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Channel measurements and models for high-speed train wireless communication systems in tunnel scenarios: a survey

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Abstract The rapid developments of high-speed trains (HSTs) introduce new challenges to HST wireless communication systems. Realistic HST channel models play a critical role in designing and evaluating HST communication systems. Due to the length limitation, bounding of tunnel itself, and waveguide effect, channel characteristics in tunnel scenarios are very different from those in other HST scenarios. Therefore, accurate tunnel channel models considering both large-scale and small-scale fading characteristics are essential for HST communication systems. Moreover, certain characteristics of tunnel channels have not been investigated sufficiently. This article provides a comprehensive review of the measurement campaigns in tunnels and presents some tunnel channel models using various modeling methods. Finally, future directions in HST tunnel channel measurements and modeling are discussed.

Keywords 5G, high-speed train (HST), tunnel scenario, tunnel channel measurement, tunnel channel model, non-stationary statistical property

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1 Introduction

High-speed trains (HSTs) have experienced a rapid development recently [1], and wireless technologies for HST communications will be considered as an important issue in the fifth generation (5G) wireless communication networks [2, 3]. With the number of HST users increasing, numerous communication

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data need to be transmitted to train passengers through wireless channels. Therefore, high-capacity and reliable HST communication networks regardless of users' locations or speeds, are required. In order to meet these requirements, HST wireless communication systems need to mitigate various challenges resulting from the high speed of trains, such as frequent handovers, large Doppler spreads, and fast travel through different HST scenarios [4, 5]. Currently, the most widely used HST communication system is the Global System for Mobile Communication Railway (GSM-R) [6]. It can be used for the train communication and control. However, it cannot satisfy the increasing communication requirements of high data rates. In recent years, the Long-Term Evolution-Railway (LTE-R) system, which is based on the LTE-Advanced (LTE-A) system, has been recommended to replace the GSM-R. Both of them adopted the conventional network architecture in which HST users inside the train communicate with outdoor base stations (BSs) directly. However, such an architecture results in high penetration losses when the signals travel into the carriages and leads to a spotty coverage, which will result in the handover failure or the high drop calls rate [6]. To overcome the above problems, the promising mobile relay station (MRS) solution has been proposed for future HST communication systems to solve the spotty coverage problem and mitigate high penetration losses of wireless signals traveling into the train carriages [7]. By considering the MRS technology, the propagation channel can be divided into two parts: outdoor channel between the BS and MRS, and indoor one between the MRS and receiver inside carriages. MRS technology can be applied to reduce the frequency handover by performing a group handover instead of individual handover with each passenger. This technology has been adopted by the International Mobile Telecommunications-Advanced (IMT-A) and WINNER II systems [8].

There are several scenarios that HST may encounter in reality, such as open space, hilly terrain, cutting, viaduct, tunnel, and station scenarios [4]. As a classical HST scenario, tunnel environment takes up a great proportion among the rail transportation, and it has attracted a lot of research interest [9]. Considering the unique propagation environment of tunnels, such as long limited space, poor smoothness of the interior walls, and the bounding of tunnel walls, propagation characteristics of signals in the tunnel scenario are quite different from those of other HST scenarios. Moreover, the length of tunnels can range from several hundred meters to several kilometres, with different shapes such as circular and rectangular sections. Since the length, size, and shape of the tunnels and the encountered waveguide phenomena have a significant effect on the propagation channel, channel characterization and modeling for tunnel scenarios are still a quite challenging topic [8]. Conventional channel modeling methods are suitable for most HST scenarios, but are not directly applicable to tunnel scenarios. Radio signals inside tunnels will suffer more reflections, diffractions, and scattering, and will also experience more severe fast fading due to the high mobility of trains. There are mainly two promising solutions to achieve the wireless coverage inside tunnels, i.e., leaky feeders [10] and distributed antenna system (DAS) [11,12]. Considering the fact that HSTs may require long tunnels, leaky feeder technologies will be more expensive especially at high operating frequencies. Moreover, the leaky feeder will be unavailable once unexpected cuts appear [9]. As a consequence, DAS is more viable than the leaky feeder [12] and it can provide better coverage, higher capacity, and easier maintenance after being installed. All these facts push the application of DAS inside tunnels and motivate the work on the HST tunnel channel modeling [10].

To better develop future HST tunnel communication systems, a comprehensive understanding of channel characteristics and accurate tunnel channel models are essential. Some measurement campaigns inside tunnels have been conducted to investigate the underlying physical phenomenon of signal propagation environments. Most of the measurement works have focused on the large-scale fading characteristics, such as path loss (PL) and shadowing fading (SF), which are crucial in network deployment and optimization. The small-scale fading channel models also play an important role in system design and schemes test. Therefore, accurate tunnel channel models considering both large-scale and small-scale fading characteristics are essential. Based on different modeling approaches, the presented tunnel channel models can be divided into deterministic and stochastic channel models. The deterministic channel models are mainly based the geometrical optical (GO) based theory [13–16], the waveguide method [17–21], and numerical methods for Maxwell equations [22–24]. The stochastic models can be classified into geometry-based stochastic models (GBSMs) and non-geometrical stochastic models (NGSMs) [25]. The aim of the paper is to survey the recent advances in channel measurements and modeling for HST tunnel scenarios and future directions.

The remainder of this paper is organized as follows. HST channel measurements in tunnel scenarios are presented in Section 2. In Section 3, some HST tunnel channel models are described. Future research directions in HST tunnel channel measurements and models are discussed in Section 4. Finally, conclusion is drawn in Section 5.

2 HST channel measurements in tunnel scenarios

Due to the high speed of trains and tunnel space limitation, measurement campaigns are difficult to be carried out accurately inside HST tunnels. Although some HST channel measurements in tunnels have been conducted in recent years, this is still a very challenging task. Here, we will briefly review and classify some tunnel channel measurements [10, 11, 17, 26–40] according to the carrier frequency, tunnel parameters, antenna configuration, and channel statistics, as illustrated in Table 1. Moreover, some important analysis of tunnel channel measurements are summarized as follows.

2.1 Measurement setup

For HST tunnel channel measurements, most works have focused on single-input single-output (SISO) antenna configuration, e.g., in [10, 11, 30]. To meet the increasing requirements of future high speed data transmission, the multiple-input multiple-output (MIMO) antenna configuration [31, 32] systems are indispensable. The benefits of increasing channel capacity by using the MIMO technology in tunnel scenario were examined and demonstrated in [32]. Therefore, more channel measurements using MIMO system in HST tunnel scenarios are necessary and significant.

Most of the existing measurement campaigns have been conducted based on the GSM-R system. A typical measurement of the tunnels on the new HSTs in Spain was introduced in [11]. It is noteworthy to mention that the frequency bands of the GSM-R system reported are 876–880 MHz for the uplink and 921–925 MHz for the downlink, since the measurement was conducted in Europe. In China and India, different frequency bands of the GSM-R system, i.e., 885–889 MHz for the uplink and 930–934 MHz for the downlink, are in use. In [11], the viability of using DAS was demonstrated. Two GSM-R BSs at the entrance and exit of the tunnel were used. Between these two BSs, there were three repeaters connected with each other using radio over fiber (RoF) technology. The measurement has taken into account the effects of tunnel propagation, including curves, trains passing from outside to inside, and the case of two trains inside the tunnel. In this paper, modal approach is used to calculate the signals propagation in straight tunnel, and ray tracing method is applied to calculate the extra attenuations in curves case and in the entrance and exit of the tunnel. When a train passes from inside to outside the tunnel, the signal wave can experience strong fading due to the change of wave impedance and diffraction effect. Moreover, two trains are used in the measurements. One train stopped at different positions, i.e., close to one transmitter and the center between two transmitters, while the other one passes by. The signal shadowing caused by blocking effect of two trains traveling inside tunnel is investigated. Furthermore, all the above cases using the iso-frequency and multi-frequency distributed transmitters solutions were measured and investigated. For the iso-frequency configuration, all the transmitters inside tunnel had same frequency. The multi-frequency trial uses the different frequencies. Compared with the multi-frequency transmitter, the iso-frequency transmitter was shown to have improvements of signal-to-noise ratio (SNR) and received power [11]. Considering that the narrowband GSM-R is mainly used for train control, rather than providing communications for passengers inside trains, and it cannot meet the high data rate requirements of future HST communications. In [33], the Universal Mobile Terrestrial System (UMTS) and LTE systems have been recommended to replace the GSM-R. In these systems, the wideband signals can be used to analyze the precise channel characteristics with enhanced time resolution. Using the extracted parameters from CIRs, such as the cluster delay, Doppler frequency spreads, K-factor and correlation among these parameters, intra-cluster characteristics are investigated. Moreover, a PL model

Table 1 Important tunnel channel measurements*

Ref.	Freq.	Scenario	Tunnel parameters	Antenna config.	Channel statistics
[10]	2.4 GHz	Arched subway tunnel	wide tunnel: 9.8 m×6.2 m, narrow tunnel: 4.8 m×5.3 m,	SISO	SF, PL, fast fading, LCF, AFD
[11]	900 MHz	Arched railway tunnel	height: 5.4 m, width: 10.7 m, length: 4000 m	SISO	PL
[31]	2.8–5 GHz	Semicircular railway tunnel	diameter: 8.6 m, height(max): 6.1 m, length: 3336 m	MIMO	PL, PDF, CDF
[32]	900 MHz	Arched subway tunnel	two-track tunnel: width: 8 m, length: 200 m, single-track tunnel: width: 5 m, length: 100 m	MIMO	CIR, Correlation coefficient
[33]	2.1376 GHz	Subway tunnel	length: 34 km	MIMO	PDP, PL, K factor, delay spread
[36]	2.4 GHz, 5 GHz	Horse-shoe shaped subway tunnel	straight: 240 m, curve: 140 m	SISO	PL, rms delay spread, channel stationarity, channel capacity
[37]	465 MHz, 820 MHz	Arched underground railway	floor width: 5.8 m, height: 4 m, length: 980 m	SISO	PL
[38]	450 MHz–5 GHz	Arched railway tunnel	length: 3000 m	SISO	PL
[39]	884 MHz, 2.45 GHz	Rectangular tunnel	width: 14.7 m, height: 6.15 m, length: 360 m	SISO	PL
[40]	2.49–4 GHz	Rectangular tunnel	wide tunnel: 2.4 m×3.1 m, narrow tunnel: 2.4 m×5.2 m,	MIMO	PL, delay spread

* PDF: probability density function; CDF: cumulative density function; LCR: level crossing rate; AFD: average fade duration; CIR: channel impulse responses; PDP: power delay profile; rms: root mean square.

for the tunnel scenarios is obtained. In [34], actual channel measurement based on the LTE system has been carried out at 1.89 GHz in a mountain tunnel. Some main propagation characteristics are investigated. In [35], the measurement campaigns are conducted at carrier frequencies of 1 GHz and 2.45 GHz, according to the measurement configuration of the fourth generation (4G) systems in railway environments. It provides detailed tunnel channel information, and can be used to develop a broadband channel model for tunnel communication systems.

In summary, HST tunnel wideband channel measurement campaigns with MIMO system, as well as larger carrier frequency and bandwidth than GSM-R are needed for future developments of HST tunnel communication system.

2.2 Large-scale vs. small-scale fading

For the better design of the future communication system in HST tunnel scenario, a comprehensive understanding of both large-scale and small-scale channel characteristics is vital. The reliable large-scale fading channel models, i.e., PL and SF, are essential to trustworthy network deployment and optimization. Most of the existing measurement campaigns for tunnels mainly focused on large-scale fading parameters. In [33, 37–42], the PL has been investigated, and in [43], the channel characteristics of different antenna setups are compared, such as PL exponent and SF. In [44], the relation between Fresnel zone and PL exponent n was analyzed based on the two-ray model. It was demonstrated that the 1st Fresnel zone is the underlying factor that will influence the n. Then, in [45], the four-slope PL channel model was proposed, by taking the free space propagation region and the extreme far region into additional consideration. All these results can be used to guide measurement campaigns and physical layer design for the communication systems in tunnel.

The accurate small-scale fading channel models also play an important role in the analysis and design of wireless communication systems, such as error control coding, interleaving, and equalization algorithms [9]. In [31], both large-scale and small-scale fading characteristics deduced from measurement data in semicircular tunnel are presented. In the case of small-scale fading, a Rice distribution can fit measurement well, and a uniform distribution can match the phase of the electric field. Moreover, the K-factor is also analyzed. In [10], a measurement was carried out in a subway tunnel and some propagation characteristics, such as LCR and AFD, have been computed and discussed. In future tunnel channel measurements, more channel statistics related to small-scale fading in HST tunnel scenarios are needed.

2.3 Far region vs. near region inside tunnel

When radio waves propagate inside a tunnel, the tunnel channel can roughly be divided into two regions based on the so-called breakpoint, namely, the near region and far region [20, 46]. Different propagation regions need different channel models to describe. The statistical properties of tunnel channels, including PL, SF, and small-scale fading characteristics, are greatly different before and after the breakpoint. Therefore, accurate determination of the breakpoint is very important for future tunnel channel measurements and models.

Based on a measurement campaign conducted in a subway environment at 2.4 GHz in [10], some signal propagation characteristics on the breakpoint were discussed, and the propagation regions, such as near region and far region, were analyzed. From the perspective of modal theory, radio propagation can be decomposed into different waveguide modes. For example, a rectangular tunnel can be considered as an oversized waveguide. According to the operating frequency and cutoff frequency, the modes propagating inside a tunnel can be estimated. In [47], the cutoff frequency for a rectangular tunnel can be expressed as

$$f_T = \frac{1}{2\sqrt{\mu_0 \varepsilon_0}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}, \tag{1}$$

where a and b represent the tunnel width and height, m and n denote the propagation modes in the horizontal and vertical directions, μ_0 and ε_0 are permeability and permittivity in free space. When the operating frequencies are higher than the cutoff frequency, the corresponding signals can propagate inside tunnel. In the near region, the field usually consists of many modes. However, with the increase of the distance between the transmitter and receiver, the higher-order modes of a signal experience stronger attenuation, and most of the higher-order modes are lost before the breakpoint. In the far region, i.e., after the breakpoint, the lowest-order mode is dominant. From the statistics point of view, the received signal can be presented as the sum of the line-of-sight (LoS) component and diffuse components reflected by tunnel walls, ceiling, and the ground [10, 48]. In the near region, the received signal may contain a strong LoS component and therefore, the Ricean K-factor can be relatively large. In the far region, the Ricean K-factor can be small, and even the Rayleigh distribution may be considered when there is no LoS component.

2.4 Typical propagation zones

In general, the LoS component can be strong in conventional HST communication scenarios. In tunnels, due to its leakproofness, the reflected rays can remain greatly and become more dominant in the received signal. Considering the long delay characteristics caused by the reflections in tunnels, tunnel channel measurements in different propagation zones should be conducted, and cluster delays should be deeply analyzed. There are roughly three propagation zones in tunnels, i.e., LoS, non-LoS (NLoS), and far-LoS (FLoS) zones. When the receiver is very close to the transmitter, the LoS propagation happens. When the train moves away from the transmitter, the LoS may disappear and the NLoS zone appears. When the train is far away from the transmitter, the FLoS zone can appear if there is no clear LoS component. In [30], three-dimensional (3D) frequency correlation functions were obtained based on measurements conducted in the aforementioned three zones and PDPs were obtained. The PDP in the LoS zone matches the exponential distribution very well. With the increase of travel distance in the tunnel, the LoS component disappears and numerous reflections remain due to the obturation of tunnel. Those reflections will lead to delay clusters, which fit the generalized extreme value distribution very well in the NLoS zone and Johnson SB distribution in the FLoS zone. This phenomenon is quite unique for tunnel scenarios and should be taken into account when designing HST communication systems [48]. In addition, considering the train passing by the transmitter, near-shadowing zone (NSZ) is observed in [10] before the LoS zone. In this short zone, the LoS between the transmitter and receiver is blocked, and the multipath propagation is dominate.

2.5 Parameters influencing radio propagation inside tunnel

The radio waves inside tunnel suffer more reflections, diffractions, and scattering. The parameters, such as tunnel size, tunnel shape, internal electromagnetic (EM) properties of tunnel walls, surface roughness, and antenna radiation and position, will affect the radio signal propagation inside tunnel [39].

Tunnel cross section has a distinctive influence on the propagation attenuation, especially with the increasing of the signal frequency [49]. There are different shapes of cross sections in real tunnels, such as circular, semicircular, rectangular, arched and oval ones. Some typical tunnel shapes are shown in Figure 1. In [50], a measurement campaign carried out in a subway tunnel has been introduced to characterize EM propagation in underground rail tunnel. It demonstrates that tunnel geometry, i.e., the shape of tunnel cross section and curves, have an important impact on the signal propagation, rather than the EM properties of materials. In [51, 52], the influence of rectangular cross section in tunnel has been investigated, and in [53] the attenuations in different tunnel shapes are analyzed.

The surface roughness and electromagnetic properties of tunnel walls also affect the radio propagation in tunnels. In [54], the influence of surface roughness has been studied. It is found that surface roughness of tunnel walls introduces additional power attenuation to radio signals. Moreover, the influence of humidity in conductivity and dielectric constant has been considered [55]. The results show that there is negligible effect on the dielectric constant, but not on conductivity. Beyond that, the position, polarization, and radiation pattern of transmitter and receiver antennas will also influence the radio wave propagation along the tunnel [56, 57]. In [58, 59], the authors provide the optimal radiation pattern and position of antenna inside the tunnel. By using the antennas with appropriate radiation pattern at an appropriate position, the attenuation of radio signals inside tunnel can be reduced. For investigating the influence of the antenna directivity on PL and time dispersion, the directional and omnidirectional antennas are considered in [60] under the LoS and NLoS underground environments. The results show that the omnidirectional antennas can offer better signal coverage in NLoS tunnel environment, while the directional antennas can reduce the time dispersion parameters to acquire a better channel capacity [60]. The polarization of the transmitter and receiver antennas has been studied in [61]. In an empty straight rectangular tunnel environment, rms delay spread of horizontally polarized transmitter and receiver antennas is greater than that of vertically polarized transmitter and receiver antennas if the tunnel width is larger that the tunnel height. In addition, the attenuation of EM wave for the horizontal polarization is lower than that for the vertical polarization.

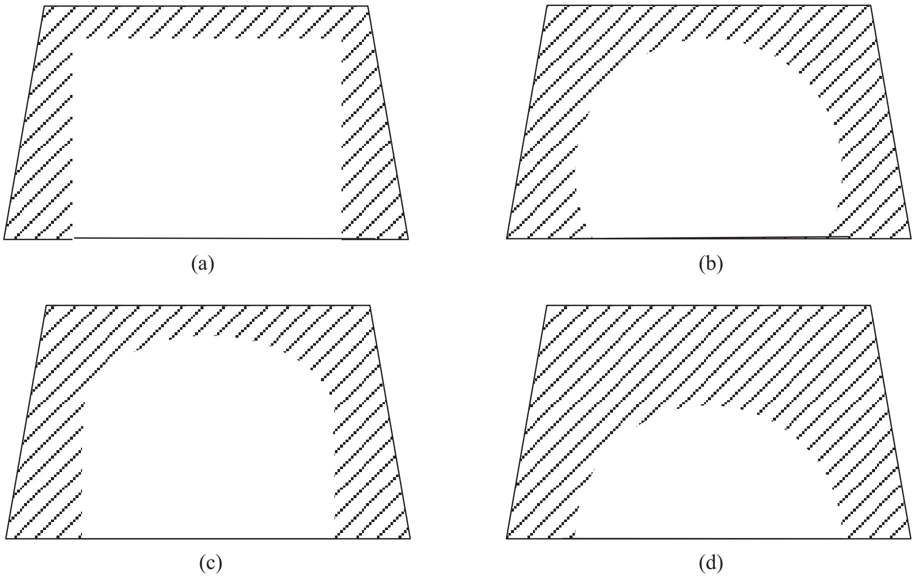

Figure 1 Typical shapes of cross sections for tunnels. (a) Rectangular tunnel; (b) arched tunnel; (c) horse-shoe shaped tunnel; (d) semicircular tunnel.

3 HST channel models in tunnel scenarios

Several HST tunnel channel models have been presented in the literature [62–69]. In this section, we will first discuss possible network architectures for tunnel scenario and then present various types of tunnel channel models according to different modeling methods.

3.1 Network architectures for tunnels

As mentioned earlier, two solutions are introduced to provide wireless coverage inside tunnels, i.e., leaky feeders and DAS [10]. Leaky feeders are widely used in current HST tunnel communications, as they can provide a good coverage and do not require special planning. However, it requires a high cost of the installation and a rather complex maintenance, especially when medium-length or even long tunnels are needed in newly-built high speed railways. In this case, solutions based on the use of antennas are becoming more attractive, such as the DAS. In DAS, all the antenna elements are installed at planned distance intervals and connected to a BS via wires or fibers. Compared with leaky feeders, the DAS can provide considerable gain in coverage, capacity, and spatial diversity against fading by using antenna elements at different locations [11]. It also has some other advantages, such as quick installation and easy maintenance. Moreover, adopting the conventional cellular architecture, where the users inside trains communicate directly with outdoor base stations (BSs), leads to several communication problems. Therefore, MRS need to be considered. It can be deployed on the surface of the train to improve the quality of received signals [6], and used to solve the spotty coverage problem and reduce the penetration loss of signals. In addition, potential applications for MIMO technique to increase the channel capacity of the propagation channel in tunnels are investigated [32, 70]. The appropriate combination of DAS, MRS, and MIMO technique, as illustrated in Figure 2, is viable to meet the continuous and high-quality wireless communication requirements inside the tunnel. Furthermore, considering other cellular architectures in the future, more HST tunnel channel models are needed.

3.2 Modeling approaches of HST tunnel channel models

According to different modeling approaches, the current tunnel channel models in the literature [71–84], presented in Table 2, can be classified as deterministic [21, 23] and stochastic channel models [63, 64, 74]. The detailed classification of tunnel channel models is illustrated in Figure 3.

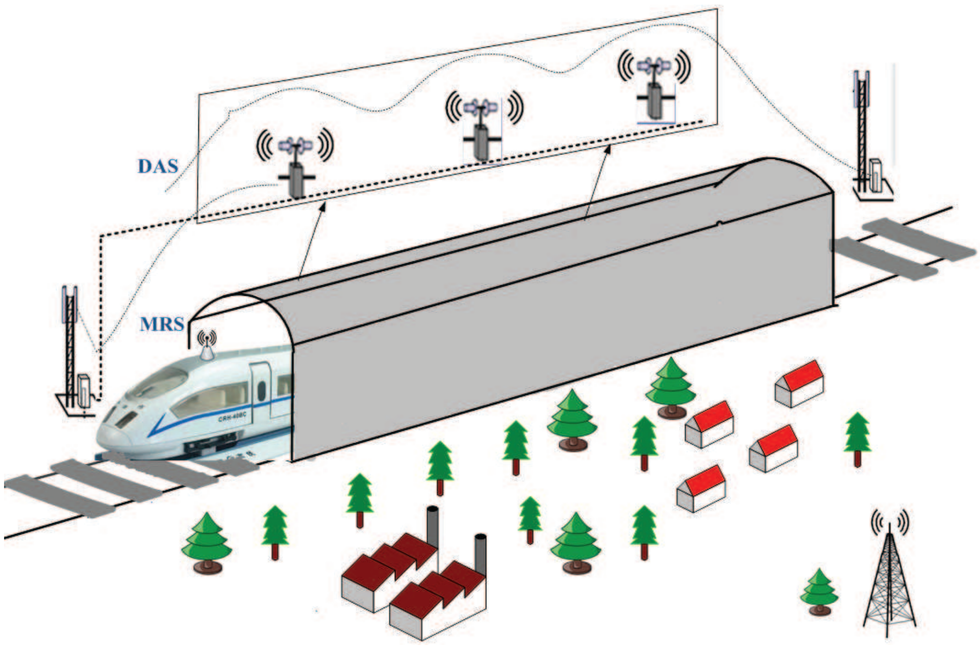

Figure 2 (Color online) HST cellular architecture for tunnel scenario.

3.2.1 *Ray-tracing channel model*

Ray-tracing technique has widely been used in predicting the radio wave propagation in confined environments like HST tunnels. Ray-tracing channel model can be applied to predict the PL and the signal delay inside tunnels at any location of the receiver [56]. Based on the GO theory and uniform-theory-of diffraction (UTD), the EM waves are regarded as optical rays reflected from the tunnel walls and diffracted near the tunnel edges. However, as a special type of indoor scenario, the tunnel environment consisting of not only the walls, but also some other obstacles, such as rails, devices and the moving trains. Since the surfaces of these obstacles are not perfectly flat, ray diffusion should be considered, and the room EM wave propagation can be applied to analyze the diffuse field. Based on the room EM theory, models of the delay power spectrum of confined room channels have also been proposed. At the receiver, the EM field is obtained by the summation of the direct ray and diffused ones. The different phases of the summed rays will result in a variation of signal power along the distance, and the signal propagation predictions in tunnels can be developed. In [85], based on a new ray launching method, a 3D ray-tracing channel model in HST tunnel scenarios was introduced. This model resulted in a complex CIR that incorporates some channel information, such as the waveguide effects in tunnels and the impact of another passing train simulations for time delay and Doppler shift.

The ray paths can be calculated by several approaches, such as the images method, shooting and bouncing ray (SBR) method, and the ray-density normalization (RDN) method. For the images method, all the reflected rays obtained at the receiver can be taken as radiated directly from the virtual sources, which can be obtained by the mirror symmetry of the transmitter. A ray-tracing model based on the images method was presented in [56] to predict the rms delay spread in a tunnel. For the SBR method, the transmitter inside the tunnel is considered as a source that shoots a large number of rays in arbitrary directions. The received signal can be obtained by the summation of all contributions within a reception sphere, the radius of which depends on the length and angle of rays. The SBR-based ray-tracing method was proposed in [86] to calculate the extra losses of tunnel curve, according to the number of reflections in the horizontal and vertical tunnel walls. For the RDN method, the radio waves that travel inside a tunnel have many propagation paths, while each propagation path is assumed to consist of several rays. The

Table 2 Important tunnel channel models*

Ref.	Channel model	Scenario	Channel characteristics	Antenna config.
[76]	Ray-tracing model	Rectangular tunnel	The received power	SISO
[77]	Ray-tracing model	Rectangular subway tunnel	PSD, Doppler spread, Doppler shift	SISO
[56]	Multi-mode model	Rectangular road tunnel, subway tunnel	Field distribution, PDP	SISO
[78]	Multi-mode waveguide model	Rectangular underground mine, Semicircular subway tunnel	Angular properties, correlation of array elements, PAS	MIMO
[79]	GO model	Rectangular underground mine	Large-scale fading, small-scale fading	SISO
[25]	FSMM	Rectangular subway tunnel	Number of states, distance interval, SNR	SISO
[80]	Propagation -graph theory based model	Arched tunnel	Channel coefficients, CIR in delay, antennas' correlation coefficient, channel capacity	MIMO
[81]	Physics-based deterministic UWB	Rectangular tunnel	Received power, rms delay spread, CIR, channel transfer function	SISO
[63]	GBSB model	Rectangular tunnel	Space-time correlation function, PDF of AoA, Rice factor	MIMO
[74]	WINNER model	Rectangular Subway tunnel	PL, fast fading, delays, AoA, AoD	MIMO
[64]	GBSM	Semicircular tunnel	Time-variant transfer function, frequency correlation function, CCF, ACF	MIMO
[82]	Hybrid model	Rectangular tunnel	Received power	SISO

* AoA: angle of arrival; AoD: angle of departure; PSD: power spectrum density; PAS: power azimuth spectrum atrix.

number of rays can be determined by the ray density and can be applied to normalize the contribution of each ray to the total field. The signals at the receiver are considered as the summation of all the rays with different amplitudes, phases, and ray densities. The RDN-based ray-tracing method can be used to calculate PL in arbitrary shaped tunnels [87].

For the ray-tracing model based on GO theory, the EM fields at any point in space can be computed as a summation of rays from all possible paths. The paths are obtained using the method of images on the ceiling, floor and tunnel side walls. Thus, the electric field is computed by taking into account the laws of reflection and the constitutive parameters of the tunnel walls as follows [56]:

$$E_x^{R_x} = E_x^{T_x} \sum_{p,q} \frac{\mathrm{e}^{-\mathrm{j}kr_{pq}}}{r_{pq}} S^p \cdot R^q, \tag{2}$$

where $E_x^{T_x}$ and $E_x^{R_x}$ are the electric fields at the transmitter and the reciter, respectively, r_{pq} is the distance between the image and the receiver, R^q and S^p are the Fresnel reflection coefficients on the horizontal and vertical walls, respectively.

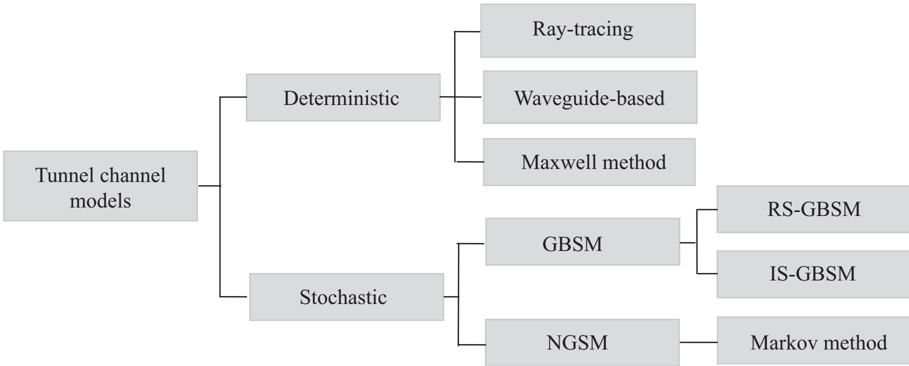

Figure 3 Classification of HST tunnel channel models.

3.2.2 *Waveguide channel model*

Considering the geometry of tunnel and the conductivity of tunnel materials, the radio waves propagate inside a tunnel can be modeled as the same way as propagating inside a waveguide. As mentioned in [88], when the frequency is higher than hundreds MHz, the waveguide effect will emerge. In addition, due to the unique structure of tunnel, there are rich reflections and scattering components which will introduce the waveguide effect inside tunnel [4]. In [21], a waveguide model was proposed, which adopts the modal theory to describe the radio wave propagation inside a tunnel that is considered as a rectangular waveguide. The mode, also called the transverse mode, is used to describe the field distribution of waveguide cross section. There are two kinds of propagation modes propagating in a waveguide: transverse electric (TE) mode (or H_{mn}) and transverse magnetic (TM) mode (or E_{mn}). Each mode has a cutoff frequency f_T, which is related to the tunnel size and mode values m and n. When a given operating frequency f_c is higher than f_T of one or more modes, these modes can exist inside a tunnel. The field distribution can be viewed as the weighted sum of all modes field. In the near region, the EM field consists of many modes, which interact and result in the rapid attenuation. There are many factors contributing to the signal attenuation in tunnels, such as the operating frequency, tunnel size, permittivity of tunnel walls, and propagation modes. In the far region, the lowest-order mode is dominant. A waveguide model can be applied to model the far region in tunnels with good approximation, while it is not suitable to approximate the signal propagation in the near region. Therefore, a waveguide model should be combined with another model, which can model the multi-mode cases, to model a completed HST tunnel channel.

With the increase of the communication frequency, the operating frequency can be higher than the cutoff frequencies of many propagation modes. Thus, there will exist a wide range of modes propagating inside tunnels. In long tunnels, when the operating frequency is up to a few GHz, the distance of near region becomes longer, and therefore the time duration that train encounters in the near region becomes longer. This means that the near region will become larger with the increase of the operating frequency inside tunnels. Moreover, when a train travels inside a tunnel, the train itself will also have an influence on the field distribution. Hence, the multi-mode wave propagation and the impact of train itself on the field distribution at higher operating frequency need to be further investigated.

3.2.3 *Full-wave model*

The full-wave model, such as finite-difference time-domain (FDTD) technique [23], can be obtained by solving Maxwell equations using numerical methods. There are several numerical methods to be applied to solve the Maxwell equations. The most often used ones are FDTD, method of moments (MoM) [89], finite element method (FEM) [90], and vector parabolic equation (VPE) method [9, 91]. The FDTD technique focuses on solving partial differential equations at discrete times and discrete points. It can be applied to study the EM propagation accurately in complex environments as it fully considers the influences of reflection, diffraction, and refraction. The MoM is a widely used approach that can solve scattering, EM boundary, and volume integral equation problems. By using MoM, the operator equations

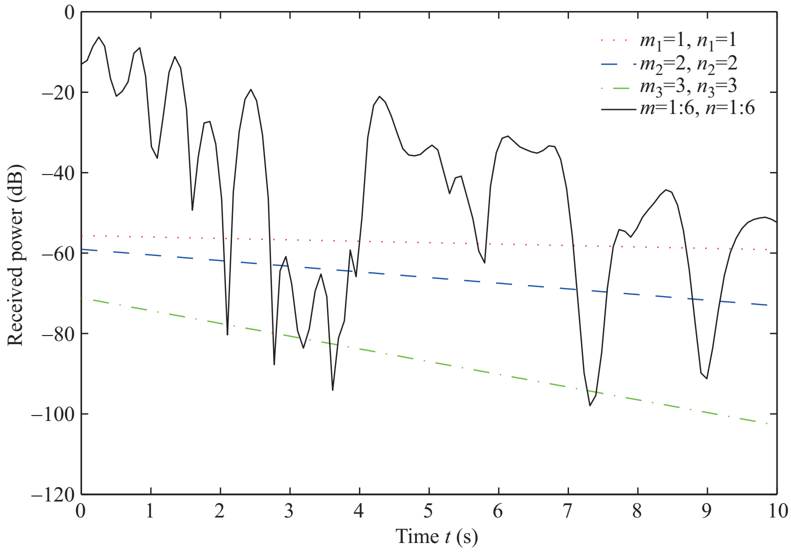

Figure 4 (Color online) The received power for multi-mode and single-mode cases in a multi-mode tunnel channel model.

can be expressed in a matrix form and EM field can be obtained by solving the matrix. The FEM is often used to find approximate solutions for partial differential equations. It can be applied to calculate EM distributions in arbitrary-shaped railway tunnels, but it has high computational complexity. This method can be used to analyze the EM field distribution in railway tunnel scenario with train [90]. The VPE method can be used to calculate the EM field in straight and curved tunnels with reasonable computational complexity [9].

3.2.4 *Hybrid model*

A variety of approaches has been applied to model the propagation channel in tunnel scenarios. Each method has its own advantages and disadvantages. To achieve the complementary advantages, hybrid channel modeling methods have been investigated. In [56], a multi-mode model was developed, which is a hybrid model that combines a GO model and a waveguide model using Poisson sum formulas. It used a mode matching technique to convert sum of rays of the GO model to sum of modes by mode intensities, and can characterize the natural wave propagation completely both in near and far regions of the source. Moreover, the PDP can also be characterized, which is related to the dispersion among modes and frequency elements. Further, based on the multi-mode model, an in-depth analysis of the tunnel channel characteristics was presented [56]. In [75], a time-dependent multi-mode model was proposed and some small-scale fading characteristics were further investigated, such as the temporal ACF and Doppler PSD. Moreover, the received power along the multi-mode and single-mode cases are shown in Figure 4. From this figure, we can observe that the lowest-order mode experiences the least attenuation and higher-order modes experience higher attenuation.

In addition, a hybrid model, which combines the ray-tracing and VPE method, is proposed in [82]. By using the advantages of VPE, the limitation of ray-tracing method can be compensated. Therefore, the appropriate combination of two models, such as GO model with waveguide model, and ray-tracing with full-wave models, can be considered in the future modeling.

3.2.5 *GBSM*

A GBSM can be characterized by the specific transmitter, receiver, and scatterer geometries which are assumed to follow certain probability distributions [92]. In RS-GBSMs, all the effective scatterers are assumed to be located on regular shapes, such as two-dimensional (2D) one-ring, two-ring, and ellipse models, and 3D one-sphere, two-sphere, and elliptic-cylinder models. Based on the relationships of geometrical shapes, the CIR can be derived and channel statistics can be further calculated [93]. In [6], a non-stationary wideband RS-GBSM for HST channels was proposed. The proposed GBSM is based on a concentric multi-ellipse model with all the model parameters as time-variant. Some small-scale fading characteristics were derived, such as the temporal ACF, spatial CCF, and Doppler PSD. It has been shown that the time-varying angles will affect the time-variant space CCFs, ACFs, and Doppler PSDs. Note that the Doppler PSD is symmetrical for isotropic cases only, and different angular parameters, such as angle of motion of HST and the initial mean AoA will affect considerately the trends of PSDs. The GBSM in [6, 94] can be applied to different HST scenarios, such as the open space, viaduct, and cutting scenarios, but not for tunnel scenarios. Because of the long and narrow space inside a tunnel, the complex structure of tunnel walls, and poor smoothness of interior walls, a tunnel can bring more scatterers. The scatterers generally concentrate on the top, bottom, and both sides of tunnel walls. Therefore, the geometric distribution of scatterers in tunnels is very different from those in other HST scenarios. In [63], a 2D narrowband geometry-based single-bounced (GBSB) channel model was proposed, which assumed that the scatterers are well-distributed on both sides of the tunnel. The CIR was expressed by the signal waves summations of different amplitudes, phases, and delays at the receiver. The proposed GBSB model is relatively simple and cannot describe the real tunnel channel. Therefore, a 3D channel model considering both the azimuth and elevation angle are needed in tunnel scenarios. In [64], a 3D GBSM for road tunnel [95] was proposed, then some key statistical properties were studied. However, this tunnel GBSM is under the wide-sense stationary assumption which is unreasonable and ignores the non-stationarity resulting from the fast movement of the transmitter and/or the receiver [96, 97]. From the above, a 3D non-stationary channel model in HST tunnel scenarios, is still desirable.

3.2.6 *FSMM*

In [25], an FSMM for tunnel channels in a communication-based train control system was proposed based on real channel measurements where the locations of the train were known. The proposed FSMM was characterized by channel states which can be defined according to different received SNR levels. Different from other existing tunnel channel models, the proposed FSMM takes the train locations into consideration, which makes the model more accurate. The tunnel can be divided into intervals in terms of the distance. Each interval is related to a state transition probability matrix and then an FSMM for tunnel channels can be designed. It has been demonstrated that the number of states has a certain influence on the accuracy of the proposed FSMM, as well the distance between the transmitter and receiver.

4 Research directions in HST tunnel channel measurements and models

In this section, we will discuss a few future research directions in HST tunnel channel measurements and models, which can be helpful for carrying out future channel measurements and developing realistic tunnel channel models.

4.1 Statistical properties

For better understanding and analyzing of the HST communication system in tunnels, the studies of the statistical properties are essential. In Table 1, some channel characteristics were obtained from channel measurements. However, most of the characteristics mainly focus on large-scale fading. In Table 2, some tunnel channel models have been proposed. However, the corresponding analysis of small-scale fading characteristics are simplified. They cannot be applied to mimic the propagation environment inside tunnel very well. Hence, it is desirable to further study the statistical properties of HST tunnel channel models.

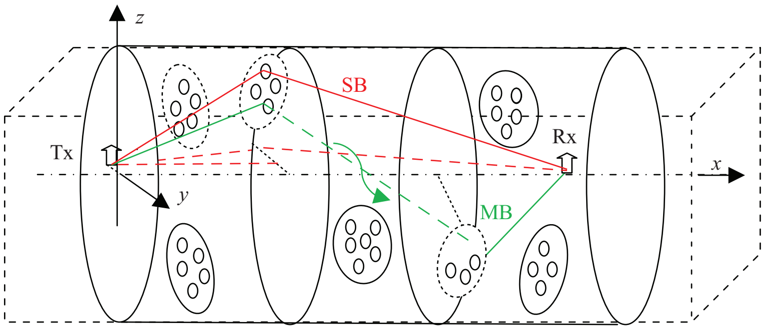

Figure 5 (Color online) A 3D RS-GBSM for HST tunnel scenarios.

4.2 Non-stationarity of HST tunnel channels

Measurements have demonstrated that the stationary interval of HST channel can retain a very short time in [98–100]. The finding applied equally in the HST tunnel channels. However, few channel measurements and models in tunnel scenarios have considered the non-stationarity features. Therefore, non-stationary channel models considering the time-variant parameters should be further investigated, and ideally verified by real-field measurements.

4.3 3D GBSMs

The existing GBSB model [63] mainly considered the 2D influences of the tunnel side-walls under the assumption of wide-sense stationary condition. It was a simplified 2D channel model without considering the elevation angle. More accurate 3D non-stationary wideband tunnel channel models are needed, which should consider the elevation angels and the influence of train itself, tunnel ground, and tunnel roof. It can be used to mimic the real tunnel channel more accurately. Combining the WINNER model method and tunnels' unique propagation characteristics, the HST tunnel surroundings can be characterized as a 3D regular shape, such as cuboid or circular model [101]. Figure 5 illustrates the proposed 3D tunnel GBSM, which consists of the LoS, single-bounced (SB) components, and multiple-bounced (MB) components. This kind of tunnel channel model can be developed under the clusters-based framework. It assumes the clusters are randomly distributed on the tunnel internal surfaces. Then, according to the geometrical relations of AoAs and AoDs, the CIR can be derived. Furthermore, the statistical properties can be further investigated, such as the temporal ACF, spatial CCF, and PSD for the HST channels in tunnel scenarios.

4.4 Generic channel model for different types of tunnels

There are several types of HST tunnels in reality, such as rectangular, circular, and arched tunnels. Different shapes of the tunnels have different impacts on channel characteristics, and will result in different degrees of attenuation of signals. In a rectangular tunnel, there are two vertical walls and two horizontal planes. In a circular tunnel, there are circular walls and a floor. Moreover, there are also two kinds of arched tunnels. One consists of an arched roof and three walls, and the other includes arched walls and a floor only. For different types of tunnels, there are different methods to model the underlying channel. However, an accurate generic channel model that can be applied to different types of tunnel channels by adjusting channel parameters is desirable and deserves further investigation in the future.

4.5 System performance

For system design and network planning, the investigation of HST tunnel communication system performance is essential. In [102], MIMO techniques have been investigated to improve link reliability using bit error rate (BER) and/or channel capacity. In addition, some alternative and easiest receiving diversity schemes, such as selection combining and maximum ratio combining (MRC), presented. In [103], the BER performance of a subway tunnel communication systems was studied by considering the space diversity techniques, such as MRC and cyclic delay diversity. Furthermore, the implementation of DAS in railway tunnel communication systems was evaluated in [104] by analyzing the coverage efficiency. In the future, some new technologies, such as Massive MIMO, can be applied to HSTs to boost their performance. Therefore, more performance analysis of HST tunnel communication systems, evaluating other schemes and considering more system performance indicators, e.g., capacity and quality of service (QoS), is required.

5 Conclusion

This article has provided a review of channel measurements and models in HST tunnel scenarios. We have surveyed tunnel channel measurements according to carrier frequencies, tunnel parameters, antenna configurations, and channel statistics. Then, we have classified some existing tunnel channel models according to different modeling methods. Some large-scale and small-scale fading characteristics have also been presented. Finally, to develop more practical HST channel models for 4G and 5G systems, some future research directions in HST tunnel channel measurements and modeling have been highlighted.

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