Terahertz Communication for Vehicular Networks

Abstract—**With the never-ending increase in the number of mobile connected devices and the need for higher data rates anywhere, anytime, higher frequency bands are being considered for communications. As millimeter-wave technology moves from research to commercial deployments, and motivated by the still limited bandwidth, the terahertz (THz) band is envisioned as the next frontier for communications. When it comes to vehicular networks, communication at much higher frequencies and, consequently, with much higher data rates brings many exciting opportunities as well as challenges. In this paper, an overview of the opportunities and challenges in THz communications for vehicular networks is provided. In addition, the papers in this Special Section which provide first-time solutions to some of these challenges, are introduced.**

Index Terms—**Beyond fifth-generation (B5G), channel modelling, data rate, terahertz (THz).**

I. INTRODUCTION

WITH the fast development of electronic devices, various emerging applications (e.g., big data analysis, artificial intelligence and 3-D media or Internet of Everything) are entering our society and leading to huge amounts of data traffic. While mobile networks are already indispensable to our society for "anywhere anytime communication," a key requirement for future beyond the fifth generation (B5G) mobile networks is the ability to handle tremendous amount of data and, in addition, very high throughput per devices (from multiple Gbps up to several Tera-bps (Tbps)) and per area efficiency (bps/km2). It is predicted that the world monthly traffic in smartphones will be about 50 Petabytes in 2021 [1], which is about 12 times of the traffic in the year 2016, as shown in Fig. 1. From Fig. 1, we can also estimate that the traffic will continuously increase at a very fast pace. Other characteristics include low delay and high reliability of communication, and a massive number of connected heterogeneous devices.

Among various data traffic, the video traffic is expected to be dominant. Video traffic already constitutes a significant fraction of the mobile traffic volume and is expected to reach 67% of the total traffic by 2017 and even more in the future. Some video traffic has already posed severe challenges to mobile networks, including the forthcoming 5G mobile networks. For instance, it is expected that at least 10 Gbps traffic is needed for one virtual reality (VR) device. While the state-of-the-art VR headsets rely on a wired connection to a local host, being able to "cut the cord" will make a huge difference to the user experience. Moreover, full High Definition video is becoming increasingly important for mobile devices, and devices using Ultra High Definition (UHD) (4K and 8K) and 3-D rendering are also expected to become widely available in not so distant future. An uncompressed UHD video may reach 24 Gbps rate, and an uncompressed 3-D video with UHD can reach 100 Gbps [2]. Ultimately, the Tbps era is around the corner [3]. Thus, new disruptive mobile network technologies have to be proposed to satisfy these traffic requirements.

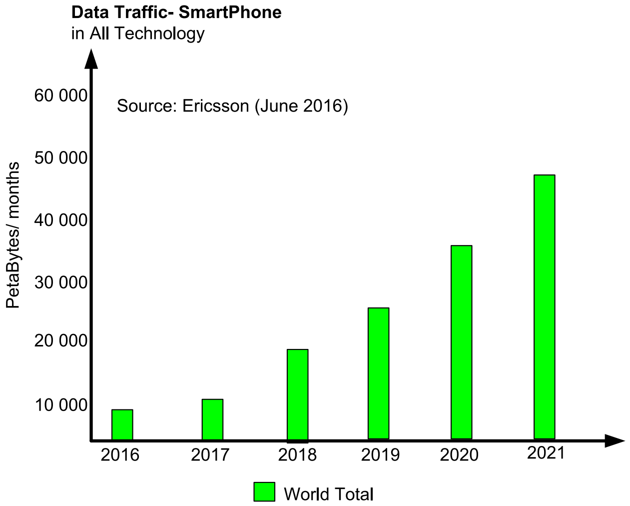

Fig. 1. World mobile data traffic volumes in smartphones (prediction) [1].

Based on the above observations, the main objectives for B5G systems are

1) extremely high data rates per device (from multiple tens of Gbps to Tbps);
2) massive amounts of connected devices;
3) ultra-massive high data rates per area;
4) ultra-reliable transmission to support various critical applications, such as vehicle-to-vehicle (V2V) communications, industrial control, healthcare, etc.

To achieve the above objectives, a very wide band is needed which cannot easily be found in frequency bands below 90 Hz. Thus, it is natural to study the radio access technologies (RATs) in THz[1] (90 GHz to multiple THz) frequency band, which have not been exploited mostly.

It has long been believed that the THz bands present serious challenges for data transmission over relatively long distances due to unfavorable propagation and atmospheric absorption characteristics. However, the smaller wavelength of THz signals also brings benefits, allowing for a much larger number of antenna elements to be integrated into devices and base stations operating in this band, enabling the use of advanced adaptive array technologies that can overcome range limitations. From a system perspective, the THz band operation presents many challenges but also opportunities. Increased link isolation due to the propagation characteristics but also opposite situations

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[1] For simplicity, in this paper, we will refer to the frequency range from 90 GHz to 3 THz as the THz band, which is wider than the usually adopted definition of THz band (300 GHz to 3 THz).

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with extreme co-channel interference due to the use of adaptive antenna array technologies necessitate new non-traditional radio access network management solutions to be developed to ensure coverage and mobility. In the same way, physical hardware and processing constraints in, e.g., the RF front-end and in baseband, impose requirements on the selection and design of the entire radio interface, from waveforms to channel coding and retransmission schemes. Moreover, the use of advanced signal processing methods requires a good understanding and accurate ways of modeling and estimating the characteristics of the propagation environment.

Based on the legacy results on millimeter wave bands, it is expected that the main properties of THz communications include 1) the high frequency provides very large available bandwidth and, thus, potentially very high data rates and 2) to combat high path loss, directional antennas are expected to be mandatory. Highly directional antennas lead to narrow beamwidths and very limited interference. Thus, a very high data rate per area can be expected. 3) High rates can also lead to low delays, provided that efficient beam search and alignment mechanisms are in place.

When it comes to vehicular networks, there are several additional reasons to explore higher frequency bands that can support multi-Gbps and Tbps links. First of all, when transmitting at such high data-rates, even if the users are mobile, the link effectively appears to be static from the data perspective because transmissions are almost “instantaneous.” Simply stated, while the system (user’s relative position, channel properties, etc.) change with time, they do so at a much slower pace than the actual data rate. Therefore, during a given frame transmission, the system seems static. In addition, even if a user has intermittent connectivity (e.g., a car connecting to base-stations only when nearby), the amount of information that can be transmitted per connection is potentially huge (1 Terabit in 1 second). Moreover, by moving to higher carrier frequencies, the impact of Doppler effect can be minimized. While this might not be an issue for car networks, it is very relevant for wireless data transmissions to or between aircrafts, which travel at very high speeds. Therefore, there are intrinsic properties that motivate the exploration of the THz band for vehicular networks.

This article provides an overview of the opportunities in terms of bandwidth that the THz band offers (see Section II), summarizes the main challenges faced in deploying THz communication for B5G vehicular networks (Section III) and discusses the papers in this Special Section (see Section IV) followed by conclusion (see Section V).

II. BANDWIDTH AVAILABILITY IN THE THZ BAND

In recent years, new services and applications have caused an explosive increase in data traffic, and the underlying network infrastructure is supposed to be reshaped to support these applications. Hence, the focus of the B5G networks will be in the extremely high-frequency band, and it is expected that this drives the requirements for a massive increase in capacity and data rates. Mobile communication systems operating at higher frequencies than those currently allocated to 5G networks are being seriously considered by industry and academy as a very promising approach to significantly boost capacity because such a system can potentially utilize the much larger spectrum bandwidth available in these frequencies. Moreover, in order to support user data rates of multiple Gbps and above in a commercially viable manner, contiguous bandwidths significantly larger than 500 MHz (being the widest bandwidth currently defined for 5G) are required. Depending on the realization of the B5G system, bandwidths in the order of multiple GHz (a few tens of GHz, up to one THz) may be needed for efficient high capacity data delivery.

TABLE I
AVAILABLE BANDWIDTH FOR DIFFERENT CARRIER FREQUENCIES

Frequency band	**Available contiguous bandwidth [GHz]**
10–10.6 GHz	0.6
14–14.5 GHz	0.5
15.7–17.3 GHz	1.6
27.5–29.1 GHz	1.6
31.8–33.4 GHz	1.6
40.5–43.5 GHz	3
45.5–47 GHz	1.5
57.0–64.0 GHz (V– band)	7
71–76 & 81.0–86 GHz (E band)	10
90–100 GHz	10
0.41 THz	65
0.49 THz	87
0.66 THz	153
0.84 THz	142
0.94 THz	48
1.03 THz	58
1.30 THz	38
1.35 THz	51
1.49 THz	92
1.56 THz	29
1.83 THz	25
1.98 THz	57

Such wide contiguous blocks of bandwidth are extremely hard to be found below 90 GHz but are available in higher frequencies above 90 GHz in abundance, and in particular in the THz frequency band. Some example frequency band allocations reflecting the availability of large contiguous bandwidths are shown in Table I. As can be seen, there are substantial chunks of spectrum in the THz frequency range that, in principle, could be used for mobile communications [4].

III. RESEARCH CHALLENGES IN THZ-BAND COMMUNICATION

There are many challenges in the realization of efficient and practical THz band communication for vehicular networks, which require the development of innovative solutions both on the device side as well as at the different layers of the protocol stack.

A. Terahertz-Band Transceiver Design

There is a need to develop new transceiver architectures that are able to operate at THz-band frequencies and, more importantly, able to exploit the very large available bandwidth. High power, high sensitivity, and low noise figure are additional transceiver features, which are required to overcome the very high path-loss at THz-band frequencies. Different technologies can be considered to achieve this goal, ranging from conventional CMOS [10] to III-V semiconductor materials [11] and novel nanomaterials such as graphene [12].

At THz frequencies, we are able to host a huge array of antenna elements (half-wavelength dipole antennas are so small at such frequencies) on our terminal devices leading to larger diversity gain and antenna directivity gain over legacy MIMO approaches. Furthermore, higher frequencies need smaller cells to overcome blocking and pathloss, while the same channel difficulties (path loss and blocking) cause the interference due to densification to decay quickly. No prior work has yet been reported on the design and fabrication of a complete THz massive MIMO transceiver, covering aspects such as antenna layout, array geometries, RF front-end architectures, local oscillator distribution, optimization of power dissipation, demodulation, baseband processing, sampling, and multichannel data aggregation [13]. Significant work is needed to proceed from conceptual prototypes to practical devices for vehicular networks.

B. Ultra-Massive MIMO Antenna Arrays

In order to overcome the very small gain and the effective area of individual THz band antennas [14], it is necessary to investigate the performance of novel very large antenna arrays for vehicles. The very small size of a THz band antenna allows for the integration of a very large number of antennas at vehicles with very small footprint [15]. The assumptions underlying the theory of THz massive MIMO communications will drive many aspects of the transceiver design, ranging from highly efficient antennas to carrier allocation. This includes the need for high-efficiency antennas with low mutual coupling and RF channel crosstalk, stable and coherent LO distribution, sharing of transceiver resources, modular and easily scalable architectures, tight RF and antenna integration, as well as the choice of carrier frequency, signal bandwidth, and antenna directivity. Some initial work has investigated the impact of phase noise, mutual coupling, and unstructured statistical hardware errors, but such studies have been limited to models rather than actual transceiver implementations [15]. However, this brings many new challenges, including the development of the feeding and control network for very large antenna arrays and the analysis of the coupling effects between nearby antennas, among others.

C. Information Theoretic Issues of Terahertz-Band Communication

Distinct advantages emerge in THz-band systems where the number of base station antennas is large compared with the number of terminals under simultaneous service. Channels to different terminals tend to become orthogonal, on the forward link simple linear pre-coding may be nearly optimal, and fast-fading diversity is established inherently. Further developments of the information theory for large-scale THz ultra-massive MIMO systems are needed in the regime of a large—but finite—number of antennas which quantify trade-offs between spectral efficiency (bit/second/Hz) and energy efficiency (bit/Joule). Key differences from the previous analysis at cellular spectrum are that few terminals might be supported per cell (due to the limited coverage area) and that channel coherence interval is smaller (due to more severe Doppler spread). The effect of noisy channel-state information has to be accounted for, presumably through various capacity bounds [16], [17]. New linear precoding strategies that exploit partial or full knowledge of slow-fading propagation coefficients and inter-cellular collaboration may materially improve performance.

D. Novel Waveforms for Terahertz-Band Communication

Radio access technologies for cellular mobile communications are typically characterized by multiple access schemes, e.g., FDMA, TDMA, CDMA, and OFDMA. In 4G mobile communication such as LTE and LTE-Advanced standardized by 3GPP, OFDMA and SC-FDMA are adopted. OFDMA was a reasonable choice for achieving good system level throughput performance in packet-domain services with single user detection. But more advanced waveforms are required for THz in future 5G and beyond vehicular systems. For example, the use of ultra-broadband pulses, just a few hundred femtoseconds long, has been recently proposed [26]. Such very short pulses allow defining almost orthogonal channels with minimal synchronization overhead on the users. In any case, while the use of these pulses minimizes the transceiver complexity and maximizes the achievable capacity, it also introduces many challenges in the design of ultra-broadband antenna arrays.

Energy efficiency is one of the key advantages driving much of the interest in THz massive MIMO systems. However, the high peak-to-average power ratio (PAPR) of orthogonal frequency-division multiplexing (OFDM) works against this advantage and can impede good downlink performance. A recent study indicates that single-carrier modulation (SCM) with an equalization-free receiver [10], [13] can theoretically achieve near-optimal sum rate performance in massive MIMO systems operating at low-transmit-power-to-receiver-noise-power ratios, independent of the channel power delay profile. This is interesting for energy efficiency since SCM can be designed to have much better PAPR performance or even a constant envelope waveform. However, the results of [13] are based on the assumption of independent Rayleigh fading channels, which will not hold in the THz regime and could jeopardize the “equalization free” result. Furthermore, implementing SCM at THz frequencies implies very tight timing constraints on the order of a few nanoseconds or less, which is nontrivial. Thus, the trade-offs involved with using SCM for THz massive MIMO need further study.

E. 3-D Channel Models

Urban networks are decidedly non-flat, yet the de-facto approach from stochastic geometry treats all transmitters and receivers as living on a 2-D plane [19]. Meanwhile, urban areas are projected to grow rapidly in population and density by 2050 according to a recent United Nations urbanization study [20], with about two thirds of the world’s population living in urban areas by then. At the same time, the number of wireless devices connected via the cellular network is also rapidly increasing and expected to accelerate, popularly referred to as the "Internet of Things" [21], [22] or machine-to-machine (M2M) communication [22]. The implications on the communication environment of these two trends will be profound: more and more devices will be used in complicated urban environments. While many of the principles of stochastic geometry extend to three dimensions, their extension to urban areas is still challenging because of the non-homogeneous distribution of users and infrastructure. The situation becomes even more challenging at THz frequencies due to the sensitivity to blockages as well as the use of highly directional 3-D beam patterns [23]. However, presently little is known about the coverage and rates achieved in dense urban networks with planar deployments of infrastructure. New mathematical tools and models are required to analyze urban geometries and to realize the potential benefits of 3-D beamforming in such environments.

F. Channel Estimation Techniques for Terahertz Communication

For very large number of antennas $\mathrm{N_t}$, channel estimation errors due to uncorrelated noise and interference are less problematic since the impact of such errors should vanish as $\mathrm{N_t} \to \infty$ [24]. The primary source of Channel State Information (CSI) errors is the limited channel coherence interval, which limits the number of orthogonal training sequences that can be used and can lead to severe pilot contamination if the system is highly loaded with terminals. For THz frequencies, an interesting aspect is the degree to which high path loss and near-Line Of Sight (LOS) propagation would mitigate the pilot contamination effect [25]. Furthermore, a primarily LOS channel environment (via THz propagation or narrow antenna array beam widths) could allow for channel estimation based on direction-of-arrival (DOA) estimation. However, the advantages of a DOA-based approach would have to be weighed against the potential need to calibrate a large array and the added complexity of DOA estimation.

G. MAC Layer Design

The ambition of using THz frequencies entails many challenges on MAC and routing layer due to a large number of antennas, special propagation features, and hardware requirements. Therefore, there is need to design proper MAC layer for THz which may differ from microwave networks in three main aspects: 1) control channel architecture, 2) initial access, mobility management and handover, and 3) resource allocation and interference management. Since the channel coherence time reduces with the carrier frequency, the MAC layer decisions need to be made more frequently. The very few MAC protocols exclusively developed for THz-band communications [14], [25] do not take into account the mobility of the users and, thus, cannot directly be utilized in vehicular networks.

H. Interference Management

There are several factors that may mitigate interference in a THz system: 1) Due to increased pathloss, signals at THz frequencies have limited range and thus allow for higher frequency reuse (full reuse). 2) Shadowing effects in LOS or near-LOS propagation will reduce leakage into adjacent cells. 3) The sheer volume of spectrum available at THz frequencies should lead to relaxed frequency reuse constraints. 4) Beamforming with a massive MIMO array leads to narrow beamwidths and high spatial selectivity, which limits exposure of signals to unintended receivers. Nonetheless, it is not difficult to envision scenarios where small adjacent THz massive MIMO cells have significant LOS overlap, and where a unity frequency reuse factor is employed to maximize capacity. As such, there will be a need for interference mitigation in these networks. In microwave networks, the spatial and temporal correlation of the interference was introduced mostly by common locations of the transmitters and receivers and is often neglected without too much consequences. In THz massive MIMO systems, however, physical blockage and high gain beam steering introduce important new sources of correlation. Potential approaches could exploit a large number of degrees of freedom available in a massive MIMO array to use subspace-based and interference alignment methods.

I. Random Matrix Theory and Terahertz Communication Analysis of Wireless Communication Systems

The mathematical analysis of THz systems can be significantly facilitated through random matrix theory (RMT) since in the limit of a large number of antennas the channel characteristics tend to become deterministic. In addition, the implications of the model parameters on the system performance can be more easily deciphered. We recall that the area of RMT has followed the rapid development of MIMO communications and a contemporary review of RMT and its application to wireless communication can be found in [27].

J. Backhaul Transmissions in the Terahertz Band

THz transmission can be beneficial in providing very high throughput backhaul in areas where it is too costly to install wire or fiber connections [28]. Massive MIMO arrays could be arranged to relay information back and forth between cells or to nearby network hubs. Such an approach would have considerable advantages over microwave backhaul links that employ dish antennas and physical antenna alignment. Cooperating massive MIMO arrays could adaptively modify their transmit and receive beams to account for changes in the environment without a physical readjustment of the array, and they could simultaneously communicate with multiple backhaul stations since their beams are electronically steerable.

K. Experimental Demonstrations, Tests and Performance Characterization of Terahertz Systems

The potential benefits of THz wireless systems shall be highlighted by real-time measurement campaigns. Ultimately, new channel models can be derived based on measurement data. The impact of practical impairments (such as timing offset, frequency offset, and phase noise) on the overall system performance has to be considered as well. Analytical techniques for the determination of the most important figures of merit of THz systems (e.g., BER, outage probability, average rates, and the amount of fading) have to be derived.

L. Health and Safety Issues in the Terahertz Band

The THz bands corresponding to a wavelength range from 1mm to 0.1 mm (100 μm). The photon energy of THz waves ranges from 0.1 to 1.2 milli-electron Volts (meV). Unlike ultraviolet, X-ray, and gamma radiation, THz radiation is non-ionizing, and the main safety concern is heating of the eyes and skin caused by the absorption of THz energy in the human body [29]–[32]. The massive amount of raw bandwidth and potential multi-Terabit-per-second (Tbps) data rates in the THz band make it a promising candidate for future broadband mobile communication networks. Therefore, it is important to understanding how the propagation of THz waves impacts the human body, as well as the inquiry of potential health effects related to THz exposures. Additionally, the current safety rules regarding RF exposure do not specify limits above 100 GHz; because spectrum use will inevitably move to these bands over time, further investigations need to codify safety metrics at these frequencies.

M. Standardization

Recently, numerous standardization and regulatory bodies dedicated attention to the mm-wave and the THz band. Worth to be mentioned, for example, is the IEEE 802.15.3c (mm-wave WPAN) group [5]. This group developed a millimeter-wave-based alternative physical layer (PHY) for the existing 802.15.3 Wireless Personal Area Network (WPAN) Standard 802.15.3-2003. This mmWave WPAN operates in the new and clear band including 57–64 GHz unlicensed band defined by FCC 47 CFR 15.255. Similarly, also the ETSI/CEPT have considered the 60 GHz band, whereas the ITU has begun developing material related to mm-wave systems for terrestrial mobile applications [6], [7]. The European projects 5GPPP mmMAGIC and FP7 MiWaveS have introduced the concept of high capacity mm-wave hotspots operating between 28 and 86 GHz overlaid onto a network of 5G base stations.

The standardization efforts for THz band communication are led by the IEEE 802.15 Wireless Personal Area Networks (WPAN) Terahertz Interest Group (IGTHz) [8]. This group was created back in 2008, with the aim of collecting under one umbrella all the standardization efforts for future communication systems in the THz band. In 2013, as a spin-off from the group, the IEEE 802.15 WPAN Task Group 3-D 100 Gbit/s Wireless (TG 3d 100 G) [9] was created, aimed at developing the first standard for 100-Gbps wireless links at frequencies between 275 GHz and 325 GHz (50 GHz window). The IGTHz became partially dormant. At this time, the TG 3d 100G group is finalizing the first internal draft of the standard being considered. Consequently, the IGTHz is ramping up its activity and moving towards higher frequency windows in the THz band, i.e., true THz bands. There is, however, no current mobile communication system operating at THz frequencies, to our best knowledge.

IV. CONTRIBUTIONS TO SPECIAL SECTION

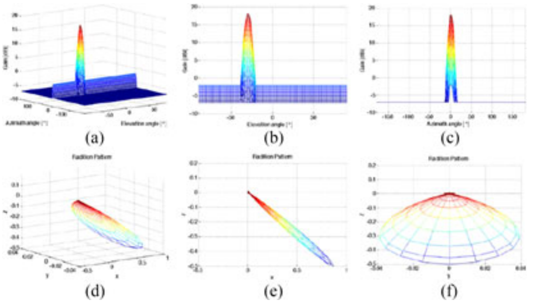


Fig. 2. Gain of a graphene-based reflectarray antenna in 3-D. (a) Gain in 3-D spherical view. (b) Gain in the elevation plane. (c) Gain in the azimuth plane. (d) Radiation pattern in 3-D cartesian view. (e) Radiation pattern in the x–z plane. (f) Radiation pattern in the y–z plane.

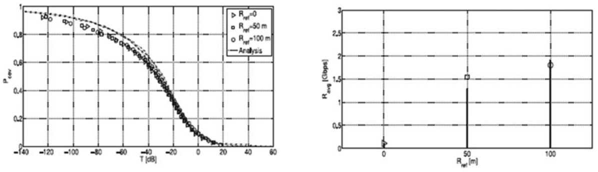


Fig. 3. G (max) BS = G (max) MT = 25 dB. Dashed (Pcov) and solid (Ravg) lines illustrate the analytical model, whereas markers illustrate Monte Carlo simulations.

This Special Section addresses some of the above challenges faced by THz communication. We have received 16 high-quality submissions and have accepted the top six papers. Summaries and main results of these papers are given below; for more detail, see [33].

In the first article, “Three-Dimensional End-to-End Modelling and Analysis for Graphene-Enabled Terahertz Band Communications,” by Han *et al.*, the authors proposed a 3-D end-to-end model in the THz band that includes the graphene-based reflectarray antenna response and the 3-D multipath propagation phenomena. Main results are shown in Fig. 2.

In the second article, “Toward the Performance Enhancement of Microwave Cellular Networks Through THz Links,” by Ntontin *et al.*, the authors consider the possibility of upgrading the already existing infrastructure of microwave base stations (BSs) by enabling them to convey information through microwave or Terahertz (THz) links, depending on the distance and whether a line-of-sight (LOS) link exists between a mobile terminal (MT) and its serving BS. Main results are shown in Fig. 3.

In the third article, “Integrated Terahertz Communication With Reflectors for 5G Small-Cell Networks,” by Taynnan Barros *et al.*, the authors propose the concept of mirror-assisted wireless coverage, where smart antennas are utilized with dielectric mirrors that act as reflectors for the Terahertz waves. The objective is to utilize information such as the user’s location and to direct the reflective beam toward the highest concentration of users. Main results are shown in Fig. 4.

In the fourth article, “On Millimeter Wave and THz Mobile Radio Channel for Smart Rail Mobility,” by Guan *et al.*, the authors introduce the applications and scenarios related to smart rail mobility, analyzed the bandwidth requirements, and clarified the motivations for developing mmWave and THz communications for railway applications. Main results are shown in Fig. 5.

In the fifth article, “Multiuser Millimeter Wave Communications With Nonorthogonal Beams,” by Xue *et al.*, the authors

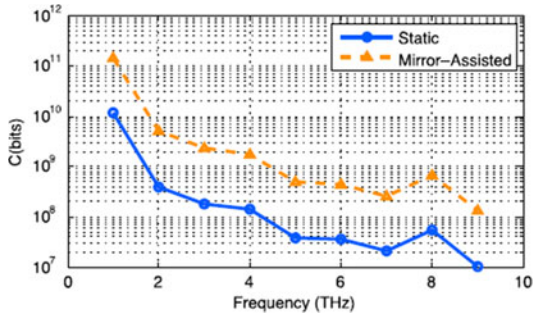
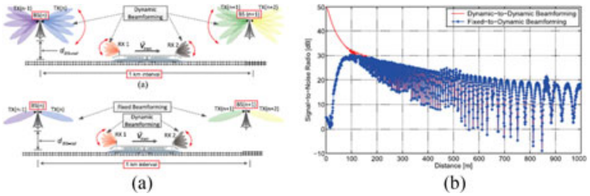
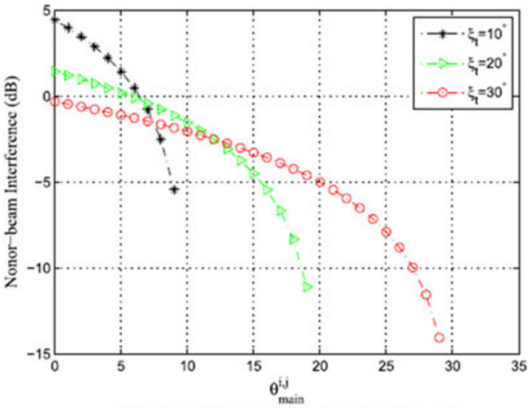


Fig. 4. Capacity as a function of frequency (THz) for a 5 × 5 m area with 5 × 5 tiles. The distance between the transmitter and the receiver is 1 m, and Δf is 1 THz. Both static and adaptive coverage are studied.



(a) (b)

Fig. 5. (a) Dynamic-to-dynamic beamforming strategy. (b) Fixed-to-dynamic beamforming strategy. SNR of the channel with two different beamforming strategies versus distance between transmitter and Rx.



(The included angle between beam i and bean j)

Fig. 6. For different ξ_t, the nonor-beam interference PkI nonor changes with $\theta_{i,j}$ main, given that $Q_m = 2$.

investigate the effect of mmWave non-orthogonal beam interference and then propose two novel solutions (i.e., dynamic beam switching and static beam selection) to coordinate the transmitting beams effectively. Main results are shown in Fig. 6.

In the final article, "Fast Channel Tracking for Terahertz Beamspace Massive MIMO Systems," by Gao *et al.*, the authors propose an a priori aided (PA) channel tracking scheme. Specifically, by considering a practical user motion model, they first excavate a temporal variation law of the physical direction between the base station and each mobile user. Main results are shown in Fig. 7.

V. CONCLUSION

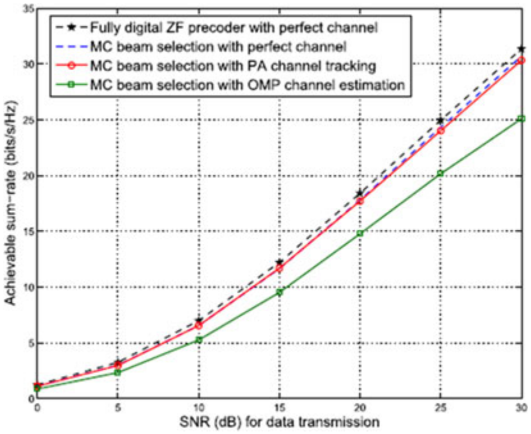


Fig. 7. Sum-rate performance of MC beam selection with different channels.

The demand for higher wireless data rates has roughly doubled every 18 months over the last decades according to Edholm's law, and it will reach Tbps rates within the next few years. Technologies which have been proposed for 5G, even the millimeter wave systems at 28 GHz, 60 GHz, and even 70/80 GHz, cannot meet these requirements as a consequence of a limited bandwidth. Abundant spectrum is still available in the THz range from 90 GHz to multiple THz which is largely unused for communications so far. Considering the recent progress in device technology, commercial THz communication systems are anticipated to become a reality in the near future, where vehicular communication might be one important application. Yet, important research challenges have to be still addressed which are related to the design of modulation, coding, channel estimation and tracking, resource allocation, MIMO systems, massive antenna array design, etc. It is expected that traditional design paradigms valid for the microwave frequency bands do not apply anymore due to the specifics of the THz systems, and novel solutions are needed. This Special Section strives to make a contribution to that end and to advance the state of the art of THz communications.

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SHAHID MUMTAZ, *Guest Editor*
Instituto de Telecomunicacões,
Lisbon 1049-001, Portugal
smumtaz@av.it.pt

JOSEP MIQUEL JORNET, *Guest Editor*
University at Buffalo, State University of New York,
Buffalo, NY 14228 USA
jmjornet@buffalo.edu

JOCELYN AULIN, *Guest Editor*
Huawei Technologies Sweden AB,
Göteborg 412 50, Sweden
jocelyn.aulin@huawei.com

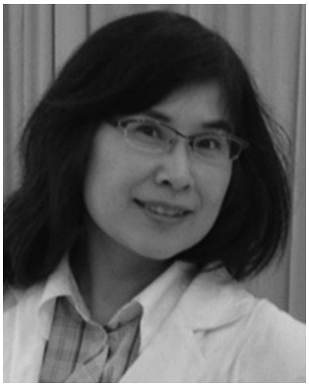
WOLFGANG H. GERSTACKER, *Guest Editor*
Universität Erlangen-Nürnberg,
Erlangen 91054, Germany
wolfgang.gerstacker@fau.de

XIAODAI DONG, *Guest Editor*
University of Victoria,
Victoria, BC V8P 5C2, Canada
xdong@ece.uvic.ca

BO AI, *Guest Editor*
Beijing Jiaotong University,
Beijing 100044, China
boai@bjtu.edu.cn

Shahid Mumtaz (SM'16) received the M.Sc. and Ph.D. degrees in electrical and electronic engineering from Blekinge Institute of Technology, Karlskrona, Sweden, and the University of Aveiro, Aveiro, Portugal, in 2006 and 2011, respectively. He has more than ten years of experience in wireless industry and is currently a Senior Research Scientist and a Technical Manager with the Instituto de Telecomunicações, Aveiro. Prior to this, in 2005, he was a Research Intern with Ericsson and Huawei Research Labs Karlskrona, Sweden. He has more than 100 publications in international conferences, journal papers, and book chapters. His research interests lie in the field of architectural enhancements to 3GPP networks (i.e., LTE-A user plan and control plan protocol stack, NAS and EPC), 5G related technologies, green communications, cognitive radio, cooperative networking, radio resource management, cross-layer design, Backhaul/fronthaul, heterogeneous networks, M2M and D2D communication, and baseband digital signal processing. In January 2015, he was elected the Vice-Chair of the IEEE Research Project on Vision of Green Standardization, and in January 2017, he was nominated the Chair of the IEEE new standardization on P1932.1: Standard for licensed/unlicensed spectrum interoperability in wireless mobile networks.

Josep Miquel Jornet (S'08–M'13) received the B.S. degree in telecommunication engineering and the M.Sc. degree in information and communication technologies from the Universitat Politècnica de Catalunya, Barcelona, Spain, in 2008 and the Ph.D. degree in electrical and computer engineering from the Georgia Institute of Technology (Georgia Tech), Atlanta, GA, USA, in 2013. He is an Assistant Professor with the Department of Electrical Engineering, University at Buffalo (State University of New York), Buffalo, NY, USA. From September 2007 to December 2008, he was a Visiting Researcher with the Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, under the MIT Sea Grant program. His current research interests are in terahertz-band communication networks, nanophotonic wireless communication, intrabody wireless nanosensor networks, and the internet of nanothings. He received the Oscar P. Cleaver Award for an outstanding graduate student from the School of Electrical and Computer Engineering, Georgia Tech, in 2009. He also received the Broadband Wireless Networking Lab Researcher of the Year Award in 2010. In 2016 and 2017, he received the Distinguished TPC Member Award at the IEEE International Conference on Computer Communications: one of the premier conferences of IEEE Communications Society. In 2017, he received the IEEE ComSoc YP and WICE Best Innovation Award. Since July 2016, he has been the Editor-in-Chief of the *Nano Communication Networks* (Elsevier) journal. He is also a member of the Steering Committee of the ACM Nanoscale Computing and Communications Conference series. He is a member of the ACM.



Jocelyn Aulin received the B.Sc. degree in applied mathematics/electrical engineering and the Ph.D. degree in electrical engineering from the Department of Electrical and Computer Engineering, Queen's University, Kingston, ON, Canada. While being engaged in her studies as a Doctoral student, she also cofounded the company Canada Computers & Electronics Inc. From 1995 to 2001, she was with Nortel Networks, Ottawa, ON. Her last position held was Senior Systems Design Engineer, working in the area of wireless communication systems. From 2001 to 2008, she was an Assistant Professor with the Department of Information and Computer Science, Telecommunication Theory Group, Chalmers University of Technology, Göteborg, Sweden. In 2007, she started a start-up company called OFDM-MAX AB, sponsored by Chalmers Innovations and a Sweden Innovationsbron grant. From 2008 to 2013, she was with Ericsson AB, Göteborg, working with 3GPP RAN4 standardization and basestation algorithms in the Baseband Performance Group. In May 2013, she joined the Sweden Research Center, Huawei Technologies Sweden AB, Göteborg. Her current research areas of interest include massive multiple-input multiple-output, beam forming, precoding, interference avoidance or mitigation, and the general areas of algorithms for wireless communication systems. She received a VINNOVA VINN NU Award.

Wolfgang H. Gerstacker (S'93–M'98–SM'11) received the Dipl.Ing. degree in electrical engineering in 1991, the Dr. Ing. degree in 1998, and the Habilitation degree in 2004, all from from the Friedrich-Alexander University (FAU), Erlangen-Nürnberg, Erlangen, Germany. From November 1999 to May 2000, he was a Postdoctoral Fellow with the University of Canterbury, Christchurch, New Zealand, sponsored by the German Academic Exchange Service. Since 2002, he has been with the Institute for Digital Communications (former Chair of Mobile Communications), FAU Erlangen-Nürnberg, where he is currently a Professor. His research interests are in the broad area of digital communications and statistical signal processing. He has conducted various projects with partners from industry and was an independent Consultant from 1998 to 2002. He is an Editor of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS. He is an Area Editor of Elsevier's *Physical Communication* and was a member of the Editorial Board of *EURASIP Journal on Wireless Communications and Networking* from 2004 to 2012. He has served as a Guest Editor of several journal special issues and has been a member of the Technical Program Committee of various conferences. He was a Technical Program Co-Chair of the IEEE International Black Sea Conference on Communications and Networking in 2014, a Co-Chair of the Cooperative Communications, Distributed MIMO, and Relaying Track of VTC2013-Fall, and a General Co-Chair of the ACM International Conference on Nanoscale Computing and Communication in 2016. He has received many awards, including the Research Award of the German Society for Information Technology (2001), the EEEfCOM Innovation Award (2003), the Vodafone Innovation Award (2004), a Best Paper Award from EURASIP Signal Processing (2006), and the "Mobile Satellite & Positioning" Track Paper Award of VTC2011-Spring.

Xiaodai Dong (S'97–M'00–SM'09) received the B.Sc. degree in information and control engineering from Xi'an Jiaotong University, Xi'an, China, in 1992; the M.Sc. degree in electrical engineering from the National University of Singapore, Singapore, in 1995; and the Ph.D. degree in electrical and computer engineering from Queen's University, Kingston, ON, Canada, in 2000. Since January 2005, she has been with the University of Victoria, Victoria, BC, Canada, where she is currently a Professor with the Department of Electrical and Computer Engineering. She was a Canada Research Chair (Tier II) from 2005 to 2015. Between 2002 and 2004, she was an Assistant Professor with the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB, Canada. From 1999 to 2002, she was with Nortel Networks, Ottawa, ON, Canada, where she worked on the base transceiver design of the third-generation mobile communication systems. Her research interests include wireless communications, radio propagation, ultrawideband radio, machine to machine communications, cyber physical systems, wireless security, e-health, smart grid, nanocommunications, and signal processing for communication applications. She was an Editor of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS from 2009 to 2014, the IEEE TRANSACTIONS ON COMMUNICATIONS from 2001 to 2007, *Journal of Communications and Networks* from 2006 to 2015, and is currently an Editor of the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY.

Bo Ai (SM'10) is currently working as a Full Professor and a Ph.D. Supervisor at Beijing Jiaotong University, Beijing, China, where he is a Deputy Director of the State Key Laboratory of Rail Traffic Control and Safety and a Deputy Director of Rail Traffic International Joint Research Center permitted by the National Ministry of Science and Technology. He is also one of the main responsible people for Beijing "Urban rail operation control system" International Science and Technology Cooperation Base and the backbone member of the Innovative Engineering Base jointly granted by the Chinese Ministry of Education and the State Administration of Foreign Experts Affairs. He is a member of the U.S.-Asia Innovation Gateway. He was a Visiting Professor with the Department of Electrical Engineering, Stanford University, Stanford, CA, USA, from March 2015 to September 2015. He is the Vice-Chair of the IEEE Vehicular Technology Society (VTS) Beijing chapter. He is a Distinguished Lecturer of the IEEE VTS. He has authored six books and published more than 270 scientific research papers in his research area including more than 70 IEEE Transactions or Journal papers. He holds 26 invention patents. He has been the research team Leader for more than 30 national projects. Recently, he has coauthored two books: One is with the European Union and North American scholars: *Fundamentals for 5G Mobile Networks* (Wiley); and the other is *mmWave Massive MIMO* (Elsevier). His main research interests are the wireless and mobile communications for rail traffic and intelligent transportation systems with emphasis on the wireless mobile communication for dispatching, safety, control, and services in rail transportation, including GSM-M for railways, LTE for railway, 5G mobile communications for railways, communication-based train control, etc. He is a Fellow of the IET. He is an Associate Editor of the IEEE TRANSACTIONS ON CONSUMER ELECTRONICS and a member of the Editorial Board of *Wireless Personal Communications*. He has been notified by the Council of Canadian Academies that, based on Scopus database, has been listed as one of the top 1% authors in his field all over the world. One of his papers was listed as a Hot paper by the World of Science (WoS), and two of his papers were listed as ESI paper by WoS. He has also been feature interviewed by *IET Electronics Letters* for his work in the area of channel modeling under rail traffic scenarios. He has received several scientific research prizes such as the First Grade of Technology Advancement Award of Shaanxi Province. His research on the rail traffic channel modeling and channel models have been written into the Chinese Industry Standard for Railways.