Guest Editorial Special Issue on "THz Communications and Networking"

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I. Introduction

THERE is an ever-increasing demand for higher data traffic volume to be handled in wireless networks. Data-intensive applications such as high-resolution video and 3-D experience are emerging fast, and a variety and a high number of new devices with extended functionalities, sensing capabilities, and intelligence are introduced and adopted. As a consequence, next-generation wireless networks need to be able to provide data rates in the order of Terabit per second (Tb/s) with high reliability and possibly low latency.

Wireless communication in the terahertz (THz) frequency band (0.1–10 THz) [1], [2] is envisioned as one of the key enablers toward ubiquitous wireless communications beyond 5G accommodating such a massive number of connected devices and ultra-high user data rates. The THz band is located in between the mmWave and the far-infrared (IR) band and is still considered one of the least investigated and exploited regions in the electromagnetic spectrum although it offers a much higher bandwidth than the mmWave range and more favorable propagation conditions than the IR band. Recently, significant progress has been made with respect to THz devices based on different technologies, and commercial THz systems are anticipated to become a reality in the near future. For example, there is a common understanding now that THz communications will become an integral part of the upcoming 6G systems family [3], [4].

THz systems are expected to be beneficial not only for traditional macroscale wireless communication networks but also for emerging paradigms such as wireless intra- and interchip communication, nanocommunication, and the Internet of Bio-Nano Things.

Although THz communication offers huge opportunities which are well recognized in principle, cf., for example, [1]–[5], many unique challenges have to be still addressed regarding aspects related to communication, networking, and system realization. For example, molecular absorption and spreading losses are much more pronounced for the THz range compared to mmWave frequencies, and outdoor THz links show a different behavior for varying weather conditions than IR channels.

This Special Issue (SI) targets presenting the most recent advances with respect to the theoretical foundations and practical implementation of THz wireless communications and networking. This includes approaches related to channel characterization and modeling; modulation, waveform design, and coding; information-theoretic analysis; channel estimation, detection, and equalization; (massive) multiple-input multiple-output (MIMO) communications; beamforming, beamtracking, and precoding, possibly assisted by a reconfigurable intelligent surface (RIS); resource allocation and multiple-access schemes; handover and routing protocols; transmission for scenarios with user mobility; devices and circuits; prototypes, testbeds, and experimental results; and applications of THz communications and networking, both at traditional macroscale and nanoscale, for example, in vehicular, aeronautical, satellite, and chip-to-chip communication systems.

II. On the Special Issue

Starting from the abovementioned vision, a Call for Papers for the SI on "THz Communications and Networking," IEEE Journal on Selected Areas in Communications, was published in the fall of 2019. The SI was aimed at compiling the latest and most significant research advances related to the modeling, design, analysis, and applications of THz wireless communications and networking as outlined above, and at fostering and envisioning new threads and directions in this still-emerging research area. The SI has attracted 49 high-quality submissions from authors based all around the world. All articles within the scope of the SI received at least three independent reviews, and the accepted articles went through at least one revision round. After such a rigorous review

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process, 19 papers were accepted covering a variety of facets of wireless communications and networking in the THz band. Furthermore, one survey paper on THz nanocommunication and networking was also accepted. Unfortunately, many fine papers could not have been included in this SI due to space constraints. We anticipate to see those papers in other venues.

In the following, the articles of the SI are grouped into topical areas, and the contribution of each accepted article is briefly discussed.

III. Summary of Accepted Articles

Nanocommunications

In the survey article titled "Survey on terahertz nanocommunication and networking: A top-down perspective," the state of the art in the research areas of electromagnetic nanocommunications and -networking in the THz domain is summarized. It should be noted that the paradigms enabling the communication with and among nanodevices will be of key importance to fully realize the potential of nanotechnology. An overview of various novel applications which can benefit from nanocommunications and -networking in the THz band is provided, and the corresponding requirements on communications and networking are outlined. The core of the survey is formed by a comprehensive overview of the available contributions related to the different layers of the protocol stack including channel modeling for THz nanocommunications and experimental results. Furthermore, the main open research problems are discussed, and some directions for future work are indicated.

In the article titled "Optimal resource allocations for statistical QoS provisioning to support mURLLC over FBC-EH based 6G THz wireless nano-networks," the authors consider terahertz nano communications where finite blocklength coding is adopted for low-latency short packet transmission and energy harvesting is included to deal with severely limited energy. The optimal resource allocation policies are proposed to achieve the maximum-effective capacity in the THz band over FBC-EH-based nano-networks. Nano-scale system models are established and the wireless channel models are characterized in the THz band using FBC. Simulation results validate the proposed schemes in supporting mURLLC.

Channel Measurements and Modeling

In the article titled "Millimeter wave and sub-terahertz spatial statistical channel model for an indoor office building," the authors present an indoor three-dimensional spatial statistical channel model for millimeter-wave and THz bands. Channel statistics based on measurement results at 28 and 140 GHz enable the establishment of a statistical channel model from 28 to 140 GHz for the indoor office scenario. A channel simulator is developed based on the channel model, which can recreate omnidirectional, directional, and multiple-input multiple-output (MIMO) channels for arbitrary carrier frequency, signal bandwidth, and antenna beamwidth.

In the article titled "A general 3D space-time-frequency non-stationary THz channel model for 6G ultra-massive MIMO wireless communication systems," the authors propose a novel three-dimensional space-time-frequency non-stationary geometry-based stochastic model, which describes channel characteristics in multiple THz application scenarios such as indoor scenarios, device-to-device communications, ultra-massive multiple-input multiple-output (MIMO) communications, and long traveling paths of users. The proposed channel model takes into consideration the non-stationarities in space, time, and frequency domains. The accuracy of the proposed channel model is verified by comparing simulation results for the relative angle spread and delay spread with measured results.

In the article titled "Channel measurements and modeling for low-terahertz band vehicular communications," the authors analyze wave propagation at 300 GHz in vehicular deployments. A mathematical model based on measured data is offered to investigate THz band channel properties in vehicular scenarios. The channel impulse response, average path loss, angular dependence, and time dependence are studied in various single-lane and multilane scenarios, to compare the results with conventional millimeter-wave vehicular systems, which would be useful for link-level or system-level simulations for prospective vehicular communication systems.

Modulation, Channel Estimation, Detection, and Equalization

In the article titled "Channel estimation and hybrid combining for wideband terahertz massive MIMO systems," the authors address the channel estimation and hybrid combining problems in wideband terahertz massive MIMO with uniform planar arrays. First, a low-complexity beam squint mitigation scheme is introduced based on true-time-delay. Next, the authors propose a variant of the popular orthogonal matching pursuit algorithm to accurately estimate the channel with low training overhead, which is then extended to the multiantenna user case.

In the article titled "Channel estimation and equalization for terahertz receiver with RF impairments," the authors investigate the channel estimation and equalization for a THz receiver with single-carrier frequency-domain equalization in the presence of wideband IQ imbalance and phase noise. Phase noise in THz transceivers would be stronger than the mmWave or lower frequency devices and the large bandwidth in THz leads to wideband IQ imbalance in THz circuits. A two-stage channel estimation method is derived to separately estimate the channel impulse response and wideband IQ imbalance parameters, and then channel equalization is designed to compensate for both wideband IQ imbalance and phase noise. Theoretical and simulation results validate the efficiency of the proposed channel estimation, and the equalization methods are shown to outperform the state-of-the-art methods.

In the article titled "Sub-terahertz wireless system using dual-polarized generalized spatial modulation with RF impairments," the authors advocate to combine generalized spatial modulation (GSM) and dual-polarized (DP) antennas for a MIMO transmission in the sub-THz domain. The proposed DP-GSM scheme makes use of the polarization index modulation dimension to improve the spectral efficiency of the conventional GSM. A joint maximum likelihood (ML) detector and a modified ordered block minimum mean-squared error (MOB-MMSE) detector, respectively, are introduced in order to detect the transmitted complex symbols, the activated antennas' indices, and their polarizations in DP-GSM. Here, the MOB-MMSE detector can approach the performance of ML detection at a significantly reduced complexity. A comprehensive performance analysis shows that the proposed DP-GSM scheme is robust to spatial correlation effects and phase noise, and outperforms a unipolarized GSM benchmark scheme. As a further advantage, with DP-GSM, the transceiver cost can be lowered by employing a reduced number of RF chains compared to dual-polarized spatial multiplexing.

In the article titled "Terahertz wireless communications with flexible index modulation aided pilot design," the authors address a transmission under phase noise in the THz regime. In general, hardware imperfections such as phase noise, in-phase/quadrature imbalance, and nonlinearity of power amplifiers have a significant impact on THz communications, and a careful system design should account for their effects. More specifically, the time-variant characteristics of the phase noise necessitate its frequent re-estimation, which can be only accomplished by the aid of pilot symbols which have to be inserted according to a dense pattern into the data stream. This, however, results in a decrease in the spectral efficiency. To tackle this issue, the authors propose a novel pilot design strategy utilizing index modulation (IM), where the positions of pilots are changed within a data frame to encode additional information bits into the pilot positions. A Turbo receiver is introduced for the joint detection of pilot positions and estimation of channel coefficients. A theoretical and simulative analysis demonstrates the efficiency of the proposed scheme.

(Hybrid) Beamforming and Beamtracking

In the article titled "Multi-hop RIS-empowered terahertz communications: A DRL-based hybrid beamforming design," the authors investigate using multi-hop reconfigurable intelligent surfaces to extend the coverage of terahertz communications between the multiple antenna-equipped base station and multiple single-antenna users. The joint design of digital beamforming matrix at the BS and analog beamforming matrices at the RISs is carried out by leveraging the recent advances in deep reinforcement learning (DRL) to combat the propagation loss. To improve the convergence of the proposed DRL-based algorithm, two algorithms are then designed to initialize the digital beamforming and the analog beamforming matrices utilizing the alternating optimization technique. Simulation results show that the proposed scheme is able to improve 50 % more coverage range of THz communications compared with the benchmarks.

In the article titled "SS-OFDMA: Spatial-spread orthogonal frequency division multiple access for terahertz networks," the authors advocate a novel multiple access scheme for THz communications, referred to as SS-OFDMA, which relies on a further developed hybrid THzPrism beamforming (HTB) architecture. The key idea of the scheme is to significantly enhance the angular coverage of THz transmission by spreading frequency subcarriers to different directions, thus overcoming the extremely narrow angular coverage due to the highly directional THz beams. In order to accommodate users distributed over a wide angular range, a user grouping algorithm is designed for SS-OFDMA, making use of SDMA principles and suppressing inter-group interference. The efficiency of transmission within an SS-OFDMA group is improved by a nonuniform beam spreading mechanism based on a joint design of digital and analog beamforming. The scheme is complemented by a resource allocation algorithm which minimizes the transmit power of the base station by an optimized subarray allocation among groups and an optimized subcarrier and power allocation for each user within a group. Remarkable advantages with respect to data rate, throughput, and power consumption in comparison to existing multiple access schemes are demonstrated.

In the article titled "Wideband beam tracking in THz massive MIMO systems," the authors propose a beam zooming based beam tracking for Terahertz massive MIMO, which exhibits severe beam squint phenomenon called beam split. The beam zooming mechanism to flexibly control the angular coverage of frequency-dependent beams over the whole bandwidth, i.e., the degree of the beam split effect, can be realized by the elaborate design of time delays in a delay-phase precoding structure. Then, the authors propose to track multiple user physical directions simultaneously in each time slot by generating multiple beams. The angular coverage of these beams is flexibly zoomed to adapt to the potential variation range of the user's physical direction. After several time slots, the base station is able to obtain the exact user physical direction by finding out the beam with the largest user received power. Unlike traditional schemes where only one frequency-independent beam can be usually generated by one radio-frequency chain, the proposed beam zooming-based beam tracking scheme can simultaneously track multiple user physical directions using multiple frequency-dependent beams generated by one radio-frequency chain. The proposed scheme is shown to achieve the near-optimal achievable sum-rate performance with low beam training overhead.

In the article titled "Power-efficient beam tracking during connected mode DRX in mmWave and sub-THz systems," the interplay of discontinuous reception (DRX) and beam tracking is studied. DRX is anticipated to become an essential element in mmWave and sub-THz transmission systems since it offers the possibility to reduce the high power consumption in the radio frequency front-end of the user equipment (UE) resulting from tracking multiple links to guarantee a reliable multiconnectivity despite frequent and severe link blockages. It is proposed to track only a subset of the available links during connected mode DRX, where the links to be tracked over time are selected via the solution of a multiple-play multiarmed bandit (MP-MAB) problem. System simulations at mmWave and sub-THz frequencies demonstrate that even suboptimal link tracking policies may result in a remarkable outage and throughput performance at a substantially reduced power consumption in the UE.

In the article titled "Wideband beamforming for hybrid massive MIMO terahertz communications," the authors propose two wideband hybrid beamforming approaches to deal with the challenging beam squint issue as a result of large bandwidth at terahertz and the large number of antennas in massive MIMO. The first method divides the whole array into several virtual subarrays to generate a wider beam and provides an evenly distributed array gain across the whole operating frequency band. The second method introduces the true-time-delay (TTD) lines and proposes a new hardware implementation of analog beamformer/combiner. This TTD-aided hybrid implementation enables the wideband beamforming and achieves the near-optimal performance close to full-digital transceivers.

Aeronautical/Aerial Communications

In the article titled "Terahertz ultra-massive MIMO-based aeronautical communications in space-air-ground integrated networks," the authors focus on THz ultra-massive (UM) MIMO-based aeronautical communication links connecting aircrafts and aerial base stations in space-air-ground integrated networks. It is shown that due to the unprecedentedly ultra-large-array aperture, ultra-broad-transmission band, and ultra-high velocity in such scenarios, triple delay-beam-Doppler squint effects have to be addressed, unlike in sub-6 GHz or mmWave massive MIMO systems. To this end, during an initial channel estimation phase exploiting rough angle estimates acquired from navigation information, precise estimates for azimuth/elevation angles, Doppler shifts, path delays, and channel gains are iteratively computed, and beam alignment is accomplished. For the data transmission phase, a data-aided decision-directed channel tracking algorithm is developed to track the beam-aligned effective channels. When the data-aided channel tracking starts to degrade, a pilot-aided channel tracking is invoked, reconfiguring the connection pattern of the RF selection network until beam alignment is achieved again and the Doppler shifts and path delays can be re-estimated for another data transmission phase.

In the article titled "Variable-bandwidth model and capacity analysis for aerial communications in the terahertz band," the authors investigate the band from 0.75 to 10 THz regarding its suitability for aerial communications among drones, jet planes, high-altitude unmanned aerial vehicles (UAVs), and satellites. The influence of altitude, transmission distance, zenith angle, and both multipath fading and beam misalignment fading is studied. Based on a transmittance analysis, a channel model is developed for aerial THz communications which characterizes the frequency-selective path gain and the power density spectrum of the colored noise. It turns out that the varying water vapor concentration across the atmosphere has a key influence. The obtained channel model is used to compute the THz channel capacity for water-filling and equal power allocations, respectively, applying a novel approach. One main result is that without fading, the sea-level capacity is enhanced by an order of magnitude for the drones and a further factor of two for the jet plane scenario, and additional significant increases for UAV and satellite cases. Furthermore, it is shown that the influence of fading on channel capacity can be neglected at higher altitudes. For example, it turns out that 10s of Tbps are achievable among jet planes and UAVs, and several 100s of Tbps are possible for satellites/cubesats at 1 km under fading. These findings indicate that the THz band is highly attractive for aerial communications.

Devices and Circuits

In the article titled "Design and performance analysis of THz wireless communication systems for chip-to-chip and personal area networks applications," the authors investigate THz transmission systems based on on-off-keying. The performance of modules in the chipsets has been measured to discuss the expected performance of the transmission system. A high-speed THz transmission system was configured by using fabricated chipsets for THz transceivers, in order to demonstrate the feasibility of the wireless communication at THz frequency bands.

In the article titled "Surface electromagnetic performance analysis of a graphene-based terahertz sensor using a novel spectroscopy technique," the authors introduce a graphene-based THz sensor and a THz spectroscopy technique, respectively, which may be beneficial towards future THz systems with combined communications and sensing capabilities. The proposed sensor allows sensing the relative permittivity of materials with a broad sensing range and fine resolution, and it can penetrate deeply into the material and precisely measure any variations in its thickness. The novel spectroscopy technique is based on the spectral amplitude and phase of the normalized reflection diagram and extracts two new spectral features referred to as accumulated spectral power (ASP) and averaged group delay (AGD) over a broad range of frequencies to determine a unique signature for each material. Furthermore, ASP and AGD offer possibilities to coherently analyze the reflection diagram, thus enabling an even more accurate sensing of various materials.

Networking Aspects and Protocols

In the article titled "Coverage analysis for 3D terahertz communication systems," a tractable analytical framework is developed in order to evaluate the coverage for a typical user in an indoor THz communication environment. The analysis is based on a realistic 3D THz system model which includes the effects of the molecular absorption loss, 3D directional antennas at both the user equipments (UEs) and the access points (APs), and the interference from neighboring APs, and it accounts for the joint impact of the blockage caused by the user itself, moving humans and wall blockers. In addition, the effect of the vertical heights of the THz devices is considered. The hitting probability, i.e., the probability of the signal corresponding to the main lobe of an interferer reaching a user, and the blocking probability are derived. Based on these quantities, an expression for the coverage probability is computed, by characterizing the regions where dominant interferers causing outages can exist, and the average number of interferers in such regions. The analysis is validated by simulation results, and it is shown that taking into account the vertical height of the THz equipment is crucial for accurate results. Furthermore, it is demonstrated that the antenna directivity at the APs has more impact on the coverage than that at the UEs.

In the article titled "The impact of multi-connectivity and handover constraints on millimeter wave and terahertz cellular networks," the impact of handover protocols is addressed which are particularly crucial for mmWave and THz communications in order to combat poor propagation characteristics, shadowing, and blockages. Such detrimental effects may cause numerous outage events and trigger frequent handovers. In principle, this may affect the reliability adversely and introduce harmful delays. In order to analyze the effect of the handover latency and the multi-connectivity degree on service continuity and reliability, a Markov chain-based model is presented, accounting for dynamic blockages, self-blockages, a multiconnectivity model, base station discovery, and handover execution times. The resulting theoretical framework may be adopted for the analysis of general blockage limited networks, and it facilitates the evaluation of trade-offs between coverage range, multi-connectivity degree, blocker density, base station deployment density, handover execution, and base station discovery times.

IV. Conclusion and Future Directions

In summary, the articles of this Special Issue make a substantial contribution towards a better understanding of the characteristics of the THz channel as well as the design and analysis of high-performance schemes for transmission and networking for various applications of THz communications.

Communication in the THz regime is still an emerging area, and a variety of challenges exist which still have to be addressed.

For example, while some adaptive modulation and coding schemes have been already developed for THz communication, further work is needed in this direction in order to come up with schemes which are fully tailored to the THz channel and the constraints imposed by THz circuits and devices. Since a high level of phase noise is present at THz frequencies, noncoherent transmission may be an appealing approach. In general, various aspects of synchronization have to be revisited for THz communication. In addition, since only low-resolution analog-to-digital converters (ADCs) can be realized at the high symbol rates typically adopted in wideband THz communication, transmission and detection schemes should be designed which can operate under strong signal quantization (even for the limit case of 1 bit quantization).

Furthermore, while previous research has focused on physical layer problems, it seems that more work on higher layer protocols related to medium access, routing and relaying, the transport layer with end-to-end quality of service (QoS) requirements, as well as network association and service discovery is compulsory. Security is an important additional concern, and while some preliminary studies are already available in this area, they can be considered only as a starting point. Similarly, the THz domain looks promising in order to realize a covert communication but more exploration is necessary.

The distance problem related to the high distance-dependent signal attenuation of the THz channel is still one of the grand challenges in THz communication. Reconfigurable intelligent reflecting surfaces (IRSs) and ultra-massive MIMO systems as discussed in this Special Issue may be an important enabling tool for large transmission distances. Here, it remains open how to accurately estimate the coefficients of thousands of parallel subchannels of such systems, and how to operate ultra-massive antenna arrays possibly assisted by IRSs in order to realize different modes. Here we envision an artificial intelligence (AI) empowered autonomous configuration of spectral, spatial, and power resources of a multiband IRS aided ultra-massive MIMO communication system with a spectral domain ranging from RF to mmWave to THz band.

Relaying is another approach in order to combat the distance problem. So far, only few works on relaying for THz communication are available. We anticipate huge benefits of properly designed relaying schemes in the THz domain. As a starting point for the design of multi-hop THz communication, a 3D end-to-end THz band channel model with polarization diversity and mobility might be developed. In general, mobility is another important aspect since a nonnegligible mobility of transceivers and scatterers may cause large Doppler shifts and spreads in the THz domain. In the context of multihop relaying, a simultaneous information and energy transmission at THz frequencies should be investigated for wireless powering of the relay/sensor nodes.

Thus, more efforts are needed in particular for outdoor scenarios with larger transmission distances and scenarios with user mobility. It should be noted that in such scenarios, the channel may also exhibit a more pronounced frequency selectivity, and more powerful equalization schemes have to be employed.

For some scenarios, still, a better understanding of the propagation characteristics is needed, such as long-delay satellite networks. In addition, a more accurate characterization of the directivity of THz antennas and propagation (non-line-of-sight (NLOS) versus LOS) would be useful. This is also related to the nature and strength of shadowing effects in the THz domain.

Finally, further progress is required with respect to system architectures and device technology. Researchers may further elaborate on the potential and limitations of fully electronic versus mixed electronic-optical system approaches. Concepts for compact signal sources and detectors with sufficient output power and sensitivity, respectively, are needed which facilitate a mass fabrication of transceivers (and antennas for ultra-massive MIMO arrays) at low cost. Various corresponding research projects are already ongoing.

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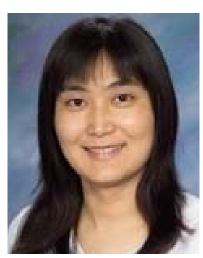

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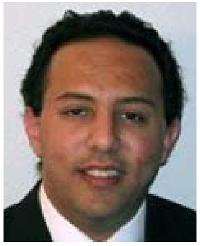

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