Guest Editorial
Advanced Signal Processing for Terahertz Communications in 6G and Beyond Networks

I. Introduction

TERAHERTZ (THz) communications has been envisioned as an enabling and highly promising technology for the sixth generation (6G) and beyond wireless networks which aim to provide full and unlimited wireless connectivity for the ubiquitous intelligent information society of 2030 and beyond. In particular, the ultra-wide THz band from 0.1 to 10 THz offers enormous potential to alleviate the spectrum scarcity and break the capacity limitation of emerging wireless systems, such as the fifth generation (5G) wireless networks. This will undoubtedly support epoch-making wireless applications that demand ultra-high quality of service requirements and multi-terabits/s data transmission in the 6G and beyond era, such as holographic communications, immersive extended reality, ultra-fast backhaul and wireless local area networks, and wireless high-bandwidth secure transmission. Moreover, THz transceivers and antennas boast an incredibly compact size, reaching sub-millimetric dimensions. This miniaturization enables the seamless integration of extremely small radios into various environments, giving rise to ground-breaking applications, e.g., the Internet of Nano-Things and wireless networks-on-chip. Furthermore, the utilization of the THz band extends beyond traditional radar and localization, opening doors to novel wireless sensing capabilities and underpinning cutting-edge applications such as healthcare nano-bio-sensing. Due to the aforementioned advantages, an unprecedented amount of spectrum within the 0.275–0.45 THz band was opened for land mobile and fixed service in 6G after World Radio Conference 2019. Additionally, the IEEE 802.15.3d standard has been established as the first wireless standard in the sub-THz band (specifically, 253–322 GHz) to support data rates of 100 gigabit/s and above.

Despite the numerous advantages, the design and implementation of signal processing algorithms in THz communications present a multitude of critical and pressing challenges that need to be tackled, such as channel modeling and estimation, physical layer transmission and reception development, and performance analysis and verification. This special issue (SI) of the IEEE Journal of Selected Topics in Signal Processing aims to present the most recent research contributions to advanced signal processing in THz communications, with the focus lying on theoretical development, algorithmic design, and potential applications. In the following, we provide a summary of the articles included in the present SI.

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II. Summary of the Papers in This SI

Channel modeling and measurement play an enabling role for signal processing in the THz band. To fulfill this role, accurate THz channel models need to be established. To meet this need, three papers build up new THz channel models.

The paper [1], entitled "Full-Wave Simulation and Scattering Modeling for Terahertz Communications", presents the modeling of scattering phenomenon of THz waves bouncing on rough surfaces. Specifically, the authors propose a generic parametric methodology to accurately model the rough characteristics based on the root-mean-square height and correlation length of a surface. Also, the authors obtain the statistical characteristics of the phase and polarization and compare them with those in the existing 3GPP channel model standards. It is shown that the phases follow the normal distribution and the cross-polarization ratios follow the logistic distribution, which stands as an important discovery that may influence the standardization activities of 3GPP working groups.

The paper [2], entitled "Virtual Antenna Array for W-band Channel Sounding: Design, Implementation and Experimental Validation", designs and validates a phase-compensated vector network analyzer based channel sounder at the W-band (75–110 GHz). To examine the practicality of the channel sounder, the authors consider both near-field and long-range propagation and apply a high-resolution channel parameter estimator to extract the multi-path parameters for the large-scale virtual antenna array, composing of both the omnidirectional antenna and the directive antenna. Finally, the directional scanning scheme measurement and the ultra-wideband channel measurement are adopted to evaluate the effectiveness and robustness of the channel sounder.

The paper [3], entitled "Comparative Analysis of Terahertz Propagation Under Dust Storm Conditions on Mars and Earth", develops a Monte Carlo simulation procedure for estimating the link attenuation due to multiple scattering by charged dust particles on the THz beam propagation path. Specifically, scattering models are developed for beams through dust, based on Mie and Rayleigh approximations for corresponding frequencies on Earth (0.24 THz) and Mars (0.24 & 1.64 THz). Simulation results are presented to examine the impact of key parameters, e.g., the number of Monte-Carlo photon packets, visibility, dust particle placement density along the beam, frequency, and transmitter-receiver distance.

Efficient signal processing, such as channel estimation, provides huge potential to support ultra-high-quality THz transmission. To unlock this potential, two papers investigate channel estimation in THz communication systems.

The paper [4], entitled "An Adaptive and Robust Deep Learning Framework for THz Ultra-Massive MIMO Channel Estimation", proposes a general deep learning (DL) framework to realize effective channel estimation in THz ultra-massive multiple-input multiple-output (UM-MIMO) systems. The proposed DL-enabled channel estimation method addresses the challenges brought by the hybrid of far-field and near-field THz channels, while achieving low and adaptive complexity as well as strong robustness against practical distribution shifts. Using theoretical analysis and simulation results, the authors illustrate the advantages of the proposed method over the state-of-the-art methods in terms of estimation accuracy, convergence rate, complexity, and robustness.

The paper [5], entitled "Low-Rank Matrix Sensing-Based Channel Estimation for mmWave and THz Hybrid MIMO Systems", addresses the channel estimation problem for wideband MIMO systems operating in the millimeter-wave (mmWave) and/or THz bands. Particularly, the authors formulate the channel estimation problem as a low-rank matrix sensing (LRMS) problem. Then, they solve it using a generalized conditional gradient-alternating minimization algorithm which accommodates different precoder/combiner structures and does not need the knowledge of array responses at transceivers. They further devise techniques to enhance the performance of LRMS channel estimators using partial or full knowledge of the array responses. The high channel estimation accuracy and low complexity achieved by the proposed solutions are finally demonstrated via simulations.

One important issue for fully harnessing the benefits of the THz band is to optimally use the abundant frequency spectrum in this band. To address this issue, three papers explore THz spectrum usage to satisfy various performance requirements.

The paper [6], entitled "Adapt and Aggregate: Adaptive OFDM Numerology and Carrier Aggregation for High Data Rate Terahertz Communications", proposes a dynamic orthogonal frequency division multiplexing (OFDM) numerology adaptation mechanism to maximize the data rate in THz communication systems. In this mechanism, the component carrier (CC) bandwidth of a single OFDM waveform is changed, and the data rate for each CC is evaluated considering the effect of hardware impairments and wireless channel statistics. To fully use the available frequency resource, the authors adopt dynamic distance-aware CC allocation and maximize the aggregated data rate through CC aggregation. The improved data rate brought the proposed mechanism is finally examined through simulation results.

The paper [7], entitled "Simultaneous Terahertz Imaging with Information and Power Transfer (STIIPT)", uses the THz band to meet communication and non-communication demands of wireless systems and presents an insightful approach – simultaneous THz imaging with information and power transfer (STIIPT). Considering a THz system from a base station to an integrated receiver (IntRx), where the nonlinear rectenna model is adopted for energy harvesting, the authors design customized on-off keying (cOOK) modulation for communication while generating a radar-like image to localize the IntRx. Aided by simulations using a THz band GaAs Schottky diode, the performance of STIIPT is demonstrated and the role of ranging information to optimize the rate-energy transfer tradeoff is examined.

The paper [8], entitled "Radio SLAM for 6G Systems at THz Frequencies: Design and Experimental Validation", uses radio simultaneous localization and mapping (R-SLAM) algorithms, derived from image processing, to map the environment and pinpoint device position in the map starting from measurements sensed by a mobile THz radar. To fully understand THz backscattering, the authors carry out an experimental characterization of the THz backscattering channel in indoor environment. The authors further assess the performance of the R-SLAM algorithms using real-world THz radar measurements and compared it with other SLAM techniques, showing the superiority of the R-SLAM algorithms.

To meet the wide range of performance requirements of 6G networks, THz communications is anticipated to be jointly used with other 6G-enabling technologies. Against this background, four papers concentrate on the use of THz communications and reconfigurable intelligent surface (RIS).

The paper [9], entitled "Analytical Characterization of RIS-aided Terahertz Links in the Presence of Beam Misalignment", analyzes the impact of beam misalignment on the performance of RIS-aided THz communication systems, by evaluating two regimes, namely, misalignment occurs (i) on the steering plane and (ii) normally to the steering plane. Through the analysis and numerical evaluation of the signal-to-noise ratio distribution, the authors find the distinction in the stochastic behavior of misalignment in the two regimes. The analytical results in this paper can be used as insightful tools for assessing the stochastic performance impacted by key parameters, including the transmitter beam width, transmitter-RIS and RIS-receiver distances, and steering angle of the RIS.

The paper [10], entitled "Simultaneously Transmitting and Reflecting Surface (STARS) for Terahertz Communications", proposes a novel paradigm, named simultaneously transmitting and reflecting surface (STARS) aided THz communications, and establishes a power consumption model based on the type and resolution of STARS elements. Considering both narrowband and wideband THz communications, the authors maximize the spectral efficiency and energy efficiency by jointly optimizing the hybrid beamforming at the base station and the passive beamforming at the STARS. Finally, the authors confirm the superiority of STARS aided THz communications over the conventional RIS aided THz communications.

The paper [11], entitled "RIS-Aided Near-Field Localization and Channel Estimation for the Terahertz System", focuses on the spherical wavefront propagation in the near field of the RIS aided THz communication system. For this system, the authors develop a near-field channel estimation and localization algorithm based on the second-order Fresnel approximation of the near-field channel. Particularly, the authors use multiple subbands for angle/distance estimations to alleviate the impact of THz channel fading peaks. Simulations are finally adopted to demonstrate the advantage of the proposed algorithm over the conventional far-field algorithm, as well as showing the high resolution accuracy obtained by the proposed algorithm.

The paper [12], entitled "Sensing User's Channel and Location with Terahertz Extra-Large Reconfigurable Intelligent

Surface under Hybrid-Field Beam Squint Effect”, investigates the sensing of user’s uplink channel and location in THz extra-large RIS systems, where the hybrid far-near field effect and beam squint effect are addressed. Specifically, the authors propose a joint channel and location sensing scheme where a location-assisted generalized multiple measurement vector orthogonal matching pursuit is designed for channel estimation and a complete dictionary based localization scheme is developed to address the hybrid field beam squint effect. To further reduce the sensing overhead, the authors propose a partial dictionary-based localization scheme that is decoupled from channel estimation. Simulation results demonstrate the superiority of the proposed channel estimation and localization schemes over the state-of-the-art benchmarks.

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