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Channel Modeling for Future High-Speed Railway Communication Systems: A Survey

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ABSTRACT The widespread popularity of high-speed railways (HSRs) urges a critical demand on high-data-rate railway communication services for both train operation and passenger experience. To satisfy the ever-increasing requirements, future HSR communication systems, such as long-term evolution for railway (LTE-R), fifth generation (5G) on HSR, and 5G for railway (5G-R), and corresponding transmission technologies, e.g., mobile relay, coordinated multipoint, massive multiple-input multiple-output (MIMO), and millimeter-wave (mmWave), have recently attracted much attention. Radio channel modeling is the foundation of design and evaluation of wireless systems and transmission technologies. This paper focuses on a survey of channel modeling for the future HSR communication systems. The significant requirements of future HSR channel models are highlighted, and recent advances in the HSR channel modeling are reviewed. Finally, potential research directions for future HSR channel modeling are outlined.

INDEX TERMS 5G, high-speed railway communications, channel modeling, multi-link, massive MIMO, millimeter-wave, nonstationarity, clustering, and deep learning.

I. INTRODUCTION

High-speed railway (HSR), as one of the economic, comfortable, punctual and environmental means for medium-to-long distance travel, is being deployed in more countries and regions for inter-city transport. The widespread popularity of HSR places critical demand on new HSR communication services for both train operation and passenger experience [1]–[5]. To improve train operational safety, broadband services such as onboard and wayside high-definition (HD) video monitoring, train multimedia dispatching, railway emergency communications, and Internet of Things for railways, are becoming increasingly crucial. In addition to the security requirements, providing high-quality broadband services for in-train passengers, e.g., mobile services, online HD television and Internet access, is also indispensable. It is evaluated that the data rate needed for fundamental HSR communications is at least 40 Mbps, and the future preferred peak data rate will be 0.5-5 Gbps [6].

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To satisfy such high-data-rate requirements, research in broadband mobile communication systems for HSR has attracted worldwide attention in recent years. In China, a special narrow-strip-shaped long-term evolution (LTE) network has been recently deployed along most of high-speed rails, which aims at enabling broadband wireless access for passengers. Since 2014, the International Union of Railways (UIC) has considered replacing the global system for mobile communications for railway (GSM-R) with LTE for railway (LTE-R), in order to support future railway services. Since the end of 2017, the first LTE-R network has been live on HST in South Korea. For the upcoming fifth-generation (5G) communication system, it is expected to cover a variety of high mobility scenarios, including HSR, subway, and highway. Due to the larger bandwidth, the 5G communication system for railway (5G-R) will be possible to simultaneously provide the high-data-rate services for train operation and passenger experience.

With regard to the 5G on HSR or 5G-R, the novel system architecture and corresponding transmission technologies have to be considered. Fig. 1 illustrates the potential

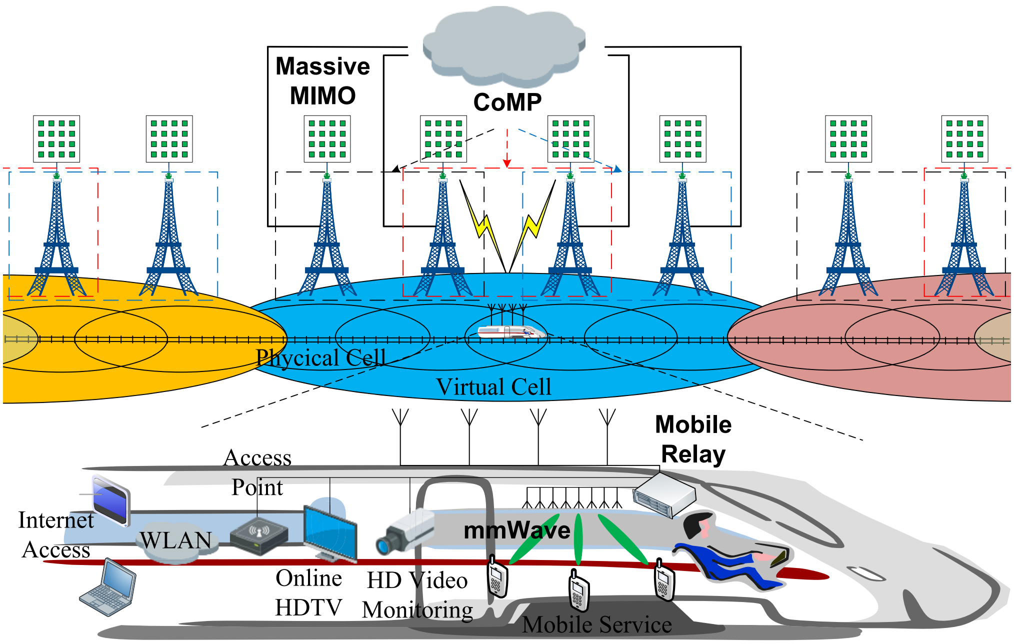

FIGURE 1. The two-hop two-frequency architecture for future HSR communication systems.

two-hop two-frequency architecture with cell combination for future HSR communication systems [7]. To reduce frequent handovers due to high mobility, cell combining is employed in this architecture where several physical cells using the same frequency and parameter settings are treated as a logical cell. One hop working at the lower frequency bands (e.g., below 6 GHz) is from the base station (BS) to the mobile relay station (MRS) on top of the train. This can avoid large penetration losses from the train body and enhances the transmission range. Another hop is from the MRS to the mobile station (MS) inside the train cars, which may employ the millimeter-wave (mmWave) band for high bandwidths. Massive multiple-input multiple-output (MIMO), which has been proved theoretically to achieve high data rate, high spectral efficiency, and high energy efficiency [8]–[12], can be used for the two hops, in order to exploit spatial diversity or form beams to track the moving MRS or to point at the MS. The transmission rate and system capacity is able to be further improved by coordinated multipoint (CoMP) in the combined cell, where two or more BSs generate a coordinated cluster and are connected to a backhaul network to exchange the data, control information and channel state information [13].

The performance of wireless systems and technologies is ultimately limited by propagation channels [14]. With regard to the future HSR communication systems, it is required to consider three types of propagation channels: multi-link channels, massive MIMO channels, and mmWave channels. These channels have various propagation characteristics, and exhibit the space-time-frequency nonstationarity. Moreover, it is necessary to establish generalized HSR channel models that can be applicable in different scenarios, frequency bands and antenna sizes. This article discusses channel modeling for future HSR communication systems. The typical requirements of future HSR channel models are presented in the next section. Then we describe recent advances in HSR channel modeling, in terms of statistical, theoretical and intelligent channel modeling. Next we outline some future research directions for HSR channel modeling. Finally, conclusions are drawn in the last section.

II. REQUIREMENTS OF FUTURE HSR CHANNEL MODELS

Radio channel models describe how channel fading behave in a given scenario, and to help design communication systems and evaluate link- and system-level performance. A proper channel model should be able to faithfully reproduce the channel parameters obtained in field measurements and accurately predict the channel impulse responses or channel frequency responses with both long-term and short-term fading. As for future HSR communication systems, there are several factors determining the requirements of HSR channel models. The first is the employed transmission technologies which decide the types of propagation channels that we need to consider, such as multi-link, massive MIMO, and mmWave channels. Thus, channel characteristics like multi-link cross-correlations, massive MIMO-related properties, and mmWave propagation characteristics should be included in future HSR channel models. Another is the operating scenarios that define types of physical environments and relevant radio propagation mechanisms. The HSR environments can be roughly classified into HSR outdoor and indoor scenarios. The HSR outdoor scenario mainly involves viaduct, cutting, station, hilly terrain, and open space (e.g., rural, suburban, and urban areas), while the HSR indoor scenario contains tunnel and the environment inside train cars. Furthermore, an important feature for HSR channels is the nonstationarity, which requires the HSR channel models to be dynamic. Additionally, to support different scenarios, frequency bands and antenna sizes, the future HSR channel models should possess leaning ability and become general. Combining these factors, significant requirements for future HSR channel models will be described from five aspects, as follows.

A. MULTI-LINK CROSS-CORRELATIONS

In the HSR multi-link propagation scenario, the cross-correlation could appear due to the presence of fixed line of sight (LoS) components or common clusters for different links. The multi-link cross-correlations comprise cross-correlations of large-scale parameters (LSPs) and small-scale fading (SSF). LSPs describe the characteristics of the channel over a relatively large area in the order of a few tens of wavelengths, such as shadow fading, K-factor, delay spread, and angular spread. The cross-correlation of shadow fading determines the macro-diversity performance of CoMP. The cross-correlation of LSPs can be incorporated in conventional single-link channel models, which are thus extended to the multi-link channel models. In addition, the SSF cross-correlation determines the micro-diversity gain of CoMP and has a strong impact on correlation matrix collinearity and sum rate capacity [15].

B. MASSIVE MIMO-RELATED PROPERTIES

Whether it is the HSR outdoor or indoor scenarios, massive MIMO will be used and thus the corresponding propagation characteristics need to be involved into the HSR channel model. As for the HSR outdoor scenarios, a linear large-scale array will not be equipped due to the limited space on BS sites. The massive MIMO arrays in the HSR outdoor environments will be three-dimensional (3D) planar or cylindrical arrays. It is necessary for a 3D channel model to provide the elevation angular characteristics, such as elevation angle spectrum and elevation angle spread [16]. The contributions in elevation domain could come via scatterers, such as steep walls in the cutting scenario, awnings in the station scenario, or other surroundings in the viaduct, hilly terrain and open space environments, and also may come from ground when the train is close to the BS. With regard to the HSR indoor scenarios, the linear large-scale array can be deployed as there is enough space on rooftops inside the tunnel or the train cars. For the linear array, the far-field distance will be linearly increasing with the number of antenna elements. When the array becomes very large, the far-field assumption may no longer be appropriate and thus the wavefront should be assumed as spherical instead of plane. Beamforming can be utilized by massive MIMO to track the moving MRS or to point at the MS. Since the array can form beams with different widths, the beam-based propagation characteristics should be investigated in both HSR outdoor and indoor scenarios. Besides, when the formed beam is narrower than a cluster, intra-cluster parameters should be considered in channel modeling.

C. MMWAVE PROPAGATION CHARACTERISTICS

Due to the limited transmission range, mmWave is suggested to be used in the HSR indoor scenarios. The mmWave channel has some well-known propagation features, such as higher propagation losses, reflection on surfaces with a roughness that is comparable to the wavelength, and higher diffraction losses [17]. However, since the HSR tunnel or the train car is a kind of closed, narrow and long circumstance, it will yield the unique mmWave propagation characteristics. The infrastructures and passengers inside the train car could have severe effects on the shadow fading, and the impact of train body in realistic tunnel scenarios should be considered.

D. NONSTATIONARITY

The very high mobility will induce the violation of wide sense stationary condition in the HSR environments [18]. The nonstationarity of HSR channels is basically due to the dynamic evolution of multipath clusters caused by the motion of the train. Specifically, the clusters exhibit appearance to disappearance (or birth to death) dynamics. This dynamic behavior should be incorporated in HSR channel modeling since it directly reflects the time variance of HSR channels. In order to achieve the non-stationary characterization, some parameters, such as the stationarity interval, cluster lifetime, the number of clusters, and the power, delay and angle of each cluster, should be obtained. In addition to the time variance, with the very large array, and very high bandwidth, the HSR channel will also be non-stationary in the space and frequency domains.

E. GENERALITY

One of the biggest problems in current HSR channel models is the weak generality. The performance of these models deteriorates sharply once they are applied to more general environments. It is expected that the future HSR channel model can be appropriate for different scenarios, frequency bands and antenna sizes. This expectation could be realized with the application of artificial intelligence (AI) to wireless communications. By means of the powerful learning ability, the channel models can support various scenarios and configurations. Moreover, the future HSR channel model should take into account the channel relevancy in the space, time, frequency and scenario domains which is important to reveal the underlying channel properties.

III. ADVANCES IN HSR CHANNEL MODELING

The current channel modeling methods can be simply divided into three categories: statistical, theoretical and intelligent channel modeling. The theoretical channel modeling can be further classified as deterministic, stochastic, and semi-deterministic types. The typical HSR channel models using these approaches and corresponding features are summarized in Table 1. Note that although some methods have not yet

TABLE 1. Comparison among different channel modeling methods.

Type	Statistical	Deterministic	Theoretical Stochastic		Semi-deterministic	Intelligent
Model	MBCM	PTBCM	GBCM	PGBCM	PGBCM with RTBCM	AIBCM
Required information	Measurement data	Geometrical and electromagnetic parameters	Statistical spatial distribution	Geometrical parameters	Geometrical and electromagnetic parameters	Extensive channel data
Accuracy	High	High	Low	Medium	High	High
Complexity	Low	High	Low	Low	Medium	Low
Flexibility	Low	High	High	High	High	High
Applied in HSR channel modeling	Yes	Yes	Yes	Yes	No	No

been applied in HSR scenarios, we still regard them as the candidates and review the recent advances.

A. STATISTICAL CHANNEL MODELING

Measurement based channel model (MBCM), as a typical statistical model, is derived from field measurement data, which aims at simulating statistical distributions such as power delay profile, power angle profile, and Doppler spectrum. The advantages of MBCM are the high accuracy and low complexity. However, the MBCM is usually site-specific and thus has low flexibility and generality. There have been a series of measurement campaigns conducted on realistic HSR lines, based on either channel sounders or existing networks [19]–[25]. According to the dedicated networks, some statistical large-scale propagation models in various HSR scenarios have been obtained [20]–[23]. These models considered the geometrical information of environments and can be more accurate. The short-term fading behavior in HSR environments, characterized by the fading severity and time-frequency-space dispersion, has been statistically modeled in [26], [27]. This study also considered the scenario with echo channel effect which is caused by the same signaling from neighboring BSs in HSR networks. Assisted by the LTE networks on HSR, the multi-link cross-correlations were measured and analyzed, and the correlation matrix collinearity and sum rate capacity of dual-link HSR MIMO channels were evaluated in [28]. A model of joint statistical characteristics for HSR multi-link channels has been proposed in [29]. In addition, the Markov chain was used to statistically model the dynamic behavior of multipath components in time domain in HSR scenarios [30]. The massive MIMO-related properties and mmWave propagation characteristics are not incorporated in existing MBCMs for HSR scenarios as measurement data are still lacking.

B. THEORETICAL CHANNEL MODELING

Due to the difficult collection of field measurement data on HSR, the theoretical method plays an important role in HSR channel modeling. There have been four theoretical channel models including ray-tracing based channel model (RTBCM), geometry based channel model (GBCM), propagation-graph based channel model (PGBCM), and PGBCM with RTBCM.

The RTBCM represents an appropriate choice when it comes to deterministic propagation modeling. To obtain the RTBCM, a detailed environment description must be provided with electromagnetic parameters of relevant materials. Due to its accuracy and flexibility, RTBCM can be used to simulate long-term fading, or to perform multidimensional channel characterization, often in combination with measurements. However, the drawback of RTBCM is high computation complexity especially for large scenarios. The RTBCM have been widely used for the indoor scenarios. Based on mmWave measurements conducted in a tunnel scenario, a RTBCM with calibrated geometrical and material parameters has been validated and used to analyze mmWave channel characteristics [31]. A paradigm for realizing the HSR channels at the mmWave band was proposed and implemented in [32], [33].

Halfway between the statistical MBCM and deterministic RT-BCM is the GBCM. In GBCMs, the scatterers are stochastically placed around the transmitter (Tx) and the receiver (Rx), on a certain geometric shape according to a statistical spatial distribution rather than a deterministic environment description. The channel impulse responses are then generated by the law of wave propagation and the geometric scattering model, which can be used to derive the channel parameters for a variety of scenarios. Due to the advantage of lower complexity and higher flexibility, the GBCM is highly suitable for the analysis and simulation of the MIMO and massive MIMO channels [34]. However, the accuracy of GBCM should be improved with the support of actual measurement data. Authors in [35] have proposed a semi-empirical MIMO GBCM for HSR viaduct scenarios, where the environment-related parameters are determined by the measurement data. In [36], a non-stationary MIMO GBCM was proposed to investigate the nonstationarity of HSR channels and the proposed model was validated by measurements in terms of stationary intervals.

The PGBCM is another kind of stochastic model, which describes the propagation environment using graph theory, with vertices representing the Tx, the Rx, and scatterers, with edges indicating propagation conditions between vertices. Unlike the GBCM, propagation graph channel modeling is a frequency domain method. The signal propagating between these edges relies on wave propagation mechanisms, and

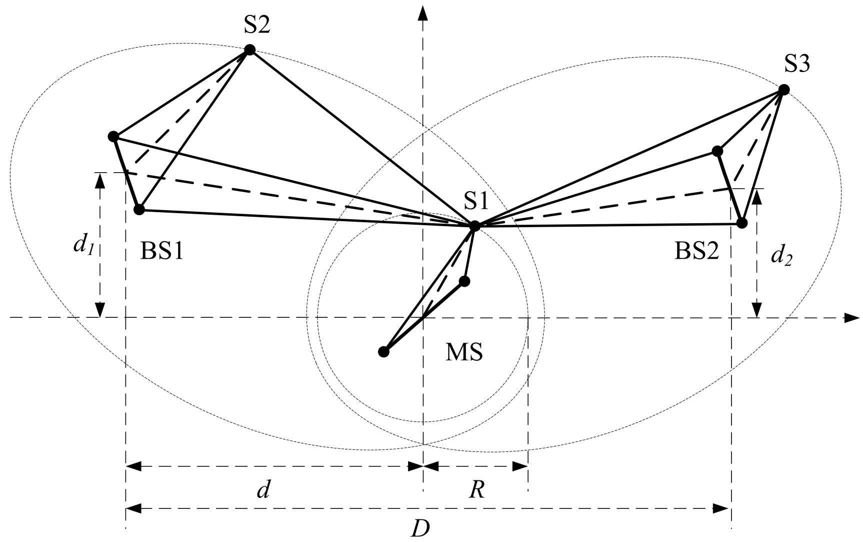

FIGURE 2. A dual-link 2 × 2 GBCM with one ring and two ellipses in HSR networks.

the propagation effect can be represented as a multiplication with the channel transfer functions when assuming these mechanisms to be linear. Different with the RTBCM, material parameters are not required in the PGBCM, which would reduce the modeling accuracy. However, the PGBCM is quite suitable for the modeling of reverberation effects and diffuse scattering, due to the lower computation complexity. In [37], channel modeling based on random propagation graphs have been investigated and used to analyze the MIMO channel characteristics in HSR scenarios. The PGBCM was applied in HSR cutting environments and achieved reasonable agreement with measurements [38].

A more accurate PGBCM with RTBCM was proposed in [39], where the generated diffuse multipath components are combined with the specular components simulated by the RTBCM to obtain complete channel representation. However, this semi-deterministic channel modeling approach has not yet been applied in HSR scenarios.

C. INTELLIGENT CHANNEL MODELING

Intelligent channel modeling, as a good way to conquer the weakness of generality in traditional channel modeling, has attracted more and more attentions in recent years. The current intelligent channel modeling is mainly depending on machine learning (ML) algorithms to establish a kind of AI based channel model (AIBCM) for describing the mapping relationship between physical scenario or configuration information and channel characteristics. There have been a few ML algorithms such as artificial neural network (ANN), K-nearest-neighbor (KNN) and random forest adopted to predict the path loss in various communication scenarios [40]–[44]. The convolutional neural network (CNN) with the inputs of Tx and Rx antenna location information was used to predict channel characteristics in mmWave massive MIMO indoor scenarios, where the training data was generated by the RTBCM [45]. Authors in [46] applied ML to channel modeling and presented a three-layer structure of "wave, cluster-nuclei, and channel". The clustering enabled channel modeling using the big data and AI technology has been presented in [47]. Until now, there is still lack of realistic AIBCM applied in HSR scenarios, and the channel relevancy is ignored in current intelligent channel modeling.

IV. FUTURE DIRECTIONS FOR HSR CHANNEL MODELING

In this section we discuss some new research directions which can be considered as guidelines for conducting the HSR measurement campaigns and developing the HSR channel models for future HSR communication systems.

A. MULTI-LINK HSR CHANNEL MODELING

Since active channel sounders are not suitable for performing HSR measurements, reported measurement campaigns used HSR LTE networks, which can be helpful for multi-link channel characterization and modeling. In HSR outdoor scenarios the LoS component and common clusters produced by the shared scatterers, e.g., the steep walls of cutting, the awnings of station, or other local surroundings, are the main contributors of cross-correlations. An irregular shaped GBCM has been used to analyze the SSF cross-correlation in distributed MIMO systems [15]. The regular shapes of GBCM can also be a possible way for modeling of SSF cross-correlation in HSR outdoor scenarios. Fig. 2 illustrates a 2×2 MIMO GBCM with the one-ring two-ellipse architecture that includes two links from BS1 and BS2 to a MRS [48]. The one ring is used to describe the distribution of local scatterers S1, while the two ellipses are employed to represent the distribution of remote scatterers S2 and S3 in the two links. The proposed GBCM only focuses on NLoS components of the two links, including the single-bounced component from S1 as well as the double-bounced component from

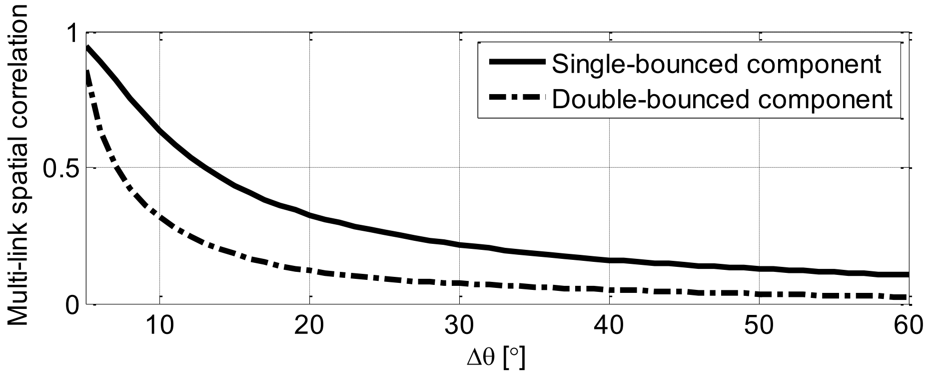

FIGURE 3. Multi-link spatial correlation results for single-bounced and double-bounced components.

S2 and S3 to S1. The scatterers are assumed to be distributed following the von-Mises distribution. The ring radius and the distance between BS1 and BS2 are denoted as R and D. The horizontal distance between the MS and BS1 and the distance between BS1 or BS2 and the rail track are indicated by d and d_1 or d_2.

We assume that the center frequency is 5 GHz, the antenna spacing is 3 wavelengths, R = 30m, D = 1000m, d = 500m, $d_1 = d_2 = 30$m. We compare the results for single-bounced and double-bounced components, as shown in Fig. 3. It can be seen that the coefficient of multi-link spatial correlation reduces as the azimuth AS increases, and the double-bounced component contributes a lower correlation than the single-bounce component. This is because the double-bounced component comprises a part of the uncommon cluster, which has no contribution on the multi-link spatial correlation.

B. MASSIVE MIMO HSR CHANNEL MODELING

To obtain elevation angular characteristics, 3D arrays need to be employed in multi-antenna HSR channel measurements. In addition, channel measurements considering beamforming should be performed for characterizing the beam-based properties and providing the intra-cluster parameters. The proposed GBCMs in the literature [35], [36] have been successfully used for HSR MIMO channel modeling, which can be further extended to the massive MIMO case by applying 3D geometric scattering models with elevation angle parameters, adopting the spherical wavefront assumption that needs to consider exact scatterer locations instead of only their direction towards the antenna.

C. MMWAVE HSR CHANNEL MODELING

In the literature mmWave SISO channel measurements have been taken in tunnel scenarios [31]. To measure the angular characteristics for mmWave, a popular way is to use a single antenna element that has to be rotated or physically moved to multiple positions to form a virtual array. Since HSR tunnels or cars have relatively small propagation environments, it would be convenient for the RTBCM to simulate the HST indoor mmWave channels. Alternatively, the semi-deterministic channel model combing the PGBCM with RTBCM can be also used.

For mmWave characteristics in HSR tunnel scenarios, the influence of train cars should be of special concern. Fig. 4 shows the ray-tracing simulation at 1.4 GHz and 38 GHz in a tunnel scenario with and without train cars. The Tx and Rx antennas are placed on top of tunnel and train cars. The simulation results of root mean square (RMS) delay spread (DS) are illustrated in Fig. 5. It confirms that the train cars have a remarkable impact on the propagation characteristics at mmWave band in tunnel scenarios.

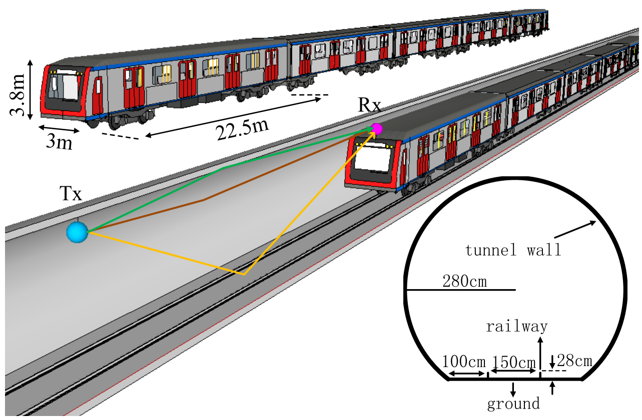

FIGURE 4. The simulation model using ray-tracing for a tunnel.

D. DYNAMIC-CLUSTER BASED HSR CHANNEL MODELING

The concept of cluster has been widely used in radio channel modeling, which can efficiently describe the physical environment. To reflect the nonstationarity of HSR channels, HSR channel modeling based on the dynamic clusters will be a potential research direction. For the dynamic-cluster based HSR channel modeling, a suitable clustering and tacking algorithm should be used to map the clusters to real scatterers and capture the cluster evolution in HSR environments [49], [50]. Then, the dynamic cluster characteristics of HSR channels can be statistically extracted and incorporated

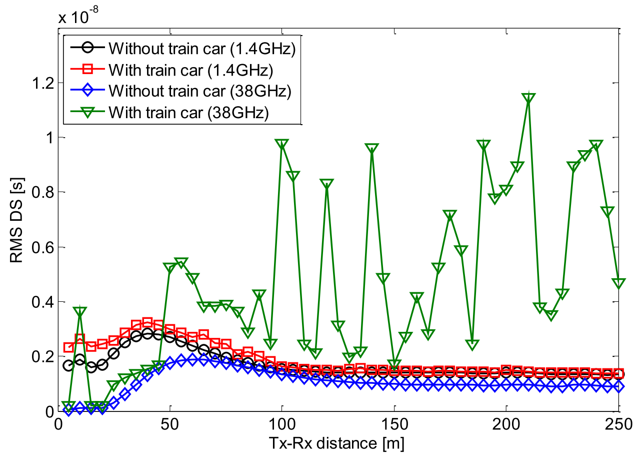

FIGURE 5. The RMS DS results obtained by the simulation model.

in a cluster-delay-line directional model. On the other hand, the time-variant cluster parameters and the cluster birth to death process in space-time-frequency domain can be also incorporated in the GBCM to establish a dynamic HSR channel model.

E. DEEP-LEARNING BASED HSR CHANNEL MODELING

With successful applications of ML to the prediction of channel characteristics, deep learning (DL) that possesses more powerful learning capacity has been increasingly used to achieve the intelligent channel modeling. The basic architecture of DL is an ANN with multiple hidden layers, called deep neural network (DNN). In DNNs, all neurons between adjacent layers are fully connected. CNN is an improved DNN architecture that inserts convolutional and pooling layers before feeding into a fully connected network, as shown Fig. 6(a). Each output in the convolutional layer is obtained by dot production between a certain filter matrix and an input matrix comprised of several neurons in the upper layer. The pooling layer is to reduce the dimensionality of each feature map but retains the most important information by averaging or searching maximum in a group of neurons in the convolutional layer. Graph convolutional network (GCN) is a newly emerging architecture aiming to generalizing CNNs to work on not only regular grid-structured sequences but also irregular graph-structured sequences. In GCNs, the graph convolution operation replaces the matrix multiplication in CNNs, as show in Fig. 6(b). Both CNNs and GCNs are capable of capturing the spatial relevancy of structured sequences. Recurrent neural network (RNN) is another architecture which adds a feedback path between the neurons in the hidden layers, as shown in Fig. 6(c). In RNNs, the current outputs depend on current and former inputs so that the network is able to capture the temporal dependence inherited in sequence data.

The CNNs have been used to achieve channel modeling and prediction, and found to have a good performance [45]. However, the temporal dependence in time varying channels cannot be learned by the CNNs. Moreover, the channel

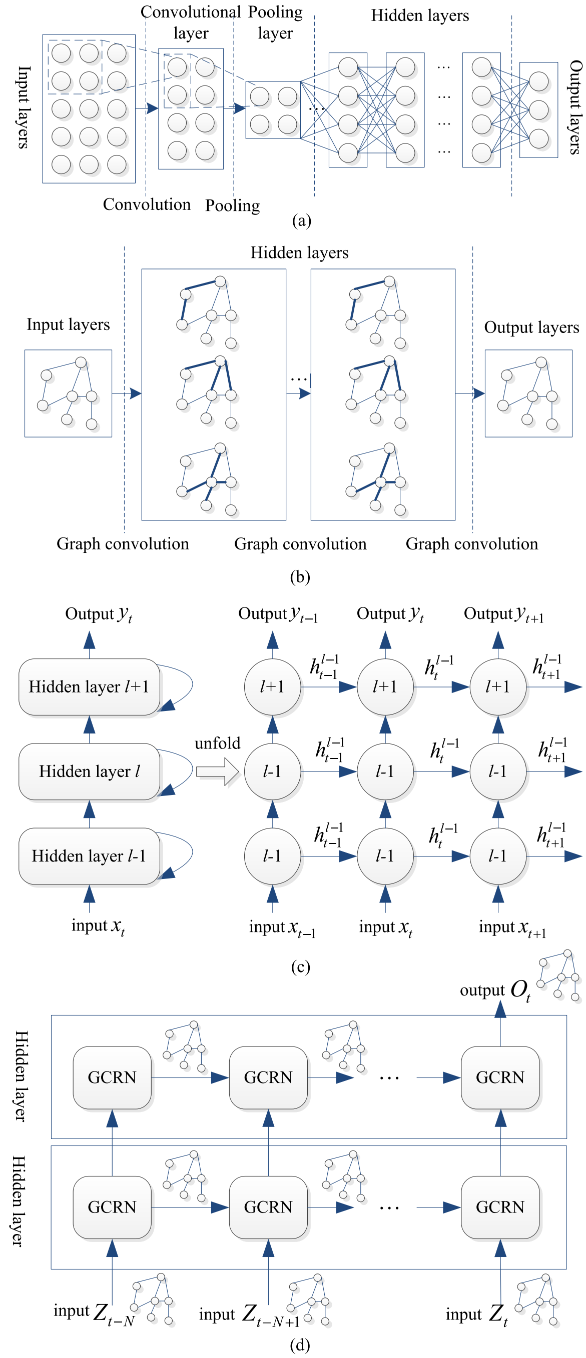

FIGURE 6. Several DL architectures. (a) CNN. (b) GCN. (c) RNN. (d) GCRN.

relevancy between scenarios is embedded in graph-structured data, which is hard to be learned by grid-based models. A possible approach is to establish a model merging the GCNs and RNNs, as shown in Fig. 6(d), which can simultaneously incorporate the channel dependence in the space, time, frequency and scenario domains.

V. CONCLUSIONS

Channel modeling is the precondition for designing and evaluating wireless systems and transmission technologies.

This article surveys the modeling of HSR channels for future HSR communication systems. The typical features required in future HSR channel models were presented, in terms of multi-link cross-correlations, massive MIMO-related properties, mmWave characteristics, nonstationarity, and generality. The state-of-the-art HSR channel modeling was reviewed and classified into statistical, theoretical and intelligent categories, and the theoretical method was further divided into deterministic, stochastic, and semi-deterministic types. It has been shown that the intelligent channel modeling method will have better performance than others. Finally, several necessary research directions were suggested for future HSR channel modeling.

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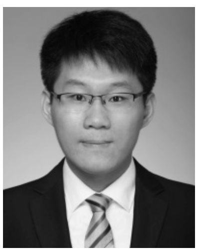

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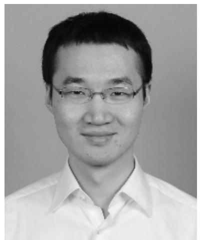

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