Terahertz-Band Near-Space Communications: From a Physical-Layer Perspective

Tianqi Mao, Leyi Zhang, Zhenyu Xiao, Zhu Han, and Xiang-Gen Xia

ABSTRACT

Facilitated by the rapid technological development of near-space platform stations, near-space communication (NS-COM) is envisioned to play a pivotal role in the space-air-ground integrated network (SAGIN) for the sixth generation (6G) communications and beyond. In NS-COM, ultra-broadband wireless connectivities between NSPSs and various airborne/spaceborne platforms are required for a plethora of bandwidth-consuming applications, such as NSPS-based ad hoc networking, in-flight Internet, and relaying technology. However, such requirements seem to contradict the scarcity of spectrum resources at conventional microwave frequencies, which motivates the exploitation of terahertz (THz) band ranging from 0.1 to 10 THz. Due to huge available bandwidth, THz signals are capable of supporting ultra-high-rate data transmission for NS-COM over 100 Gb/s, which are naturally suitable for the near-space environment with marginal path loss. Against this background, this article provides an extensive investigation on THz-band NS-COM (THz-NS-COM) from a physical-layer perspective. First, we summarize the potential applications of THz communications in the near-space environment, where the corresponding technical barriers are analyzed. Second, the channel characteristics of THz-NS-COM and the corresponding modeling strategies are discussed. Third, three essential research directions are investigated to surpass the technical challenges of THz-NS-COM: robust beamforming for ultra-massive antenna array, signal-processing algorithms against hybrid distortions, and integrated sensing and communications. Several open problems are also provided to unleash the full potential of THz-NS-COM.

INTRODUCTION

Near space, ranging from 20 to 100 km in altitude, is considered as the last piece of the puzzle in the sixth-generation (6G) space-air-ground integrated network architecture [1]. In recent years, the exploitation of near space has been greatly accelerated by the technical breakthrough of near-space platform stations (NSPSs) consisting of near-space airships and balloons. Representative progress includes X-Station by StratXX [2] and Loon Project by Google [3]. StratXX managed to realize mature airship products at 21 km above the ground with super-light and super-strength materials, which enables high-speed data services with broad coverage of 106 km2. On the other hand, in the Loon Project, thousands of commercial near-space balloons equipped with advanced transceiving devices were deployed into the stratosphere for over 300 days’ flight, constituting an ad hoc network to ensure coverage of reliable Internet access for rural/disaster regions. Thanks to these advancements, the near-space communication (NS-COM) network is established to provide wireless connectivities between NSPS constellations and terrestrial/aerial/space platforms.

For future 6G applications, NS-COM is expected to provide broadband Internet services to billions of terrestrial and aerial users with ubiquitous coverage [4], which necessitates ultra-fast and ultra-reliable data transmission over extremely long distance, namely, over 100 km for inter-NSPS and NSPS-satellite links. Such requirements cannot be satisfied with traditional microwave frequencies due to scarcity of available spectrum resources and limited antenna gains. Fortunately, the terahertz (THz) band (0.1–10 THz) has emerged as a promising choice for 6G networks and beyond [5], which can readily attain data transmission over 100 Gb/s with ultra-broad available bandwidth. Due to sparsity of the atmosphere in the stratosphere and above, THz signals experience much less molecular absorption loss in near space than its terrestrial counterpart, thus enabling data transfer over long distances at sufficiently high altitudes, namely, inter-NSPS and NSPS-airplane/satellite links. Furthermore, thanks to the ultra-short wavelength of THz signals, ultra-massive antenna array is enabled to provide sufficient beamforming gain with compact sizes, which can support long-range directional transmission of NSPS under room limitations for communication payloads. Aside from communications, the THz spectrum also presents its superiority in sensing applications, where high resolution of range and velocity estimation can be achieved with ultra-broad signal bandwidth and THz-scale center frequency. This realizes a number of integrated sensing and communication (ISAC) applications of NSPSs (e.g., positioning/monitoring and Internet services for civil aircraft, or reconnaissance for military purposes). Table 1 compares NS-COM systems at different frequencies including sub-6 GHz, millimeter-wave (mmWave), free-space optical, and THz frequencies. It can be seen that...
Despite its attractive merits, practical implementation of THz-NS-COM is facing a plethora of new technical challenges. First, the channel modeling for NS-COM data links can be complicated due to the inconsistent property of the near-space atmosphere at different altitudes, which becomes even harder by involving the random movement/rotation of NSPSs by wind effects. These make the existing channel models for space/air/ground scenarios no longer applicable for THz-NS-COM. For instance, the channel models for satellite-airplane links can hardly be compatible with the NSPS-airplane counterpart due to the lower but more stochastic mobility of NSPS than satellite nodes. Second, the“razor-sharp” beams of THz-NS-COM systems pose great difficulty to antenna alignment, leading to degradation of the array gains, especially when communicating with airplanes/satellites of high mobility. Such array gains can be further deteriorated by the delay-beam squint effects originating from the huge communication bandwidth of THz-NS-COM [6]. Third, THz-NS-COM systems suffer from severe hardware impairment at NSPS front-ends, which couples with the time-frequency doubly-selective channel fading, constituting deleterious nonlinear distortions on the THz signals. Finally, despite the promising prospects of ISAC, the use of ultra-broad THz spectrum causes a serious expenditure issue of transceiver devices. Besides, the extremely high center frequency at THz scale exacerbates the Doppler shift effects, causing performance degradation of target sensing. At present, there have been limited research efforts on the THz-NS-COM framework [6, 7]. More specifically, the channel modeling issue was investigated for inter-NSPS links at the altitude of 16 km, where desirable frequency subbands were determined according to distance-adaptive frequency selectivity of the wide-band channel and colored molecular absorption noise [7]. Additionally, [6] proposed a sophisticated channel estimation and tracking design for THz-band NSPS-to-airplane links, under triple delay-beam-Doppler squint effects originated from the inherent properties of THz waves.

In this article, the great potential and technical barriers of THz-NS-COM are extensively investigated, and some useful guidelines are provided to overcome the challenges yet to be conquered. The main contributions of this article are summarized as below:

- The characteristics of THz propagation channels in the near-space environment are revealed, and different strategies of channel modeling are evaluated for THz-NS-COM.
- We discuss three potential technologies to deal with the aforementioned challenges in THz-NS-COM. Specifically, the beamforming issue is explored under mobility of the transceiving platforms and the squint effects induced by THz-band antenna arrays. Possible solutions to the hybrid distortions caused by hardware imperfections and doubly-dispersive channel are then discussed from the signal processing perspective. Further, we

The main contributions of this article are summarized, and some useful guidelines are provided to overcome the challenges yet to be conquered.
investigate the ISAC design of THz-NS-COM under considerations of hardware cost and robustness to the strong Doppler shifts.

- Several open problems corresponding to the implementation of THz-NS-COM.

Channel Characteristics of THz-NS-COM:
In the terrestrial propagation environment, THz signals suffer from severe spreading loss and molecular absorption loss than the lower-frequency counterparts. For THz-NS-COM, on one hand, the spreading loss issue also poses significant difficulty to long-range transmission approaching hundreds of kilometers, which necessitates sufficiently high antenna gains at the transceiver. Luckily, this requirement can be realized by establishing highly directional beams with ultra-massive THz antenna array. Nevertheless, the utilization of “razor sharp” beams brings more stringent requirements on the antenna alignment accuracy at the same time. This leads to non-negligible antenna misalignment fading even for slight rotation or flutter of the NSPS, not to mention the airplane/satellite nodes with higher mobility. Furthermore, the inhomogeneous propagation environment of THz-NS-COM results in changing refractivity with respect to the altitude, which causes undesirable refraction during THz signal propagation, adding more difficulty in transceiving beam alignment.

On the other hand, although the atmospheric sparsity leads to marginal molecular absorption effects under inter-NSPS and NSPS-satellite scenarios, it cannot be overlooked for NSPS-airplane data links near the bottom of the stratosphere, where the density of water vapor is relatively higher than the upper region of near space. This induces additional frequency selectivity to the propagation channel between NSPS and aerial platforms [9], which cannot be neglected for sufficiently large communication bandwidth. Also note that the traditional terrestrial modeling for molecular absorption loss based on homogeneous assumption of the transmission medium is no longer valid for THz-NS-COM due to inhomogeneity of the high-altitude atmosphere, as stated above [10]. Hence, mathematical modeling of molecular absorption loss needs substantial modification, which should be a function of transmission distance, center frequency, and the atmospheric temperature and pressure curves across different altitudes. Aside from signal attenuation, the molecular absorption phenomenon also generates colored noise components, termed molecular absorption noise, which originates from black-body radiation of the atmosphere. The characteristics of such ambient noise depend on the resonant frequencies of different types of atmospheric molecules, which can be modeled by the antenna brightness temperature following the Rayleigh-Jeans law or Planck’s law [10].

Propagation Environment of THz-NS-COM:
As shown in Fig. 2, the near-space region includes most of the stratosphere, the mesosphere, and a fraction of the ionosphere, where the constituent, temperature, and pressure of the atmosphere present inhomogeneous peculiarities at various altitudes. More specifically, the ozone gas, with the superior capability of ultra-violet radiation absorption, is generally distributed in the lower stratosphere. This phenomenon further causes a non-monotonic changing pattern of the atmospheric temperature at the bottom of the stratosphere, which declines to almost -60°C at the altitude of 20 km due to the absorption effects of the ozone layer, while approaching 0°C at 50 km above the ground. Furthermore, despite the extremely low atmospheric pressure in most of near space, its variations near the bottom of stratosphere are non-negligible for channel modeling of the NSPS-airplane links. Additionally, unlike the space environment, the wind effects cannot be overlooked in near space, which cause random movement/rotation of the NSPS, leading to additional difficulty in antenna misalignment. To conclude, the complex propagation environment of THz-NS-COM makes its channel model quite different from its space/air/ground counterparts.

Channel Modeling for THz-NS-COM:
Traditional channel modeling strategies for THz communications can be classified into deterministic and stochastic methods [9]. On one hand, the deterministic strategies are dependent on the knowledge of properties of the transmission medium, geometrical information of the propagation environment, the positions as well as relative
velocities of the transceiver nodes, and so on. Despite its superior accuracy on channel modeling, it is challenging to obtain the aforementioned knowledge, especially for the complicated propagation environment of THz-NS-COM. Furthermore, the deterministic methods usually suffer from high computational overhead, which may be impractical for NSPS-mounted payloads with limited size, weight, and power consumption.

On the other hand, the stochastic methods only utilize the empirical channel measurements for channel modeling, which are featured by the geometry-based stochastic channel model (GBSM) widely employed for standard propagation modeling, for example, 3rd Generation Partnership Project (3GPP) Technical Reports. Since detailed knowledge of the propagation environment is no longer required for stochastic methods, the computational complexity can be eliminated, which, however, induces additional channel modeling errors. Artificial intelligence (AI) has been introduced recently to physical-layer design, such as demodulation and channel estimation. The AI-based receiving strategy can overcome different obstacles that may be intractable for classical mathematical receivers, namely complex propagation environment and severe nonlinear distortions in THz-NS-COM data links [5]. Inspired by this concept, the artificial neural network is also expected to support channel modeling of THz-NS-COM in the near future. For instance, the generative adversarial network (GAN) architecture can be invoked to enlarge the training set of channel measurement data. The massive amount of training data is further exploited by a convolutional neural network for channel modeling, which can implicitly characterize a plethora of factors in the propagation environment of THz-NS-COM, such as altitude/distance-dependence and frequency selectivity of the path loss, the mobility of transceiver terminals, and resultant antenna misalignment fading.

**Robust Beamforming for UM-MIMO**

**Challenges and Key Techniques**

THz-NS-COM is required to support long-range data links over 100 km, which necessitates highly directional transmission with a sufficiently large antenna gain. Although the cumbersome parabolic antennas are inapplicable for NSPSs with limited payload budget, utilization of the THz frequencies can readily enable ultra-massive antenna arrays to achieve superior beamforming gain with a compact size. Nevertheless, the ultra-massive multiple-input multiple-output (UM-MIMO) system for THz-NS-COM suffers from inevitable delay-beam squint effects [6], as illustrated in Fig. 3a. Specifically, when the direction of incoming signals is non-perpendicular to the antenna array, different propagation delays of the received signals can be witnessed at various receive (Rx) antennas. Due to extremely high-rate sampling for ultra-broadband THz transmission, the resultant delay gap between antennas can approach several symbol periods, yielding non-negligible inter-symbol interference (ISI). This phenomenon is referred to as the delay squint effect. Furthermore, the phase shifters for classical analog beamforming are designed based on the center frequency of the consumed bandwidth, which leads to severe beam split effects (beam squint effects) for THz UM-MIMO with ultra-broad bandwidth. This is because the frequency-independent analog precoder is not aligned with most subcarriers within the employed spectrum, resulting in severe degradation of beamforming gain. To adddress these technical challenges, a true-time delay unit module was implemented before the analog beamformer against the delay-beam squint effects [6], as presented in Fig. 3b. Explicitly, by inducing specially designed propagation delays to different transmit (TX) antennas, the true-time delay units are capable of counteracting the delay squint effect, and realizing a frequency-dependent phase-shifter network to ensure desirable beam directions across the overall communication bandwidth.

Aside from the delay-beam squint effects, the antenna misalignment issue cannot be overlooked in THz-NS-COM. Due to the use of highly directional beams over ultra-long-range transmission, even a slight position/orientation change of the NSPS terminals can result in severe beam misalignment fading, not to mention the civil aircraft or satellite nodes. Furthermore, unlike the aerial/satellite communication networks, where the flight trajectories of transceiving platforms usually follow predetermined routes, the mobility of NSPS nodes (especially for balloons) is irregular due to elusive wind effects. This makes the beam tracking for THz-NS-COM even more challenging. To address this issue, the beam split effects can be cleverly exploited for fast beam training. Explicitly, the coverage of split beams can be flexibly adjusted by true-time delay units to include the spatial directions of the NSPS nodes, which allows beam tracking of multiple spatial directions of transceiver terminals in each time slot, thus accelerating the beam training process. For more details, readers can refer to [11, references therein].

**Open Issues**

**Beam Tracking under Scattering and Refraction Effects:** In comparison with lower frequencies, THz signal transmission with ultra-short wavelength suffers from more severe scattering and refraction effects [5], which originate from the existence of aerosol particles and the inhomogeneous atmospheric medium. Despite the
sparsity of atmosphere in the near-space environment, the scattering and refraction effects can be significantly accumulated along the ultra-long transmission distance, which cause non-negligible deviations of the beam directions. Therefore, angular modifications of the transceiver beams are required during beam tracking to counteract the bending effects based on the properties of the propagation environment, such as atmospheric temperature, pressure, and constituents at different altitudes and latitudes.

UM-MIMO with NSPS-Mounted Reconfigurable Intelligent Surface (RIS): THz-band UM-MIMO systems tend to require numerous radio frequency (RF) chains and a complex feeding network for analog beamforming. This results in high hardware overhead and energy consumption, which contradict the limited budget for the NSPS-mounted communication payloads. To this end, the RIS, a passive meta-surface composed of numerous programmable metallic elements, can be employed for replacing the classical phased array antennas. By emitting THz electromagnetic waves onto the RIS through irradiation and adjusting the reflecting coefficients of RIS elements, an RF-chain-free data transmission with analog beamforming can be realized without the need of feeding network. Nevertheless, such a RIS-assisted transmitter suffers from limited amplitude adjustment of the reflecting coefficients of RIS elements. This adds great difficulties in realizing quadrature amplitude modulation (QAM), causing performance loss at high spectral efficiency. Furthermore, the discrete rotated phases of RIS elements in practice inevitably degrades the analog beamforming, which demands careful investigation to meet the stringent requirement of beam alignment in THz-NS-COM.

Despite its capability of attaining ultra-broadband data transmission, the THz spectrum has often been recognized as the “THz gap” due to the immature transceiving technology between classical microwave and infrared frequencies. This causes severe hardware imperfections, including phase noise, in-phase/quadrature (I/Q) imbalance, nonlinearity of the power amplifier and frequency multiplier, and more, as illustrated in Fig. 4. Unlike the lower-frequency counterparts, the hardware imperfections of the THz front-ends present wideband characteristics due to the ultra-broad bandwidth, including frequency selectivity of I/Q imbalance, possible inter-carrier interference (ICI) caused by the higher-frequency components of the phase noise, and memory effects of device nonlinearity. Furthermore, the NSPS-mounted transceivers tend to employ the direct-conversion architecture to reduce the implementation cost, which, however, is especially sensitive to hardware impairment. To tackle this problem, existing parameter estimation and compensation techniques for terrestrial THz communications can also be employed to the NSPS-mounted transceiver. Specifically, at the transmitter, the Tx I/Q imbalance and nonlinearity of the power amplifier must be jointly estimated before pre-compensation, which is a non-convex problem due to the complicated distortion model and high coupling of the hardware imperfection parameters. To circumvent this obstacle, these parameters can be estimated via sophisticated alternating iterative methods. At the receiver, a multi-stage post-processing algorithm [12] can be invoked to eliminate the remaining Rx I/Q imbalance and transceiver phase noise: a) Estimating the equivalent channel of physical channel and I/Q imbalance via extended Kalman filtering

b) Decoupling the I/Q imbalance and physical channel by solving a blind deconvolution problem

c) Equalizing/compensating for the I/Q imbalance, physical channel, and phase noise subsequently

Aside from the hardware impairment, the propagation channel of THz-NS-COM suffers from non-negligible frequency selectivity and strong Doppler shift effects, resulting from extremely high operating frequency and drastic mobility of the user terminals (e.g., civil aircraft, fighter planes, and satellites). Consequently, a complex time-frequency doubly-dispersive channel is constituted, which becomes even more complicated by incorporating the frequency-selective property of Doppler shifts due to huge communication bandwidth, referred to as Doppler squint effects. These factors pose additional difficulties to the aforementioned channel estimation, decoupling, and equalization phases. The orthogonal time-frequency space (OTFS) philosophy may help to address this issue. To be more specific, the data symbols are modulated in the delay-Doppler domain to obtain better resilience against Doppler shifts. Moreover, additional channel sparsity can
be attained by converting the time-frequency channel to the delay-Doppler domain, which may further simplify the operations from a) to c) in the previous paragraph. Regarding the noise components, compared to most terrestrial receiving terminals where thermal noise is dominant, the quantum noise, originated from the uncertainty principle, may not be overlooked in the THz-NS-COM system when operating at extremely low-temperature and THz-scale frequencies. This quantum noise, together with the thermal noise and colored molecular absorption noise, may cause considerable difficulty in signal detection at the NSPS, which motivates advanced signal processing techniques against these complex hybrid noise effects. For instance, the generalized Anscombe transform can be applied to process the mixed Poisson-distributed shot noise and Gaussian thermal noise to generate an equivalent additive white Gaussian noise (AWGN) channel. Also, noise whitening techniques might be feasible to deal with the colored noise components.

Open Issues

Low-Complexity Transceiver Design: Existing compensation schemes for wideband hardware imperfections suffer from extremely high computational complexity. This motivates low-complexity transceiver design for THz-NS-COM to alleviate the burdens of NSPS-mounted communication payloads. In the existing literature, the narrowband hardware imperfections are approximately modeled as additive noise components based on the Bussgang Theorem for complexity reduction of transceivers processing, which requires further investigation by considering the wideband I/Q imbalance and nonlinearity of the power amplifier.

Optoelectronic Transceivers for THz-NS-COM: In classical electronic THz communication systems, frequency multipliers are required for generation of the THz-band carriers from lower frequencies, which induce additional nonlinearity from the multiplier chain. Alternatively, we can circumvent the use of nonlinear frequency multipliers by invoking optoelectronic methods for THz-frequency generation based on a direct modulation scheme using quantum cascade lasers (QCLs) or the heterodyne scheme using a uni-traveling carrier photodiode (UTC-PD) photomixer [13]. Furthermore, the optoelectronic THz communication system suffers from marginal phase noise due to the extremely narrow linewidth of the laser signals. Nevertheless, current optoelectronic methods mainly rely on bulky front-end devices, which are still unsuitable for NSPS applications with limited communication payload carrying capability, thus necessitating compact chip-based design of the optoelectronic THz transceiver.

Integrated Design of Sensing and Communications

Concepts and Key Techniques

Aside from broadband data transmission, the THz signal is also capable of target sensing with superior resolution of ranging and velocity estimation, attributed to its ultra-wide bandwidth and THz-scale carrier frequency, respectively. Since the path loss is substantially higher in the near-space propagation environment than its terrestrial counterpart, THz frequencies can realize accurate radar sensing over 100 km. The detection range can be further extended by the use of UM-MIMO with highly directional beamforming, which also supports simultaneous sensing at various directions by generating multiple TX beams. Therefore, the NSPS-mounted THz radar can enable numerous military/civilian applications (e.g., reconnaissance, navigation, and positioning). To satisfy the constraint on the size of NSPS-mounted payloads, the sensing and communication subsystems can be fused together by sharing the same hardware platform set. For signal transmission, one straightforward way is to design different waveforms for the sensing and communication subsystems, respectively, both following a time-division duplex (TDD) working mode. However, sometimes we require concurrent operation of data transmission and radar sensing, which can be realized by integrated waveform design for the dual functions. Despite the randomness of the communication signals, orthogonal frequency-division multiplexing (OFDM) can attain perfect auto-correlation property by employing constant-amplitude modulation formats, making it suitable for radar sensing [14]. However, the implementation of OFDM inevitably induces the complex transceiver structure and extra power backoff of the power amplifier due to high peak-to-average-power ratio (PAPR), which is especially undesirable for NSPS-mounted THz front-ends. To tackle this issue, a multi-subband waveform for joint radar and communications can be developed based on the philosophy of distributed single-carrier frequency-division multiple access (SC-FDMA) [15]. Specifically, the overall spectrum is divided with multiple non-overlapped subbands, where a radar sequence with perfect correlation property and the data symbol components are modulated at non-intersecting frequency points. By this arrangement, the ISAC waveform ensures broadband communications without mutual interference, and at the same time can inherit good correlation property from the radar component, since the radar and data components are approximately orthogonal. Besides, only several narrowband analog-to-digital converters (ADCs) are required for sampling instead of full-band ADCs, thus reducing the expenditure of NSPS-mounted communication payloads. Additionally, to reduce the PAPR, optimized phase shifts can be imposed on each subband of the ISAC waveform without destroying the correlation property of the radar components [15].

Despite the low mobility of NSPS, the THz-scale center frequency and high speed of the aerial user terminals contribute to pronounced Doppler shift, which degrades the sensing performance. To be more specific, additional dominant range sidelobes can be induced by strong Doppler shifts, leading to a higher false alarm rate and reduced peak-to-side-lobe level of the radar range profile. To address this issue, differential encoding can be invoked to counteract the Doppler shift effects by multiplications between a received sample and the conjugate of its neighboring one. However, this method becomes invalid at low signal-to-noise ratios (SNRs) attributed to amplification of the noise components. Alternatively, the waveform parameters are specially designed to adjust the positions of dominant range sidelobes based on number theory, which eliminates possible false alarms by moving these side lobes outside the region of interest.
Open Issues

Collaborations of Sensing and Communications: Instead of treating each other as interferences, the performance of THz-NS-COM can be enhanced by collaborations of both functions. Specifically, THz-NS-COM systems are especially prone to beam misalignment fading due to the “razor sharp” beam shape and unpredictable mobility of NSPS terminals. To alleviate this issue, the THz radar detection results with ultra-high resolution can be utilized to assist existing beam alignment strategies for higher accuracy and time efficiency, which requires in-depth research in the future.

Electromagnetic Compatibility (EMC) Issue: As shown in Fig. 5, numerous sensing-related missions can be realized by extra NSPS-mounted radars/sensors aside from the ISAC payload, such as pollution monitoring, scientific observation, and military reconnaissance. The aforementioned tasks rely on different pivotal technologies like synthetic aperture radar (SAR) imaging and molecular line spectroscopy, which attain superior performance when operating at THz frequencies. By such arrangement, it will be essential to consider the EMC issue between the ISAC devices of THz-NS-COM and other THz-band instruments, in order to suppress possible mutual interference between different sensing applications of NSPS.

Conclusion

In this article, the novel THz-NS-COM philosophy is investigated from the physical-layer perspective. Specifically, the prospects of THz-NS-COM are envisioned by highlighting its attractive merits, such as capabilities of realizing ultra-broadband long-range communications and superior ISAC performance. However, THz-NS-COM is still facing significant challenges for its practical implementation. To provide some guidelines for research on THz-NS-COM, the characteristics of the propagation channel and its modeling methods are first discussed. Afterward, the technical barriers and potential technologies of THz-NS-COM are specified from three aspects of beamforming for UM-MIMO, transceiver signal processing against hybrid distortions, and ISAC applications. Meanwhile, the corresponding open issues are also provided for future investigation.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China (NSFC) under grant numbers 62171010, U22A2007 and 61827901, in part by the Beijing Natural Science Foundation under grant number L212003, and in part by the Postdoctoral Science Foundation of China under grant number 2022M720361.

References

[1] M. C. Ozdemir, “Conceptual Changes by Use of Near Space,” Proc. IEEE/AIAA 32nd Digital Avionics Systems Conf., East Syracuse, NY, Oct. 2013, pp. 3E1–3E10.
[2] G. K. Kurt et al., “A Vision and Framework for the High Altitude Platform Station (HAPS) Networks of the Future,” IEEE Commun. Surveys & Tutorials, vol. 23, no. 2, 2nd qtr. 2021, pp. 729–79.
[3] Loon: Expanding Internet Connectivity with Stratospheric Balloons v1, https://x.company/projects/loon/, accessed Mar. 10, 2022.
[4] G. K. Kurt et al., “A Vision and Framework for the High Altitude Platform Station (HAPS) Networks of the Future,” IEEE Commun. Surveys & Tutorials, vol. 23, no. 2, 2nd qtr. 2021, pp. 729–79.
[5] Z. Chen et al., “Terahertz Wireless Communications for 2030 and Beyond: A Cutting-Edge Frontier,” IEEE Commun. Mag., vol. 59, no. 11, Nov. 2021, pp. 66–72.
[6] A. Liao et al., “Terahertz Ultra-Massive MIMO-Based Aeronautical Communications in Space-Air-Ground Integrated Networks,” IEEE ISAC, vol. 39, no. 6, June 2021, pp. 1741–67.
[7] A. Saeed et al., “Variable-Bandwidth Model and Capacity Analysis for Aerial Communications in the Terahertz Band,” IEEE ISAC, vol. 39, no. 6, June 2021, pp. 1768–84.
[8] Layers of Earth’s Atmosphere: https://www.britannica.com/science/atmosphere/Troposphere/2/media/1/41164/99826, accessed Mar. 24, 2022.
[9] C. Han and Y. Chen, “Propagation Modeling for Wireless Communications in the Terahertz Band,” IEEE Commun. Mag., vol. 56, no. 6, June 2018, pp. 96–101.
[10] J. Kokkoniemi et al., “Channel Modeling and Performance Analysis of Airplane-Satellite Terahertz Band Communications,” IEEE Trans. Vehic. Tech., vol. 70, no. 3, Mar. 2021, pp. 2047–61.
[11] J. Tan and L. Dai, “Wideband Beam Tracking in THz Massive MIMO Systems,” IEEE JSAC, vol. 39, no. 6, June 2021, pp. 1693–1710.
[12] Z. Sha and Z. Wang, “Channel Estimation and Equalization for Terahertz Receiver with RF Impairments,” IEEE JSAC, vol. 39, no. 6, June 2021, pp. 1621–35.
[13] L. Zhang et al., “Beyond 100 Gb/s Optoelectronic Terahertz Communications: Key Technologies and Directions,” IEEE Commun. Mag., vol. 58, no. 11, Nov. 2020, pp. 34–40.
[14] X.-G. Xia, T. Zhang, and L. Kong, “MIMO OFDM Radar IROI Free Range Reconstruction with Sufficient Cyclic Prefix,” IEEE Trans. Aerospace Electron. Syst., vol. 51, no. 3, July 2015, pp. 2276–93.
[15] T. Mao et al., “Waveform Design for Joint Sensing and Communications in Millimeter-Wave and Low Terahertz Bands,” IEEE Trans. Commun., to appear.

Biographies

Tianqi Mao (maotq@buaa.edu.cn) is a research fellow in the School of Electronic and Information Engineering, Beihang University, China.

Lei Yi is currently pursuing a Master’s degree in the School of Electronic and Information Engineering, Beihang University.

Zhenyu Xiao is a professor in the School of Electronic and Information Engineering, Beihang University.

Zhiyu Han is a John and Rebecca Moores Professor in the Electrical and Computer Engineering Department and the Computer Science Department, University of Houston, Texas.

Xiang-Gen Xia is the Charles Black Evans Professor in the Department of Electrical and Computer Engineering, University of Delaware.