A Holistic Investigation on Terahertz Propagation and Channel Modeling Toward Vertical Heterogeneous Networks

Kürşat Tekbıyık, Student Member, IEEE, Ali Rıza Ekti, Member, IEEE, Güneş Karabulut Kurt, Senior Member, IEEE, Ali Görçin, Senior Member, IEEE, Halim Yanikomeroglu, Fellow, IEEE

Abstract—User-centric and low latency communications can be enabled not only by small cells but also through ubiquitous connectivity. Recently, the vertical heterogeneous network (V-HetNet) architecture is proposed to backhaul/fronthaul a large number of small cells. Like an orchestra, the V-HetNet is a polyphony of different communication ensembles, including geostationary orbit (GEO), and low-earth orbit (LEO) satellites (e.g., CubeSats), and networked flying platforms (NFPs) along with terrestrial communication links. In this study, we propose the Terahertz (THz) communications to enable the elements of V-HetNets to function in harmony. As THz links offer a large bandwidth, leading to ultra-high data rates, it is suitable for backhauling and fronthauling small cells. Furthermore, THz communications can support numerous applications from intersatellite links to in-vivo nanonetworks. However, to savor this harmony, we need accurate channel models. In this paper, the insights obtained through our measurement campaigns are highlighted, to reveal the true potential of THz communications in V-HetNets.

I. INTRODUCTION

Flexible wireless communication architectures including small cells, cell-free designs, heterogeneous networks (HetNets), and multi-band connectivity are widely aspired by the telecommunication industry for the user-centric system designs toward 6G and beyond to provide the required quality of service (QoS) levels among users [1]. Even though free-space optics (FSO) and mmWave technology have been discussed over the years, they are not capable of making this dream possible on their own. Terahertz (THz) wireless communication will be one of the critical enablers for 6G since it proposes a solution for the unlicensed band scarcity below 100 GHz and it can be employed by not only macro-scale networks (e.g., inter-satellite links) but also by nano-scale networks (e.g., nanonetworks) [2]. The small cell concept has not been fully deployed yet because of the backhaul and fronthaul cost. It is thought that along with the vertical expansion of terrestrial networks into space, the pervasive connectivity can be provided, as well as the backhaul and fronthaul required by small cell and cell-free topologies [3]. This 3D-network structure, depicted in Fig. 1, is termed as the vertical heterogeneous network (V-HetNet). As THz communications can offer an enormous bandwidth and ultra-high data rates, it stands out among the competing solutions that are likely to be used in V-HetNets. Although the transceiver costs for THz communication are currently high, a cost reduction is expected with the developments in semiconductor technologies.

This study presents an overview of the THz-enabled V-HetNets framework. Below, we explain the motivation behind the THz communications in V-HetNet and address challenges. Also, by interpreting THz channel behavior with measurement results, tips are given on how the system design and requirements will be affected by channel behavior in V-HetNets. Finally, we pinpoint the open issues for the realization of THz-enabled V-HetNets by considering the measurement results.

II. WHY TERAHERTZ BAND?

A. Utilizing the not Fully-explored Frequencies

There is a need to push the carrier frequency beyond the mmWave band to overcome the spectrum scarcity below 100 GHz. The THz band allows wireless communication through tens of GHz bandwidth. Even though the path loss increases with frequency, the antenna gain is related to the square of the operating frequency. Therefore, high gain antennas can cope with the extreme path loss in the THz band. As known, antennas with high operating frequency have relatively narrow beams compared to lower frequencies; hence, THz antennas can be utilized in point-to-point links to backhaul small-cells. Moreover, since the antenna size decreases with frequency, it is possible to place a massive number of antennas on small surfaces. For example, it is possible to cover 1 mm² area with four antennas at 300 GHz. Beyond the massive-multiple-input multiple-output (mMIMO), namely ultra-massive-MIMO (UM-MIMO) [4], can be employed to leverage the communication distance as well as the data rate enhancement.
B. Revolutionary Network Design Towards 6G

1) Cell-free Networking: It is widely acknowledged that an architectural revolution is needed in 6G and beyond [5]. Tiny cells and a cell-free architecture are demanded to cater the data-hungry end-users. In this regard, the high path loss, which is the main drawback of the THz band, can be turned to account for the cell-free design. In other words, the THz band is the region with the highest frequency reuse factor. Thus, it can be concluded that the THz band is ideally suited for the cell-free networking. Not only backhaul from access points (APs) to core network but also links between AP and user equipments can utilize THz waves to build up a cell-free network and satisfy the high data rate for backhaul. To support cell-free networking, a user-centric approach can be adopted for the spatial multiplexing by using UM-MIMO. Additionally, distributed APs are required fronthauling to the central processing unit. Therefore, cell-free networking can utilize the THz waves to avoid fiber construction to every AP.

2) Vertical Heterogeneous Networks: Recently, since aerial APs such as unmanned aerial vehicles (UAVs), NFPs, and high-altitude platform stations (HAPSs) attract considerable attention, there has been a vertical directional expansion in the wireless network, which has not been seen until now. Furthermore, it seems that data flow between satellites and earth will increase more than ever in the coming years [6]. Although a dense satellite network has started to be established with the Starlink project and the Kepler project, the studies in this area are still nascent. FSO and mmWave technologies have been proposed for the inter-satellite and satellite-to-X links. However, mmWave can only serve through a total of 9 GHz bandwidth of the available unlicensed bands. On the other hand, CubeSats are designed for LEO operation, they need to move with a velocity of $28 \times 10^3$ kph to keep their orbits. This velocity necessitates fast beam steering; hence, FSO with a mechanical gimbaled beam steering mechanism is susceptible to track the moving target. However, one face of 1U CubeSat can be theoretically covered by $10^4$ antennas operating at 300 GHz. Furthermore, to the extent allowed by the flight dynamics, the bottom of the NFP’s wings can be covered with thousands of antenna. Therefore, THz enables to fast track a moving receiver with the help of electronic steering.

Also, THz mMIMO setups can be grouped to serve a different number of users according to demand as illustrated in Fig. 2. Thus, it enables the flexible communication network that can be dynamically shaped in conformity with the need [7]. Given the effort of each new generation to make the network more flexible, THz communications has the potential to be a crucial enabler for 6G and beyond.

3) Hybrid Connectivity: Ultra-reliable and low-latency communications in 5G require a high QoS due to stringent requirements on availability and latency. Diversity and network availability increase as the user communicates with more than one AP to improve QoS. We infer that 6G and beyond systems can employ different technologies to enhance the
III. Operational Challenges

Attractive properties of THz wireless communication can make it possible to build up the wireless communication network of the future. Nevertheless, there are many challenges to overcome. The state-of-the-art semiconductor technology cannot generate high power THz waves. However, some promising transceiver designs have been proposed. It seems that a high output power transceiver will be designed by discovering the essence of graphene and complementary metal-oxide semiconductor (CMOS). Although the transmit power of CMOS power amplifiers is about 1-10 mW, they are in line with SWaP constraints [9]. Fortunately, it is possible to design high gain antennas in this spectra to recover the signal power.

In V-HetNets, we do not expect THz waves to suffer a severe loss in inter-satellite communication. The main problem is the operating temperature of the satellites. The temperature fluctuates concerning the position of Earth and Sun. Satellites already have a thermal control system (TCS) to maintain stable operation against changes in operating temperature. However, it may require to review the design of TCS. Recently, NASA Jet Propulsion Laboratory has pushed receiver design limits toward CubeSats. THz-enabled satellite communication in the near future is not pie in the sky.

Since HAPSs fly above the troposphere, which 99% of the water vapor in the atmosphere is at this layer, no severe path loss is expected between HAPSs and LEO satellites. But, the relatively high speed between HAPSs and satellites, and the sharp beam of THz antennas require stringent tracking of transmitter and receiver. The electronic steering functionality of UM-MIMO can provide fast and accurate tracking with the cost of large antenna arrays.

A high attenuation rate is observed between HAPSs and ground stations since water vapor absorbs most of the power semiconductor companies [8]. Therefore, adopting mmWave and THz band communication will stimulate the economy along with supporting data rates in the Tbps regime, novel usage scenarios, and applications. Thus, network operators exhibit particular interest in the proper adoption of the THz band communication, which can further reduce the total cost of ownership, capital expenditures, and operational expenditures. Deploying a macro base station in a crowded and populated location such as downtown and providing seamless high-speed data rate connectivity to the remote islands and rural/suburban areas can be quite challenging and also very expensive due to the harsh geographical conditions. Thus, extending the wireless connectivity with the help of existing infrastructure to the areas beyond the reach of the fiber line by using the THz band is anticipated to reduce the total cost. First, no additional or significant upgrades are needed for the backhaul traffic by the network operators since already existing infrastructure will be used for the traffic offloading which will ease the traffic congestion problem. Second, as for the software and hardware of the radio access network, there is no need for extreme modifications. Furthermore, the recent advances in the semiconductor technology enable to design at THz frequencies; thus, antenna and chip can be integrated into the same package, which will reduce the production cost.

C. Applications from Planetary-scale to Nano-scale

In the V-HetNet framework toward 6G and beyond, it is envisioned that the world, which was previously connected by ground and undersea fiberoptic cables, is now connected over a wide space network. The near future communication technology pushes the limits of science-fiction. With the development of e-health technologies, billions of nanodevices and sensors need to be connected with a unified and seamless network. It is envisaged that using the THz band at the vertical network will be useful to meet the latency and data rate required by e-health and haptic applications. For example, the THz band paves the way for unprecedented applications initially suffering from the size, weight, and power (SWaP) constraints. The size of nanomachines can only be satisfied by the THz antennas. As illustrated in Fig. 1, THz waves can be employed in the harmony of nanonetworks, body area network (BAN), and wireless local area network (WLAN). For instance, nanomachines communicate with each other and sensors with THz waves. BAN can utilize either THz or mmWave (e.g., WiGig). The backhaul of AP can be a directional THz beam.

D. Economic Feasibility

To achieve resilient and reliable connectivity, mmWave and THz band connection are needed as described in Section II. Furthermore, the mmWave technology market in the telecommunication industry, which is anticipated to reach $10.92 billion by 2026 with a growing compound annual growth rate of 36.3% per year, along with the corresponding industrial ecosystem, makes it attractive for the network operators and

QoS levels. For example, in the THz band, different sub-bands/windows can be used for communication at the same time, or complementary technologies such as mmWave, FSO, and THz can be used simultaneously.

Fig. 2. THz networks can employ ultra-massive antenna arrays; hence, it can be turned into an advantage by dynamically adjustable beam pattern and multiple spot flexibility.
of the THz wave, and the region where the water vapor is most dense in the atmosphere is up to 20 km above the Earth. The atmospheric attenuation coefficient at 300 GHz is around 3 dB/km and 30 dB/km for very light and dense humidity levels, respectively. The attenuation coefficients imply that the THz wave is much more advantageous than FSO in terms of path loss [3, 10].

Another challenge lies in UAV communication because of the nature of UAVs. UAVs with high mobility vibrate slightly, even when they are suspended in the air, due to flight aerodynamics. This poses a serious challenge to THz communication, which has a very narrow antenna beam. The loss due to misalignment between THz antennas is known to be severe [11]. The beam search may take a long time after the antenna alignment deteriorates due to the narrow beams of the antennas. At this point, we think that it would be appropriate to make THz communication with wider beams using beam broadening. Also, the phased array can be adaptively controlled with the help of a Kalman filter and gyroscope on the UAV; however, this can cause energy scarcity for battery-dependent UAVs.

As high data rate THz pulses have very short-times; multipath components may not overlap with the first-path component. However, the propellers’ periodic behavior may give rise to rotor modulation. As the wavelength is much smaller than propellers, a simple blockage model can be utilized to analyze the effect of the rotor modulation.

There are additional challenges that may occur in each layer of V-HetNet. Some of these include beam steering, high-performance computation, and low-complexity tracking. Also, ultra-large antenna array configuration, mutual coupling among antennas, and correlation among sub-channels should be jointly considered in the design of UM-MIMO [12].

One of the main challenges is to estimate the propagation channel for UM-MIMO THz communication. Since it is expected to use multiple-input multiple-output (MIMO) systems with thousands of antennas, novel intelligently designed channel acquisition algorithms are needed. Deep learning (DL)-based channel estimation techniques can be utilized ubiquitously. The sparse nature of THz wireless channels allows with thousands of antennas, novel intelligently designed channel acquisition algorithms are needed. Deep learning (DL)-based channel estimation techniques can be utilized ubiquitously. The sparse nature of THz wireless channels allows
distributed channel estimation methods that can be used for large-scale MIMO systems. These methods leverage the sparsity and low complexity of THz wireless channels, making them suitable for high-data-rate communication systems.

It is worth stating that intelligent spectrum sharing protocols are in high demand by THz V-HetNets owing to the fact that hundreds of billions of devices will be connected. Deep reinforcement learning (DRL) and blockchain are promising techniques to meet this demand.

IV. OVERVIEW OF MEASUREMENT STUDIES
A. Channel Modeling Methodologies

Having fully operational next-generation communication systems should start with obtaining a detailed knowledge about the properties of the propagation channel. Wireless channel modeling is mainly categorized under two approaches: deterministic and stochastic methods. The deterministic methods are propagation medium-specific. They require the model of the environment in-depth with the material characteristics and dimensions. Even though they pose an accurate channel model for a given environment, the computation complexity is extremely high, and it exponentially increases with the dimensions of the environment. Ray-tracing is the most used deterministic technique for channel modeling. Ray-tracing models the scattering, diffraction, and reflection effects in with geometric optics that become more accurate due to the stronger corpuscular behavior in the THz band [12]. Finite-difference time-domain, method of moments (MoM), and finite element method (FEM) are some of the other deterministic channel modeling techniques. Since MoM and FEM are working in the frequency domain, these methods do not seem to be the best approach as they require excessively complex computations in channel modeling for a huge THz band.

Unlike deterministic modeling, stochastic channel modeling aims to create a channel model independent of the environment as much as possible. For this purpose, a statistical average of many measurements is used to create the channel model. For the stochastic channel modeling, measurements are usually carried out with a vector network analyzer (VNA) or channel sounder. The main difference between these devices is the domain where they perform operations. Channel sounder computes the channel impulse response by using an uncorrelated m-sequence, but VNA composes many narrowband measurements to create channel transfer function. VNA performs more accurate channel modeling due to calibration for each narrowband and encountering low noise, but the measurement time is long [13]. Another difference is that VNA-assisted measurement does not require extra clock synchronization due to two ports in the same device, whereas channel sounder requires a strict external clock to sync two distinct ports.

Due to the presence of the colossal bandwidth, multipath components can be distinguished. The nature of the THz band leads to severe frequency selectivity. As a result, conventional small scale flat fading models are not appropriate, and the broadening effect cannot be ignored.

It is shown that the cluster behavior is encountered in the time of arrival distribution, which is assumed as a Poisson process by the Saleh-Valenzuela model, can be modeled with the Gaussian mixture model (GMM) [12]. We suggest using the Dirichlet process mixture and GMM to find the number and parameters of mixtures.

B. Measurement Setup and Results

In this section, we detail the THz measurement campaigns and results. Firstly, VNA-assisted measurements are carried out to observe THz channel behavior with high spectral resolution. Afterward, pulse-based measurements for short-range THz communication will be addressed since on-off keying (OOK) is seriously envisaged for use in THz wireless communications [14]. The VNA-assisted measurement provides high spectral resolution at the cost of long measurement time while the pulse-based method lacks high resolution, but it allows taking measurements in a short time.

1) VNA-assisted Channel Modeling: An experimental measurement setup is constructed in the anechoic chamber with dimensions of 7m × 3m × 4m as seen in Fig. 3. To eliminate
the specular effects, the perimeter of the system is covered with absorbent material. The measurement setup consists of a VNA, WR-03 waveguided extension modules, and an extender controller. WR-03 extension modules expand the VNA, whose upper limit is 67 GHz, to THz band by multiplying RF input signal with 18. It should be noted that in cases where an extender module is used, it should be preferred to use as few frequency multipliers as possible. This is observed due to the increasing number of striking, phase distortion, and intermodulation product effect increases. A single multiplier, if possible, is preferred to avoid mentioned distortions. The extender module employed in this setup includes only one frequency multiplier.

Driving VNA with the input signal in between 13.34 GHz and 16.67 GHz results in THz waves with carrier frequencies in between 240 GHz and 300 GHz. To protect the phase and amplitude stability, instead of using all the band provided by the extender, measurement is taken in the band between 240 and 300 GHz by not using the edge points of the band [11]. The IF signals downconverted at transmitter and receiver are used to find channel transfer function by comparing them to acquire scattering parameters (i.e., $S_{21}$). VNA-assisted channel modeling provides high-frequency resolution by taking measurements. In this setup, 4096 frequency points are employed within the operation band demarked by the VNA. As a result, 14.648 MHz spectral resolution is provided by the measurement setup.

By using measurement results, the frequency dependency of the path loss is revealed in [11]. The measurement results indicate similar channel behavior at varying distances. However, the loss in some frequency intervals is higher than in others. For example, there is a noticeable reduction in the power of the received signal between 270 GHz and 290 GHz. As stated above, antenna alignment is crucial for THz communication because of the relatively narrow beamwidth. It is shown that the pointing error in antenna alignment gives rise to a sharp fall in the received power. Since the received power decreases exponentially, it is reasonable to model this decay as an exponential distribution. The pointing errors between receiver and transmitter are pointed as challenges in Section III. Thus, how pointing error degrades the received power is investigated by tilting the antennas. As seen in Fig. 4, the antenna misalignment causes a decrease in the received peak power. The power decrease concerning the peak power corresponding to the line-of-sight (LOS) path is approximately 2.3 dB and 13 dB for 10° and 20° tilts, respectively. These results clearly demonstrate the need for precise alignment between the transceivers. Similar to [10], the humidity has no significant effect on the received signal power. In the light of measurement results, it is proved that THz-enabled V-HetNets strictly need an accurate resolution in the beam steering as well as beam broadening before fine-tuning. Despite the low attenuation in this band due to humidity, it is known that spectral lines are created by water vapor out of this window. Moreover, Mie-scattering owing to rain droplets and fog attenuation must be considered in the V-HetNet design.

2) Pulse-based Channel Modeling: As OOK modulation is mainly considered for THz communication, specifically in nanonetworks, we prepare a measurement campaign to analyze the channel behavior for a pulse train [15]. The measurement setup detailed above is used without change except for using a signal generator and a spectrum analyzer rather than VNA. As two ports are on distinct devices, the synchronization is ensured by connecting the reference clock of the signal generator to the external clock input of the spectrum analyzer via a cable. The band between 275 GHz and 325 GHz is measured by feeding the extender module with a pulse train generated by the signal generator. The width of the pulse is limited with a minimum of 140 ns due to signal generator capability. At the receiver side, the pulse train is recorder during 1ms by taking 100, 000 I/Q samples. The study focuses on path loss relations with frequency and distance. In this regard, Fig. 5 denotes both frequency and distance related path loss. The same pattern through the band is observed for each range. It is shown that relatively short-distance communication is more exposed to frequency selectivity. This severe frequency selectivity plays an important role when choosing multiple access technology. For example, code-division multiple access suffers from high-cost equalizer to recover the received signal. However, we
strongly believe that subcarrier-based access technologies, like orthogonal frequency division multiple access, are suitable to employ in the THz networks. Yet, it is seen that peak-to-average power ratio reduction methods are required owing to an excessive number of nodes.

Due to frequency dependency, the linear path loss model may not be adequate in such a wide band. We denote that the path loss obeys the two-slope model [15]. It is the evidence that the distance is another determinant along with frequency for the channel model as distinct from lower frequency bands. By employing the two-slope model, the normalized received power is illustrated in Fig. 6 for the unit power transmitter at 300 GHz. These results imply that the distance-dependent channel characteristics require distance-aware medium access control (MAC) to control physical layer parameters such as modulation order and coding rate.

The high frequency reuse factor due to high path loss enables the design of small cell networks and cell-free architectures. The measurement results point that the most challenging part of THz-enabled V-HetNets is the link between HAPs and terrestrial APs as the main path loss arises through the long distance, where the majority of water molecules in the atmosphere are found and the antenna alignment is compelling over the long-distance. Because of the frequency selectivity, the THz band can be divided into sub-bands; thus, using different sub-bands can support the multiple connectivities in the V-HetNets.

V. OPEN ISSUES AND RESEARCH DIRECTIONS

a) Cell-free Networking: To construct the user-centric network of the future, it is required to satisfy a decentralized seamless connection. Therefore, promising tools such as Radio Stripes, metasurfaces (e.g., reconfigurable intelligent surfaces), and holographic beamforming need to meet THz wireless communication. Moreover, DL can be employed for the efficient operation of cell-free networks (e.g., controlling transmitter power in UM-MIMO).

b) Software-defined and Self Organizing Networks: The software-defined network and self-organizing network pave the way for not only ubiquitous connection but also low-cost network operation. They require dynamic MAC, spectrum sharing, and spectrum switching. DL, and DRL enable to improve the elasticity of networks by considering feedback from the medium to find optimal network policy. Moreover, federated learning allows to distribute the computation cost over the thousands of the connected devices, and therefore the central processing unit may not be needed. On the other hand, multi-band antennas and RF chains are required to support spectrum switching.

c) Channel Modeling and Estimation: In some situations, the LOS link may not be available, and the communication may be carried out through a non-line-of-sight link; hence, reflection and scattering of THz waves must be investigated in the V-HetNet framework. There is not sufficient amount of studies to model the spatial correlation in UM-MIMO channels. For this purpose, it seems possible to develop low-complexity methods with compressed sensing by utilizing the sparsity of THz channels. Also, it is expected that DL-based approaches will be useful for understanding channel characteristics. For instance, generative adversarial networks are able to generate infinitely many channel states, so we can model the channel estimation methodology, which is due to the effect of fast changes in channel characteristics. It is noted that the weather conditions such as rain, fog, and clouds have crucial impacts on the channel characteristics in backhaul and fronthaul of 6G V-HetNet. Therefore, the weather conditions should be considered in the models. Although the channel modeling document by IEEE 802.15.3d Task Group points to some weather impacts on the channel, it needs further investigation.

VI. SUMMARY

THz-enabled V-HetNets provide not only ubiquitous connection but also relatively low-cost dense networks. As pro-
ACKNOWLEDGEMENT

We are grateful to Dr. Serhan Yarkan, Emre Ulusoy, and the staff of TUBITAK Millimeter-Wave and Terahertz Technologies Research Laboratory for their support during the measurements.

REFERENCES

[1] P. Yang, Y. Xiao, M. Xiao, and S. Li, “6G Wireless Communications: Vision and Potential Techniques,” IEEE Network, vol. 33, no. 4, pp. 70–75, Jul. 2019.

[2] K. Tekbıyık, A. R. Ekti, G. K. Kurt, and A. Görçin, “Terahertz Band Communication Systems: Challenges, Novelities and Standardization Efforts,” Physical Communication, vol. 35, Aug. 2019.

[3] M. Alzenad, M. Z. Shakir, H. Yanikomeroglu, and M.-S. Alouini, “FSO-Based Vertical Backhaul/Fronthaul Framework for 5G+ Wireless Networks,” IEEE Commun. Mag., vol. 56, no. 1, pp. 218–224, Jan. 2018.

[4] I. F. Akyildiz, C. Han, and S. Nie, “Combating the Distance Problem in the Millimeter Wave and Terahertz Frequency Bands,” IEEE Commun. Mag., vol. 56, no. 6, pp. 102–108, Jun. 2018.

[5] S. Chen, Y.-C. Liang, S. Sun, S. Kang, W. Cheng, and M. Peng, “Vision, Requirements, and Technology Trend of 6G: How to Tackle the Challenges of System Coverage, Capacity, User Data-Rate and Movement Speed,” IEEE Wireless Commun., pp. 1–11, Feb. 2020.

[6] I. F. Akyildiz and A. Kak, “The Internet of Space Things/CubeSats,” IEEE Network, vol. 33, no. 5, pp. 212–218, Sep. 2019.

[7] C. Lin and G. Y. L. Li, “Terahertz Communications: An Array-of-Subarrays Solution,” IEEE Commun. Mag., vol. 54, no. 12, pp. 124–131, Dec. 2016.

[8] Stratistics Market Research Consulting Pvt Ltd, “Millimeter Wave Technology - Global Market Outlook (2017-2026),” Available: https://tinyurl.com/87r2uqz. Accessed on Apr. 20, 2020.

[9] A. Tang, T. Reck, and G. Chattopadhyay, “CMOS System-on-Chip Techniques in Millimeter-Wave/THz Instruments and Communications for Planetary Exploration,” IEEE Commun. Mag., vol. 54, no. 10, pp. 176–182, Oct. 2016.

[10] G. A. Siles, J. M. Riera, and P. Garcia-del Pino, “Atmospheric Attenuation in Wireless Communication Systems at Millimeter and THz Frequencies,” IEEE Antennas Propag. Mag., vol. 57, no. 1, pp. 48–61, Feb. 2015.

[11] A. R. Ekti, A. Boyaci, A. Alparslan, I. Unal, S. Yarkan, A. Goricin, H. Arslan, and M. Uysal, “Statistical Modeling of Propagation Channels for Terahertz Band,” in IEEE Conf. on Standards for Communications and Networking (CSCN), 2017, pp. 275–280.

[12] C. Han and Y. Chen, “Propagation Modeling for Wireless Communications in the Terahertz Band,” IEEE Commun. Mag., vol. 56, no. 6, pp. 96–101, Jun. 2018.

[13] B. Peng, K. Guan, A. Kuter, S. Roy, M. U. Patzold, and T. Kuerner, “Channel Modeling and System Concepts for Future Terahertz Communications: Getting Ready for Advances Beyond 5G,” IEEE Veh. Technol. Mag., pp. 2–9, Mar. 2020.

[14] J. M. Jornet and I. F. Akyildiz, “Femtosecond-Long Pulse-Based Modulation for Terahertz Band Communication in Nanonetworks,” IEEE Trans. Commun., vol. 62, no. 5, pp. 1742–1754, May 2014.

[15] K. Tekbıyık, E. Ulusoy, A. R. Ekti, S. Yarkan, T. Baykas, A. Görçin, and G. K. Kurt, “Statistical Channel Modeling for Short Range Line-of-Sight Terahertz Communication,” in IEEE Int. Symp.on Personal, Indoor and Mobile Radio Communications (PIMRC), 2019, pp. 1–5.

BIOGRAPHIES

KÜRAT TEKBİYİK [StM’19] (tekbiyik@itu.edu.tr) is pursuing his Ph.D. degree in Telecommunication Engineering at Istanbul Technical University and is also researcher at TUBITAK BILGEM.

ALI RIZA EKTİ received Ph.D. degree in Electrical Engineering from Department of Electrical Engineering and Computer Science at Texas A&M University in 2015. He is currently an assistant professor at Balikesir University and also senior researcher at TUBITAK BILGEM.

GÜNEŞ KARABULUT KURT [StM’00, M’06, SM’15] (skurt@itu.edu.tr) received the Ph.D. degree in electrical engineering from the University of Ottawa, Ottawa, ON, Canada, in 2006. Between 2005 and 2008, she was with TenXc Wireless, and Edgewater Computer Systems, in Ottawa Canada. From 2008 to 2010, she was with Turkcell R&D Applied Research and Technology, Istanbul. Since 2010, she has been with ITU. She is also an Adjunct Research Professor at Carleton University. She is serving as an Associate Technical Editor of IEEE Communications Magazine.

ALİ GÖRCİN received his Ph.D. degree in University of South Florida (USF) on wireless communications. He worked for Anritsu Company during his tenure in USF and worked for Reverb Networks and Viavi Solutions after his graduation. He is currently holding an assistant professorship position at Yildiz Technical University in Istanbul and also serving as the vice president of TUBITAK BILGEM.

HALIM YANIKOMEROGLU [F] (halim@sce.carleton.ca) is a full professor in the Department of Systems and Computer Engineering at Carleton University, Ottawa, Canada. His research interests cover many aspects of 5G/5G+ wireless networks. His collaborative research with industry has resulted in 36 granted patents. He is a Fellow of the Engineering Institute of Canada and the Canadian Academy of Engineering, and he is a Distinguished Speaker for IEEE Communications Society and IEEE Vehicular Technology Society.