Terahertz Communications for Massive Connectivity and Security in 6G and Beyond Era

Nan Yang and Akram Shafie

ABSTRACT

Terahertz (THz) communications (THzCom) has experienced a meteoric rise of interest due to its benefits for ultra-high data rate transmission in the sixth generation (6G) and beyond era. Despite this, the research on exploring the potential of THzCom for other performance targets anticipated by 6G, including massive connectivity and security, is still in its infancy. In this article, we start with briefly describing the unique peculiarities of THz channels and then discuss theoretical frameworks to facilitate the analysis and design of THz transmission for achieving massive connectivity and security. Then we discuss promising spectrum management strategies, including the exploration of multiple THz transmission windows and frequency reuse with multiplexing and signal processing, to substantially increase the number of supported users and identify to-be-tackled challenges. We further present important research directions based on the principles of physical layer security, such as new spectrum allocation policies and beamforming algorithms, to fight against eavesdropping in THzCom systems, ushering in secure THzCom systems.

INTRODUCTION

Our society is in the era of mobile wireless Internet with explosive big data. While the fifth generation (5G) wireless systems are being deployed worldwide, the telecommunications community has identified emerging use cases and technologies needed for an intelligent information society in the 2030s [1], most of which have quality of service (QoS) requirements far beyond what 5G can offer. For example, as a promising technology allowing doctors to perform remote surgeries, holographic telepresence often requires vast amounts of data (e.g., holographic images from multiple viewpoints) to be instantly communicat-ed at data rates of several hundred gigabits per second or beyond 1Tb/s [1], which is 10–100 times higher than the maximum data rate of 5G. To satisfy such unprecedented QoS requirements, the global research community and industry have reached a consensus to exploit frequencies at the terahertz (THz) band (0.1–10 THz) for the sixth generation (6G) and beyond wireless systems [2]. In particular, the relatively low THz band (e.g., 0.1–0.3 THz) is envisioned to be regulated for use in 6G [3], while the higher THz band (e.g., 0.3–1 THz) is anticipated to be adopted in beyond 6G. The THz band has enormous potential to meet the demands of 6G, such as its far richer spectrum resources (e.g., tens up to hundreds of gigahertz bandwidth) than the millimeter-wave (mmWave) band adopted by 5G, and its capability to accommodate thousands of miniature antennas [2]. Thanks to the recent advances in THz hardware and the opening of the THz spectrum for research [3], designing THz communication (THzCom) strategies for 6G and beyond wireless systems has become an emerging trend. From a communication and signal processing perspective, rapidly increasing efforts have been devoted to THzCom for achieving the QoS target of ultra-high data rate, aiming to realize promising 6G applications such as terabit per second WiFi for conferences and smart offices, and terabit per second links in wireless data centers, as shown in Fig. 1.

It is worth noting that the ultra-high data rate is not the sole QoS requirement of 6G that THzCom can potentially satisfy. In particular, the abundant spectrum resources at the THz band and the frequency- and distance-dependent nature of THz spectrum have substantial potential to meet other QoS requirements, including massive connectivity and high security. For example, THzCom-aided 6G systems can be adopted to serve a huge number of users with reasonably high data rate requirements, such as indoor and outdoor mega-sporting events (e.g., Olympic Games) and smart factories with massive wirelessly connected machine-type devices, as shown in Fig. 1. Also, THzCom-aided 6G systems must guarantee and maintain a very high level of secrecy if used in wireless data centers and military communication networks, displayed in Fig. 1. Against this background, our article discusses the advancements, opportunities, and challenges of using THzCom to support massive connectivity and security in 6G and beyond wireless systems, with the primary focus on spectrum management and signal processing. This discussion makes our article substantially different from existing works focusing on ultra-fast THz transmission.

In this article, we first briefly describe the characteristics of THz channels, based on which the theoretical frameworks to analyze the connectivity and security performance of THzCom systems are...
investigated. Then we identify new ways to achieve massive connectivity by exploring the rich THz spectrum resources and devising multiplexing and signal processing schemes. Furthermore, based on the principles of physical layer security, we delve into novel spectrum allocation policies and signal processing algorithms to safeguard THzCom systems. For both massive connectivity and security, we discuss open problems and future research directions to facilitate the establishment of theoretical frameworks and the design of spectrum management and signal processing strategies.

**THz Channel Characteristics and Performance Evaluation Frameworks**

One fundamental challenge to fully unleash the potential of THzCom is to understand the unique characteristics of THz channels that are not encountered at lower frequencies and then apply such characteristics into the analysis, design, and development of THzCom systems. Compared to the channels accommodating the current wireless systems, the signals transmitted over THz channels experience very high spreading loss as well as frequency- and distance-dependent molecular absorption loss, exhibit high sparsity, and are very vulnerable to blockages, described as follows:

**Spreading Loss:** In wireless propagation, the spreading loss increases quadratically with frequency when the apertures of antennas, with frequency-independent gains, decrease at both ends of a wireless link. Given very high THz frequencies, the signal propagated over a THz link is impacted by severe spreading loss (e.g., the free space spreading loss experienced by a THz signal transmitted over 10 m is over 100 dB) [4].

**Molecular Absorption Loss:** The THz band is uniquely characterized by the molecular absorption loss resulting from the phenomenon that THz signal energies are absorbed by water vapor and oxygen molecules in the propagation medium. The severity of molecular absorption loss depends on the operating frequency and transmission distance. Specifically, some THz frequencies are very sensitive to molecular absorption. Thus, molecular absorption peaks exist at such frequencies, where the THz signal energy profoundly decreases. This existence creates distance-dependent transmission windows (TWs), as illustrated in Fig. 2. Within TWs, drastically varying molecular absorption loss is experienced, and this variation increases with the transmission distance, as shown in Fig. 2. The molecular absorption loss is a must-consider property for analyzing and designing THzCom systems, where the advantages of multiple TWs and their frequency and distance dependencies need to be explored.

**Sparsity:** The wavelengths of THz signals are extremely short (e.g., at the level of millimeter and sub-millimeter), which is comparable to the surface roughness of typical objects in the environment. This implies that surfaces considered smooth at lower frequencies are rough in THzCom. When THz waves hit such rough surfaces, very high reflection, diffraction, and scattering losses occur, leading to high sparsity of THz channels. The problems caused by this high sparsity, such as poor multiplexing gain, need to be properly addressed when designing effective signal processing algorithms for THzCom.

**Vulnerability to Blockages:** Given the extremely short wavelength of THz signals, THz propagation is very vulnerable to various blockages. Specifically, objects with small dimensions, such as a person holding a THz device, moving humans, and indoor construction including walls and furniture, can be impenetrable blockers. This vulnerability significantly limits the distance of THz transmission and boosts the importance of line-of-sight (LoS) propagation in THzCom.

---

FIGURE 1. Massive connectivity and security oriented THzCom in 6G and beyond wireless applications.

The THz band is uniquely characterized by the molecular absorption loss resulting from the phenomenon that THz signal energies are absorbed by water vapor and oxygen molecules in the propagation medium. The severity of molecular absorption loss depends on the operating frequency and transmission distance. Specifically, some THz frequencies are very sensitive to molecular absorption. Thus, molecular absorption peaks exist at such frequencies, where the THz signal energy profoundly decreases. This existence creates distance-dependent transmission windows (TWs), as illustrated in Fig. 2. Within TWs, drastically varying molecular absorption loss is experienced, and this variation increases with the transmission distance, as shown in Fig. 2. The molecular absorption loss is a must-consider property for analyzing and designing THzCom systems, where the advantages of multiple TWs and their frequency and distance dependencies need to be explored.
Understanding the fundamental characteristics of THz channels, including the aforementioned ones and others (e.g., temporal broadening and weather impact), is critical for integrating THz-Com into 6G and beyond wireless systems. In order to design ready-to-use THzCom systems, there is an emerging need to establish generalized mathematical frameworks for analyzing key performance metrics of THzCom systems in practical and complex environments, such as the system shown in Fig. 3. This need becomes more intense when we focus on massive connectivity and security, both of which have rarely been investigated.

To satisfy this need, we need to develop theoretical approaches for analyzing the user capacity of complicated THzCom systems, for example, a system with distributed access points (APs) and a huge number of users. Here, the user capacity is defined as the maximum number of users supported by a THzCom system. It is noted that supporting simultaneous transmission toward multiple users using an  LoS channel at very high frequencies is possible if antenna spacing is much larger than the wavelength of signals. Triggered by this, the spatial degree of freedom (DoF) of THzCom systems needs to be derived as a function of dominant factors, including the number of radio frequency (RF) chains at the AP and the number of THz propagation paths in the environment [5]. Then this function can be extended to incorporate other performance-limiting factors, including the angular spreads of channels, number and resolution of phase shifters, space between adjacent antennas, number and layout of APs, and number and properties of blockages. Once completed, we can use it jointly with existing performance evaluation frameworks, such as those analyzing the coverage probability of THzCom systems, and the secrecy rate and secrecy outage probability of wireless systems, to reveal the trade-offs between the connectivity, security, rate, reliability, and energy and spectral efficiencies of complicated THzCom systems.

**Massive Connectivity in THz Communications**

Efficient spectrum allocation based on carrier-based modulation is pivotal to harness the potential of the THz band for massive connectivity. With carrier-based modulation, the transmitted data is first modulated into single- or multi-carrier waveforms (or pulses) and then the modulated signals are upshifted to THz frequencies via frequency multipliers. Recently, the *multi-band-based spectrum allocation* scheme has been discussed as a promising scheme where TWs are divided into multiple non-overlapping sub-bands. These sub-bands are used to provide ultra-high data rate transmission toward multiple users, ideally not causing interference to each other. Despite recent studies examining the benefit of THz spectrum allocation for massive connectivity (e.g., [5]), there are several pressing challenges. On one hand, the huge spectrum spanning multiple THz TWs needs to be allocated among all the users in a THzCom system. On the other hand, frequency reuse techniques need to be adopted to repeatedly use the frequency resources in a THzCom system. We next present the principles, challenges, and solutions related to using multiple TWs and frequency reuse in THzCom, where the potential massive connectivity strategies for THzCom are summarized in Fig. 4.
Exploring Multiple Transmission Windows for Massive Connectivity

In THzCom, one fundamental challenge is caused by the high frequency selectivity of the molecular absorption loss within the spectrum spanning multiple TWs. In particular, the variation in molecular absorption loss among the spectrum to be allocated to each user would be very high. This needs to be addressed by new solutions.

One promising solution is sub-band assignment. In multiuser THzCom systems, the distance-dependent property of the molecular absorption loss needs to be explored since users are positioned at different distances from the AP. With this exploration, distance-aware multi-carrier (DAMC)-based sub-band assignment has been reported as an effective method to ensure fairness among users, since it assigns the sub-bands in the center region of the TW to the links with longer distances and the sub-bands at the edges of the TW to the links with shorter distances [6]. However, it remains unanswered whether or not DAMC-based sub-band assignment is optimal when the THzCom design objective is to maximize the sum throughput and/or the number of supported users. Moreover, it is reported that the DAMC-based sub-band assignment is only applicable within one TW. Thus, new problems arise when the to-be-allocated spectrum of interest spans multiple TWs. For example, the number of sub-bands in each TW needs to be optimally decided, and the set of users served by each TW needs to be identified. This necessitates the optimal design of sub-band allocation. Furthermore, considering equal sub-band bandwidths, the optimal sub-band assignment can be designed as mixed-integer nonlinear optimization problems and solved by adopting the transformation from binary variables to real variables and the successive convex approximation techniques. However, solving such problems can be very complex. To address this issue, non-traditional optimization techniques with low complexity need to be devised.

Another promising solution is varying bandwidth allocation. It is found that the variation in molecular absorption loss among users is very high when each user is allocated the same amount of spectrum resources (or equivalently, the same bandwidth). This variation can be reduced by allowing users to occupy varying sub-band bandwidth in spectrum allocation [7], as shown in Fig. 2. This design introduces new problems. First, tractable expressions need to be formulated to model the molecular absorption coefficient against the frequency within the spectrum region spanning multiple TWs. Second, the spectrum allocation problem with varying sub-band bandwidth is highly non-convex, which cannot be solved using traditional optimization techniques. This necessitates the use of emerging optimization techniques such as machine learning (ML). For example, model-free unsupervised learning can be used to obtain the near-optimal solutions.

Apart from the challenges caused the molecular absorption loss, another yet-to-be-tackled challenge is to counteract the channel squint effect (CSE) at antennas. Here, the CSE refers to phase shift errors occurring in THz beamforming, since THzCom generally has a large bandwidth. To mitigate the CSE, THz true-time delays (TTDs) can be used as the alternative to phase shifters in THz digital antenna arrays by adjusting the phase shift relative to the operating frequency.

Frequency Reuse with Multiplexing and Signal Processing for Massive Connectivity

Frequency reuse has great potential for THzCom systems to support a huge number of users, through adopting overlapping THz frequency resources repeatedly. With the recent advancement in THz band digital processors, it has come to light that THzCom systems can handle reasonable signal processing complexity. This opens the avenues for applying frequency reuse into THzCom, paving the way to materialize massive connectivity in the 6G and beyond era. The interference caused by frequency reuse in THzCom systems was recently analyzed [8]. Apart from performance analysis, new spatial and power-domain multiplexing strategies operating at the THz band are needed for adopting frequency reuse in THzCom systems.

One of the most encouraging spatial multiplexing strategies is beam sectorization. In a THzCom system with beam sectorization, each AP can perform beamforming to form non-overlapping beam sectors with high directional gains, and the entire THz spectrum available in the system is reused within-in beam sectors. In each beam sector, the spectrum can be divided into non-overlapping sub-bands, which are assigned to AP-user links. Two challenges need to be tackled to reap the most benefit from beam sectorization, explained as follows:

- The first challenge is inter-sector interference cancellation, which minimizes or eliminates the impairment caused by non-ideal beam shapes. To tackle this challenge, we can embrace digital filter design and adopt phase antenna arrays while considering a ripple constraint on the in-sector power pattern.

- The second challenge is to identify sector regions, which can be addressed by 2D sector deployment. Most sector deployment designs have aimed at horizontal sectorization, since vertical sectorization causes high interference if the vertical distances between the users and the AP are not comparable to the horizontal distances. Nonetheless, THzCom systems typically have limited transmission distance; thus, the horizontal and vertical distances between the users and the AP are comparable to each other. This motivates the use of vertical sectorization in THzCom systems, while ensuring low interference. By performing horizontal and verti-
FIGURE 5. Sum throughput of three HBF schemes, namely, cluster-based minimum mean squared error (MMSE) HBF, cluster-based zero-forcing (ZF) HBF, and non-cluster HBF, in a THzCom system where a 256-antenna AP with 16 RF chains serves 160 or 320 users.

Security in THz Communications

Security is an exciting and challenging problem in THzCom systems. Specifically, the information sent by a legitimate transmitter is received by not only legitimate receivers but unintended receivers (referred to as eavesdroppers). Thus, establishing effective secure communications is a testa-
Secure THzCom can be achieved by exploring the abundant spectrum availability at the THz band, as well as the frequency- and distance-dependent nature of molecular absorption loss within the abundant spectrum. Specifically, we can divide the abundant spectrum at the THz band into a huge number of sub-bands and then dynamically select a certain number of sub-bands for secure transmission, based on the distance between the AP and legitimate users and the distance between the AP and eavesdroppers. This forms the distance-adaptive absorption peak modulation (DA-APM) scheme [13]. Given that the molecular absorption loss depends on frequency and distance, the path loss variation with distance in one sub-band is likely to be different from that in another sub-band. Hence, a well-thought-out selection of sub-bands can achieve a small path loss at the legitimate user but a large path loss at the eavesdropper, which enlarges the difference in signal quality between them and in turn improves the secrecy, as shown in Fig. 6. Specifically, the eavesdropper’s received signal power is less than 50 percent of the legitimate user’s received signal power, and can be less than 10 percent at some frequencies. This shows the potential of spectrum allocation for secrecy enhancement. Notably, it is very difficult for the eavesdropper to intervene sub-band selection, as the selection is made based on distances, unless it moves closer to the legitimate users, which is easy to identify.

Despite the potential of the DA-APM scheme, there are still open challenges to safeguard THzCom systems. By looking closely at the DA-APM scheme, we find that the sub-band selection problem, especially for the THzCom system with a large number of users, can be a mixed-integer nonlinear problem. To solve this problem, we can resort to binary-to-integer variable transformation, together with successive convex approximation, for attaining near-optimal solutions. Also, the DA-APM scheme only considers equal bandwidth of sub-bands. If this consideration can be relaxed by varying the bandwidth of sub-bands, a more dramatic change in path loss will occur within sub-bands, which brings higher security when the eavesdropper is positioned farther than the legitimate user. Furthermore, to effectively implement the DA-APM scheme, new THz signal design with smooth power spectral density is required to avoid signal leakage to the eavesdropper.

Signal Processing for Security

It is worthwhile mentioning that the existing secure communication schemes discussed in the literature cannot be applied when eavesdroppers exist in close proximity to legitimate users. To overcome this bottleneck, frequency diverse array (FDA)-based beamforming has emerged as an attractive solution. At the FDA, linear phase progression is adopted over the aperture and induces an electronic beam scan. When applying an additional linear frequency shift, the FDA generates a new term which brings a scan angle that varies with the range of the far-field. This intentionally introduces frequency offsets among array antennas and decouples the highly correlated channels of legitimate users and eavesdroppers. Such decoupling capability allows the FDA to degrade the received signal quality at eavesdroppers and accordingly enhance the secrecy performance.
There are several open questions to reap the potential of FDA-based beamforming. First, there is a clear need to develop the hardware of efficient FDAs. In the THz band, widely spaced arrays can act as FDAs due to their range-dependent array pattern. Thus, an effective design of widely spaced arrays can group antennas into several subarrays and separate these subarrays over hundreds of wavelengths to reduce their correlation. Second, the comparison between linear FDAs and random FDAs needs to be conducted. Using linear FDAs, the achieved direction and range are coupled. Thus, multiple direction-range pairs may exist such that the eavesdropper receives the same signals as the legitimate user, impairing secure transmission. To tackle this problem, random FDAs can be utilized where each transmit antenna is randomly, but not linearly, allocated a narrow- or sub-band frequency. Thus, random FDAs decouple the correlation between direction and range, making itself promising for robust secure THzCom [15]. Third, the far-field beam pattern produced by FDAs is time-variant, as the frequency increments between adjacent antennas are small. This time-variant property may enable short-time secure transmission, which can be used to safeguard the transmission of control signals between an AP and legitimate users (e.g., in a smart factory). To support long-time secure transmission of data signals, this time-variant property needs to be addressed. Fourth, advanced signal processing algorithms, such as transmitter AN and confidential broadcasting, can be jointly used with FDAs to further improve the secrecy performance, where its memory requirement may be examined.

**Conclusion**

This article has provided an overview and comprehensive discussions on massive connectivity and security issues in THzCom systems by fully exploiting the challenges and opportunity brought by THz spectrum. First, the establishment of new performance analytical frameworks under the key characteristics of THz signal propagation has been revealed. Then new and effective approaches, in terms of spectrum management and signal processing, have been discussed to increase the number of supported users and enhance the secrecy performance of THzCom systems. In this discussion, critical challenges and promising research directions have been presented, offering insightful guidance to develop THzCom systems accommodating massive connectivity and promoting security.

**References**

[1] H. Tataria et al., “6G Wireless Systems: Vision, Requirements, Challenges, Insights, and Opportunities,” *Proc. IEEE*, vol. 109, no. 7, July 2021, pp. 1166–99.
[2] I. F. Akyildiz et al., “Terahertz Band Communication: An Old Problem Revisited and Research Directions for the Next Decade,” *IEEE Trans. Commun.*, vol. 70, no. 6, June 2022, pp. 4250–85.
[3] V. Petrov, T. Künner, and I. Hosako, “IEEE 802.15.3d: First Standardization Efforts for Sub-Terahertz Band Communications toward 6G,” *IEEE Commun. Mag.*, vol. 58, no. 11, Nov. 2020, pp. 28–33.
[4] K. Guan et al., “Measurement, Simulation, and Characterization of Train-to-Infrastructure Inside-Station Channel at the Terahertz Band,” *IEEE Trans. Terahertz Sci. Techn.*, vol. 9, no. 3, May 2019, pp. 291–306.
[5] H. Yuan et al., “Cluster-Based Multi-Carrier Hybrid Beamforming for Massive Device Terahertz Communications,” *IEEE Trans. Commun.*, vol. 70, no. 5, May 2022, pp. 3407–20.
[6] C. Han and I. F. Akyildiz, “Distance-Aware Multi-Carrier (DAMC) Modulation in Terahertz Band Communication,” *Proc. 2014 IEEE ICC*, Sydney, Australia, June 2014, pp. 5461–67.
[7] A. Shafie et al., “Spectrum Allocation with Adaptive Sub-Band Bandwidth for Terahertz Communication Systems,” *IEEE Trans. Commun.*, vol. 70, no. 2, Feb. 2022, pp. 1407–22.
[8] J. Ye et al., “Modeling Co-Channel Interference in the THz Band,” *IEEE Trans. Veh. Tech.*, vol. 70, no. 7, July 2021, pp. 6319–34.
[9] H. Zhang et al., “Energy Efficient Resource Allocation in Terahertz Downlink NOMA Systems,” *IEEE Trans. Commun.*, vol. 69, no. 2, Feb. 2021, pp. 1375–86.
[10] Z. Ding et al., “Application of Non-Orthogonal Multiple Access in LTE and 5G Networks,” *IEEE Commun. Mag.*, vol. 55, no. 2, Feb. 2017, pp. 185–91.
[11] Z. Hosain and J. M. Jornet, “Hierarchical Bandwidth Modulation for Ultra-Broadband Terahertz Communications,” *Proc. 2019 IEEE ICC*, Shanghai, China, May 2019, pp. 1–7.
[12] N. Yang et al., “Safeguarding 5G wireless communication networks using physical Layer Security,” *IEEE Commun. Mag.*, vol. 53, no. 4, Apr. 2015, pp. 20–27.
[13] W. Gao et al., “Distance-Adaptive Absorption Peak Modulation (DA-APM) for Terahertz Covert Communications,” *IEEE Trans. Wireless Commun.*, vol. 20, no. 3, Nov. 2020, pp. 2064–77.
[14] W. Gao, C. Han, and Z. Chen, “DNN-Powered SIC-Free Receiver Artificial Noise Aid Terahertz Secure Communications with Randomly Distributed Eavesdroppers,” *IEEE Trans. Wireless Commun.*, vol. 21, no. 1, Jan. 2022, pp. 563–76.
[15] J. Hu et al., “Artificial-Noise-Aided Secure Transmission with Directional Modulation Based on Random Frequency Diverse arrays,” *IEEE Access*, vol. 5, 2017, pp. 1658–67.

**Biographies**

**Nan Yang** (nan.yang@anu.edu.au) is an associate professor with the School of Engineering at the Australian National University. His research interests include THz and mmWave communications and machine learning in communications.