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Bridging the Terahertz Gap: Channel Modeling for Next-Generation 6G Wireless Networks

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ABSTRACT: The THz spectrum (0.1–10 THz) is a region between optics and electronics, and it is still not fully explored and is unlicensed. Recent studies show that it will bring a revolution in technology, especially in the field of communication. Future communication technologies such as 6G and Terabit DSL will utilize this THz band as it has the capability to support high data rates in Tbps. For designing an efficient system that propagates these THz waves with low loss, it is required to understand the propagation channel properly. THz channel modeling is at its infancy stage, and a detailed investigation of channel behavior is required to study the efficient propagation of THz waves. In this study, the methods applied to the modeling of the THz channel are discussed in detail. Although channel modeling is a broad topic here only the methods and techniques are discussed along with their advantages and limitations. Lastly, the challenges and the future direction in the field of THz channel modeling are also discussed.

1. INTRODUCTION

The traffic of data rate is exponentially increasing day by day with the increase in the number of devices such as smart watches and smart rings. The number will be growing rapidly, and there is no sign of dwindling. The concept of smart cities, smart cars, smart grids, autonomous cars, etc., almost everything around us, is being modified to be smart, and they will also be required to communicate and transfer information. This will further increase the data rate requirement with high bandwidth and high-speed links. Current technologies such as 4G, 5G, and G-fast can somehow manage to compensate for the requirement, but it is seen that they do not provide sufficient bandwidth required for future applications. Already, the electromagnetic spectrum is becoming scarce, especially in the lower end of microwaves, i.e., below 6 GHz. Various researchers have proposed several solutions to overcome this scarcity, such as spectrum sharing [1], spectrum aggregation, cognitive radio [2], and ultra-wideband (UWB) technology [3]. These proposals are good but not a permanent solution and have different issues such as security threads [4]. One promising solution is to move to the upper-frequency range such as the terahertz (THz) range. After the deployment of the mmWave by the 5G, the world is now looking for 6G that will enable new services and applications such as unmanned vehicles and streaming ultra-high-quality video online, and it is expected that 6G will utilize the THz spectrum range.

The THz frequency band is a range between the microwaves and infrared in the electromagnetic spectrum. Its frequency range starts from 0.1 to 10 THz. THz has been initially utilized in the field of astronomy to detect water, nitrogen, and other atmospheric molecules can be detected in the THz band [5]. The recent advancement in fiber laser technology and generation and detection of THz waves through photoconductive antennas stimulated by lasers made this spectrum approachable. THz band has recently gained a lot of attention in a variety of fields such as communication, spectroscopy, sensing, and imaging due to its potential abilities. The unique feature of the THz band, such as its ability to penetrate through some materials and detect molecular vibrations, makes it a valuable and promising field for future research and development.

Due to the unique properties and characteristics of the THz spectrum, it is considered a promising candidate for future communication systems and technologies. A highly available bandwidth can support a high data rate of about several terabits per second and, of course, can handle a large number of devices; and it is also expected to be the encouraging candidate for secure communications. THz communication systems will revolutionize the near future wireless communication systems. However, the propagation of such high frequencies experiences much losses as compared to microwaves or mm-waves, and THz is also mostly affected by atmospheric molecules and particles. These lead to many challenges in modeling the THz channel such as atmospheric attenuation, scattering, and high path loss. Also, due to the lack of understanding of the propagation of the THz channel, the deployment of THz systems is limited.

To solve the challenges and issues related to the THz band and its propagation, an accurate and reliable channel model is

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required, as this will lead to a more precise understanding of the behavior of the THz channel. An accurate channel model will facilitate the development of an efficient THz communication system and better modulation techniques and signal processing methods.

2. THZ CHANNEL MODELING

The channel plays an important role in wired or wireless communication systems, as it is the medium through which the THz waves propagate between a transmitter and a receiver. It is very crucial to construct an accurate THz channel model for the development of THz communication systems. The channel model is the process of mathematical representation of the behavior of a communication channel, including the effect of interference, propagation of EM waves through a channel, and other related effects that might affect the performance of the communication channel. Various techniques have been proposed for accurate THz channel modeling including Ray tracing, Statistical Models, Hybrid models, and Machine learning models. Each of these modeling techniques has its strengths and weaknesses and depends on the specific system requirements and scenarios. Figure 1 categorizes the THz channel models in terms of the environmental scenario, the type of losses it incorporates, and by methods being employed.

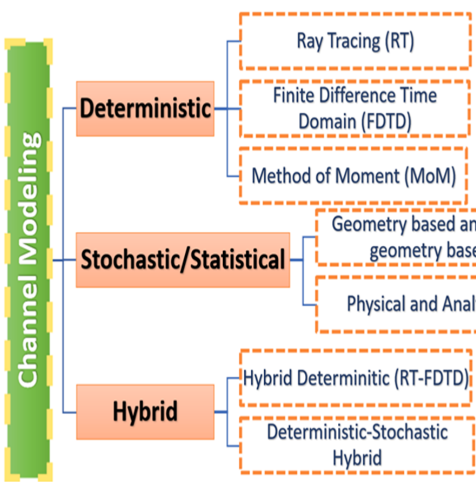

FIGURE 1. Classification of channel modelling.

In this study, channel modeling is based on the method employed. However, channel modeling and its classification are generally a broad section to discuss, and a large number of books and research publications are available. However, only updated methods employed in channel modeling are considered here. A detailed review of each type of channel modeling is discussed in the following section.

2.1. Deterministic Channel Modeling

The deterministic model is one of the important models in the category of THz channel modeling as it aims to provide an accurate prediction of the behavior of the signal based on the deterministic set of parameters. This model relies on the solution of Maxwell's electromagnetic wave equations in a specific environment and is a site-specific model. This model is used when the physical characteristics of the channel are known. The physical characteristics can be indoor such as the placement of tables and chairs, and outdoor simulation such as the geometry of the environment, i.e., buildings, trees, and other terrestrial reflectors or scattering optics. The orientation and location of the transmitter and receiver are also incorporated in this type of model [6]. Deterministic models have also been employed in the THz standards, i.e., IEEE 802.15.3d standard. The deterministic model is a highly accurate model at the expense of the intensive computational process.

Deterministic models have been further classified into the Ray Tracing (RT) method [7, 8], Method of Moment (MoM) [9], and Finite Difference Time Domain (FDTD) method [10]. Each of these sub-classifications is defined in the following sub-sections.

2.1.1. Ray Tracing (RT)

Deterministic models are typically based on the ray tracing technique which utilizes geometrical optics to model the path of EM waves as they propagate through the communication channel. Ray tracing in the THz spectrum can be utilized to model the different scenarios in wireless communication such as indoor classrooms, offices, and nano networks. As the name implies, in RT, rays are launched at some period through the transmitter at one location of the scenario and detected by the receiver at a different location. This is based on free space propagation in which the scattering, diffraction, reflection, and other types of effects on rays are taken into account. Figure 2 depicts the typical ray tracing model of an indoor office for THz propagation showing the reflected and diffracted rays from different indoor obstacles. The transmitter and receiver are placed on the corner walls of the office.

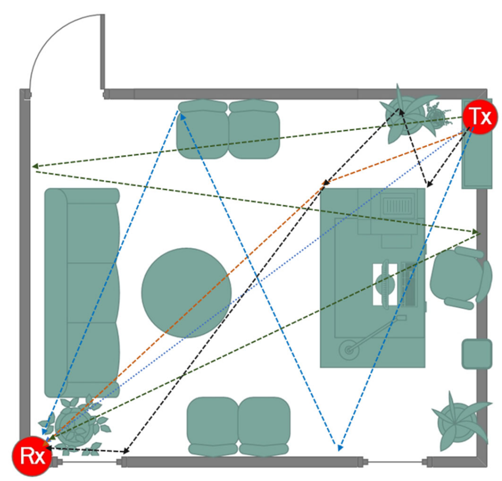

FIGURE 2. Ray tracing model of indoor office scenario.

RT is a popular method for simulating the THz channel that is more suitable in the indoor environment. This method is time-consuming for large and complex environments, but it provides accurate results for high-directional antennas. High efficiency and advanced acceleration 3D ray tracing techniques are required to increase the performance of the simulator and pro-

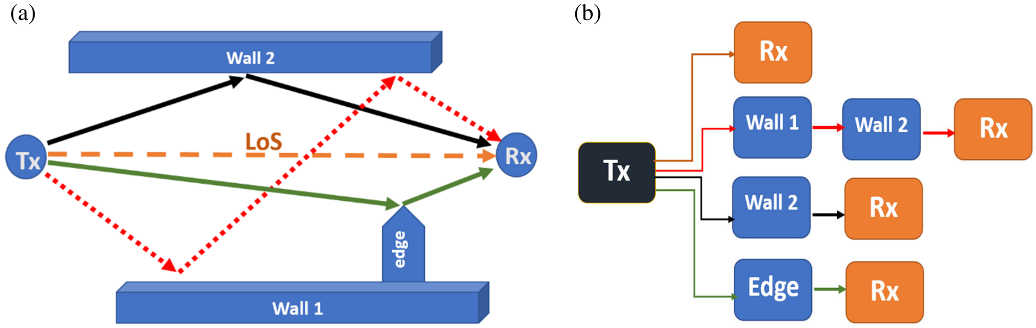

FIGURE 3. Propagation scenario. (a) Arbitrary representation. (b) Visibility tree representation.

vide propagation characteristics of the environment precisely. For complex scenarios, ray tracing techniques require much accuracy. There are several proposed strategies for the efficient capturing of propagation paths in the ray tracing process which are defined in the following subsections.

i. Visibility tree strategy: To increase the effectiveness of ray tracing simulations, a specialized algorithm called visibility tree [11] is applied. To implement this method, the simulation environment must be divided into smaller areas and arranged in a hierarchical structure. The hierarchy is based on the visibility relationships between the areas, and branches of the tree are allocated for regions that are not visible to one another. The visibility tree strategy has the advantage of reducing the number of ray-object intersection tests required for the simulation which in turn reduces the simulation's computational complexity. Figure 3 shows the visibility tree representation of an arbitrary propagation scenario.

ii. Ray launching [12] is another method in which the ray for 2D and 3D is launched in this manner along all possible azimuth angles or combinations of azimuth and elevation angles. The paths change direction due to reflection, diffraction, and so on, and the ray is followed along the paths until it leaves a predetermined area of interest, becomes weaker than the assumed threshold, or reaches its destination.

iii. Image Method [13] is another method that is suitable for a simple environment only. To simplify the analysis, the imaginary or counterpart of the actual object is introduced. This virtual object is the image or reflection of the actual object with respect to the boundary plane. To calculate the path loss and other channel characteristics, the transmitting and receiving antennas' reflections are first collected in images. The antennas and their reflections are mirrored with respect to a ground plane to generate the images, thus facilitating the ability to compute the channel characteristics. The image technique has the capability of significantly reducing the computation time needed for precise channel modeling and providing precise channel models for both indoor and outdoor environments.

iv. Point Cloud Ray Tracing (PCRT) [14–16] is the technique used for simulating EM propagation in a complex environment. A three-dimensional cloud is used to represent the geometry of the environment. PCRT gives accurate and precise results at the expense of the high processing time. PCRT has the capacity to accurately simulate wave propagation in immensely complex indoor [17] and outdoor [18] environments, such as indoor spaces with a lot of walls, barriers, and reflective surfaces. PCRT can also be used to simulate multiple reflections and diffractions, which is essential in many wireless communication applications.

Ray tracing technique is a good choice for the THz channel modeling in the deterministic method. A variety of work has been done using this technique in different environments and applications such as those based on ray tracing, and a 3D THz channel model has been designed by Han and Akyildiz using a graphene antenna array [19]. The communication model for the future railway train with other trains and infrastructure has been modeled [20]. In 2013, Preibe et al. validated the model with the measurement data for the indoor propagation environment using the ray tracing method [21].

2.1.2. Finite Difference Time Domain (FDTD)

The finite difference time domain technique is a numerical technique that solves Maxwell's electromagnetic wave equations to characterize the channel in both the time and space domains. Practically real-world scenarios are quite complex with different types of materials. It is important to solve Maxwell equations numerically to get accurate data due to the effect of every object in the environment. FDTD method has been widely employed in THz channel modeling due to its accuracy in simulating the propagation of electromagnetic waves in complex and realistic environments. This technique is capable of handling complex geometries and boundary conditions and allows for the modeling of a wide range of material types, including dispersive and lossy media. The design of THz communication systems can be improved with the support of FDTD simulations, which can offer crucial information on the characteristics of THz waves in various situations, such as indoor and outdoor environments.

However, this method requires a large number of computational resources, which can limit its use for large-scale environmental simulations, and it may thus not provide detailed infor-

TABLE 1. Comparison of strengths, weakness, and scenarios of deterministic channel modelling.

Methods	Strengths	Weaknesses	Suitable Scenario
Ray Tracing	Accuracy	Geometrical information needed in detail	Indoor, High-speed trains, vehicle to vehicle
Finite Difference Time Domain	Very High accuracy	High resources requirement	Intra-devices, Chip to chip communication
Moment of Method	handle both conductive and dielectric materials	computationally intensive	large structures or complex geometries

mation due to limited resources. One solution is proposed by Wang et al. [22] to combine the advantage of FDTD to characterize the complex structure accurately which cannot be obtained precisely by ray tracing by taking advantage of ray tracing to sweep wide areas where FDTD has limitations, hence ignoring the limitations of both techniques. FDTD technique for the intra-device scenario at the THz range is compared with ray tracing by Fricke et al. [23], and it was concluded that the simulation time taken by the FDTD is much large even for a small environment. FDTD technique is also used in the modeling of human tissue [24], antenna properties [25], etc. FDTD can provide a detailed and precise channel model of any complex environment with the availability of better computational resources.

2.1.3. Method of Moment (MoM)

Method of Moment is also a numerical approach to model a THz channel and solve Maxwell's EM equations precisely by differential equation analysis. When the obstacles become smaller and approach the wavelength of the THz, ray tracing cannot provide accurate data as it works better in modeling big objects in a large environment. This limitation is eliminated by MoM, which is a better alternative in this situation. The MoM method was earlier used to analyze different materials such as metals, dielectrics, and magnetic materials in terms of their electrical and magnetic shielding properties [26]. Modeling for indoor radio wave propagation used MoM by Adeogun et al. [27]. Yang et al. compared the RT method with MoM for modeling the indoor propagation analysis [28]. MoM can be combined with RT to utilize the advantages of both methods so as to achieve a reliable estimation method as a hybrid method of combining MoM and RT is proposed in [29]. The two models are developed using various methods and assumptions, and therefore combining them could be challenging.

A disadvantage of MoM is that it can be computationally intensive when modeling large structures or extending the frequency range. This is because the number of unknowns increases with the size and complexity of the problem, resulting in large matrices that require significant computational resources and time to solve. Additionally, this technique may not be suitable for modeling certain types of structures, such as sharp corners or edges that may lead to inaccurate results. Table 1 defines the strengths, weaknesses, and suitable and preferred scenarios for the corresponding deterministic channel model.

2.2. Stochastic Channel Model

The stochastic channel modeling method that creates the model of the communication channel based on measurement data. This model is also known as the statistical channel model as it provides statistical analysis of the communication channel by the spatiotemporal approach. This model does not totally cite specific as in the case of the deterministic model, but it mostly describes the indoor, outdoor, and indoor hotspot environment and constructs the channel model based on the measured data. The stochastic model is not as accurate as the deterministic one, but it is much simpler in comparison. The deterministic models need high-volume space memory to store and update the information. Statistical channel modeling is however favored due to its advantages over deterministic one as statistical channel modeling is specific to the type of environment such as microcell, urban, and rural ones, and no requirement for the geometry details is involved in the modeling of any environment, thus it is fast in terms of computational requirements, providing the channel model results very fast.

Statistical models can be categorized in two ways. One is either geometry-based statistical channel models (GSCMs) or non-geometry-based statistical channel models (NGSCMs) while the other classification is based on either physical or analytical methods. Each category is defined in the following section.

2.2.1. GSCM vs NGSCM

As the name suggests the GSCM-based channel statistical model depends on the geometry of the site or environment to be modeled while the NGSCM model is based on the stochastic manner of channel. The GSCM idea was proposed in the 1990s [30, 31]. This model is similar to the deterministic model, but the difference is in the location. In the deterministic channel model, the location of the specified scatter is based on a database of the environment while in the GSCM channel model, the locations of the scatters are arranged in stochastic manner to a certain probability distribution [32]. A configurable stochastic channel model was presented by [33] using multi-directive antennas. The angle of arrival (AoA) is an important factor for understanding the effect of antenna, and the statistical model for AoA is presented in 2002 [31]. For the indoor scenario at THz, GSCM based channel model is proposed in [34] by combining cylindrical, elliptical, and spherical models and by considering the LoS, single, and double bounce at the receiver. On the other hand, NGSCM, as the name suggests, is nongeometrical, and it

TABLE 2. Comparison of strengths, weakness, and scenarios of stochastic channel modelling.

Methods	Strengths	Weaknesses	Suitable Scenario
GBSCM	Accurate	More complex and detailed geometry required	Outdoor environment
NGBSCM	Simple, low computational burden	Less accurate	Indoor environment
Analytical	Low complexity	Low accuracy	UM-MIMO
Physical	Accurate and Precise results	Detail knowledge about the environment is required	Indoor, High-speed trains, vehicle to vehicle

is also called parametric stochastic model (PSM). This model is purely based on a stochastic channel model. In a given channel, NGSCM aims to achieve the statistical parameters of the medium, and it defines only the path between transmitter and receiver. NGSCM model determines and defines the direction of arrival (DoA), delay, and direction of departure (DoD). A widely accepted NGSCM model was proposed by Saleh and Valenzuela [35] known as Saleh-Valenzuela (SV) model. Based on reflections from different surfaces and obstacles, this model provides cluster-based impulse response, and multipath components are regarded as delay traps. There are a number of models following the SV model such as indoor residential environment channel modeling [36], indoor multipath propagation [35], and underwater acoustic sensor network modeling [37]. Another NGSCM model is Zwick model [38] which is applicable for indoor as well as the MIMO channel characterization.

NGSCM channel models are popular and are preferred due to their low computational requirements and simplicity. However, some challenges, such as devices moving at longer distances, make it very hard to describe the relationship between the progressive changes in DoA, DoD, and the time delay.

2.2.2. Analytical and Physical

An analytical method is based on mathematical equations simplifying the assumption to model the channel. This model characterizes the impulse response of the channel that includes the antenna characteristics. On the other hand, the physical model aims to provide the statistics of the channel that are independent of the arrival time, power delay profile, and other antenna parameters [39]. In multi-antenna systems, the analytical method forms a matrix by a method called matrix-based model. A matrix that illustrates the connection between the transmitted and received signals serves as a representation of the channel response. The matrix is built using statistical parameters that capture the delay, attenuation, and phase shift of the channel. Simply, the analytical method correlates the impulse response of the matrix to describe the statistical properties of the channel. Another model is the Kronecker model [40], which is a matrix-based model. The Kronecker model presupposes that there are two separate components to the spatial correlation of the channel, one for transmitting and one for receiving. The correlation matrix for the channel as a whole is created by combining the smaller correlation matrices that represent these two components. This process is known as the Kronecker product. This assumption will be invalid as the THz antenna will have UM-MIMO antennas and low path loss due to a decrease in communication distance [41], and the antenna will not be considered as a point source, so the far-field assumption will also become invalid [42]. One solution to utilize this model in MIMO is proposed in [43] to use the beam domain channel model (BDCM), and further [44] describes spherical wavefronts and near fields in BDCM. Along with Kronecker, virtual channel representation (VCR) [45] and Weichesel-Berger [46] are also generally considered correlation based stochastic channel models. These correlation-based models are used to evaluate the performance of the massive MIMO antenna systems as they have low complexity [47]. The geometry-based channel models discussed in the above section also lie under the physical model. The combined elliptical model, one ring model, and one disk model are types of physical models that are jointly called geometry-based statistical propagation. The one-ring model, which takes into account local dispersion from obstacles placed on a ring around a subscriber unit, is the most widely used geometry-based stochastic model applicable to the MIMO channel [48]. The local scattering ratio (LSR), a parameter that indicates the omnidirectional distribution of scatterers on a local ring and a low value that denotes directional scatterer distribution, is a feature of the combined elliptical ring model [48]. On the other hand, the one-disk model has a large single between the receiver and transmitter where the scatters are evenly spaced [49].

Both physical and analytical models have their own advantages and limitations, and they depend on the choice of specific application requirements, accuracy level requirements, and resource availability. Table 2 defines the strengths, weaknesses, and suitable and preferred scenarios for the corresponding stochastic channel model.

2.3. Hybrid Channel Model

As discussed in the above sections, deterministic and stochastic models have their own limitations and advantages. Deterministic model is very useful and well known for its accuracy level at the expense of high consumption of resources and time along with high complexity. However, stochastic models are preferred due to their low complexity and limited resources requirement at the expense of accuracy. There are different techniques proposed by different researchers with their limitations and advantages discussed above. Therefore, a solution is to provide a hybrid model that utilizes the advantages of deterministic as well as stochastic modeling approaches. Hybrid channel modeling is to be utilized in future communication systems and technologies such as 6G. A variety of proposals have been suggested by different researchers for hybrid modeling by combining different deterministic approaches [50] also categorized as hybrid deterministic approach (RT-FDTD) and by combining deterministic and stochastic approaches [51].

2.3.1. Deterministic Hybrid Approach

This approach is a combination of FDTD and RT techniques. As discussed in the above sections, FDTD can provide an accurate channel model through rough surfaces, complex structures, and boundary discontinuities at the expense of high computational requirements. On the other hand, RT requires fewer computational resources but provides a less accurate model. Usually in environmental scenarios boundary discontinuities and complex structures are rare, and it is not the best choice to use a resource-intensive approach on simple structures too. Therefore, it is better to model an approach in which complex structures (usually a smaller portion of the environment) are solved by a high computational approach such as FDTD while the rest of the simple structures are processed by the RT method to reduce overall complexity level and resource requirement while maintaining the accuracy level to model the THz channel [52]. A typical scenario for a deterministic hybrid approach is shown in Figure 4. hybrid approaches is followed in these UWB body

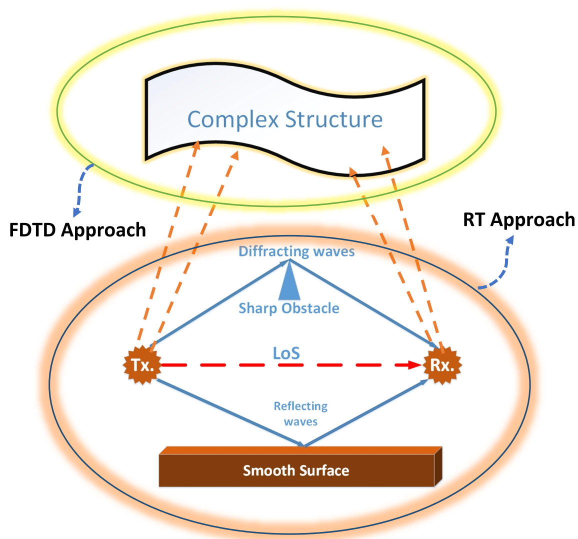

FIGURE 4. Representation of RT-FDTD approach for simple and complex structures.

and molecular optical properties studies.

As the frequency goes up, the wavelength approaches the dimension of the roughness of the surface. So, in the THz band, complex and rough surfaces are processed through the FDTD [53] while the rest of the environment is solved by RT to provide optimal trade-off between complexity and accuracy. The hybrid approach using RT and FDTD to model the channel for the indoor environment [54], wall penetration from outdoor to indoor [54], massive MIMO networks [52], UWB body radio channel model [56], and molecular optical properties calculations [57], and the comparison of FDTD, RT-FDTD, and multi-region FDTD on the human exposure evaluation is done by Bernardi et al. [55]. This hybrid model has also been utilized in different commercial simulation EM solvers such as the High-Frequency Structure Simulator (HFSS).

This model is best suitable for the THz channel modeling as at such high frequencies structure becomes rough, and this model provides both accuracy and simplicity. However, there are some limitations and challenges too such as the introduction of the transit boundaries between the FDTD and RT. Another limitation is that extensive knowledge of the environment is required. Several hybrid approaches are proposed in extension such as time-efficiency and multiple interaction between RT and FDTD [50].

2.3.2. Deterministic-Stochastic Hybrid Approach

The deterministic and stochastic models both have their advantages and limitations. If accuracy is not required, stochastic model is the best option, but accurate results and behavior of environment are essential for understanding the behavior of channel, and it requires high resources and is complex. Deterministic models provide good accuracy, but they cannot produce the spatial consistency and temporal evolution of the cluster correlation. In the THz communication system, multiple antennas will be utilized, and due to their inherent directional properties, the correlation between the channels is not captured as the same effect cannot be guaranteed due to the random generation of the propagation links. Similarly, the site has a dynamic nature, so the angle and direction of transmission and reception are not defined. Therefore, in order to overcome these issues, a combination of stochastic and geometrical approaches is needed. There are several hybrid models proposed by different researchers as discussed below.

One of the most popular hybrid approaches is the quasi-deterministic (Q-D) model. This model was suggested in the early 2000s for the cm-Wave communication channels [58]. This model generates the dominant multipath components from the environment, and then it simulates the MPC's cluster associated with the dominant MPCs. The parameters such as DoA, DoD, delay in the intra-cluster are expected similar. Additional MPCs are considered to capture the dynamic nature of the environment.

Quasideterministic model is successfully validated and applied to a variety of applications such as for the mm-wave channel model for the indoor channel at 60 GHz [59, 60]. For the sub-THz model, the hybrid approach for indoor channel modeling at 300 GHz was utilized to generate DoA of intra-cluster rays [61, 62]. Another sub-THz Semideterministic channel model was proposed by Chen et al. [63] for an indoor communication model at 140 GHz. mm-wave evolution for Backhaul and Access, IEEE 8.2.11ay [64], office environment [60], and corridor environment [65] applications is also validated using the quasi-deterministic model. In [66], the authors modeled the angle of arrival for both intra- and inter-cluster sub-paths for indoor THz communication channel, and the Poisson process and Von Mises distribution were applied to get AoA for both intra- and inter-cluster sub-paths. Table 3 defines the strengths,

TABLE 3. Comparison of strengths, weakness, and scenarios of hybrid channel modelling.

Method	Strengths	Weaknesses	Suitable Scenario
Deterministic Hybrid	High Accuracy	Details of environment and material properties needed	Intra-Device, Indoor
Deterministic-Stochastic Hybrid	Good accuracy, less complex	Require much data	Vehicle to Vehicle, High-speed trains

TABLE 4. Comparison of different parameters of THz channel modelling.

Methods	Deterministic Model	Statistical Model	Hybrid Model
Accuracy	Highly accurate	Low	High
Geometrical Requirements	Detailed	Minimum	Moderate
Resources Requirements	Very high	Low	Moderate
Complexity Level	High	Low	Medium

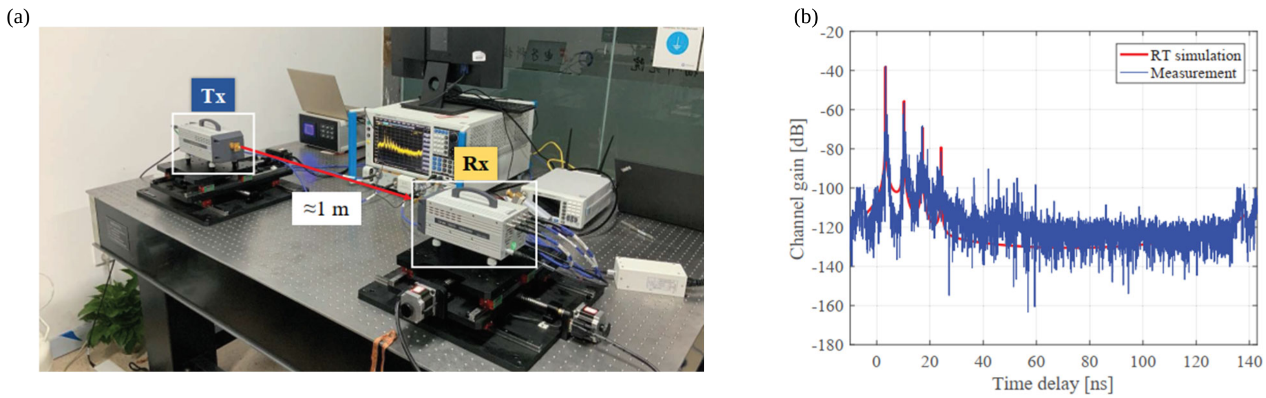

FIGURE 5. Measurement setup for the THz channel [67]. (a) Measurement setup. (b) Comparison between simulation and measurement.

weaknesses, and suitable and preferred scenarios for the corresponding hybrid channel model.

Different channel models for the THz communication are discussed above, and every model has its own advantages, limitations, and requirements. Table 4 shows the comparison among the above three THz channel models in terms of accuracy, requirements, and complexity levels.

3. CASE STUDY FOR REALISTIC THZ CHANNEL MODELING

In order to validate and strengthen the THz channel model, a case study has been discussed here for the short distance LOS wireless communication system in the frequency range of 330 GHz to 365 GHz [67]. A vector network analyzer (VNA) was utilized to measure the channel characteristics for proposed frequency band with 5001 frequency points. The distance between transmitter and receiver is about 1 meter, and the experimental setup is shown in Figure 5(a).

The simulation and measurement configurations were kept similar, and a good matching was achieved between the simulated RT method and measurement results as can be seen in Figure 5(b). There is an error of less than 1 dB in the power domain while in the time domain (time delay), error is even smaller than 0.1 ns [67].

Another channel modeling has been performed for realistic THz channel modelling for the close proximity communication such as kiosk downloading available at train stations, airports, and metro stations [68]. As the propagation distance in the kiosk downloading ranges in centimeters, the channel characteristics are determined by the position of the transceiver and the design of the kiosk. Figure 6 shows the comparison between RT simulated by the stochastic approach and measured results.

The frequency range was selected from 220 GHz to 340 GHz, and VNA was used for measurement purposes. The maximum distance was selected as 3.9 meters, which is quite large for kiosk downloading channel. It can be seen from the comparison plot that calibrated RT simulation can accurately reproduce and describe similar results to the measured kiosk downloading channel [68].

Due to the unavailability of many THz devices and equipment, it is very hard to perform measurements at different locations, and device mobility analysis is difficult to test experimentally. Therefore, computer simulations such as RT and other types of techniques and models are used to analyze communication in different scenarios such as outdoor scenarios.

TABLE 5. Summary of a few channel models proposed for THz communication.

S. No.	Modeling Approach	Scenario	Frequency	Applications
1	Ray Tracing [20]	LoS, NLoS	300 GHz	High-speed Train
2	Stochastic [70]	LoS	0–10 THz	Nano-Network
3	Stochastic [71]	LoS, NLoS	300–314 GHz	Chip to Chip
4	NGBSCM [72]	Under vehicle propagation, LoS	300 GHz	Vehicle to Vehicle
5	Deterministic [73]	LoS	0.5–1.5 THz	Intra-body
6	Stochastic [74]	LoS, O-LoS	300–312 GHz	Data centre
7	Statistical [75]	Conference room	60 GHz	WLAN system

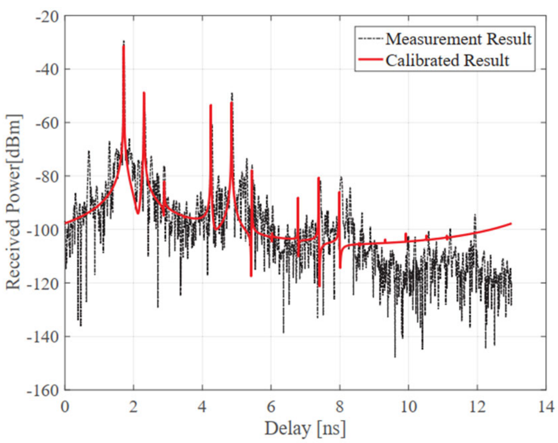

FIGURE 6. Comparison of simulated and measurement kiosk downloading channel [68].

4. DISCUSSIONS

The THz band is still not fully explored, and it is expected to revolutionize the near future communication system. THz band will be utilized in future wireless technologies such as 6G and communication systems such as UM-MIMO and will be used in a variety of applications and environmental scenarios such as chip-to-chip wireless communication, high-speed trains, indoor and outdoor, vehicle-to-vehicle. Modeling a proper and efficient channel that accurately describes the behavior of the channel at THz spectrum is important, and and some of the proposed THz models are discussed in Section 2. Every model has its own advantages and limitations, and it is dependent on the choice of environment and scenario of the channel to be modeled. Table 5 shows the summary of the above-discussed channel models for the THz range along with their modeling approach and frequency range.

Deterministic models provide high-precision results about the environment being modeled, but high computational resources and long-time consumptions are the limiting factors of this model. Additionally, due to the dynamic behavior of the environment, this model also cannot provide better results in such cases. Ray tracing is the most popular type of deterministic model, and it can model most of the scenarios at the THz band. As at THz range waves become shorter and behave quasi-optical, and geometrical optics methods such as RT can be efficient, but still further studies on material behavior at THz are needed. On the other hand, for short distances such as chip-to-chip communication [69], FDTD is better and provides better performance in complex small-scale structures.

Stochastic or statistical channel models are widely applied as they are simpler in terms of resources required and are fast, but the accuracy is to be sacrificed in return. Stochastic channel modeling is adopted in most of the THz wave propagation models due to its flexibility. In particular, physical models are based on experimental measurements and observations of the channel, whereas analytical models use mathematical functions to describe the statistical characteristics of the channel (e.g., arrival time and angle distribution of the MPCs). The advantages of analytical models include greater flexibility and simpler mathematical alteration. They can be easily modified to investigate the effects of various parameters and be used to simulate a wide variety of scenarios. They are limited, though, by the model's assumptions, which might not always correspond to the channel's actual physical characteristics. On the other hand, physical models are based on actual measurements and observations of the channel. This improves their ability to accurately predict channel behavior, particularly in complex environments where analytical models may be insufficient.

Hybrid modeling combines the advantage of both, the accuracy of the deterministic model and the simplicity of the stochastic model. When working with complex structures, the deterministic hybrid modeling method improves the accuracy of the geometrical optical method like RT. In the Q-D method, critical components that predominate in the channel are traced deterministically, and this method can be adapted to different scenarios and prove for high accuracy with low complexity. GBSCM is widely adopted in the THz channel model as it is flexible in terms of environmental geometries and channel characteristics. Also, for ultra-massive MIMO (UM-MIMO), the GBSCM model is applicable, because it supports the precise calculation of propagation distance for each antenna element.

5. CHALLENGES AND FUTURE DIRECTIONS

No doubt the THz band is a promising candidate for future communication technologies and networks. Channel modeling for such high frequencies is still at its infant stage and needs to be studied more for its accurate results and conclusions. As compared to the lower frequencies, THz communication channels are more affected by metrological effects such as rain, fog, snow, and various atmospheric gases. Therefore, in the THz range, losses at the molecular level are also considered, hence creating many challenges and problems for the researcher to model an accurate channel model. In the THz range, the wavelength becomes shorter, and the diffraction effect will have less effect on the waves; however, material roughness, dust, and raindrops will increase the scattering effect as the THz wavelength approaches the size of these materials [76]. An appreciable research progress has been made to achieve an accurate channel model with less complexity. The hybrid channel modeling provides better results in the various communication channels and scenarios, but still, a lot of room is available, especially for the NLOS approach.

Measurement campaigns are also required to validate the precision of THz channel models for different scenarios such as LOS, NLOS, forests, and mountains. The lack of appropriate measurement equipment or costly devices and the requirement for specialized knowledge in THz frequency band measurements make it difficult to make accurate measurements of THz channels. THz-band ultra-wideband communication promises increased channel capacity. To model joint propagation characteristics in multiband operations, investigate any correlation between bands, and suggest an appropriate physical layer design, it is necessary to take the frequency selectivity of such wideband channels into account since Reconfigurable Intelligent Surfaces (RIS) can be utilized. Spatial consistency is an important parameter to consider in THz communication, and it is presently based on omnidirectional antennas [77]. As THz antennas will be directional, the directivity parameter also needs to be considered. Additionally, the developed models must adequately consider the polarization characteristics, azimuth, and elevation angles of departure and arrival of multipath components [78]. Additionally, near field effect will also be considered, as the distance between transmitter and receiver is less than Rayleigh distance, and in this case rays, DoA, and AoA cannot be constant [79], so spherical waves should be considered.

The development of more accurate hybrid models that combine the benefits of both deterministic and stochastic approaches is required for sub-THz bands. The incorporation of machine learning techniques to increase the effectiveness and accuracy of THz channel modeling are some future research directions in this field. Both the mm-wave channels path loss prediction [80] and clustering using unsupervised learning [81] already use AI-based methods. Therefore, it would be possible and perhaps even more appropriate to use such techniques for channel parameter modeling and extraction for the more complex THz band. There is also a need for research into how atmospheric conditions and climate change affect THz communication systems, as this could have a major impact on potential future uses for THz technology.

6. CONCLUSION

The channel modeling methods and techniques for future THz communication system are discussed in this paper in detail. No doubt, THz will be the future of communication networks and technologies, so, much focus is on the THz band, especially on system design and channel modeling. The classification of the channel modeling is listed, and in this study, only classification based on the methods and techniques is considered. Many modeling methods and techniques are proposed and discussed in the above study that provide good accuracy with low complexity and fewer resource requirements. However, every method has its own advantages and limitations to be applicable to the specific environment and scenario. The above study shows that there are still a lot of challenges to model an accurate model for THz wave propagation. AI, machine learning, deep learning, and the recent availability of THz equipment that facilitates the THz measurement will no doubt assist in the design of accurate and efficient THz models for future communication systems.

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AUTHOR CONTRIBUTION

Arslan Ahmed is the primary author of this paper, and he has written the entire paper, compiled all necessary information, and presented it in an understandable manner. Fauziahanim Che Seman and See Khee have supervised and suggested relevant research papers and provided guidance on the scope and the focus of the review. Fatin and Izhar have provided guidance on the overall structure, organization, and formatting of the paper.

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