Recent Developments and Future Challenges in Channel Measurements and Models for 5G and Beyond High-Speed Train Communication Systems

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The authors review the HST channel measurements conducted in different scenarios and frequency bands, and the advanced HST channel models. They present a novel HST channel model incorporating the mmWave and massive MIMO propagation characteristics, and its frequency non-stationarity is analyzed. Finally, future directions are discussed.

Abstract

The fast developments of high-speed train (HST) and growing communication demands of users pose new challenges for HST communication systems. To provide reliable communication services, key 5G communication technologies, such as millimeter-wave (mmWave) and massive multiple-input multiple-output (MIMO), and potential architectures, such as coordinated multipoint and mobile relay station, are considered in future railway communications. New technologies and architectures will bring new channel propagation characteristics. Accurate channel models that can capture these channel characteristics play a critical role in the design and test of future railway communication systems. This article reviews the HST channel measurements conducted in different scenarios and frequency bands, and the advanced HST channel models. Then a novel HST channel model incorporating the mmWave and massive MIMO propagation characteristics is presented, and its frequency non-stationarity is analyzed. Finally, some future directions are discussed.

Introduction

High-speed trains (HSTs), as a fast, convenient, environmental friendly, and flexible means of transportation, has received widespread attention in recent years. More and more passengers tend to travel on HSTs, which brings a heavy burden on current railway communication systems with increasing communication requirements. The existing Global System for Mobile Communication Railway (GSM-R) is primarily used for communications-based train control rather than providing personal communication service. Some access technologies, such as Long Term Evolution for Railway (LTE-R), WiMax, and IEEE 802.20, are recommended to provide broadband communication services [1]. Those technologies can support megabits-per-second order data transmission, but still do not meet the expected gigabits-per-second order throughput for future HST communication systems. The fifth generation communication system for railway (5G-R) will probably provide high data rate transmissions for railway-specific network and passenger communications. In addition, contemporary HSTs are going through unprecedented developments, and the maximum moving speed record has been constantly refreshed. In the document International Telecommunication Union — Radiocommunication Standardization Sector (ITU-R) M.2083-0, HSTs are desired to move at more than 500 km/h speeds. The French National Rail Cooperation enables up to 575 km/h high mobility, Japan's HST speeds can reach 603 km/h, and China's CIT500 HST achieves its maximum speed of 605 km/h [1]. The increase in speed will raise some new challenges (i.e., frequent and fast handover, large Doppler spread, etc.) toward the existing rail communication systems.

To overcome these problems and provide seamless connectivity for 5G and beyond HST communication systems, potential technologies, such as massive multiple-input multiple-output (MIMO), millimeter-wave (mmWave), and beamforming, are considered to support reliable HST broadband communication services [2]. Moreover, potential architectures, such as mobile relay station (MRS), distributed antenna system (DAS), and coordinated multipoint (CoMP), are involved to improve the link performance [3]. In order to mitigate the penetration losses of propagation signals from outdoor base stations (BSs) to inside train users, the MRSs deployed on the train surface are considered to provide multihop coverage and improve signal quality. Massive MIMO is adopted to improve the performance of data transmission and system capacity at transmitter (Tx) and receiver (Rx) [4]. The antenna array gains can be achieved from diversity and beamforming. The correlation coefficient of massive MIMO is large, which will in reverse degrade its performance. In this case, the impacts of spatial-temporal correlation and intercarrier interference caused by high mobility of trains should be overcome to eliminate the multiple antenna gain loss [4]. Moreover, distributed MRS antennas with appropriate spacing can also be deployed on top of a train to mitigate the beamforming effect. MmWave with

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large bandwidth can provide high data transmission rate for the outdoor link between the MRS and BS. In [1], the 5GCHAMPION project aims to enable the 5G mmWave technologies at 24–28 GHz to provide a broadband connection with high mobility. The Electronics and Technology Research Institute (ETRI) presented a mobile hotspot network working at 24–30 GHz mmWave band. It is expected to support gigabit-per-second transmission rate over moving speed up to 400 km/h. In the Third Generation Partnership Project's (3GPP's) evaluation, the Macro+Relay HST architecture was included, and the mmWave band around 30 GHz was permitted to provide high data rate transmission. All these potential technologies will introduce new channel characteristics and features for future railway communication channels.

Some channel measurement campaigns and channel modeling in HST scenarios have been carried out to study the potential physical phenomenon of wireless channels. In [1], the channel measurements at 64.5 GHz for regional train environments were presented. Then the path loss (PL) and root mean square (RMS) delay spread were investigated. Moreover, the mmWave channel measurements at 31.625 GHz for HST tunnels were carried out, and some related channel characteristics, such as power delay profile (PDP) and channel impulse response (CIR), were given. In [5], the channel measurements at 93.2 GHz were carried out with 2 GHz bandwidth, and several channel characteristics, such as PL and amplitude statistics, were analyzed. Beyond that, some theoretical HST channel models have been discussed. In [6], the QuaDRiGa-based mmWave HST channel model was given. Then the CIR of the proposed model and related cumulative distribution functions of delay and angular spreads were studied. In [1], a ray tracing channel model for an mmWave HST scenario was presented. Based on the simulations, the channel characteristics including PL, Doppler shift, and coherence time were analyzed. Furthermore, many efforts have also been devoted to standard channel modeling. In the rural scenario of WINNER II, as well as the moving network of IMT-A channel models, the corresponding channel non-stationarities were analyzed by deploying MRSs. Considering that the stationary intervals are larger than realistic measured ones, both models cannot describe real HST channels effectively. Besides, some 5G standard channel models, such as COST2100, QuaDRiGa, 3GPP, 5GCM, and mmMAGIC, can also support high-mobility scenarios. However, COST2100 cannot support multiple antennas and high-frequency communications. The QuaDRiGa model can support massive MIMO, but does not include mmWave band. The 3GPP channel model considered the rural scenario of HST but ignored the other HST scenarios. The mmMAGIC channel model just mentioned high-mobility scenarios but gave no detailed information [7]. Although some research works have been conducted, accurate HST channel models that can describe the real propagation characteristics of HST wireless channels precisely are still missing. Therefore, having a complete understanding of HST channels and proposing accurate models are essential to the developments of future railway communications.

The remainder of this article is structured as follows. The current HST channel measurements are reviewed in detail. The requirements for future HST channel models are outlined, and some recent HST channel models are summarized. Future research directions are discussed. Finally, conclusions are given.

Channel Measurements for Future HST Wireless Communication Systems

Channel measurement data are regarded as credible data sources to reflect realistic channel information. Based on the measurement data, channel parameters can be extracted, and then channel models can be established. For instance, the fourth generation (4G) channel models for sub-6 GHz frequency bands are created from extensive channel measurements [8]. To better design and evaluate the future 5G and beyond HST communication systems, the channel measurements data obtained from advanced channel sounding systems are crucial. The existing channel measurements for HST scenarios are mainly at lower frequency bands, and only a few are at mmWave bands. Furthermore, due to the particularity of HST scenarios, HST channel measurements are still challenging.

Future HST Cellular Architecture and Propagation Scenarios

The future railway communication system should realize smart, green, and integrated transport and provide continuous reliable communication services, including onboard and wayside high definition video surveillance, onboard real-time high speed data transmission, and the Internet of things for railways [9]. To acquire sufficient bandwidth and channel capacity, some potential technologies, such as mmWave and massive MIMO, can be adopted in the future railway outdoor communication systems. In 3GPP evaluation [1], the mmWave HST scenario was proposed. It consists of a three-tied network architecture. The first tie network is a BS unit connected to a 5G and beyond network, the second one is the remote radio heads connected to the BS, and the third one is the MRS fixed on the roof of a train with intra-wagon users. For intra-wagon communications, some promising indoor communication technologies, such as mmWave, terahertz (THz), and massive MIMO using beamforming can be considered. Massive MIMO will be applied to provide high gains to overcome high PL of mmWave and THz communications. Moreover, CoMPs can also be employed in the combined cell to acquire diversity gain and improve transmission efficiency in an HST communication system [3]. In the combined network, two or more BSs can connect with each other to form a coordinated cell to exchange data. The network architecture for a future railway communication system is illustrated in Fig. 1 by considering one or more key technologies. Different technologies will introduce different channel characteristics.

Furthermore, different wireless propagation environments will bring different multipath effects. Therefore, different propagation scenarios should

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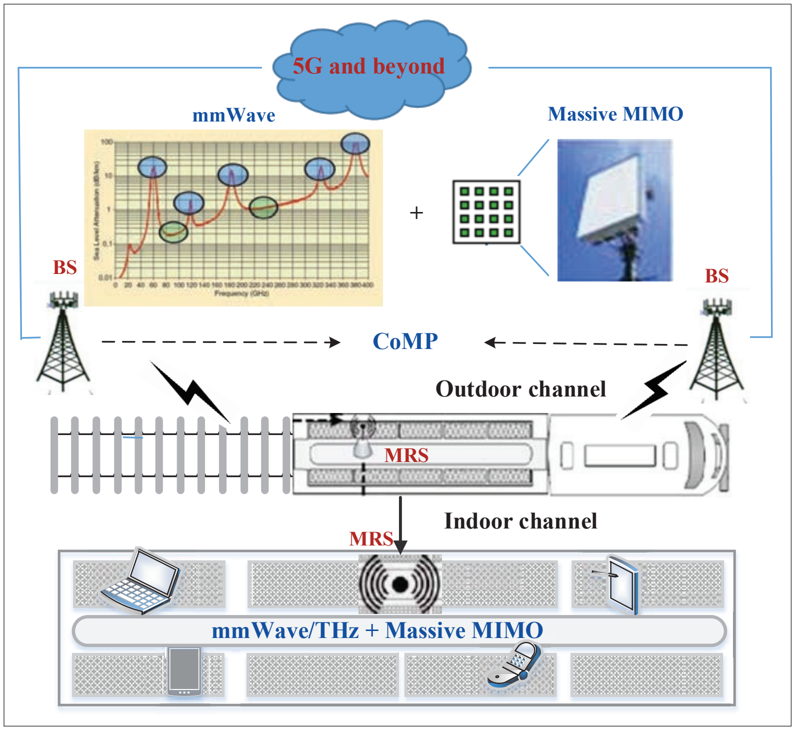

Figure 1. Network architecture for future railway communications.

be defined and distinguished. Trains may experience more than one scenario when traveling. These scenarios can be roughly divided into six categories, including open space, hilly terrain, viaduct, tunnels, cutting, and stations. Moreover, from the point of wireless propagation, the communication scenarios are defined as five categories, that is, train-to-infrastructure, intra-train, inter-train, inside the train station, and infrastructure-to-infrastructure. Based on the aforementioned scenarios, some measurement campaigns for HST communications have been conducted.

Measurement Setup and Parameters

Before conducting channel measurements, the positions of predefined Tx and Rx antennas at different heights should be selected to mimic the BS and mobile station in different environments. In [3], channel measurements at sub-6 GHz frequency bands for three HST scenarios were introduced by applying both active and passive sounding methods. Propsound, an active channel sounder, was employed to conduct the viaduct and cutting scenarios measurements. It adopted the vertical dipole antenna at Tx and a special HUBER+SUHNER antenna at Rx. Moreover, a passive LTE sounder was used to conduct measurements in the station scenario. It deployed a directional antenna at Tx and the HUBER+SUHNER antenna at Rx. In [10], a wideband channel sounder was used to develop HST channel measurements at sub-6 GHz frequency bands. The Tx equipped with a directional antenna was deployed on the BS, and the Rx equipped with a vertical polarized omnidirectional antenna was fixed on the train window.

MmWave band channel sounding is more practical for the development of future railway communications by comparing with sub-6 GHz frequency bands. Due to the directionality and attenuation of mmWave, channel measurements for mmWave HST scenarios are more challenging [8]. Several mmWave channel sounders were introduced in [8]. The existing mmWave channel sounders are usually limited by rotating the high-gain horn antenna; therefore, they cannot be used to capture the dynamic channel characteristics. MmWave channel sounders adopting the stepped frequency system need a relatively long time to record, which is beyond the coherence time of mmWave non-stationary channels. Moreover, limited by the phase synchronization at Tx and Rx, the existing mmWave channel sounders cannot extend range and mobility. Therefore, currently few mmWave channel sounders can be used to measure the non-stationary mmWave channel. Through deploying the electronically switched 16-element Rx array, the first mmWave sounder was proposed [8]. It can conduct mobile measurements at a speed up to 100 km/h. Some channel measurements have been summarized at both sub-6 GHz and mmWave bands for mobility scenarios, as listed in Table 1. However, how to conduct mmWave massive MIMO channel measurements for HST scenarios is still a challenging task. Moreover, more intra-wagon channel measurements for HSTs are also needed.

Channel Models for Future HST Wireless Communication Systems

Channel models are reflections of the real radio propagation channels, which can be classified as deterministic and stochastic ones. For a deterministic model, all parameters are fixed. In a site-specific environment, the channel measurements can be conducted using a channel sounder to obtain the CIRs in the time domain and the channel transfer function (CTF) in the frequency domain. Once the measurement data is stored, it is deterministic. Moreover, based on the geometrical optics (GO) theory and uniform theory of diffraction (UTD), precise channel models for specific environments can be obtained by ray tracing methods, which can simulate signal propagation by tracing each ray. For the stochastic model, it adopts a stochastic manner to mimic the propagation environment with the presence of at least one random parameter. Accurate channel models can greatly help to reveal the mechanisms of complex radio wave propagation, which can also be used for the system design and network evaluation of future railway communications.

The cellular architectures, such as DAS, CoMP, and MRS, need to be considered in future railway communication systems. Furthermore, the promising 5G technologies, such as mmWave and massive MIMO, should also be introduced. With adopting one or more solutions, some HST channel models have been established, which include large-scale fading and small-scale fading models. Herein, we mainly focus on the latter. According to the modeling methods, frequency bands, and channel statistics, the advances in HST channel models are summarized in Table 2. Moreover, the characteristics of intra-wagon channels resemble those of indoor scenarios, and thus can be modeled using

Ref.	Cellular architecture	Scenario	Carrier frequency	Bandwidth	Train speed	Channel statistics
[1]	MRS	Tunnel	31.625 GHz	250 MHz	400 km/h	PDP, CIR
[3]	MRS	Viaduct, cutting, station	2.35 GHz, 2.35 GHz, 1.89 GHz	50 MHz, 50 MHz, 18 MHz	198 km/h, 198 km/h, 285 km/h	Power angular spectrum, RMS angular spread, spatial correlation
[5]	MRS	RMa	93.2 GHz	2 GHz	500 km/h	PL, amplitude statistics
[6]	MRS	RMa	28 GHz	933 MHz	6.3 km/h	Averaged PDP, K-factor, delay spread, angular spread
[10]	MRS	RMa	2.4 GHz	40 MHz	300 km/h	Distance-based ACF, power gain, RMS delay spread
[11]	MRS	RMa	2–3 GHz	25 MHz	300 km/h	CIR, shadowing fading, delay spread, Doppler spread

Table 1. Recent developments of HST channel measurements.

Ref.	Channel model	Deterministic/stochastic	Frequency band	Train speed	Channel statistics
[1]	Ray tracing model	Deterministic	mmWave	300 km/h	Doppler shift, coherence time
[5]	GBSM	Stochastic	mmWave	500 km/h	PDP, K-factor, RMS delay spread, angular spread
[6]	QuaDRiGa-based channel model	Stochastic	mmWave	500 km/h	CIR, SNR, RMS delay spread, angular spread
[10]	Dynamic channel model	Stochastic	Sub-6 GHz	300 km/h	Power gain, RMS delay spread
[12]	FSMC	Stochastic	Sub-6 GHz	350 km/h	Correlation coefficient, state transition probabilities
[13]	Propagation graph model	Stochastic	Sub-6 GHz	198 km/h	PDP, Doppler PSD, RMS delay spread, Doppler spread

Table 2. Recent developments of HST channel models.

some existing mmWave and THz indoor channel models. Due to the relatively limited space of HST indoor scenarios, ray tracing channel models can be considered.

Modeling Approaches

Ray Tracing Channel Model: The ray tracing channel model can provide a precise characterization of a propagation channel. Based on the GO theory and UTD, the multipaths from the direct, reflection, refraction, and diffraction can be obtained. Each path is tracked by one ray, which contains the amplitude, delay, and angle information. The received signal is the summation of all rays. The accuracy of a ray tracing model highly relies on detailed descriptions of HST environments, including different scenarios, structures of objects, and electromagnetic parameters. In [8], 3D mmWave ray tracing models were provided for HST outdoor and tunnel scenarios. Moreover, the materials that can influence the propagations were determined. In [1], ray tracing channel models were proposed for different HST scenarios, and some channel characteristics including the power contributions of multipath, reflection order, PL, and breakpoint were analyzed. Furthermore, some key parameters in typical scenarios, such as Doppler shift, coherence time, and polarization ratios, were also investigated.

Due to the limitations of measurement equipment, traveling scenarios, and permission issues, HST channel measurements at mmWave frequency bands encounter great challenges. It is a tendency to explore the future HST channel characteristics by combining the limited mmWave measurement results with extensive ray tracing simulations.

GBSM: The geometry-based stochastic channel models (GBSMs) can be divided into regular-shaped (RS) GBSM and irregular-shaped (IS) GBSM. The CIRs can be achieved based on the geometric relationships. The GBSM has been extensively applied to HST channel modeling. In [14], a two-dimensional HST ellipse model was proposed. Then some channel characteristics were derived. This model just considered the sub-6 GHz frequency band, and cannot be used to mimic the mmWave band channel. Moreover, some standard channel models belonging to IS-GBSM are provided for HST scenarios. In [6], a QuaDRiGa-based channel model was proposed. It can support the mmWave band. In [5], a 3D GBSM for 3GPP mmWave HST scenarios was presented. By incorporating the time-variant line of sight (LoS), reflected multipath, and scattering multipath, the non-stationarity of mobile channels can be captured by the model mentioned above.

FSMC: The finite-state Markov model (FSMC) adopting the first-order Markov chain has been applied to describe the fading channels. But it is not available in HST scenarios due to the rapidly time-varying features. In [12], a novel HST FSMC channel model was provided. It has the ability to capture the variation of HST channels and track the time-varying process. In the proposed model, the influence of train speed on temporal charac-

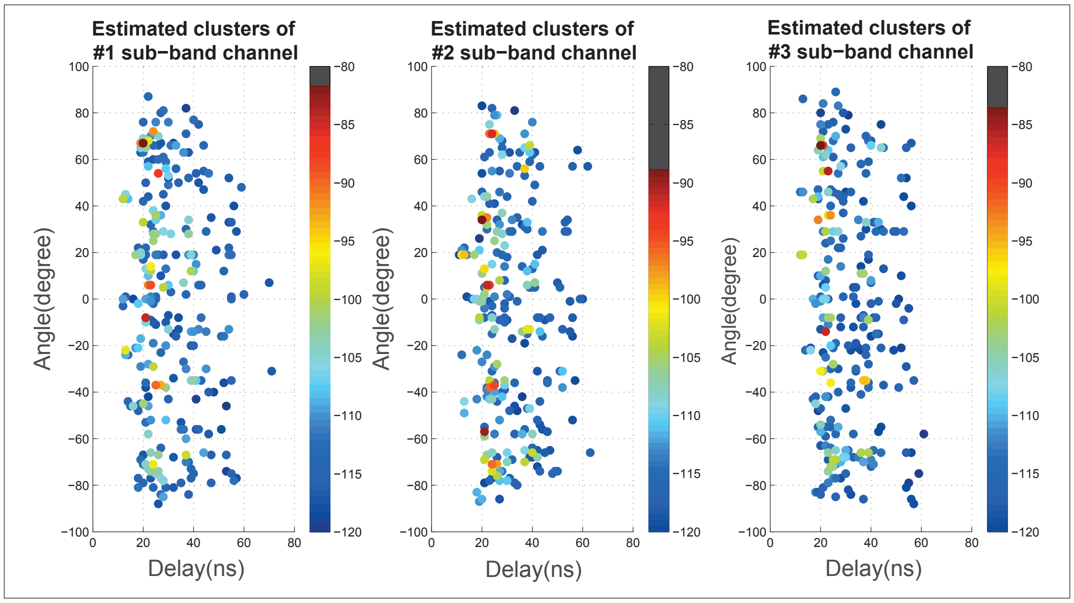

Figure 2. The measured power angular spectrum at different sub-bands.

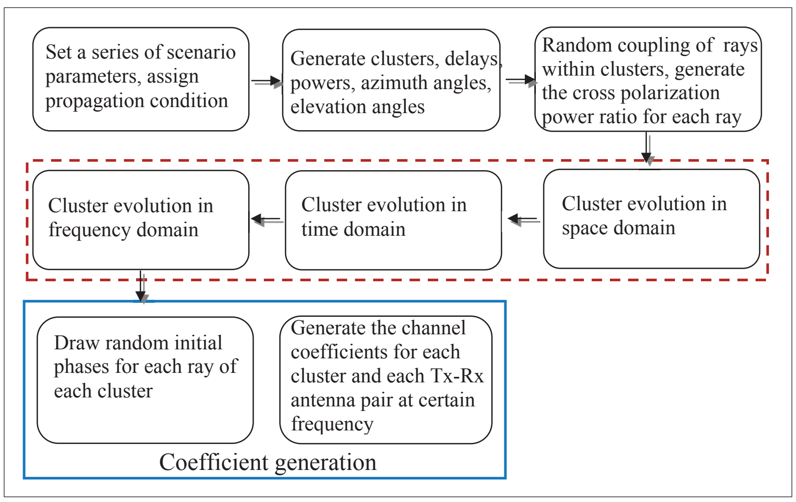

Figure 3. The modeling process of the novel HST channel model.

teristics was introduced. Moreover, the channel states were defined using the signal-to-noise ratios (SNRs). The FSMC model is mathematically tractable and can provide an accurate description of time-varying channel statistics in HST scenarios. To guarantee the accuracy of the model, high order Markov chains are needed to model the fast time-varying channels [12].

Propagation Graph Model: Based on graph theory, the propagation graph model can be established using a series of vertices and edges. The vertices stand for the Tx, Rx, and scatterers, while edges stand for the propagation conditions between the vertices. In [13], a propagation graph model for the HST cutting scenario was presented, which consists of LoS, single bounced, and double bounced components. The channel characteristics were further studied and better validated by measurements. It is easy to use this kind of model to show the propagation characteristics in the frequency domain rather than in the time domain. Therefore, the propagation graph model can be used for mmWave HST channel modeling.

HST Channel Statistics

From Tables 1 and 2, most channel statistics were investigated at sub-6 GHz frequency bands. Moreover, some important second-order channel statistical properties were also provided. A non-stationary GBSM was proposed by considering all the parameters time-variant [14]. Then the time-variant space cross-correlation function (CCF), autocorrelation function (ACF), space-Doppler power spectrum density (PSD), and local scattering functions (LSFs) were derived. The ACFs are used to measure the time correlation of the channel. Using the ACF, the coherence time can be acquired, which denotes the smallest positive value of time difference that the values of ACF fall to a certain percentage. Moreover, by a Fourier transform of ACF, the PSD is obtained. It gives the average power along the Doppler frequency. The CCFs are used to measure the space correlation of the channel, and the coherence distance can be derived from the CCF. The LSF is also an important channel statistical property, which can assess the non-stationary behavior of the channel over angles and Doppler domains. Besides the above, to better analyze the non-stationarities of channels, the quasi-stationarity regions in different domains are investigated. During the quasi-stationarity regions, the statistics of the channel and neighbor channel have high similarity. Hence, the channels are approximately seen as stationary. Once beyond that region, the channel will be regarded as non-stationary. The biggest difference between the sub-6 GHz and mmWave HST channels lies in the non-stationarities in different domains. Different from the conventional HST channel, the future mmWave channel should include the frequency non-stationarity.

The existing HST channel models are mainly focused on sub-6 GHz channels. Due to the high frequency and ultra-wide bandwidth, the characteristics of mmWave channels are greatly different from the sub-6 GHz channels. MmWave has its own characteristics, such as high PL and severe atmospheric attenuations, which make the mmWave channel modeling more challenging. Moreover, mmWave has a very high delay resolution. All these channel characteristics make the wide-sense stationary (WSS) assumption in the frequency domain no longer valid. The mmWave channel exhibits the non-stationarities over the frequency ranges. Here, the 28–30 GHz frequency band channel measurements are used to present the frequency characteristics. The bandwidth is divided into three sub-bands, each with 667.5 MHz bandwidth. The amplitudes of the selected three sub-band channels are slightly different, as shown in Fig. 2. These amplitudes are obtained from different sub-bands but in the same channel environment. From this figure, we can see that the channel characteristics of mmWave channels are different at different sub-bands. The conclusion is also applicable to the mmWave HST channels. To the authors' knowledge, the non-stationarity in the time domain has been mentioned in the conventional HST channels. However, there is still no space-time-frequency non-stationary channel model that can completely mimic the mmWave massive MIMO HST channels.

The Space-Time-Frequency HST Channel Model for 5G and Beyond

In this section, a novel mmWave massive MIMO HST channel model that can cover the space-time-frequency non-stationarity is introduced, and the modeling process is shown in Fig. 3. The spherical wavefront characteristics of massive MIMO HST channels result in the channel non-stationarity in the space domain. Moreover, the relative changes between the wavelength and sizes of scatterer objects influence channel statistics among different frequencies, and bring non-stationarity in the frequency domain. Based on the WINNER II and Saleh-Valenzuela (SV) channel models, a 3D twin-cluster HST channel model is obtained. The proposed CTF is a function of time, frequency, and number of antennas, and also contains lots of channel parameters, such as the azimuth and elevation angles, Doppler frequency, delays, velocity of Rx, and powers. All these parameters can be updated continuously by geometrical relationships of Tx, Rx, and clusters.

To fully describe the non-stationarities of HST channels, the proposed HST channel model will introduce continuous cluster evolutions in different domains. The propagation environments between the Tx and Rx are abstracted as randomly distributed clusters. During different periods in different domains, different clusters can be observed. Here, we take the non-stationarity in the frequency domain as an instance. The 2 GHz bandwidth is divided into four sub-bands. Within each sub-band interval, the channel can be regarded as constant. But among different sub-bands, the evolutions of frequency axis will be considered and denoted by birth and death processes [15]. Each cluster has its own survival probability, and a frequency related factor is defined to adjust this survival probability. The frequency non-stationarity is illustrated in Fig. 4. It should be noted that the frequency factor needs to be verified by future measurements.

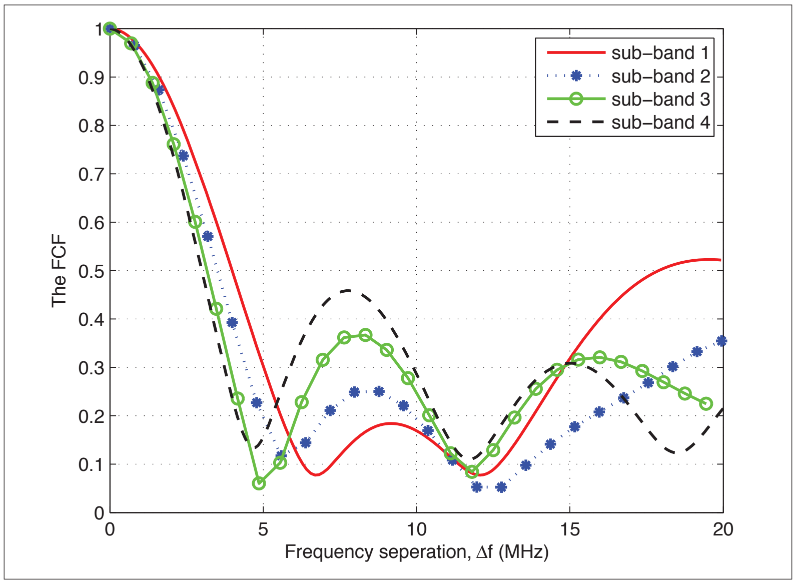

Figure 4. The frequency correlation functions of the mmWave HST channel model at different sub-bands.

Future Research Directions

In this section, some future directions related to the HST channel modeling for 5G and beyond communications are discussed.

Standardized HST Channel Models

To maintain the consistency of 4G and 5G channel models, it is recommended that the standardized channel models mimic the practical propagation environments in future HST communication systems. Currently, there are several up-to-date 5G standardized channel models that can support high mobility scenarios. However, a complete standardized HST channel model covering all the HST scenarios is still missing. Therefore, more efforts can be devoted to improve the standardized HST channel models.

Big-Data-Enabled HST Channel Modeling

Big data is being applied to many aspects of people's lives. As communication data exhibits exponential growth, wireless communications have come into the era of big data. Due to the ultra wide frequency range and high mobility of HSTs, the amount of measurement data is huge. Big-data-enabled channel modeling becomes inevitable. It is feasible to establish HST channel models by using the data analytical tools, such as data mining and machine learning algorithms. Moreover, some machine learning algorithms, such as artificial neural networks and convolution neural networks, can be used in channel modeling. Although some big-data-enabled channel modeling approaches have been developed, the related research is in the preliminary phase. This kind of model aims to cover all the traveling scenarios of HSTs. The combination of data-driven and model-driven models is the trend for future HST channel modeling.

Measurement-Based HST Channel Modeling

For the HST channel modeling, the channel measurements play important roles in the modeling process. Due to the limitations of specific environments, HST channel measurements are lacking. The current

The future HST communication system adopting new technologies will face many challenges. In the future HST channel modeling, one of the most important problems is about the joint non-stationarities of HST channels. Therefore, more performance analysis considering the space, time, and frequency non-stationarities for 5G and beyond HST communication systems is required.

measurements have been carried out at traditional frequency bands or in the single-antenna case. In the existing HST measurements, the channel non-stationarities over space, time, and frequency have not been sufficiently studied. Moreover, HST channel measurement campaigns considering mmWave and massive MIMO are still missing. To better describe the real HST channel characteristics, more channel measurements need to be conducted.

System Performance Analysis

For the design and network evaluation of the future railway communication system, the system performance of HST communications is the basis. In [14], the performance analysis of HST communication systems was studied using performance indicators such as throughput, SNRs, bit error rate, and channel capacity. The future HST communication system adopting new technologies will face many challenges. In future HST channel modeling, one of the most important problems is the joint non-stationarities of HST channels. Therefore, more performance analysis considering the space, time, and frequency non-stationarities for 5G and beyond HST communication systems is required.

Conclusions

This article has reviewed the recent advances in HST channel measurements and models. The HST channel measurements have been classified according to different propagation scenarios, carrier frequencies, bandwidths, train speeds, and channel statistics. Moreover, the recent HST channel models have been presented based on modeling approaches, frequency bands, stationarity, and channel statistics. Future railway communication systems are considered to support mmWave, massive MIMO, and MRSs to provide reliable communication services. Here, a novel HST channel model that can describe the mmWave and massive MIMO characteristics has been introduced, and the frequency non-stationarity has been depicted and investigated. Finally, some future directions are discussed. These results can be helpful to conduct future HST channel measurements and develop more accurate HST channel models.

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