Device-to-Device Communications at the TeraHertz band: Open Challenges for Realistic Implementation

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Abstract—**One of the key parameters that plays a major role in enabling the data rate requirements is spectrum or bandwidth which is scarce and expensive. Therefore, spectrum management policies are required to optimize its usage to meet all the requirements and the promised data rate growth. Another strategy to deal with spectrum scarcity is to move towards higher frequency bands (Terahertz bands) which are expected in the next 6G communication standard. It is therefore important to develop not only new techniques that enable efficient dynamic spectrum access and sharing at such bands but also suitable channel models for the Terahertz bands. Meanwhile, offloading mechanisms are very promising for cellular networks where a plethora of options have been proposed in the research arena in terms of Device-to-Device (D2D), Licensed Assisted Access (LAA), or WiFi offloading, among others; but their behaviour, when operated at high frequencies (Terahertz band) remains unclear. Therefore, this paper will tackle two technologies that will shape future networks: Terahertz channel modeling/communications and offloading mechanisms.**

I. INTRODUCTION

6G, the next-generation mobile network, is anticipated to bring about a technological transformation in modern societies by providing an ultra-reliable high-speed communications infrastructure that will serve billions of devices, machines, and vehicles. Leading cellular network providers to predict that more than 29 billion devices will be connected to the internet at all times by the year 2023 [1]. These devices will contribute massive amounts of data that will need to be pipelined over future 6G networks under the umbrella of future smart cities connected autonomous cars, and IoT applications.

6G technology aims to support a myriad of new applications, services, and devices, including ultra-reliable, low-latency communications (uRLLC), high user mobility, massive IoT/M2M connectivity, and high data rates, thus calling for new spectrum management and access strategies and techniques that meet these new requirements [2].

However, the resources, with great focus on the spectrum, must be optimized to provide ultimate performance. On the other hand, the processing capability both at the network and users' equipment should be more powerful and adaptive. The complexity of 6G networks will hence be unprecedented, due to the very diverse applications, ultra-low latency requirements for critical vehicle communication, growing demand for high positioning accuracy for location-based services, and dense, heterogeneous architectures.

The recent studies for user behavior in current 4G/5G systems show a great interaction directly among the users, especially through social media applications. The standardization bodies have been aware of this trend and the Device-to-Device (D2D) communication technology has been already included in the Rel.12 of the 3GPP [3] standard as a way of coping with such a user communication trend. Within D2D, the users' equipment can then directly connect and communicate with each other if they are geographically located within close vicinity, and without passing the communication through the system base stations (eNBs). D2D offers great performance benefits, as it can, for instance, reduce traffic at the backhaul network links, thus alleviating traffic congestions at such links, increase spectrum spatial reuse, and reduce the power consumption of devices. However, D2D poses several challenges to the system, as the communication is not centralized and several internal mechanisms have to be changed for operators (e.g., billing) to enable D2D communications. As the system is not centralized when operating D2D communications, one of the main technical challenges resides in how the users will share the spectrum without colliding in the wireless channel, for which several techniques have been proposed (e.g., how to sense the spectrum before accessing), thus providing a feasible way for communications without collisions (i.e., errors).

The already congested sub-5 GHz communication band does not have any remaining bandwidth to enable the promised (and required) high data rates in 6G, suggesting to move toward higher frequency bands as the most viable solution. The key enabler to achieving larger data rates, higher Quality of Service (QoS), lower delay, and other 6G metrics, is having more available bandwidth for 6G systems, which translates into opening up larger and higher spectrum blocks, reaching the Terahertz (THz) above 300GHz bands which means the THz band will play a vital role in 6G.

High frequency bands are more attractive for 6G due to several factors, including (i) bandwidth available at those very high frequencies is much larger than that available at low frequencies, (ii) such frequencies have small wavelengths, allowing the use of a higher number of transmit/receive antennas, thus enabling massive Multiple-Input Multiple-Output (MIMO) schemes [4], and (iii) the short range of transmitted signals increases spatial reuse of spectrum, thus increasing network capacity and spectrum efficiency. However, THz access comes with its transmission impairments, such as reduced channel diversity, increased path loss, lowered non-line-of-sight (NLOS) component (due to for example much less diffraction) that translates into more coverage holes, all of which give rise to serious challenges for the actual implementation of the THz frequencies in commercial systems. Therefore, such high frequencies are well suited for D2D communications, because the short-range property does not impact them, as D2D users are always within range of one another, making a perfect marriage between the two technologies. Moreover, the data exchange among D2D users is usually very large because they are sharing videos/photos over social media or competing in online gaming, thus large data rates are required, motivating the use of the large THz bandwidth [5].

In summary, bandwidth clearly jumps out as a major challenge for 6G. Although spectrum regulatory bodies have responded by opening up and allowing the use of new spectrum bands in the sub-6GHz and mmWave frequencies, but these frequency bands are not enough and high frequencies (in the THz band) will be soon required. A lot of work is still needed to benefit from such new spectrum bands and hence overcome THz challenges, mainly due to their sensitivity to weather conditions and line-of-sight propagation requirements [6], thereby requiring highly adaptive spectrum management and understanding the characteristic of propagation in THz band. In this paper, we investigate the possibility to make effective use of the THz band for D2D communication. Firstly, we tackle the THz channel characteristics where molecular absorption leads to frequency selectivity. Secondly, based on such selectivity, we propose using the frequency bands with less molecular absorption loss on the cellular links, while the rest of the bands on the D2D links to reduce the interference in the D2D communication. In addition, we show some important foreseen challenges that need to be overcome in order to realize the effective use of the THz band for D2D applications.

II. THZ CHANNEL CHARACTERIZATION

One of the important tasks for the research community to enable THz communications is to understand the characteristics of propagation in the THz band, in order to realize reasonable wireless communications in THz. While there are a number of research activities in the millimeter-wave band, but very limited research activities in terms of wireless communications in THz.

The propagation in the THz band has two important aspects. The first one is that path loss is significant due to the high frequency, and the second one is that molecular absorption leads to significant frequency-selectivity even in a line-of-sight case. Molecular absorption is a key factor at the THz band, where the molecules in the air absorb electromagnetic (EM) radiation. At THz frequencies, water vapor is the main reason for the absorption losses.

Fig. 1 shows the molecular absorption for 1 km distance following the ITU-R model in sub-THz (100GHz-1THz). The ITU-R P.676-8 model is a line-by-line based spectroscopic model and its results correspond to those obtained with the HITRAN database [7].

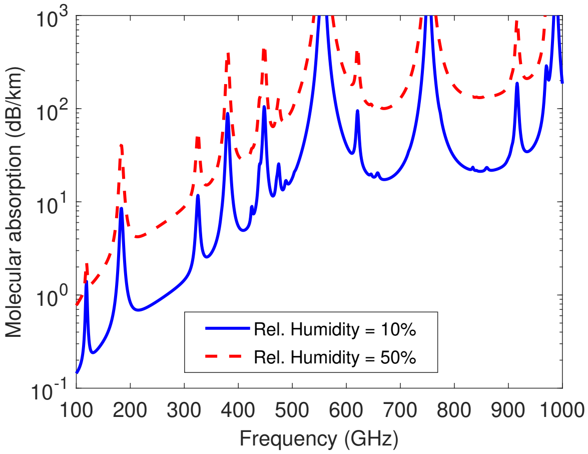

Fig. 1. Molecular absorption, temperature 25 degrees Celsius, relative humidity 10% and 50%.

The transmittance for the whole THz (up to 10THz) is shown in Fig. 2 in case of 10 cm distance and line-of-sight [8]. The left y-axis in Fig. 2 shows the transmittance result which is a function of frequency and the right y-axis is raised cosine (RC) filter which is used to choose a frequency band that we need. The red curve at 7.15 is

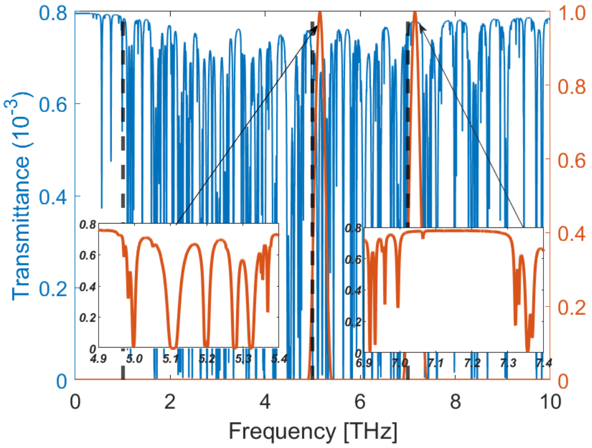

Fig. 2. Transmittance of Terahertz channel. The distance, pressure, relative humidity and temperature, are 10 cm, 1010 hPa, 69.6 %, and 25 degrees Celsius.

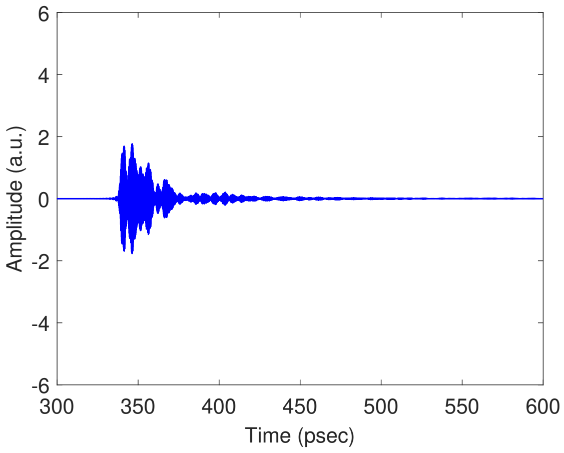

Fig. 3. Impulse response (the center frequency 5.15THz and bandwidth 0.5 THz, and LoS).

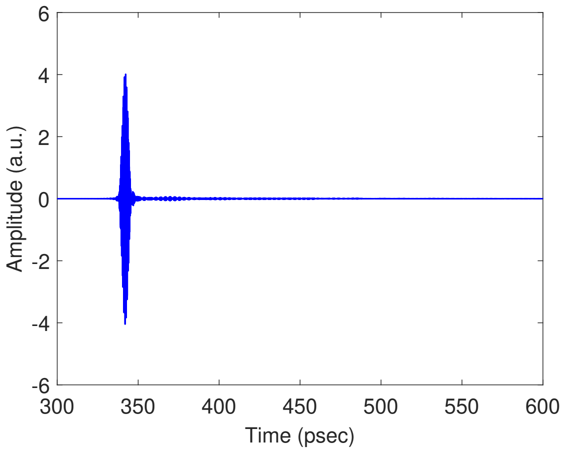

Fig. 4. Impulse response (center frequency 7.15THz, bandwidth 0.5 THz, and LoS).

inside the relatively flat region of channel response while at 5.15 the channel response significantly varies.

Significant frequency selectivity due to the molecular absorption can be confirmed in the transmittance and a degree of frequency selectivity depends on the frequency band. For example, the frequency selectivity at 5 THz is more than the frequency selectivity at 1 THz and 7 THz which are shown as black lines in Fig. 2. This fact indicates that a selection of frequency bands influences the performance of wireless communications in THz. In the case of narrowband communication, such as with 100GHz, it may be possible to select a frequency band without significant frequency selectivity. The attenuation level due to molecular absorption and spreading loss affects the performance of the narrowband communication.

For high data rate communication such as 1Tb/sec, the frequency selectivity may be unavoidable in most frequency bands as shown in Fig. 2. An effect of frequency selectivity is an important issue for wireless communications in THz.

A time domain channel model for the wideband is necessary to reveal the effect of the frequency selectivity. The reasonable time domain channel model is impulse response which can be obtained by the transmittance, which only indicates the amplitude component, and phase component. In [9], a linear phase criterion has been used to obtain the phase component, however, the linear phase criterion violates causality in the impulse response. For this issue, the works in [10] have shown that a minimum phase criterion is appropriate to obtain the phase component to satisfy causality. The impulse response depends not only on the target frequency band but also on relative humidity, pressure, and temperature.

Figs 3 and 4 show the impulse responses at 5.15 THz and 7.15 THz, respectively, where the assumed frequency bandwidth is 0.5 THz in both cases (a.u. means arbitrary unit). According to Fig. 2, the frequency selectivity at 5.15 THz is more significant than the frequency selectivity at 7.15 THz. Therefore, the impulse response at 5.15 THz in Fig. 3 indicates several delayed paths, which may cause inter-symbol interference over the wireless link. On the other hand, the impulse response at 7.15 THz in Fig. 4 mainly consists of the direct path. The inherent delay spreads of 5.15 THz and 7.15 THz impulse responses are $11ps$ and $2.1ps$, respectively. These results indicate that the attenuation and effect of frequency selectivity causing the inter-symbol interference has to be considered to select an adequate frequency band.

For the validity of this time domain impulse response, the analytically obtained received signal with the impulse response is compared to the experimental measured received signal in Fig. 5. Due to the limitation of hardware, the center frequency is set to 0.4THz, however, the analytical result is in agreement with the measurement result.

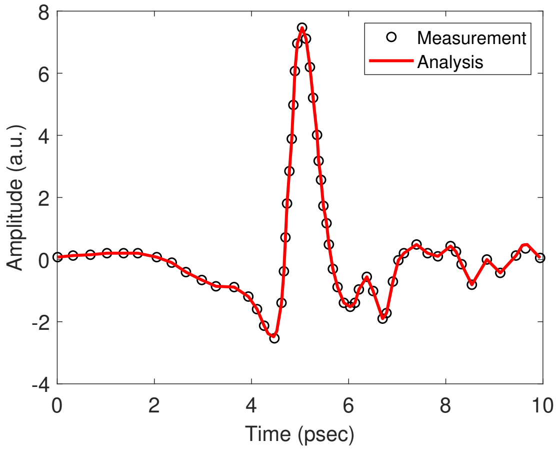

Fig. 5. Comparison of a measurement result and analysis in terms of received signal at 0.4 THz center frequency and 0.4 THz bandwidth, relative humidity 52%, temperature 22 degrees Celsius, pressure 1015.9 hPa [10].

III. FREQUENCY ALLOCATION FOR D2D COMMUNICATION AT THZ BANDS

Device-to-Device (D2D) communication is another key technology adopted by 3GPP standards since its rel. 12, thanks to its offered ultra-low latency. D2D can operate in both licensed or unlicensed bands, enabling a wide range of applications and overcoming several challenges such as alleviating traffic congestion bottlenecks at network backhaul links, decreasing power consumption of 6G devices, and increasing the required data rate. Due to its short coverage and high data rate requirement, it is a perfect scenario for the application of THz.

Multiple different types of 6G devices, running various applications with different QoS requirements and traffic demands, will be connected to and supported by the 6G network infrastructure. Some of these applications can be offloaded towards D2D connections to avoid overloading the system infrastructure. The selection of which applications and under which QoS requirements is of great importance to benefit from D2D technology, especially when used in the THz band. This diversity will result in heterogeneous access to the 6G's wideband spectrum, where different bands will experience different occupancy and usage behaviors with variability across time, frequency, and space.

Compared with the traditional frequency band, molecular absorption loss as a special aspect of the THz band increases exponentially with distance. Therefore, dense deployment of D2D links is expected in 6G, where it is important to avoid interference between cellular links and D2D links, as well as co-channel interference among D2D links. THz usage over D2D would have another advantage in this regard; thanks to THz small coverage, its interference will be much smaller than sub-5 GHz connections.

The approach to solve this problem is to control the attenuation such that attenuation between different players is maximized, while attenuation within each D2D-link is still tolerable. How can we engineer the channel to implement this? Free space path loss can be controlled rather weakly by selecting the center frequency. For example, over 10 meters the free space attenuation is 102 dB at 300 GHz and 108 dB at 600 GHz. Over 1 cm, the free space attenuation at 300 GHz is 42 dB and at 600 GHz 48 dB. When distance increases 10 times, the free space path loss increases by a fixed amount (20 dB).

But a special feature of communication at the THz band is the molecular absorption which can limit co-channel interference [11], which is totally different than free space path loss and is more suitable for engineering the channel since it strongly varies when the frequency is varied. Also, its behavior as a function of distance follows different law (exponential) than free space path loss (square-law). Resource allocation can use the fact that the molecular absorption varies as a function of frequency [12].

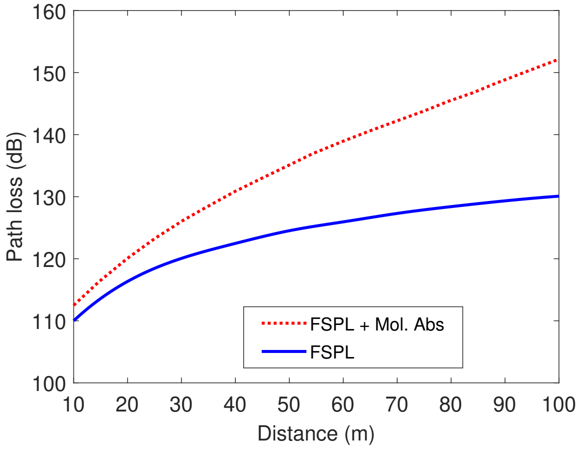

Fig. 6. Free space path loss and free space path loss with molecular absorption, target link distance 10 meters.

Therefore, we can use molecular absorption to control the amount of co-channel interference among D2D links, notice that usually there is not any coordination among the autonomous D2D links so that interference among them can be a serious issue, and its mitigation in a dense scenario is required. Thus, the basic idea is to take advantage of the exponential behavior of the molecular absorption at THz band to reduce due interference to other D2D links due to path loss in linear scale being $\exp(k_a^{\mathrm{TOT}} d)$, where d is the distance and k_a^{TOT} is the frequency-dependent absorption coefficient [13]. Fig. 6 shows how at 10 meters link distance the molecular absorption leads to only a small loss in performance but at 100 meters distance, its additional loss is significantly increased leading to reduced co-channel interference. If we can tolerate more attenuation at our link distance, the attenuation at 100 meters gets even much higher.

In the sub-THz band, there are several molecular absorption peaks with radically different attenuation levels, such as 380 GHz, 448 GHz, 557 GHz, 752 GHz, and 988 GHz. Consequently, the THz bands' allocation can take this fact into consideration by allocating the ones with less molecular effect to the cellular links, that require to ensure larger coverage. The rest of the band could be shared among D2D links, which typically are short in distance. In scenarios reporting high co-channel interference, the peaks mentioned before can be exploited.

The value of attenuation, and thus the generated interference, can be easily calculated at the transmitter with the availability of temperature and humidity sensors, as well as the target communication distance. Therefore, the allocated THz frequency can be adaptively or opportunistically selected for each targeted user, based on the running application QoS demands or generated co-channel interference. For example, molecular absorption at 380 GHz can be around 3 dB per 10 meters. This means that extra attenuation (on top of the free space path loss) from interferers from 100 meters away will be 30 dB.

Moreover, reduced interference also allows for lower transmit power, which is a crucial resource for D2D equipment. D2D is expected to be running over dense scenarios in 6G, and therefore, power reduction would stand as a crucial resource in 6G, for which THz can assist.

IV. OPEN CHALLENGES

There are several open challenges need to be answered for the realization of THz communication and their optimization in 6G systems. We name here some of the most important ones.

THz hardware challenges: A major open research area within THz relates to the hardware deployment and testbed demonstrators set up, where the high frequency constitutes a challenge within all communication units. An outstanding challenge for deployment is related to the generation of THz signals (carriers), as the few results on THz generation used either the electronic-devices RF signals with frequency multiplication or decreasing the frequency from photons-based approaches, both being nonsuitable; and motivating the search for a specific technique tailor-made for THz carrier generation [14]. In March 2019, the FCC opened for the first time the spectrum from 95GHz to 3THz for experimental licensing, giving a great push for the deployment of actual testbeds and products on the THz technology. Standardization activities have already started before that date, with the IEEE 802.15.3d paving the way towards the manufacturing and commercialization phases; thus requesting a great investment in the deployment efforts and searching for solutions to hardware challenges.

Metasurfaces impact on THz: The wireless channel has been traditionally considered as a random effect not controlled by the engineering design, and rather a wide range of schemes try to adapt to its randomness. Recent advances in electronics opened the door for a paradigm change, with the creation of a smart radio environment where the signal propagation is a design parameter. Its core concept is related to the metasurface, which is a novel material that can regulate electromagnetic reflections on it, by creating an EM discontinuity that is controlled and optimized following several objectives. Metasurfaces received large attention from the research community [5], as they can increase the coverage considerably. Metasurfaces and THz constitute a perfect combination as signal propagation (and coverage) is the major challenge for THz, and metasurfaces can play a great role in improving it. Moreover, the high frequencies will enable the deployment of a large number of metasurfaces in a small area, thus being practical for commercial standards.

Software-Defined Antennas for THz: The usage of beamforming has been included in many standards years ago, providing very good performance in terms of coverage, data rate, and quality, among others. The high frequency of THz will enable the deployment of an extremely large number of antennas in small sizes, boosting the concept of Massive MIMO. Novel beamforming techniques are required to exploit the huge number of antennas while being highly dynamic and adaptable to the scenario. Several proposals appeared in literature, where Holographic beamforming [15] is a potential candidate showing promising results for 3D beamforming and being very dynamic by relying on Software Defined Antenna (SDA). The selection of the most suitable beamforming technique for THz is an open problem that needs further research and development.

The impact and benefit of AI on the channels allocation at THz: Artificial Intelligence (AI) [4] has become a mature technology used in several disciplines, both in research and industry. It has been attracted by the field of wireless communication thanks to its capabilities for automatic detection and self-learning etc. In the THz systems, in order to overcome the path loss / molecular absorption challenges and provide its potential, high adaptability to the environment is essential. AI can play a vital role in predicting and detecting the frequencies highly affected by absorption loss for a highly adaptive resource allocation process, and as discussed along with the paper, adaptability is of great importance in THz systems. AI can be classified into several categories and the decision on the most suitable one and how to propose techniques that are specific for THz resource allocation is still a green area of research.

V. CONCLUSION

THz communications will be one of the basic pillars of 6G systems, and this paper is to highlight some of the recent updates for its implementation, as well as open challenges to tackle for their consideration. THz is characterized by its low coverage, so one of the most interesting use cases for its implementation is the D2D scenario, where multi-connected D2D communication capability is already available in 4G/5G systems; allowing a device to directly communicate with multiple different devices. The merge of THz-D2D over 6G would pave the way for new various forms of communications, including point-to-point, multi-cast, and broadcast, where even the IoT devices can communicate directly with each other using the licensed (in-band) or unlicensed (out-of-band) spectrum. THz-D2D would stand as one of the 6G key technology enablers for achieving flexible wideband access, increasing spectrum usage efficiency, and addressing bandwidth shortages.

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