 220 GHz. In the case of photonic technologies (Section 3.1.3), 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 12.5 Gbps data transmission over 0.5 m in [75]. In [108], the photonic components in the testbed are upgraded to support 24 Gbps. More recently, in [46], a hybrid system composed of a photonic transmitter and a MMIC-based receiver at 237.5 GHz is used to create a stable 100 Gbps over 20 m.

Simulation platforms will also play a major role in the design, development and validation of link, network and transport layer solutions. For example, in [109], Nano-Sim is presented. This is an extension to the well-known network simulation platform ns-3 to be able to simulate nanoscale communication networks in the Terahertz Band. While in Nano-Sim the physical layer is drastically simplified, it serves as a starting point for the simulation of nanonetworks. The incorporation of the channel model and the physical layer solutions into ns-3 as well as in other network simulation platforms such as OPNET or OMNeT++, will ease the development of networking solutions for THz Band communication networks.

6. Conclusions

The Terahertz Band (0.1–10 THz) is envisioned to satisfy the need for Tbps wireless links in the near future. THz Band communication will address the spectrum scarcity and capacity limitations of current wireless systems, and enable a plethora of applications, such as ultra-fast massive data transfers among nearby devices, or high-definition videoconferencing among mobile personal devices in small cells. In addition, the THz Band will also enable novel networking paradigms at the nanoscale, such as Wireless NanoSensor Networks and the Internet of Nano-Things.

In this paper, we have surveyed the state of the art in THz Band technology from the device perspective, by investigating the transceiver architectures of different technologies, as well as novel ultra-broadband and very large antenna arrays designs. Moreover, we have highlighted the communication challenges and provided potential solutions in terms of channel modeling and at the different layers of the protocol stack, from the physical layer up to the transport layer. Finally, we have reviewed the state of the art in terms of experimental and simulation platforms and identified the main challenges in their realization. We believe these challenges define a roadmap and will stimulate the research for the development of this new frontier for wireless communications.

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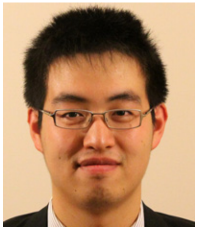

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