Channel Modeling and Characteristics for 6G Wireless Communications

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Abstract

Channel models are vital for theoretical analysis, performance evaluation, and system deployment of the communication systems between the transmitter and receivers. For six-generation (6G) wireless networks, channel modeling and characteristics analysis should combine different technologies and disciplines, such as high-mobility, multiple mobilities, the uncertainty of motion trajectory, non-stationary nature of time/frequency/space domains. In this paper, we begin with an overview of the salient characteristics in the modeling of 6G wireless channels. Then, we discuss the advancement of the channel modeling and characteristics analysis for next-generation communication systems. Finally, we outline the research challenges of channel models and characteristics in 6G wireless communications.

Index Terms

Channel model, 6G communication networks, Characteristics analysis

I. Introduction

Sixth-generation (6G) systems are envisioned to provide extremely low-latency and high data rate service for end-users in the space-air-ground-sea wireless networks over the world (see Fig. 1). There will be an ever-increasing demand for higher-capability and wider-spectrum communications of mobile technologies [1]. For the system design, performance analysis as well as algorithm development and its optimization for the 6G communication networks, it is essential to gain insight into the underlying statistical properties between transmitters and receivers in 6G wireless networks.

Channel models are the basis of system design, theoretical analysis, performance evaluation, optimization, and deployment of wireless communication systems for network planning and optimization in large- and small-scale fading propagation environments. Current literature on investigating the channel characteristics mainly focus on path loss and delay spread; however, the analysis on link-level propagation channel characteristics are still missing. In contrast to fixed-to-mobile systems, channel modeling and characteristics analysis for 6G should consider the high-mobility, multiple mobility, uncertainty of motion trajectory, non-stationarity in time/frequency/space domains, etc. This further explores the quantification of the differences among spatial-cross channels, the identity of different spatial channel models, as well as the channel characteristics under the application of artificial intelligence technology. Faced with the new characteristics of 6G wireless channels in typical frequency bands and scenes, the increasing dimension of the antenna array causes the channel to be non-stationary in the spatial domain; the increasing moving speeds of the mobile transmitter (MT) and mobile receiver (MR) results in the temporal non-stationarity of the channel; while the increasing of the system bandwidth contributes to the frequency domain non-stationarity of the

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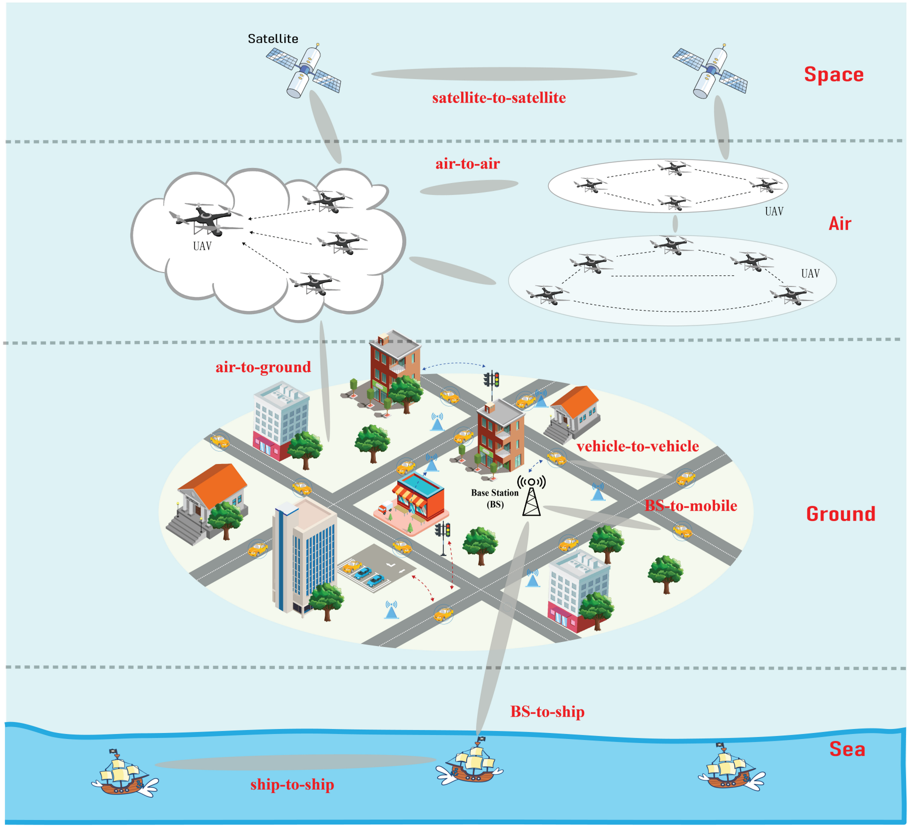


Fig. 1. 6G space-air-ground-sea integrated networks.

channel; thereby reveling the complex relationships among the non-stationary channel characteristics in space/time/frequency domains, typical frequency band (such as, mmWave, THz, and visible light communication) communication scenarios (e.g., hot spot, macrocell, and microcell), and system configuration.

Nevertheless, the researchers have paid many efforts to tackle the challenges in fifth-generation (5G) channel modeling. A. Molish *et al.* [2] highlighted the importance of accurate measurement-based channel models for describing 5G communication environments by various measurements. Channel measurements in dynamic scenarios were conducted in [3] by J. Zhang *et al.* in order to investigate the no-stationary properties of the channel in the vertical dimension, which promotes the multiple-input multiple-output (MIMO) technology from theoretical research to engineering applications. C.-X. Wang *et al.* proposed various simulation models in [4], which can be beneficial to provide efficient solutions to compare and promote different proposals for 6G communications. Besides, simulation models based on GBSMs for different communication environments can be referred to in [5]. Furthermore, R. He *et al.* [6] summarized various applications of artificial intelligence in 5G/beyond 5G (B5G) wireless communication networks, including the applications in channel measurements, channel modeling, and channel estimation, which provides a novel solution to extract the characteristics of channel data for 6G accurately. However, the research on 6G channel models is still missing.

II. Key Characteristics of 6G Channel Models

6G channel models, in general, are broadly categorized into stochastic and deterministic models, e.g., the ray-tracing method, as shown in Fig. 2. Specifically, since ray-tracing needs to reconstruct three-dimensional (3D) space (including both the azimuth and elevation angles) for searching rays, the computational complexity is relatively high, mainly suitable for specific communication scenarios. However, the statistical channel modeling, which is a widely used modeling solution, relies on numerical data analysis from a range of communication environments. In practice, the stochastic models can be groped into geometry-based stochastic models (GBSMs), correlation-based stochastic models (CBSMs), QuaDRiGa models, extended saleh-valenzuela stochastic models, and propagation graph model. Moreover, GBSMs can be divided into regular-shape GBSMs

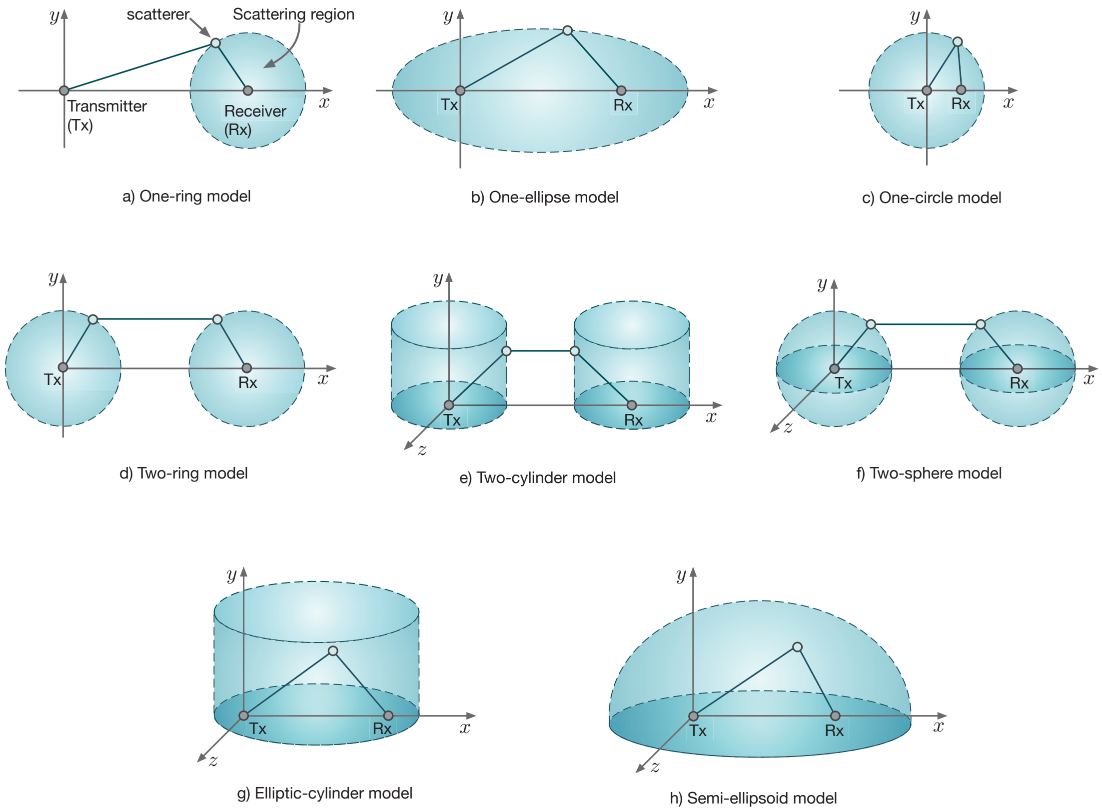


Fig. 2. Classical regular-shape geometry-based stochastic models (RS-GBSMs).

(RS-GBSMs), irregular-shaped GBSMs (IS-GBSMs), and non-geometrical stochastic models (NGSMs), where the former two are based on the scatter shape. However, the latter one, such as cluster-based channels, can be modeled by the combination of the waves emerging from the transmitter impinge on the first reflection cluster, the received waves received from the last reflection cluster, as well as the virtual link between the first and last reflection clusters [7]. Generally, the Poisson process is widely adopted to describe the distribution of the clusters, while the Gaussian distribution is used to model the azimuth and elevation angles of the propagation links.

A. 6G Communication Scenarios and GBSMs

It is generally expected that the scatterers in 6G communication environments will be randomly distributed between a transmitter and a receiver. It should be noted that the propagation path lengths and their corresponding angle of departures (AoDs) and angle of arrivals (AoAs) in different scenarios can be obtained based on the geometric relationships, which effectively reduce the complexity of investigating the propagation characteristics in 6G channels. There are several geometry-based models in the existing research work for describing the distribution of roadside interfering objects. Fig. 2 gives an example of using the one-ring, one-ellipse, and one-circle models to characterize the wireless channels in microcell-, microcell- and picocell ular scenarios. Furthermore, two-ring, two-cylinder, and two-sphere models for characterizing vehicles moving around the transmitter/receiver will play their roles in the two-dimensional (2D) plane and 3D space propagation environments. Moreover, the ellipse and elliptic-cylinder or semi-ellipsoid models are useful for describing 2D plane and 3D space communication scenarios for 6G, respectively. Due to the high complexity of investigating the statistical properties between the transmitter/receiver in 6G communication channels, it will be beneficial to integrate the RS-GBSMs in Fig. 2 to accurately describe the propagation environments of the links between the transmitter and receiver.

To this end, the authors in [8] suggested a combined two-ring and ellipse model for V2V communications to describe the distributions of the moving vehicles and scatterers, respectively. Subsequently, the authors in [9] provided a combination of two-sphere and elliptic-cylinder models for V2V channels in 3D scattering environments. The authors in [10] suggested a two-cylinder model to investigate the impact of the motion state of vehicles, e.g., moving or static, on the statistical properties of V2V channels. Recently, the authors in [5] considered a two-cylinder model to describe the road-side high buildings and a semi-ellipsoid model to describe the scattering environments in tunnel scenarios for 3D propagation channels.

B. MIMO Channel Modeling for 6G Networks

Classical Rayleigh and Rician channel models can, in principle, provide the information on power level distributions and Doppler shifts of the propagated signals from the transmitter to the receiver. Based on this speculative knowledge, spatial channel models further exploit the concepts of propagation delays, AoD, AoA, and configuration of the transmit and receive antenna arrays. By taking different trade-offs into considerations, MIMO systems can effectively improve communication performance from the perspective of reliability, spectral efficiency, and energy efficiency. The differences in the locations between the elements at both ends of the antenna array, different transmit-, and receive-antenna pairs can form different sub-channels in MIMO channels, leading to non-linear properties of the angular parameters along with the antenna arrays. Therefore, the departure angles of the waves, i.e., the azimuth angle of departure (AAoD) and the elevation angle of departure (EAoD), as well as the arrival angles, i.e., the azimuth angle of arrival (AAoA) and elevation angle of arrival (EAoA), are computed based on their geometric positions and configuration of the antenna array. Besides this, MIMO antenna arrays with high spatial resolution can distinguish the position of close receivers in 3D scattering environments. In light of this, it is required to precisely model the propagation paths and angular parameters in both horizontal and vertical components for each scattered multipath in 6G wireless channels.

C. Channel Measurements for 6G Networks

In general, channel measurement is a direct and efficient solution to study any wireless channels. Current channel sounders for 5G are limited in their performance to fully satisfy the demands of channel measurements, such as the frequency band, signal bandwidth, number of radio frequency channels, dynamic system, measurement speed, etc. As 6G channels should consider various frequency bands and high-dynamic communication scenarios, such as device-to-device (D2D), vehicle-to-vehicle (V2V), and high-speed train (HST) channels. It is essential to conduct a variety of channel measurements to consider the path loss, multi-band, shadow fading, blocking effect, multipath clustering, moving speeds/directions/time of the mobile transmitter and mobile receiver, etc. for fulfilling the requirements of future 6G channels. Meanwhile, the measured data should be processed by high-resolution channel parameter estimation algorithms.

D. 6G High-Dynamic Channel Characteristics

In general, channel modeling for 6G wireless communications should conduct high-dynamic propagation characteristics because of the high-speed motion of the transmitter and receiver, which explores the non-stationary channel characteristics in space/time/frequency domains. In general, high-dynamic channels have different non-stationary propagation characteristics for different scenarios, different frequency bands, different channels, and different moving time, speeds, and directions of the transmitter and receiver. In 6G high-dynamic communication scenarios such as highways, urban areas, suburbs, and rural areas, the high-dynamic characteristics vary depending on the scene density, traffic density, and road conditions. Based on the extracted multipath information, it is possible to analyze the 6G high-dynamic channel characteristics, including the path loss, shadow fading, power delay distribution, delay spread, angle spread, Doppler power spectrum, blocking effect, antenna effect, and time-varying non-stationary characteristics.

A 6G channel model should take into account the high-mobility, Doppler frequency (or spread), and the cross-correlation between different propagation links. In recent years, the increasing complexity of distribution of roadside objects in the mobile communication environment has driven the research community to take into account the significant number of obstacles, diffraction of electromagnetic waves around objects, and signal scattering. These complex interactions of the waves generate multipath propagation between the transmitter and receiver. Theoretically, various general channel models should be introduced by incorporating concepts that explicitly characterize the channel model parameters of high-dynamic communication scenarios.

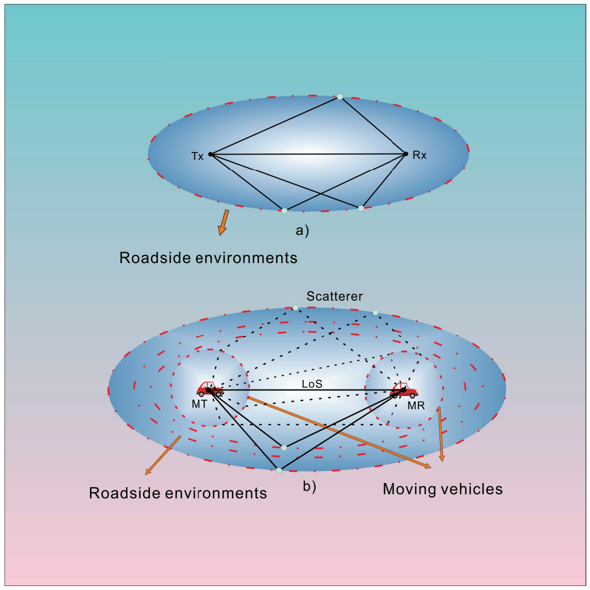


Fig. 3. 6G geometry-based channel models: a) narrowband channels; b) wideband channels.

E. Optimization of 6G Channel Characteristics

In the current research on mobile communication channel modeling theory, the complex CIRs are mainly used to derive and analyze the important transmission characteristics of 6G channels, such as the cross-correlation of propagation paths in time and frequency domains, Doppler power spectrum densities, power delay spectrum, and stationary interval. To explain, complex matrix with the elements being the complex CIRs of the propagation components between different transmit- and receive-antenna pairs is used to represent the MIMO channels. The results in [5] suggested that the computational complexity to study the statistical characteristics using the aforementioned solution is very high. However, the simulations take a significant amount of time and the accuracy is not very high with the real measurements.

Lately, since 6G channel modeling and characteristics analysis should combine different technologies and disciplines, which pose a high computational complexity of modeling approach and long simulation time compared to 5G. To solve this issue, there is an urgent need to propose effective solutions to optimize the complex CIRs, such as Euler Theorem, Unitary matrix transform. The main aim would be reducing the simulation time of investigating propagation characteristics in simulation channel models and improving the accuracy.

F. Extension of Bandwidth and Space Dimension

Results in [8] showed that in narrowband channels the waves share the similar propagation delays, which results in the scattering environments being modeled by an ellipse model with a transmitter and a receiver located at the foci of the ellipse, as illustrated in Fig. 3a. In general, the ellipse model is in principle the foundation for modeling both narrowband frequency non-selective channels and wideband frequency selective channels. Hence, the existing literatures on GBSMs mainly adopt ellipse models to describe narrowband channels, as shown in Fig. 3b.

It is proved that the propagation components between the transmitter and receiver in V2V channels for different taps with different delays lead to different statistical properties. Due the reflection of moving vehicles and roadside scatterers, 6G channels are generally composed of line-of-sight (LoS) and non-LoS (NLoS) propagation components. Therefore, it is important to study the propagation components of waves with different delay spread. As shown in Fig. 3b, multiple confocal ellipses models can be used to effectively represent the wideband frequency-selective fading channels. For each ellipse with MT and MR as the foci, the signals transmitted by the MT share the same propagation delay before arriving at the MR. Nonetheless, since the physical properties of the waves of the single-bounced rays are different from those of the double-bounced rays, the resultant CIRs in wideband channels are generally inclined to yield scatterers for different propagation delays. Therefore, it is important to study

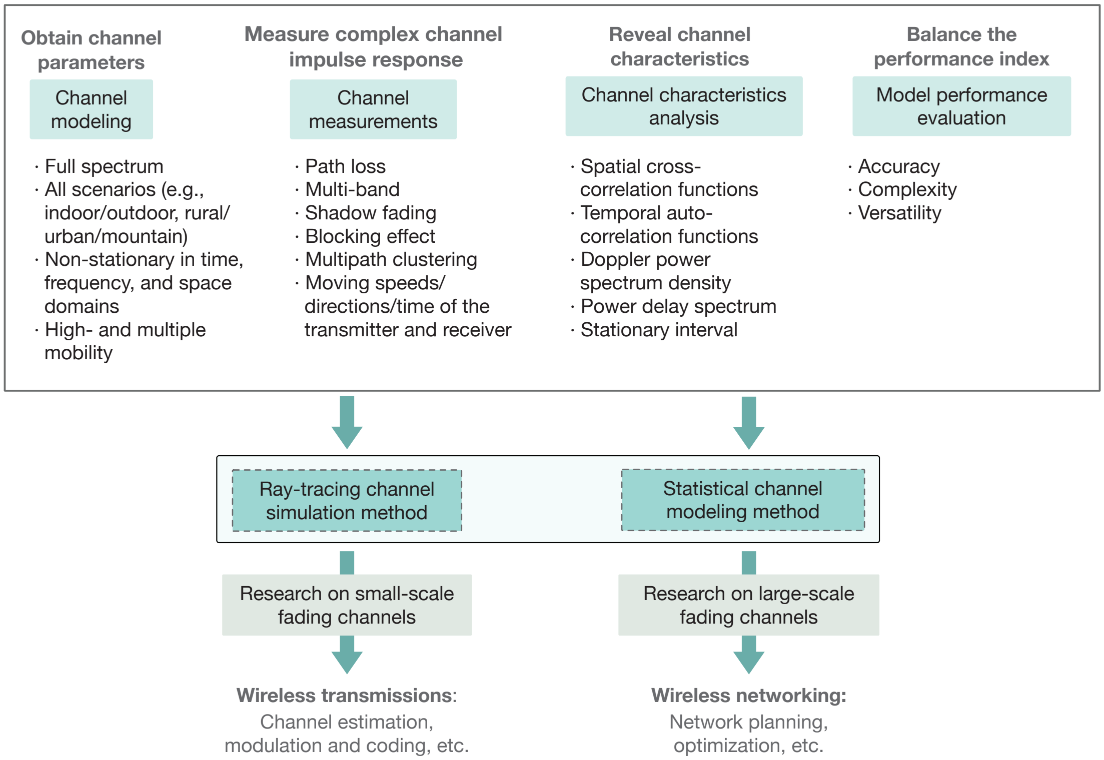


Fig. 4. Framework of the 6G channel modeling and characteristics analysis.

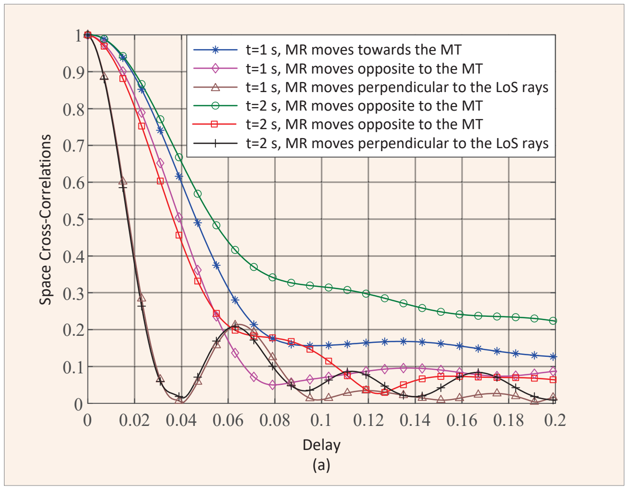
the statistical characteristics of 6G channels in support of different communication scenarios. In the early studies, the research on the narrowband single-input single-output channel modeling mainly in the time domain, which was then extended to the wideband single-input single-output for investigating the non-stationary nature in time and frequency domains. Subsequently, the literature focus on the research on the non-stationarity of the channels in the space/time/frequency domains. Lately, the ultra wideband ultra massive MIMO channel modeling from the perspective of space/time/frequency domain was discussed.

III. Current Status of 6G Channel Models

For link-level performance analysis and comparison of different communication proposals in 6G, it is vital to observe the insights of wireless channels' statistical properties between the transmitters and receivers. Thus, it is important to propose different modeling methods for accurately describing the 6G channels and conduct channel measurements for extracting model parameters. Moreover, optimization solutions for investigating channel characteristics are worthwhile to investigate. Fig. 4 illustrates a broad overview of the 6G channel modeling and the analysis of the characteristics. In the following, we discuss the recent progress in the channel models for 6G wireless communication systems.

A. Time and Space Non-Stationarities

Since a variety of advanced technologies will be comprehensively used in 6G networks, these channel models will pose unique characteristics and specific inner- and outer-correlations. Most of the standard 5G channel models, i.e., WINNER II, WINNER+, and IMT-A channel models, mainly adopt the wide-sense stationary uncorrelated scattering (WSSUS) assumption. Specifically, these models introduced the time-evolution of the clusters to mimic the non-stationary nature of channels for extremely short intervals, considering the time variation of real communication scenarios [11]. Therefore, the assumption, as mentioned earlier, will not always hold in the 6G high-mobility wireless channels. Note that the goal of 6G channel modeling is to improve the matching accuracy of wireless channels with the real communication scenarios, where the non-stationarity of the channels should be considered from the time/space/frequency domains.



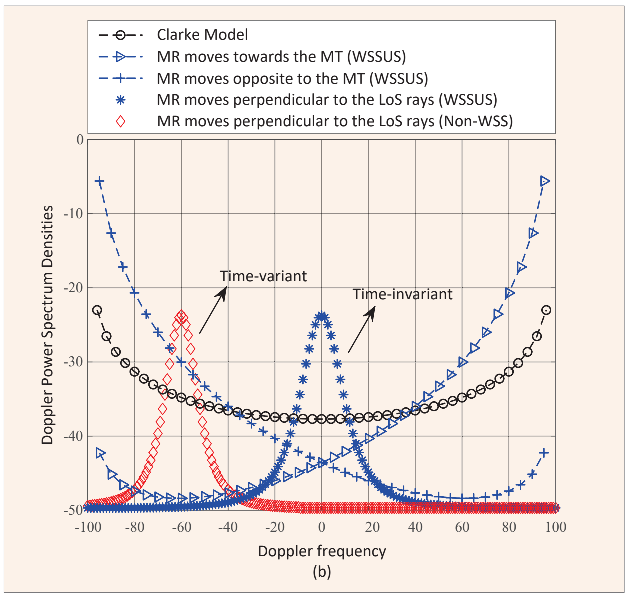


Fig. 5. Simulation results: a) Space correlation functions of NLoS and LoS rays parameterized by the moving time and directions of the MT and MR; b) Doppler power spectrum densities for WSSUS and non-WSS channels parameterized by the moving directions of the MT and MR.

For example, in 6G V2V channels, the mobile transmitter and receiver's high-speed mobilities lead to non-stationary characteristics in the space, time, and frequency domains. For air-to-ground communications in UAV environment, the channel characteristics are however affected by the multi-mobility (e.g., UAV transmitter, ground receiver, and moving clusters), the uncertainty of 3D moving trajectory (large elevation angle), non-stationary nature in the time domain, differences between air-to-ground and air-to-air channels, and large shadow fading [12]. Therefore, it is essential to study the new characteristics of 6G wireless channels in typical frequency bands, which will have important theoretical significance and application value for analyzing 6G high-dynamic mobile communication systems. As shown in Fig. 5, the space cross-correlations, which characterize the time and space non-stationary nature of wireless channels, have different behavior as the moving time of the MT and MR increase from 1 s to 2 s; meanwhile, when the moving directions of the MT/MR vary, the space cross-correlations have different statistics. Furthermore, Fig. 5b shows that the Doppler power spectrum densities of non-WSS channels vary over time, thereby having some differences with the time-invariant properties of the Doppler spectrum in WSSUS channels.

B. Massive MIMO Channel Modeling

In fixed-to-mobile propagation scenarios, the departure and arrival directions of the signals result in slight phase variations. In this case, the salient characteristics related to the transmit antenna array are similar to those to the receive antenna array, which can result in the point source assumption in the transmitter and receiver. Nonetheless, when we aim to apply MIMO technology in wireless channels to improve the system performance, each antenna has a different perspective according to its configuration of the transmit and receive antenna arrays. In recent years, an enhanced multi-antenna technology equipped with hundreds of antennas, termed a large-scale antenna, has been widely studied to meet the considerable traffic and connections requirements in 6G networks. However, the measurements in [13] have shown that the far-filed assumption (also named plane wavefront assumption) is valid only when the propagation distances are larger than the Rayleigh distance $2M^2/\lambda$, where λ is the wavelength and M is the size of the array. Therefore, the signal wavefront emitted from the transmit-receive antenna array to the clusters is assumed to obey the spherical assumption, which leads to different angular parameters (i.e., AoAs and AoDs) and phase shifts for different antenna elements in the same array [7]. Furthermore, because of the large-scale properties of the antenna array in massive MIMO channels, the clusters are no longer stationary on the array axis. In other words, a cluster is observable to the part of transmitting or receiving elements of an antenna array. In light of this, it is essential to adopt the birth-death process to describe the non-stationary properties of the massive MIMO channel caused by clusters in both spatial and temporal domains.

C. High-Dynamic Channel Modeling and Characteristics

A standard 6G channel model needs to consider the high-dynamic scenarios, such as HST, D2D, V2V, and unmanned aerial vehicle (UAV) communications. For such scenarios, it is important to study the non-stationary nature in the time domain, large Doppler spread, and severe fading. Simultaneously, multi-mobility (e.g., moving transmitter, moving receiver, and moving scatterers), spatial consistency, and multi-link correlation should also be considered. However, since the mobility of moving transmitters (e.g., UAV transmitter) is high and the moving trajectories are relatively arbitrary, it is required to use the channel models in the 3D scattering environments, exploiting both the horizontal and vertical angles to describe the air-to-ground and air-to-air communications in a UAV environment. In general, UAV channels should consider the high mobility, 3D random trajectory, i.e., large elevation angles, time non-stationary, and the difference between the air-to-ground and air-to-air channels.

D. Artificial Intelligence-assisted Channel Modeling and Characteristics

Given the recent developments in artificial intelligence-assisted communications for 6G, it is essential to introduce machine learning and deep learning technologies into wireless channels. This has a potential of near-real-time data-optimization of reducing the parameter dimension of 6G mobile channels for partly predicting wireless channel properties for unknown scenarios, unknown frequency bands, and time instant [14]. In particular, it is possible to extract useful multipath information based on big data, artificial intelligence, machine learning as we begin to observe the channel. Afterward, the real-time channel propagation characteristics can be predicted according to the initial time channel information and the moving states of the mobile transmitter and receiver. Nevertheless, this direction requires substantial further research.

IV. Challenges for 6G Channel Modeling and Characteristics Analysis

Compared to the channel modeling and characteristics analysis for 5G, 6G channels will consider various frequency band and communication scenarios. As shown in Fig. 6, the development of the channel model in 6G largely depends on the global coverage, all spectrum, several emerging applications, and network security. In the following, we outline a comprehensive summary of open research problems for the channel modeling and characteristics analysis for 6G communications.

A. A General 6G Channel Model for Global Coverage Scenarios

Since 6G wireless communications are expected to cover low-earth-orbit (LEO) satellite communications, UAV communications, V2V communications, underwear acoustic communications, it is essential to derive a general 6G channel model for

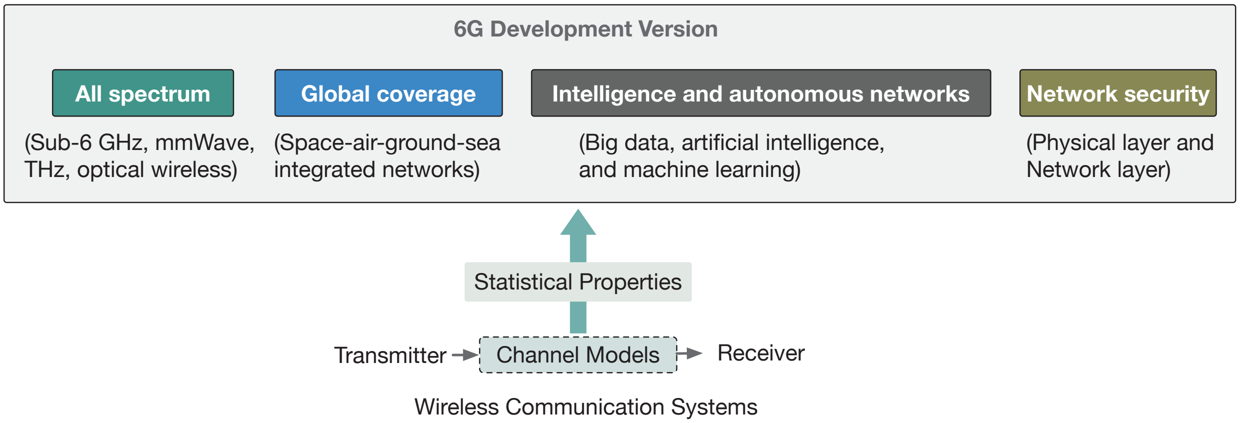


Fig. 6. Development version for 6G wireless communications.

describing a so-called *space-air-ground-sea* integrated network by adequately adjusting the model parameters. 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. Specifically, by setting the number of the configuration of the transmit and receive antenna arrays or distances properly so that the Rayleigh distance is fulfilled, the general channel model can be deduced to a conventional MIMO channel model. Furthermore, the high-mobility and time evolution of the general channel model can be removed by setting the time-variant model parameters as time-invariant ones, which results in the fixed-to-fixed channel models. Besides that, the MIMO channel model can reduce to conventional multiple-input single-output (MISO) and single-input single-output (SISO) channels by setting the transmit/receive antennas number. Overall, due to the heterogeneous characteristics of 6G wireless channels and the different scales of radio waves, it is an open problem to model 6G general channel models.

In general, the statistical properties of 6G channels are significantly affected by both roadside scatterers in the 3D space [10]. Therefore, the cluster level angular parameters (AoD and AoA) should be jointly modeled by von Mise distribution. Furthermore, the cluster evolution on the time axis and array axis should be modeled separately. In general, when we aim at investigating the time/frequency/space domain non-stationary nature of 6G channels, it is of importance to take into account the real-time velocity and trajectory variation of the transmitter, receiver, and clusters, which result in relatively large Doppler spread; meanwhile, the path loss and shadow fading in 6G channels should be considered.

B. Channel Models for Intelligent Refection Surface

Intelligent reflecting surface, generally composed of a large amount of cost-effective near-passive elements that can manipulate the incident signals with an adjustable phase and amplitude shifts, is regarded as a key and emerging technology in 6G networks. To take advantage of intelligent reconfigurable reflecting surface-assisted wireless communication systems for 6G, it is critical to model intelligent reflecting surface-assisted channels in wireless scenarios. However, the investigation of the channel characteristics to validate and evaluate the performance of intelligent reflecting surface systems remains open.

C. Network Security for 6G Wireless Networks

The implementation complexity of 6G *intelligent* communication systems will lead to specific vulnerabilities in wireless communication systems and frameworks. Denial-of-service attacks on deep learning applications, control-flow hijacking, classification escape, and data pollution attacks [15] are some of them. In this context, it is of importance to consider the strong security in 6G networks. In general, robust network security for 6G communications, also known as endogenous network security, including the physical layer security and network layer security. It is still an open issue to design a secure 6G wireless channel models leveraging state-of-the-art security solutions.

D. Performance Evaluation of 6G Communication Systems

The performance evaluation of channel models can be measured in terms of accuracy, complexity, and versatility. Specifically, the accuracy can be judged by comparing the statistical properties of channel models with real measurements. The complexity can be measured by the number of model parameters, the amount of calculation, and simulation time. Moreover, the versatility mainly considers whether the model framework can accurately tracking the propagation characteristics of the communication channels for different frequency bands and different communication scenarios. In general, a standard channel model should bring a balance among accuracy, complexity, and versatility.

V. Conclusions

In this paper, we present an overview of the channel modeling and characteristics analysis for the coming 6G communication systems. The underlying development trend of channel models has been discussed, including the geometry-based stochastic models, high-dynamic channel characteristics, optimization of channel characteristics, and the extension of bandwidth and space dimension. Afterward, we have presented the current status in 6G channel models and characteristics. Finally, we discuss the research challenges of channel modeling and characteristics analysis for 6G. The research on 6G channel modeling is in its infancy, and a substantial research effort has to be carried out for the design of future communication systems.

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