6G WIRELESS CHANNEL MEASUREMENTS AND MODELS

Trends and Challenges

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In this article, we present our vision of the application scenarios, performance metrics, and potential key technologies of 6G wireless communication networks. We then comprehensively survey 6G wireless channel measurements, characteristics, and models for all frequency bands and all scenarios, focusing on millimeter-wave (mm-wave), terahertz, and optical wireless communication channels under all spectra; satellite, unmanned aerial vehicle (UAV), maritime, and underwater acoustic communication channels under global coverage scenarios; and high-speed train (HST), vehicle-to-vehicle (V2V), ultra-massive multiple-input, multiple-output (MIMO), orbital angular momentum (OAM), and industry Internet of Things (IoT) communication channels under full application scenarios. We also provide future research challenges of 6G channel measurements, a general standard 6G channel model framework, and models for intelligent reflection surface (IRS)-based 6G technologies and artificial intelligence (AI)-enabled channel measurements and models.

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Introduction

In terms of application requirements, making communications mobile and broadband was the major evolution from 1G to 4G wireless communication networks, while 5G has expanded from mobile broadband (MBB) in 4G to enhanced MBB (eMBB) plus the IoT. The IoT further includes massive machine-type communications (mMTC) and ultrareliable and low-latency communications (uRLLC). Beginning in 2020, 5G wireless communication networks have been deployed worldwide. However, 5G will not be able to meet all of the requirements of future networks. Therefore, research has started on 6G wireless communication networks, which are planned to be deployed after 2030 [1].

While 5G mainly concentrates on eMBB, mMTC, and uRLLC, 6G wireless communication networks are expected to further enhance MBB, expand the boundary and coverage of the IoT, and make networks/devices more intelligent. In [1], the authors named the enhanced three scenarios as *further-eMBB, ultra-mMTC*, and *enhanced uRLLC*. Several other application scenarios, such as long-distance and high-mobility communications and extremely low-power communications, are also promising. Here, we classify the application scenarios as *strengthened eMBB/mMTC/uRLLC* and other new scenarios. The new scenarios include space–air–ground–sea integrated networks, AI-enabled networks, and so on.

Driven by new application requirements, 6G has to introduce new technical requirements and performance metrics. The peak data rate for 5G is 20 GB/s, while it can be 1–10 TB/s for 6G networks due to the use of terahertz and optical wireless bands. The user-experienced data rate can achieve gigabyte per second levels with the aid of high-frequency bands. The area traffic capacity can be more than 1 GB/s/m^2. The spectrum efficiency can increase 3–5 times, while the energy efficiency can increase about 10 times compared to that of 5G by applying AI to provide better network management. The connection density will increase 10–100 times due to the use of extremely heterogeneous networks (HetNets), diverse communication scenarios, and large bandwidths of high-frequency bands. The mobility will be supported to higher than 1,000 km/h due to the movements of ultra-HST, UAVs, and satellites. The latency is expected to be lower than 1 ms. In addition, other important performance metrics should be introduced, e.g., cost efficiency, security capacity, coverage, intelligence level, and so on, to evaluate 6G networks in a more comprehensive way.

To meet these application requirements and performance metrics, 6G communication networks will have new paradigm shifts and rely on new enabling technologies. The new paradigm shifts can be summarized as global coverage, all spectrums, full applications, and strong or endogenous security. To provide global coverage, 6G wireless communication networks will expand from terrestrial communication networks in 1G–5G to space–air–ground–sea integrated networks, including satellite, UAV, terrestrial ultradense networks (UDNs), underground communications, maritime communications, and underwater acoustic communications. To provide higher data rates, all spectra will be fully explored, including sub-6 GHz, mm-wave, terahertz, and optical wireless bands. With the aid of AI and big data techniques, key technologies and applications will be highly integrated to enable full applications. Furthermore, AI can enable dynamic orchestration of networking, caching, and computing resources to improve network performance. The last, but not the least, trend for 6G is to enable strong or built-in network security when developing it, including physical layer and network layer security. This is quite different from the development strategies of 1G–5G, which first make networks work and then consider whether the networks are secure and how to improve network security.

6G-enabling technologies aim to greatly increase the sum capacity, which is approximated by the summation of Shannon link capacities of different types of channels over HetNets considering interference. As illustrated in Figure 1, the sum capacity can be increased by increasing the signal bandwidth, signal power, number of channels in space/time/frequency domains, and number of HetNets or coverage as well as reducing the interference and noise, thereby increasing the signal-to-interference-plus-noise ratio.

To realize 6G networks with these new trends and enabling technologies, the underlying 6G wireless channels need to be thoroughly studied, since wireless channels are the foundation for system design, network optimization, and performance evaluation of 6G networks.

6G Channel Measurements and Characteristics

6G wireless channels exist at multiple frequency bands and in multiple scenarios, as illustrated in Figure 2. The channel sounders and channel characteristics for each individual channel show great differences [2]. Here, a comprehensive survey of different types of 6G channels is presented by grouping them under all spectra, global coverage scenarios, and full application scenarios. A summary of 6G channel measurements and characteristics is displayed in Table 1.

6G Channel Measurements and Characteristics for All Spectra

mm-wave/Terahertz Channel

In general, mm-wave refers to the 30–300-GHz band, while terahertz denotes the 0.1–10-THz band. Thus, the 100–300-GHz band shares some common characteristics with mm-wave and terahertz, such as large bandwidth, high directivity, large path loss, blockage effects, atmosphere absorption, and more diffuse scattering [3]–[5]. While mm-wave is applied to achieve gigabyte per second level transmission data rates of up to several hundred meters with several gigahertz bandwidths, terahertz is known to achieve terabyte per second level transmission data rates of up to tens of meters with several tens of gigahertz bandwidths. Terahertz bands show more severe path loss, atmosphere absorption, and diffuse scattering than mm-wave bands.

The mm-wave channel has been well studied at some typical frequency bands, such as the 26/28-, 32-, 38/39-, 60-, and 73-GHz bands, even though mm-wave channel measurements with MIMO antennas, high dynamics (such as V2V), and outdoor environments are still needed. An illustration of the measured 28-GHz mm-wave V2V channel obtained from our real channel measurements is displayed in Figure 3. The line-of-sight (LOS) power and total power vary over the 2,000 snapshots, which validates the nonstationarity of the channel. In [3], recent developments and future challenges of mm-wave channel sounders and measurements were given. In [4], some preliminary path

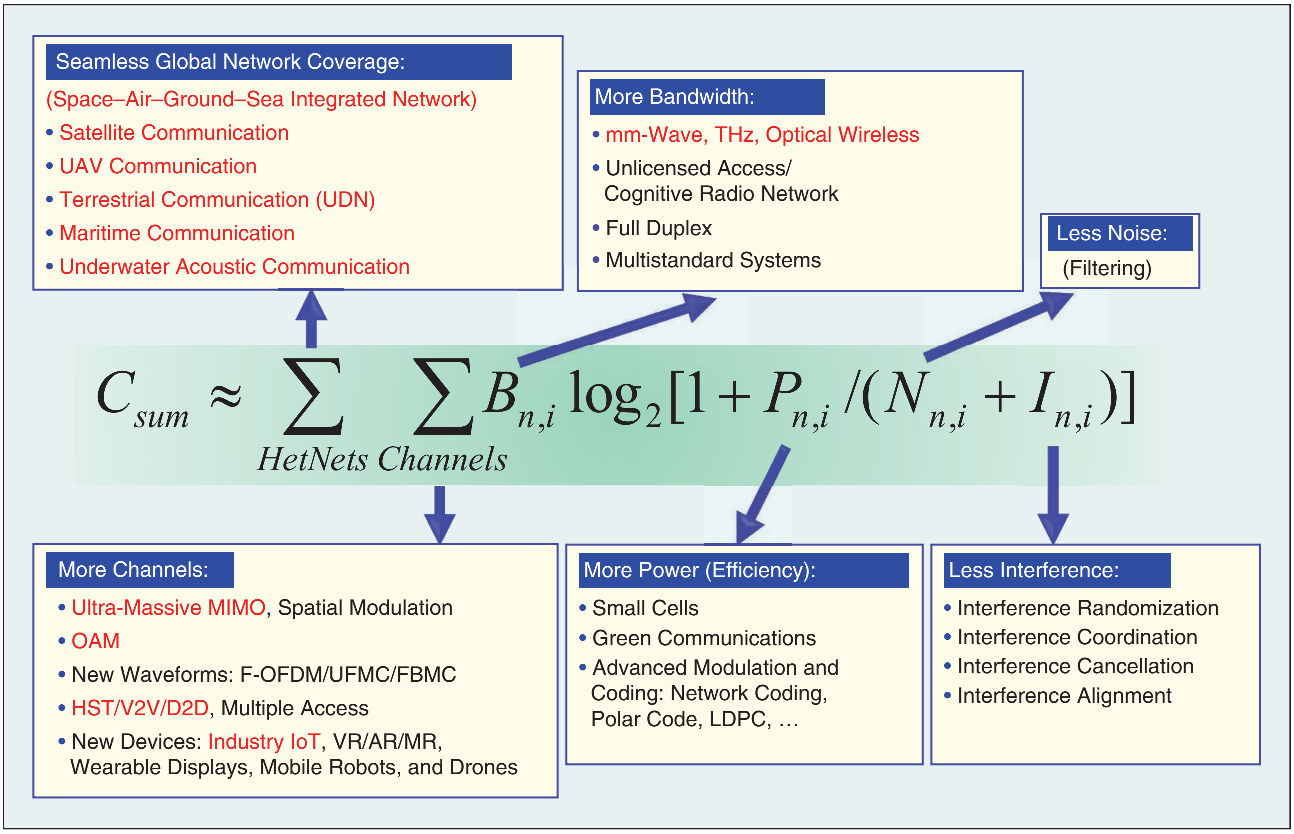

FIGURE 1 6G-enabling technologies. D2D: device to device; VR: virtual reality; AR: augmented reality; MR: mixed reality; F-OFDM: filtered orthogonal frequency-division multiplexing; UFMC: universal filtered multicarrier; FBMC: filter bank multicarrier; LDPC: low-density parity check.

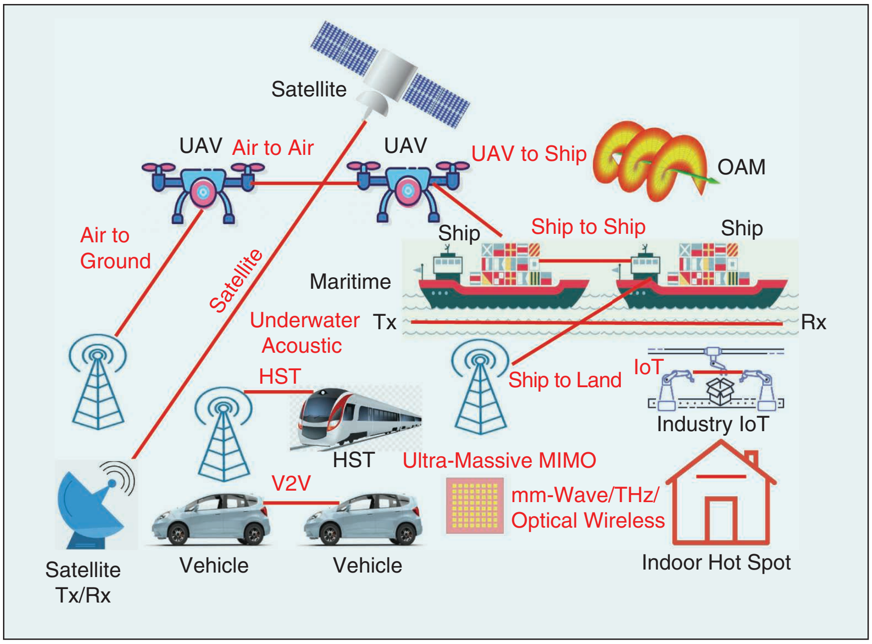

FIGURE 2 Different types of 6G wireless channels. Rx: receiver; Tx: transmitter.

loss, partition loss, and scattering measurements were conducted at 140 GHz. Most current terahertz channel measurements are around the 300-GHz band. The channel characteristics above 300 GHz are still not clear and need extensive channel measurements in the future.

Optical Wireless Channel

Optical wireless bands refer to electromagnetic spectra with carrier frequencies of infrared, visible light, and ultraviolet, which correspond to wavelengths in the range of 780–106 nm, 380–780 nm, and 10–380 nm, respectively [6]. They can be used for wireless communications in indoor, outdoor, underground, and underwater scenarios. Optical wireless channels show some unique channel characteristics, such as complex scattering properties for different materials, nonlinear photoelectric characteristics at the transmitter/receiver ends, background noise effects, and so on. The channel scenarios can be further classified as directed LOS, nondirected LOS, nondirected non-LOS (NLOS), tracked, and so on [6]. The main difference between optical wireless and traditional frequency bands is that there is no multipath fading, Doppler effect, and bandwidth regulation. The measured channel parameters include channel impulse response/channel transfer function, path loss, shadowing fading, root-mean-square (RMS) delay spread, and so on.

6G Channel Measurements and Characteristics for Global Coverage Scenarios

Satellite Channel

Satellite communication has attracted much interest in wireless communication systems and is considered a promising solution to provide global coverage due to its feasible services and lower cost [7]. In general, satellite communication orbits can be divided into geosynchronous orbit and nongeostationary orbit. The circular geosynchronous Earth orbit (GEO) is 35,786 km above Earth's equator and follows the direction of Earth's rotation. Nongeostationary orbits can be further classified as low Earth orbit (LEO), medium Earth orbit (MEO), and high Earth orbit (HEO), depending on the distance of satellites from Earth. The usually applied frequency bands are the Ku (12–18 GHz), K (18–26.5 GHz), Ka (26.5–40 GHz), and V (40–75 GHz) bands. The satellite communication channel is largely affected by weather dynamics, including rain, cloud, fog, snow, and so on. Rain is the major source of attenuation, especially at frequency bands above 10 GHz. In addition, the satellite communication channel shows extremely large Doppler frequency shift and Doppler spread, frequency dependence, large coverage range, long communication distance, and so on. As the distance is extremely long, the channel can be viewed as LOS transmission, and multipath effects can be ignored. Meanwhile, high transmitted power and high antenna gains are needed to combat the

TABLE 1 ***A summary of 6G channel measurements and characteristics.***

Wireless Channel	*Measured Frequency Bands*	*Measured Scenarios*	*Channel Characteristics*
mm-wave/terahertz channel	26/28-, 32-, 38/39-, 60-, and 73-GHz bands (mm-wave); around 300 GHz (terahertz)	Indoor and outdoor	Large bandwidth, high directivity, large path loss, blockage effects, atmosphere absorption, more diffuse scattering
Optical wireless channel	Mainly 380–780 nm	Indoor, outdoor, underground, underwater	Complex scattering properties for different materials, nonlinear photoelectric characteristics at the Tx/Rx ends, background noise effects
Satellite channel	Ku, K, Ka, and V bands	GEO, LEO, MEO, and HEO	Rain/cloud/fog/snow attenuation, extremely large Doppler frequency shift and Doppler spread, frequency dependence, large coverage range, long communication distance
UAV channel	2, 2.4, and 5.8 GHz	Urban, suburban, rural, and open field (air to air and air to ground)	3D random trajectory (large elevation angle), high mobility, spatial and temporal nonstationarity, airframe shadowing
Maritime channel	2.4 and 5.8 GHz	UAV to ship, ship to ship, and ship to land	Sparse scattering, sea wave movement, ducting effect over the sea surface, time nonstationary, long communication distances, climate factors
Underwater acoustic channel	2–32 kHz	Underwater environments	High transmission loss, multipath propagation, time-varying, Doppler effects
HST/V2V channel	Sub-6-GHz and mm-wave bands	Open space, hilly terrain, viaducts, tunnels, cutting*, stations, and intrawagon (HST); highway, urban street, open area, university campus, and parking lot (V2V)	Large Doppler frequency shift and Doppler spread, nonstationarity, effect of train/vehicle, velocity and trajectory variations
Ultra-massive MIMO channel	Sub-6-GHz, mm-wave, and terahertz bands	Indoor and outdoor	Spatial nonstationarity, channel hardening, spherical wavefront
OAM channel	mm-wave	LOS and NLOS (reflection)	Multiplexing gain, beam divergence and misalignment, degradation in reflection scenarios
Industry IoT channel	Sub-6 GHz	Industry IoT environments	Varied path loss, random fluctuations, NLOS propagation, large numbers of scatterers, multimobility

*Cutting is where the HST passes a U-shaped geographical cut surface between hills.

high path loss caused by the long-distance and high-frequency bands.

UAV Channel

There has been increasing use of UAVs in recent years for both civil and military applications. The UAV channel shows some unique channel characteristics, such as 3D deployment, high mobility, spatial and temporal nonstationarity, and airframe shadowing [8], [9]. In general, the UAV channel can be classified as air-to-air and air-to-ground channels. Two types of aerial vehicles are used for channel measurements, i.e., small/medium-sized manned aircraft and UAVs. Channel measurements for the first kind are expensive, while the second kind can largely reduce the cost [8]. Both narrowband and wideband channel measurements have been conducted, most of which are at the 2-, 2.4-, and 5.8-GHz bands. The measured environments include urban, suburban, rural, and open field. The measured channel parameters include path loss, shadowing fading, RMS delay spread, *K*-factor, amplitude probability density function (PDF)/cumulative distribution function (CDF), and so on.

Maritime Channel

As a part of the space–air–ground–sea integrated networks, the maritime communication channel mainly includes air-to-sea and near-sea-surface channels [10]. For air-to-sea channels, the UAV or relay is used as the base station (BS) to communicate with ships on the sea surface. This type of channel is also named the *UAV-to-ship channel*. For the near-sea-surface channel, a ship can communicate with other ships (ship to ship) or fixed BS near the sea (ship to land). The unique features of the maritime propagation environment cause many new channel characteristics, such as sparse scattering, sea wave movement, ducting effect over the sea surface, time nonstationary, long communication distances, and climate factors, which show great differences from conventional terrestrial wireless channels. Maritime channel measurements were conducted at the 2.4- and 5.8-GHz bands with maximum distances of up to 10 km [10]. The path loss, RMS delay spread, and *K*-factor were studied.

Underwater Acoustic Channel

The underwater acoustic channel faces many challenges. Because of the ambient noise in the oceans, the applicable frequency is low, and the transmission loss is high. Horizontal underwater channels are prone to multipath propagation due to refraction, reflection, and scattering. The underwater acoustic channel disperses in both the time and frequency domain, which leads to the time-varying and Doppler effects. Channel measurements were unusually conducted at several kilohertz, ranging from 2 to 32 kHz.

6G Channel Measurements and Characteristics for Full Application Scenarios

HST/V2V Channel

Previous HST communication systems are mainly global systems for mobile communication railway and long-term evolution for railway. Recently, the 5G network has been applied to HST to improve the quality of services [11]. The speed of ultra-HST is hoped to exceed 500 km/h in the future, which causes problems such as frequent and fast handover and large Doppler spread. mm-wave/terahertz and massive MIMO are potential key technologies to be utilized in HST communication systems. Some preliminary channel measurements have been conducted for

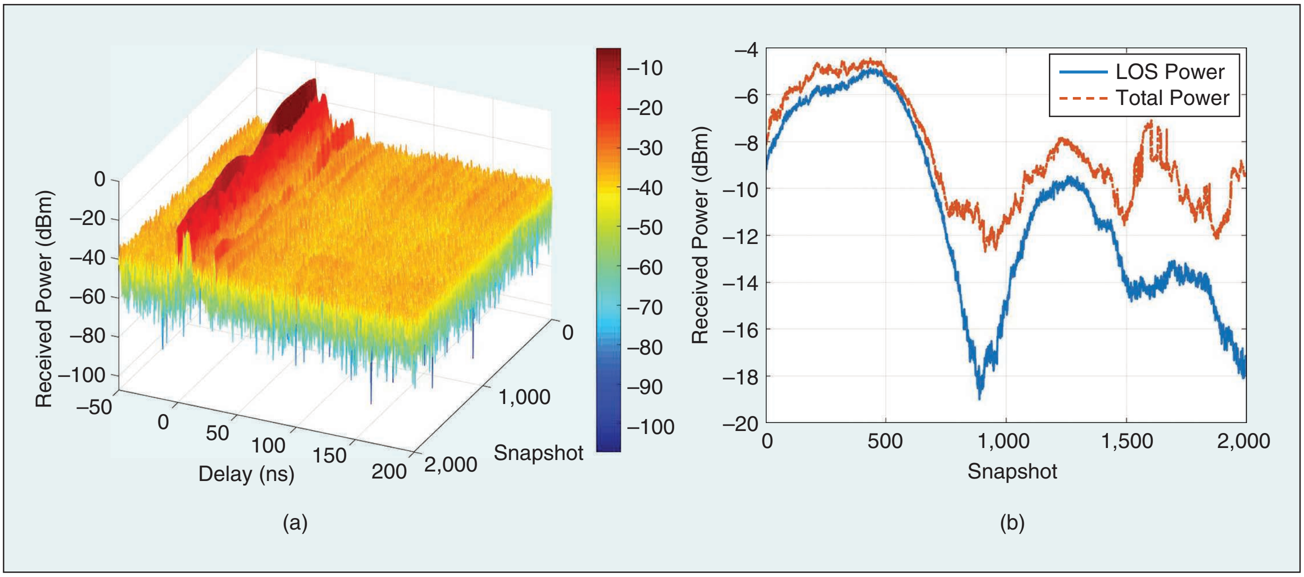

FIGURE 3 The measured mm-wave V2V channel variations at the 28-GHz band. (a) The measured mm-wave V2V channel at the 28-GHz band. (b) The received power variations.

HST environments, including open space, hilly terrain, viaducts, tunnels, cutting, stations, and intrawagon [11].

The vehicular network is a typical industry vertical application of 5G/6G for the uRLLC scenario. The channels include V2V, vehicle-to-infrastructure, and vehicle-to-pedestrian channels and are called *vehicle to everything* in general. The V2V channel at the sub-6-GHz band has been widely investigated, while the mm-wave V2V channel needs more measurements. A survey of current mm-wave V2V channel measurements was given in [12]. In summary, V2V channels were measured at the 28-, 38-, 60-, 73-, and 77-GHz bands. All of them are configured with a single antenna at both sides. The measured environments include highway, urban street, open area, university campus, parking lot, and so on. mm-wave V2V MIMO or even massive MIMO channel measurements with high mobility are promising in the future. How to measure these in an efficient and low-cost way is still an open issue.

Ultra-massive MIMO Channel

Ultra-massive MIMO utilizes thousands of antennas to largely improve the spectral and energy efficiency, throughput, robustness, and degree of freedom of wireless communication systems. It can be combined with other key technologies, such as mm-wave/terahertz, V2V, and HST communications. Due to the use of a large antenna array, the channel shows a spherical wavefront, spatial nonstationarity, and channel hardening properties, which have been validated by previous massive MIMO channel measurements at sub-6-GHz/mm-wave bands in indoor and outdoor environments. At the sub-6-GHz band, the dimension of the massive MIMO array can be several meters. At the terahertz band, due to the development of plasmonic nano-antenna arrays, it is possible to realize ultra-massive MIMO of up to $1{,}024 \times 1{,}024$ [13]. For the 0.06–1-THz band, metamaterials enable the design of plasmonic nano-antenna arrays with hundreds of elements in a few square centimeters. For the 1–10-THz band, graphene-based plasmonic nano-antenna arrays with thousands of elements can be embedded in a few square millimeters [13].

OAM Channel

OAM has attracted widespread interest in many fields, especially in telecommunications, due to its potential to increase capacity by multiplexing. The number of orthogonal OAM modes in a single beam is theoretically infinite, and each mode is an element of a complete orthogonal basis that can be employed for multiplexing different signals, thereby greatly improving spectrum efficiency. OAM represents electron rotation around the propagation axis generated by the energy flow. OAM-based communication can be obtained from traditional MIMO theory under certain conditions. However, beam divergence and misalignment will severely decrease the transmission distance of OAM waves. Moreover, reflection will destroy the orthogonality of OAM waves, degrading the performance in an NLOS scenario. Up to now, there have been limited channel measurements to verify the feasibility of OAM in different scenarios.

Industry IoT Channel

In industry IoT environments, various robots, sensors, and mechanical devices need massive connections in a robust and efficient manner [14]. The industry IoT channel exhibits many new channel characteristics, such as varied path loss, random fluctuations, NLOS propagation, large numbers of scatterers, and multimobility. Only a few channel measurements have been conducted in industry IoT environments, which are mainly at the sub-6-GHz band, as in current IoT standards. However, channel measurements at mm-wave bands are also promising in industry IoT environments for future massive connections with high transmission data rates.

6G Channel Models for All Frequency Bands and All Scenarios

Large-scale channel characteristics consist of path loss and shadowing fading, while small-scale channel characteristics are caused by multipath fading. In general, channel models can be classified as deterministic and stochastic models. Deterministic channel models include the measurement-based model and ray-tracing model. The map-based model and point-cloud model are simplified ray-tracing models. Stochastic models can be further classified as the geometry-based stochastic model (GBSM), correlation-based stochastic model (CBSM), and beam domain channel model (BDCM). Deterministic channel models are suitable for link-level simulation and can achieve high accuracy at the cost of high computing complexity, while stochastic channel models have the tradeoff of acceptable accuracy, moderate complexity, and adaptable flexibility; thus, they are suitable for system-level simulation. The GBSM includes pure-GBSM and semi-GBSM. Pure-GBSM can be classified as either regular- and irregular-shaped ones. Semi-GBSM is adopted in many standardized channel models. Due to the unique channel characteristics of different types of 6G wireless channels, many large- and small-scale fading channel models have been proposed using different channel modeling methods to accurately describe the underlying channels.

6G Channel Models for All Spectra

In [3], mm-wave channel models were surveyed. Deterministic channel models include the ray-tracing, map-based, and point-cloud models. The ray-tracing model is applied to IEEE 802.11ad, while the map-based model is applied to Mobile and Wireless Communications

Enablers for the Twenty-Twenty Information Society (METIS). The quasi-deterministic (Q-D) model is used in Millimetre-Wave Evolution for Backhaul and Access (MiWEBA) and IEEE 802.11ay. The stochastic models include Saleh-Valenzuela, propagation graph, and the GBSM. The GBSM is used in several standardized channel models, such as NYU WIRELESS, 3rd Generation Partnership Project (3GPP) 38.901, METIS, and mmMAGIC. The ray-tracing model and the GBSM are also widely used in terahertz channel modeling. Meanwhile, human/vegetation blockage and rain/cloud/snow/fog attenuations also need to be modeled for the mm-wave/terahertz channel. The temporal autocorrelation function (ACF) and spatial cross-correlation function (CCF) for the terahertz channel are presented in Figure 4. As the frequency increases, the temporal ACF and spatial CCF tend to be smaller with the same time difference and antenna index difference.

For the optical wireless channel, the proposed deterministic models include the recursive model, iterative model, DUSTIN model, ceiling bounce model, and geometry-based deterministic model. The proposed stochastic models are classified as GBSMs and non-GBSMs. A detailed description of each optical wireless channel model was given in [6].

6G Channel Models for Global Coverage Scenarios

As the satellite communication channel is mainly for LOS transmission, the received signal is stable in general, except for the effects of weather conditions and tropospheric scintillation. Most current channel models are concerned about the PDF of the received signal amplitude. According to the received signal strength, the channel condition can be classified as good, moderate, and bad and can be modeled using Markov chain. Meanwhile, some preliminary works have tried to use the GBSM to model the satellite channel.

A comprehensive summary of air-to-ground large-scale path models was given in [8]. UAV small-scale channel models are defined as deterministic and stochastic. The deterministic models include ray-tracing and analytical models, such as the two-ray model. The stochastic models include the regular-shaped-GBSM, irregular-shaped-GBSM, non-GBSM, and Markov model.

Ray tracing can be used as a deterministic simulation method for the maritime channel and underwater acoustic channel. Apart from it, the two-ray model and three-ray model are also used in practice. The stochastic models include the GBSM and two-wave with diffusion power (TWDP) model. Rayleigh, Ricean, and log-normal distributions are usually used for the underwater acoustic channel.

6G Channel Models for Full Application Scenarios

For HST and V2V channels, high mobility and nonstationarity need to be considered. A summary of HST channel models was presented in [11]. Ray tracing can be used to simulate the HST/V2V channel. Stochastic channel models include the GBSM, QuaDRiGa-based model, dynamic model, Markov model, and propagation graph model. A comparison of the complementary CDF (CCDF) of the stationary intervals from HST channel measurements and models is exhibited in Figure 5 [15]. The proposed general 3D nonstationary 5G channel model in [15] is more realistic than the WINNER II channel model.

For the ultra-massive MIMO channel, the spherical wavefront, nonstationarity, and cluster appearance and disappearance properties need to be considered. In general, the spherical wavefront can be modeled in the GBSM with accurate propagation distance calculation for each individual antenna element. The nonstationarity is usually

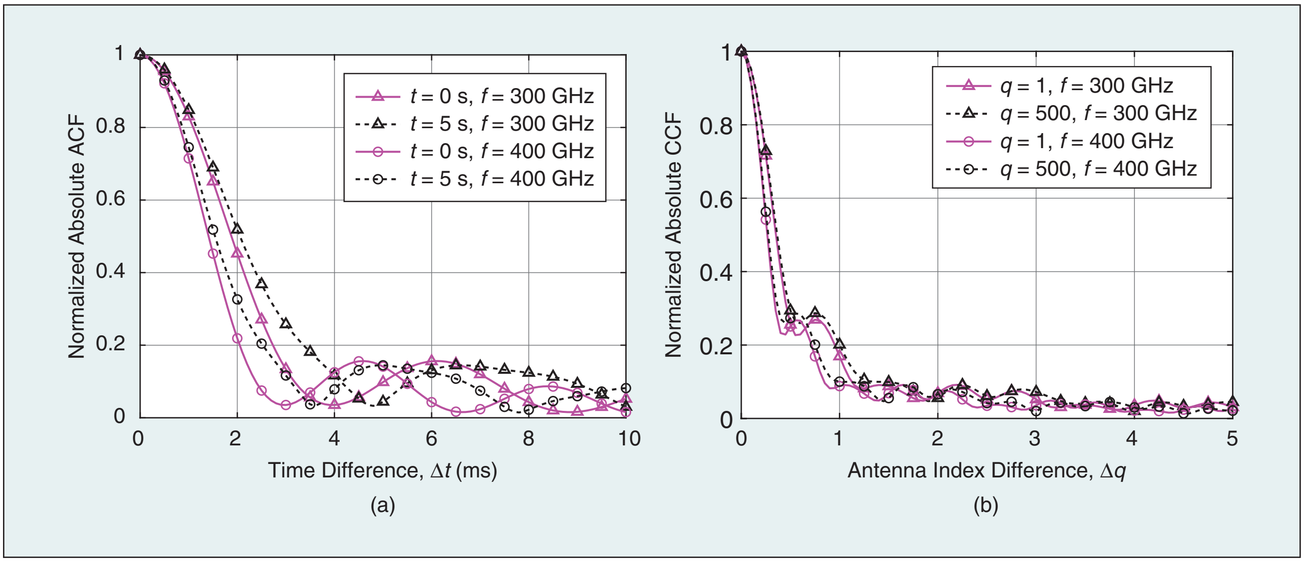

FIGURE 4 (a) The temporal ACF for the terahertz channel. (b) The spatial CCF for the terahertz channel.

modeled by the concept of visible regions and the cluster birth–death process.

For the OAM channel, current research focuses on OAM wave generation/detection, antenna design, and the discussion of OAM potentials in wireless communications. The limited OAM channel analysis results mainly aim to verify the feasibility of OAM in different scenarios. Channel modeling for OAM wave propagation is still an open issue.

In [14], different path loss channel models were compared for industry IoT channels, including the free-space path loss model, single-slope model, 3GPP models (rural macro, urban macro, urban micro, and indoor hotspot models), industry indoor model, and overall path loss model. The free-space path loss model is used as a baseline. The single-slope model uses the apparent transmit power and path loss exponent to describe the signal strength. 3GPP models use different models for the four scenarios. The industry indoor path loss model is based on extensive channel measurement results. The overall path loss model takes the LOS/NLOS condition into account to better describe the fluctuating channel status.

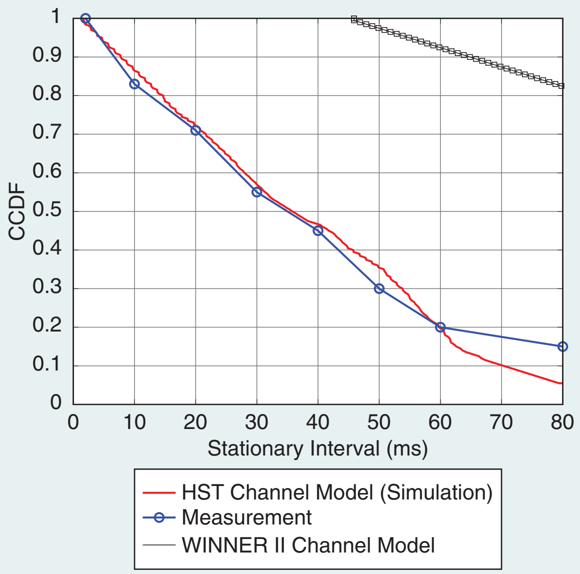

FIGURE 5 A comparison of stationary intervals from HST channel measurements and models [15].

Comparison of Channel Modeling Methods for Different Frequency Bands and Scenarios

A summary of small-scale channel models for different frequency bands and scenarios is presented in Table 2. In principle, ray tracing can be used to model most types of 6G channels. However, its application to higher terahertz and optical wireless frequency bands needs further investigation, as the material properties at these frequency bands are lacking. It is also not applicable for the satellite communication channel due to the long distance and wide area. The GBSM has the widest generality and acceptable accuracy and complexity, which can be a good basis of future 6G standard channel models by assuming different geometry shapes and adding unique channel characteristics for different frequency bands and scenarios. Other modeling approaches can also provide valuable insights for specific frequency bands and/or scenarios, such as the BDCM, which converts the underlying channel to the angle/beam domain. OAM channels and industry IoT channels need further study. Moreover, channel models for the combination of different frequency bands and scenarios, such as mm-wave/terahertz + massive MIMO + HST/V2V, mm-wave + satellite/UAV/industry IoT, and mm-wave + maritime + UAV, are challenging and need more attention in the future.

TABLE 2 ***A summary of small-scale channel models for different frequency bands and scenarios.***

Wireless Channels	*Channel Models*
mm-wave/terahertz channels	**Deterministic**: ray tracing, map-based, point cloud; **Stochastic:** GBSM and non-GBSM (Q-D, propagation graph)
Optical wireless channels	**Deterministic**: recursive model, iterative model, DUSTIN model, ceiling bounce model, geometry based deterministic model; **Stochastic**: GBSM and non-GBSM
Satellite channels	**Stochastic**: GBSM and non-GBSM (Markov model)
UAV channels	**Deterministic**: ray tracing, analytical models; **Stochastic**: GBSM and non-GBSM (Markov model)
Maritime channels	**Deterministic**: ray tracing, two-ray model, three-ray model; **Stochastic**: GBSM and non-GBSM (TWDP)
Underwater acoustic channels	**Deterministic**: ray tracing; **Stochastic**: GBSM
HST/V2V channels	**Deterministic**: ray tracing; **Stochastic**: GBSM and non-GBSM (Markov model, propagation graph model)
Ultra-massive MIMO channels	**Deterministic**: ray tracing; **Stochastic**: GBSM and non-GBSM (BDCM, CBSM)
OAM channels	Not available
Industry IoT channels	**Deterministic**: ray tracing; **Stochastic**: GBSM

Future Research Challenges

6G Channel Measurements

High-performance channel sounders are important to measure 6G channels in a fast and efficient way. The mm-wave channel sounders include vector network analyzer (VNA)-based sounders, Keysight/National Instruments/Rohde and Schwartz commercial off-the-shelf sounders, and custom-designed sounders, such as the sounders from Durham University, NYU WIRELESS, the University of Southern California, the National Institute of Standards and Technology, and so on [3]. For terahertz channels, most channel sounders are based on VNA with additional up- and downconverters to achieve different terahertz bands. Instead, a photon modulator and detector are used for optical wireless communication channels. Other equipment/conditions, such as weather stations, UAVs, boats, waterproof materials, vehicles, and large antenna arrays, are needed for specific channel measurements. Thus, 6G channel measurements are more challenging yet are indispensable and urgent, especially for high-frequency bands, high mobility, long distance, and more severe environments.

General Standard 6G Channel Model Framework

For 5G and previous generations, it is preferred that the standardized channel models use a general channel model framework with different parameter sets for different scenarios. A general 3D nonstationary 5G channel model was proposed in [15] to cover the four challenging scenarios, i.e., massive MIMO, HST, V2V, and mm-wave. All of the channel models are concentrated on only terrestrial communication networks and frequencies up to mm-wave bands. However, 6G channels exist over the space–air–ground–sea integrated networks with frequencies of up to the optical wireless bands, which makes it more challenging to derive a general channel model framework. As 6G wireless channels become heterogeneous and show different scales over the wavelengths, how to describe 6G wireless channels with a general standard channel model framework is an open issue that needs careful investigations. For example, how should we integrate the channel characteristics of radio-frequency bands (up to terahertz) and optical wireless bands, terrestrial scenarios and space–air–sea scenarios, and various 2D and 3D mobility requirements with trajectory and speed changes? How do we find the extremely complicated relationship among 6G channel characteristics, frequency bands, scenarios, and system setup parameters? How do we evaluate the performance of 6G channel models in terms of accuracy, complexity, and generality?

Channel Measurements and Models for IRS-Based 6G Technologies

IRS is a recently proposed concept beyond massive MIMO, where future human-made structures are electronically active with integrated electronics and wireless communication, making the entire environment "intelligent." IRS can be implemented with ultra-massive antenna arrays and controlled by reconfigurable processing networks with the aid of AI and machine learning (ML). As the wireless channel becomes intelligent and reconfigurable, IRS shows great potential to satisfy future demands. Channel measurements and modeling, which are open issues in current research work, are indispensable to validate IRS.

AI-Enabled Channel Measurements and Models

As the number of new frequency bands, scenarios, and antennas increases, the size of the measurement data grows rapidly and will be too huge to process with traditional data processing methods. Some preliminary works have shown the potential of AI and ML to enable wireless channel measurements and models, for example, multipath component (MPC) clustering, scenario classification, and channel prediction, by using clustering, classification, and regression algorithms. An illustration of AI-enabled channel measurements and models is depicted in Figure 6. Different ML algorithms, such as artificial neural network, convolutional neural network, and generative adversarial network, can be applied to wireless channel modeling [3], [11]. One of the benefits of applying AI and ML over traditional channel modeling methods is that they can predict wireless channel properties.

Conclusions

In this article, we presented a vision of the new paradigm shifts of 6G wireless communication networks as well as the performance metrics and application scenarios. A comprehensive survey of 6G channel measurements, characteristics, and models was given to address the trends for all frequency bands and all scenarios, including mm-wave, terahertz, and optical wireless communication channels under all spectra; satellite, UAV, maritime, and underwater acoustic communication channels under global coverage scenarios; and HST, V2V, ultra-massive MIMO, OAM, and industry IoT communication channels under full application scenarios. More channel measurements need to be conducted for emerging frequency bands and scenarios. In general, ray tracing and the GBSM can serve as the common deterministic and stochastic modeling methods, respectively, for most 6G channels by considering individual channel characteristics. The future challenges of 6G channel measurements and models were pointed out.

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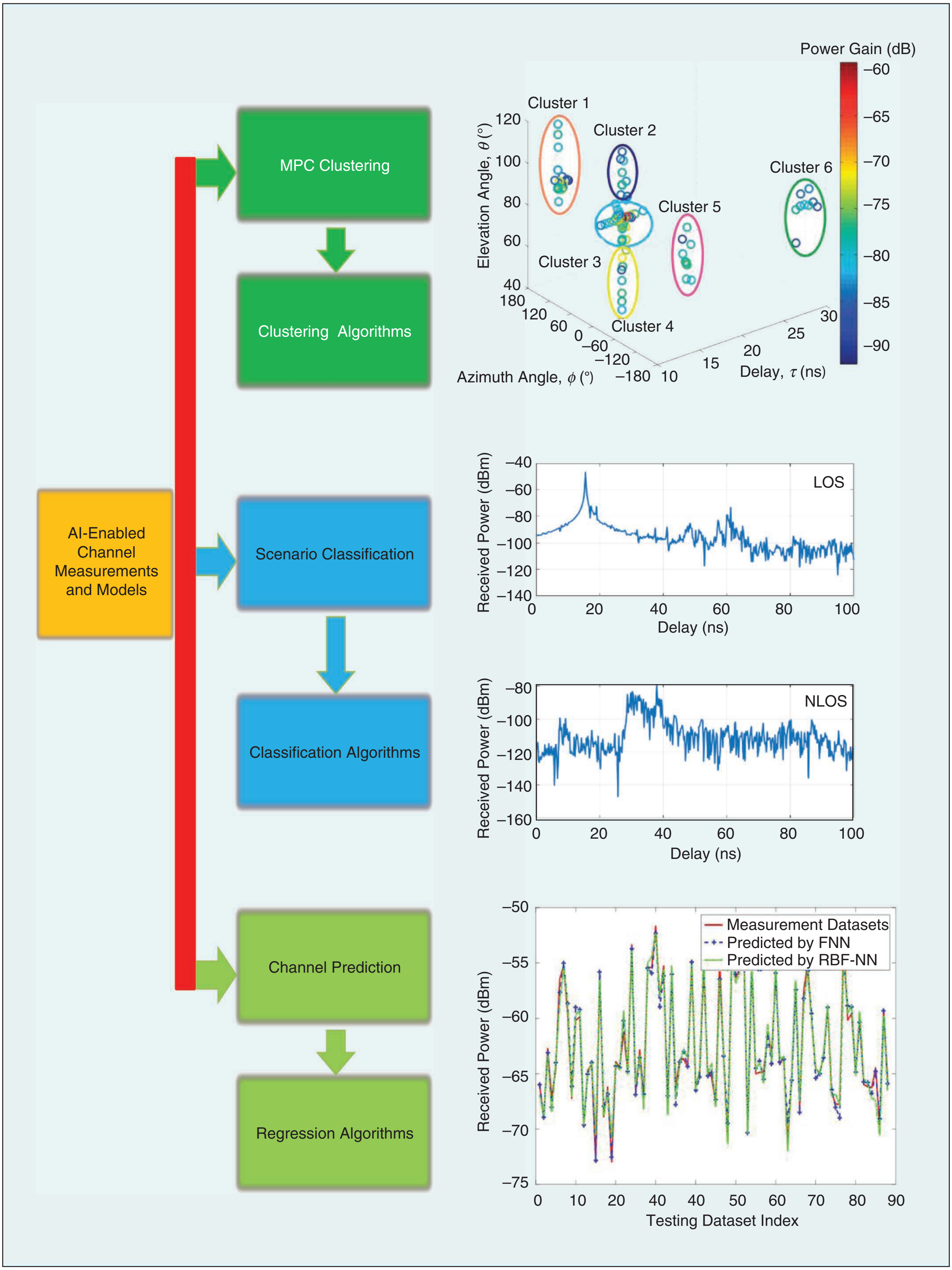

FIGURE 6 An illustration of AI-enabled channel measurements and models.

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