Potential key challenges for terahertz communication systems

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ABSTRACT

The vision of 6G communications is an improved performance of the data rate and latency limitations and permit ubiquitous connectivity. In addition, 6G communications will adopt a novel strategy. Terahertz (THz) waves will characterize 6G networks, due to 6G will integrate terrestrial wireless mobile communication, geostationary and medium and low orbit satellite communication and short distance direct communication technologies, as well as integrate communication, computing, and navigation. This study discusses the key challenges of THz waves, including path losses which is considered the main challenge; transceiver architectures and THz signal generators; environment of THz with network architecture and 3D communications; finally, Safety and health issues.

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1. INTRODUCTION

The standardization of 5G has been completed and deployment commenced in many cities across the globe [1]. However, the exponential increase in data traffic due to the growing number of connected devices, which it is foreseen that may leapfrog hundred(s) of connected devices per cubic meter. In addition, future uses and novel applications such as virtual reality (VR), augmented reality (AR), 4K/8K UHD video, 3D communications, autonomous driving, and other applications and scenarios that have not been currently imagined yet in existence [2]. The present deployed 5G communications will find it difficult to satisfy the data rates and ultra-low latency requirements of these applications. These challenges are considered a critical driver toward the development of communication systems to a new era of wireless network, sixth generation (6G). Given into 5G networks and its foreseeable evolution and the tremendous potentials that will be provided compared to previous generation networks, what should there be in 6G that is not in 5G or in its long-term evolution? Academic, industrial and research communities are already starting working on identifying, defining and evaluating the key relevant enabling technologies that will shape 6G [3, 4]; which are expected to be deployed by 2030 [5, 6].

The vision of 6G communications is an improved performance of the data rate and latency limitations and permit ubiquitous connectivity. In addition, 6G communications will adopt a novel strategy enabling new communication experiences with virtual existence and universal presence will be readily available anywhere. Moreover, 6G communications will use notable applications, such as holographic calls, flying networks, and tele-operated driving [7, 8]. Further, 6G is expected to provide high reliability and more security, comparing with conventional wireless networks. However, among all technological works pertaining to 6G, THz and artificial intelligence (AI) are the most promising. These technologies are considered as revolutionary technologies in the area of wireless networks [9, 10]. For these novel technologies to be incorporated in the future networks, a radical change is required in the design principles by the industry practitioners [11].

It is expected that 6G wireless networks will witness a radical transformation, making it substantially different from the previous generations and will revolutionize the wireless evolution from "connected things" to "connected intelligence". Not only that, 6G communications will offer services that are beyond just mobile Internet, but as well support ubiquitous AI services from the core network comprising the data centers through the transmission backhauls and finally to the end devices. In other words, the transformation will not be limited to domain, but will usher in an era of interdisciplinary cooperation between information technology and wireless communication. Meanwhile, the AI will be crucial towards the design and optimization of 6G networks, configurations, topology, protocols, and operations [12, 13]. To address the spectrum crunch in 4G communications, the millimeter wave (mmWave) spectrum was proposed and adopted. Unfortunately, this new spectrum bandwidth is incapable of meeting the bandwidth requirement of holographic videos. Obviously, this presents difficult issues such as spatial spectral efficiency and the required frequency bands for connectivity [14, 15]. Hence, a large bandwidth will be required, which can be found in THz bands, known as a gap band between the microwave and optical spectra as shown in Figure 1, which it is the subject of this study, THz waves.

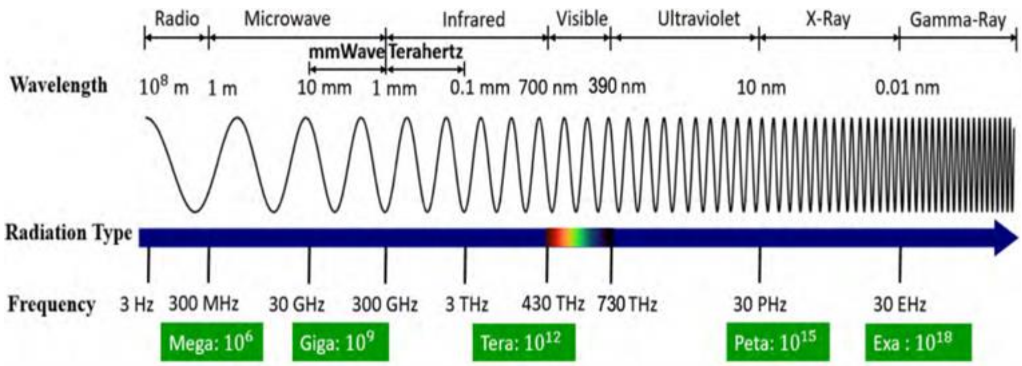

Figure 1. Electromagnetic spectrum and wavelength of terahertz waves [8]

This work discusses the substantial issues and key challenges of THz waves as shown in Figure 2. Restricted by size constraints, this work investigates in depth controversial research topics on the basis of their respective sub-domains to achieve a precise, concrete, and concise conclusion. This article will contribute significantly to opening new horizons for future research directions by providing new references that could support the pursuit of enabling THz waves.

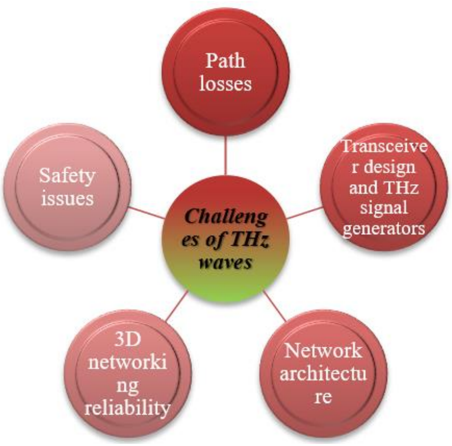

Figure 2. Key challenges of THz waves

The rest of the article is organized as follows; The path loss challenge is discussed in section 2. Transceiver architectures and THz signal generators are discussed in section 3. The network architecture is discussed briefly in section 4. Section 5 discussed environment of THz with 3D communications. Safety and health issues are discussed in section 6. Finally, section 7 concludes the work.

2. PATH LOSSES

Another strategy to assist the research community to explore the THz spectrum can be in the form of arranging THz sub-domains based on their absorption and reflection coefficients [16]. Explicitly, this approach serves as a guide to the suitability or otherwise of using any of THz spectrum for communications and other application purposes. Another issue that demands investigation is how to address scenarios supporting multiple applications [17]. In this case the ensuing harmonic overlaps can be mitigated by careful frequency planning. Furthermore, the sensitivity of weak signal suffers signal depreciation making detection one of the major limitations impeding the versatility of this band [18]. The THz electromagnetic spectrum is roughly categorized into favorable spectrum windows atmospheric below 500 GHz and above 500 GHz as shown in Figure 3 [19]. It is obvious as we move the THz region from 30 GHz onwards, there is an increase in free space path loss, molecular atmospheric absorption and total signal loss. The high free space path loss can be compensated by higher antenna obtainable in this region because of the high signal directivity components. Apart from the adverse impact of the free space loss, higher frequencies transmission increase complication and parallelism in RF hardware and the decrease beam width leading to problem of signal acquisition and beam tracking in mobile applications [20, 21]. In addition to technological boundaries, penetration through various materials and reflections from surfaces are other factors to be considered when categorizing the radio spectrum.

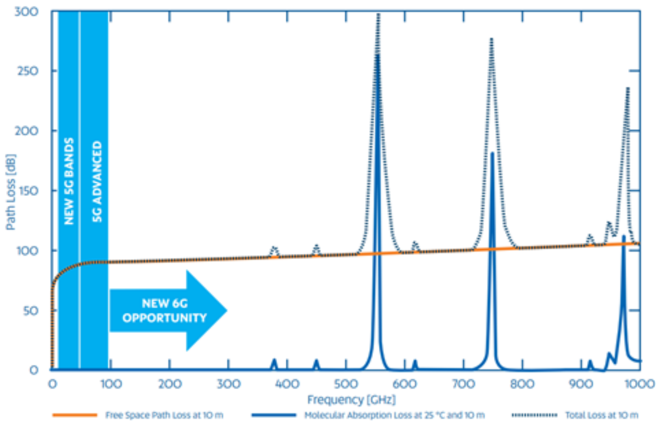

Figure 3. Spectral windows, the effect of free space loss, and water vapor absorption at a distance of 10 m [22]

Identifying the issue of high path loss at THz frequencies is important. More important is proposing strategies to mitigate these abnormalities. A plausible solution set will be the deployment of highly directional dynamic massive MIMO antennas. These antennas are equipped with a narrow beam width array and, hence minimizing interference. This approach is currently proposed in 5G communication as a strategy towards increasing spectral efficiency. When fully explored, the signal-to-interference-ratio will increase resulting to the massive data rate per communication density. Thought highly directional antenna can increase the system data rate, there are other structural issues that must be addressed before deploying THz communications in wireless communications. For instance, till this moment, no channel model has been proposed and suggested the THz band with exception to those within the 300 GHz for stationary indoor scenarios [23]. Moreover, ultra-high rates are attributable to ultra-high energy utilization. This implies that, energy-efficient communications are unavoidable both at the digital signal processing and radio interface levels [24].

Basically, the upcoming ultra-fast THz communication systems will support holographic call, researchers should explore the desirability of the stochastic approach as a solution set towards 3D channel model to design 6G deployment scenarios, including 3D beamforming [25]. 3D channel modelling is an interesting research area with rich potential both in 5G communications and unmanned aerial vehicle communications. In a bid to increase the confidence level, any analytical channel characterization simulation is expected to be subjected to real world deployment scenario either in the form of testbed before receiving approval. Mobility support within a multiuser THz cellular environment must receive attention as well and must support different kinds of mobility scenarios experience in wireless communication environment. Any analysis in mobility is expected to consider the issue of handover simultaneously [26]. THz cellular environment will witness excessive handover issues because of the small cell topology and consequently, a unique solution is required.

3. TRANSCEIVER DESIGN AND THZ SIGNAL GENERATORS

One of the greatest concerns towards the use of THz spectrum is how to design a new transceiver module because the current designs are not suited for THz band frequencies [27]. In this regard, on-going efforts are in offing to tackle this issue. For instance, the DARPA T-MUSIC program is researching on SiGe HBT, CMOS/SOI and BiCMOS circuit integration, and are optimistic of attaining the power amplifier threshold frequencies 500-750 GHz [28]. The semiconductor industry will solve these challenges, however, the novel designs for highly dense antenna arrays will be needed, to overcome the relative minute wavelengths and physical size of RF transistors comparable to element spacing in THz arrays. In addition, a great deal of innovation is needed to suppress the excessive propagation attenuation common at THz band frequencies. Other extra issues such as high power, high sensitivity, and low noise figure should not be neglected during the fabrication of THz enabled transceivers [29]. Furthermore, the THz transceivers are performance-constrained, from the viewpoint of transmission power (and distance). Silicon germanium (SiGe), gallium nitride (GaN), gallium arsenide (GaAs), and indium phosphide (InP) are among the popular option for THz signal generators and detectors [30]. Equally, the transmission distance for GaN, GaAs, and InP based transceivers are bounded. Designing a novel THz band transceiver architecture has become a necessity. The issue of imperfect hardware features, including nonlinear amplifier, phase noise, limited modulation index [28, 31], and so on, can severely mar the quality of transmitted signals. It is also possible that issues may arise in the design of antennas and waveforms, and energy efficient signal processing. Therefore, novel transceiver technologies have become essential towards fabrication of state-of-the-art THz sources (hardware), especially for the medium-to high-end part of the THz band (>300 GHz) [32]. Both the conventional CMOS technology and the recently introduced nanomaterials, such as Graphene, can be used for new transceiver designs for THz-enabled devices [33]. However, analytical testing should be supported by real experimentation to re-assess the performance of any proposed design.

4. NETWORK ARCHITECTURE

In [34], the authors proposed the next generation system network topology, in which mmWave, THz, and conventional microwave bands function jointly, and proposed a medium access control (MAC) protocol that switches among the various bands for data transmissions. However, this model may be unreliable for THz-only ultra-dense system networks [35]. The reason being that the THz frequency band is massive (i.e., roughly 10 THz in total), the attributes of diverse carrier frequency windows are quite different, particularly from the context of transmission distance. In furtherance of the goal of provisioning of pervasive ultra-high-rate access in complex environments, over-hauling the currently deployed MAC protocols and network deployment schemes are imperative. From the MAC design, a critical issue that needs further research is the channel coding scheme to be deployed. Are the current error detecting and error correcting codes sufficient to work in these frequencies [36]. Which of the forward error correcting codes will result to optimal performance when considered from the viewpoint of high path loss and weak diffusion signals. Highly directional signals are easily blocked and hard for mobility applications. Recall that in the presence of excessive path loss the transmission distance becomes small. Thus, new error control mechanisms should be proposed, and new networking strategies should be developed to improve the coverage and support the seamless connection [37]. Undoubtedly, Tbps per link wireless networks has tremendous potential to enhance, the aggregated traffic flowing through the network and the Internet dramatically. Thus, the upper layers such as transport layer protocols compromising TCP and UDP will undergo morphological changes to be able to deal with upper layer issues such as congestion control [38, 39].

5. 3D NETWORKING RELIABILITY

6G must support communications in 3D space. This requires concerted research on various fronts; i) Measurement and (data-driven) modelling of the 3D propagation environment [40], ii) New approaches for 3D frequency and network planning, iii) New network optimizations for mobility management, routing, and resource management in 3D [41]. In addition, fundamental 3D performance, in terms of rate-reliability-latency trade-offs and SE, is needed. Such analysis must quantify the spectrum, energy, and communication requirements that 6G needs to support the identified driving applications [42]. Recent works in [43, 44] provide a first step in this direction.

On the other hand, the Poisson point process (PPP) is a widely used mathematical tool to model the randomness obtainable in real network deployment and coverage probability scenario [45]. Nevertheless, the fundamental assumptions commonly used in PPP are that objects are distributed randomly in space and hence unpredictable. This model is not entirely correct because in both mono and multi-tier heterogeneous networks, transmitter deployment is static in contrast to mobile devices that exhibit random distributions [46]. In studying base station location, a pattern has emerged in which some base stations attract more traffic while others don’t. In small cell networks will witness more users, signifying user-centric hotspot areas, while there will be repulsed (low traffic) observed at the macrocell level to signify rural and urban deployments. This assumption is in consonant with the issue of excessive handover as described earlier. Due to the imperfection of the PPP techniques, it will not adequately model the 6G networking environment. Furthermore, PPP has shown versatility in the 2D plane until now and has been extended the 2.5D domain [47, 48]. If this same model must be deployed to derive the 3D channel model of the emerging network, there is need to address this issue.

6. SAFETY ISSUES

The photon energy THz radiation is between 0.1 to 12.4 meV, which is a less than three times of ionizing photon energy levels. Thus, THz radiation is considered as a non-ionizing photon energy [49, 50]. Accordingly, the concern source with THz frequencies is a heating which is considered the main reason for cancer risk [51]. However, the principle of thermal hazards and standards for non-ionizing radiation is designed by the FCC and international commission as given in [52]. Moreover, electromotive-force transmission should be a novel concept to be introduced in 6G to mitigate health concerns.

7. CONCLUSION

The exponential increase in data traffic due to the growing number of connected devices, which it is foreseen that may leapfrog hundred(s) of connected devices per cubic meter. In addition, future uses and novel applications. Thus, the future networks will require bandwidths in several gigahertz; accordingly, THz is considered one of the most promising technology for future networks to perform optimally. This paper covered various aspects of THz technology for 6G networks with different perspectives. The opportunities and research challenges for THz technology on the way to the commercialization of the next generation communication network are presented.

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