Recent Trends in Terahertz Communication: Applications and Open Research Problems

Anusaya Swain
Department of Electronics and Communication
National Institute of Technology Rourkela
Odisha, India
520ec1008@nitrkl.ac.in

Shrishail M. Hiremath
Department of Electronics and Communication
National Institute of Technology Rourkela
Odisha, India
hiremaths@nitrkl.ac.in

Koushik Batchu
Department of Electronics and Communication
National Institute of Technology Rourkela
Odisha, India
batchukoushik@gmail.com

Vijay Kumar
Center for Nano Science and Engineering
Indian Institute of Science Bangalore
Bangalore, India
vijayk@iisc.ac.in

***Abstract*—Over the past years, the demand to meet the bandwidth requirement forces us to increase the carrier frequency used for wireless communication. To fulfill the rapid increase of mobile data demand the research community addressed the development of wide radio bands such as millimeter wave (mmW) frequencies and others were attracted towards the optical communication frequency which allowed high data rates, better physical security, and avoids the interference of electromagnetic waves. With an exponential rise in the data traffic the terahertz frequency band seems to be promising to support the next generation wireless network beyond fifth-generation (5G) as well as bridging a gap between optical frequency range and millimeter wave frequency range. This paper provides a review on key technologies encountered in THz wireless communication systems such as channel modeling, beamforming, and beam tracking using Massive MIMO and use of artificial intelligence (AI) based framework to meet the future demands for future generation networks and also provide a case study on THz channel modeling using the machine learning technique. It also throws light on the challenges faced in THz communication.**

***Index Terms*—Terahertz, beamforming, channel estimation, Massive MIMO, channel modeling.**

I. Introduction

With an exponential rise in the data traffic, the terahertz (THz) frequency band seems to be promising to support the next generation wireless network beyond fifth-generation (5G) as well as see through the gap between optical frequency and millimeter wave frequency range. The THz bands are envisioned to achieve a data rate in the order of gigabits per second. The communication using THz band will mitigate the problems related to scarcity in the spectrum and in addition to that there will be increment in capacity of wireless communication systems. The problem in transceiver design is slowly getting solved due to recent advancements in electronic, plasmonic, and photonic technologies. Still, there are many limitations of THz specific transceiver architecture in terms of design and development. Some of the communication challenges like waveform design, modulation schemes, channel modeling, beamforming, channel estimation, coding, and detection which needs to be thoroughly investigated so that it can give better performance and can be practically deployable in near future. Therefore, efficient signal processing techniques in the baseband need to be developed and analyzed [1].

The wireless data rate has doubled every 2 years and hence there is a demand for bandwidth to achieve ultra high data rate in wireless communication systems [2]. For satisfying the increasing high data rates in wireless communication, advanced modulation schemes as well as signal processing techniques has to be used which will increase the spectral efficiency which in turn enhances the network capacity [3]. Even with the advancement of physical layer and improving the hardware components such as antennas, transceivers, detectors, sources, etc, it is impossible for the traditional communication system to accomplish a data rate of 100 Gigabits per second and even several terabits per second [6]. With this rate of growth of wireless traffic and to fulfill the users accelerating demands, an interest to find a suitable frequency band in the radio spectrum has come in the research fraternity [9].

The millimeter wave (mmW) communication scheme is presently considered for fifth generation networks which is able to provide a bandwidth ranging from hundreds of megahertz to several gigahertz but are not sufficient to fulfill the requirement of increasing data traffic for the forthcoming wireless communication. In addition to that, the researchers are attracted towards the free space optical (FSO) communication because of its large bandwidth, less power consumption and license free spectrum. The drawbacks related to FSO is that the communication using this frequency range is highly affected by environmental conditions like cloud, fog. There is a difficulty in beam forming, suffered from high diffusion reflection loss, high background noise, and have a limited power budget.

To enable the ultra high speed communication beyond the 5G terahertz (THz) frequency band seems to be promising. The frequency range of terahertz varies from 100 GHz to 10 THz which falls in the boundary region between optical frequency and radio frequency. The terahertz band is also called sub millimeter band and has a wavelength between 3 millimeter and 30 micrometers. The advantages of terahertz frequency band is that it provides high bandwidth, good high link directionality, chances of less eavesdropping, can be used as a good substitute under inconvenient environmental conditions. They are highly preferred for communication in uplink and non line of sight communication. Other advantages of this frequency range include easy detection, penetration into opaque materials and provides high selectivity to the molecules which have resonance frequencies within THz band. At present three major technologies are used for ultrahigh speed transceivers in THz band and they are Graphene, Galium-Nitride (GaN), and Silicon-Germanium (SiGe). THz band is insensitive to the effects of atmosphere in outdoor wireless communication. It is easy for tracking the beam in THz band than in optical frequency band which highly affects the mobility capability of the wireless communication systems.

Another advantage is that this frequency band uses reflection paths for enhancement of the link gains in indoor related applications. To achieve the 100 Gigabits per second many groups were formed and many projects were initiated like Third Generation Partnership Project (3GPP), task Group 3d (TG3d), Wireless Area Networking of THz Emitters and Detectors (WANTED) plan, etc. There are wide variety of applications like wireless data centers, backhauling/ fronthauling as well as close-proximity communication such as kiosk downloading and device-to-device communication [9]. Many countries worldwide are investing and working to contribute to the practical application of 5G and beyond.

The rest of the paper is organised as follows: Section II discusses the system model. An overview of the key technologies of terahertz communication is provided in Section III. In Section IV, applications related to THz communication are discussed and a case study on THz channel modeling using machine learning is described in section V along with simulation results. Challenges and research opportunities are discussed in section VI. And finally, the paper is concluded in section VII.

II. SYSTEM MODEL

A system model of typical THz communications is shown in Fig. 1. At this infant stage, it is very challenging to describe a general system model for terahertz communications. As the dynamic array gains are important in reducing the distance problem the Array of subarrays (AoSAs) antenna elements tends to be a benchmark in future THz systems. The transmitter and receiver sides are configured with adaptive AoSAs. Each sub array is fed with a dedicated radio frequency chain after every digital to analog converter and before every analog to digital converter. In multi user configuration, each sub array is detached from its neighboring sub arrays due to high directivity. Sub array paths may be highly correlated in a point to point setup due to low spatial resolution [1].

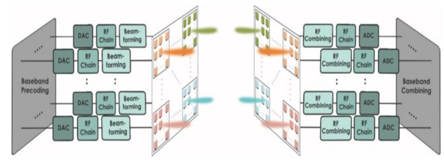

Fig. 1. System Model of THz Communication [9].

III. KEY TECHNOLOGIES IN THZ COMMUNICATION

Efficient signal processing techniques are required for two reasons. Firstly, it should be able to account for the usage of massive MIMO antenna systems as well as overcome the short distance communication. Secondly, it must mitigate the mismatch between the THz bandwidth and digital baseband system. Some of the key technologies in which research are required for the future feasibility of THz communication includes channel modeling, beamforming, channel estimation, novel waveforms for THz.

A. Channel Modeling

For maximization of THz bandwidth allocation and to improve the spectral efficiency it is important to establish efficient channel modeling which will help for the characterization of channel and propagation measurements. Till now THz wireless communication systems have been applied to indoor communications within short range distance because THz waves experience free space attenuation and loss due to molecular absorption. For the line of sight (LOS) link, due to spreading and molecular absorption loss it results in high amount of frequency selective path loss. The molecular absorption is caused due to molecular resonances because of oxygen and water vapor. Similarly, in non line of sight (NLOS) propagation, THz propagation gets affected by reflection loss which depends on the shape, roughness, and material of the surface [3]. First of all THz propagation has to be modeled for LOS, NLOS, diffracted, reflected, and scattered path as well as static and time varying channel scenarios have to be taken into account and then the antenna arrays which largely influence channel properties has to be considered. In [3], an equivalent deterministic channel model was developed which considers both NLOS and LOS propagation. In [3], they have used ray tracing simulation approach and Kirchhoff's scattering theory to analyze the impact of molecular loss, reflection loss, and channel capacity for both LOS and NLOS propagation in the frequency range 0.1 to 1 THz using updated molecular High Resolution Transmission (HITRAN) 2012 database. THz measurement results within the 240GHz – 300GHz band for short range LOS channels are provided in [4]. In [5], they discussed different methodologies in channel modeling which are categorised as statistical, deterministic, and hybrid. The deterministic approach is site-specific, which requires detailed geometrical information of the environment in which it is propagating, spatial positions of the receiver and transmitter and properties of materials. In this type of

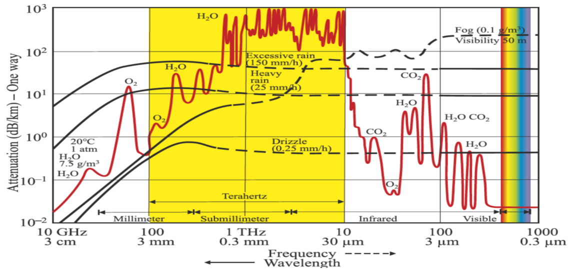

Fig. 2. Comparison of the attenuation impacts of different environmental effects at different frequencies [2].

modeling ray tracing approach and Finite Difference Time Domain (FDTD) [5] which is also called as Yee's method is used. A statistical method uses random processes and distributions for modeling of the channel parameters which comprises of the number of paths, delay, path gain and coupling and is also not site-specific and obtained mostly depending on empirical measurements. Therefore, a model of the statistical impulse response is needed to be evolved in the band of THz frequency, instead of reusing narrow band fading models like Rician or Rayleigh. Deterministic channel modeling has high accuracy but consumes more time and resources and on the other hand statistical modeling has low accuracy as well as low computational complexity. So, Hybrid methods seems interesting in which a stochastic scatterer placement and RT hybrid approach (SSRTH) can be developed. In our case study, we discussed ML based channel modeling.

B. Beamforming in THz

The important point in beam forming technique is to maximize the gain of the antenna by finding the optimal precoding and combining vectors. As an individual antenna will be having a fixed radiation pattern but antenna array can change their radiation pattern during transmission and reception in both time and frequency domain [2]. In beam tracking it is important to collect the accurate angle of departure of transmitter and accurate angle of arrival of receiver. In this technique, the transmitter has to send training bits in sequence in a particular direction and then the receiver will be able to do the estimation of the angle of departure according to the received signals. These antennas are used in mobile broadband services, application related to communications like ultra reliable communication, low power machine type and non communication related applications like radar, positioning, and sensing. The number of paths and beams in THz are more sparse as compared to millimeter waves. In [2], they have discussed five Massive MIMO related research directions that is Six-dimensional positioning, Extremely large aperture arrays, Large-scale MIMO radar, Holographic Massive MIMO, and Intelligent Massive MIMO. They have discussed the concepts and vision behind those Massive MIMO techniques and have threw light on some of the open research areas related to that. The limitations of transmission loss in THz wave is high path loss and molecular absorption in the atmosphere due to water and oxygen. So, to compensate for the high transmission loss between transmitter and receiver high gain antennas are required [9]. So, we need large-scale phased array antennas for THz communication system. This type of antenna can concentrate the electromagnetic energy in a particular direction. This is done by using the beam interference criterion which adjusts the phase and amplitude of the array elements. High gain and high directivity beams can be generated by using array antennas.

C. Channel Estimation

To accurately direct beams by avoiding the misalignment issues and to carry out beamforming mechanism, accurate channel state information is necessary which makes channel estimation in THz extremely challenging. The study of the effect of atmospheric absorption on high frequency signals is important. Fig. 3 shows how the frequency bands suffer from attenuation over distance due to atmospheric absorption. THz and mmWave suffer less loss in comparison to sub 6 GHz bands. The loss may be less than 10dB/Km of extra loss than what is caused by the propagation in free space upto 300 GHz. These frequency bands of mmWave and THz can be considered for high speed mobile networks in 6G even upto 10 Km or beyond. Many techniques are considered to decrease the complexity of channel estimation in THz like fast channel tracking algorithms, compressed sensing based techniques, learning based techniques etc, [1]. In high mobility scenarios fast channel tracking [10] can be used as an alternate option to reduce the estimation overhead for THz beamspace massive MIMO. Electronically steered directional antennas with high gain can overcome this attenuation in atmosphere which indicates that the mobile industry can work well upto 800 GHz in the future [11]. In [17], channel estimation approaches such as least square (LS) and minimum mean square error (MMSE) are used to estimate the second-order statistics of the THz channels. Joint activity detection and channel estimation technique is used in [18] to decrease the number of pilots and computations complexity in wideband random massive access THz systems. After successful implementation of compressed sensing techniques in millimeter wave frequency band [19], the technique is used for estimating the channel in THz.

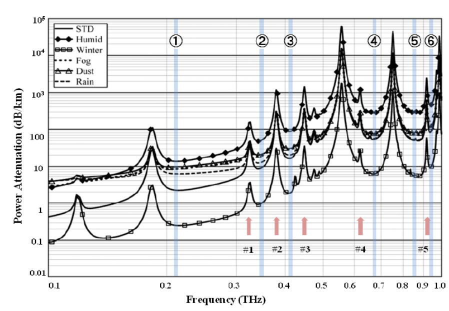

Fig. 3. Atmospheric absorption of electromagnetic waves at sea level vs frequency under various conditions of humidity [7].

D. Novel Waveforms for THz-Band Communication

There are several multiple access techniques like OFDMA, CDMA, FDMA, TDMA for radio access technologies of mobile cellular communication. LTE, LTE-Advanced, OFDMA, SC-CDMA was adopted for 4G communication. But more advanced waveforms are required for terahertz in future 5G and beyond. Recent research has proposed the use of ultra-broadband pulses which are a few hundred femto seconds long which benefits us to have orthogonal channels and minimum overhead on the users. In addition to that, it maximizes the capacity and minimizes the transceiver complexity but poses challenges for the designing of ultra-broadband antenna arrays. Energy efficiency is the advantage in THz massive MIMO systems but a high peak to average power ratio (PAPR) works against this concept. A recent study showed the use of single carrier modulation (SCM) without an equalizer in a receiver to achieve the near optimal sum rate performance in massive MIMO systems which operate at low transmitter power to receiver power ratio and is not dependent on channel delay profile [1]. This is suitable for energy efficiency as SCM can achieve better PAPR performance. But implementation of SCM in THz needs tight timing constraints in the order of nanoseconds or less which is not feasible. Therefore, there is a trade offs in using SCM in THz massive MIMO systems.

IV. APPLICATIONS

Sensing: THz enabled sensing applications to make use of both wide channel bandwidth at above 100 GHz ie., sub mm wavelength, frequency selectivity as well as absorption properties of various materials. THz enables numerous sensing based applications security body scanning, health monitoring systems, spectrometer for detection of explosives, gas sensing, miniaturized radars for gesture detection, wireless synchronization etc, and can also be applied to commercial applications such as transportation and shopping [12].

Imaging: Light Detection and Ranging (LIDAR) can provide high resolution but can't work when the weather conditions are foggy, raining, or cloudy. But as the THz channel does not get much affected by weather or ambient light so radar with frequencies in THz band are more productive to infrared or light based imaging such as LIDAR. THz radar can be used for flying in bad weather conditions making it suitable for military purposes as well as for national security. THz waves acquire many beneficial traits from microwave and visible light such as high bandwidth and small wavelength which helps in high resolution images with moderately sized imaging systems [12].

Space Applications: In contradiction to the THz communications on the ground, the space applications in the free environment of the atmosphere do not suffer from the atmosphere attenuation, which is vital for the space communications in THz band. Further, the THz wave systems can provide much higher bandwidth resources than the traditional microwave and mmWave systems, and the attenuation of THz wave systems compared with the laser communication systems is smaller under the harsh environment such as rain, fog, haze, and battlefield [13].

The inter-satellite links between low earth orbit (LEO) and geostationary (GEO) satellites and the links between LEO and GEO satellites can be provided by THz systems. For high reliability of communication depending on various factors such as weather conditions and the location the microwave, millimeter wave, free space optics along with THz can be used practically to provide links between satellite and earth [1] [13].

Wireless Cognition: It is a concept of communication link allowing the machine or devices working in real time scenario to do huge computations remotely. For instance, a drone fleet might not have a power budget to carry out huge computations. But with the help of wide bandwidth, real time computations to carry out complex tasks, fast data rate, perception might be executed at a particular fixed base station which supports real time cognition and wireless connection for the drone fleet. Therefore without the availability of local cognition platform robots, autonomous vehicles can be designed in the same way to perform cognitive processing remotely [12].

Automotive Applications: Unmanned aerial vehicles are available to the public commercially and also for civilian purposes such as weather control, traffic detection, forest fire recognition, communication broadcasting etc,. For heights above 16 Km the impact of moisture is imperceptible hence making the THz attenuation trivial. Due to the massive bandwidth available in THz systems, it helps in protection against various attacks like jamming and eavesdropping. In addition to that, THz links can also be used for the communication between airplanes and UAVs to help in providing internet availability for the flights rather using the satellite services [6] [9].

V. CASE STUDY: MACHINE LEARNING-BASED CHANNEL MODELLING IN TERAHERTZ

Under complex scenarios such as unknown channel properties, low latency requirement in dense networks, the conventional method find it difficult for reliable communication. The approach based on deep learning helps us in designing communication systems without even having accurate knowledge of mathematical models where the common channel equalization and estimation techniques find difficult to describe mathematically [8]. To solve large scale communication problems with a large number of antennas and users, deep learning has attracted a numerous researchers and it is because of its parallel architecture and high computation capability [14]. For characterization and propagation measurements of the channel, it is essential to carry out the modeling of channel. This, in turn, will enhance the spectral efficiency and the bandwidth.

Several attempts for channel modelling based on machine learning have been beneficial in understanding the properties of the channel like blockage prediction, classification of LOS and NLOS environment etc,. To classify Line of Sight (LOS) and Non Line of Sight environment Support Vector Machines (SVM) is used [15]. To predict the blockage in sub 6 GHz channels a deep neural network is used in [16]. In this section we present modeling of terahertz channel using neural network. The channel parameters are generated using ”NYUSIM: The Open Source 5G and 6G Channel Model Simulator software”, Version 3.0 [20].

A. Simulation Results

We have considered an indoor scenario with both Non line of sight (NLOS) and Line of sight (LOS) environment and the specifications of the channel is given in Table I.

TABLE I
SPECIFICATIONS OF CHANNEL PARAMETERS

SlNo	Parameters	Value
1.	Frequency	100 GHz
2.	RF Bandwidth	800 MHz
3.	Distance	50 m
4.	Tx and Rx Array Type	ULA
5.	No of Tx and Rx antenna Elements	64

Using the parameters given in Table I, we have collected the received power (dBm) values from the Power Delay Profile of the channel. We have considered a multi layer perceptron network which includes an input layer, 25 number of hidden layers and an output layer. Given input and output data, finding the best MLP network is what termed as the data fitting problem. Here we are trying to fit the output of the MLP network with the measured values of the received power obtained from the power delay profile of the channel. The simulated results are shown in Fig.4 and Fig. 5.

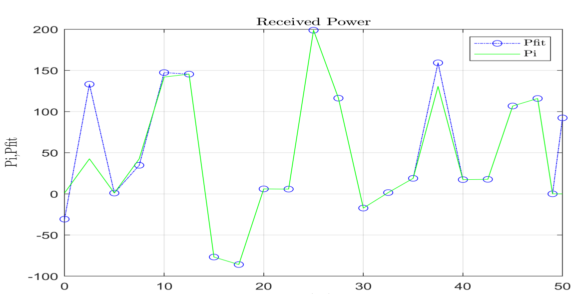

Fig. 4. Result of network fitting with the measured received power values in LOS environment.

Fig. 4 and Fig. 5 illustrate the channel path loss modeling using neural network. Pfit represents the output of the MLP network and Pi represents the measured received power values

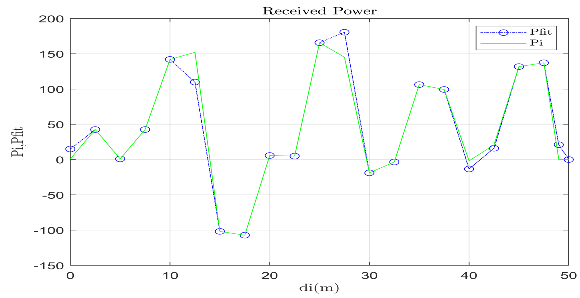

Fig. 5. Result of network fitting with the measured received power values in NLOS environment.

from the power delay profile. The figure shows that the output of the MLP approximately fits with the measured received power values with a certain amount of error.

VI. CHALLENGES AND RESEARCH OPPORTUNITIES

Due to the presence of a large number of antennas and due to hybrid beamforming channel estimation is difficult in THz communication. This is because practically in channel coherence time the hybrid beamforming does not allow the digital baseband to directly obtain the dimension of the channel thus making it difficult to acquire the accurate channel state information. For this purpose, beam scanning and searching techniques can be used. There are a lot of studies that focuse on LOS and NLOS propagation but to have a better understanding of the channels more research has to be carried out to observe how the mobility factor affects the channel behaviour under different conditions [4]. In deterministic channel modeling there are some opportunities to determine the material properties, develop a more efficient 3D ray tracing simulator, study the time-varying properties of the channel to analyze the movement of transceiver statistically, the transition of change between LOS and NLOS. In statistical channel modeling one can study temporal broadening effects and spatial joint modeling. In hybrid modeling one can try Ray tracing Finite-Difference Time Domain (RT-FDTD) approach and Statistical and RT Hybrid (SRH) approach [5].
The training overhead in channel estimation can be tried to be reduced by using compressed sensing technique or scattering nature of THz waves [6]. Beam alignment is very important for beam switching because once beam alignment breaks beam tracking wants the beam switching to rebuild the link. Thus complex codebooks need to be developed which contributes to the realization of more accurate angle estimation. Channel modeling and development of efficient protocols and algorithms for channel estimation needs to be developed is another open problem. As the delay domain and spread angle affects the performance, positioning is very important and then the interaction between positioning and communication has to be taken into account. A fast beam scanning method is used for 3D for beamforming scheme but it is inefficient and time consuming. So research can be aimed to reduce the

consumption of resources by predicting the trajectories of the target. The spatial and massive diversity resolution achieved by Large-scale MIMO radars has to be studied extensively. For Deep Learning approach to be used there are several challenges to be considered like performance analysis, data related problems, implementation oriented challenges, and algorithmic challenges [8].

VII. CONCLUSION

This paper provides an overview and a case study of necessity, challenges, applications, observations, and opportunities of terahertz Communication. There is a breakthrough in science and technology through the application of THz communication. The frequency band of THz which ranges between 0.1-10 THz meets various requirements of the market beyond the 5G and communication demands. Many applications of THz wireless with short wavelength and ultra wide bandwidth will enable communications, sensing, imaging, cognition, space applications and positioning capabilities used by automatic machines, autonomous vehicles appear to be a favorable spectrum for the wireless communication in the future. Opportunities like channel modeling, channel estimation, waveform design, and beamforming are discussed in this paper. Research in THz comprises many areas of science; therefore it is important to build the integration and coordination between different disciplines which will lead the way towards the ultra-high speed communications. In addition to that, we have performed the channel modeling of the terahertz channel by using a multi perceptron network (MLP) and the simulation results show that the output of the network approximately fits with the measured received signal power obtained from the power delay profile.

REFERENCES

[1] H. Sarieddeen, M.S. Alouini, and T. Y. Al-Naffouri, "An Overview of Signal Processing Techniques for Terahertz Communications," *in Proc. IEEE*, vol. 109, no. 10, pp. 1628-1665, Oct. 2021.

[2] E. Bjornson, L. Sanguinetti, H. Wymeersch, J. Hoydis,and T. L. Marzetta, "Massive MIMO is a Reality—What is Next? Five Promising Research Directions for Antenna Arrays," [Online]. Available: https://arxiv.org/abs/1902.07678. Accessed: Jun. 2019.

[3] A. Moldovan, M. A. Ruder, I. F. Akyildiz, and W. H. Gerstacker, "LOS and NLOS channel modeling for terahertz wireless communication with scattered rays," *in Proc. IEEE Globecom Workshops (GC Wkshps)*, USA, Dec. 2014.

[4] A. R. Ekti, A. Boyaci, A. Alparslan, I. Unal, S. Yarkan, A. Gorcin, H. Arslan, and M. Uysal, "Statistical modeling of propagation channels for Terahertz band," *in Proc. IEEE Conference on Standards for Communications and Networking (CSCN)*, Finland, Sep. 2017.

[5] C. Han and Y. Chen, "Propagation Modeling for Wireless Communications in the Terahertz Band," *in IEEE Communications Magazine*, vol. 56, no. 6, pp. 96-101, Jun. 2018,

[6] Z. Chen, X. Ma, B. Zhang, Y. Zhang, Z. Niu, N. Kuang, W. Chen, L. Li, and S. Li, "A survey on terahertz communications," *China Communications*, Feb. 2019.

[7] Z. Hossain and J. M. Jornet, "Hierarchical Bandwidth Modulation for Ultra-broadband Terahertz Communications," *in Proc. of the IEEE International Conference in Communications (ICC)*, China, May 2019.

[8] L. Dai, R. Jiao, F. Adachi, H. V. Poor, and L. Hanzo, "Deep Learning for Wireless Communications: An Emerging Interdisciplinary Paradigm," *IEEE Wireless Communications*, vol. 27, no. 4, pp. 133-139, August 2020.

[9] H. Elayan, O. Amin, R. M. Shubair, and M. S. Alouini, "Terahertz communication: The opportunities of wireless technology beyond 5G," *in Proc. International Conference on Advanced Communication Technologies and Networking (CommNet)*, Morocco, Apr. 2018.

[10] X. Gao, L. Dai, Y. Zhang, T. Xie, X. Dai, and Z. Wang, "Fast Channel Tracking for Terahertz Beamspace Massive MIMO Systems," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 7, pp. 5689-5696, July 2017.

[11] S. A. Busari, K. M. S. Huq, S. Mumtaz, J. Rodriguez, Y. Fang, D. C. Sicker, S. Al-Rubaye, and A. Tsourdos, "Generalized Hybrid Beamforming for Vehicular Connectivity Using THz Massive MIMO," *IEEE Transactions on vehicular Technology*, vol. 68, no. 9, pp. 8372-8383, September 2019.

[12] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Madanayake, S. Mandal, A. Alkhateeb, and G. C. Trichopoulos, "Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond," *IEEE Access*, vol. 7, pp. 78729-78757, June 2019.

[13] T. Nagatsuma and A. Kasamatsu, "Terahertz Communications for Space Applications", *in Proc. Asia-Pacific Microwave Conference (APMC)*, Japan, Nov. 2018.

[14] V. Kumar and S. K. Patra, "Feature Engineering for Machine Learning and Deep Learning Assisted Wireless Communication," *Metaheuristics in Machine Learning: Theory and Applications* Springer, 2021.

[15] B. Chitambira, S. Armour, S. Wales, and M. Beach, "NLOS Identification and Mitigation for Geolocation Using Least-Squares Support Vector Machines," *in Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, USA, Mar. 2017.

[16] M. Alrabeiah and A. Alkhateeb, "Deep Learning for mmWave Beam and Blockage Prediction Using Sub-6 GHz Channels," *IEEE Transactions on Communications*, vol. 68, no. 9, pp. 5504-5518, September 2020.

[17] C. Lin and G. Y. L. Li, "Terahertz Communications: An Array-of-Subarrays Solution," *IEEE Communications Magazine*, vol. 54, no. 12, pp. 124-131, Dec. 2016.

[18] X. Shao, X. Chen, C. Zhong, and Z. Zhang, "Joint Activity Detection and Channel Estimation for mmW/THz Wideband Massive Access,"*in Proc. IEEE International Conference on Communications (ICC)*, Ireland, Jun. 2020.

[19] A. Alkhateeb, J. Mo, N. Gonzalez-Prelcic, and R. W. Heath, "MIMO Precoding and Combining Solutions for Millimeter-Wave Systems," *IEEE Communications Magazine*, vol. 52, no. 12, pp. 122-131, Dec. 2014.

[20] S. Sun, G. R. MacCartney Jr., and T. S. Rappaport, "A Novel Millimeter-Wave Channel Simulator and Applications for 5G Wireless Communications," *in Proc. IEEE International Conference on Communications (ICC)*, France, May 2017.