This article has been accepted for inclusion in a future issue of this magazine.

6G THz Propagation Channel Characteristics and Modeling: Recent Developments and Future Challenges

Jun Wang, *Student Member, IEEE*, Cheng-Xiang Wang, *Fellow, IEEE*, Jie Huang, *Member, IEEE*, and Yunfei Chen, *Senior Member, IEEE*

***Abstract*—The terahertz (THz) band is expected to play a more important role in the sixth generation (6G) communication networks. It can provide large bandwidth and high-speed transmission rate to support prospective 6G scenarios from space to ground and from macro-scale to nano-scale. However, the THz channel characteristics vary greatly for different scenarios. This paper presents a multi-dimensional overview of propagation channel characteristics and modeling for potential THz communication scenarios, including ground, space, and nano-scale communications. The atmospheric attenuation and propagation mechanisms are firstly discussed for ground scenarios. Then, the channel measurements, characteristics, and models for specific ground scenarios, including indoor office, data center, kiosk, smart rail, and massive MIMO are investigated. Following this, the THz space communication channels are summarized according to the satellite altitude. Futhermore, THz nano-scale communication channels including on-chip and body centric are analyzed. Finally, future research challenges are outlined.**

***Index Terms*—6G, channel characteristics, channel models, THz**

I. Introduction

The demand for data traffic and transmission rate of wireless communications is growing exponentially. Terabits per second (Tbps) links will be required in the near future. Unfortunately, traditional wireless networks operating at sub-6 GHz or even millimeter wave (mmWave) bands cannot meet such requirements. This motivates the exploration of higher frequency bands and the corresponding transmission theory. In this case, the terahertz (THz) band ranging from 0.1 THz to 10 THz has been promoted as a key wireless technology to meet the requirement. The THz band can effectively alleviate the increasingly scarce spectrum resources and relax the capacity constraints on current wireless networks.

This work was supported by the National Key R&D Program of China under Grant 2020YFB1804901, the National Natural Science Foundation of China (NSFC) under Grants 61960206006 and 61901109, the Key Technologies R&D Program of Jiangsu (Prospective and Key Technologies for Industry) under Grants BE2022067 and BE2022067-1, the Frontiers Science Center for Mobile Information Communication and Security, the Research Fund of National Mobile Communications Research Laboratory, Southeast University, under Grant 2021B02, the High Level Innovation and Entrepreneurial Doctor Introduction Program in Jiangsu under Grant JSSCBS20210082, the Fundamental Research Funds for the Central Universities under Grant 2242022R10067, and the EU H2020 RISE TESTBED2 project under Grant 872172. (Corresponding authors: Cheng-Xiang Wang and Jie Huang)

J. Wang, C.-X. Wang, and J. Huang are with the National Mobile Communications Research Laboratory, School of Information Science and Engineering, Southeast University, Nanjing, 210096, China, and also with the Purple Mountain Laboratories, Nanjing, 211111, China (email: {jun.wang, chxwang, j_huang}@seu.edu.cn).

Y. Chen is with the School of Engineering, University of Warwick, Coventry, U.K. CV4 7AL (email: Yunfei.Chen@warwick.ac.uk).

Recently, great achievements have been made in THz key technologies, such as THz channel modeling, multi-beam antenna design, front-end chip design, baseband signal processing, and resource management [1]. On one hand, compared with the mmWave band, the THz band has larger bandwidth to support higher transmission rate. On the other hand, compared with the optical band, the THz band has better penetration ability. Hence, the THz has appeared in many 6G white papers from various institutions due to its huge application prospects. The potential applications of the THz range from space to ground and from macro-scale to nano-scale, as shown in Fig. 1. More specifically, THz can be used to solve the technical problems of high-speed transmission in space communication networks, including satellite-to-ground, satellite-to-aircraft, and inter-satellite links. Current satellite communications mainly rely on microwave bands and lasers. The simultaneous operating of thousands of satellites at the microwave band may cause great interference to each other. Laser communication requires very accurate alignment and is susceptible to orbital disturbances. Unlike lasers, the THz band has wider beam to keep link reliability. The THz band also has wider application scenarios in terrestrial wireless communication networks, including indoor office, wireless data center, wireless data backhaul, wireless kiosk, wireless multimedia service, short-range wireless connection on a desktop, etc. In addition, THz can also play an important role in nano-scale applications, including on-chip/inter-chip communications and wireless nanosensor networks. Among them, THz on-chip wireless communications may provide high-speed links and reduce the complexity of chip layout simultaneously, while THz wireless nanosensor networks are able to support health monitoring and wearable or implantable devices.

None of the above applications will be realized without the research on channel characteristics and channel models. The divergence on propagation channel characteristics between different application environments requires a comprehensive research. For example, the propagation mechanisms of reflection, diffraction, and scattering at the THz band need to be studied for all scenarios. Terrestrial and satellite-to-ground THz communications need to consider atmospheric attenuation, while it can be ignored in outer space beyond the atmosphere. Line-of-sight (LoS) path is mainly considered in space THz communications. In addition, the high-speed

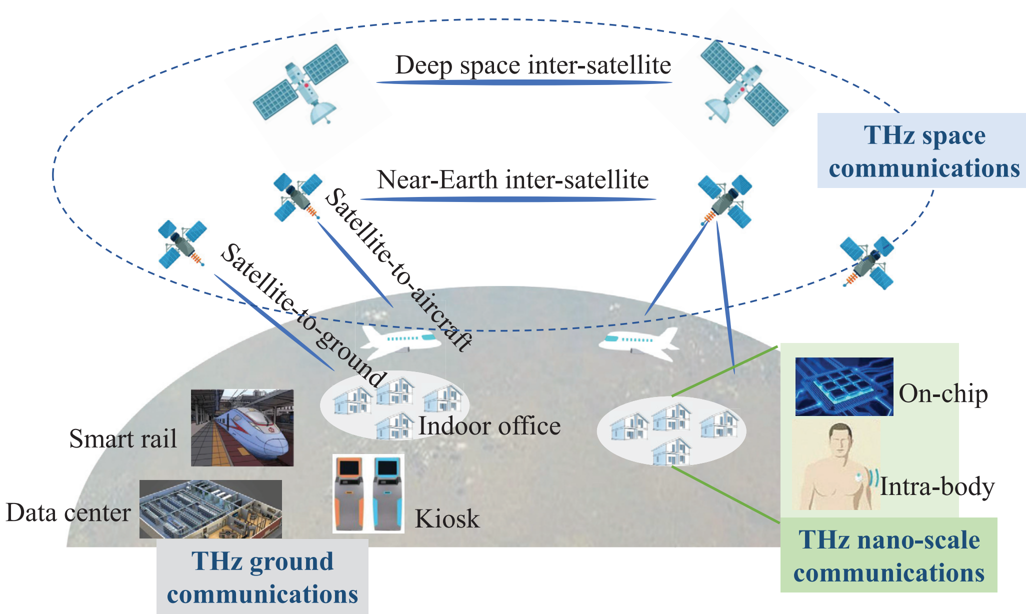


Fig. 1. Typical THz application from space to ground and from macro-scale to nano-scale.

motion of satellites and the instability of orbits will have a great impact on THz space communications. For nano-scale THz communications, atmospheric absorption is ignored for on-chip wireless communications and body area networks. However, the influences of on-chip devices and human skin or organs need to be considered in channel characterization.

Channel modeling is the foundation for system design, optimization, and performance analysis. How to capture the channel characteristics with mathematical expressions is the key problem of channel modeling. Channel models are divided into deterministic models and stochastic models, depending on whether all the channel parameters are deterministic or not. All parameters of deterministic channel model are determined by electromagnetic wave propagation theory. Ray tracing is a typical deterministic channel modeling method. The channel parameters, such as amplitude, delay, angle, and polarization, can be calculated by some algorithms. Deterministic channel models provide high accuracy for specific environments, but the computational complexity is also high. Stochastic chan-nel models contain one or more random variables and can be divided into geometry based stochastic models (GBSMs) and correlation based stochastic models (CBSMs). The CB-SMs generate the channel matrix according to the channel correlation. Due to the lack of description of the physical environment, the accuracy of CBSMs is relatively low. The GBSM has a good trade-off between accuracy and complexity, so it is more suitable for system analysis. At present, the main standardized channel models are GBSMs, such as the third generation partnership project (3GPP) TR 38.901 channel model and the international telecommunication union (ITU) M.2412 channel model.

THz wireless channels have been discussed in earlier survey papers [2]–[4] from different aspects. A holistic survey on THz channel measurements, channel modeling methods, and channel simulator have been provided in [2]. In [3], THz channel sounding, ray tracing simulations, and stochastic channel modeling were discussed in details. In [4], THz applications in vertical heterogeneous networks method were summarized. Channel measurement methodologies and channel modeling approaches were also discussed. However, none of these papers clarified the propagation channel characteristics for different THz scenarios. In order to better understand THz propagation channel characteristics and models for various scenarios, a comprehensive investigation is provided in this paper.

The remainder of this paper is organized as follows. The THz propagation channel measurements, characteristics, and models in the ground communication scenarios are reviewed in Section II. In Section III, THz space communication channels are discussed. THz nano-scale communication channels are analyzed in Section IV. Furthermore, in Section V, future research directions are discussed. Funally, conclusions are drawn in Section VI.

II. THz Propagation Channel Measurements and Modeling in Ground Scenarios

The ground is the main region of human activity. Most communications take place on the ground. In this section, we will first analyze the propagation mechanisms of the THz wave. Then, propagation channel characteristics and models will be presented for different ground scenarios.

The propagation of THz waves on the ground is severely attenuated by the atmosphere, including absorption, scattering, and scintillation. The absorption is caused by molecules in the atmosphere, including water molecules and oxygen molecules. The energy of the THz wave is absorbed by the atmospheric molecules to weaken the signal energy. The atmospheric scattering is mainly caused by hydrometeors (raindrop particles, snow, ice crystal particles, and fog droplets) and aerosols

TABLE I
CHANNEL MEASUREMENTS FOR THZ GROUND SCENARIOS.

Ref.	Scenario	Frequency	Bandwidth	Channel statistics
[6]	Indoor office	350 GHz and 650 GHz	20 GHz	Delay PSD, angular PSD
[8]	Data center	280–320 GHz	40 GHz	Path loss, shadowing, delay PSD
[9]	Kiosk	220–340 GHz	120 GHz	Received power, path number
[10]	Smart rail	300–308 GHz	8 GHz	Delay PSD, angular PSD, Rician K-factor, delay spread

(smoke, water-soluble aerosols, sand, etc.). Atmospheric scintillation is the fluctuation of the signal caused by turbulence in the atmosphere. The Jet Propulsion Laboratory (JPL) spectral database (https://spec.jpl.nasa.gov/) and the high-resolution transmission (HITRAN) database (https://hitran.org/) contain molecular spectral of various atmospheric gases at the THz band. The troughs of the absorption spectrum are regarded as transmission windows. In these windows, the absorption of signal energy by the atmosphere is relatively small. Selecting these frequencies is helpful for the implementation of THz communications.

In addition, the multipath propagation mechanisms also have significant influence on channel characteristics, including reflection, scattering, and diffraction. The wavelength is less than 1 mm and close to the surface variations of many common objects when the frequency is above 300 GHz. Thus, the propagation mechanisms are quite different from those at lower bands. Channel measurements have been conducted for different propagation mechanisms. In [5], the relationship between surface roughness and diffuse scattering of different materials was investigated. It was found that common materials in indoor offices were considered to be rough at THz band. The ratio of scattering power increases with the raise of the frequency. These propagation mechanisms are crucial for analyzing the characteristics of THz propagation channels.

Besides the above channel propagation mechanisms, we mainly focus on four ground scenarios, indoor office, wireless data center, kiosk, and smart rail. These scenarios cover several aspects of working, traveling, and entertainment. THz channel measurements for these scenarios are summarized in Table I. In addition, considering that massive MIMO technology will be utilized at the THz band, we will also analyze the THz massive MIMO channels in detail.

A. Indoor office

The indoor office is one of the most common scenarios. The size of the office is usually of a few meters. The channel measurements for the indoor scenario at 350 GHz and 650 GHz in [6] proved that the multipath components (MPCs) are spatially resolvable up to 650 GHz. Ray tracing based THz indoor channel models generate channel parameters by electromagnetic calculation. For THz indoor GBSMs, the distributions of random parameters are also estimated. Recently, a novel three-dimensional (3D) hybrid dynamic channel model was proposed considering the molecular absorption and diff use scattering [7]. This channel model combined deterministic and stochastic modeling approaches. The distributions of clusters were generated randomly while parameters of each ray were obtained separately based on the deterministic calculation.

B. Data center

Wireless data centers operating at THz band are able to provide low-latency networking and dynamic scalability critical to next-generation cloud computing infrastructures. This scenario is completely different from the traditional indoor office. There are abundant scatterers in this scenario, including racks and cables. From the channel measurements in [8], scattering objects, such as server rack frames/pillars, were found to be helpful for non-line-of-sight (NLoS) links. The cooling airflow in the data center has a negligible effect on THz propagation. The power cords and mesh doors of the server racks contribute approximately 20 dB and 6 dB of additional attenuation, respectively. In addition, the authors in [8] proposed a cluster-based channel model for the THz data center environment. The statistical properties of the proposed channel model, such as shadowing and delay PSD, were validated by measurement data.

C. Kiosk applications

Kiosk is considered to be an important way to achieve high-speed download. Its communication environment consists of a fixed kiosk transmitter (Tx) and a movable receiver (Rx). There is usually a front cover between the Tx and the Rx in the kiosk. MPCs between Tx and Rx have a significant impact on achievable data rates. The authors in [9] carried out channel measurements for the kiosk scenario from 220 to 340 GHz. Polyethylene-terephthalate was used to simulate the front cover of the Tx. Different angles of arrival/departure and different cover positions were measured. It was reported from these measurements that the LoS path and second-order reflections contribute over 97% of the received power and the odd order of reflections is absent. It is because when the signal is reflected by the cover plate, it needs an extra reflection to reach the receiver side. In addition, a corresponding GBSM was proposed in this paper, providing a complete set of parameters based on the measurement data for kiosk.

D. Smart rail

Applying THz band to railway communications can support smart rail mobility. Due to the special physical environment of the railway station, its propagation channel characteristics are very different from other indoor environments. The authors in [10] carried out channel measurements of five specific

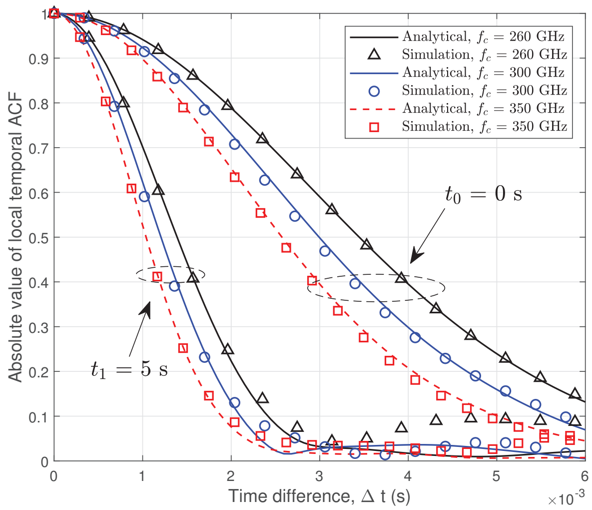


Fig. 2. The comparison of time-variant ACFs for the first cluster.

communication links in the railway station, including train-to-infrastructure, inside station, train-to-train, infrastructure-to-infrastructure, and intra-wagon. Typical channel parameters and statistical properties of the THz channels for these five links were extracted, including the Rician K-factor, delay PSD, and angular PSD. Furthermore, all parameters for channel generation were presented and could be input into the 3GPP-like channel generators.

E. Massive MIMO

In addition to these specific scenarios, the application of new technologies, such as massive MIMO, needs to be considered. Large-scale antenna arrays can compensate for the huge path loss. The antenna element at the THz band has a smaller size than that at a lower frequency so that ultra-massive MIMO is possible at the THz band. Spherical wave causes angular drifts from different antenna elements. In addition, some scatterers are only partially visible to some antenna elements on the array axis. Recently, a general 3D THz GBSM was introduced in [11]. The space-time-frequency (STF) non-stationarities caused by ultra-massive MIMO, long traveling paths, and large bandwidths were also considered. In Fig. 2, a typical THz indoor scenario with massive MIMO is simulated. The Tx is fixed and the Rx moves at a speed of 0.6 m/s to emulate human walking. the difference of autocorrelation functions (ACFs) for the first cluster at different time instants and frequencies can be observed, verifying the non-stationarities in temporal and frequency domains. In addition, asymmetric communication systems composed of digital beamforming arrays were recently proposed. The antenna patterns of uplink and downlink can be adjusted according to actual transmission requirements. Scattering distributions for the uplink and down-link channels with different beamwidths are shown in Fig. 3. It can be observed that the scatterers are sparsely distributed and concentrated in the direction of the main lobe of the antenna pattern.

III. THz Space Communication Channel Modeling

In this section, propagation channel characteristics and modeling of THz space communications will be discussed. Space communications are divided into inter-satellite and satellite-to-ground communications. Moreover, inter-satellite communications are classified into deep space and near-Earth scenarios according to their orbital altitudes. The altitude of satellites, environment factors, and main channel characteristics are summarized in Table II.

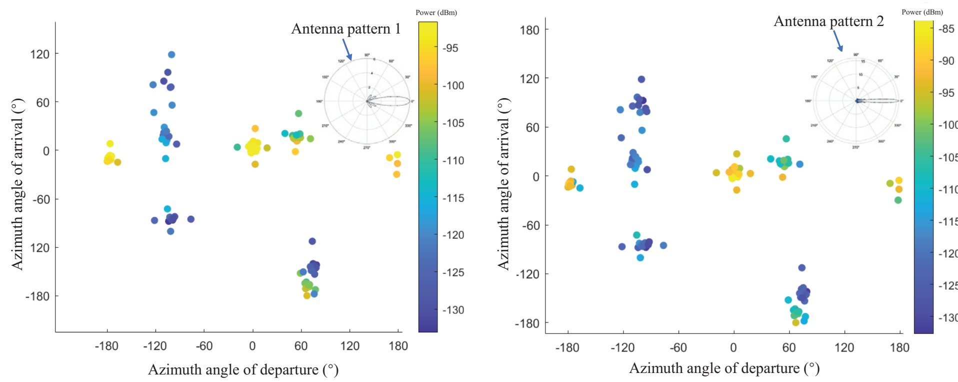
A. Deep space inter-satellite channels

Deep space scenario is defined as a satellite located outside the geostationary orbit. There is no atmospheric attenuation but it is greatly affected by solar activities, such as solar wind and solar flares. The solar wind is a high-speed flow of charged particles from the Sun moving at a speed of 200–800 km/s. The solar flares are a process of sudden and large-scale energy release in a local area of the Sun surface, causing instantaneous heating of the local area. The solar flares emit various electromagnetic waves, accompanied by a sudden increase in particle radiation. The wavelength of the radiated wave spans the entire electromagnetic spectrum. In addition, the noise from the cosmic has a huge effect on the channel. The noise comes from the expansion of the universe and the peak value of this radiation is at 282.1 GHz. This noise leads to extra path loss at this specific frequency.

The effects of solar activities on channel characteristics were studied in [12]. The geometric relationship between the Sun and the two satellites has a great influence on the satellite link. The key indicator is the angle formed by the Sun and the two satellites after joining the link. When the angle is too large, it means that the two satellites are located on two sides of the Sun. It is difficult to carry out inter-satellite communication in this case. The solar wind induced change in refractive index was also modeled, quantifying the angle of refraction through the plasma based on a Lorentz oscillator model. This model characterizes the interaction of electrons with electromagnetic fields. However, since the THz band is much higher than the resonant frequency, this effect on the path loss is small and almost negligible.

B. Near-Earth inter-satellite channels

The near-Earth region is defined as the region between 400 km and the altitude of geostationary orbit from the sea level. The atmosphere in this area is thin, and the absorption and scintillation effects caused by the atmosphere are negligible. However, the ionosphere of the Earth is very active here. This layer is ionized by solar radiation. Propagation of electromagnetic waves in the ionosphere is affected by free electrons and ions, forming ionospheric plasma. The propagation of electromagnetic waves in the ionosphere is mainly measured by the plasma frequency, the collision frequency, and the depolarization caused by the Faraday rotation. Plasma frequency is a measure of the frequency of oscillation of free electrons and ions due to Coulomb forces in an electric field. It depends only on the electron density, which varies



(a) Scattering distribution with antenna pattern 1 (Beamwidth: 25°)

(b) Scattering distribution with antenna pattern 2 (Beamwidth: 10°)

Fig. 3. Scattering distributions with different antenna configurations.

with geographic location, altitude, observation time, electron temperature, etc. Collision frequency measures the strength of interaction between charged electrons, ions, and neutral particles. When a linearly polarized wave passes through an electromagnetic field, the rotation of the polarization plane relative to the incident wave will be generated under the influence of the electromagnetic field, which is mainly caused by the ionosphere. The collision frequency is temperature-dependent and modeled as electron-ion, electron-neutral, and ion-neutral collision functions. The increase in temperature causes stronger collisions.

By modeling these three ionospheric effects separately, the THz channel of inter-satellites in near-Earth regions can be accurately characterized. The influence of ionosphere is highly correlated with frequency. At the THz band, the ionospheric electron density has a relatively small influence when we calculate the total path loss.

C. Satellite-to-ground channels

Typically, the altitude of the aircraft is much lower than that of the satellite. Whether it is a satellite-to-ground or a satellite-to-aircraft THz link, it will go through both the ionosphere and the atmosphere. Through the analysis of terrestrial communication channels and near-Earth satellite channels, it is not difficult to find that the ionosphere has little influence on THz, mainly due to the absorption and scintillation effects caused by atmospheric analysis. In the atmospheric molecular absorption model, altitude is one of the key parameters affecting the degree of absorption. Since the satellite-to-ground link needs to go through the entire atmosphere, and the atmospheric molecular thinning is different at different altitudes, absorption losses need to be additionally considered. The work in [13] presented the non-homogeneous atmospheric absorption model, which took into account the variation of water vapor content with latitude, longitude, and altitude through meteorological data, and the variation of the mixing ratio of other molecules with altitude. In addition, since the latitude and longitude of the satellite and the ground terminal are generally different, the link is not perpendicular to the atmosphere, but traverses the atmosphere obliquely. This needs to be taken into account when calculating the path loss.

In satellite links, the entire atmosphere is usually assumed to be parallel to the Earth's surface. This assumption holds true for stationary or slow-moving satellite links on the ground. This plane assumption makes it difficult to distinguish the effects of different altitudes of the atmosphere when considering the satellite-to-aircraft link, where the aircraft is flying at high speeds and changes in altitude. In [13], a modeling approach for sloping paths through the atmosphere was given. It divided the atmosphere into equally spaced layers, calculated the propagation distance of the aircraft through the different layers separately, and calculated the absorption loss through the different layers at the same time. The THz atmospheric absorption calculated in this method is more accurate.

IV. THz Nano-scale Communication Channel Modeling

The size of THz devices is relatively small compared with that at the low frequency band. Thus, it can be used in nano-scale communication scenarios. The main scenarios of THz nano-scale communications are on-chip wireless communication and in-body or wearable wireless devices.

A. THz on-chip wireless communications

THz wireless networks-on-chip (WiNoC) allows wireless communications between different devices on a chip. The biggest advantage is that it can significantly reduce the direct connection of wires and reduce the chip size. The electromagnetic wave on the chip mainly propagates as surface wave and guided wave. Surface waves are the coupling excitation of electromagnetic waves and collective oscillation waves on the solid surface, such as lattice vibration waves or free electron oscillation waves. Guided waves are electromagnetic waves in which all or most of the electromagnetic energy is confined in a limited cross-section and transmitted in a certain direction. These two modes of electromagnetic wave propagation are highly frequency-selective, so the path loss oscillates periodically in the THz band, with a period corresponding to the frequency of the two adjacent surface wave modes.

TABLE II
PROPAGATION CHANNEL CHARACTERISTICS FOR THZ SPACE COMMUNICATION SCENARIOS.

Scenario	Altitude of satellite	Environmental factors	Channel characteristics
Deep space inter-satellite	>36000 km	Solar activities	Solar wind and solar flares have great impacts on the signal power.
Near-Earth inter-satellite	400–36000 km	Ionosphere	The influence of ionosphere at THz band is weak.
Satellite-to-ground	400–36000 km	Ionosphere and atmosphere	The thickness of the atmosphere needs to be considered.

Due to the huge difference between different chips, the current THz on-chip channel model is mainly a deterministic channel model obtained by full-wave simulation or ray tracing. A complete full-wave on-chip simulation would be very time-consuming. In [14], the authors performed a rigorous analysis of electromagnetic fields using Sommerfeld integrals to characterize WiNoC channels at the THz band. The authors analyzed the WiNoC architecture, chip design, and on-chip transceiver design, and calculated in detail the representation of the electric and magnetic fields of the WiNoC layered structure. In addition, the impact of different chip designs on the THz wireless propagation channels was analyzed and verified by full-wave simulation.

B. THz body-centric nano-scale communications

The THz band is also suitable for biomedical applications, because it passes through biological tissue with little damage, unlike high-frequency radiation. Therefore, the THz band has been widely used in the field of medical imaging. With the development of nano-sensor, THz body-centric nano-scale communications have attracted great research interests. Body-centric nano-scale networks are proposed to provide fast and accurate disease diagnosis and treatment.

In this scenario, the THz link needs to pass through human tissue. In addition to distance-dependent propagation losses, there are also molecular absorption and scattering losses in human tissue. In the calculation of propagation loss, it is necessary to use the effective wavelength in human tissue. The effective wavelength needs to be corrected by the dielectric constant of the propagation environment. Because water molecules absorb THz more seriously, tissues or organs with more water will cause larger attenuation. The loss caused by blood is the largest, followed by skin, and the absorption loss of fat is relatively small. In addition, particles and molecules in the human body also cause the scattering. When the scattered particle diameter is smaller than the wavelength of the propagating electromagnetic wave, the applied electric field induces a dipole in the particle. The oscillation of electric field leads to the oscillation of the induced dipole. The dipole radiates in all directions, which results in Rayleigh scattering. Mie scattering occurs when the particle diameter is approximately the same as the wavelength of the electromagnetic wave. Specular or geometric scattering occurs when the size of object is large compared to the wavelength. In [15], the authors proposed a numerical model of THz loss in the human body. The propagation channel characteristics and channel capacity of different human tissues were calculated and verified through the analytical model.

V. FUTURE RESEARCH CHALLENGES

Although there have been considerable progress in THz propagation channel study, as a promising technology for 6G, many challenges still remain. In this section, we will describe some of these challenges, especially those related to 6G developments.

A. Exploration of more scenarios

In addition to the application scenarios mentioned in this article, THz is expected to play a more important role in the future integrated space-air-ground-sea network. Some applications temporarily limited by current device precision may become new THz scenarios, such as maritime communications, vehicle-to-vehicle, high-speed train, etc. In addition, THz technology can also be combined with other emerging technologies, such as reconfigurable intelligence surface (RIS) and integrated sensing and communication (ISAC). When these technologies are developed at THz band, the corresponding propagation channel characteristics require further study.

B. THz Channel measurements for all scenarios

Due to the limitation of the channel sounder and propagation environment, the channel characteristics analysis of some specific THz scenarios can only be carried out through theoretical analysis. However, measurement data is always an important basis for analyzing channel characteristics. When THz is applied to new scenarios or technologies, channel measurements are the first work to study the channel characteristics.

C. Pervasive THz channel modeling for all scenarios

By comprehensively understanding the channel characteristics of each THz scenario, a unified mathematical framework is established for a pervasive channel model. By adjusting the model parameters, the pervasive THz channel model can include specific channel models as special cases. How to accurately describe channel characteristics of various THz scenarios in a pervasive channel model framework is still a big challenge.

D. Artificial intelligence (AI) based predictive THz channel modeling

With the increase of channel measurement data, the complexity of the channel measurement analysis will greatly increase. By using machine learning algorithms, AI may deeply explore the complex relationship between channel model parameters and statistical properties, in order to find their intrinsic connections. Furthermore, AI can also be used to predict the channel characteristics in the future time and at unknown frequencies.

E. THz radio channel modeling

The 6G THz propagation channel presents significant non-stationarity in space, time, and frequency domains. In addition, the emergence of ultra-massive MIMO, holographic MIMO, RIS, etc., introduces the coupling between wireless propagation channels and antennas. Hence, antennas and propagation channels are inherently considered together in the radio channels. Antennas cannot be separated directly from propagation channels when analyzing the channel characteristics. It is beneficial to the design and actual deployment of 6G THz wireless communication systems from a systematic perspective.

VI. Conclusions

This paper has provided a comprehensive overview of propagation channel characteristics and modeling for existing THz applications. The scenarios have been divided into three types, i.e., ground, space, and nano-scale communications. For ground communications, atmospheric attenuation and propagation mechanisms have been investigated. Then, propagation channel characteristics and modeling of specific scenarios have been summarized. THz space communications have been studied, including deep space, near-Earth space, and satellite-to-ground links. We have also discussed the THz nano-scale on-chip and body-centric communications. Finally, future research challenges have been pointed out.

References

[1] C.-X. Wang, J. Wang, S. Hu, Z. Jiang, J. Tao, and F. Yan, "Key technologies in 6G THz wireless communication systems: A survey," *IEEE Veh. Technol. Mag.*, vol. 16, no. 4, pp. 27–37, Dec. 2021.

[2] C. Han, Y. Wang, Y. Li *et al.*, "Terahertz wireless channels: A holistic survey on measurement, modeling, and analysis," *IEEE Commun. Surveys Tuts.*, early access, doi: 10.1109/COMST.2022.3182539.

[3] K. Guan, H. Yi, D. He, B. Ai and Z. Zhong, "Towards 6G: Paradigm of realistic terahertz channel modeling," *China Commun.*, vol. 18, no. 5, pp. 1–18, May 2021.

[4] K. Tekbiyik, A. R. Ekti, G. K. Kurt, A. Gorcin, and H. Yanikomeroglu, "A holistic investigation of terahertz propagation and channel modeling toward vertical heterogeneous networks," *IEEE Commun. Mag.*, vol. 58, no. 11, pp. 14–20, Nov. 2020.

[5] F. Sheikh *et al.*, "Scattering and roughness analysis of indoor materials at frequencies from 750 GHz to 1.1 THz," *IEEE Trans. Antennas Propag.*, vol. 69, no. 11, pp. 7820–7829, Nov. 2021.

[6] H. Zhao, L. Wei, M. Jarrahi, and G. J. Pottie, "Extending spatial and temporal characterization of indoor wireless channels from 350 to 650 GHz," *IEEE Trans. THz Sci. Technol.*, vol. 9, no. 3, pp. 243–252, May 2019.

[7] Y. Zhang, L. Zhao, and Z. He, "A 3-D hybrid dynamic channel model for indoor THz communications," *China Commun.*, vol. 18, no. 5, pp. 50–65, May 2021.

[8] C. Cheng, S. Sangodoyin, and A Zajić, "THz cluster-based modeling and propagation characterization in a data center environment," *IEEE Access*, vol. 8, pp. 56544–56558, 2020.

[9] D. He, K. Guan, A. Fricke, B. Ai, R. He, Z. Zhong, A. Kasamatsu, I. Hosako, and T. Kürner, "Stochastic channel modeling for kiosk applications in the terahertz band," *IEEE Trans. THz Sci. Technol.*, vol. 7, no. 5, pp. 502–513, Sept. 2017.

[10] K. Guan, D. He, B. Ai, *et al.*, "Channel characterization and capacity analysis for THz communication enabled smart rail mobility," *IEEE Trans. Veh. Technol.*, vol. 70, no. 5, pp. 4065–4080, May 2021.

[11] J. Wang, C.-X. Wang, J. Huang, H. Wang, and X. Gao, "A general 3D space-time-frequency non-stationary THz channel model for 6G ultra massive MIMO wireless communication systems," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 6, pp. 1576–1589, June 2021.

[12] S. Nie and I. F. Akyildiz, "Channel modeling and analysis of inter-small-satellite links in terahertz band space networks," *IEEE Trans. Commun.*, vol. 69, no. 12, pp. 8585–8599, Dec. 2021.

[13] J. Kokkoniemi, J. M. Jornet, V. Petrov, Y. Koucheryavy, and M. Juntti, "Channel modeling and performance analysis of airplane-satellite terahertz band communications," *IEEE Trans. Veh. Technol.*, vol. 70, no. 3, pp. 2047–2061, Mar. 2021.

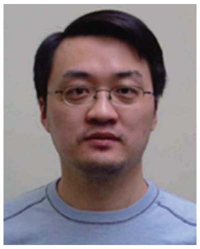
[14] Y. Chen and C. Han, "Channel modeling and characterization for wireless networks-on-chip communications in the millimeter wave and terahertz bands," *IEEE Trans. Mol. Biol. Multi-Scale Commun.*, vol. 5, no. 1, pp. 30–43, Oct. 2019.

[15] K. Yang, A. Pellegrini, M. Munoz, A. Brizzi, A. Alomainy, and Y. Hao, "Numerical analysis and characterization of THz propagation channel for body-centric nano-communications," *IEEE Trans. THz Sci. Technol.*, vol. 5, no. 3, pp. 419–426, May 2015.

Jun Wang (S'20) received the B.E. degree in Information Engineering from Southeast University, China, in 2016. He is currently pursuing the Ph.D. degree in the Nation Mobile Communications Research Laboratory, Southeast University, China. His research interests is THz wireless channel measurements and modeling.

Cheng-Xiang Wang (S'01-M'05-SM'08-F'17) received his Ph.D. degree from Aalborg University, Denmark, in 2004. He joined Heriot-Watt University, Edinburgh, United Kingdom, in 2005 and became a professor in 2011. Since 2018, he has been with Southeast University, China, as a professor and is now the Executive Dean of the School of Information Science and Engineering. He is also a part-time professor with Purple Mountain Laboratories, China. His current research interests include wireless channel measurements/modeling and 6G wireless communication networks. He is a Member of the Academia Europaea, a Member of the European Academy of Sciences and Arts, a Fellow of the Royal Society of Edinburgh, a Fellow of the IET and a Highly Cite Researcher recognized by Clarivate Analytics in 2017–2021.

Jie Huang (M'20) received the B.E. degree in Information Engineering from Xidian University, China, in 2013, and the Ph.D. degree in Communication and Information Systems from Shandong University, China, in 2018. From October 2018 to October 2020, he was a Postdoctoral Research Associate in the National Mobile Communications Research Laboratory, Southeast University, China, supported by the National Postdoctoral Program for Innovative Talents. From January 2019 to February 2020, he was a Postdoctoral Research Associate in Durham University, UK. He is currently an Associate Professor in the National Mobile Communications Research Laboratory, Southeast University, China and also a researcher in Purple Mountain Laboratories, China. His research interests include millimeter wave, THz, massive MIMO, intelligent reflecting surface channel measurements and modeling, wireless big data, and 6G wireless communications.



Yunfei Chen (S'02-M'06-SM'10) received the B.E. and M.E. degrees in electronics engineering from Shanghai Jiao Tong University, Shanghai, China, in 1998 and 2001, respectively, and the Ph.D. degree from the University of Alberta in 2006. He is currently working as an Associate Professor at the University of Warwick, U.K. His research interests include wireless communications, cognitive radios, wireless relaying, and energy harvesting.