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Terahertz Channel Propagation Phenomena, Measurement Techniques and Modeling for 6G Wireless Communication Applications: a Survey, Open Challenges and Future Research Directions

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Abstract—The Terahertz (THz) band (0.1-3.0 THz) spans a great portion of the Radio Frequency (RF) spectrum that is mostly unoccupied and unregulated. It is a potential candidate for application in Sixth-Generation (6G) wireless networks as it has the capabilities of satisfying the high data rate and capacity requirements of future wireless communication systems. Profound knowledge of the propagation channel is crucial in communication systems design which nonetheless, is still at its infancy as channel modeling at THz frequencies has been mostly limited to characterizing fixed Point-to-Point (P2P) scenarios up to 300 GHz. Provided the technology matures enough and models adapt to the distinctive characteristics of the THz wave, future wireless communication systems will enable a plethora of new use cases and applications to be realized in addition to delivering higher spectral efficiencies that would ultimately enhance the Quality-of-Service (QoS) to the end user. In this paper, we provide an insight into THz channel propagation characteristics, measurement capabilities and modeling methods along with recommendations that will aid in the development of future models in the THz band. We survey the most recent and important measurement campaigns and modeling efforts found in literature based on the use cases and system requirements identified. Finally, we discuss the challenges and limitations of measurements and modeling at such high frequencies and contemplate the future research outlook toward realizing the 6G vision.

Index Terms—6G, channel measurements, channel modeling, channel sounding, deterministic modeling, diffuse scattering, molecular attenuation, propagation, Radio Frequency (RF), statistical modeling, stochastic modeling, Terahertz (THz), wireless communications.

LIST OF ABBREVIATIONS

6G	Sixth-Generation
AI	Artificial Intelligence
AoD	Angle of Departure
AoSA	Array of Sub-Arrays
BER	Bit-Error-Rate
CW	Continuous-Wave
FDTD	Finite-Difference Time-Domain
FFT	Fast Fourier Transform
GBSM	Geometry-Based Stochastic Model

GMM	Gaussian Mixture Model
GVD	Group Velocity Dispersion
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IFFT	Inverse Fast Fourier Transform
ISI	Inter-Symbol Interference
iWNSN	In vivo Wireless Nano Sensor Network
LDPC	Low-Density Parity Check
LoS	Line-of-Sight
ML	Machine Learning
MMIC	Monolithic Microwave Integrated Circuit
mmWave	millimeter Wave
MoM	Method of Moments
NGBSM	Non-Geometry-Based Stochastic Model
RFoF	Radio Frequency over Fiber
RF	Radio Frequency
RS	Reed-Solomon
RT	Ray-Tracing
SC	Sliding Correlator
SNR	Signal-to-Noise
SV	Saleh-Valenzuela
Tbps	Tera-bit per second
TDS	Time-Domain Spectroscopy
THz	Terahertz
ToA	Time of Arrival
UTC-PD	Uni-Travelling-Carrier Photo-Diode
WLAN	Wireless Local Area Network
5G	Fifth-Generation
AoA	Angle of Arrival
AP	Access Point
B-D	Birth-Death
B-K	Beckmann-Kirchhoff
BS	Base Station
CIR	Channel Impulse Response
CTF	Channel Transfer Function
D2D	Device-to-Device
DFT	Discrete Fourier Transform
DSSS	Direct Sequence Spread Spectrum
EESS	Earth Exploration Satellite Services
FDS	Frequency-Domain Spectroscopy
FSPL	Free-Space Path Loss
Gbps	Giga-bit per second
GOA	Giant Optical Activity

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HEMT	High Electron Mobility Transistor
HST	High-Speed Train
InP	Indium Phosphide
Inter-Satellite Link	ISL
LO	Local Oscillator
LTCC	Low Temperature Co-Fired Ceramic
MIMO	Multiple-Input Multiple-Output
MPC	Multi-Path Component
NLOS	Non-Line-of-Sight
P2P	Point-to-Point
PN	Pseudo Noise
QoS	Quality-of-Service
R-R	Rayleigh-Rice
RIS	Reconfigurable Intelligent Surface
RMS	Root Mean Square
Rx	Receiver
SI	International System of Units
SISO	Single-Input Single-Output
SV	Support Vector Machine
T2I	Train-to-Infrastructure
Tx	Transmitter
UM-MIMO	Ultra-Massive Multiple-Input Multiple-Output
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Everything

I. INTRODUCTION

AS the demand for higher data rates is growing exponentially, data rates that exceed 1 Tera-bit per second (Tbps) could be required beyond 2030 [1]. Very high data rates are anticipated in indoor locations where lower costs can be expected for extending wired backbone networks compared to using optical cables while ITU [2] reported that by the year 2030, wireless systems will be as significant as wired cellular systems. A recently published white paper by CISCO estimated that average Fifth-Generation (5G) cellular speeds will reach 575 Mbps by 2023, resulting in a 13-fold increase to the speeds recorded in 2018 [3]. Additionally, Ericsson highlighted the imminent need for capacity as global mobile data traffic is estimated to grow by a factor of 4.5 to reach 226 ExaBytes per month in 2026 [4]. This unprecedented need for higher speeds and larger bandwidths in sight of the currently saturated spectrum below 300 GHz [5] has motivated research in parts of the Radio Frequency (RF) spectrum that have been faintly explored in order to meet the growing needs of the wireless communications industry [6], [7], [8]. A recently published white paper [9] derived within the "6G Flagship" by the university of Oulu in 2019, mentioned that Sixth-Generation (6G) systems should be able to deliver Tbps speeds and that the way to achieve these is through efficient utilization of the THz spectrum. Nevertheless, initiatives for realizing the 6G vision have been recently launched such as the "Next G Alliance" project by the USA and "Heat-X" European 6G flagship project [10].

A. Introducing the THz Band

The frequency band that lies between the microwave and infrared regions of the electromagnetic spectrum spanning

from 100 GHz to 3,000 GHz is termed as the THz band, with wavelengths ranging from 3 mm to 0.1 mm [11]. Recently, the THz band has received lots of attention as a promising candidate for various applications that can be classified in the fields of wireless cognition [12], [13], [14], sensing [15], [16] Imaging [17], [18], communications [19], [20] and positioning [21], [22], offering advantages such as ultra-fast data transmission [23], increased bandwidth [24] and microsecond latencies [25]. While the THz wave has proven to be successful in spectroscopy for sensing applications such as material characterization [26], weather characterization [27] and study of astronomical objects [28] due to its frequency selective nature, some first applications identified where the THz wave could be applied to in 6G networks for wireless communications include Point-to-Point (P2P) scenarios such as kiosk downloads [29], wireless links in data centres [30], intra-device communications [31] and wireless backhaul/fronthaul link extensions [32]. Nonetheless, as the technology continues to mature providing the appropriate beam-steering and tracking capabilities at THz, along with the expected evolution of the semiconductor technology and the ability to enable higher levels of power generation to combat the high losses present in the atmosphere and free space, applications that include mobility and require longer range communication links can also be realized. Applications as such include Wireless Local Area Networks (WLANs), smart rail mobility [33], inter-satellite links (ISL) [34], Vehicle-to-Everything (V2X) communications [35] and Device-to-Device (D2D) communications [36]. Last but not least, THz has found great interest in future nano-networks within the medical industry for in-body via nano-machine molecular communications [37], [38].

The aforementioned opportunities are ones that arise due to the unique characteristics held by the THz wave in addition to the largely unoccupied and unregulated region that this end of the spectrum offers. For the development of an efficient communications system with high data rates, deriving the characteristics of the propagation channel by accurate modeling is a necessity. So far, most studies have been limited to frequencies up to the millimeter-wave (mmWave) spectrum (30-300 GHz) due to the lack of high frequency generators and sensitive detectors. At frequencies > 300 GHz propagation models need to consider high path loss, molecular absorption and diffuse particle scattering (due to the short wavelength < 1 mm), as the most important phenomena that are very prominent especially as we shift higher up in the THz frequency spectrum. These characteristics are crucial in the development of successful communications systems in terms of hardware, software and protocols [39].

B. Enabling Technologies for THz waves

THz research cannot be pondered as something "new". The first paper ever published [40] dates back to 1893 and it involved THz spectroscopy. However, the term "THz" was not common and instead it was referred to as "obscure" radiation. In the experiments conducted there was a source and detector of THz radiation and by placing different materials in between, absorption coefficients were measured, much like a lot of

Fig. 1: Integrated THz systems evolution. (a) Power produced from different sources vs frequency, (b) Efficiency or sensitivity of detectors vs the ability to reconfigure and control these technologies [44].

the measurements conducted nowadays [41], [42], [43]. This shows that while a lot of work has been carried out and a lot of materials have been characterized, there is still a lot of interest and work to be done in basic spectroscopy at THz.

What has happened recently, is that there is a growing realization that the photonics and electronics research coincides and there is an ongoing merging of the electronics and photonics fuse of the world [44]. In recent years there has been a lot of progress in some key metrics and Fig. 1(a) shows one of these metrics in the form of power produced by various different sources vs frequency where e.g., the power produced by silicon sources in 2018 has increased by many orders of magnitude compared to the power levels produced by silicon in 2008, while other examples also show similar sort of improvement. This also shows that the production of integrated systems is possible and that enough power can be generated to do something useful with it. Various techniques are currently being carried out for the development of efficient sources and detectors of THz radiation [45], [46], [47] to bridge the ‘gap’ between conventional electronics and optics. Some of which, have made THz systems affordable and realizable by overcoming existing limitations through novel architectural designs and device structures. On the electronics side, solid-state electronics technologies such as GaAs-based Schottky diodes, Monolithic Microwave Integrated Circuit (MMIC), InP heterojunction bipolar transistors (HBTs), high electron mobility transistors (HEMTs) and Resonant-Tunnelling Diode (RTD) can now enable high power level generation from 100 μ W up to the mW range [48], [49], [50], [51]. This shows an increase of more than double in a decade, especially at frequencies exceeding 1 THz. Likewise, various photonic technologies within the THz band have been developed recently that enable μ W Continuous-Wave (CW) power generation including photomixing approaches such as Uni-Travelling-

Carrier Photo-Diode (UTC-PD) and also Quantum Cascade Lasers (QCLs) which are diode lasers capable of operating below 2 THz [52], [53], [54]. DFG/parametric generation within the 1-2 THz range is also another option at THz that enables mW radiated power levels to be obtained [55], [56].

On the other hand, there are many other important metrics besides power that require consideration such as, efficiency or sensitivity of detectors as illustrated in Fig. 1(b). These metrics are important as it is not just a matter of whether it is possible to generate a THz signal but to also manage to tune and control things such as the direction, spectral content and polarization of the THz beam [57], [58]. In the spectrum above 1 THz reaching up to 10 THz, photonic based systems such as QCLs, Si-photonics and UTC-PD devices are expected to play an important part, especially where tuning of > 1 THz is required. It is equally important however, whether these things can be done fast and in a programmable and reconfigurable manner which would require the use of phased arrays [59], [60], [61], [62] that are currently not commercially available. At THz, the beam is required to be very directive in order to combat the high path loss. In a mobile scenario, e.g., when someone walks across the room and the beam needs to follow them, such technology, is known as beam tracking and acquisition, or otherwise, “device discovery” [63], [64]. For the beam to know where to go and to do so quickly enough, phased arrays and processing techniques such as adaptive beamforming are essential [65].

C. Standardisation Efforts

A first standard on wireless communications at 300 GHz has been defined by the IEEE 802.15 THz Interest Group known as IEEE 802.15.3d-2017 [66], as an amendment to the IEEE 802.15.3-2016 [67] 60 GHz standard, for operation up to 100 Giga-bits per second (Gbps). The 300 GHz system can utilize

8 different channel bandwidths between 252-321 GHz as multiples of 2.16 GHz [68], as illustrated in Fig. 2. Both single carrier and on-off modulation schemes are being employed which are combined with Low-Density Parity-Check (LDPC) and Reed-Solomon (RS) codes. Some of the applications identified for this range include P2P scenarios such as kiosk downloads, data centre communications, fronthaul/backhaul, intra-device communications and WLANs.

Spectrum allocation currently ends at 275 GHz for active services, but is not completely unregulated as it is assigned for passive services such as Earth Exploration Satellite Services (EESS) and radio astronomy that gather information based on the resonant frequencies of the molecules and therefore these systems are only receiving and not transmitting [69]. These resonant frequencies are occupied within bands that cover most of the spectrum between 275-1,000 GHz, meaning that if we want to allocate these bands for active services and employ THz communications, this needs to happen by sharing the spectrum [70]. Furthermore, all frequencies between 1,000-3,000 GHz may be also used for both passive and active services [70] though they have not yet been allocated to any service. In regards to the bands between 275-450 GHz, the ITU-R has invited its members to conduct sharing studies to see under which conditions and within which frequency bands sharing is possible. At WRC 2019 [69], four contiguous bands were identified between 275 and 450 GHz (275–296 GHz, 306–313 GHz, 318–333 GHz, and 356–450 GHz) with large bandwidths i.e.- one of them with 94 GHz available for unrestricted use in total, based on ITU-R studies [71] for land mobile and fixed services without the need to protect EESS. The Horizon 2020-EU-Japan joint project called ThoR has also conducted a sharing study [72] for interference mitigation taking into account the operational characteristic of both passive and active services and its findings are in line with the ITU-R studies. Three bands have been identified (296-306 GHz, 313-318 GHz and 333-356 GHz) in line with bands where proper mitigation is required [73] to avoid harmful interference and allow for coexistence with other applications, while for radio astronomy, on the contrary, proper mitigation techniques are already available.

In conclusion, Frequency bands > 275 GHz are inherently capable for implementing wireless systems with data rates of 100s of Gbps. Feasibility of wireless THz communication based on current developments and hardware demonstrations has been proven while the first standard is available and so is the spectrum and therefore THz communication is a real option for employing in future wireless 6G networks.

D. Related Works

To the authors' awareness, no survey paper exists in literature that covers thoroughly THz channel propagation phenomena, measurements and modeling in the THz band. Very interesting survey papers that cover channel measurements and modeling can be found in literature that mainly focus on the 5G mmWave bands < 100 GHz [74], [75], [76]; however, propagation characteristics differ from those found at THz and therefore so do measurement capabilities and modeling

Fig. 2: IEEE 802.15.3d 252-321 GHz bandwidth allocation plan [68].

techniques. Many informative papers can be found that cover many aspects of THz communications such as applications, technologies and propagation characteristics [77], [78], while some other publications survey channel measurements and modeling for 6G applications [79], [80]; however, they do not focus on THz alone but cover various aspects of 6G channel modeling at different frequency ranges. Furthermore, a very useful article found in [81], provides guidelines and considerations for fixed P2P scenarios in the 300 GHz band while in [82] an article can be found that considers modeling methods at THz along with current issues and future considerations. Moreover, an overview for communications within nano-networks in the THz band is presented in [83] that covers different aspects of nano-communications and includes a summary of the available methods in modeling for applications such as nano-device in-body communications and on-chip communications.

Much to the information provided on THz by different articles and surveys mentioned above that cover different aspects of THz communications related to characteristics, applications, technologies along with studies on the 6G vision and the role THz will play; an in-depth survey on measurement and modeling of the THz channel is still not available. In this survey, we aim to narrow this gap in a top-down (holistic) manner, by drawing all our efforts in identifying what has been done so far and what can be further done, as well as what the problems are and how to solve them. Finally, we bring together all of the knowledge we have gathered, as such, to provide a useful insight to the modeling scene in order to motivate and aid in the development of future 6G wireless communications systems operating at THz frequencies.

E. Contributions of this Survey

The aim of this paper is to provide a thorough review of the work found in literature that focuses on measurements and modeling of the propagation channel at THz that would aid in the development of future models to characterize

the propagation environment for the deployment of future communications systems. Initially, we describe the different propagation characteristics in terms of specific attenuation due to path loss and precipitation as well as attenuation resulting from various interactions with different materials. We then describe the use cases at THz and identify what the system requirements for conducting measurements are. Next, we describe the methods that can be employed for channel sounding at THz as well as channel modeling techniques that can be applied to characterize wave propagation at THz. Furthermore, we survey important works found in literature related to channel characterization for potential 6G applications. Onward, we present open challenges along with solutions for modeling at THz frequencies higher than 300 GHz ($\lambda < 1$ mm), where the current spectrum allocation ends and modeling efforts are still in their early stages. The contributions of this survey are summarized as follows:

- We begin by presenting the different THz propagation phenomena experienced in free space at THz and their associated models and describe the unique interactions experienced by the THz waves in the surrounding environment at this frequency band.
- Secondly, we define and give a short description of the use cases identified and set the system requirements for conducting measurements at THz based on these use cases. Then, we describe the channel sounding options available that are required for performing measurements at THz, discuss their advantages and disadvantages and discuss how they address the measurement requirements identified.
- Next, we explore the physical and analytical modeling approaches that could be employed at THz to describe the channel behaviour and discuss which methods are most popular for extracting the propagation channel's characteristics.
- We survey scenario oriented as well as general channel measurement campaigns and modeling efforts found in literature at THz for static P2P and dynamic scenarios that include mobility.
- Finally, we present challenges in measurement and modeling at frequencies > 300 GHz and discuss possible solutions and research directions that can contribute to the future modeling scene.

F. Outline

The structure of this paper is concisely illustrated in Fig. 3. The remainder of this paper is structured as follows; Initially, the main propagation phenomena at THz and their modeling is presented in Sec. II. Sec. III, introduces the use cases for wireless communications in the THz band as well as the system requirements for performing meaningful channel measurements and associated performance metrics. In Sec. IV, THz channel sounding methods are introduced which are necessary for conducting measurements based on the use cases identified in order to determine which method is best to be employed depending on each use case's requirements. Channel

Fig. 3: Structure of this paper.

modeling methods that can be followed for extracting the propagation channel's characteristics in the THz band categorized as deterministic, stochastic and hybrid are described in Sec. V. In Sec. VI, the most recent and significant modeling efforts for potential static and dynamic 6G applications as well as for material roughness behavior are reviewed. Open issues and challenges being faced along with solutions and research directions for future modeling works are discussed in Sec. VII. Finally, we conclude the findings of this paper in Sec. VIII.

II. THZ PROPAGATION PHENOMENA

Accurate channel modeling and characterization is required for successful deployment of THz systems that can comply with the demands of future wireless communication systems. To characterize the THz channel accurately and efficiently, it is of high importance that the nature of the propagation environment at this frequency range is considered. The THz wave possesses many unique characteristics that make it advantageous in comparison to microwave and mmWave communications such as increased speed and capacity. Propagation phenomena considered in the microwave and mmWave bands include path loss, shadowing, penetration loss and diffraction. In the THz band, different propagation conditions besides the high path loss become much more pronounced such as molecular

Fig. 4: Free space path loss for the frequency range 1-1,000 GHz with unity gain Tx and Rx antennas.

absorption and particle scattering. The effects of rain, fog and cloud also need to be taken into account as in the mmWave bands, while the effects of dust [84] and turbulence [85] are also limiting propagation phenomena, though they are often not as significant.

A. Free Space Path Loss

Free Space Path Loss (FSPL) is generally defined as inevitable attenuation experienced by a wave propagating in free space between two isotropic antennas [86]. It is described by the Friis transmission formula given by Eq. (1),

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2} \quad (1)$$

where λ is the wavelength, d is the distance the wave will travel, with P_t being the transmit power and G_t , G_r being the Transmitter (Tx) and Receiver (Rx) antenna gains. According to Eq. (1), the received power $P_r(d)$ decreases with the square of the frequency and distance, i.e.- the FSPL attenuation increases proportionally with the decrease in $P_r(d)$. Fig. 4 represents the FSPL for a P2P link for three different separation distances up to 3 THz. Initially, substantial path loss well over 100 dB is formed at 100 GHz, with a 20 dB per decade increase resulting in an increase by 20 dB from 0.1 THz to 1 THz to 10 THz and nearly 10 dB increase from 1 THz to 3 THz. However, in Fig. 4 it is assumed that the antenna gains are equal to unity as calculated from Eq. (2),

$$G_{t,r} = \frac{4\pi A_{et,er}}{\lambda^2} \quad (2)$$

and the attenuation observed is simply the path loss. If the gain includes information on the aperture area (A_{et}) of the Tx (A_{et}) and Rx (A_{er}) antennas as in Eq. (2), the term λ^2 from Eq. (1) moves from the numerator to the denominator in Eq. (3),

$$P_r(d) = \frac{P_t A_{et} A_{er}}{d^2 \lambda^2}. \quad (3)$$

This means that if the ratios:

$$\frac{A_{et}}{\lambda} \quad \text{and} \quad \frac{A_{er}}{\lambda}$$

are maintained at any frequency, then the path loss does not change. Therefore the antenna size requirements as we go up in frequency reduce. But at the same time it is generally not possible to increase A_{et} or A_{er} at any single frequency beyond a corresponding limit because the aperture efficiency falls consistently in cases such as horn antennas or parabolic dish reflectors. Array antennas as the other solution also have an equivalent limitation in that the increase in number of elements will result in higher feed losses. Also at THz the closer physical spacing where feeds do not physically size down will cause substantial practical difficulties and further lossy characteristics. Finally, an omnidirectional antenna cannot increase its aperture, which is already nearly as low as an isotropic antenna, by virtue of its design. Therefore based on the above observations, though in theory an increase of A_{et} and/or A_{er} will overcome path loss, it is inhibited by physical limitations. To compensate this attenuation, highly directional and high gain antennas are required at the Tx and Rx ends which will be much needed, considering the output power decreases with inverse square proportionality to frequency and transmit power will most likely not exceed the order of a few dBm [87] any time soon.

B. Attenuation by Atmospheric gases

At THz the main form of attenuation of the signal is expected due to meteorological attenuation known as atmospheric absorption. The spectrum below 1 THz is considered as the most beneficial and attractive for wireless communications since above that the attenuation is severe and hence, substantially limits the communication distance. When the wavelength of the THz wave approaches the dimensions of water and oxygen molecules, resonances are generated at selective carrier frequencies resulting in large attenuation peaks that degrade the signal severely playing a major role in link budget calculations [27]. In Fig. 5 we can observe the atmospheric

Fig. 5: Atmospheric attenuation in free space for the range 1-1,000 GHz.

attenuation by water and oxygen molecules over the 1-1,000 GHz frequency range. This specific attenuation γ is calculated by the ITU-R model [88] by aggregating the spectroscopic resonant behaviour of water γ_0 and oxygen molecules γ_ω as in Eq. (4),

$$\gamma = \gamma_0 + \gamma_\omega = 0.1820fN''(f) \text{ (dB/km)} \quad (4)$$

where $N''(f)$ is the imaginary part of the complex refractive index that can be directly obtained from THz Time-Domain Spectroscopy (TDS) measurements.

As illustrated in Fig. 5, below 300 GHz the attenuation is minimal reaching up to a few dB while in the underlined spectral windows between 385-440 GHz, 453-510 GHz, 630-705 GHz and 815-890 GHz the attenuation ranges up to 100 dB/km which still is a substantially massive amount of attenuation, comparable with the attenuation we expect from a Faraday cage. Therefore even with 1 km we already lose 100 dB on top of the ~ 150 dB in free space. So 250 dB is far too much attenuation to achieve long distance communications. In addition, different frequency-selective attenuation peaks are observed due to the resonant behavior of molecules in the atmosphere causing severe attenuation levels some of which exceeding 10,000 dB/km that would have to be strictly avoided. In the region between 1 to 3 THz the signal undergoes significant attenuation by water and oxygen molecules in the atmosphere and the next atmospheric windows are found between 1.3 and 1.6 THz where the signal is attenuated in the order of a few 100s of dB and may be potentially utilized only for near-field communications (< 0.1 m) [89].

Nonetheless, the applicability of the ITU-R model for the frequency range 450-1,000 GHz was questioned by O'Hara and Grischkowsky [90], as alternative sources that modeled the > 1 THz resonant frequency line contributions to the frequencies < 1 THz by molecular response theory and the absorption continuum using the two-parameter continuum approach, showed more consistency resulting in a closer match to THz-TDS experimental results of total absorption [91], [92]. Moreover, molecular absorption noise is another contributing factor that degrades the signal strength that requires further analysis and appropriate modeling [93].

C. Rain and Snow Attenuation

Additional forms of meteorological attenuation that the THz wave may experience when propagating in an outdoor environment are those of rain and snow [94]. The ITU model provided in [95], describes the rain attenuation, γ_R in dB/km experienced by the THz wave over the 1-1,000 GHz frequency range given by the power-law relationship in Eq. (5),

$$\gamma_R = kR^a \text{ (dB/km)} \quad (5)$$

calculated by the rain rate R (mm/h) where k and a are frequency dependent coefficients derived from scattering calculations at vertical and horizontal polarizations. As the rain droplets' shape and size are in similar order to the wavelength, the propagation losses must be represented as a function of polarization and wavelength. In Fig. 6 the rain attenuation

Fig. 6: Rain attenuation for horizontal polarization in the frequency range 1-1,000 GHz.

for horizontal polarization regarded as parallel to ground propagation for the 1-1,000 GHz frequency range can be observed, representing the worse case of attenuation. Four different scenarios of rain are shown where the rain rate can vary from less than 0.25 mm/h for light rain to over 50 mm/h for extreme rain conditions. These losses are seen to flatten out around 100 GHz, beyond which no additional attenuation is expected within the bands of interest up to 3 THz [96]. The reason for the constant attenuation at higher frequencies is that particle scattering has moved from Rayleigh to Mie scattering [97] due to the shorter wavelength making it more applicable, indicating that particle scattering with pattern similar to that of a dipole radiation pattern (Rayleigh scattering) changes to a more direct scattering pattern with a forward lobe (Mie scattering). These losses may not be as significant as the path losses and atmospheric losses but will have to be considered regardless for accurate channel characterization. With regards to attenuation due to snow, an equivalent ITU propagation model does not exist and the snow particles are merely considered as rain droplets [98]. Therefore, Eq. (5) can also be used to compute the specific attenuation due to snow even though it tends to slightly overemphasize the loss [99].

D. Cloud and Fog Attenuation

Another meteorologically induced condition similar to that of rain and snow that can cause fading in an outdoor environment, is that of fog and cloud. Fog and cloud may be considered as the same atmospheric phenomena, that vary only by height above ground. Both phenomena are defined by the ITU model [100] under the assumption that the wave travels solely through a uniform fog or cloud environment. The specific attenuation γ_c can be computed by Eq. (6),

$$\gamma_c(f, T) = K_l(f, T)M \text{ (dB/km)} \quad (6)$$

where K_l is the cloud water specific attenuation coefficient ((dB/km)/(g/m³)) found by applying a Rayleigh based double-Debye scattering model that is used to extract the dielectric

Fig. 7: Fog or cloud specific attenuation for the range 1-1,000 GHz.

permittivity of water and which holds for frequencies between 1–1,000 GHz. M (g/m^3) is the liquid water density in the fog or cloud while T and f are the temperature and carrier frequency, respectively. In Fig. 7 we can see the specific attenuation effects of fog/cloud at a temperature of 20°C for 100 GHz carrier frequencies that are typically around 0.05 (g/m^3) for medium fog/cloud where the visibility range is in the order of 300 m, and 0.5 (g/m^3) for heavy fog/cloud where the visibility range drops to 50 m. The losses, similar to those of rain and snow, are much smaller than those of path loss and atmospheric absorption and can be easily compensated for as the attenuation forming at 100 GHz is around 5 dB with an increase of about 15 dB from 0.1 to 1 THz for the worst case condition of heavy fog/cloud. Beyond this region and up to 3 THz, the attenuation formed does not vary significantly and increases by just a few dB [96].

E. Vegetation Attenuation

The presence of vegetation in an outdoor environment plays a significant role in signal attenuation at THz and may reduce the maximum achievable data rates [101]. High amounts of absorption would be expected due to the high water content while the effects of scattering need consideration as to whether vegetation can contribute to the received signal by Non-Line-of-Sight (NLOS) propagation. Currently, no specific model exists that computes the propagation loss due to vegetation other than the ITU model [102] which holds for frequencies up to 60 GHz. This is because the lack of measurement data makes it difficult to develop an appropriate model at THz frequencies. The THz-TDS technique could be utilized to measure the water content on leaves and the data collected could be later on fed into models that characterize the outdoor propagation environment [103].

F. Other Propagation Phenomena

Similar to both microwave and mmWave radiation, THz waves can penetrate through different non-conducting mate-

rials such as plastic, clothing and paper [104], [105]. However, strong absorption of the wave, depending on material structure and thickness is extremely possible. Penetration at THz is limited by the low output power levels and varies by thickness and composition of the material it interacts with [106], [107], [108], while the THz wave is non-invasive to the human body and is therefore highly susceptible to link blockage in indoor locations (i.e.- when a user is moving across the room) which becomes a major issue when employing communications systems with highly directive antennas. Furthermore, diffraction effects common in the lower bands < 100 GHz that can be described e.g., by the Knife-edge and/or Uniform Theory of Diffraction (UTD) models, are much reduced by comparison at THz due to the higher directivity, but nonetheless, may be considered as a form of multipath propagation that could contribute to the overall signal strength [109].

Moreover, the scattering behaviour of THz waves from different surfaces with different roughness levels is unique at THz owing to the short wavelength and a good understanding of it is required for the development of future channel models. A representation of the different interactions of the THz waves at a material's surface are illustrated in Fig. 8. EM waves that are directed on a smooth surface should have an equal angle of incidence and reflection (specular reflection). However, when the surface is rather rough, diffuse scattering of the EM waves happens resulting in a loss of intensity in the specular direction. As the THz wave has a very short wavelength, the scattering of the waves off a rough surface will cause multipath propagation. These rough surfaces can be quantified for THz frequencies, as having edges that vary between them less than 1 mm for frequencies > 300 GHz. Otherwise, for edges greater than 1 mm the surface may be considered as smooth. Additionally, multi-layer reflections and reflections within in-homogeneous materials are also another possibility at THz especially as the permittivity (ϵ_r) of the material gets closer to unity resulting in additional diffuse components [110]. Other factors that influence the amount of scattering besides wavelength include the size, shape and refractive index of the scatterer [111].

The received impulse response vs time delay for different propagation cases where Line-of-Sight (LoS) is the strongest form of propagation are seen in Fig. 9. Diffuse reflections from rough surfaces cause Multipath Components (MPCs) to propagate randomly and arrive at slightly different times and angles; thus, forming clusters at the peak of the most significant arriving component in contrast to the clear peak expected from a specular reflection off a smooth surface and therefore require careful consideration [112], [113], [41]. Two well known methods that can be employed to predict particle scattering are the Rayleigh-Rice (R-R) [114] and Beckmann-Kirchhoff (B-K) [115] models that consider smooth and rough material surface interactions, respectively. Temporal broadening is another effect observed at THz that causes multipath dispersion over time due to the high frequency selectivity as well as fading in the received power levels as also seen in Fig. 9.

Fig. 8: Material surface interactions in the THz band.

Fig. 9: Received impulse response magnitude vs time delay demonstrating signal arrival and propagation effects experienced in terms of dispersion, fading, specular and diffuse reflection.

III. USE CASES AND REQUIREMENTS

For future communication systems deployment, the use cases identified lay a set of requirements and limits for performing meaningful channel measurement campaigns. On that account, in this section the applications for THz communications are briefly presented. Onward, a general set of system requirements for conducting practical channel measurements are described in order to help in the selection of the appropriate measurement equipment for each of the use cases identified.

A. Applications for THz Communications

The governing factor that drives a meaningful measurement campaign is the application scenario under investigation. Generally, all applications identified would benefit from THz links that would enable high data rate transmissions. Initially, it would be sensible to investigate scenarios that can be characterized by fixed P2P links where the Tx and Rx antennas are considered to be stationary for the whole duration of the measurement such as intra-device, backhaul/fronthaul, data centre communications and kiosk downloads (though in this scenario the Rx side may be subject to minor displacement as the user would have to align the device to the Tx side).

In the foreseeable future, advancing from fixed P2P scenarios to mobile scenarios, other applications are also envisioned in the THz band such as communications within V2X networks, WLANs, D2D communications, ISLs and High Speed Train (HST) communications. These applications would require Multiple-Input Multiple-Output (MIMO) capabilities to achieve extremely high data rates and also large capacities to accommodate a large number of users. Beam steering algorithms for device discovery requiring a high degree of Angle of Arrival (AoA) and Angle of Departure (AoD) estimation as the Tx and Rx will have no a priori knowledge of each other's position, would become essential in order to realize modeling of such applications.

Table I establishes the requirements for channel modeling as to what exactly they are in terms of use cases in relation to expected ranges and environments as well as expected propagation conditions and required antenna characteristics. The use cases identified in the THz band are briefly described as follows:

- **Kiosk/Desktop Downloads:** Users downloading a large number of data files from a "vending" type machine to their device such as phone or laptop over a short range in a very short period of time.
- **Data Center Networks:** Wireless network seamless connectivity between racks in a data center at ultra-high speeds replacing wired connections to simplify data cen-

TABLE I

TARGETED APPLICATION SCENARIOS FOR THZ COMMUNICATIONS AND MINIMUM REQUIREMENTS FOR CONDUCTING CHANNEL MEASUREMENTS.

Application	Propagation Environment	Typical Range	Propagation Characteristics	Antenna Alignment Requirements
Kiosk Downloads	Indoor; Limited movement by users	~ 0.5 m	LoS, NLoS	Manual alignment of Rx by user
Data-Center Networks	Communications between servers in data center	$\sim$ a few 10s of m	LoS; NLoS	Manual alignment
Intra-Device Communication	Communication within devices; fixed links	$\sim$ a few cm	LoS; NLoS with significant multipath contribution	Fixed alignment
Backhaul/Fronthaul	Fixed wireless link extensions	~ 100 m	LoS; Atmospheric attenuation; fog and Rain attenuation; very high path loss	Highly directive antennas; fixed alignment
WLAN	Indoor; mobile users	~ 20 m	LoS; NLoS; scattering	Dynamic beam steering
HST Communication	Communications within trains and between station infrastructure and train	< 100 m	LoS; Directed-NLoS; dynamically varying conditions; atmospheric attenuation; high path loss	Dynamic beam steering; high AoA estimation accuracy
Inter-Satellite Links	Communications between satellites in orbit	~ 1 km	LoS; satellite drift	dynamic beam steering
V2X Communication	Communications between vehicles	< 100 m	LoS; reflected path; dynamically varying conditions; atmospheric attenuation; fog and rain attenuation; high path loss	Dynamic beam steering; high AoA estimation accuracy
D2D Communication	Communications between user devices	~ 1 m	LoS; dynamically varying conditions; molecular attenuation;	dynamic beam steering
Nano-Network Communication	Nano-device communication within nano-networks; in-vivo;	$\sim$ a few cm	Tissue penetration loss; scattering	Dynamic beam steering

ter deployment and maintenance in terms of installation costs and hardware configuration/reconfiguration and also to improve cooling.

- **Intra-Device Communications:** Chip-to-Chip, board-to-board as well as on-board and on-chip wireless THz links within devices that eliminate the need for wired connections, thus reserving more space within the device and reducing energy consumption.
- **Wireless Backhaul/Fronthaul:** Fronthaul THz links to extend usually beyond where the fibre can't reach to give broadband access to the end user. Backhaul THz links used to connect the base station to the core network.
- **WLAN:** Wireless connectivity that would require connections between various access points by replacing fibre-optic cables and thus enabling higher data rates.
- **HST Communications:** High data rate communications between train and infrastructure as well as intra-wagon communications that will enable seamless connectivity, safer travel and lower costs.
- **Inter-Satellite Links:** Communication links between satellites that lie outside the earth's atmosphere that do not suffer by molecular attenuation. Unlike the optical bands at THz, strict beam alignment requirements are less imposing and enough to maintain a good alignment as satellites shift away from their orbits. Along with the large bandwidth that is currently not available in the lower bands, the THz band is a good candidate to be employed for future ISLs.
- **V2X Communications:** THz Communications within vehicular networks that can support a wide range of scenarios involving vehicles, infrastructure and pedestrians offering benefits such as enhanced user experience, improved road safety and air quality.
- **D2D Communications:** D2D communications have surfaced as a major technology for enhancing spectrum

utilization in the next generation of cellular networks. D2D exploits the close proximity of various devices in order to share resources efficiently so that higher data rates, reduced latency and higher levels of system capacity can be achieved.

- **Nano-Networks:** Nano-machine enabled communications such as in-vivo communications within sub-mm sized regions inside the human body that are otherwise not accessible by any other medical device.

B. Requirements for THz Channel Measurements

a) **Bandwidth:** While the spectrum is vastly available above 300 GHz in the THz regime, channels at multiples of 2.16 GHz have been introduced that allow for contiguous bandwidths of a few 10s of GHz targeting data rates of 100 Gbps. More specifically, as per [66], data rates around 100 Gbps can be achieved with an 8-PSK modulation scheme with about 50 GHz bandwidth. Higher order modulation schemes should be employed to give higher data rates, such as 64-QAM that is able to provide data rates > 200 Gbps for the same bandwidth (~ 50 GHz) [66]. To satisfy the capacity requirements and achieve high data rates, channels composed of many 10s of GHz of contiguous spectrum that can be freely allocated for active services with high order modulation and sophisticated coding schemes will be required.

b) **Antenna Directivity/Alignment:** Side-lobe suppression and spatial filtering are the main requirements for antennas operating at THz, something that cannot be provided by omni-directional antennas used in the lower frequency bands. Therefore, highly directive antennas with high gain are required which are very much necessary to combat the high path loss and large atmospheric absorption effects of the highly frequency selective THz channels and also provide strong enough signal components that would be detected by the receivers. The antenna selected should be easily rotated and

measurements should adapt to each scenario by interchanging the antennas for accurate channel characterization. Additionally, with the use of multiple antennas in the form of phased arrays and in conjunction with technological advancements in beam-forming and beam-steering along with improvements in AoA estimation algorithms, high directionality and high gain could be acquired that would be used to achieve the desired data rates.

c) **Link Distance:** The measurement distance separating the Tx and Rx side of the communications channel determines the extent to which accurate channel measurements at THz frequencies can be conducted. Indoor measurements require Tx-Rx separation distances of a few meters while in outdoor scenarios 10s and even 100s of meters of measurement distances will be required where various effects would have to be catered for such as a large number of reflections from buildings, vegetation and fading from meteorologically induced attenuation. Cabling is a largely negative factor that currently affects measurements over long distances. A Radio Frequency Over Fiber (RfOF) extension for frequency channel sounding was developed for the first time in [116] to extend the Tx-Rx channel measurement distance above 100 m and was successfully demonstrated in an outdoor environment. An important factor here is the system limitation when a THz radio link has several GHz of system bandwidth. The standard definition for noise figure is derived from the added noise by the receiver, N_{Rec} :

$$F = 1 + \frac{N_{\text{Rec}}}{N_0} = 1 + \frac{T_{\text{Rec}}}{T_0} \quad (7)$$

where N_0 is the the noise power added by the receiver and both have corresponding noise temperatures from use of kTB. Therefore taking an ambient temperature T_0 of 290 K, this calculates to form -84 dBm for 1 GHz bandwidth then up to -74 dBm for 10 GHz bandwidth. This noise floor would increase by up to another 10 dB based on the noise figure at the receiver defined as:

$$\text{Noise Figure} = 10\log_{10} \left(1 + \frac{T_{\text{Rec}}}{T_0} \right) \quad (8)$$

where T_{Rec} is the temperature of the added noise from the receiver. So what is measured over fibre might exceed what is achievable actually by a THz system.

d) **Dynamic Range:** The dynamic range of the equipment used for measurements is very important in determining the signal strength of different MPCs. A high order of diffuse reflections coming from the very short wavelength of the THz wave interacting with irregularities on surfaces similar in magnitude to the wavelength and indeed significant contributions of specular reflection components resulting from the highly directive beam are expected. For that reason, the dynamic range of the measuring equipment will help in identifying these resulting components that will be very helpful to determine the effect they have on the overall received signal strength. Therefore, the noise floor must be at a low enough level to achieve a high dynamic range, quantified as the difference between the strongest power component received and noise level.

e) **Doppler Sampling Rate:** The Doppler effect is where the propagating waves' frequency changes based on the velocity of a moving object in relation to the sources vicinity. E.g., a user moving across the room and blocking the signal transmission in an indoor scenario or equivalently a vehicle moving away from a stationary source located on another vehicle in a nearby lane in an urban scenario. The maximum Doppler shift, $f_{d,\text{max}}$ can be described by Eq. (9),

$$f_{d,\text{max}} = \frac{v_{\text{max}}}{\lambda} = f_c \cdot \frac{v_{\text{max}}}{c_0} \quad (9)$$

where v_{max} is the maximum velocity of the moving object, λ is the wavelength, f_c is the carrier frequency and c_0 is the speed of light.

For a user moving across the room with a velocity of 6 km/h with a wavelength of 1 mm at 300 GHz, that would result in a $f_{d,\text{max}}$ of 1.6 kHz. Similarly, for a vehicle travelling at a velocity of 60 km/h for the same wavelength that would give us a $f_{d,\text{max}}$ of 16.7 kHz. This parameter is extremely important to consider when measuring the dynamic behavior of the channel to obtain its time-variant characteristics while its effects will be much more significant at THz compared to the lower frequency bands. In order to avoid aliasing effects where signals become indistinguishable from one another and cannot be reconstructed at the Rx, the Doppler spectra must be sampled sufficiently fast at a rate $\geq 2f_{d,\text{max}}$ in accordance with the Nyquist-Shannon sampling Theorem [117], [118].

f) **Multi-Path Resolution:** High timing accuracy that will enable accurate characterization with high delay resolutions is expected with equipment capable of capturing the characteristics of the rich multipath environment when measuring over large bandwidths where clusters of MPCs would be easily detected by their Time of Arrival (ToA). As an example, in [119] measurements over an ultra-wide frequency range of 250 GHz were conducted using a VNA that allowed for a very high delay resolution of 4 picoseconds given 1600 data points. Clear and similar in shape LoS and specular peaks could be seen, while distorted peaks with different clusters of distinguishable MPCs appeared as a consequence of diffuse particle scattering from rough surfaces of various test materials' placed intentionally as reflectors in the propagating environment. High precision rotational [120] and translational [121] stages are also required to capture multipath propagation within the angular and spatial domains when performing such measurements.

g) **Other Requirements:** The choice of channel sounder to be used largely depends on the given application scenario e.g., whether its for material characterization, a fixed P2P communication scenario or a mobile scenario and what other requirements the targeted application has, such as bandwidth, speed, accuracy etc. What is a common need, is that of a relatively cheap and compact channel sounder that is easy to transport and one where cabling between the channel sounder and Tx/Rx would be as less complicated as possible to avoid calibration issues that are very common when performing these measurements. Furthermore, for short range scenarios, the channel sounder itself when large in size may act as an undesired reflector. In addition, to allow for accurate

Fig. 10: Experimental setup for THz signal generation. (a) THz-TDS, (b) THz-FDS.

THz channel measurements the channel sounding system has to be characterized itself in order to establish metrological traceability to the International System of units (SI) [122].

IV. THz CHANNEL SOUNDING TECHNIQUES

As a requirement to communications system design, profound knowledge of the propagation environment is essential. In order to develop future channel models, channel measurements are the first and most important step that require state of the art sounding equipment and correct methods to be available. THz measurements have been mainly conducted by three distinct channel sounding methods. These include the well known THz-TDS [123], Vector Network Analyser (VNA) [124] and Sliding Correlator (SC) channel sounder [125], while THz-FDS (Frequency-Domain Spectroscopy) [126] is another very promising channel sounding option. In this section, the performance of these channel sounding methods is described and compared with measurement requirements that may vary depending on the application scenario.

A. THz-TDS Measurements

THz-TDS [123], as depicted by Fig. 10(a) is a channel sounding technique where material properties are being probed by ultra-short light pulses. These pulses are converted to the THz range using photo-conductive switches (GaAs or InGaAs/InP) irradiated by femtosecond lasers at the source of the Tx and the received optical impulses detected at the Rx are converted to an electrical signal [127]. The received time domain signal is then processed by Fast Fourier Transform (FFT) to the frequency domain as a much more efficient implementation of the Discrete Fourier Transform (DFT) used to extract its spectral content. Moreover, since the received signal is complex (i.e.- containing both amplitude and phase information) it can be used to calculate the complex refractive index whose real part is used for measuring material thicknesses and the imaginary part used for calculating resonant absorption and extracting conductivity directly without the need

for additional modeling [123]. THz-TDS has the advantage of large bandwidth measurements where bandwidths up to 10 THz have been achieved [128] allowing for a wide range of spectral fingerprints of different dielectric materials to be identified, supplemented by a very good dynamic range (~ 100 dB) and tunable timing resolution that is achieved by adjusting the distance the two pulses will propagate; hence, enabling paths to be resolved within femtoseconds [123]. Additionally, since this is a pulsed technique, it allows for time-gating that can increase the Signal-to-Noise (SNR) ratio which normally decreases with thickness or number of layers, and allows for content extraction between multi-layered structures of sub-mm thicknesses; thus, proving to be excellent at measuring the scattering parameters and electrical properties of various material samples [129].

B. THz-FDS Measurements

THz-FDS [126] is a channel sounding technique that employs CW THz radiation to probe the material properties. The THz-FDS measurement setup is illustrated in Fig. 10(b). It is a technique that utilizes optical heterodyne detection in high-bandwidth photo-conductors that involves optical signal and oscillating wave mixing where the combined product gives an electrical signal at the difference frequency of the two lasers. It offers an excellent dynamic range (~ 100 dB) for large bandwidth measurements (~ 6 THz). Two lasers at adjacent frequencies are used to illuminate the photo-mixer and the applied bias creates a photo-current that is modulated at the beat frequency. This allows for the antenna to transmit the THz wave and produce a monochromatic beam. Furthermore, by tuning the lasers, the THz wavelength can be adjusted. The main advantage of THz-FDS compared to THz-TDS is that it offers the user a very high frequency resolution (10 MHz typ.) at a user determined range or fixed frequency and a comparatively lower cost [126].

Nevertheless, the THz-FDS technique as with THz-TDS is limited by its very small output power and large size and

cannot be used for long range channel characterisation and for a wider range of scenarios. Furthermore, this technique cannot capture the dynamic behaviour of the channel such as Doppler spread due to moving scatterers blocking the direct path, as it requires the channel to be stationary for the whole duration of the measurement, which may take several minutes.

C. VNA Measurements

The main technological advancements related to capturing the characteristics of the propagation channel are namely, VNA [124] and SC [130] channel sounders. The VNA, whose operation is more well known works by sending a stimulus signal from the Tx to the Rx and processing the received signal to obtain the channel properties. It measures the frequency response, which is essentially a measure of the phase and magnitude of the received signal by processing sequentially a great number of Channel Transfer Functions (CTFs) as a function of increasing frequency within the band of interest and then aggregating them together to generate a broadband CTF, i.e.- the S_{21} parameter which is a measure of the signal coming out of port 2 in relation to the signal entering port 1 of the VNA and is used to characterize distance-varying measurements. Onward, using Inverse Fast Fourier Transform (IFFT) the Channel Impulse Responses (CIRs) are generated as a function of time delay similar to those shown earlier in Fig. 9, section II. A VNA can provide full synchronization between the received and transmitted signal enabling individual calibration and coherent averaging over long times for the suppression of noise because of the large number of narrowband measurements [131]; hence, making it ideal for narrowband channel characterization. To extend the frequency range of the VNA to the THz range, frequency extensions are employed for the up conversion of the signal [132], [133].

A VNA based measurement setup is depicted in Fig. 11. The setup consists of a VNA connected at the Tx and Rx sides to frequency extender modules which in turn are connected to a waveguide and horn antenna that must be fixed precisely to avoid causing any signal reflections back to the frequency extender. To realize such a setup practically and enable an accurate measurement campaign and account for system errors in transmission and also due to source mismatches, system directivity and reflection tracking [119], the VNA/ extender heads require lengthy calibration techniques,

Fig. 11: Schematic of a VNA based measurement setup with frequency extenders employed for up-conversion of the signal.

e.g., Short, Offset-short, Load and Thru (SOLT) [134]. One of the key limitations related to measurements using VNAs is that the frequency extenders have to be connected via physical connections to maintain phase synchronization; thus, the measurements are constrained in terms of Tx-Rx separation distance while at these short distances the VNA must be placed somewhere near the Tx and Rx ends therefore, acting as an unwanted reflector and scatterer. Furthermore, the cabled connections between Tx and Rx are very sensitive and may affect the calibration if they are moved around. Another key limitation of the VNA is the ability to measure the propagation characteristics over ultra-wide frequency ranges of a time-variant channel influenced by moving scatterers i.e.- humans that cause blockage and scattering of the signal. In such complex cases, the applicability of VNAs is no longer viable since they take too long to perform a full frequency sweep surpassing the channel coherence time [130], and therefore not allowing for dynamic channel variations such as Doppler shifts to be captured in order to analyze the effects of link blockage. Nevertheless a VNA can provide an excellent dynamic range (~ 120 dB) [134] and a very high delay resolution [110] allowing for a very large number of MPCs to be resolved over significantly broad bandwidths; Nonetheless, the bandwidth is directly dependent upon the selected waveguide interface [135] used for Single-Input Single-Output (SISO) measurements. Frequency extender modules that are commercially available can operate between 50 GHz to 1.1 THz with varying bandwidths that reach up to 350 GHz in the higher end [136].

D. Sliding Correlator Measurements

The most popular channel sounding method that can yield real-time results is the SC based measurement method that utilizes the Direct Sequence Spread Spectrum (DSSS) technique that was first introduced by "Cox" of the Bell Laboratories [137]. The SC based time-domain channel sounding method, operates by transmitting a broadband Pseudo-Noise (PN) sequence $S_{Tx}(t)$ along the channel $h(t)$ from the Tx to the Rx as a stimulus signal resulting to the received signal $b(t)$ given by Eq. (10),

$$b(t) = \int h(\zeta) \cdot S_{Tx}(\tau - \zeta) d\zeta \quad (10)$$

and calculated by convolution of the propagating signal with the time-varying channel. At the receiving side, cross-correlation of the received signal with an identical but delayed by τ complex conjugate of the PN sequence $S_{Rx}^*(t - \tau)$ takes place as in Eq. (11),

$$\begin{aligned} E\{b(t)S_{Tx}^*(t - \tau)d\zeta\} \\ &= E\left\{\int h(\zeta)S_{Tx}(t - \zeta)S_{Rx}^*(t - \tau)d\zeta\right\} \\ &= \int h(\zeta)S(\tau - \zeta)d\zeta. \end{aligned} \quad (11)$$

Given the auto-correlation function $P(\tau - \zeta)$ of the PN sequence can be described by a Dirac-impulse shape which

TABLE II
COMPARISON OF THE FOUR DIFFERENT CHANNEL SOUNDING TECHNIQUES.

	TDS / FDS	VNA	SC
Measurement Domain	Time / Frequency	Frequency	Time
Bandwidth	> 5 THz	a few 100s of GHz	8 GHz
Dynamic range	~ 100 dB	~ 120 dB	~ 30 dB
Speed	milliseconds to 1 min / several mins	several minutes per sweep	1,000s of CIRs generated per sec
Frequency resolution	10 GHz typ. / 10 MHz typ.	10 MHz typ.	—
Real-time	Yes / No	No	Yes
Range	< 1 m	a few 10s of m	a few 10s of m
Spectral selectivity	No / Yes	Yes	No
Use Cases/Applications	Intra-device links, scattering properties; molecular attenuation	Kiosk downloads, WLAN, outdoor, backhaul/fronthaul	V2X communications, HST communications, dynamic link blockage, D2D communications

then equals to the CIR, a maximum length sequence (*m-sequence*) can therefore be used as a PN sequence to be transmitted as a reference signal in order to approximate the Dirac-impulse shaped function [118], [138], [139]. The advantage of this channel sounding method is that it can capture all the frequency points at the same time so that it is not as slow as frequency scanning measurements conducted using a VNA.

In Fig. 12 a simplified schematic of a SC based channel sounder is presented. The pseudo-noise sequence is mixed up to achieve the targeted frequency range before modulation, known as the baseband. In order to estimate the complex CIRs in the baseband, the Tx and Rx sides need to be in synchronization to achieve phase recovery at the Rx side, something that is achieved by the clock source that is used to drive the Local Oscillator (LO) on the Tx and Rx sides with a high degree of precision. Hence, an SC can measure a dynamic channel but not a mobile channel due to the clock source.

Time-domain SC operates at much higher speeds and allows for dynamic variations of the channel to be captured caused i.e.- by moving scatterers. However, strong thermal noise consequently may affect the precision in obtaining the results due to the lack of measurement bandwidth that is limited by the semiconductor technology [130]. SC channel sounding in the mmWave bands below 100 GHz with real-time capabilities that allow for fast electronic steering of the THz beam through the use of phased antenna arrays has been recently demonstrated [140], [141], [142]. Nevertheless, the first SC channel sounders at THz have also been introduced at 140 GHz [106] with 4 GHz bandwidth and at 300 GHz [125] at an ultra-broad bandwidth of 8 GHz, with the latter being

able to capture 17590 CIRs per second, while also having 4×4 MIMO capabilities.

E. Summary

Table II summarizes and compares the capabilities of the four main channel sounding techniques described in this section and names a few of the applications that these methods would work best for. Ideally channel sounders in the future would maximise these capabilities that are imperative for achieving better characterization of the propagation channel and would adapt to a wider range of scenarios and potential applications in the THz band.

V. THZ CHANNEL MODELING METHODS

Deriving the channel characteristics by appropriate modeling is the next step after conducting measurements in communication systems design. Current modeling approaches can be either described as deterministic or stochastic in the form of Geometry-Based Stochastic Models (GBSMs) and Non-Geometry-Based Stochastic Models (NGSMs). Deterministic models such as Ray-Tracing (RT) [143] require precise modeling of the propagating environment in terms of positioning of the antennas, geometry and properties of the scatterers present, in a mapped 3D environment to determine the power received at each point in space. Deterministic models, even though they can accurately predict the characteristics of the propagating environment, suffer from high computational complexity and large simulation times. On the other hand, stochastic models, are ones that use measurement data to give a statistical description of the propagation channel. NGBSMs are those where the scatterers are not modeled explicitly and the propagation channel is considered as a number of delay taps where by deriving probability density functions through extensive empirical data collection we can establish the channel model. In GBSMs probability distributions are used to describe the properties of scatterers and then fundamental laws of wave propagation are used to characterize the propagation process. The delay taps in NGBSMs are replaced by clusters in GBSMs that represent a collection of MPCs with similar properties where the clusters are distinguishable from one another. In the following sub-sections we describe these models in more detail as to their applicability at THz frequencies.

Fig. 12: Schematic of a Correlation based channel sounder.

Fig. 13: The RT method for deterministic channel modeling.

A. Deterministic Channel Modeling

Deterministic channel models are ones that use the electromagnetic laws of wave propagation to determine the signal power received at a particular location in a 3D mapped environment. Deterministic channel modeling approaches in the THz band involve accurate geometric modeling of the wave propagation environment by EM theory and require exact knowledge of the boundary conditions. Accurate positions of the Tx and Rx antennas along with geographical positions and properties of different material present such as shape and dielectric constant are needed to ensure the measured and expected results are in conjunction. The most popular and common deterministic channel modeling technique that has been employed successfully is known as RT [144].

RT in the THz spectrum can be employed to model various scenarios related to wireless communication scenarios within e.g., indoor office rooms, data centres and nano-networks. It is a method by which rays are launched at regular time intervals and are detected based on propagation in free space where effects such as reflection, scattering from rough surfaces as well as edge diffraction and clustering are accounted for as illustrated in Fig. 13. Advanced acceleration and high efficiency 3D RT techniques need to be developed that can increase the simulator's performance and which consider the propagation environment characteristics precisely. Detailed geographic and geometric knowledge of the propagation environment in each scenario is essential for accurate modeling. In order to accurately employ RT to estimate the channel characteristics, the model requires parameters such as angle of incidence to the reflective surface, propagation distance and the

complex permittivity of the materials considered as reflectors in the model. Depending on the complexity of the model higher accuracy in the estimated results may be achieved. For this, the scattering behaviour considering a high order of diffuse reflections needs to be accounted for, which requires knowledge of how well each material absorbs energy and how rough the material is. Moreover, when RT needs to be applied to simulate practical MIMO systems where high data rates can be achieved, the computational complexity increases massively as the simulation needs to account besides scattering, communication between multiple antennas over ultra-wide frequency bands [145]. Furthermore, it is a challenge to be able to analyse the time-varying properties of the channel. This accounts for switching between LoS and NLoS scenarios, varying the Tx and Rx locations as well as varying conditions in the atmosphere and of the surrounding scatterers in the propagation environment.

On the other hand, Finite-Difference Time-Domain (FDTD) [146] and Method of Moments (MoM) are numerical methods that can be used to account for back-scattering of the rays. They are methods that can solve Maxwell's equations precisely by integral (FDTD) and differential (MoM) equation analysis. They can provide accurate estimates of spatial distributions when detailed geometric knowledge is required in terms of roughness of materials, shape etc. However, The amount of computational resources required for simulations are extensively large and the processes are time consuming therefore limiting the size of the environment to be modeled. This is because the solution to Maxwell's equations requires a set of points spaced out in the order of a wavelength so that a

numerical solution to the equations can be found. This means that the computational complexity of the problem increases massively as the frequency and amount of scatterers increases. Both the FDTD and MoM approaches mentioned are very attractive and may be combined with RT to provide a more reliable estimation method. Although; combining the two models together may be quite challenging since they are devised using different tools and assumptions. Furthermore, large-scale and small-scale interactions are tightly coupled and thus the hybrid model developed needs to consider mutual coupling before deployment. For the development of an efficient model at THz, additional parameters need to be considered such as polarization, indoor-to-outdoor propagation and channel variations caused by moving scatterers [147].

B. Stochastic Channel Modeling

Stochastic channel models are ones that use empirical data to provide a statistical analysis of the channel by a spatio-temporal approach. These models are based on measurement campaigns and require much less complexity in terms of computing resource requirements compared to deterministic models. Although, measurement time to obtain good accuracy in the results is a limiting factor. Due to the higher order frequencies and larger bandwidths, wideband channels in the THz regime require multipaths to be resolved in the time domain. Narrow-band fading models such as Rayleigh and Ricean may therefore no longer be required and a statistical model that can generate the CIRs needs to be developed. This would require us to obtain the spatio-temporal characteristics of the propagation channel which are described in more detail as follows:

- **Spatial Characteristics:** Spatial parameters can be extracted from a Power Angle Profile (PAP) that involves statistical distributions of the different multipaths in the form of power received over AoA and AoD. PAP measurements can be conducted by varying a highly directional antenna in azimuth and elevation using high precision rotational and translational stages and recording the power received with the advantage that no phase information is required to steer the beam in the wanted direction in contrast to electronic beam-steering [148]. Misalignment of the antennas and signal arriving from different angles will cause power losses, and therefore it is important to know how much power is received at a given point in time. Root Mean Square (RMS) angular spread is a spatial parameter that can be extracted from the PAP which describes the power arrival dispersed over the angles of incidence the antenna is being varied. Despite the high directivity of antennas at THz, this angular spread may prove to be significant especially at longer distances, i.e.- in an urban environment, where spreads in the order of $\pm 40^\circ$ were recorded when measured using a 30° beamwidth horn antenna [116].
- **Temporal Characteristics:** The temporal behavior of the channel can be described in the form of a Power Delay Profile (PDP) which records power received over ToA of the different arriving MPCs where each component

Fig. 14: SV model representing exponential decay of clusters and rays over time.

represents a single channel delay tap. It is important that the channel sounding method employed offers a high delay resolution to separate the different multipaths over very small periods of time. Time dispersion parameters such as RMS delay spread and coherence bandwidth are parameters that can be extracted from the PDP and are used to provide information for the design of transmitters and receivers that can overcome the effects of fading. At THz frequencies, very small delay spreads would be observed, where up to 4 ns delay spreads were measured experimentally in an indoor environment at 300 GHz [149].

Many factors need to be considered in the future for accurate channel modeling. Clustering behaviour is observed when the arriving MPCs or otherwise intra-cluster components have similar distributions in terms of ToA and AoA/AoD. Saleh and Valenzuela [150] proposed a widely acceptable NGBSM known as the Saleh-Valenzuela (SV) model that provides a cluster based impulse response based on reflections from different surfaces where MPCs are modeled as delay taps. It assumes that MPCs vary uniformly in phase and have powers that are Rayleigh distributed and which decay exponentially based on a Poisson distributed ToA of MPCs and clusters. Fig. 14 shows the SV model's impulse response that represents the mean square power $\overline{\beta^2(t)}$ over time where clusters are seen to decay with a rate of Γ with cluster arrival time T_l for $l = 0, 1, 2 \dots$ and MPCs are seen to decay with a rate of γ with MPC arrival rate τ_{kl} , where k is the MPC arrival time for $k = 0, 1, 2 \dots$ within the l^{th} cluster. Extensions of the SV model have already been developed at lower frequencies [151], [152], [153] to account for the cluster AoA in addition to its temporal behavior. Thus, PDP and PAP measurements may be used as a basis from which the SV model can be applied to at THz to fit and verify the resultant clustering behavior [154], [155], [156].

In order to further analyze the multipath behavior within individual clusters, a second order profile for exponentially distributed multipaths such as the Gaussian mixture model

Fig. 15: The cluster oriented GBSM.

(GMM) [157] [158] which is a cluster oriented GBSM that can be adopted for approximating AoA/AoD and identifying similarities between the different MPCs within a cluster or otherwise inter-cluster components. A generalized representation of a cluster based GBSM is depicted in Fig. 15 that shows a collection of rays being launched from the Tx with similar AoD, reflected at the surface of a scatterer and detected at the Rx at some AoA and ToA. As per Eq. (12),

$$\sum_n^M (\alpha_{Tx}^I) (\alpha_{Rx}^2) (e^{j\theta_n}) (e^{j\phi_n}) (e^{j\omega\alpha}) [\bar{\Phi}] \quad (12)$$

these individual rays n are summed up to form a single cluster with a phase at the Tx ($e^{j\theta_n}$) and mean AoD of θ , and phase at the Rx ($e^{j\phi_n}$) with mean AoA of ϕ , where the total number of rays is denoted as M . Then by computing the gain of each individual ray at the Tx (α_{Tx}^I) and Rx (α_{Rx}^2) sides as a function of polarization $\bar{\Phi}$, a single complex number is formed representing a single delay tap of the multipath channel, where the real and imaginary parts are Gaussian distributed and therefore the single complex number formed is Rayleigh distributed. The Doppler effect could also be accounted for by adding the term $e^{j\omega\alpha}$ to the equation where ω relates to the Doppler frequency.

C. Hybrid Channel Modeling

Now what seems to be happening at THz, is that a hybrid modeling approach, that is, a combination of both deterministic and stochastic methods is currently being preferred. To capture the received power at every point in space and time, channel sounding at THz often makes use of mechanically translational and rotational antennas; though, taking a very large sample of measurement data is often extremely time consuming and modeling the environment in a stochastic

manner with high levels of accuracy is extremely difficult. Therefore, in order to extend the sampling intervals within a 3D environment to further extract the statistical behavior of the channel, software simulators such as RT are employed which by themselves often appear rather simplistic due to lack of knowledge of the propagating environment and limited computational resources. When empirical measurements are conducted, there are often different components and effects that appear which are not captured by RT simulators such as dense MPCs. Thus, by feeding the RT simulator a set of empirical data, it can be then calibrated by replicating this data through extensive simulations to enable a much larger data set as an extension to the limited data sets collected by measurements. Therefore, statistical modeling with stochastic scatterer placement and RT Hybrid channel modeling could inevitably satisfy all the propagation conditions and may prove to be a promising method for the development of future models that combine the advantages held by deterministic and empirical models so that a balance can be obtained between accuracy of the results held by deterministic models and reduced complexity held by stochastic models generated from empirical data. Nonetheless, the hybrid approach still fails to address the problem of complexity due to the need of extensive measurement and long simulation times. Therefore, it should be pointed out, that this hybrid approach could benefit from machine learning to reduce the extent of measurements required [159].

VI. THZ CHANNEL CHARACTERIZATION FOR 6G APPLICATIONS

In this section we highlight the main channel measurements and modeling contributions found in literature for describing the stationary as well as dynamic behavior of the THz channel.

We categorize these models based on the application scenarios identified in section III for future THz communications.

1) **Kiosk/Desktop Downloads:** Kiosk downloading may be considered as a short range communication scenario where file exchange between user devices such as smartphones or PCs and "vending" type machines can be pondered as prospective use cases with the potential to provide the so called "information showers" and achieve extremely high data rates targeting 100 Gbps [160]. Propagation in such use cases may be assumed to be LoS over a short distance (< 1 m) with the uncertainty of user equipment antenna misalignment where the user would have to essentially point the receiving device towards the transmitting end. The presence of a front cover window would induce specular reflection while the Tx side would have to be equipped with a high gain antenna to compensate for propagation losses as antennas placed i.e.-within a smartphone would have their signal strength reduced significantly because of the smartphone casing. Song *et al.* [161] presented a kiosk data downloading model based on a MMIC for the transmitter with Indium Phosphide (InP) based High Electron Mobility Transistor (HEMT) semiconductor technology along with concepts and considerations for small packaging for receiver modules based on the Low Temperature Co-Fired Ceramic (LTCC) technologies, where 20 Gbps error free transmission was achieved over 1 m. This Kiosk downloading system was further prototyped for operation at 300 GHz and tested experimentally and a link budget plan was also presented [162]. He *et al.* [29], [163] presented a stochastic channel model for 3 different Kiosk downloading scenarios at 300 GHz where up to 6th order reflections were considered and channel parameters were obtained based on measurement and calibrated ray-tracing results. Salhi *et al.* [164] investigated broadband angular channel characteristics by conducting measurements for 5 different frequency bands up to 321 GHz for a short range indoor desktop download scenario that can be considered as a very similar use case to the kiosk download scenario. Recently, short range characterization was extended to carrier frequencies of 625 GHz with 250 GHz bandwidth to measure the channel properties in the ultra-wideband [119], [110]. It was found that specular components from nearby scatterers are significant while reflections from various materials can induce diffuse components that form clusters due to the high frequency selectivity at THz, which nonetheless, is extremely unpredictable.

2) **Data Center:** A data center can be referred to as the infrastructure within a building that contains racks with servers with links connecting together the different racks as well as the servers within these racks [165]. A potential application of the THz wave because of the high bandwidth availability is wireless data center communications where the cabled connections would be replaced by ultra-fast and high data rate wireless links. This would offer the advantages of flexibility and low costs as well as easier to maintain environmental conditions provided by cooling technologies for equipment operation. Cheng *et al.* [166] presented a THz MIMO channel sounding measurement campaign in a data centre like environment at 300-312 GHz where LoS and Directed-NLoS (DNLoS) propagation were considered and the data was modeled in

the form of delay dispersion, shadowing gain and path loss. Similarly, an amplitude fading analysis and Doppler modeling was considered for a 4×4 system, and a 2D geometrical model based on moving scatterers was also presented and validated with measurement data [167]. Characterization of different propagation phenomena for a wireless data centre was considered in [30] while PAP and PDP measurements in an actual data centre were presented in [168] for various P2P scenarios. In [169] a stochastic channel model was developed based on the ray tracing approach that was used to derive the statistical properties of the channel where up to 21 different paths with their associated delays and losses were considered in the simulation along with dispersion effects caused by phase changes from small movement of the Tx and Rx. An evaluation of the propagation channel in a THz wireless data centre was presented in [170] where the effects of humidity were considered. Finally, in [156] a cluster based model as a modification of the SV model was presented where the effects of cooling on signal transmission were accounted for along with path loss and shadowing effects. The model was further validated with measurement data.

3) **Intra-Device:** The continuous rise in data transfer within modern day devices where communications between components, different layers of motherboards and within on-chip networks are expected, has lead to complicated layout structures, reduced processor space and high energy level consumption [171]. As such, high data rate intra-device THz wireless communication links may prove to be a solution. The propagation environment to be considered for channel modeling is very small, in the order of a few cm due to the casing of the device. The antenna requirements may be more flexible with less directive characteristics but communications are expected to rely not only on LoS propagation but also by significant multipath scattering contributions within the small enclosure by NLoS propagation. Examples of intra-device communications include board-to-board, chip-to-chip [172], [31] as well as in-chip communications [173], [174], [175]. Fu *et al.* [31], presented measurements conducted within a metal casing at 300 GHz with the results showing that the received power is sensitive to the heights of the Tx and Rx sides. In [176] characterization of transmission scenarios for THz intra-device communications was presented. Measurements were conducted in the frequency range between 270-320 GHz with LoS and NLoS scenarios being considered where the narrow propagation environment was found to induce less multipath contribution while the impact of printed circuit boards was found to play a role in NLoS communication but has not been yet investigated in more detail. Data rates of 0.95 Tbps were achieved by full-wave simulations in [177] for wireless on-chip communications that interconnect cores in a multi-processor. In [178] the effects of multipath propagation on the link budget due to multi-layer housing structures for on-chip communications were studied and may prove to be beneficial if careful chip layer structure is considered.

4) **Backhaul/Fronthaul:** Wireless backhaul/fronthaul links are potential use cases for future THz communications with LoS as the main propagation characteristic. A backhaul link is a fibre based or wireless link that connects the base station

to the core network and is in the km range. Current wireless backhaul links are not sufficient for future capacity and latency requirements and therefore a potential solution might be that of THz wireless transmission as a wireless extension of the optical fiber between rural and highly populated urban areas to ensure high-speed connectivity everywhere in a cost effective manner [179]. Fronthaul links can be used to give broadband/high speed access to the end user when operating at higher frequencies at places where the broadband customer does not have fiber connectivity and where the link distance is much smaller compared to the backhaul. THz transmission can be applied to 5G fronthaul links in order to optimise and speed up the implementation of 5G connectivity in urban areas and thus; can provide more flexibility to avoid the expensive fibre connections currently required for 5G system deployments. Automatic planning algorithms [32], [180] for the backhaul/fronthaul links are essential in designing guidelines for successful deployment of these links. Planning for these scenarios should involve identifying the shortest LoS link where highly directive antennas that will minimize multipath propagation will be employed. For terrestrial links we can assume that communications will be below the height of clouds; however, the effect of attenuation due to fog may be significant. The applicability and feasibility of such transmission has already been proven by MMIC based technology and demonstrated at large distances of 850 m at carrier frequencies of 240 GHz where data rates of 64 Gbps were achieved [181].

5) **WLAN:** Typical indoor communications in the THz band will involve scenarios such as office rooms and conference rooms. Such scenarios would have to consider LoS, link blockage, and scattering as the main propagation phenomena and will be mainly applied for interconnecting access points and not for user access. Notably, considering that the WiGig 60 GHz standard [182] is of such limited range, then THz cannot be expected to go any further with communication links ranging up to 20 metres. Calibrated RT simulations were presented in [184] for indoor radio channels by taking account different frequency points within the evaluated range due to varying propagation conditions and a novel calibrating method was employed that uses both spatial and temporal information that significantly improve the accuracy of the RT tool [185] and extend its applicability to much wider frequency ranges. The RT tool developed was built upon common image theory for reflections [186] and Kirchhoff scattering [187] analysis and the results were further validated against measurement data collected at 300 GHz. Choi *et al.* in [188], proposed a novel GBSM for THz channels that mathematically describes the specular component of a single induced cluster from indoor reflections that can be utilized when the main LoS component is blocked. The model also accounts for the scattering loss and has the advantage of reduced complexity in comparison to RT. The model was verified against a mirror-image procedure to aid in evaluating the physical characteristics and evaluate the system-level performance of the THz channels. In [189], RT simulations were carried out in an indoor office room where clustering due to multipath reflections from materials' of known permittivity were identified and the effects of multipath propagation on the PAP and PDP were considered. The effects

of clustering were validated against the SV model as they were found to follow an exponential decay pattern.

In [190] RT modeling of short-range wireless communications in a typical office environment was presented for the atmospheric windows below 1 THz. Statistical modeling was considered in terms of AoA, AoD and ToA and Up to 4th order reflections were considered in the simulation. It can be deduced that LoS components have the greatest contribution in received power while in the NLoS case the power received from reflections was much less, though it could supplement the LoS when it is not available (e.g., due to blockage) but a high reliability communications system cannot be dependent on these components.

The effects of antenna misalignment on the received power will play a very important role at THz due to their high directivity, and as such, they are modeled as a random process in [191] where monte carlo simulations were used to evaluate these effects while RT was used to determine the resolvable paths and their associated gains and losses as a result of propagation in an indoor office room. Similarly, the effects of different antenna directivities on resolvable paths for different applications in terms of propagation losses, fading and delay spreads were investigated in [192] and it was found that antenna directivities for fixed P2P applications should be higher than applications with positional uncertainty such as communications on board a desktop in the presence of non-stationary devices such as laptops where lower directivities could cater for antenna misalignment.

In [193] indoor channel measurements were conducted in the recently standardised bands between 275-321 GHz for THz communications in a typical office scenario. Calibrated RT was performed, and a spatial and temporal analysis of the results was provided based on measurement data. MIMO channel capacity was calculated for a 2×2 system where a capacity of 6.21 bit/s/Hz was obtained. RT results were further compared against measurement data and were found to be in good agreement. Nonetheless; diffuse scattering was not considered in the analysis. A modified version of the SV model used to characterize the THz channel for indoor THz communications with antenna sub-arrays operating at 300 GHz was presented in [194]. An upper bound on the ergodic channel capacity was obtained in relation to the number of antenna sub-arrays and as a function of distance where the capacity decreased with an increase in the distance and the array gain decreased with the increase in sub-array number. The ergodic channel capacity at a distance of 10 m with 40 antenna sub-arrays was found to be 0.125 Tbps. Stochastic modeling of the indoor propagation channel by considering both time and frequency domains [195] in a statistical analysis of ultra-wideband channels in the 275-325 GHz band was provided for a realistic office scenario and the results were verified against calibrated RT simulations. The model accounts for AoA/AoD, ToA and phase together and considers channel dispersion for each resolvable path and so can be used to simulate practical MIMO systems. Angular spreads of a few degrees were observed while 3×3 MIMO capacities ranging between 5.5-7.3 bit/s/Hz were measured.

Furthermore, Priebe *et al.* [196] conducted channel measurements at 300 GHz with a 10 GHz bandwidth. Mea-

measurements of diffraction and absorption coefficients of different materials placed between the transmitter and receiver were conducted such as glass, MDF and Plexi-glass where absorption coefficients of 9.98 cm^{-1} , 4.31 cm^{-1} and 2.59 cm^{-1} were measured, respectively. Measurements were also conducted for two separate indoor scenarios, a P2P link of devices on a desktop and the connection of a laptop to an access point within the office room. LoS and Directed-NLoS (DNLoS) propagation scenarios were considered up to 2nd order reflections. An interference investigation was also demonstrated by using a two-ray model [197] while an empirical narrowband path loss model was proposed for the investigated scenarios. Important to mention, that DNLoS propagation that was initially proposed in [198], differs from the traditional concept of NLoS that is mainly used for sub-6 GHz communications as non-directed NLoS contributions to the received signal strength may be in many cases insignificant at THz. However, as we have mentioned previously for cases such as intra-device communications where wave propagation is confined to a small space, the NLoS components will play a major role. In [199] a coverage and achievable data rate analysis was conducted for an indoor environment at THz frequencies. A Single Frequency Network (SFN) was adopted where multiple AP's transmit the same information over the channel within the same frequency range. This can be used to combat the distance problem and extend the transmission range. The minimum data rates for each user are considered for different resource allocation schemes. The results show an increase in the minimum achievable data rates from 25% using a single AP to 95% using a total of 20 AP's.

Zhao *et al.* [155] extended THz indoor channel characterization to higher frequencies by providing results for the 650 GHz band in comparison to the 350 GHz band. An indoor scenario was considered with a 10 GHz bandwidth at both the low band and high band. A temporal and spatial analysis was performed and from the results it was found that the NLoS component is sufficiently strong to compensate for the received signal in case of a moving user blocking the main LoS component, though achievable data rates were reduced by about 50% at both bands for the NLoS case in comparison to the LoS case. Channel dispersion effects were also considered with delay spreads of less than 80 ps being recorded due to the high directivity while hardly any diffraction was observed. It can be deduced that RT simulations may prove to be efficient at evaluating indoor channels at frequencies beyond 300 GHz due to the high correlation between the identified paths and indoor environment, though knowledge of the materials present in the environment is required to obtain accurate results.

Shafie *et al.* [200] presented a 3D model accounting for the effects of dynamic user blockage, antenna directivity and interference caused by nearby access points by considering factors such as molecular absorption, the height of the devices and transmission distance. The effect they have on coverage was considered and the authors provide suggestions for performance enhancement considerations. A 3D dynamic channel model for tracking the LoS beam between user equipment and access point in an indoor scenario described by a Kalman filtering algorithm and Markov Process by considering varia-

tions over time in the propagation channel was described by Nie and Akyildiz [201]. The results were further validated against RT simulations where the effects on the capacity were addressed generating satisfying results. A 3D MIMO non-stationary indoor GBSM was proposed by Wang *et al.* [202] where the channel parameters were varied spatially and over time and the impulse responses were generated. LoS, NLoS and diffuse scattering were considered in the model and different characteristics were studied in the form of time, space and frequency correlation functions. The theoretical GBSM developed was verified against simulations and were found to be in good accordance. A statistical model based on empirical data collected from measurements using a channel sounder recording over 15 000 thousand PDPs and a detailed clustering analysis was presented by Ju *et al.* [203] that indicates cluster paths, powers and delays while the data collected was also validated using simulation for the cases of LoS and NLoS propagation.

When highly directive antennas are employed, even the slightest change of degree in movement may cause beam misalignment. In cases where the user e.g., is playing a game on his phone which requires dynamic rotational movements and micro-displacements, the effects of beam misalignment may severely affect the reliability of a high data rate link. Petrov *et al.* [204] characterized these micro interactions between the user and his mobile phone in terms of beam misalignment and its effect on the achievable data rates were modeled mathematically in the form of angular and Cartesian micro-mobility where it was found that these effects may have a serious impact on the capacity of the THz link while dynamic beam alignment in contrast to periodic alignment may increase the spectral efficiency by 10-15 %.

Peng *et al.* [205] introduced a novel 3D AoA estimation method for dynamic indoor THz channels using a forward-backward algorithm for calculating the Bayesian interference. AoA movement in the algorithm was represented as a Markov process and the Bayesian interference was used to combine the likelihood and a priori information providing a better estimation rather than the likelihood itself. The model considers human movement in terms of translation and rotation of user equipment (i.e.- smartphone) from which the statistical probabilities were obtained. A ray launching simulator for Bayesian interference is adopted to generate the channel model for the indoor scenario. Going one step further, Peng *et al.* [206] proposed an AoA estimation model for dynamic indoor propagation that considers spatial correlations to describe the dynamic properties of a user moving within the given environment due to time information correlations resulting from the low user speed and statistical movement pattern as well as space information correlations due to similar user displacement in case of a MIMO scenario. The Bayesian filter was fitted to improve accuracy of estimation of AoA, while simulation results show that this cooperative estimation method considering space and time correlations can improve the performance in each scenario. Very Recently, A two-step AoA estimation method was also devised by Peng *et al.* [207], to solve the problem of received power due to unknown locations of user equipment and access points. After initial

AoA is estimated by considering that the power received over different angles is correlated over different frequencies. In this way the model could be applied at lower frequencies, and then used to provide a rough estimation at the THz range, thus, reducing computational complexity which is much higher at THz. The results were also validated using channel sounding measurement data.

The unavoidable densification of access points expected at THz because of the limited output power and need for high gain and antennas that limit the communications distance requires efficient deployment to avoid complexity and resource limitations. Singh and Sicker [208] addressed these effects by proposing efficient access point deployment through numerical modeling considering the maximum radius of coverage to minimize the number of access points deployed and the use of repeaters to assist for coverage. Similarly, Shafie *et al.* [209] considered access point densification and its effects on maximum achievable capacity. A 3D model was developed that considers basic propagation characteristics along with access point locations and human movements that block the signal modeled as a Poisson processes. The model framework consists of LoS as well as reactive connectivity modeling where users switch between access points in case of blockage, hence, overcoming molecular absorption effects and enhancing link reliability.

6) HST Communications: In a new era of smart, green and intelligent transport, high data rate communications and high speed broadband access to HST users is expected to be delivered by the next generation of mobile communications to realize the vision of "smart rail mobility" that consists of communications between trains, passengers and infrastructure [33]. The most promising application of THz however, is in the Train-to-Infrastructure (T2I) channel to deliver very high data rates of 100 Gbps etc. but with very narrow beamwidths in comparison to mmWave. Regarding the intra-wagon channel, for links between users and access points, the large bandwidth at THz could be potentially exploited in the future for high data rate transmissions and to accommodate a large number of users though mmWave should be sufficient to provide HD video applications at present [33].

For any given complex communications scenario that includes a high order of mobility, new paradigms of channel modeling have to be developed. Due to limited channel sounding, there is a need for extensive calibrated ray-tracing simulations in order to develop the stochastic channel model. Limited measurements means a limited degree of freedom as full dimensional channel information are required from measurement directly and hence, the need for simulation. For instance, The T2I inside-station channel was characterized in [210] for the first time. The measurements were conducted using a channel sounder at 304.2 GHz centre frequency with 8 GHz bandwidth. The results extracted from the PDP were presented in terms of Rician k -factor and RMS delay spread. Two scenarios were considered to emulate the channel when the train is stopping and a ray-tracing simulator was developed for the given scenarios that was calibrated bases on the measurements. The results obtained show that the 2nd order of reflection is sufficient to account for in the absence of the

main LoS component while the inner wall of wagon when the door opens can reflect multipaths with unexpected long delays and has to be considered before system deployment.

Guan *et al.* in [211], employed calibrated-RT simulations to investigate the intra-wagon scenario for the first time. Similar to the inside-station channel the 2nd order reflections were found to be strong enough to compensate the main delay component. In order to make something useful out of this characteristic of HST channels, some reflectors or a Reconfigurable Intelligent Surface (RIS) [212] can be used in a DNLoS scenario to generate the first order reflection when the LoS path is not available. For system design there may be some special propagation elements to consider such as multipaths arriving with the same delay but from very different directions. Onward, an detailed analysis of the calibration and validation processes for the RT simulator was presented in [213] and extended to a wider range of scenarios where the Rx positions were varied and for a greater degree of freedom. From the analysis it is obvious that at THz, propagation characteristics differ from the lower bands and channel multipath sparsity is a major characteristic with much smaller delay spreads expected at 300 GHz when compared to the 60 GHz band. In addition, Furthermore, Guan *et al.* [214] presented a capacity analysis for all five smart rail mobility applications identified at 300 GHz.

7) Inter-Satellite Links: The increasing demand for improved coverage in the Internet-of-Things (IoT) field has encouraged the industry to support research to achieve a highly reliable and fast communications network to deliver space and aerial links on top of the existing terrestrial networks. This is expected to be achieved by the deployment of CubeSats/nano-satellites that are preferred to conventional satellites typically deployed in Low-Earth-Orbit (LEO) Medium-Earth-Orbit (MEO) and Geosynchronous-Equatorial-Orbit (GEO) constellations [215] as they are lower in size, weight and cost. Currently, communications within the LEO, MEO and GEO constellations are accommodated within the microwave bands up to 75 GHz while they are also achieved within the optical bands using lasers. Due to the saturated spectrum in the microwave bands [216] where these constellations operate as well as the limitations in beam alignment to achieve LoS propagation and synchronisation of satellites within the optical bands [217], an alternative solution is required. The THz band poses as a candidate for future ISL links as it holds a number of advantages. Firstly, atmospheric attenuation in the uppermost layers of the earth's atmosphere is a lot less prominent due to the thin air, while effects such as rain, cloud and fog are non-existent resulting in much longer communications distances. Furthermore, the THz band can provide higher data rates and capacity than the lower bands while it holds less strict beam alignment requirements in comparison to communication links operating within the optical bands. Nevertheless, channel propagation for ISL's differ in comparison to terrestrial links. Channels that have to be considered for ISL deployment include the near-earth channel and the deep-space channel. Parameters that are used to describe propagation within the ionosphere in the near-earth channel include the plasma frequency, collision frequency and depolarization of

electrons and ions caused by the Faraday rotation [218]. Furthermore, for deep-space channel propagation, factors that require consideration involve cosmic microwave background radiation, noise effects due to solar brightness, and solar effects such as flares and wind.

Some early studies have explored the possibilities of ISL communications [219], [220], and a capacity analysis in [221] for an ISL was conducted where 100 Gbps were achieved at a relatively short-range communications distance of 1 km operating at 340 GHz and 2.5 Gbps at 100 km inter-satellite distance, with the later requiring a 62 dBi gain antenna, 50 cm aperture area and an output power of 1 W. Nie *et al.* [222], considered the propagation effects present in near-earth and deep-space channels and developed a channel model to investigate diversity techniques used to achieve higher throughput. Their analysis has shown that near-earth channel propagation in the ionosphere does not affect the THz link significantly while for the deep-space channel only major solar activity can cause angular instabilities. Large Doppler variations due to motion of the satellites are also expected as observed using FDTD simulations in [223]. In [224] a performance analysis for LEO ISL's was conducted where it was found that the Rician fading channel model best describes the channel in terms of LoS propagation and Doppler variations while results were presented in terms of packet arrival rate and violation probability indicating the impact they have on backlog and delay performance. Finally, diversity techniques such as space and polarization diversity as explored in [225] should be carefully utilized to maximize the throughput.

8) **V2X Communications:** The next generation of mobile communications is one where it is expected that the requirements of V2X communications will be fulfilled. A network that is extremely intelligent and able to conquer the requirements of high data rates, ultra-fast, ultra-reliable and ultra-low latency exchange of information is a future vision for 6G V2X communications [226]. The need for enhanced road safety and inter-connectivity that satisfies the requirements mentioned, directs us to communications in the THz band that are vital in achieving huge amount of throughput, though ultra-reliable information exchange may be difficult to achieve with the current technology [227]. Particularly, highly directive THz links in the lower end of the spectrum may be utilized for large information exchange within vehicular fleets of semi-autonomous vehicles performing cooperative driving [228] as well as for data relaying in congested networks to enhance connection reliability [229]. Efforts in developing models at THz for V2X communications so far have been limited by advancements in technologies of transceiver design, new waveforms, design of phased arrays along with dynamic beam-forming and beam-steering. Therefore, taking into consideration such Doppler and beam-forming capabilities being still too bad at mmWave, at THz it may be necessary to have such communications between vehicles at points where they are stationary, such as to do 'vehicle kiosk downloading/uploading'.

Petrov *et al.* [230], conducted an interference study that considered the impact in terms of direct transmission and multipath reflections from vehicles on the side lane for an urban and highway V2V communications scenario at 300

GHz. A 2D geometric model was developed to predict the interference and it was found that the interference largely depends on the angle of the antennas radiation pattern where for angles greater than 40° multipath reflections from the side lanes contribute significantly to the interference, while for angles less than 20° the interference caused was minimal. Then, Eckhardt *et al.* [231] conducted a detailed propagation analysis based on measurement data obtained at 300 GHz for V2V communications in a stationary environment. The scenarios considered include LoS propagation in a single-lane scenario and reflections from nearby vehicles for various multi-lane scenarios as well as under-vehicle propagation. These measurements may contribute to future propagation modeling for vehicular communications. Nonetheless, more complex scenarios have to be investigated in the future that take into consideration factors such as road surface properties, vegetation and a large number of mobile vehicles. In [232], an initial study of signal losses resulting from material penetration and reflections at 300 GHz for various vehicular scenarios was conducted, though a much more detailed analysis is required and for a greater range of scenarios.

Busari *et al.* [233], described a generalized 3D model for communication between mobile users cars and infrastructure for an outdoor scenario by making use of the hybrid beam forming architecture to realize massive MIMO. The model considers a single-path LoS channel where different equidistant access points are placed along the road with a fixed speed for the mobile user and vehicle. Large and small scale fading were investigated along with the Doppler frequency. Moreover, Yi *et al.* [234] examined Vehicle-to-Infrastructure (V2I) channel for urban and highway scenarios at 300 GHz with 8 GHz bandwidth. Measurements were conducted using a SC channel sounder and RT was employed for the analysis of the propagation environment. The attenuation due to rain and snow in the propagation channel was also considered as it contributes to the path loss and were found to be 26 dB/km and 348 dB/km, respectively. Notably, the attenuation due to snow completely differs from what is expected from the theory presented in section II where it is expected to be similar to that of rain, indicating that more measurements need to be taken to account for this effect. The authors have concluded that future works need to account for traffic flow since LOS communication cannot be guaranteed between different vehicles. A time-varying propagation model that aims at characterizing the V2I urban channel was proposed in [235]. The time-varying characteristics were captured using a Birth-Death (B-D) process in terms of the multipath behavior of the channel within an RT model. Based on the RT model, a time-varying GBSM was developed that considers multipath propagation as a result of specular reflections and spherical wave propagation from which a statistical analysis was derived.

A 3D channel model based on propagation resulting from a reflect-array antenna composed by graphene material that is dynamically reconfigurable by tuning its chemical composition was presented in [236] that considers LoS, NLoS and scattered paths which could be adopted in vehicular networks. The model which was simulated using RT techniques, due to the presence of the reflect-array achieved a delay spread reduction

by over 1 ns to less than 0.1 ns showing an improvement to the coherence bandwidth and very small angular spreads $< 0.12^\circ$ that were one tenth of the spreads found without beam-forming. However, the beam-forming gain of 18 dB achieved in the main direction requires a very small variation in beam alignment angle of $< 11^\circ$.

9) **D2D Communications:** D2D communications can be considered as a promising technology by which the spectral efficiency within a cellular network can be maximised by utilizing devices that are in close proximity to each other without the need to go through the Access Points (AP's) or base stations (BS's) [237]. The communicating devices can share resources efficiently in order to achieve higher data rates, reduced latency and higher throughput in order to improve the Quality-of-Service (QoS) and enhance user experience [238]. It has several use cases including local services, emergency communications, mobile tracking and positioning, extending cellular coverage etc. An envisioned scenario would be devices communicating at a very short-range (e.g. two devices placed on the same table) in a Wireless Personal Area Network (WPAN). Toward realizing D2D communications in the THz band, there are certain challenges faced in characterizing D2D propagation channels that have to be addressed. Some of these challenges include neighboring device discovery, mobile device tracking, managing interference between neighboring devices and enhancing the link reliability [36].

Abbasi *et al.* [239], presented urban double-directional measurements for D2D applications in the 140-141 GHz band covering distances up to 15 m on a linear route. A statistical analysis was carried out in the spatial and angular domains where delay spreads and angular spreads were calculated. RMS delay spread was found to have a relation with direction with small delay spreads in low power directions and larger delay spreads in high power directions recorded, while angular spreads were found to increase by $5\times$ at the end of the route compared to the beginning.

Kim and Zajić described a 2D GBSM for short-range D2D communications in [240]. The geometric model consists of concentric sectors with the presence of uniformly distributed scatterers around the Tx and Rx and accounts for LoS, and NLoS while considering first and second order rays. Based on the geometric model, a time-invariant statistical model was developed for short range multipath fading channels that was analysed in terms of PDP and frequency correlation function. To validate the model two scenarios were considered; the first scenario considered LoS desktop propagation at a centre frequency of 300 GHz with 20 GHz bandwidth and the second scenario involved NLoS desktop propagation in the D-band (110-170 GHz). The results were compared with theory and simulated using a novel sum-of-sinusoidal method were a good agreement has been found with the approximations of the geometric model.

10) **Nano-Networks:** The THz channel has been found to be a candidate for many applications including those in the medical domain. For modeling the channel for in-vivo applications, the human tissue needs to be considered. Path loss can be computed based on different molecular characteristics, scattering from cells within the tissue, distance between the

nano-machines and frequency of operation. Different models have recently been developed for in-vivo nano-machine communication within the human tissue. Jornet and Akyildiz [241] presented a channel modeling and capacity evaluation for EM wireless nano networks in the THz band between 0.1-10 THz. They assumed that since communication between nano-machines will be made over a very short range, the concepts of molecular absorption should be heavily accounted for and the concept radiative transfer theory [242] was employed for modeling the path loss and system noise while the model developed can be easily modified for use in various nano-network applications as it takes contributions from different concentrations and types of molecules. In [243] a channel model along with a link budget analysis was presented for In vivo Wireless Nano Sensor Networks (iWNSN's) in the THz band. Propagation phenomena inside the human body were analysed mathematically, the path loss was computed while taking into account molecular absorption from human tissue, wave scattering from body particles and the effects of spreading on the propagation of the wave. The results of the model were validated through electromagnetic wave simulations. The model developed may facilitate the design and deployment of future iWNSNs.

Yang *et al.* [244] investigated the characteristics of wave propagation inside the human body in the THz band and performed an initial study of the nano-network system performance. A path loss model was developed, and the results were verified through software simulations. Based on the path loss and noise level for propagation of the wave, the channel capacity was studied to give an insight on the performance of nano machines within the nano-network showing that at very small distances ($\sim$ mm) rates as high as 100 Tbps can be achieved. Abbasi *et al.* [245] proposed a statistical path loss model for channel characterization inside the human tissue for In-Vivo networks. The model aims to provide a deeper understanding of wave propagation inside the human tissue and the losses associated with it. It considers the frequency of operation, the distance separating nano-machines within the network and number of sweat ducts in the form of a numerical skin model considering the different skin layers and their thickness. The accuracy of the channel model proposed was validated by comparing the results to simulation and THz-TDS measurements of the skin sample between 0.1-4 THz. The statistics of error prediction in terms of standard deviation and mean were presented and the results were found to agree well with the measured ones. A stochastic model that considers different forms of noise that may impact propagation within nano scale systems was considered by Elayan *et al.* [246] by deriving probability distributions of the noise sources. It was found that Doppler induced noise has the greatest contribution compared to other sources of noise such as black body noise and Johnson-Nyquist noise. Vegni and Loscri [247] investigated the chiral parameters such as DNA chains and biomolecules and their effects on LoS and NLoS propagation as well as their effects on the capacity within a given medium in the 4-10 THz frequency range where the frequency selectivity at THz creates an effect known as Giant Optical Activity (GOA) [248].

11) **General Models:** In this part we present some noteworthy modeling contributions that target to extract the main channel characteristics at THz and which can adapt to a wide range of scenarios. Han *et al.* [249] presented a multi-ray deterministic model that was developed based on RT techniques for the frequency range of 0.06-10 THz. A narrow-band model was initially created and the multi-ray model was formed based on superposition of the sub-bands. A thorough analysis on propagation effects such as LoS, scattering, diffraction, reflection and broadening effects along with common theory such as Kirchhoff scattering and knife edge diffraction were employed to analyze simulated results by varying the distance and observing the frequency selectivity of the channel. RMS Delay spreads of 0.19 ns were found at 0.3 THz that dropped significantly to 51.7 ps at 0.7 THz over a 3 m distance resulting to coherence bandwidths of 1.06 GHz and 3.87 GHz respectively. The broadening effects were found to increase with an increase in frequency because of the higher frequency selectivity resulting from the short wavelength, hence, limiting the achievable data rates. The wideband channel capacity was also estimated over the 0.06-1 THz range using the water-filling power allocation method to be 75 Gbps with a 10 dBm power at a 3 m distance. The simulated results were compared against experimental measurements found in literature below 1 THz where some material properties are accessible, though at higher frequencies the frequency selectivity is highly unpredictable to assume the validity of the model. Moldovan *et al.* [250] proposed an indoor channel model for 0.1-10 THz considering LoS and NLoS propagation where specular as well as diffuse roughness components were considered. The LoS component was found to be dominant even though at larger distances the NLoS component becomes more significant and in some cases dominant due to constructive interference between the indirect paths. Data rates of 1 Tbps were simulated over a 1 m distance with a power of 1 W, while the capacity of just the NLoS component was found to be 100 Gbps when modeled by a water-filling approach between 0.1-1 THz. Tsujimura *et al.* [251] illustrated a casual channel model for the THz band. This work aimed to address the issue of deriving the impulse response from transmittance by assuming linear phase that leads to a symmetric impulse response before and after the most significant LoS component where it is not realistically possible for the signal to arrive before the main delay tap since it makes the model non-casual. The model developed can address this issue and was validated with THz-TDS measurement data < 2 THz that agree well with the results. A variation can be observed in the coherence bandwidth obtained from the impulse response as a function of the centre frequency that may be used to determine the frequency selection for wireless communication systems. A generalised 3D THz channel model was presented in [252] for 6G Ultra-Massive MIMO wireless communication systems that considered non-stationarities in the channel and cluster evolution in frequency, space and time domains and which can be applied for a variety of applications such as indoor, D2D communications.

12) **Surface Roughness Modeling:** Surface roughness is a measure of the finely spaced micro-irregularities on the surface

texture which is composed of three components namely, roughness, waviness, and form [253]. The effect surface roughness will have on the scattering behavior depends on the surface height relative to the wavelength. Factors that describe the roughness of a surface are the RMS height that allows for a fair comparison of the roughness of materials with similar structures and correlation length which is the length from a point on the surface to a short distance where the heights of the rough surface are correlated with each other.

In [254] rough surface scattering measurements were conducted in the low THz range for automotive radar applications at frequencies up to 1.1 THz. Back-scattering coefficients were measured and varied over the angle of incidence, to determine the reflective properties of sandpaper of known permittivity at different grit levels. The backscattering coefficients were measured at frequency of 300 GHz over a bandwidth of 8 GHz. The authors of the paper have deduced that by increasing the frequency, the EM roughness of an individual surface also increases causing diffuse scattering and an increase in the signal back-scattered from the road surface. In addition, the backscattering coefficient decreases significantly as the incidence angle increases. Furthermore, in [255] the authors examined the backscattering of EM signals at frequencies of 300 GHz and 680 GHz with 4 GHz bandwidth from surfaces with different roughness. The backscattering coefficients were measured for over a range of incident angles for different samples of sandpaper of grit levels 50, 120 and 220. At 300 GHz the backscattering from sandpaper with grits 120 and 220 were found to be specular and the signal quickly decreased with the increase in angle. At 680 GHz, backscattering from sandpapers with grit 50 and grit 120 were diffuse, while backscattering from sandpaper with grit 220 combines specular and diffuse reflections.

In [256] the roughness parameters of metallic surfaces were characterized using THz reflection spectra. Kirchhoff's approximation was used as a theoretical model and was compared to the results obtained from measuring the reflection spectra of aluminium using Fourier transform spectroscopy. The RMS roughness levels were measured, and a good agreement was found between the theoretical and experimental results. The reflectance measurements were made using a spectrometer while the RMS roughness was measured using a stylus surface profilometer. The range of frequencies considered in the experiment varied between 0.3 to 3 THz. The results were presented in terms of reflectance and wave-number where the RMS roughness curve was compared to the Gaussian fit.

In [257] a theoretical and empirical evaluation of the effects sub-micrometer roughness has on the effective conductivity in the THz regime was presented. Two frequency ranges were considered at 400 and 650 GHz that were achieved using an open quasi-optical resonator where the THz waves are usually incident to the sample. The statistical analysis performed using the measurement data was validated using two closed-form models and a finite-element simulation. It was found that the Mie-scattering based and finite element approaches are more accurate for smoother samples relative to the skin depth. For surface considerations greater than the skin depth it was

found that the Hammerstad and Bekkadal models provide more accurate predictions of effective conductivity. The results presented in this paper can be set as benchmark for new and improved models of effective conductivity in the THz regime.

In [258] the influence of surface roughness on THz reflection measurements is considered. This paper aimed at providing an insight in the performance of THz TDS for the detection of hazardous substances for security applications. The measurements undertaken involve smooth and rough metallic and dielectric surfaces varied over angle of incidence and degree of surface roughness (grit). A Maitai femto-second laser in a THz-TDS setup was employed for the measurements. The frequency range considered was 0.1-3.0 THz and the results were validated based on radar theory.

In [259] a study was performed to provide an insight to the different measurements conducted used to determine the properties of different material in the THz channel. The absorption coefficient and the refractive index were calculated for the frequency range of 70 to 110 GHz. Surface roughness measurements were also performed for frequencies beyond 100 GHz (up to 410 GHz) to predict reflection and scattering of the wave more accurately by using equipment available for optical 3D micro and nano-metrology [260].

In [261] rough surface scattering was investigated for both indoor and outdoor scenarios at carrier frequencies of 100, 200, 300 and 400 GHz. NLOS and LOS scenarios are considered based on signal reflections from building walls. The Bit Error Rate (BER) performance was measured relative to the output power. It was shown that the losses caused by scattering off the rough surface of the walls were much less than the losses caused by absorption at all measured carrier frequencies, while the losses caused by absorption were seen to increase with frequency. To achieve error-free transmission the transmitted power needs to be higher to account for absorption and scattering.

A. Summary for 6G Channel Modeling Efforts

Table III summarizes and compares the most important scenario-specific modeling contributions found in literature. Since channel models in the THz band mainly rely on channel measurements, many more measurement campaigns must be undertaken in order to realize 6G applications and make use of the vastly available spectrum between 0.1-3.0 THz for future communication systems design. Having a closer look, we can deduce that these efforts lack characterization of the channel particularly above 300 GHz and are quite sparse for some of the envisioned applications. Furthermore, it is obvious that there is a lack of sounding equipment with MIMO capabilities that are imperative for realizing long distance communications and achieving high throughput levels. A more thorough analysis regarding requirements of future channel modeling efforts follows in section VII.

VII. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

A. Open Issues and Challenges

From the work analyzed in this survey paper, there are some open issues and challenges in modeling techniques that need

to be improved upon while other future research directions are set.

1) **Diffuse Particle Scattering:** Models such as R-R and B-K that are used to characterize scattering from material surfaces may no longer be applicable and therefore require further consideration at THz. The R-R model while it performs well at predicting scattering from various angles at generally smooth surfaces and takes into consideration polarization of the waves, it fails doing the same for rough surfaces. On the other hand, the B-K model performs better for rough surfaces but is not as effective at wider angles due to effects such as absorption and shadowing, while it does not account for effects such as polarization [262]. Also very important at THz is that there is a very thin Fresnel zone. When different echoes arrive but the Fresnel zone is blocked by scatterers, this causes quite separate specular rather than diffuse reflections of some rough surfaces as diffuse scattering happens where the tip of the Fresnel zone is incident on the rough surface. This is an important characteristic that opens up more work.

2) **Atmospheric Channel Dispersion:** Atmospheric Group Velocity Dispersion (GVD) is a broadening effect observed in THz atmospheric channels which can affect significantly the maximum achievable data transmission rates [263]. GVD is a measure of how different channels, media may affect the duration of the pulse propagating through them. As the THz channel is dominated by atmospheric effects such as water vapor, the resonances occurring within the water particles introduce GVD due to different frequency components propagating at different velocities. Another property that requires consideration are the Doppler shifts that may also cause the broadening of THz pulses in presence of moving scatterers within a multipath environment and is extremely important when modeling radar sensing applications such as vehicle tracking [264]. Since the THz channel is highly frequency selective, GVD is caused leading to a distortion and broadening of the pulse waveform along with Inter-Symbol Interference (ISI). Factors that may limit transmission rates and cause GVD that need to be explored further include link distance, water vapor density and channel bandwidth. In [265] a novel method is developed for compensating atmospheric channel dispersion for THz wireless communication using a cohort of stratified media reflectors.

3) **Capturing Time-Varying Channel Characteristics:** So far channel characterization was mainly focused on static scenarios where P2P links will be employed. But in reality most cases will have to adapt to dynamic variations of the channel characteristics due to the highly directive characteristic of the THz waves. Link blockage will be a major issue, especially when planning for deployment of THz communications in scenarios where the presence of moving scatterers would affect coverage massively or in scenarios where dual mobility is involved when two devices are communicating with each other, i.e.- D2D communications. Moreover, in more advanced cases, i.e.- two vehicles communicating with each other, where both the Tx and Rx side are moving and at very high speeds, significant channel variations would occur continuously and large Doppler shifts would have to be accounted for over extremely short periods of time. With

TABLE III
IMPORTANT MODELING EFFORTS CHARACTERIZING THE TERAHERTZ CHANNEL FOR 6G WIRELESS COMMUNICATION APPLICATIONS.

Ref	Application	Scenario	Freq. (GHz)	Modeling approach	Antenna	Channel Statistics	Measurement Campaign
[163], [29], [162]	Kiosk download	LoS, parallel, tilted, tilted and parallel, multiple order reflection	220-340	RT-stochastic	SISO	Rician K-factor, RMS delay spread, fading amplitude, ToA, AoA, AoD, BER, path loss	VNA
[164]	Desktop download	LoS, varying receiver angle	50-75, 75-110, 110-170, 140-220, 220-325	Stochastic	SISO	ToA, AoA, fading amplitude	VNA
[119], [110]	Indoor	LoS, Specular reflection, scattering	500-750	Stochastic	SISO	PDP, fading amplitude, ToA	VNA
[166], [167], [30]	Data center	LoS, NLoS, DNLoS, Rack-to-Rack, Blade-to-Blade	300-312	Stochastic	4 × 4 MIMO, SISO	path loss, shadowing gain, RMS delay spread, doppler shift, Rician K-factor, delay dispersion, coherence bandwidth	VNA
[168]	Data center	inter-rack, intra-rack, top of rack, P2P	300.2–308.2	Stochastic	SISO	AoA, AoD, ToA, FSPL, path attenuation, polarization	SC
[169]	Data center	LoS, NLoS	300-350	RT-stochastic	SISO	Delay spread, angular spread, amplitude fading, PL-angle correlation, PL-delay correlation, phase and frequency dispersion	VNA
[170]	Data center	LoS, scattering	190-310	theoretical	SISO	atmospheric absorption, path loss, capacity	-
[156]	Data center	LoS, NLoS, OLoS	300-320	Stochastic	SISO	Delay spread, path loss, cluster powers, shadowing gain, correlation	VNA
[172], [31]	Chip-to-Chip	LoS, DNLoS, NLoS	300-314	Stochastic	SISO	Path loss, delay spread, coherence bandwidth, amplitude fading	VNA
[176]	Intra-device	LoS, NLoS	270-320	Stochastic	SISO	Amplitude fading, delay spread	VNA
[177]	WiNoC		0-1.0 THz	Deterministic		path loss, capacity, BER, ISI, field intensity	-
[178]	OWiNoC	NLoS		FDTD-empirical		Free space path gain, link budget	Laser source
[32]	Backhaul	LoS	275-325	RT	SISO	Interference, SINR, rain, fog and cloud, atmospheric attenuation	-
[181]	Urban	LoS	224-256	NGBSM	SISO	atmospheric attenuation, rain and fog attenuation, path loss, error vector magnitude	-
[116]	Urban	LoS, NLoS	141-148.5	NGBSM	SISO	Path loss, AoA, AoD, angular spread, cluster spread	
[184]	Indoor	LoS, NLoS, scattering	300-310	Calibrated-RT	SISO	AoA, AoD, ToA, delay spread, cost function, vertical/horizontal polarizations	VNA
[188]	Indoor	LoS, NLoS, DNLoS, scattering	300	GBSM	SISO	Atmospheric attenuation, path loss, AoA in azimuth and elevation, clustering	-
[189]	Indoor	LoS, NLoS	300	RT	SISO	AoA, AoD, ToA, clustering	-
[190]	Indoor	LoS, NLoS	300,350,410, 670,850	NGBSM, RT	SISO	FSPL, atmospheric attenuation, ToA	-
[191]	Indoor	LoS, NLoS	300	RT	SISO	path loss, SNR, BER, antenna gains	-
[192]	Indoor	LoS, NLoS	300	RT	SISO	amplitude fading, delay spread, propagation losses, antenna directivities, path loss, k-factor	-
[193]	Indoor	LoS, NLoS	275-321	Calibrated-RT	2 × 2 MIMO	AoA, AoD, ToA, path loss, delay spread, angular spread, polarization	SC
[194]	Indoor	LoS	300	NGBSM	MIMO	Capacity, array gain, clustering, ToA, path gain, AoA/AoD, array steering vector	-
[195]	Indoor	LoS, NLoS	300	Calibrated-RT	3 × 3 MIMO	amplitude fading, delay spread, angular spread, k-factor, vertical, horizontal polarizations	VNA
[196]	Indoor	LoS, NLoS	300	GBSM	SISO	Interference, amplitude fading, diffraction, ToA, AoA, AoD, path loss, FSL, delay spread	VNA
[155]	Indoor	LoS, NLoS, scattering	350, 650	Calibrated-RT	SISO	Clustering, path loss, AoA, AoD, SNR, Capacity, delay spread, coherence bandwidth	VNA
[200]	Indoor	LoS, NLoS	1070	GBSM	SISO	Molecular absorption, interference, coverage probability, SINR, polarization, blockage, AP-UE distance, directivity	-
[195]	Indoor	LoS, NLoS	60-10000	RT	SISO	K-factor, capacity, path gain, path loss, doppler	-
[202]	Indoor	LoS, NLoS	300,325,350	GBSM	M-MIMO	Autocorrelation, spatial correlation, frequency correlation, non-stationarity, AoA, AoD, cluster power and delay, fading amplitude	-
[203]	Indoor	LoS, NLoS	140	NGBSM	MIMO	Delay spread, angular spread, path loss, number of clusters, cluster delays and powers, ToA, AoA, AoD, spatial lobe and subpath number and power	SC
[204]	Indoor	LoS	-	GBSM	SISO	Capacity and outage, micro-mobility rotational effects and beam powers	-
[205], [206], [207]	Indoor	Sitting with smartphone, walking with smartphone, notebook on legs, LoS, NLoS	300	Ray launching, empirical	SISO, MIMO	Bayesian interference, dynamic AoA estimation, shadowing, log-likelihood, mean antenna gain, path loss, space-time correlations, eigenvalue	SC
[208], [209]	Indoor AP deployment	Static and dynamic user movement, LoS path	320-9570, 1-1080	Deterministic	SISO	outage, handoff, AP-AP distance, path loss, required power, cell packing, repeater assistance, k-factor, spectral efficiency, antenna beamwidth, cell radius, spreading loss, molecular absorption, capacity	-
[210] [211], [213], [214]	T2I/inside-station, Intra-wagon, I2I	LoS, light-NLoS, deep-NLoS	300-308	quasi-deterministic, calibrated RT	SISO	path loss, shadow fading, RMS delay spread, Rician K-factor, azimuth/elevation angular spread of arrival/departure, channel gain cross-polarization ratio, cross correlations capacity	SC
[222]	ISL	LoS	100-10000	GBSM	SISO	Polarization and frequency diversity, beam misalignment loss, link capacity, solar wind effects, attenuation and absorption by atmosphere, rain, cloud and fog, plasma frequency, electron density	-
[223]	ISL	LoS	-	Theoretical	SISO	Doppler wavelength shift, time delay number of laser link hops	-
[224]	ISL	LoS	-	Stochastic network calculus	SISO	Doppler frequency shift, noise, delay and backlog performance, Rician fading	-

Ref	Application	Scenario	Freq. (GHz)	Modeling approach	Antenna	Channel Statistics	Measurement Campaign
[225]	ISL	LoS	-	deterministic	SISO	Polarization diversity, Q-factor, BER, eye opening, received power	
[230]	V2V	LoS, reflection, scattering	300	deterministic, stochastic	SISO	Multipath interference, SNR, link capacity, SIR, reflection and scattering losses	THz-TDS
[232]	V2V	LoS, reflection, penetration	300	NGBSM	SISO	Reflection and penetration losses, path loss, AoD, AoA	SC
[231]	V2V	LoS, side reflection, rear reflection, under-vehicle propagation, blockage	300	NGBSM	4 × 4 MIMO, SISO	Path loss, path gain, AoA, AoD, ToA, delay spread, angular spread	SC
[235]	V2I	LoS, NLoS	110	RT, time-varying GBSM	SISO	Path loss, ToA, DoA, correlation probability, delay spread, MPC Birth-death process analysis.	-
[236]	intra-vehicle, inter-vehicle, vehicle-to-roadside	LoS, reflection, scattering	60-1000, 300-400, 800-900	RT	SISO	AoA, AoD, Capacity, path gain, delay spread, coherence bandwidth	-
[234]	V2I	LoS, NLoS	300-308	Calibrated-RT	SISO	Path loss, Rician k-factor, AoA, AoD delay spread, angular spread, rain, snow	SC
[240]	D2D desktop	LoS, NLoS, single-reflection, double-reflection	0-60	GBSM	SISO	ToA, frequency correlation function	-
[241]	Nano-network	LoS	0-10000	Stochastic	SISO	Path loss, molecular absorption noise, capacity, power allocation, radiative transfer theory	-
[252]	D2D Urban	LoS	140-141	NGBSM	SISO	path loss, delay spread, angular spread	VNA
[243]	iWNSN	LoS, scattering	100-10000	Stochastic	SISO	Intra-body Spreading, molecular absorption, scattering loss by human tissue	-
[244]	Intra-body	LoS	500-1500	Deterministic, stochastic	SISO	Capacity, path loss related to frequency, distance and dielectric loss of human tissue	-
[245]	Intra-body	LoS	500-1500	Deterministic, stochastic	SISO	Tissue absorption, spreading loss, error prediction between model and data	THz-TDS
[246]	iWNSN	LoS, scattering	-	Stochastic	SISO	Johnson-Nyquist noise, black body noise, Doppler shift noise, total noise power spectral density	-
[247]	In-cell	LoS, NLoS	4000-10000	Deterministic	SISO	path loss, reflection loss, giant optical activity, chirality effects, power allocation	-
[249]	Indoor	LoS, NLoS, scattering, diffraction	60-10000	Theoretical, empirical	SISO	path gain, AoA, ToA, delay spread, coherence bandwidth, channel capacity, path loss, broadening factor	-
[250]	Indoor	LoS, NLoS, scattering	100-10000	Deterministic	SISO	Path loss, capacity	-
[251]	General	LoS, reflected path	0-2000	Theoretical, empirical	SISO	Fading amplitude, coherence bandwidth, roughness standard deviation, absorption coefficient, transmittance, delay, linear phase	-
[252]	Indoor/D2D	LoS, NLoS, scattering	300-350	GBSM	UM-MIMO	angular spread, delay spread, space-time-frequency non-stationarities, cluster angle-power-delay, cluster angular spread, delay spread	-
[254]	Rough surface Characterization	Back-scattering for various grit levels	300	Empirical	SISO	Backscattering coefficient, received power, RMS of surface roughness, EM roughness, relative permittivity, polarization varying	THz-TDS
[255]	Rough surface characterization	Backscattering for various grit levels	79,300,680	Empirical	SISO	RMS of surface roughness, scattering coefficients, EM roughness	VNA
[256]	Rough surface characterization	Metallic surface reflection spectra	300-3000	Theoretical, empirical	SISO	Reflectance, RMS roughness, fitting coefficient	Spectroscopy, stylus surface profilometer
[257]	Rough surface characterization	Scattering	400, 650	Theoretical, empirical	SISO	Conductivity	Hemispherical quasi-optical resonator
[41]	Rough surface characterization	Reflection, scattering	100-1000	GBSM, deterministic	SISO	Absorption coefficient, refractive index, reflection coefficient calculations	THz-TDS
[42]	Rough surface characterization	Reflection, diffuse scattering	100-4000	Empirical	SISO	Path gain, AoA, AoD	THz-TDS
[43]	Rough surface characterization	Reflection, diffuse scattering	60-4000	Empirical	SISO	Fading amplitude, ToA	THz-TDS

advances in the beam tracking and beam-steering capabilities and phased array technologies at THz, we may be able to capture these extremely sensitive channel parameters, given that proper channel sounder architecture enables us to capture this information extremely fast in real-time by generating thousands of PDPs every second and over large bandwidths that is limiting factor when it comes to dynamic channel sounding architecture.

4) RF EMF Exposure: The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has so far defined exposure guidelines up to 300 GHz [266]. Subsequently, it becomes a case of what happens beyond that range that will allow limits to be set. THz radiation is generally considered as a form of non-ionizing radiation due to the low photon energy (0.1 to 12.4 meV compared to 12 eV required for an electron to be released from an atom for radiation to become ionizing [267], [268], [269]), making it far less likely to cause health hazards in the form of gene mutations and illnesses such as cancer. In fact, it can be

expected that if you point a THz source towards e.g., a human hand and the power levels are sufficiently large i.e.-1 Watt it would actually hurt causing a burning sensation. Recent studies however, have shown that with high intensity transmission, different biological molecules exhibit absorption spectra inducing resonances that may damage but also repair DNA and protein cells [270], [271]. Research is still at its early stages and due to the lack of measurement data we are unable to determine THz health effects to establish radiation limits caused by short-term and long-term exposure. Furthermore, exposure effects on the body may be different, more in regard to where the devices may be used on the body, such as in smart glasses/watches that then could directly couple or radiate to the skin and eyes. Therefore, it is extremely important to be able to understand the health effects by appropriate modeling at a molecular level to understand the biologicals to enable guidelines to be written indicating exposure limits for safe use of THz radiation.

B. Future Research Directions

1) **UM-MIMO Channel Modeling:** As the wavelength is extremely small at THz frequencies, antenna arrays with a large number of elements can be placed compactly in a small amount of space to form Ultra-Massive Multiple-Input Multiple-Output (UM-MIMO) that could potentially tackle the distance problem [272]. The spectral efficiency of cellular networks can be improved by the unprecedented array gain and spatial multiplexing offered by UM-MIMO which can offer the capability of increased data rates and capacity [273]. The concept of UM-MIMO with 1024 antennas placed on the Tx and Rx side respectively was introduced in [274] and could be achieved by the use of plasmonic meta-materials [275], [276] that could form nano-antenna Array of Sub-Arrays (AoSA) architectures [277] which will be used to tackle the distance problem and allow high data rate links for communication distances of several tens of meters, while the first efforts in developing a model as such were presented in [278], [279]. Existing models are not adequate to characterize the UM-MIMO channel efficiently and accurately and therefore there is a large gap in literature when it comes to modeling these sorts of channels. Models developed would have to consider the isolation between the antenna elements and antenna array configuration. As the amount of antennas increases the effects of diffuse scattering will have a big impact on the spatial and temporal dispersion at THz [115]. The huge amount of data that would have to be processed resulting from the large number of specular and diffuse reflections and the resulting clustering behavior that are inevitable at THz would lead to massive computational resource requirements that may require utilization of AI methods to enable precise and efficient characterization of the propagation channel. Furthermore, as the array dimensions grow larger, the plane wave assumption may no longer be valid for rough surface scattering characterization, and estimating the AoA of different MPCs would become extremely difficult. Alternatively, the spherical wave model [280], [281] may be applied instead to improve the accuracy of the estimated results [282], [283].

2) **Material Characterization:** The ITU-R P.1238-10 recommendation [284] models the effects of building materials on radio wave propagation for indoor systems and WLANs up to 450 GHz; Though these models are not validated by measurement, something that has only been done up to 100 GHz based on the ITU-R P.1238-7 recommendation [285]. Nevertheless, in [286] simulations for in-office and in-street scenarios were conducted for the 90-200 GHz frequency range that consider material properties such as permittivity and conductivity and aim to extend the applicability of the ITU model for characterization of these materials up to 200 GHz. Determining material parameters can assist in characterizing the propagation channel in terms of absorption losses and multipath scattering behaviour. Parameter extraction methods used in the lower microwave bands, such as waveguides [287] and resonant cavities [288] are no longer a viable option due to problems related to the much smaller dimensions at THz. One interesting method that can be used to obtain these parameters is by using calibrated RT simulators fed by experimental data

where extensive simulations could be used along with different algorithms [289], [290] to extract material parameters such as the dielectric constant. The experimental data can be collected through simple free space reflection and transmission as well as only transmission measurements using a VNA, though each method has its own related uncertainty to be accounted for when it comes to parameter extraction [291].

3) **AI enabled Channel Modeling:** The overwhelming growth of wireless data is pushing towards the limits of communications system performance. This exponential growth in wireless data poses as a challenge and future wireless communications systems will require powerful algorithms for different services. The applications of Artificial Intelligence (AI) in the field of wireless communications is receiving a lot of attention and the use of Machine Learning (ML) as an application of AI are currently being explored for radio propagation prediction [292], [293], [294]. As such, An AI driven approach by reinforcement learning was presented in [295] for periodic AoA probability estimation by feeding estimates from previous states to the algorithm for indoor scenarios, while RT and human movement modeling are used to validate the accuracy of the algorithm. Moreover, a possible data mining technique that can be employed for radio channel characterization involves the use of Support Vector Machines (SVMs). SVM is a supervised learning model that is based on finding the optimal position of hyper-planes in an N -dimensional space that separates the data points into different classes and has been employed in antenna design parameter prediction [296] as well as for clustering analysis [297].

The existing channel modeling techniques, either deterministic or measurement based have certain challenges and difficulties that make it hard for us to make an accurate characterization of the propagation channel. When it comes to deterministic models, long simulation times and high number of computational resources especially with larger bandwidths and increasing number of antennas, make the modeling of the channel at THz very difficult. Measurement based techniques on the other hand, such as GBSM and NGBSM would require a great amount of empirical data that would take too long to obtain as it is very difficult to characterize the channel at every point in space at these larger bandwidths using the current channel sounding techniques; hence, these models use limited sets of data leading to less accurate characterization. New ways need to be explored that would allow much more efficient and detailed analysis of the data so that the accuracy can be improved and at the same time simulation times can decrease.

AI enabled channel modeling requires a large amount of data as input to the algorithms. This data is used to train these algorithms and make predictions. In this way the computational complexity can be greatly reduced as long as the predictions made are accurate and the algorithms are robust for modeling different scenarios. The disadvantages posed by hybrid deterministic-stochastic models in regards to simulation time and limited channel sounding prohibit large scale characterization. At THz particularly, small-scale interactions due to the short wavelength (<1 mm) above 300 GHz are relevant and cannot be modeled efficiently over large bandwidths with

the existing techniques.

4) **Hybrid Channel Modeling:** It is apparent that the hybrid modeling approach where empirical data are fed to RT simulators to extend the limited data sets is very popular. Similarly, we believe that channel characterization should be expanded and complemented by the use of various stochastic and deterministic models to describe each part of signal propagation from one end of the communications system to the other. As an example, many empirical data sets can be collected and an SV type model can be used for grouping MPCs together and a second order GMM can be used to describe MPCs within arriving clusters. Furthermore, FDTD/MOM modeling can be employed to model a portion of the propagating environment when RT simulations do not provide enough information about the channel. It provides much higher accuracy and manages computational complexity since it can be applied to model areas of complex discontinuities [298]. These methods can be then tuned within a unified model, in parallel with great knowledge of the weather conditions and scatterer properties, and employed along with ML techniques that could perhaps allow for this characterization to be expanded over larger bandwidths due to technological limitations of real-time channel sounders which are preferred for collecting data, but are limited by their short bandwidths.

5) **Improved Channel Sounding:** Channel sounding at THz within a 3D environment allows for a spatial and temporal analysis that can characterize and predict the behaviour of wave propagation in terms of ToA, AoA and Doppler shifts. Good knowledge of these parameters enables prediction of a communications systems performance and highly influences standardisation processes. The impact directive antennas have in dynamic scenarios have a major impact on system performance, and the lack of experimental knowledge at THz frequencies draws the need for new measurement procedures for correct system evaluation and design. Different sounder architectures will have to be developed and compared to improve the estimation accuracy and enhance the bandwidth. A proper model has to be then developed that is calibrated with measurement data which will allow for estimates independent of channel sounding device. Phased arrays and their behaviour when sounding the channel with wideband signals in terms of mutual coupling between antenna elements, near field effects, the effects of non-linear distortions as well as uncertainties in the measurement procedures, are big challenges that need to be correctly investigated to achieve a high degree of accuracy in parameter estimation.

Moreover, channel characteristics that are vital in system design such as delay and Doppler spread, coherence time and bandwidth are heavily dependent on the spatial characteristic of the antenna, which acts as a spatial filter due to its high directivity. This means that channel characteristics and system design including modulator design, symbol structure and RF front end design become largely dependent on one another. Therefore, to perform channel measurements at THz, all parts of communication system design need to be characterized and evaluated to optimize the performance and enable accurate high data rate measurements in order to realize THz communications, and that can be done by tweaking the performance

of each component individually and measuring their effects on the system's BER [299]. Future 6G systems will need these capabilities that are still in their early stages at THz.

VIII. CONCLUSIONS

This paper provided an overview of measurements and modeling of the propagation channel at THz. It begins with an introduction to the THz band stating what applications could be realized and discusses the THz integrated systems evolution and provides information of the standards being developed. THz propagation characteristics such as FSPL, meteorological attenuation and diffuse scattering were further introduced. Measurement requirements along with THz channel sounding methods were then described based on the applications identified. Afterward, an extensive review of the state of the art measurements and modeling in the THz bands was presented along with useful information about the requirements for each application scenario. Finally, an insight was given to the issues and challenges faced at modeling in the THz spectrum as well as the ongoing research opportunities that are being realized to tackle the challenges faced for communication systems modeling at THz. This paper provides a solid understanding of channel propagation phenomena, measurement techniques and modeling at THz and gives a good knowledge base for future work to be conducted to realize various applications targeted for operation at this band.

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