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IEEE access special section editorial: millimeter-wave and terahertz propagation, channel modeling, and applications

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EDITORIAL

IEEE ACCESS SPECIAL SECTION EDITORIAL: MILLIMETER-WAVE AND TERAHERTZ PROPAGATION, CHANNEL MODELING, AND APPLICATIONS

The demand for ever-increasing wireless data transmission rates and throughput area-densities, especially with regard to microcellular networks, internet access, back-hauling, inter-device transmission, and sensing applications, has spurred the exploration of new spectra in the millimeter-wave (30–300 GHz) and terahertz bands (0.1–10 THz), and the study of techniques for multi-Gigabit transmission based on very high-gain antennas [items 1) and 2) in the Appendix].

Besides the greater spectrum availability, one of the consequences of the small wavelength at mm-wave and terahertz is the need for massive Multiple Input Multiple Output (MIMO) antenna arrays with very narrow beams to overcome the Friis path loss. At such high frequencies, arrays can be compact, and with the help of powerful beamforming techniques (pencil-beamforming), they can yield optimum spectrum spatial reuse and consistently high signal to interference ratios [item 3) in the Appendix]. However, to gain this advantage, multipath-propagation spatial characteristics must be known, which can be accomplished through smart channel-estimation techniques or through other methods, including the real-time use of ray-based propagation models [item 4) in the Appendix]. Moreover, the use of multiple bands in the mm-wave and terahertz frequency ranges will allow the implementation of very high-accuracy sensing and localization techniques [item 5) in the Appendix] that will foster a variety of interesting applications, with special regard to industrial and vehicular systems as well as security enforcing systems [items 6) and 7) in the Appendix].

The abovementioned topics are particularly timely in view of the definition of forthcoming sixth-generation (6G) communication systems that will make use of such frequency bands.

To fully exploit the potential of mm-wave and terahertz spectrum, a deep understanding of the propagation channel is required, including topics such as materials properties, blockage, and scattering due to people, vehicles, drones, and so on, outdoor propagation effects, and multidimensional, multifrequency channel characterization including polarization. Moreover, multidisciplinary studies on link components including antennas, devices, and pointing systems are necessary, especially for the development of reliable terahertz communications systems [item 8) in the Appendix].

The foregoing issues and topics are the subject of investigation of this Special Section's contributions. The Special Section aroused enthusiasm and attracted 23 high-quality contributions that will be briefly described by subtopics below, starting with the invited article ''Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond,'' by Rappaport *et al*.

The invited article encompasses the whole topic of the Section, providing an overview of the challenges and opportunities of wireless communications at carrier frequencies above 100 GHz. This frequency range is considered as one of the strong candidates for the 6th generation of wireless communications. The contribution discusses propagation effects such as atmospheric attenuation, diffraction, reflection, and scattering, with a special focus on these phenomena up to 142 GHz. Further topics considered in the article are beamforming and antenna arrays required to mitigate the high path loss. Furthermore, the contribution discusses the bridge to other applications such as imaging or localization in the same frequency range.

I. OUTDOOR STUDIES AND APPLICATIONS

In addition, from Rappaport *et al*., the article ''Exploiting high millimeter-wave bands for military communications, applications, and design'' shows how military applications can leverage the mm-wave technology developed for 5G and the propagation characteristics at mm-wave frequencies to fulfill specific requirements such as covertness, high data rates, and adaptation to quickly changing environmental conditions. The article shows that the higher mm-wave frequencies provide significantly better path loss conditions for network links in a field command post or robotic swarm, where the antenna apertures are constrained to a fixed, relatively small area. Moreover, atmospheric absorption peaks in the mm-wave region between 50 and 70 GHz (and higher frequency mm-wave bands) provide an opportunity to adaptively tune the covertness of the network and its potential to mutually interfere with nearby communications.

Outdoor propagation issues are also addressed by Dupleich *et al.* in ''Multi-band propagation and radio channel characterization in street canyon scenarios for 5G and beyond.'' The article introduces simultaneous multi-band measurements comparing sub-6 GHz channels with those at 30 and 60 GHz for street canyon environments in Germany and Japan using the same measurement equipment. The analysis of the large-scale parameters shows a large influence of the geometry of the scenario on the channel, encouraging the introduction of deterministic modeling components within geometry-based stochastic channel models as an effective way to get improved propagation models.

Rain and foliage have different effects on outdoor communications at millimeter frequencies than they do at lower frequencies. The article ''Rain statistics investigation and rain attenuation modeling for millimeter-wave short-range fixed links,'' by Huang *et al*., examines the effect of rain on 25.84 and 77.52 GHz building-to-building links, including ''wet antenna'' attenuation, which can be a significant part of the total. Measured results are compared with some success to the ITU-R P.838-3 model, but the distance factor in ITU-R P.530-17 is found to be inappropriate for short links.

In ''Measurement-based characterization of 39 GHz millimeter-wave dual-polarized channel under foliage loss impact,'' by Lv *et al*., a channel measurement campaign has been conducted in a rich vegetation area. Four transmitter-to-receiver polarization configurations are considered in the measurements, and statistics of channel delay spread, angular spread, and foliage loss are established with respect to polarizations. A novel ''polarimetric directional-dependent XPD spectrum'' is introduced and used to analyze the impact of polarization on channel dispersion properties.

II. VEHICULAR PROPAGATION

In the general framework of millimeter/terahertz-wave wireless communications, vehicular networks can greatly benefit from small antenna size, which allows antennas or even arrays to be easily embedded into a vehicle, such as a car, train coach, or drone.

Kampert *et al*., in ''Millimeter-wave communication for a last-mile autonomous transport vehicle,'' present an interesting investigation of 5G mm-wave communication links for a low-speed autonomous vehicle, focusing on the effects of the antenna positions and beam-width on both the received signal quality and the link performance. It is observed that the excess loss for communication with roadside infrastructure is nearly independent of the beam-width, while the increase in the root mean square delay spread plays a minor role in the resulting signal quality since the absolute times are considerably shorter than the typical duration of 5G new radio symbols.

Intravehicular mm-wave transmission over the unlicensed 60-GHz spectrum represents a potential solution to realize high-speed Internet access inside a mass transit vehicle, which is in turn connected to the fixed network through a vehicle-to-infrastructure link. In ''60-GHz millimeter-wave propagation inside bus: Measurement, modeling, simulation, and performance analysis,'' Chandra *et al*. present measurement-based modeling and performance evaluation of 60 GHz mm-wave wireless links inside a bus. It is observed that the distance of the user from the access point and the specified data rate has a large impact on the bit-error rate performance of the intravehicular mm-wave link.

A ray tracing-based characterization of 300 GHz channels is conducted for urban and highway scenarios in ''Characterization for the vehicle-to-infrastructure channel in urban and highway scenarios at the terahertz band,'' by Yi *et al*. The attenuation caused by rain and snow is taken into account by applying it to individual rays being simulated. The resulting vehicle to infrastructure channel characteristics for urban and highway scenarios under sunny, rainy, and snowy conditions are presented in the article for various system configurations. The influence of the terminal height is specifically addressed, revealing the significance of strong reflections observable in the 300-GHz frequency band.

In ''Analyzing radar cross section signatures of diverse drone models at mmWave frequencies,'' by Semkin *et al.*, quasi-monostatic radar cross-section (RCS) measurements of different unmanned aerial vehicles at 26–40 GHz are presented. The RCS signatures of nine different multi-rotor platforms are studied in co- and cross-polarization conditions. These results are helpful in the design and testing of radar systems employing mm-wave frequencies for superior drone detection. Matching intuition, measurements confirm that larger drones made of carbon fibers are easier to detect, whereas drones made from plastic and Styrofoam materials are less visible. The measurement results are published as an open database, creating an invaluable reference for engineers working on drone sensing.

III. SENSING

Radar detection is also addressed by Gao *et al.* in the article ''Study of the extended phase shift migration for three-dimensional MIMO-SAR imaging in terahertz band,'' where the application to imaging problems of 3-D-MIMO synthetic aperture radar at a frequency of 100 GHz is described. The approach uses analytical expressions for the scattered field and applies a phase shift migration technique. Based on the proposed method, a bistatic prototype imager is designed and exploited to investigate the 3-D imaging results for different targets and computational complexity, demonstrating the good performance of the proposed method not only for simple cases but also for more complex scenarios like image reconstruction in a multilayer medium.

IV. INDOOR PROPAGATION

Besides the outdoor environment, mm-waves can be used for indoor scenarios, where the limitations of the harsh path-loss range dependence are blunted by the overall shorter communication range.

In the article ''An indoor channel model for high data-rate communications in D-band,'' by Pometcu and D'Errico, the authors propose a cluster-based channel modeling according to the extended Saleh–Valenzuela approach for indoor line-of-sight (LOS) and non-line-of-sight (NLOS) environments. Double directive measurements were carried out by means of a vector network analyzer and external mm-wave converters in the frequency range from 126 to 156 GHz. Angular resolution was achieved with two 20 dBi gain horn antennas. The propagation scenarios were characterized as laboratory, conference room, and office, respectively. For the LOS/NLOS scenarios, a large distance of 10.6 m and different obstruction situations were considered including blocking by humans, doors, and wall partitions. Path loss, delay spread, angular spread, intra- and inter-cluster characteristics are calculated from the measured data. It is observed that the log-normal distribution fits the intra-cluster fading better than the Rayleigh distribution. The angular distribution often reveals strong secondary reflections which can be exploited by beamforming.

Indoor propagation is also addressed by Yue *et al.*, in "Measurements and ray tracing simulations for non-line-of-sight millimeter-wave channels in a confined corridor environment," with a special focus on radio propagation beyond the corner of a two sections corridor. Narrowband and wideband channel characterization is carried out, based on both experimental measurements and ray-tracing simulations. Path loss is modeled according to a parametric analytical expression, where the parameters account for some geometrical characteristics of the corridor, such as the corner angle and the length of the line of sight section. Log-Normal variables are introduced to account for shadowing effects and for the impact on path loss of the antennas position in the corridor cross-section. Multipath amplitudes and fast fading are statistically analyzed, with Rice distribution representing the best-fitting model in most of the cases. The article includes wideband characterization of the power delay profile, which decays along the corridor according to a piecewise exponential model with delay spread of few nanoseconds, and of the angle spread, which decreases with increasing distance along the corridor.

A major drawback of mm-wave and terahertz propagation is represented by its sensitivity to blockage, i.e., when the waves have to propagate through obstacles like building walls in the case of signal transmission from outdoors to indoors, or when human bodies unexpectedly come to shadow the millimeter-wave link.

The article "Empirical results for human-induced shadowing events for indoor 60-GHz wireless links," by Ahumada *et al.*, reports on measurements of fading statistics caused by one or more individuals moving in the vicinity of WiGig-type radio link. The authors find that the characterization of a wireless channel is highly dependent on the environment, with the possible occurrence of deep fades of 40 dB and burst of fades that can significantly limit data rates.

In the article "Measurement-based millimeter-wave angular and delay dispersion characteristics of outdoor-to-indoor propagation for 5G millimeter-wave systems," by Lee *et al.*, the authors present the results of an extensive wideband sounding campaign at 32 GHz. The measurement scenario was directed towards outdoor-to-indoor propagation through windows in large office buildings. Unlike some well-known studies, this research focuses on delay and angular dispersion in addition to attenuation. The results reveal the influence of open-space versus closed-room office environments and of window glass metallization. The results may be very useful for 5G beamforming systems design. These results are important since 3GPP does not properly predict the delay-angular statistics for outdoor-to-indoor propagation at millimeter-wave frequencies.

V. CHANNEL THEORY AND SOUNDING TECHNIQUES

MIMO systems are a good fit with mm-wave communications since the small element size and separation result in compact arrays. However, mm-wave MIMO technology presents other problems, some of which are discussed within this section. The article "Time stability of untethered electronic switched MIMO millimeter-wave channel sounders," by Sun and Papazian, targets channel sounder systems design issues. MIMO channel sounder systems normally use switched antenna access at both transmitter and receiver sides. Because propagation directions of arrival and departure are estimated from the antenna interface signals, very high coherency requirements during switching periods have to be met. This includes high phase stability over coherent processing intervals on the micro- and millisecond scale, medium-term time stability for propagation delay estimation, and long-term stability for time frame synchronization measured in hours for real field measurement campaigns. The mutual synchronization problem is aggravated since the transmitter and the receiver have to work in an untethered mode and because they might be moving. This combination of short-term, low-phase noise limits, as well as precise timing requirements over long periods, results in high demands on timing circuit design and on performance evaluation of switched MIMO sounder systems, which are most challenging for mm-wave frequencies (28, 60, and 83 GHz in the article). The authors also propose a practical method to remove a constant initial time error, and experimentally estimate the time stability of their channel sounders.

Given the highly dynamic character of mm-wave channels, channel state estimation, which is particularly important to achieve good performance in MIMO and beamforming schemes, represents a major concern. The article "Millimeter-wave time-varying channel estimation via exploiting block-sparse and low-rank structures," by Cheng *et al.*, proposes a novel, two-stage channel estimation method that exploits the block-sparsity and low-rank characteristics of mm-wave time-varying channels. Simulation results show the good performance of the proposed method.

Because of the intrinsic difference, in terms of dispersion and dynamics, between mm-wave broadband channels making use of very directive beams and sub-6GHz channels, some well-established assumptions need to be reconsidered. In "Investigating validity of wide-sense stationary assumption in millimeter-wave radio channels," by Iqbal *et al*., the validity of the wide sense stationary (WSS) assumption is investigated. The authors find that when antenna directivity and/or bandwidth increases, the radio channel impulse response in the slow-time does not remain a WSS process. This means that the independent, identical distribution, complex Gaussian assumptions leading to Rice and Rayleigh distributions cannot be applied. However, measured channels are WSS in the frequency domain, and the coherence bandwidth increases with an increase in antenna directivity.

VI. INTRA- AND INTER-DEVICE COMMUNICATIONS

Because of the tiny wavelength, wireless technology at millimeter, terahertz, and even optical frequencies is enabling Wireless Networks on Chip (WiNoC), which may represent a breakthrough to meet the need for increasing computing performance in multi-core/multi-chip architectures. In fact, several issues about WiNoC have not been thoroughly investigated yet, including the characterization of the wireless channel at the chip scale across the frequency spectrum.

In this regard, the article "Wave propagation and channel modeling in chip-scale wireless communications: A survey from millimeter-wave to terahertz and optics," by Abadal *et al*., reports on the state of the art in wave propagation and channel modeling for WiNoC. The survey is mainly limited to deterministic methods, as the intra- or inter-chip environment is fixed and known beforehand and, therefore, suited to deterministic characterization. In the mm-wave bands, communication is likely to be greatly impaired by the presence of a thick layer of lossy silicon, resulting in a quite large path-loss, even for distances of few centimeters. Increasing antenna directivity can hardly be a solution, as few antennas can be embedded on-chip at millimeter frequencies. Furthermore, near-field effects are expected to play a role in some cases. Antenna on-chip integration is much easier at optical frequencies, but the propagation loss is even worse compared to the millimeter band. Moreover, multipath propagation can become a critical issue. The authors conclude that the terahertz band may represent a reasonable trade-off between antenna size, propagation distance, and communication throughput.

The article "Intra- and inter-chip transmission of millimeter-wave interconnects in NoC-based multi-chip systems," by Narde *et al*., investigates communication properties between on-chip omnidirectional antennas for intra- and inter-chip wireless links in multichip computing systems. The study is focused on the millimeter band. Both simulation and experimental activities are carried out at 30 GHz, whereas simulation outcomes are reported for flip-chip packaging environment at 60 GHz. Results show that the propagation scenario may affect wireless communications in different ways, ranging from the reduction in antenna radiation efficiency, depending on the silicon resistivity and on the presence of packed wires close to the antenna elements, to the frequency and spatial fluctuations of the transmission coefficients likely due to multipath phenomena. Based on the experimental measurements at 30 GHz, the authors also propose a large-scale, log-normal path-loss model, which can be beneficial for system-level architecture design.

Wireless communications in the terahertz band are addressed by Zhang *et al.* in "Mutual coupling reduction for ultra-dense multi-band plasmonic nano-antenna arrays using graphene-based frequency selective surface." In order to overcome the limitations represented by the propagation losses in the terahertz band and the low output power of the terahertz sources, nano-antenna arrays in ultra-massive MIMO system can be considered as a way to increase the communication range. Because frequency-selective molecular absorption occurs in the terahertz band, multiband nano-antenna arrays should be conceived to simultaneously exploit the different transmission windows. To this aim, the tunability of graphene-based plasmonic devices can be relied on. In very dense nano-antenna array structures, array performance and the communication distance can be reduced by mutual coupling effects triggered by surface plasmon polaritons propagating between the radiating elements. In this framework, the authors suggest using the graphene frequency tunability to eliminate coupling by inserting frequency selective surfaces (FSS) into the array substrate. By means of numerical simulations, the authors show that the FSS decoupling structure can eliminate both coupled magnetic and electric fields, with negligible impact on the array radiation pattern.

Reconfigurable intelligent surfaces (RIS) represent another field of application for mm-wave inter-device communications. RIS can dynamically change their back-scattering and absorption characteristics and, therefore, are being proposed to enhance performance of next-generation wireless systems. Since RIS are composed of electrically small surface-mounted radiating elements called cells or "atoms," equipped with logic circuits that need to be interconnected and externally controlled, the use of mm-wave wireless inter-atom communications is particularly attractive to reduce space consumption, propagation delays, and manufacturing costs. In "Exploration of intercell wireless millimeter-wave communication in the landscape of intelligent metasurfaces," by Tasolamprou *et al.*, different wireless interconnection solutions are presented and evaluated.

To conclude this Editorial, the Guest Editors would like to thank all the authors who submitted their high-quality research articles to this very successful Special Section. Guest Editors highly appreciate the contributions of the reviewers for their constructive comments and suggestions. They would also like to thank the guidance from IEEE Access Editor-in-Chief and staff members.

APPENDIX
RELATED WORK

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REINER S. THOMÄ (Fellow, IEEE) received the degrees in electrical engineering and information technology from TU Ilmenau, Germany. Since 1992, he has been a Professor of Electrical Engineering (Electronic Measurement Technology) with TU Ilmenau. With his group, he has contributed to several European and German research projects and clusters. His research interests include array signal processing, propagation measurement and modeling, high-resolution parameter estimation, multidimensional channel sounding, over-the-air testing of multiple antenna systems in virtual electromagnetic environments, MIMO-, mmW-, and UWB-radar sensors for object detection and tracking, and joint communication and radar sensing (cooperative passive coherent location). In 2007, he received the Thuringian State Research Award for Applied Research, both for contributions to high-resolution multidimensional channel sounding. In 2014, he received the Vodafone Innovation Award. In 2020, he also received the EurAAP/ESoA Propagation Award.

THOMAS KÜRNER (Fellow, IEEE) received the Dipl.-Ing. degree in electrical engineering and the Dr.-Ing. degree from the University of Karlsruhe, Germany, in 1990 and 1993, respectively. From 1990 to 1994, he was with the Institut für Höchstfrequenztechnik und Elektronik (IHE), University of Karlsruhe, working on wave propagation modeling, radio channel characterization, and radio network planning. From 1994 to 2003, he was with the Radio Network Planning Department at the headquarters of the GSM 1800 and UMTS operator E-Plus Mobilfunk GmbH & Company KG, Düsseldorf, where he was a Team Manager, radio network planning support, responsible for radio network planning tools, algorithms, processes, and parameters, from 1999 to 2003. Since 2003, he has been a Full University Professor of Mobile Radio Systems with the Technische Universität Braunschweig. His research interests include indoor channel characterization and system simulations for high-speed short-range systems, including future terahertz communication systems, propagation, traffic and mobility models for automatic planning and self-organization of mobile radio networks, and vehicle-to-x communications. In 2012, he was a Guest Lecturer with Dublin City University within the Telecommunications Graduate Initiative in Ireland. He has been involved in several international bodies. He has actively contributed to the channel modeling document supporting the standardization of IEEE 802.11ad. He was the Chair of IEEE 802.15.3d TG 100G, which developed the worldwide first wireless communications standard operating at 300 GHz. He is also chairing the IEEE 802.15 TAG THz. He is also the EU Coordinator of the EU-Japan Project ThoR, and the spokesman of the DFG Research Unit Meteracom on Metrology for THz Communications. He is also a member of the Board of Directors of The European Association on Antennas and Propagation (EurAAP). In 2019, he received the Neal Shepard Award.

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KE GUAN (Senior Member, IEEE) received the B.E. and Ph.D. degrees from Beijing Jiaotong University, in 2006 and 2014, respectively. In 2009, he was a Visiting Scholar with the Universidad Politecnica de Madrid, Spain. From 2011 to 2013, he was a Research Scholar with the Institut fuer Nachrichtentechnik (IfN), Technische Universitaet Braunschweig, Germany. From September 2013 to January 2014, he was invited to conduct joint research at the Universidad Politecnica de Madrid. He is currently a Professor with the State Key Laboratory of Rail Traffic Control and Safety, School of Electronics and Information Engineering, Beijing Jiaotong University. He has authored/coauthored two books and one book chapter, more than 200 journal articles and conference papers, and four patents. His current research interests include measurement and modeling of wireless propagation channels, high-speed railway communications, vehicle-to-x channel characterization, and indoor channel characterization for high-speed short-range systems, including future terahertz communication systems. He is also the Pole Leader of the European Railway Research Network of Excellence (EURNEX). In 2015, he was awarded a Humboldt Research Fellowship for Postdoctoral Researchers. He was a recipient of the 2014 International Union of Radio Science (URSI) Young Scientist Award. His articles received eight best paper awards, including the IEEE Vehicular Technology Society 2019 Neal Shepherd Memorial Best Propagation Paper Award. He has served as a Publicity Chair for PIMRC 2016, the Publicity Co-Chair for ITST 2018, the Track Co-Chair for EuCNC, the International Liaison of EUSIPCO 2019, the Session Convener for EuCAP 2015–2019, and a TPC Member for many IEEE conferences, such as Globecom, ICC, and VTC. He has been a delegate in 3GPP and a member of the IC1004 and CA15104 initiatives. He is also an Editor of IEEE Access, *IET Microwave, Antenna and Propagation*, and *Physical Communication*; and a Guest Editor of IEEE Transactions on Vehicular Technology and *IEEE Communication Magazine*.

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