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An overview of the frequency bands and channel models envisioned for 6G networks

***Abstract**. This paper analyzes the frequency bands and channel models that are potentially applicable in 6G networks such as: low band (below 1 GHz), mid-band (1-24 GHz) and high band (24-300 GHz) and deterministic channel modeling, stochastic channel modeling and combined stochastic-deterministic channel modeling, respectively. Given the exceptional attributes of the THz spectrum, it is imperative to develop a deeper understanding of its characteristics, part of which also constitutes the employment of innovative techniques to model and measure channel characteristics.*

***Streszczenie.** W artykule dokonano analizy pasm częstotliwości i modeli kanałowych mających potencjalne zastosowanie w sieciach 6G, takich jak: dolnopasmowe (poniżej 1 GHz), średniopasmowe (1-24 GHz) i górnopasmowe (24-300 GHz) oraz deterministyczne modelowanie kanałów, odpowiednio stochastyczne modelowanie kanałów i kombinowane stochastyczno-deterministyczne modelowanie kanałów. Biorąc pod uwagę wyjątkowe cechy widma THz, konieczne jest głębsze zrozumienie jego charakterystyki, czego częścią jest również zastosowanie innowacyjnych technik do modelowania i pomiaru charakterystyki kanału. (**Przegląd pasm częstotliwości i modeli kanałów przewidywanych dla sieci 6G**)*

Keywords: 6G, THz, frequency bands, channel models.
Słowa kluczowe: 6G, THz, pasma częstotliwości, modele kanałów

1. Introduction

The utilization of the THz band, which spans the 0.1 to 10 THz frequency range, exhibits potential for satisfying the demands of 6G in 2030 and beyond [1]. This band possesses the capacity to accommodate a substantial quantity of connected devices and deliver ultra-high user data rates on a scale of terabits per second (Tbit/s) [2]. Moreover, the THz band boasts an abundance of available bandwidth resources and can achieve ultra-high communication rates, rendering it a crucial choice air interface technology for Tbit/s communication. It is anticipated that THz communication will be implemented in contexts such as holographic communication, small-scale communication, ultra-large-capacity data backhaul, and short-distance ultra-high-speed transmission. In addition, the exceedingly large bandwidth of the THz band permits high-precision positioning and high-resolution image sensing of network and/or terminal devices, which constitutes a promising avenue for THz communication applications [3].

The THz frequency band has historically been one of the less examined frequency bands owing to the lack of effective and feasible transceivers and antennas [4]. Nevertheless, in the past decade, significant advancements have enabled the creation of practical THz communication systems, with its multi-GHz bandwidth, the THz spectrum presents a promising solution to the issue of spectrum scarcity and has the potential to substantially enhance the capacity of current wireless systems [5]. Choosing suitable processes and material properties for THz devices is primarily determined by their characteristics and cutoff frequencies. The selection of appropriate technology for THz applications involves various factors, such as cost, output power, efficiency, maturity of interconnection and packaging technologies, and integration capabilities. In the THz band, a large antenna array is typically required to ensure transmit power. With increasing operating frequency, high integration is crucial. The small wavelength of THz presents both advantages and challenges in implementing a large-scale antenna array with a small size [2].

Compared to low frequency millimeter waves and microwaves, as well as high frequency visible light, the THz channel displays distinct characteristics. THz waves exhibit stronger frequency selectivity, a more pronounced scattering effect, and a greater transmission loss than millimeter waves. In contrast to light waves, THz waves demonstrate reduced path loss, higher volatility, stronger reflected energy, and lower susceptibility to blocking. Therefore, conventional models and techniques for measuring millimeter waves, microwaves, and visible light systems are not directly transferable to the THz band, highlighting the significance of developing specific THz channel measurement instruments. While statistical channel modeling is commonly used in mobile communication standard channel modeling applications such as the (3rd Generation Partnership Project) 3GPP standard channel model, it is inadequate in meeting the demand for a new spectrum and high-precision channel modeling in specific scenarios [6].

Creating a channel model for THz wireless communications necessitates meticulous consideration of numerous vital factors such path loss, path loss exponent, received power etc. Furthermore, as most use cases entail indoor deployment and short communication range, reflections and penetrations from walls, ceilings, floors, and all objects must be taken into account. Due to the absence of availability of THz equipment, only a few studies have been conducted on the subject thus far. Identifying the frequency bands and channel models envisioned for the 6G networks is essential to achieve these objectives.

Our main goal in this paper is to present a detailed theoretical analysis of frequency bands and derive guidelines for the development of Thz channel models that will be potentially applicable in 6G systems. The remainder of this article is organized as follows. Section II introduces the 6G spectrum allocation. Section III presents channel modeling, measurements and methodologies in different environments. Conclusion and future work are addressed in section IV.

2. 6G spectrum allocation

The field of mobile communication technology has undergone substantial changes over the years, with each new generation (Third Generation (3G), Fourth Generation (4G), and Fifth Generation (5G)) introducing novel technologies and features to facilitate increasingly advanced services. The next significant advancement is expected to take place with the introduction of 6G, which may be commercially available before 2030 and subsequently adopted widely by that year. However, this will necessitate the availability of the requisite spectrum by 2030. The current 5G services, including enhanced mobile broadband (eMBB), ultra-reliable and low latency communications (URLLC), and massive machine-type communications (mMTC), will continue to advance and improve as the technology progresses towards 6G. Additionally, advances in communications, sensing, imaging, displays, and Artificial Intelligence (AI) will lead to the emergence of new services, such as truly immersive extended reality (XR), high-fidelity mobile holograms, and digital replicas, which may require data rates of up to 1 Tbps [7].

To fulfil the requirements of the next generation of wireless communication, a significant amount of spectrum ranging from hundreds of MHz to tens of GHz is necessary. The implementation of 6G technology will enable hyper-connectivity between humans and devices, providing the ultimate multimedia experience. To achieve enhanced coverage and capacity, 6G will require spectrum coverage across a range of frequencies, including low, mid, and high bands. While the existing bands below 6 GHz are suitable for coverage and can be modified for 6G, additional spectrum in the mid-band and sub-THz spectrum will be necessary to meet the demands of this technology [7]. Furthermore, research on 6G technology has already commenced. The main emphasis of 6G technology lies in the frequency bands.

2.1 Potential spectrum bands for 6G networks

Throughout the evolution from 3G to 5G mobile communication technologies, there has been a consistent trend of employing higher and wider frequency bands. While the 2 GHz band is utilized for 3G, the 2.3 GHz and 2.5 GHz bands are also employed for fourth-generation technologies. Furthermore, in the 5G era, the 3.5 GHz and (millimeter wave) mmWave bands are catering to new services, including a variety of vertical applications. Some of these frequency bands have been repurposed for subsequent generations of mobile communication technologies. Typically, the initial deployment of a new generation of mobile communication systems occurs in a fresh frequency band, with additional bands and repurposed bands from previous generations being utilized later for network expansion as the ecosystem grows. This approach is also anticipated for sixth-generation technologies [7].

As time progresses, it is becoming increasingly difficult to allocate frequency bands exclusively for mobile communication. Therefore, it is imperative to employ efficient utilization of limited frequency resources across the low- to high-band range. In the forthcoming 6G era, the judicious and adaptable deployment of frequency bands, both spatially and temporally, is anticipated to assume greater significance. Additionally, regulatory measures are chiefly employed to tackle interference concerns within or between adjacent bands for diverse services. Given that 6G seeks to optimize spectrum efficiency, innovative technologies for spectrum sharing and compatibility with adjacent bands will be among the most crucial advancements [7].

2.1.1 Low-band “Below 1 GHz”

Each successive generation of communication technology from Second Generation (2G) to 5G has incorporated a low-band spectrum element to facilitate broad area coverage in rural regions and enhanced indoor penetration in urban areas, resulting in a consistent user experience. It is predicted that 6G will also necessitate a low-band spectrum. While reusing existing low-band spectrum is an option, it is also critical to investigate whether additional low-band spectrum from spectrum bands below 1 GHz will be required. The utilities industry, IoT, emergency and military systems, broadcasting networks, and wireless microphones are among the current users of low-band spectrum who may be impacted by such a decision. The low-band (below 1 GHz) presents difficulties in obtaining wide bandwidth compared to other bands. Nevertheless, due to its exceptional propagation characteristics, it provides extensive area coverage and deep indoor penetration [7].

2.1.2 Mid-band “1-24 GHz”

The mid-band spectrum holds great value due to its ability to provide both coverage and capacity, making it a critical component in the upcoming 6G era. Throughout the various technological generations, including 3G to 5G, mid-band deployments have seen an increase in frequency and bandwidth, thereby making it necessary to acquire additional mid-band spectrum for network expansion. Nevertheless, obtaining exclusive use of this spectrum proves to be challenging as there are already several incumbent services operating within the 1 to 24 GHz frequency range. Therefore, it is imperative to explore globally harmonized frequency bands to foster economies of scale, which would enable affordable devices and services, while still taking into consideration the flexible regional and local use of mid-band spectrum through appropriate sharing means. Studies conducted on the 6G spectrum in the mid-band range have generated considerable interest on a global scale. This interest stems from the fact that the propagation advantage offered by existing International Mobile Telecommunications (IMT) bands below 6 GHz is advantageous for coverage enhancement, as compared to the high-band consisting of millimeter-wave and sub-THz bands. Previous World Radiocommunication Conferences (WRCs), such as WRC-07 and WRC-15, have identified various frequency ranges for IMT, which are depicted in figure 1 [7].

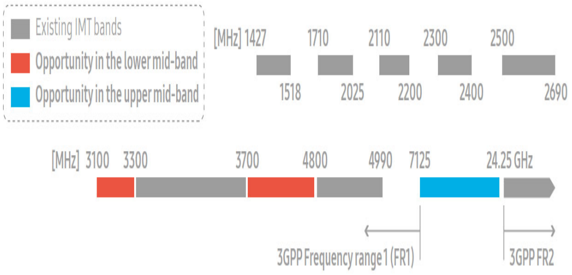

Fig. 1. Existing IMT bands and opportunity in the mid-band [7]

In regard to the mid-band frequency range, it has been discerned that there are two sub-frequency ranges that should be considered. The first sub-frequency range is the lower mid-band, which spans from 1 to 7 GHz. The second sub-frequency range is the upper mid-band, which extends from 7 to 24 GHz. These sub-frequency ranges have been identified in accordance with the WRC-23 agenda item, FCC's rulemaking process, and the 3GPP frequency ranges [7].

2.1.3 High-band “24-300 GHz”

mmWave band “24-92 GHz” - The significance of employing the mmWave spectrum is emphasized due to its ability to support higher capacity and bandwidth in contrast to mid-band and low-band, as observed by the continued surge in mobile data traffic within densely populated metropolitan regions or during peak periods. During the WRC-19 conference, various sub-bands were designated within the mmWave band for IMT, as depicted in Figure 2 [7]. It is worth noting that the 28 GHz band, which is deemed as a 5G frontier band, has already been put into commercial use in countries such as the United States, South Korea, Germany, Finland, Italy and Japan. The 24-92 GHz range of the high band permits the provision of high-capacity services with broad contiguous bandwidth, albeit with potential limitations in terms of coverage.

Fig. 2. Availability of mmWave bands [7]

Sub-THz band "92-300 GHz" - The high-frequency range of the sub-THz band, ranging from 92 to 300 GHz, is suitable for the provision of both existing and novel communication services that require ultra-high capacity and ultra-low latency, such as holograms and XR. The 92-300 GHz frequency range has potential bands for communication, which are presented below. According to the International Telecommunication Union - Radiocommunication (ITU-R) Radio Regulations, the 92-300 GHz range is allocated globally for various services, including mobile services, as illustrated in Figure 3. For contiguous wide frequency bands, the candidate frequency ranges should include those currently allocated for mobile services, as well as some frequency ranges with the potential for future mobile service allocation, such as 1 and 2 shown in Figure 3 [7].

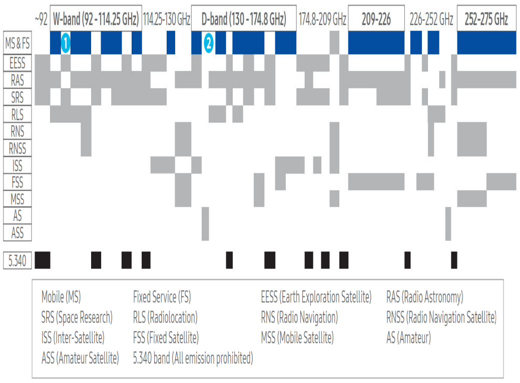

Fig. 3. Global allocation of the 92-275 GHz spectrum range [7]

There are viewpoints such as in [7] which propose that the sub-THz frequency range, specifically the D-band (130-174.8 GHz), should be taken into account for fixed service purposes such as backhaul. A plethora of technical feasibility investigations and experiments are currently underway across the world to ascertain whether these two frequency bands can be utilized for mobile applications [7]. It is highly probable that traditional fixed and mobile service applications may coexist under certain circumstances. Prior to drawing any conclusions, all conceivable alternatives must be retained for the possibility of leveraging sub-THz for mobile applications. In the times to come, it will be crucial to explore ways to effectively distribute the sub-THz frequency range for mobile services in conjunction with passive and fixed services. Samsung is engaged in various research efforts in the field, such as conducting channel measurement campaigns and demonstrations, as part of which initial findings have revealed that leveraging the sub-THz band for 6G technology will provide new spectrum opportunities and that sub-THz bands could be feasibly utilized for 6G [8][9][10][11][12]. In parallel, Ericsson is focused on developing a testbed for radio access networks (RAN) that operates within the 92-100 GHz frequency range [7].

3. Channel modeling

The advancement of THz communication technology necessitates not only the development of efficient THz devices, but also an investigation into the THz channels themselves. Given the distinctive characteristics of the THz spectrum, it is imperative to employ innovative approaches to model and measure the channels. Traditional channel modeling techniques pose difficulties due to the high propagation loss and frequency-dependent molecular absorption features of the THz spectrum [4].

3.1 Channel measurements

Initially, investigation into the transmission of THz waves was chiefly theoretical and driven primarily by the atmospheric sensing community. The interaction between THz waves and matter is explained by closed-form analytical models established on radiative transfer theory, which plays a critical role in the propagation of THz signals. The first comprehensive channel models for the THz band were obtained by merging physics, electromagnetics, and communication theory [4]. Channel measurement is fundamental in characterizing the spectral attributes and formulating channel models and is accomplished with techniques such as Electromagnetic (EM) wave theory and full-wave simulation. Recently, research campaigns in the lower THz band have been initiated as THz technology has become more refined [13-17]. These experiments have a twofold objective: to authenticate physics-based analytical models and to create data-driven models that are more straightforward and favored by standardization bodies such as the 3GPP. Despite the numerous measurement techniques that have been implemented for a significant duration, THz channel measurement systems encounter distinctive hurdles. These systems require the detection of expansive frequency spectra, facilitate remote sensing due to the elevated path loss, and execute complete scanning of the spatial domain within an acceptable timeframe, even when utilizing high-directivity antennas [4].

3.1.1 Frequency-Domain Vector-Network-Analyzer-Based Method

The Vector Network Analyzer (VNA) is a widely used tool for measuring the frequency response of linear systems, one frequency at a time, and is frequently employed for the characterization of discrete electrical/RF components, as well as for measurement of wireless channels by connecting transmitting and receiving antennas to the VNA ports [18]. Despite its widespread usage, the VNA is subject to a number of limitations, including low output power, high noise, limited distance, and long measurement times. While external power sources and low-noise amplifiers can mitigate the issues of low output power and high noise, optical fiber and directional transmissions can be utilized to extend the distance. However, the long measurement times remain a hindrance to the application of the VNA in dynamic THz channels [18]. Nevertheless, a 140 GHz channel measurement system was established in collaboration with Huawei, using the VNA method, which permits end-to-end measurement solutions in an indoor meeting room. This system was used by [19] to investigate channel parameters, as well as the temporal and spatial distributions of multipath scenarios. In [20], a VNA-based technique to generate a channel measurement system for urban settings that operates at approximately 140 GHz. This method has been constructed specifically for urban scenarios [20]. In [21-23], assessments utilizing VNA technology were conducted at a frequency of 300 GHz on various electronic devices, namely a desktop computer, a motherboard, and a data center.

3.1.2 Time-Domain Sliding Correlation Method

Another method for channel measurement is based on the transmission of a signal with an autocorrelation function of a Dirac delta, allowing for high transmit power with a low Peak-to-Average Power Ratio (PAPR) and real-time measurements. The Dirac delta function is a mathematical construct that is called a generalized function on real numbers, whose value is zero everywhere except at zero, and whose integral over the entire real line is equal to one. However, there are two main challenges associated with this approach [35]. Firstly, the power spectral density is often unevenly distributed. Secondly, ultra-high sampling rate Digital-to-Analog Converters (DACs) and Analog-to-Digital Converters (ADCs) are required. The sliding correlation method has been proposed to address the latter issue, allowing for an increase in Signal-to-Noise Ratio (SNR) by using different chip rates for the correlation process between the transmitter and receiver, which expands the measurement duration [24]. A measurement platform that operates in real-time and operates at a frequency of 140 GHz was established in [25] through the use of an established method [26]. The platform has been used for an assortment of purposes including the analysis of reflection and scattering propagation characteristics [26], the examination of large-scale fading and multipath characteristics of indoor channels [27], and the assessment of receive powers and interference for satellite measurements [28]. In a similar vein, Technische Universität Braunschweig, in collaboration with Beijing Jiao Tong University (BJTU) [29], developed a measurement system for 300 GHz that is based on correlation.

3.1.3 Direct Pulse Method

The direct pulse method, also known as Terahertz Time-Domain Spectroscopy (THz-TDS), is a simple approach that runs in parallel to the two methods mentioned above. This technique involves training very narrow pulses in the time domain with a period larger than the maximum excess delay. The maximum excess delay refers to the relative delay between the first-arriving component and the multipath component whose energy falls below a certain threshold from the strongest one. By utilizing this measurement method, it is possible to easily obtain the channel impulse response from the observation of the received signals. This can be achieved by considering both the amplitude of the channel impulse response and the delay between the transmission time and sampling time. The direct pulse method is most suitable for THz waves with ultra-broad bandwidth [4]. However, it has some limitations, including low power, large equipment size, short distance, and a limited range of applications that are restricted to the measurements of reflection, scattering, and diffraction properties induced by narrow beams. The THz-TDS method has been utilized to measure the interference of THz channels at 300 GHz, and the data was analyzed stochastically [30]. Furthermore, [31] and [32] have conducted measurements using this method to investigate the reflection coefficients of building materials at 100-1000 GHz [31] and the reflection coefficients of stratified building materials [32]. The THz-TDS method has also been applied to measure diffusion coefficients of rough surfaces at 200-400 GHz [33]. Table 1 presents an overview of THz channel measurement techniques.

Table 1. THz channel measurement techniques [4]

	VNA	Sliding correlation	Direct pulse
Domain	Frequency	Time	Time
Signal	Single carrier	Auto-correlated sequence	THz pulse
Distance	Limited by physical link	Supports long-distance measurement	Limited by pulse power
Scenarios	Short distance	Long distance	Very short distance
Advantages	Large frequency range and bandwidth	High measuring speed	Large measuring bandwidth
Drawbacks	Low measuring speed	Small bandwidth; High complexity	Large size; Low transmit power; Limited measuring distance

Table 2 presents a review of relevant works addressing the method that they have used in channel modeling.

3.2 Channel Modeling Methodologies

A very important step in communication system design is to derive the channel characteristics through appropriate modeling. There are two types of modeling approaches currently used: deterministic and stochastic. Stochastic modeling includes Geometry-Based Stochastic Models (GBSMs), Non-Geometry-Based Stochastic Models (NGSMs), and Correlation-Based Stochastic Models (CBSMs) [2]. Deterministic models, on the other hand, utilize the laws of wave propagation to determine the signal power received at a specific location in a Three Dimensional (3D) mapped environment. In the THz band, accurate geometric modeling of the propagation environment is required along with knowledge of boundary conditions and the positions and properties of the Tx and Rx antennas, as well as different materials present such as their shape and dielectric constant. While deterministic models accurately predict the characteristics of the propagating environment, they suffer from high computational complexity and large simulation times. Stochastic models, on the other hand, utilize measurement data to provide a statistical description of the propagation channel. Non-Geometry-Based Stochastic Models (NGBSMs) do not explicitly model the scatterers in the propagation channel but instead consider it as a set of delay taps. By collecting empirical data and deriving probability density functions, the channel model can be established. In contrast, GBSMs use probability distributions to describe the properties of scatterers and fundamental laws of wave propagation to characterize the propagation process. Clusters replace delay taps in GBSMs and represent a collection of multipath components (MPCs) with similar properties, where the clusters are distinguishable from each other. CBSMs are suitable for cases with wide scattering, but this is not the case with THz links that use highly directive beams, so they are not considered further here [2]. Table 3 shows some of the channel models in the THz range.

able 2. Overview of some of the latest published work

Reference	Method	Outline of published work
Mbugua [18]	VNA	This article presents the use of RoF techniques in a VNA-based channel sounder. The channel sounder's validation and specification includes the frequency range of 1–30 GHz for the back-to-back setup and 26.5–30 GHz for over-the-air measurements
Yu [19]	VNA	The temporal and spatial distributions of multipath scenarios, as well as channel parameters, were examined.
Abbasi [20]	VNA	This article presents a VNA-based method for creating a channel measuring system designed primarily for urban environments that operates in the range of 140 GHz.
Kim [21]	VNA	On a desktop computer, assesments using VNA technology were carried out at a frequency of 300 GHz.
Kim [22]	VNA	On a computer motherboard, assesments using VNA technology were carried out at a frequency of 300 GHz.
Cheng [23]	VNA	On a data center, assessments using VNA technology were carried out at a frequency of 300 GHz.
MacCartney [25]	Sliding Correlation	This article describes the establishment of a 140 GHz real-time monitoring platform.
Ju [26]	Sliding Correlation	A variety of applications, such as the examination of reflection and scattering propagation properties, have made use of the platform in [36].
Xing [27]	Sliding Correlation	The large-scale fading and multipath properties of indoor channels have been examined using the platform in [36].
Xing [28]	Sliding Correlation	The evaluation of receive powers and interference for satellite measurements has been done using the platform in [36].
Rey [29]	Sliding Correlation	In this article a measurement system for 300 GHz that is based on correlation was developed.
Hossain [30]	Direct Pulse	The interference of THz channels at 300 GHz has been measured using the THz-TDS method, and the data was evaluated stochastically.
Piesiewicz [31]	Direct Pulse	In this article they have conducted measurements using this method to investigate the reflection coefficients of building materials at 100-1000 GHz
Jansen [32]	Direct Pulse	In this article they have conducted measurements using this method to investigate the reflection coefficients of stratified building materials
Jansen [33]	Direct Pulse	In this article the THz-TDS method has been applied to measure diffusion coefficients of rough surfaces at 200-400 GHz

Table 3. THz channel modeling methods [2]

Channel Modeling	Models
Deterministic Channel Modeling	Ray-Tracing; Ray-Launching; METIS; 3GPP NR; IMT-2020; Finite-Difference Time-Domain; Method of Moments
Stochastic Channel Modeling	Tapped delay line; Saleh-Valenzuela; Zwick; Gaussian Mixture; Zero-mean 2nd order GMM
Combined Stochastic-Deterministic Channel Modeling	QuaDriGa MiWeba

3.2.1 Deterministic Channel Modeling

The utilization of the Ray-Tracing (RT) technique is widely recognized as the predominant deterministic channel modeling approach in the IEEE 802.15.3d standard for wireless communications [34]. Its versatility in modeling various static scenarios in the THz spectrum, particularly those present in indoor office rooms, data centers, and nano-networks, has made it a preferred choice in the field. Recent studies as in [34] have indicated that the utilization of RT in the optical spectrum is applicable for the purpose of modeling and characterizing fundamental propagation mechanisms in the THz bands. This discovery has rendered it highly relevant in simulating precise point-to-point (PtP) application scenarios for operation within the THz frequencies of 6G networks.

The ray-launching method is an alternative technique to RT that employs the use of rays launched on a coordinate grid based on angular directions and propagation laws similar to those used in RT. The method involves tracing the path of each ray towards the grid in simulations and accounting for any changes in direction based on a predefined power threshold level within the grid. This approach also offers the benefit of being able to simulate multiple Rx locations based on a single Tx without a significant increase in computational complexity, making ray-launching a highly efficient tool for modeling practical systems [34].

The deterministic methodologies represented by the METIS [35], 3GPP NR channel model [36], and IMT-2020 channel model [37] employ RT map-based modeling to create realistic models for a variety of application scenarios in 5G networks. This modeling strategy employs a simplified geometric representation of the environment in which scatterers are designated to represent objects and transmitters/receivers are designated as point sources. However, the drawback of this approach is its requirement for knowledge of the network layout, which may not always be readily available.

In contrast to RT and ray-launching techniques, Finite-Difference Time-Domain (FDTD) and Method of Moments (MoM) are numerical methods that can effectively consider the backscattering of rays [38]. These methods solve Maxwell's equations with high accuracy through integral (FDTD) and differential (MoM) equation analysis, offering precise estimates of spatial distributions that necessitate intricate geometric information, such as material roughness and shape. Nevertheless, these methods involve high computational demands and are time-intensive, which restricts the size of the environment that can be simulated. This is due to the fact that obtaining a numerical solution to Maxwell's equations necessitates a set of points spaced out in the order of a wavelength, resulting in an increase in computational complexity as the frequency and number of scatterers grows. Although both FDTD and MoM approaches have their benefits, they can be combined with RT to provide a more precise estimation technique. Combining diverse models can present a challenge due to the variations in tools and assumptions. Nevertheless, a hybrid approach that integrates FDTD and RT modeling has been demonstrated to be effective in sub-6 GHz bands [39], as evidenced by a study that reported notable improvements in Root Mean Square (RMS) error and Central Processing Unit (CPU) time when compared to RT-only operation. Additionally, this hybrid method has been applied to mmWave bands by incorporating diffuse surface scattering interactions derived from FDTD into a ray tracer, resulting in more precise outcomes [40].

3.2.2 Stochastic Channel Modeling

Stochastic channel models employ a spatiotemporal approach based on empirical data from measurement campaigns to statistically analyze the channel. Compared to deterministic models, these models require fewer computing resources, but the time taken to obtain accurate results from measurements can be a limiting factor. In the THz regime, narrow-band fading models may no longer suffice due to the presence of wideband channels with higher order frequencies and larger bandwidths that require the resolution of multipaths in the time domain. To model the wideband channel characteristics, a statistical model capable of generating the Committed Information Rate (CIRs) must be developed. Therefore, it is imperative to obtain the spatiotemporal characteristics of the propagation channel in order to model the wideband channel characteristics [34].

The clustering behavior is observed when the arriving MPCs have similar distributions in terms of Time of Arrival (ToA) and Angle of Arrival/Departure (AoA/AoD). To model this behavior, Saleh and Valenzuela [34] proposed the Saleh-Valenzuela (SV) model [34], which is widely accepted and based on a cluster-based impulse response using reflections from different surfaces. In the SV model, MPCs are modeled as delay taps and assumed to vary uniformly in phase with powers that are Rayleigh distributed and decay exponentially based on a Poisson distributed ToA of MPCs and clusters. The SV model was modified in [41] to account for the presence of antenna subarrays and the effects of molecular absorption in the indoor THz channel. This modified model was validated based on measurements from [42] at 300 GHz. It considers the cluster arrival time and ray arrival time within each cluster as a function of the number of elements of the sub-array. In addition to the spreading loss, this modified model also accounts for the transmission behaviors by considering the effects of molecular absorption.

The Zwick model is a non-geometric-based stochastic model that can be used for both indoor and Multiple-Input Multiple-Output (MIMO) channel characterization [34]. This model takes into account physical wave propagation properties and characterizes multipath components by a transfer matrix that includes losses, delay, direction of arrival, direction of departure, and scattering properties. The model has been verified in the millimeter-wave bands and has the potential to be applied at THz frequencies as well [34].

GBSM models, or Geometric-Based Stochastic Models, are models used to describe wireless channels based on the physical arrangement of scatterers in the environment. These models can be divided into regular and irregular shapes based on how effective scatterers are assigned to the environment. Regular shapes are assigned in the form of one-ring, two-ring, and elliptical distributions, while irregular shapes follow a random distribution. These models are highly reliable and robust against link and network failures. The one-ring model is suitable for MIMO channel modeling and backhaul applications where the base station is located at a height without obstructions, and the access point is surrounded by scatterers. The two-ring and elliptical models are relevant for indoor environments in 6G networks where there are many scatterers present on both sides of the communication channel [34].

Other common backhaul topologies include the star, chain, and tree topologies. The star topology is inferior due to poor frequency reuse, while the chain topology has the disadvantage of network failure when one link fails. The tree topology is a mixture of the chain and star topologies, with fewer links prone to failure and requiring protection [34].

In order to analyze the multipath behavior within individual clusters, a second order profile for exponentially distributed multipaths such as the Gaussian Mixture Model (GMM) [42], which is a cluster oriented GBSM that can be adopted for approximating AoA/AoD standard deviation Probability Distribution Function (PDFs) of different materials for identifying similarities between the different MPCs within a cluster or otherwise inter-cluster components.

The Gamma mixture model (GMM) has been used to analyze short-range THz propagation channels in [43]. They compared the performance of GMM and Gamma mixture model for parameter estimation based on measurements in the 240-300 GHz band. Although GMM was found to be able to describe the propagation channel, the Gamma mixture was found to have a closer relationship between the actual and predicted probability distribution of powers. In another study, the Gamma mixture model was employed to characterize shadowing effects caused by multipath scattering in intra-device link scenarios by modeling the PDF of the path loss fluctuations [34]. The Gamma mixture model was found to be effective in dealing with large bandwidths and sudden changes in the THz communications channel.

Peng and Kürner [44] proposed a stochastic channel model for wireless data centers operating at 300 GHz, which was later included in the IEEE 802.15-15-0207-003d standard [45]. The model was validated through delay and angular spreads by calibrated ray-tracing simulations from [34]. The model takes into account both line-of-sight (LoS) and non-line-of-sight (NLoS) paths and considers delay and angle path loss correlations, as well as phase and frequency dispersion. It can be used to estimate the performance of wireless links within data centers operating at 300 GHz, which are becoming increasingly important for high-speed data transfer and real-time data processing applications. The channel model has also been used to evaluate the performance of 5G and 6G wireless systems operating in the terahertz frequency range, where the channel characteristics are significantly different from those at lower frequencies.

Table 4 shows existing stochastic models presented so far, also the maximum frequency for which they have found applicability in characterizing THz propagation for the envisioned applications [34].

Table 4. Stochastic channel models with potential applicability at THz frequencies [34]

Model	Approach	Frequency (GHz)
Tapped delay line	GBSM	625
Saleh-Venezuela	NGBSM	350
Zwick	NGBSM	60
Zero-mean 2nd order GMM	GBSM	300
Gamma Mixture	GBSM	312

Boujnah et al. [46], developed a stochastic channel model for wireless data centers operating at 300 GHz, which incorporates a link quality assessment method. The model assumes a uniform rack placement topology with nodes situated on top of the racks and THz reflectors placed on the ceiling. The goal is to minimize the effects of blockage and interference, and to establish connections between non-adjacent nodes through secondary paths. Simulation results demonstrate that the proposed topology facilitates THz communications within a data center, with enhanced connectivity and minimal interference.

A stochastic model for indoor radio channels operating at 300 GHz is presented in [13]. The model's accuracy was verified using calibrated RT simulations in an office scenario. The model developed incorporates propagation in the temporal, angular, and frequency domains, taking into account time-of-arrival, angle-of-arrival/angle-of-departure, frequency-dependent phase rotations, and dispersion. The model enables stochastic simulation generation under realistic conditions and accommodates multiple antenna concepts. Additionally, a stochastic model for the 270-320 GHz frequency range has been developed based on the IEEE 802.15-15-0166-00-003d standard [45]. The model accounts for LoS and NLoS links in a predefined configuration for board-to-board communications, while also evaluating the effects of walls and printed circuit boards on the received signal [34].

3.2.3 Combined Stochastic-Deterministic Channel Modeling

Currently, a combination of deterministic and stochastic methods is being favored in THz hybrid modeling. Mechanically translational and rotational antennas are used in channel sounding to capture the received power at every point in space and time [34]. However, gathering a large sample of measurement data is time-consuming and modeling the environment accurately in a stochastic manner is difficult [40]. Software simulators are used to extend the sampling intervals within a 3D environment to extract the statistical behavior of the channel. These simulators may appear simplistic due to limited computational resources and a lack of knowledge about the propagating environment. RT simulators may not capture all the different components and effects observed in empirical measurements, such as dense MPCs. To address this limitation, stochastic channel generators are calibrated by feeding them with empirical data, and then replicating this data through extensive simulations to obtain a much larger data set than that collected by measurements [34].

The nature of the propagation channel at THz exhibits high-frequency selectivity and is quasi-optical. This quasi-optical behavior suggests that image-based ray tracing can predict the spatio-temporal characteristics of wave propagation and assist in quasi-deterministic channel modeling. The MiWEBA project [34] framework for backhaul and access adopted the Quasi-Deterministic modeling approach based on a predefined network layout [34]. This approach allows for stochastic cluster formation, which consists of the most significant MPCs and provides a geometric description of the propagation environment, taking into account attenuation, reflection, scattering, blockage, and mobility effects. Alternatively, RT can provide a mathematical center for the most significant MPC without the MPC being physically present at that location, which can serve as an alternative to cluster formation [34].

In addition, QuaDriGa [47] is a quasi-deterministic stochastic channel generator that includes modules enabling the implementation of 5G standardized stochastic models such as 3GPP and map-based models. It has been demonstrated that QuaDriGa can be effectively used in THz bands, and it has been successful in characterizing various railway scenarios such as T2I and inside station channels at 300 GHz. Its performance has been validated by measurement data and cloudRT simulations [48].

The combination of RT and FDTD methods can provide accurate modeling in a time-efficient manner for THz communication [39]. The FDTD method is used for modeling the region close to scatterers, while the RT method models the rest of the wireless channel. This hybrid approach has been used for indoor channel modeling and is preferred in THz communications due to its high time efficiency and accuracy [49]. Additionally, the hybrid approach can provide even higher computation efficiency due to the stochastic component and capture sufficient channel information for higher accuracy thanks to the deterministic part [4].

Depending on different applications, different approaches are used for channel generation and system-level or link-level evaluation [2]. Some of the suggested channel modeling methods are listed in Table 5.

Table 5. Terahertz channel modeling methodology [2]

Application	Channel modelling method
Communication	Stochastic
Positioning	Stochastic (GBSCM)
Localization and mapping	Ray-based
Imaging and recognition	EM-based

4. Conclusion

Given the range of services that 6G is expected to support, diverse requirements will apply across different geographic areas. These requirements comprise wide coverage with low capacity, wide coverage with high capacity, wide coverage with low latency, low coverage with high capacity, and low coverage with low latency. The current bands below 6 GHz, which are currently utilized by 2G/3G/4G/5G, are appropriate for coverage and can be repurposed for 6G. Nonetheless, in order to fulfill the demands of 6G, supplementary and new spectrum in the mid-band and sub-THz spectrum with its vast available bandwidth will be indispensable.

As an initial step to design the 6G spectrum concept, we have identified three groups of bands: low-band (below 1 GHz), mid-band (1-24 GHz), and high-band (24-300 GHz). The low-band spectrum is presently employed by various sectors including the utilities industry, IoT, emergency and military systems, broadcasting networks, as well as wireless microphones. In contrast, the mid-band spectrum will be utilized for purposes other than mobile communication, such as space research, mobile satellites, meteorological satellites, and so on. The high-band spectrum, specifically 24-92 GHz, has the potential to provide high-capacity services with wide contiguous bandwidth, albeit with potential coverage limitations. Additionally, the frequency range of 92-300 GHz is suitable for both current services and novel services that necessitate ultra-high capacity and ultra-low latency, such as holograms and XR. Currently, based on the results of our research, the mobile communication industry, 6G research projects, and academia are exploring sub-THz bands as a crucial frequency range for 6G, with substantial R&D efforts underway. Despite this, research on sub-THz communication remains in its early stages. To facilitate the commercialization of 6G by 2030, it is essential to begin discussing and planning the use of sub-THz bands for mobile applications at this stage.

Given the exceptional attributes of the THz spectrum, it is imperative to employ innovative techniques to model and measure these channels. The techniques presented in this paper include the Frequency-Domain Vector-Network-Analyzer-Based Method, the Time-Domain Sliding Correlation Method, and the Direct Pulse Method. Based on the conducted measurements, it can be inferred that the Direct Pulse Method, also known as THz time-domain spectroscopy, is well-suited for THz waves with ultra-broad bandwidth. This method incurs low power, has a large equipment size, is limited to short distances, and has a range of applications. These applications are restricted to the measurement of reflection, scattering, and diffraction properties induced by narrow beams.

Based on the research conducted thus far and the published literature, it can be concluded that a hybrid technique consisting of Ray Tracing and Finite Difference Time Domain methods can yield highly precise models for THz communication in a time-effective manner. The FDTD method is used for modeling the region close to scatterers, while the RT method models the rest of the wireless channel. This hybrid approach has been used for indoor channel modeling and is preferred in THz communications due to its high time efficiency and accuracy.

Future research efforts should prioritize the development of efficient THz channel measurement systems that can account for the unique characteristics of THz waves, as current measurement methods used for low-frequency bands are not suitable. Additionally, accurate and flexible THz channel models must be developed, and outdoor and mobile channel measurements and models should be explored to enhance the design and deployment of THz wireless communication systems.

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