Terahertz band communications: Applications, research challenges, and standardization activities

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Terahertz Band Communications: Applications, Research Challenges, and Standardization Activities

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***Abstract*—Terahertz frequency band, 0.1–10THz, is envisioned as one of the possible resources to be utilized for wireless communications in networks beyond 5G. Communications over this band will be feature a number of attractive properties, including potentially terabit-per-second link capacities, miniature transceivers and, potentially, high energy efficiency. Meanwhile, a number of specific research challenges have to be addressed to convert the theoretical estimations into commercially attractive solutions. Due to the diversity of the challenges, the research on THz communications at its early stages was mostly performed by independent communities from different areas. Therefore, the existing knowledge in the field is substantially fragmented. In this paper, an attempt to address this issue and provide a clear and easy to follow introduction to the THz communications is performed. A review on the state-of-the-art in THz communications research is given by identifying the target applications and major open research challenges as well as the recent achievements by industry, academia, and the standardization bodies. The potential of the THz communications is presented by illustrating the basic tradeoffs in typical use cases. Based on the given summary, certain prospective research directions in the field are identified.**

I. Background and Motivation

The constant growth in users' demands for the data rates in wireless networks lead to the continuous increase in the amount of frequency-space resources, allocated per user. Due to the fact that infinite densification of wireless networks with access points has obvious limitations [1], this demand is naturally converted to the further increase in the total bandwidth occupied for radio access technologies. The most illustrative example of this trend is the evolution of an IEEE 802.11 family of technologies, branded as "Wi-Fi" – a de-facto standard for the WLANs for the last decades [2]. Starting from 22 MHz channels in legacy IEEE 802.11–1997, the allocated bandwidth evolved to 2.16 GHz in IEEE 802.11ad in less than twenty years [3]. The proposal for the next generation of this technology, IEEE 802.11ay, are even more aggressive and desire to occupy up to 8 GHz. The latest value is even higher than the carrier frequency of legacy Wi-Fi solutions, including the fairly recent IEEE 802.11ac released in the end of 2013, less than three years from now [4]. However, if one aims to increase bandwidth further, they face several problems other than just the technical challenge of wideband radio. Due to the frequency regulations, there are no blocks wider than 10 GHz left in the bands below 100GHz [5]. The first available blocks of such size are above 275 GHz, which is already in lower terahertz (THz) band.

THz band is, to some extend, a unique frequency region. While the bands above and below THz band (namely, the microwave/mmWaves and the infrared) have been already extensively explored, THz remains one of the least-studied zones in the EM spectrum. THz band is exactly between the frequency regions of oscillator-based and photon emitter-based approaches to generate the EM signal, which leads to difficulty of signal generation at THz frequencies, known colloquially as "THz gap". The second drawback of the band, limiting its utilization, is the high level of molecular absorption loss, caused by the absorptive resonance of certain molecules in the propagation environment [6], [7]. In addition, the free space loss at THz frequencies is inherently high, calling for the use of extremely directional antennas to ensure the reasonable communication range.

At the same time, a massive amount of available bandwidth (theoretically, up to several THz – three orders of magnitude higher than unregulated regions at mmWave frequencies) leads to potential aggregate capacity of *several terabits-per-second*, which allows to handle the traffic from almost any imaginable application. Unlike visible light, THz waves still penetrate some thin objects [8] and, thus, are able to carry the data even in certain non-line-of-sight (NLoS) topologies [9]. For instance, the data transmission/reception by a smartphone in a pocket is possible. Finally, due to wavelength in the order of hundreds of micrometers, THz communications can be used to enable interaction between miniature objects and thus supply emerging micro-scale robots with the communication capabilities.

Summarizing, despite the difficulties, THz band is characterized by a number of strong advantages that makes it suitable for a number of applications (see Fig. 1). Not aiming to provide a detailed retrospective into the history of THz communications, in this paper we focus on the current state-of-the-art and future research directions in this rapidly developing area.

The rest of the paper is organized as follows. We review the key target applications for THz communications in Section II. We then enumerate and discuss the major issues and open research challenges preventing from immediate exploitation of the band in Section III. In Section IV we study the major engineering tradeoffs, illustrating the feasibility of THz communications in certain regimes. We summarize the relevant standardization activities in Section V. Finally, in the last

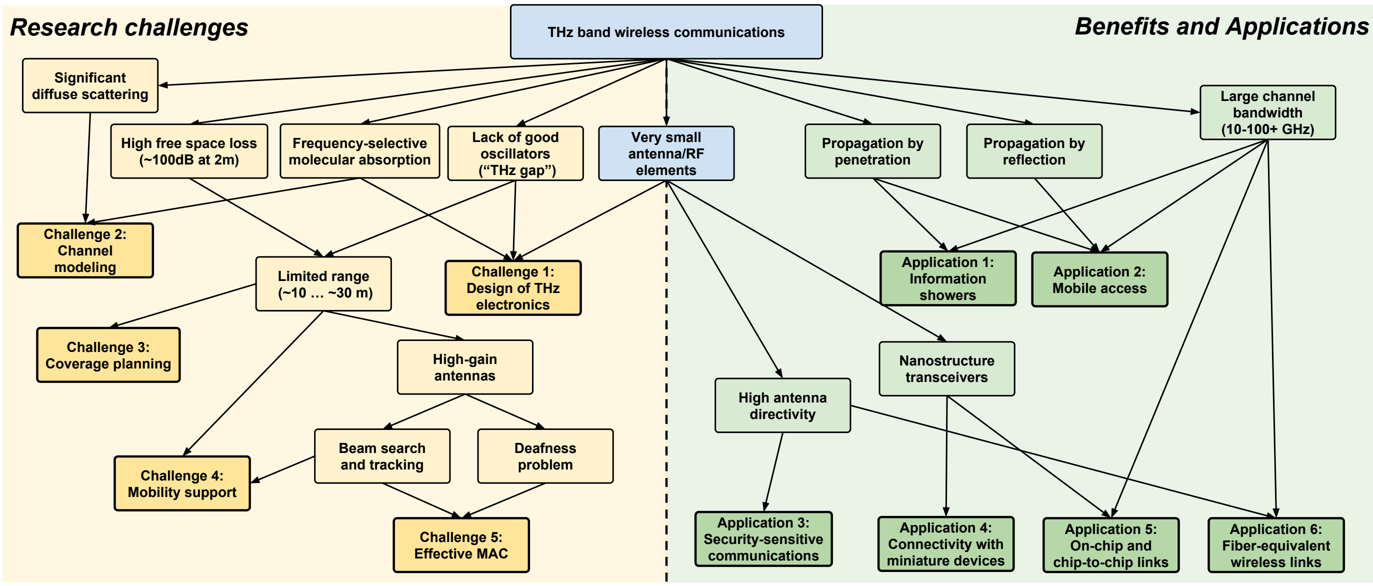

Fig. 1. The "tree" of THz communications features, applications and research challenges.

section we identify three major research directions community is now focusing on, each targeting its own group of problems.

II. Applications of THz Communications

Appearance of THz communications brings to life several groups of potential applications. Some of them present the evolution of existing ones, while the others are almost infeasible without the discussed technologies. This section enumerates the major applications and usage scenarios for THz communications and well as briefly mention the motivation for them and the envisioned benefits.

1) Information showers: The inherently small communication range of THz cells inspired the community to search for the scenarios, where small (few meters radius maximum) and extremely high-rate (up to Tbps) cells can be used in the most efficient way. This group of ideas is typically branded as "information shower" or, less frequently, "data shower". The concept suggests deployment of THz access points (APs) in the areas with high human flow (e.g. gates to the metro station, public building entrances, shopping mall halls, etc.). With such a deployment strategy, each of the passing user is able to receive bulk data (up to several GBs), just while passing this AP. Such information showers can be used do seamlessly deliver software updates as well as other types of heavy traffic, such as high-quality video (e.g. a movie to watch in a train). As the contact time between the user's terminal is very small (in the order of seconds), the introduction of information showers to the existing networking architecture requires partial redesign of several layers to enable fast nodes association and authentication as well as timely content delivery to the appropriate information shower and caching it there. Meanwhile, it has been recently demonstrated that in certain scenarios introduction of just few THz APs and forwarding all the heavy and delay-tolerant traffic to them whenever possible, allows to substantially offload the macro-scale network (e.g. WLAN or cellular) [11].

2) Mobile access: The applicability of THz communications to typical usage scenarios (e.g. indoor WLAN access) is limited due to considerable propagation losses. This could be addressed by trading the capacity of THz access points for coverage, primarily by reducing the utilized bandwidth and moving the entire communications from above 1 THz to the so-called "lower terahertz" carriers around 300GHz. As a result, it is possible to create reliable wireless links over tens of meters while retaining the capacity of tens of gigabits per second, which makes Wi-Fi-like THz access points (or even femto-cells for cellular access) become feasible. This application is both one of the most desirable ones, but also very challenging due to requirement of reliable beam tracking and effective medium access control. Section IV studies some of the engineering tradeoffs to enable this use case.

3) Security-sensitive communications: An ability to create highly directional beams with miniature size antenna arrays in conjunction with the high theoretical capacity of THz links results in a number of benefits for the security-sensitive usage, especially in military applications. The typical military scenario presents a battlefield with numerous heterogeneous units (soldiers, armoured personnel carriers, tanks, etc.) forming a THz ad hoc network. The primary advantage of the considered technology in comparison to lower frequencies is a physical inability to eavesdrop or even notice the transmission for any node located outside the transmitter beam. Therefore, the security of the transmitted data can be ensured not only by the proper encryption scheme, but also by the geometry of the network itself. The idea of utilizing directional THz antennas to improve the security of the military links has been recently expanded for the civil use as well. Particular use cases range from the ATM with wireless authentication up to the kiosk downloading. The nature of THz links with limited communication range and narrow beams also provides a fruitful ground for the physical layer security techniques,

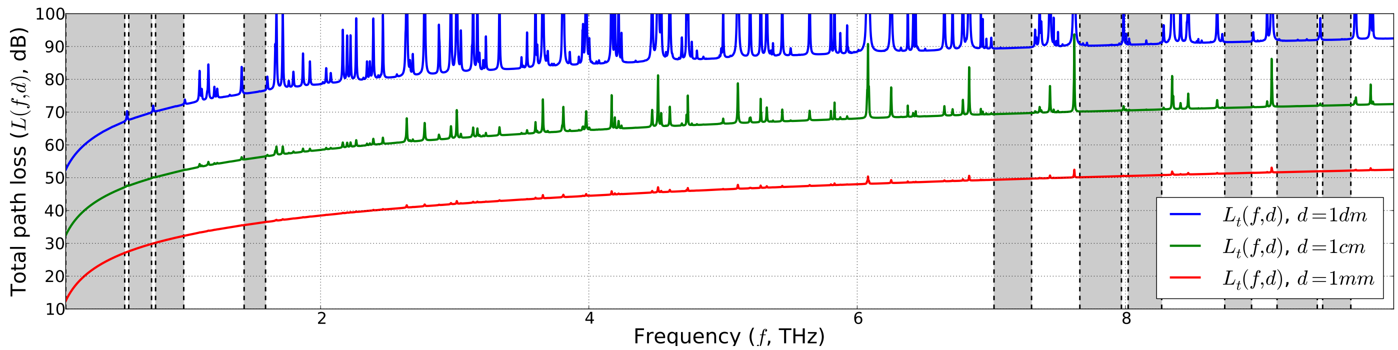

Fig. 2. The total path loss, $L_t(f, d)$, and transparency windows in the THz frequency band [10].

which, generally speaking, introduce some artificial "noise" into the signal before the transmission. The confidentiality of the message in this case is ensured by the fact that only the valid received, transmitter is now pointing to, has sufficiently good channel to decode the data.

4) Fiber-equivalent wireless links: The strategy for next-generation wireless networks (5G and Beyond) envision the appearance of numerous high-rate small cells, operating in the mmWaves spectrum [12]. This approach is considered as almost the only feasible solution to rapidly increase the area spectral efficiency, and, thus, support emerging bandwidth-greed applications in the area of virtual and augmented reality, holographic communications and many more. In addition to a number of challenges with interference minimization, handover support, there is also a challenge to provide a reliable fronthaul and backhaul links, where a wired or optical solution is not all the time the best option. For instance, the recent proposals by Huawei and many otherssuggest deployment of high-rate small cells on street lamps, where the constant power supply is presented by design, while the data link is not. In such a case, wireless fronthaul/backhaul is considered as a promising alternative. Moreover, the recent suggestions of applying UAVs for coverage and capacity extensions, cause the need to provide the wireless connectivity for them as well.

The envisioned data rates in mmWave small cells (access link) are in the order of several gigabits-per-second, thus, the capacity of the fronthaul/backhaul link should be several times higher to guarantee reliable and timely data delivery from multiple users, currently connected to the small cell. With this in mind, the bandwidth available in the THz frequencies is an attractive resource, while the high propagation loss in THz band (backhaul links might be considerably longer than the fronthaul ones) can be compensated by the extremely high antennas directivity. The feasibility of multi-gigabit-per-second wireless links in the lower THz band for the distances up to 1 km long have been recently experimentally validated in [13] and [14].

5) Connectivity with miniature devices: The possibility to create micro-scale transceivers operating in the THz band naturally leads to the desire of incorporating the envisioned micro- and nano-scale robots with such a feature. These so-called "nanorobots" usually incorporate a very primitive logic due to size and power consumption limitations and, thus, are technically incapable to perform any substantial task alone. On the contrary, by connecting with numerous other nanorobots that can form a network, capable to assist the society in many different areas, starting from the environmental sensing and medicine and up to PPDR. In contradiction to large-scale THz communication systems, envisioned to be built around massive antenna arrays of hundreds or even thousands of elements [15], micro- and nano- ones are to be equipped with very basic radio modules with just a few (or even a single) antennas. Consequently, the communication range in these nano networks is limited to centimeters. At the same time, the capacity of the links is several orders of magnitude higher that the envisioned data rate, thus, living the room for trivial and non-efficient modulations and coding schemes, such as On/Off Keying [16].

6) On-chip and chip-to-chip links: Due to several limitations of further increase in the CPU frequency, the horizontal scaling of the computing power by incorporation of more and more computing cores per chip is today considered as the primarily approach. Unfortunately, majority of the typical computer tasks do not feature so-called "data parallelism", so the cores have to constantly interact with each other sharing the common data and synchronizing their activities. Moreover, this communications have to be extremely fast and reliable. Therefore, providing an underlying connectivity solution for the chips/cores/registers/caches/etc. is of crucial importance for the desired computational performance level. Naturally, with the growth in the amount of communication nodes, computer scientists start more and more often reusing the solutions from the communications and networking world, where many problems they face today (e.g. time synchronisation, channel access, routing, etc.) have already been addressed. This trend is mostly covered by the umbrella of "Networks-on-Chips" and, simplifying a lot, suggests reusing some of the networking techniques to design efficient solutions for data exchange between different entities within a single computer. There is also a room for the wireless solutions in this world, since in case of a substantial number of cores per chip (e.g. 64 and more) the wired network concepts face a number of issues with topology complexity and routing. While the community aims to utilize the microwave and mmWaves spectrum for board-to-board communications [17], [18], on-chip and chip-to-chip links can only be enabled with a substantially smaller transceivers (sub-mm scale), thus, calling for the need of THz band radio to be used. Graphene-based THz electronics is one of the primarily enablers of massive multicore wireless networks-on-chip [19].

III. Major Research Challenges

A. Design of THz Electronics

One of the major reasons for slow progress in THz communications is the presence of a unique technical challenge with signal generation, so-called "THz gap". Simplifying a lot, THZ frequencies are too high for the regular oscillators to be efficient and too low for the optical photon emitters to work in. So far, THz waves are typically generated by either one of these methods, accompanied by a proper frequency multiplier/divider, thus, presenting considerably low output power (usually, in the order of $-10\,\mathrm{dBm}$). Despite the fact, there are some emerging proposals, such as usage of novel type of antennas (e.g. graphene plasmonic antennas) to generate the THz waves [20], the progress in this field is slow, thus, preventing the rapid expansion of THz communications. Consequently, the test beds are quite expensive, so the number of research units, which could afford buying/renting them, is also limited. At the same time, potential rewards of utilizing the band and substantial amount of resources invested by different players (both industrial and governmental) slowly but constantly push the progress in this field.

B. THz Channel Modeling

There are many crucial effects to be taken into account, when building a channel model for THz wireless communications. First of all, the notable level of frequency-selective molecular absorption results in several so-called "transparency windows" (see Fig. 2). Therefore, building a propagation model even for the free space scenario is already challenging and results in a need to introduce an extra exponential component in addition to the conventional power law in the pathloss equation [21], [22]. Secondly, as the majority of use cases implies indoor deployment and short communication range, reflections and penetrations from walls, ceiling, floor and all the objects have to be taken into account. Due to high cost of THz equipment only few studies on the subject have been conducted so far (e.g. [8] and [23]). Then, due to the wavelength at THz frequencies been in the order of hundreds of micrometers, THz waves scatter from almost any object in real scenario, both indoor and outdoor [9]. Finally, the presence of directional antennas further complicates the analysis as some of the received components (e.g. coming from the main beam) have to be prioritized over the others [24].

There are two major approaches to analyse the THz waves propagation in a given environment. First one is so-called "determenistic" approach, typically based on ray-tracing or ray-launching methodology. If the environment is fully described in terms of sizes, shapes and materials of the present objects, this approach gives a reasonably accurate picture [25]. The major drawback of this method, besides computational complexity, is the fact that the results can hardly be applied for modified scenario even in the case of small changes been introduced. The second approach, on the contrary aims to built a stochastic channel model, averaging the impact of environment rather than focusing on particular configuration. Following this approach, two similar stochastic channel models for the THz communications have been recently proposed in [26] and [27].

C. Coverage Planning

Coverage planning for THz faces challenges similar to those faced by mmWave systems operating at 60 GHz carrier, with key concerns around the availability of the unblocked (preferrably, LOS) path between the transmitter and receiver. As a result, THz access networks will likely have to provide coverage from multiple locations to ensure good reliability of the connection [28].

Of course, appropriate tools would need to be developed to facilitate the planning process, which would have to utilize very detailed 3D models of the environment to ensure accurate results. Consequently, automation of such planning process will likely be necessary due to the sheer number of the antennas that need to be deployed, since manual planning of an ultra-dense network is a prohibitively tedious and expensive proposition.

D. Effective Medium Access Control

While the problems faced by such MAC design would be similar in nature to those of more conventional mmWave systems, they would be significantly amplified. For example, if a mmWave system of a particular range had to try 16 antenna configurations during link configuration, the THz system with 5x higher carrier frequency would likely have to deal with up to 400 configurations (assuming they use 2D planar phased arrays). Naturally, any naive MAC design would not be able to achieve any reasonable link setup time in such conditions, thus calling for application of advanced signal processing techniques, such as compressed sensing, multi-antenna precoding, and others.

In addition, antenna gains needed for THz links of reasonable range make the usage of RF beamforming compulsory, even for basic signaling messages. While mmWave systems such as IEEE 802.11ad and Wireless HD may use quasi-omnidirectional antenna patterns for some discovery and signaling messages, THz band protocols will not have such luxury, thus calling for radically new MAC design. This issue is further elaborated in subsection IV-B.

E. Support for Nodes Mobility

Nearly all wireless access links strive to enable the mobility of the communicating peers, and THz access will likely follow the same idea. However, considering the issues of antenna gain discussed previously, it would be no easy feat to ensure the tracking of the already established beam configuration for mobile devices. For example, simply extrapolating the common beamforming training approach to THz frequencies,

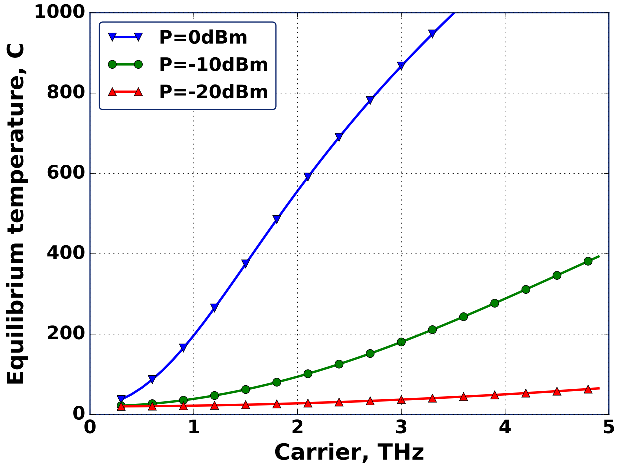

Fig. 3. The equilibrium temperature of THz antenna element at different frequencies.

results in prohibitively long training sequences for CSMA/CA protocol, as shown further in subsection IV-C. Thus, implementors would likely have to come up with reliable ways to predict movements, and not just respond to them after the fact.

IV. Engineering Tradeoffs

This section summarizes some of the important fundamental limits and engineering tradeoffs in THz wireless networks.

A. Antenna Equilibrium Temperature

First of all, any radio communication is about energy transfer. Due to small antenna size, it becomes important to study how much energy can be radiated with THz antennas without encountering overheating issues. In any practical antenna, some portion of the supplied RF energy gets absorbed and turned into heat, which must be dissipated. To estimate the scale of the issue, we find the total heat dissipated from a square patch antenna element with physical dimensions of $\lambda/3/2$, where λ is the wavelength. $\lambda/2$ in this formula refers to the resonant size of the antenna element, and extra 3 is to take into account the antenna size adjustment due to dielectric substrate antenna is placed on (e.g. ceramic). In this case, taking into according the heat radiation via Stefan–Boltzmann law and convection between the antenna element and the environment, the total dissipated power at room temperature, P_{diss}, is given by

$$P_{diss} = \frac{\lambda^2}{36}\left(\sigma(T_a^4 - T_r^4) + h_{air}(T_a - T_r)\right), \quad (1)$$

where T_a and T_r are the antenna and room temperatures, respectively, and h_{air} is the air heat transfer coefficient. We then balance the P_{diss} with the amount of total consumed power, $P_{cons} = P_{Tx}(1-\eta)$, where P_{Tx} stands for the transmit power and η is the antenna efficiency, and arrive to

$$\begin{aligned} P_{diss} \geq P_{cons} \rightarrow \sigma \cdot (T_a^4 - T_r^4) + h_{air} * T_a \\ - \left(T_r * h_{air} + 36 P_{Tx} * (1-\eta)/\lambda^2\right) \geq 0 \end{aligned} \quad (2)$$

that has to be solved for T_a.

Fig. 3 presents equilibrium temperature of the patch antenna from (2) for the range of THz frequencies with $\eta = 0.95$ and $h_{air} = 100\,\text{W/m}^2\text{K}$. As can be observed from this figure, for the desirable transmit power of 0dB the temperature has reasonable values (under 50°C) only till $\approx 300\,$GHz. The same bound holds up to 1 THz frequency for $P_{Tx} = -10\,$dBm and up to 3 THz for $P_{Tx} = -20\,$dBm. Concluding, traditional metallic antennas support the transmission powers comparable to lower frequencies only in the lower THz band. If one aims to go higher in either frequency or power, antenna elements have to follow other radiation principles, or larger number of elements should be driven to distribute the heat load.

B. Communication Range of Cellular Access

Further, let us look at the aspect of achievable communications range for THz networks. We compare two cases: 1) both Tx and Rx antenna array are 2D phased planar arrays of $M\times M$ elements; and 2) Tx antenna array is 2D grid of $M\times M$ elements, while the Rx antenna is (quasi-)omnidirectional, i.e. has no gain. Let us further assume that it was possible to achieve a perfect alignment of Tx and Rx beams, thus looking at the theoretical upper bound. To perform our analysis, we calculate the maximum allowed coupling loss in dB, L, as

$$L = P_{Tx} + (173 - 10\log_{10}(B)) + G_{Tx} + G_{Rx} - S, \quad (3)$$

where P_{Tx} is the transmit power in dB, B is the allocated bandwidth, G_{Tx} and G_{Rx} are Tx and Rx gains in dB, respectively, and S is the target SNR value at the mobile device. We then estimate the communication range from a free-space path loss equation, fixing the central frequency f and arriving at

$$d = 10^{L/20+7.38-\log_{10}(f)}. \quad (4)$$

Fig. 4 presents the maximum communication range from (4) with $P_{Tx} = 0\,$dBm, $S = 5\,$dB, $B = 10\,$GHz, and assuming $M\times M$ antenna array to yield the main beam gain of $\approx N$. As can be seen from this figure, the communication range in the lower THz band is limited to tens of meters for directional-directional case and less than *two meters* for directional-omni. As such, we qualitatively show that high gains at both Tx and Rx antennas are required for WLAN applications even at lower THz.

C. Communication Range for Distributed Multiple Access

As stated in the previous subsection, the WLAN-range THz links require substantial antenna gains on both Tx and Rx sides. However, this requirement causes a problem for the non-coordinated multiple access (e.g. as in IEEE 802.11 standards), as MAC design in such conditions faces strong directional deafness problems. To work around this issue, one can apply a spread spectrum technique as a replacement of the Rx antenna gain for signaling frames. In simple terms, increasing the transmission time N times compensates $G_{Rx} = N$, given by $M\times M$ antenna array at Rx. However, in this case, substantial amount of overhead is introduced, thus, theoretically limiting

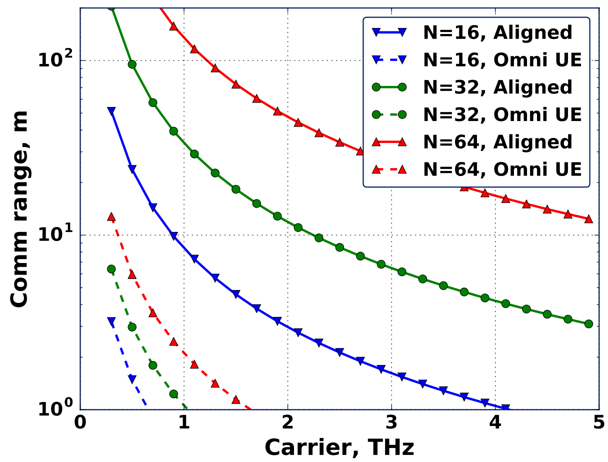

Fig. 4. Theoretical communication range of THz mobile access.

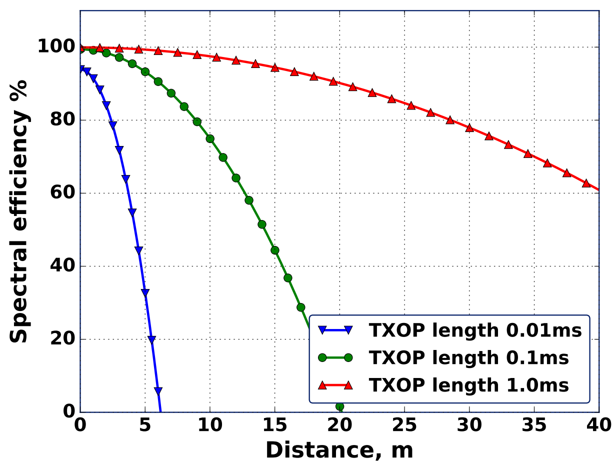

Fig. 5. Decrease of THz communications spectral efficiency with distance, when serving delay-critical traffic from a mobile user.

the applicability of this scheme for delay-bounded traffic, as imposed in 5G and Beyond [12].

In this subsection, we quantitively investigate this tradeoff and present the numerical dependencies between the required communication range and the estimated spectral efficiency of the suggested spread spectrum technique. To keep it simple, we study this question, applying the THz band physics to the conventional IEEE 802.11 distributed coordination function (DCF). In this case, the application layer delay bound limits the maximum value of transmit opportunity (TXOP) duration (this value should be also scaled appropriately to the number of currently active users). The maximum duration of TXOP, in turn, limits the duration of the data frame, which directly gives an upper bound of the spectral efficiency, S as

$$S \leq \frac{t_{Data}}{t_{TXOP}} = \frac{t_{TXOP} - 3t_{RTS} - 3t_{SIFS}}{t_{TXOP}} = 1 - 3\frac{t_{RTS} + t_{SIFS}}{t_{TXOP}}. \quad (5)$$

In this study, and following to some extent IEEE 802.11ad, we set the duration of short inter-frame space (SIFS) as 4 OFDM symbols, each with duration τ. Each OFDM symbol is transmitted over N_{FFT} subcarriers. Therefore, $\tau = N_{FFT}/B$, where B is the channel bandwidth. We also approximate the duration of Request-to-Send frame (RTS) with the same 4 symbols, but repeated G_{Rx} times to compensate the absent Rx antenna gain. As a result, the maximum spectral efficiency, S_{max}, can be derived as

$$S_{max} = 1 - 3\frac{t_{RTS} + t_{SIFS}}{t_{TXOP}} = 1 - 12\tau\frac{1 + G_{Rx}}{t_{TXOP}} = 1 - 12\frac{N_{FFT}(1 + G_{Rx})}{t_{TXOP}B}, \quad (6)$$

where the required G_{Rx} value can be obtained by inverting (3) and (4).

Fig. 5 presents this dependancy for three different durations of TXOP and assuming 10 GHz channel bandwidth. As can be observer from this figure, the spread spectrum technique is extremely inefficient when handling nodes with delay-critical traffic. For instance, the effective communication range for $t_{TXOP} = 0.1$ ms (10 users, each with IMT-recommended 1 ms delay bound) is limited to just 15 meters, with Tx power of 0 dBm and 15 dB antenna gain. At the same time, when the bound on the delay are not that strict (e.g. $t_{TXOP} = 10$ ms), the discussed scheme can be applied with minimal restrictions.

Summarizing, while the non-critical traffic can be handled well in THz systems with non-coordinated multiple access, the support for delay-critical types of applications (e.g. the Tactile Internet) can be given only in case both Tx and Rx antennas are directional. Therefore, the design of the efficient and reliable medium access protocol for THz communications, capable to work in directional–directional case is one of the important research questions in the field of study.

V. Standardization of THz Communications

Standardization of THz wireless communications started in early 2008, when IEEE has established a Interest Group on THz communications (IGthz) under the IEEE 802.15 umbrella. During the next five years a number of involved units from Technical University of Braunschweig, NICT, Intel, and Sony have been studying the major features and basic tradeoffs in the field. The results of their work were used in 2013 to narrow the focus of the involved parties and convert the Interest Group into a Study Group on THz communications. The aim of this unit was to formulate the goals and prepare a site for the standardization process of THz communications. The latter started in 2014, branded by IEEE as a Task Group on "100G Wireless" (TG100G, IEEE 802.15.3d) and aiming to design a standard for PHY and MAC layers of THz communications. The frequency range has been mostly limited to 275–325 (50GHz bandwidth) window [29], while fronthaul and backhaul for 5G, close-proximity P2P communications, including THz information showers, as well as Data Centers scenario (a special case of a backhaul connectivity, aka "wireless" ethernet) and intra-device communications have been identified as the most relevant for the selected sub-band.

Since 2014, over five hundred individual contributions have been made and considered by the involved parties. The major published deliverables of the unit are enumerated below:

1) *Applications Requirements Document (ARD) [30].*
Released: May 2015.
ARD contains description of applications and use cases with their performance and functional requirements. The document presents the envisioned network architectures for different use cases and specifies the target communication range and data rates for the selected applications. The ARD is the initial "requirements" document that is broadly used in the further research activities by the IEEE 802.15.3d Task Group.
2) *Channel Modeling Document (CMD) [31].*
Released: March 2016.
CMD presents a summary of the major propagation characteristics of lower THz waves in typical environments. The document also specifies the suggested channel models for each of the target scenario, ranging from the intra-device connectivity up to the wireless fronthaul. The relevant data to calculate the link budget in certain environments is also given. CMD has to be used as a reference, when submitting further technical contributions to the Task Group.
3) *Technical Requirements Document (TRD) [29].*
Released: March 2016.
TRD should serve as a guideline to develop technical proposals. The document provides an extract from ARD and specifies the target requirements for the proposed solutions in terms of most important metrics (range, data rate, BER, etc.). The latest versions of TRD also give some insights of the possible medium access control protocol for the lower THz band communications.
4) *Evaluation Criteria Document (ECD) [32].*
Released: March 2016.
ECD is currently the shortest document from the listed here. It draws the major guidelines for the future technical contributions and should serve as a framework for evaluating proposals to the Task Group with some performance criteria been claimed.

Summarizing, the Task Group has recently accomplished Phase 1 and is now preparing the call for participation for the wider community. As an outcome of the recent discussions, IEEE 802.15.3d aims to propose the first draft of the amendments to 802.15 Working Group by the end of 2016. The current proposal is to start submitting the amendments for the Letter Ballots in January 2017 and then submit the improved version for the IEEE Sponsor Ballot by July 2017 [33].

VI. Conclusions and Envisioned Trends

THz band presents an attractive and currently available resource to enable several unique applications in medical, environmental and military fields. Due to a number of challenges and features, THz communications have been simultaneously studied by different communities (physics and nanotechnology to medicine and computer science) from various points of view, which resulted in a substantial fragmentation in the literature. Aiming to harmonize the picture, in this paper, we provide a brief summary on the potential applications, open research challenges, engineering tradeoffs and recent standardization activities in the field of study.

Based on the performed analysis, we can clearly identify three major directions in the research on THz communications. First of all, the utilization of lower THz frequencies in the range 275–325 GHz to benefit the already existing applications. This direction is currently in the stage of applied research and engineering with majority of basic tradeoffs already been investigated. The first direction is the also the only one currently considered by the standardization bodies. The major focuses in the first direction are currently in development of cost-efficient electronics for the lower THz band and design of associated channel access and networking protocols. The second direction targets design and manufacturing of the full scale THz transceivers, capable of transmitting terabits of data per second. The major attention here is concentrated on design and fabrication of graphene-enabled ultra-massive MIMO systems. This research direction presents a balance between the fundamental and applied research, as some elements of the desired communication systems are not yet specified. Finally, the third and the longest-term research direction is focused on enabling the communication between micro- and nanoscale devices. This direction presents a very early stage of the research with numerous open problems: design of antennas, computational units for signal processing, buffers for data storages, and associated energy supplies.

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