Challenges Toward Wireless Communications for High-Speed Railway

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***Abstract*—High-speed railway (HSR) brings convenience to peoples' lives and is generally considered as one of the most sustainable developments for ground transportation. One of the important parts of HSR construction is the signaling system, which is also called the "operation control system," where wireless communications play a key role in the transmission of train control data. We discuss in detail the main differences in scientific research for wireless communications between the HSR operation scenarios and the conventional public land mobile scenarios. The latest research progress in wireless channel modeling in viaducts, cuttings, and tunnels scenarios are discussed. The characteristics of nonstationary channel and the line-of-sight (LOS) sparse and LOS multiple-input–multiple-output channels, which are the typical channels in HSR scenarios, are analyzed. Some novel concepts such as composite transportation and key challenging techniques such as train-to-train communication, vacuum maglev train techniques, the security for HSR, and the fifth-generation wireless communications related techniques for future HSR development for safer, more comfortable, and more secure HSR operation are also discussed.**

***Index Terms*—Channel modeling, composite transportation, cuttings and tunnels, high-speed railway (HSR), operation control system, train control data, viaducts.**

Manuscript received November 22, 2013; revised January 29, 2014; accepted March 1, 2014. Date of publication April 30, 2014; date of current version September 26, 2014. This work was supported in part by the National Natural Science Foundation of China under Grants 61222105 and U1334202, by the Fundamental Research Funds for the Central Universities under Grant 2010JBZ008, by the Project of State Key Laboratory of Rail Traffic Control and Safety under Grant RCS2014ZT11, and by the Key Project of the Chinese Ministry of Education under Grant 313006. The Associate Editor for this paper was F.-Y. Wang.

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Digital Object Identifier 10.1109/TITS.2014.2310771

I. Introduction

With the fast development of high-speed railway (HSR) in the world, the maximum train moving speed has reached nearly 575 km/h, trialed by the French National Rail Corporation. With increased train speed, the issue of train operation safety has attracted more and more attention. The ground infrastructure (e.g., trackside equipment), the moving body (e.g., train), and the signaling system are in general the three main parts contributing to the HSR operation safety. Of these three parts, the signaling system, which is also called the train operation control system, is the key part and is regarded as the nerve center of the HSR system. A standard has been set up for the train operation control system, which is known as the European train control system (ETCS) for HSR and the communication-based train control (CBTC) system for subway [1]. To realize a safe operation of the HSR, a large number of studies on intelligent transport system applications have been conducted [2]–[6]. In order to make the train operation control system work better, maintaining a reliable communication link between the train and the ground, dedicated mobile communications play a key role. Such a communications system is called the global system for mobile communications for railway (GSM-R), a narrow-band communication system.

With the rapid growth of railway services, broadband communication systems for railway called long-term evolution for railway (LTE-R) will be deployed. Except for the train control data transmission, LTE-R is also expected to offer passengers services such as Internet access and high-quality voice or mobile video broadcasting. For instance, many wireless system deployments are currently being developed to realize driverless railway and subway systems, such as in New York, NY, USA; Paris, France; Malaga, Spain; and Singapore [7]. Another example of broadband communication application for railway is the radio communication systems that are devoted to providing Internet access to the train passengers. This is not a very common feature (as of today) because it is expensive to implement. However, some HSR operators begin to offer this service using ad hoc networks. On the other hand, telecommunications companies may extend its coverage area to railway tracks, permitting the passengers to access to it. This is very common in both subway and commuter trains. However, it cannot be considered as railway communications. One of the European HSR operators started in 2005 to offer Internet access to its customers [8]. The access technology was a combination of satellite access and terrestrial access based on IEEE 802.11 [9]. There are many other technologies (in use or in the development stage) devoted to provide passengers with access to the Internet, such as the Mobile Wideband Global Link System [10]. In Spain, the TECRAIL project [11] has been carried out to evaluate the feasibility and performance of a broadband system (LTE) on railway communications and signaling systems. LTE for railway was determined in the 7th World Congress on High-Speed Rail to be the next-generation communication system for HSR [12]. Within IEEE 802.15 Task Group 4p, a standard for "Positive Train Control" is currently being developed [13]. The development of this standard has been triggered by the "Rail Safety Improvement Act of 2008" of the United States Congress. The scope of this standard is to monitor and control train movements. Various frequency bands in the range from 161 up to 5800 MHz are considered.

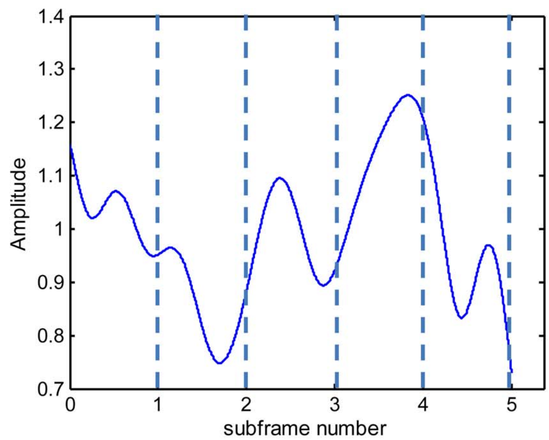
Whether it is a GSM-R, an LTE-R, or an IEEE 802.15.4p system, to guarantee a reliable communication, the major prerequisite condition is a thorough knowledge of the propagation characteristics of the wireless channel. Wireless channel modeling is the important basis and the essential means for communication network planning and optimization, the transmitter and receiver design, and the physical and upper layer key technologies selection. There are some influential research groups focusing on wireless channel measurement and modeling. Rappaport *et al.* are now working toward 60-GHz wireless communications and channel modeling [14]. Matolak *et al.* drew their attention on vehicle-to-vehicle (V2V) channel modeling [15]. As for the studies of channel modeling methodologies, Sivertsen *et al.*, Cheng *et al.*, and Guan *et al.* devoted themselves to the research studies on the multi-input–multi-output orthogonal frequency-division multiplexing (MIMO-OFDM) channel modeling [16], the geometry-based stochastic channel modeling [17], and the ray-tracing technique [18], respectively. Richter *et al.* proposed a novel flexible algorithm called RIMAX for channel parameter extraction from channel sounding measurements [19]. In addition to the academic circles, some international academic organizations such as the European cooperation in the field of scientific and technical research (COST) and the WINNER project group [20] and some companies such as MEDAV in Germany and Elektrobit in Finland also do a lot of work on channel modeling, standardization, and the supply of channel measurement instruments. Although much remarkable progress has been achieved in the area of wireless channel modeling, most results are for public land mobile communications, but not for dedicated mobile communications for railways. As some research has shown, when key techniques developed for public land mobile radio (such as synchronization [21]–[23] and channel estimation [24]) are applied to the existing wireless network of HSR, the communication quality is poor, with a high rate of dropped calls and low data rate observed [25]. Matolak and Athens also found that nonstationary V2V channel models yielded results (for OFDM access) that are much different than those on stationary channels [26]. Following the conclusions drawn from [27] and [28], in a suburban area but with HSR-specific topography of cuttings [27] or viaducts [28], the path loss prediction results between the Hata model [29] and that of the actual test results obtained from Zheng-Xi HSR lines in China show that the conventional Hata model prediction error may reach 20 dB. What causes such large prediction performance degradation? The description in Sections II and III aims to provide an answer to this question.

Except for the fundamental problems of wireless channel modeling, the working frequency band should be taken into careful consideration due to serious interference and security problem. The next-generation broadband wireless communication system for HSR and other related technologies should be also mentioned, as will be described in subsequent sections.

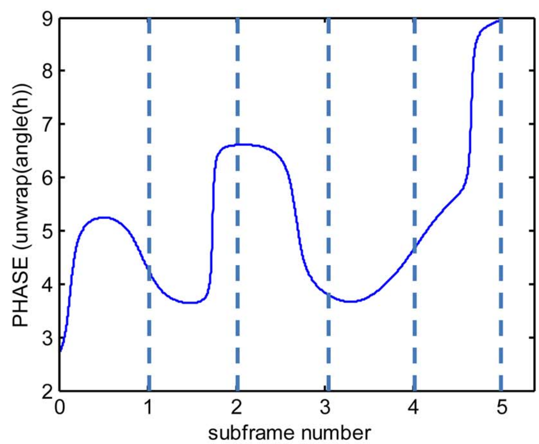
II. Differences Between Rail Mobile Communications and Public Land Mobile Communications

Some of the typical features for HSR must be addressed. Special propagation scenarios, high moving speeds over 300 km/h, higher requirements of quality of service (QoS), harsh electromagnetic environments, and interference are the main differences between rail mobile communications and public land mobile communications.

1) As is known, knowledge of the wireless channel is the fundamental basis for the planning of wireless communications network and the design of transceiver. A wireless channel has a close relationship with physical conditions, topography, and the surrounding environments. The typical railway environments are characterized by special scenarios such as viaducts, cuttings, tunnels, crossing bridges, railway stations, marshaling stations, and some combined scenarios such as the tunnels group and the combination of viaducts and tunnels. Based on the actual test data collected from Zheng-Xi HSR lines, conclusions are drawn that these special scenarios sometimes cause deep fading of the signals [30], [31]. In addition, obstacles such as passing trains, arched grids, wind barriers, and the acoustic barriers along the railway tracks may cause extra path loss due to obstruction, reflection, diffraction, or scattering. This may be cast into the concept of urban furniture proposed by Gougeon *et al.* [32], where the trees, and the wire rods, and the traffic signs, the street lamps in the urban areas are referred to as the urban furniture, which may cause the reflection or diffuse scattering loss. Similarly, the special scenarios along the railway lines can be regarded as the railway furniture.
2) High speeds over 300 km/h for HSR bring new problems that may not be encountered in highway traffic. In general, for highway traffic with moving speeds below 200 km/h, the wireless channel is often assumed to be wide-sense stationary uncorrelated scattering (WSSUS), which may not pertain for HSR. For one reason, when the speeds of the train are over 300 km/h, the wireless channel exhibits rapidly time-varying and nonstationary features. For another reason, the line-of-sight (LOS) component exists in the majority of the HSR scenarios, and the number of scatterers and obstacles is limited. Thus, the spatial correlation between different multipath elements can be large, resulting in the correlated



(a)



(b)

Fig. 1. (a) Amplitude variation versus LTE subframe number. Data stream follows the LTE Release 9 V9.2.0 standard [32]. The sampling rate is 30.72 MHz, with 30 720 samples for one subframe; the working frequency is 2.4 GHz. Typical extended pedestrian A channel model. The moving speeds are 360 km/h. Five subframes are observed. (b) Phase variation versus LTE subframe number. Data stream follows the LTE Release 9 V9.2.0 standard [32]. The sampling rate is 30.72 MHz, with 30 720 samples for one subframe; the working frequency is 2.4 GHz. Typical extended pedestrian A channel model. The moving speeds are 360 km/h. Five subframes are observed.

scattering. Simulations have been carried out based on LTE Release 9 V9.2.0 [33] to verify fast variation of the wireless channel within one subframe of 1-ms duration.

Fig. 1(a) and (b), respectively, shows the amplitude and the phase variation of the signals versus LTE subframe number through the wireless channel. It is clearly shown in Fig. 1(a) and (b) that the channel varies quickly and randomly within one subframe. It is inappropriate to adopt the channel estimation method such as the linear interpolation method to estimate a rapidly varying channel since this method assumes the channel to be essentially constant over a subframe. This in another way to illustrate that the pilot design pattern presented in LTE Release 9 V9.2.0 cannot support high moving speeds. High mobility also introduces the high Doppler frequency shifts and spreads. If the train frequently moves between different physical environments, such as from viaducts to cuttings or tunnels, fast variation of the multipath structure results. This may introduce time-varying Doppler shifts superimposed on each multipath component, greatly increasing the difficulty of channel estimation and Doppler shifts estimation. The phenomenon of birth–death of multipath may arise. Moreover, frequent handover may happen when there is a high-speed train (HST) operation, which results in the drop calls or, more seriously, the interruption of reliable transmission of the train control signals.

3) The QoS requirements either in narrow-band communication system GSM-R or in broadband communication system LTE-R are somewhat higher than that of the public land mobile communication network, for example, GSM or LTE. Some performance evaluation indexes such as transmission interruption rate have never appeared in the GSM system. GSM is mainly used for voice communication, and it even allows for dropped calls occasionally. However, GSM-R is in charge of the train control signals transmission; hence, it requires much more reliable communication. In the standard of ETCS [1], the QoS requirement for GSM-R should be satisfied with testability, controllability, reliability, effectiveness, maintainability, safety, and security. Note that dedicated mobile communications in HSR are for train operation control services. Taking the parameter of transmission delay for train control signals transmission as an example, correct train control signals should be transmitted within 10 s for HSR operation control system and within 3.6 s for subway operation control system. If the operation control system received no information or incorrect train control signals in a required time range, it will start the automatic train control mechanism, and the train or the subway may automatically stop. For another example, the call setup time for trunking communication services in LTE-R is less than 300 ms, whereas such requirement is 5 s in LTE system.
4) GSM-R in China uses the 883- to 889-MHz frequency band for the uplink and the 930- to 934-MHz frequency band for the downlink, as shown in Fig. 2. This frequency band is shared with services offered by the operator of China Mobile. This can yield serious cochannel interference. The bandwidth of 4 MHz is divided into 19 frequency channels (from No. 999 to No. 1017). In a GSM-R network, the frequency reuse factor is from four to seven, which means that four frequency channels are available in each cell at most. The GSM-R system is required to support more and more services, such as train control, dispatching, and train and environment monitoring. Thus, the GSM-R frequency band will become more and more crowded, and the intrasystem interference is serious. WiFi technology is used in subway for train-to-ground communications in China. It operates at 2.4 GHz, an unlicensed frequency band, which will have serious interference and security problems. Moreover, there will be strong electromagnetic interference caused by the arched grid network used as train power supplies.

The previously mentioned explanations of the main differences between the rail mobile communications and the public land mobile communications will be further addressed by a review of the latest research on channel modeling under HSR scenarios.

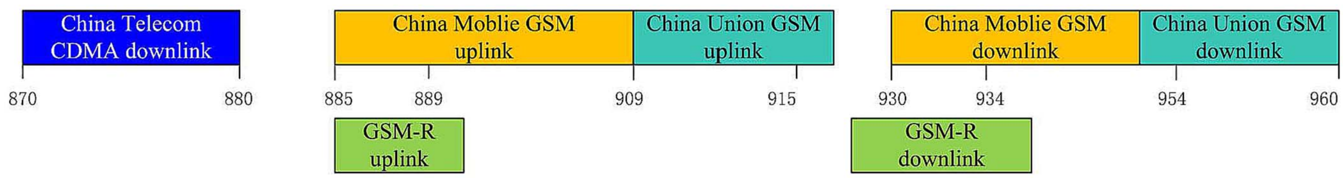


Fig. 2. Diagram of 800- to 900-MHz frequency allocation in China.

III. Wireless Channel Modeling Under HSR Scenarios

Here, the latest progress in wireless channel modeling for HSR is presented. The scene partitioning for HSR, channel measurements, channel modeling for cuttings, viaducts and tunnels, and antennas modeling are discussed in detail.

A. Scene Partitioning for HSR

The path loss and multipath effects are in disparity under various propagation environments, leading to the impossibility of accurate pass loss predictions under different propagation environments with the same channel model. That is to say, radio wave propagation scene partitioning plays an important role in wireless channel modeling. Special HSR scenarios such as cuttings, viaducts, tunnels, and crossing bridges have significant impacts on the propagation characteristics. However, these HSR scenarios have rarely been investigated. Few channel measurements and standard channel models have actually been developed.

Several international organizations and related standards should be mentioned when we refer to the scene partitioning. International Mobile Telecom System 2000 defines nine terrestrial scenarios and four satellite scenarios [34]. The Universal Mobile Telecommunications System (UMTS) developed by 3GPP defines a smaller set of radio propagation environments, which adequately span the overall range of possible environments [35]. For practical reasons, these operating environments are an appropriate subset of the UMTS operating environments described in Recommendation ITU-R M.1034 [34]. The WINNER project group defines four typical scenarios, including in and around building, hot spot area, metropolitan, and rural scenarios. The only scenario appropriate for HSR defined in the WINNER project is the WINNER D2 model (rural moving network) [20]. However, this model has only one LOS path, inappropriate for most special HSR scenarios such as cuttings, tunnels, and crossing bridges. Moreover, the working frequency of WINNER D2a is at the 2- to 6-GHz frequency band, unsuitable for dedicated mobile communications network for HSR operating at 930 MHz.

As part of the latest work of the research group of Prof. Bo Ai, the HSR scenes are partitioned into 12 types. Detailed description about scene partitioning for HSR can be found in the literature [36]. Table I summarized the scene partitioning for HSR.

TABLE I
Scene Partitioning for HSR

Scenes	Definitions	Scenes	Definitions	Scenes	Definitions
S1	Viaduct	**S5**	Water-5a: River and lake areas	**S9**	Mountain-9a: Normal mountain
			Water-5b: Sea area		Mountain-9b: Far-mountain
S2	Cutting	**S6**	Urban	**S10**	Desert
S3	Tunnel	**S7**	Suburban	**S11**	Combination scenario-11a: Tunnel-group
					Combination scenario-11b: Cutting-group
S4	Station-4a: Medium or small sized station	**S8**	Rural	**S12**	In-carriage-12a: Relay transmission
	Station-4b: Large station				
	Station-4c: Marshalling station and container depot				In-carriage-12b: Direct transmission

B. Channel Measurements at High Moving Speeds

Pass loss prediction modeling has a close relationship with the topography and the physical environments, whereas the multipath fast fading modeling has a close relationship with the moving speeds. High moving speeds make the work of the channel measurements more challenging. One scheme of channel measurements is the utilization of the existing GSM-R network. In order to pick up samples that can capture the fast fading characteristics, the distance between two adjacent fades should be, at most, $\lambda/2$, corresponding to a time interval of $\lambda/2v$, where v is 100 m/s when the train moves at the speeds of 360 km/h. Then, the sampling interval between two adjacent samples at 900 MHz should be $[3 \times 10^8/(900 \times 10^6 \times 100 \times 2)] \approx 0.0016$ s, which means 1600 samples per second. In this scheme, the measurement instrument is equipped on the train, receiving signals transmitted from the running communications network. The cells for HSR communications provide zonal coverage along the railway tracks and generally use five or seven different frequency channels for cell multiplexing. Therefore, if we want to pick up samples at the same frequency channel when the train moves along the tracks, it should have to pass through other four frequency channels, which means that the actual sampling rate should be $1600 \times 5 = 8000$ samples/s. Thus, this measurement scheme invokes strict requirement for the fast enough sampling rate of the measurement instruments.

Another scheme of channel measurement is the utilization of channel sounder, as shown in Fig. 3 [37].

This measurement is conducted on Beijing–Tianjin HSR. The No. 0 high speed integrated inspection train (NHSIIT) at the speeds of approximately 240 km/h is employed. The transmitter antenna is equipped on the NHSIIT, whereas a large

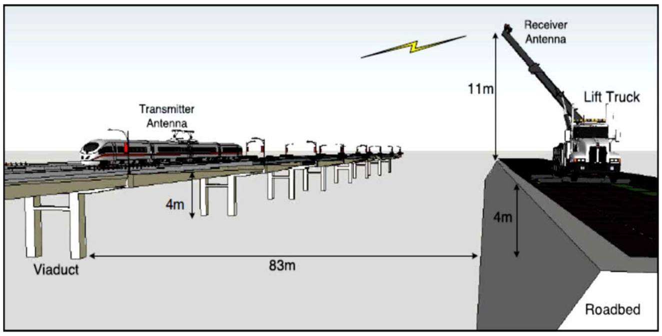


Fig. 3. Channel-sounder-based channel measurements in high-speed moving train [37].

crane is adopted to equip the receiver antenna. The viaducts and roadbeds are covered with agricultural fields with no scatterers and reflectors around. The campaign is performed with Propsound channel sounder at a center frequency of 2.35 GHz with 10-MHz bandwidth. The transmit power is 37 dBm. Direct sequence spread spectrum signals are used to probe the channel. The receiver records the samples on a hard disk as raw in-phase or quadrature data. However, limited by the transmit power of the channel sounder, the measuring range has to be limited within about 2 km. In addition, this scheme cannot measure different communication links simultaneously.

It is noteworthy that both approaches fail to have a good tradeoff between reflecting the practical propagation channel characteristics and presenting a comprehensive description of the channel parameters. The channel measurement, particularly the MIMO channel measurement at high moving speeds, still remains to be an uneasy task. This is probably why the WINNER group fails to come to a definite conclusion on high Doppler shifts and no standard channel models for HSR at high moving speeds have been developed yet.

C. Channel Modeling Under Viaduct Scenario

Viaduct is the most common scenario for HSR. Viaducts, on average, make up 40% for a typical railway line [38], [39]. Fig. 4 shows an actual viaduct scenario in HSR, where the railway track is usually placed on the surface of a viaduct, to ensure flatness of the tracks and to avoid steep inclines, thus enabling high speeds of the train. As reported in [38]–[40], a typical HSR viaduct has a height H from 10 to 30 m. The base station (BS) antennas are usually positioned 10–20 m away from the railway tracks with a relative antenna height h (vertical distance between the BS antenna and the receiver antenna) of 20–30 m. The receiver antennas are placed in the middle part of the train, mounted on the top at a height of 30 cm above the roof of the train.

The propagation channel of the viaducts is found to be greatly influenced by the physical environments, the directional BS antennas, and the viaduct height. In [41] and [42], a special bottom area of the directional BS antenna in HSR is observed and defined, leading to a series of breakpoint models in the viaduct channels, e.g., the path loss is found to be a piecewise function of the distance with a break point at 400 m. Moreover, the path loss is also very sensitive to the viaduct height. In [40], it is found that a higher viaduct leads to a larger path

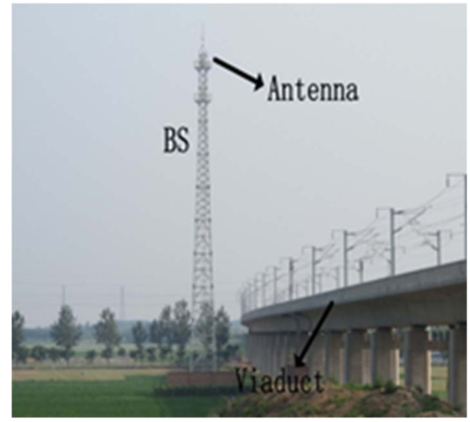


Fig. 4. View of the viaduct scenario in HSR.

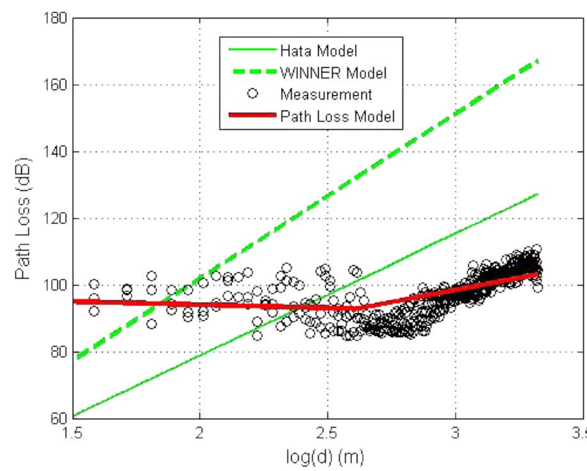


Fig. 5. Example plot of the path loss in the viaduct scenarios, from [38].

loss exponent n, and a simplified model is proposed, which is expressed as

$$n = k_1 H + k_2 h + \frac{k_3}{h} + k_4 \tag{1}$$

where H and h are the viaduct height and the relative antenna height, respectively. The coefficients k can be obtained by using a regression fit. Equation (1) shows a very interesting phenomenon that, with the increase of the viaduct heights, the path loss exponents increase as well, different from our traditional ideas and observations. This is because a higher viaduct leads to fewer reflected and scattered components, with the reduced power at the receiver compared with that of the plain propagation. Following these observations in the measurements, He *et al.* proposed a path loss model covering both height dependence and distance dependence for the HSR viaduct scenarios in [38]. An example plot of the path loss model, together with the measurements, is shown in Fig. 5, where the measurements were conducted on three 10-m-high viaducts of HSR line at 930 MHz. We can see that the proposed piecewise model in [38] and the measurements are in good agreement. The directional BS antenna leads to a breakpoint of the distance-dependent path loss at 400 m, and the curve of the proposed path loss model fits the measurements well. The Hata model [29] and the WINNER model in D2 scenario [20] path loss curves are also plotted for comparison, where we can generally

Fig. 6. View of the cutting scenario in HSR.

TABLE II
PARAMETERS FOR CUTTINGS

	Deep Cuttings							Shallow Cuttings		
Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
W_{up}(m)	52.01	50.86	55.26	55.72	53.93	58.30	63.17	48.38	49.77	50.24
W_{down}(m)	18.77	16.85	18.57	18.25	14.78	15.16	18.51	17.14	17.97	16.96

observe 10- to 30-dB errors, indicating poor fit to the actual measurements.

It is also noteworthy that a heuristic analytical propagation model using the geometrical optics and the uniform theory of diffraction is proposed [43] and is found to have good performance to predict the propagation pass loss under the viaduct scenarios. The shadow fading in the viaduct scenarios is found to follow the lognormal distribution [38], [40].

As for the small-scale fast fading in the viaducts, both the root-mean-square error distribution test [44] and the Akaike information criterion (AIC)-based evaluation [38] are used. It is found that the Ricean distribution outperforms the test and evaluation results. Similarly, the Ricean K-factor is also found to be a piecewise function of the distance due to the directional BS antennas in HSR. A detailed formulation is presented in [38] covering the effect of the viaduct height on channel characteristics. Moreover, the composite channel in the viaduct scenarios is analyzed and is found to follow a Suzuki distribution. As was reported in [38], the viaduct reduces the severity of fading by providing clear LOS propagation with few received reflection and scattering components. A higher viaduct makes the reduction of the severity of fading more distinct.

D. Channel Modeling Under Cutting Scenario

Cutting is another common scenario in HSR. It is used on uneven ground, to help the HST pass or "cut" through large obstacles such as hills [42], as shown in Fig. 6. It ensures flatness of the railway lines. The regular cutting is very common today, where the steep walls on both sides of the rails have almost the same depths and slopes [43].

The cutting has been divided into deep cuttings and shallow cuttings, and the typical structural parameters of ten groups of the cuttings in HSR are shown in Table II [46].

In Table II, W_{up} and W_{down} are the widths of the top and bottom of the cutting, respectively. The widths of the cutting and the depth H are found to be influential in radio wave propagation. In [45], a set of statistical modeling methods based on the goodness-of-fit evaluation is proposed to examine the effect of the structure parameters of the cuttings on the propagation models. In [46], the path loss models for the cuttings with different depths are provided. However, systematic investigations of the height dependence with sufficient number of samples to give statistically relevant results are still a task for future research.

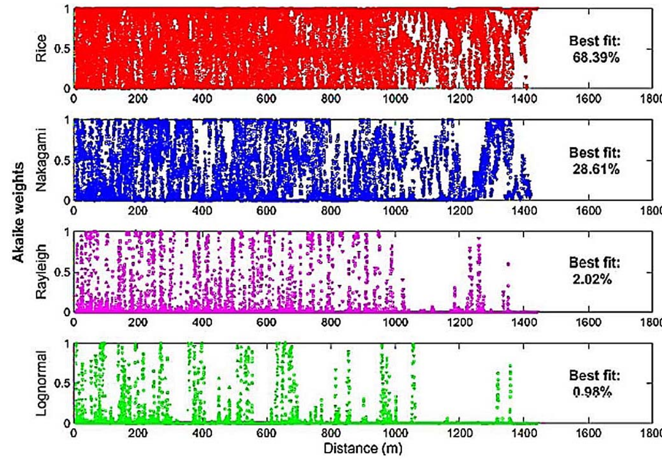


Fig. 7. Akaike weights and the percentage of the best fit for four candidate distributions based on the measurements in cuttings, from [45].

An important feature of the cuttings is the rich reflection and scattering components caused by the steep walls on both sides of the railway tracks. Abrishamkar and Irvine regarded the cutting as an open area with low reflection [47]. However, based on the actual test data and theoretical analysis, He *et al.* proved that the conclusion is incorrect [45]. It is found that, although the high BS antennas create a relatively clear LOS channel, the steep walls on both sides introduce rich reflection and scattering components at the receiver. By using the AIC-based evaluation, the percentages of the best fit for four types of distributions are compared, as shown in Fig. 7. The Ricean distribution has the best fit percentage of 68.39%. In the cutting scenarios, it is found to have a very low K-factor around 1.52 dB due to the rich scattering components [30].

E. Channel Modeling Under Tunnel Scenario

Although many literature deal with the channel modeling inside tunnels, there are still two main problems unsolved. The first is the multimode waveguide mechanism, and the second is the breakpoint determination for different propagation mechanisms inside tunnels. Latest research has found many interesting phenomena inside the tunnels. One is the newly proposed concept of *far line of sight (FLOS)* in [48]. Mostly, the direct ray makes the main contribution to the received signal, with reflections contributing much smaller amounts. However, in some special environments such as the subway tunnel, with the increase of the distance between the transmitter and the receiver, the influence of the direct ray is becoming negligible, whereas the influence of the reflection is becoming considerable, leading to a special characteristic of delay distribution. The FLOS

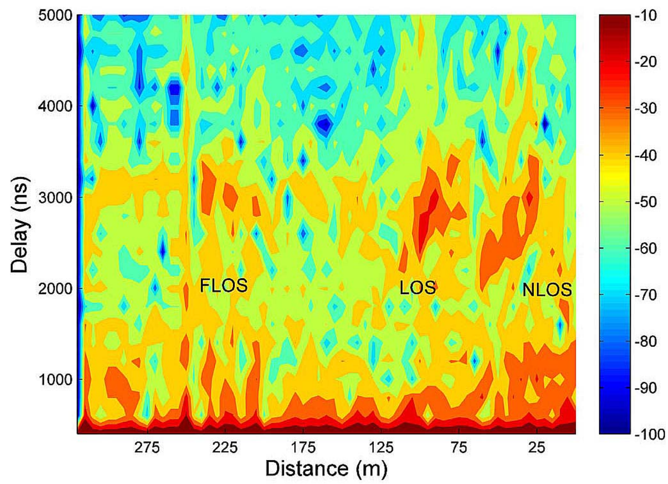


Fig. 8. Example plot of the PDP measured inside a subway tunnel in Madrid, Spain, from [50].

region is usually located 100–300 m apart from the transmitter inside tunnels.

Recently, it has been also found that the delay characteristic inside the subway tunnel is affected by the presence of the station, which changes the regular geometric structure of the tunnel, leading to extra reflection components and an increase in the delay spread [49]. In Fig. 8, we present an example plot of the measured power delay profile (PDP) in the subway tunnels of Madrid [49]. The parameters of the classical Saleh–Valenzuela model were derived to characterize the long delay clusters in the subway tunnels. Fig. 8 presents the measured PDPs at 2.4 GHz for LOS, non line of sight (NLOS), and FLOS regions in a 2600-m-long slightly curved subway tunnel. It shows that, in the subway tunnel, the 1- to 3-μs delay clusters (from the reflections caused by the station in the subway tunnel) are very strong, even in the LOS and FLOS regions. The measured large delay spread shows that the subway tunnel has large delay dispersion when the train is close to the station, which should be carefully considered when designing the subway communication networks. This observation is useful for the dedicated mobile communication network design within HSR tunnels, since there are also many railway constructions around the entrance/exit of the HSR tunnels, for example, the power lines and the pillars. These scatterers may lead to a large delay spread around several microseconds.

Another finding is the *near-region* phenomena inside tunnels based on the referenced antenna configuration on the train in a Madrid subway [50]. Along with the increase of the distance between the transmitter and the receiver, for the relatively small-size users (such as pedestrians and light cars), the free-space propagation mechanism appears first at the shortest distance, the multimode waveguide effect establishes later at slightly larger distance. For relatively large-size users (such as long trains in subway tunnel), the first appeared mechanism is the *near shadowing*. The corresponding definition and critical condition about near shadowing are presented in [51]. Then, the free-space propagation occurs before the waveguide propagation if LOS recovering is earlier than the end of the free-space propagation. Otherwise, the multimode waveguide propagation is behind the near shadowing effect; no free-space propagation exists.

Fig. 9 shows the near-region phenomenon inside tunnels. In order to present a clear explanation for Fig. 9, some introductions are given as follows.

- The channel path loss in the *free-space propagation zone* can be modeled by the free-space model.
- The propagation loss in the near shadowing zone is modeled with the utilization of the principle of least squares curve fitting on the measured data in [52]. Details of the modeling and the related parameters can be found in [51] and [52].
- The critical condition of the near shadowing phenomenon can be defined as the case that the widest part of the 60% of the first *Fresnel zone* is touched by the vehicle.
- In the *multi*mode propagation zone, a limited multimode model is utilized. By assuming the arched and circular tunnel approximated to an equivalent rectangular tunnel, the quantity and the type of modes are determined by the frequency and the structure of the tunnel. Then, by introducing two modified factors (the tilt loss and the roughness loss) [53], the propagation loss at all the coordinates can be analytically calculated. Details can be found in [54].
- Dividing Point 1 in Fig. 9 locates at the distance when the maximum first Fresnel zone touches any one of the tunnel walls. Details and simplified formulas of Dividing Point 1 in rectangular, circular, arched, and arbitrary cross-sectional tunnels are given in [55]–[58]. This model has been validated by five groups of measurement campaigns conducted in various tunnels. Dividing Point 2 between the near shadowing zone and the next zone locates at the distance of the length of the large-size user. By assuming an equivalent rectangular or a circular tunnel, the location of Dividing Point 3 is defined as the distance where the second-fundamental modes have suffered one reflection from the vertical or the horizontal walls.

In Fig. 9, the equations can be employed to realize fast communication network planning for various types of users. In order to keep good readability of this paper, the definitions and derivations of the equations are not presented here. However, details of all the cited equations and notations can be found in [59]. By making a brief review on the advancement of wireless communication systems, it is found that the near-region phenomenon inside tunnels lengthens considerably owing to the increase in working frequencies. Above all, almost all the channel models developed based on the measurements from one tunnel cannot be suitable for another one. There is a lack of commonly used channel models for tunnels.

Another special scenario for HSR, the crossing bridges are usually built over the cuttings to ensure necessary transportation for people around the HSR. The crossing bridge over the cutting leads to NLOS propagation within a short distance, causing an extra large-scale loss of about 5 dB [31]. However, there is no obvious change in the small-scale fading behavior caused by the crossing bridges [41]. For a high-speed moving train, this temporary change from LOS to NLOS will not significantly affect the fading behavior at the receiver.

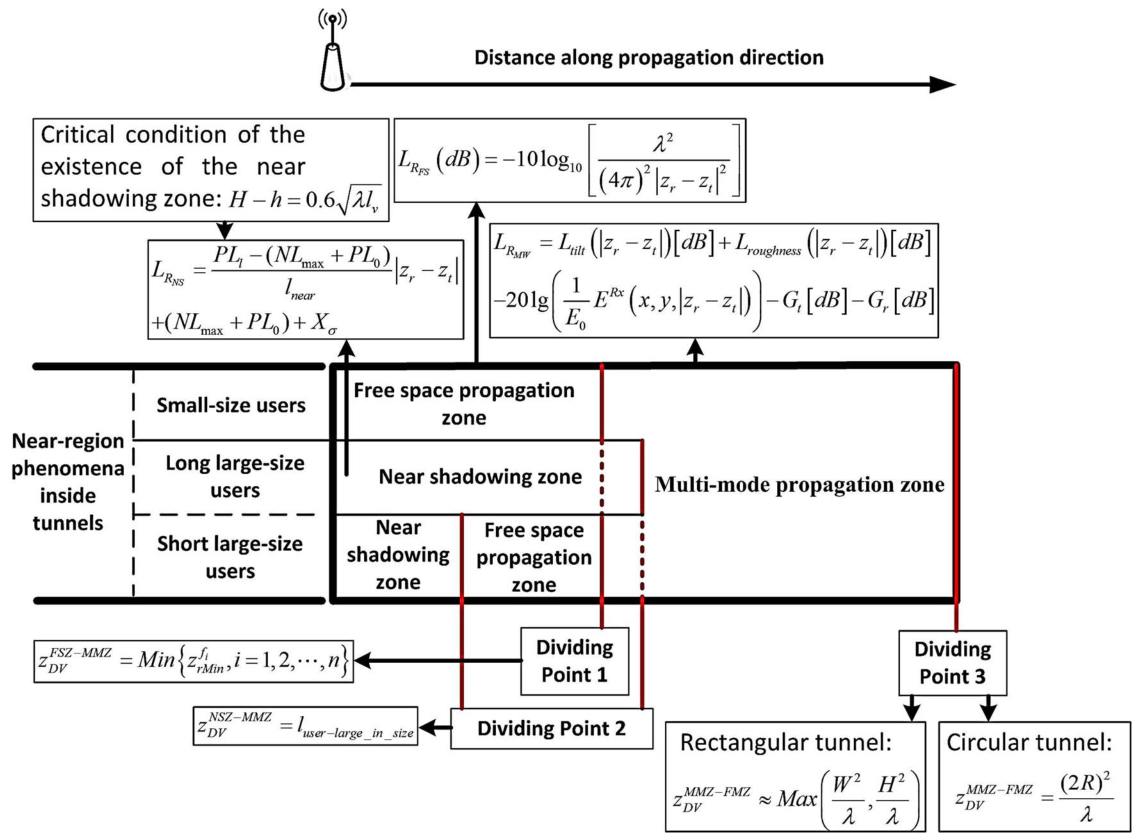


Fig. 9. Panorama of the propagation inside the near region of tunnels [51].

F. Antennas Modeling

The antennas modeling should be independent with that of the wireless channel modeling. These are two different things. One is for the exploration of the wireless channel characteristics, and the other is for the antennas performance evaluation. Many people misunderstand because the test data received by the receiver are affected by both the antenna settings and the channel conditions. The aim of the antennas modeling is to establish the relationship between the condition of the field strength coverage and the variation of the height, the angle, and the polarization of the antennas. As for multiantenna system such as MIMO system [3], or the massive MIMO system [60], which is regarded as one of the key technologies in fifth-generation (5G) mobile communication systems, the relative position of different antennas and the degree of the correlation among different antennas are all contributing to the antennas modeling. Up to now, very few papers have dealt with the research of antenna array structure for HSRs.

In [61], the authors conducted the research on the performance comparisons in terms of channel capacity when the antenna array has different forms, such as uniform linear array (ULA), uniform circular array (UCA), star, and uniform rectangular array (URA), as shown in Fig. 10.

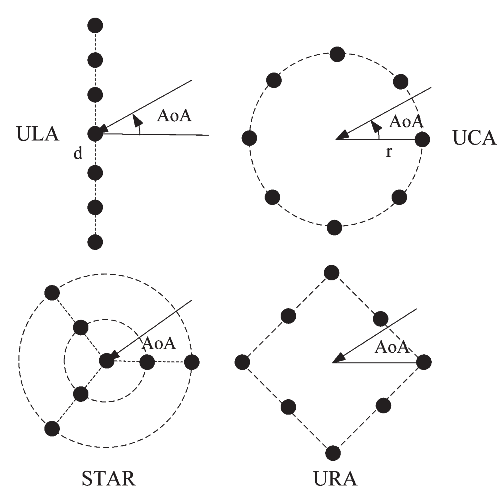


Fig. 10. Different antenna array configurations, including ULA, UCA, star, and URA.

The ergodic channel capacity simulation results of four different antenna array configurations are shown in Fig. 11. The channel capacity of each antenna array is simulated according to the real HST scenario. The simulation parameters are as follows. It is assumed that the BS is located 30 m away from the track. The carrier frequency is 900 MHz. The velocity of the train is set to be 360 km/h. Thus, the maximum Doppler shift is 300 Hz. The number of antenna elements is eight, the same in ULA, UCA, and URA. The star array has seven elements due to its symmetrical configuration. It is assumed that all these elements are vertically polarized and have an interelement spacing of 1λ, where λ is the wavelength of the light. The D2a scenario in the WINNER II channel model with LOS path has been adopted [20].

From Fig. 11, we can see that the performance of ULA is superior to all the other three antenna array forms when the simulation parameters are the same. The performance of ULA

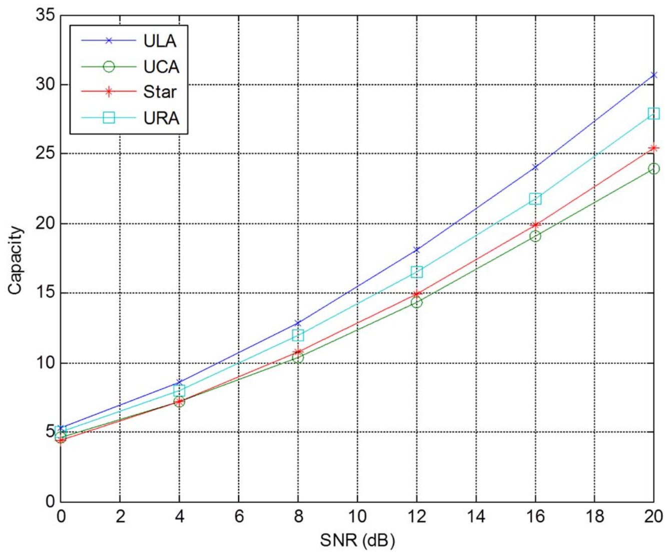


Fig. 11. Capacity comparison of four antenna array configurations, including ULA, UCA, star, and URA.

is also related with the azimuthal orientation of the array. In the other three types of antenna arrays, URA provides a better performance.

Based on the wireless channel characteristics in HSR, there is often one dominant LOS component and sparse multipath in the environment, generally degrading the MIMO performance. An optimal MIMO antenna, which is called reconfigurable antenna array, is designed in [62] to maximize the channel capacity in the low-rank LOS Ricean channel. An optimal MIMO antenna combination for HSR is proposed in [63]. It contains four types of parameters for MIMO antenna array configuration corresponding to the four different channel regions defined in [61] when the train runs toward the BS. For the optimal MIMO antenna and location, Christopher *et al.* [64] have carried out a vehicular (automobile) MIMO measurement to investigate the effect of antenna array location, roof, or two sides of the car on the MIMO system performance. The array on the roof can obtain more signal power. However, the diversity gain can be obtained if the array is located on the two sides of the car. A new tool, which is called "*Virtual Drive*," is developed by Reichardt *et al.* [65], [66]. It consists of the vehicular environment, a traffic model, and a 3-D ray-tracing tool. With this software tool, different V2V or vehicle-to-infrastructure (V2I) scenarios can be simulated, and the channel is calculated by *ray-tracing method* to find an optimal MIMO antenna configuration.

Up to now, there have not been so many scholars or research groups paying their attention on the MIMO or the massive MIMO channel modeling for HSR scenarios. It is still on its way.

G. Availability of GIS Data

Detailed geographic data have to be made available in order to model the different scenes. On a large scale, such data are available for terrain height only using data retrieved, for example, from the Shuttle Radar Topography Mission (SRTM) [67]. Other data can be found using the framework of the OpenStreetMap initiative [68]. For example, such OpenStreetMap-Data have been used to model car-to-X-communication in urban environments [69]. Current publications describing the modeling of objects such as viaducts, crossing bridges, or train stations are using data that have been manually measured by a laser distance meter, e.g., [31]. When applying the corresponding propagation models, an effort has to be made to derive all relevant data at least in a semiautomatic way. Geographic information system (GIS) data are the fundamental basis for ray-tracing method, which is used for the software simulation of the actual physical scenes and the accuracy verification of the wireless channel models. Moreover, GIS is also very important for Global Positioning System (GPS) location in HSR [70]. For example, GPS-based train positioning can be used to detect the missing train compartments left on the railway tracks. Based on the location information of the missing train compartments, the dispatcher and the train driver can obtain prewarning messages to avoid the collision of the trains.

IV. Challenging Key Technologies for HSR Communications

In addition to the wireless channel modeling for HSR, some challenging key technologies for future development of HSR should be paid more attention.

A. Working Frequency Band

As pointed out in Section II, GSM-R shares the same working frequency band with the public land mobile communication network, as shown in Fig. 2, which will cause serious cochannel interference. With the increase of various railway services, the frequency resources will be seriously limited, particularly in railway hub areas. As for subways, some commonly unlicensed frequency bands such as 2.4 GHz used in CBTC systems may risk the integrity and confidentiality of the train control data.

With the emergence of the new services for HSR, the comfortable and humanized demands for future HSR development, broadband communications for HSR have come to the agenda. LTE system can achieve high capacity, low latency, and high reliability [71]. Twenty frequency bands have been defined by 3GPP for LTE frequency-division duplexing (FDD) and nine bands for LTE time-division duplexing [72]. IEEE 802.15 Task Group 4p has defined a total of 16 frequency bands [13], including four bands between 161 and 220 MHz, one band at 450 MHz, seven bands between 770 and 928 MHz, and five bands between 4965 and 5800 MHz. With regard to the suggestions of LTE frequency band allocation from 3GPP, the planning and the usage of the LTE frequency band in China are shown in Table III.

From Table III, it is known that 700 MHz is used by the State Administration of Radio Film and Television of China. It is easy to realize a wide range of communication network coverage with low cost of construction. However, such frequency band is influenced by the national policies and difficult to be released. The 1.4-GHz frequency band has been used as the municipal LTE communication trial network for the subway system in China. If 1.4 GHz is adopted for LTE-R dedicated mobile communication network for train-to-ground communications, there will be serious cochannel interference. The 1785- to 1805-MHz frequency band has been allocated for the dedicated

TABLE III
LTE FREQUENCY BAND ALLOCATION IN CHINA

Frequency band	3GPP suggestion	Services
1850-1900 MHz	TDD/FDD (Uplink)	1800-1920 MHz: TD-SCDMA; 1850-1880 MHz: mobile and fixed communications
1880-1920 MHz	TDD	TD-SCDMA, trail communication network for TD-LTE
1910-1930 MHz	TDD	CDMA2000
1930-1990 MHz	TDD	1920-1935 MHz: CDMA2000; 1940-1955 MHz: WCDMA; 1960-1990 MHz: mobile and fixed communications
2010-2025 MHz	TDD	TD-SCDMA
2300-2400 MHz	TDD	2320-2370 MHz: TD-SCDMA, trail communication network for TD-LTE; 2370-2400 MHz: mobile and fixed communications, radio positioning
2500-2690 MHz	TDD	TD-LTE of China Mobile
around 700 MHz	FDD	Mainly used by the State Administration of Radio Film and Television of China
around 800 MHz	FDD	806-821 MHz, 851-866 MHz: Digital trunking system; 825-840, 870-885 MHz: CDMA; 885-889 MHz, 930-934 MHz: GSM-R; 890-909 MHz, 935-954 MHz: China Mobile GSM900; 909-915 MHz, 954-960 MHz: China Unicom GSM900; 841-869 MHz bands are unused.
around 1.4 GHz	FDD	Mobile and fixed communications, satellite communication services
around 1.7 GHz	FDD	1710-1725 MHz, 1805-1820 MHz: China Mobile GSM1800; 1745-1755 MHz, 1840-1850 MHz: China Unicom GSM1800; 1785-1805 MHz: for dedicated mobile communications
1920-1980 MHz	FDD	1920-1935 MHz: CDMA2000; 1940-1955 MHz: WCDMA; 1960-1990 MHz: mobile and fixed communications

communications such as the Fire Bureau and the sea ports in economically developed eastern coastal areas. However, it is also possible to be allocated to LTE-R due to less interference and easy application of the frequency bands. As we know, the higher the working frequency band is, the larger the path loss and the more substantial the signal fading. Higher frequencies exhibit weaker diffraction capability, which is very important for the railway dedicated mobile communications. If 2.6 GHz is adopted, with typical transmit power levels, the radius of a cell is no more than 500 m, resulting in a dense layout of the BSs for HSR. This will cause a large investment and frequent handovers.

Above all, it is suggested that the 800-MHz + 1800-MHz frequency band dual mode is deployed for HSR dedicated mobile communications. The high priority service is working in the 800-MHz frequency band, and the low priority service is working in the 1800-MHz frequency band.

B. LTE for Railway

As GSM-R manufacturers said, the life cycle of GSM-R will be coming to an end in 2025, whereas the International Union of Railways (UIC) said that the development of the next-generation mobile communication systems for railway is to bypass third-generation mobile communications and come to LTE-R directly. As announced by both GSM-R manufacturers and UIC, however, LTE-R must be designed to be backward compatible with GSM-R. The IP packet network in LTE replaces the circuit domain data, whereas the voice services for railway are mainly supported by the circuit domain. Therefore, in the early stage of the construction of the LTE-R system, the packet data services and the multimedia services will be carried by the LTE-R network, whereas the voice services and the train control data services in the circuit domain will still be carried by the GSM-R network. With the gradual maturity of LTE-R, all the railway services will be then gradually transferred to the LTE-R system. Above all, the coexistence of LTE-R and GSM-R will be required for a long time.

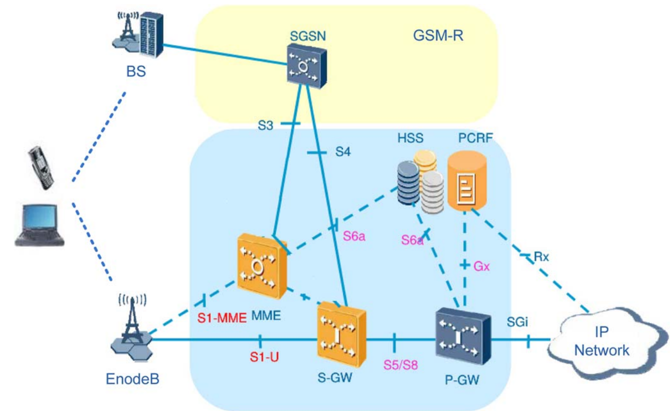


Fig. 12. Communication network architecture of LTE-R.

What is the need for the development of LTE-R system for railways? The E-train project group of UIC has summarized over 200 kinds of communication services for railways [73]. As the investigation results from the E-train project concluded, to ensure the safe operation of the trains, to elevate the operation efficiency, and to improve the QoS, there are over 200 kinds of services: train dispatching, train control, train operation communication, safe video monitoring, wireless monitoring for the railway infrastructure, monitoring of the train state, remote fault diagnosis, automatic train operation, mobile ticketing, travel information, transportation and the tracking management of containers and dangerous goods, etc. These railway services requirements appeal to the coming era of the railway broadband mobile communications.

LTE-R is not just a simple move from LTE for public land mobile communications network to the railway environments. It has some differences from public LTE in the aspects such as radio propagation environments, network layout, services, and QoS requirement. Based on LTE communication network architecture [74], the suggested architecture for LTE-R is shown in Fig. 12, consisting of only two user-plane nodes (EnodeB and S/P-GW), simpler than GSM-R. The handovers between EnodeBs are handled over the X2 interface rather than in the BS controller. There is a lack of maturity on time-division LTE (TD-LTE) in high moving speeds of HST. Therefore, the hybrid network mode of TD-LTE and LTE FDD for railways is required.

Due to the high mobility and high requirements of QoS, the key technologies for LTE-R include the fast synchronization, the channel estimation and equalization, the Doppler shift estimation and correction, the wireless channel modeling, and

TABLE IV
RECOMMENDED PARAMETERS FOR LTE-R

Performance index	Recommended value	
Bandwidth	≥10 MHz	
Data rate	Uplink: 10 Mbps, Downlink: 4 Mbps	
Peak spectral efficiency	Medium and low moving speed (0-200 km/h)	Uplink: 2.5 bps/Hz, Downlink: 5 bps/Hz
	High moving speed (>200 km/h)	Uplink: 1.5 bps/Hz, Downlink: 2.5 bps/Hz
Handover success rate	≥ 99.5%	
Connection loss rate	≤ 10^{-2}/h	
Network attachment delay	≤ 30 s (95%), ≤ 35 s (99%), ≤ 40 s (100%),	

the MIMO technique with strong correlation property. The frequency band used by the next-generation railway mobile communication network is higher than that by the GSM-R network, resulting in a much smaller distance between two adjacent BSs. Thus, frequent handover appears, and a fast handover technique with high reliability is needed.

Based on the special services requirements for railways and the typical characteristics of broadband communications, the preferred performance indexes for broadband communications of railways are given, although, up to now, there are no agencies or research teams giving such parameters. What we have listed in Table IV are for reference only.

C. Nonstationary and LOS Sparse Channel

High mobility leads to the violation of WSSUS condition for wireless channel under HSR scenarios. Nonstationary channel is a very interesting issue with great value for the selection of physical layer technologies such as synchronization, channel estimation, and equalization. It has been mentioned in Section II that high-speed moving train will pass through many combined scenarios within a very short time interval. How to determine the boundaries of stationary channel regions and how to deal with such fast-varying channel for the receiver are very crucial and challenging. Birth and death process of multipath with Markov chains may be utilized to describe such phenomena.

With the development of intelligent transportation system [75], [76] and the LTE-R system, MIMO system under high-speed rails scenarios has becoming a hot topic. Under most HSR scenarios, the BSs are located less than 30 m away from the tracks, and most of the BS antenna heights are more than 30 m; hence, the LOS component exists in the majority of the HSR scenarios, and the scatterers are limited, revealing sparse channel characteristics. The spatial correlation between multi-antennas elements is high owing to the linear dependence of the LOS rays' phases on the receive elements. Then, the concept of LOS MIMO appears. The effectiveness of using multiple antenna is demonstrated in LOS propagation environments [77]–[79]. The LOS MIMO channel under HSR scenarios has its own characteristics, which needs to be approached in a different way. It is randomly time varying: its identifiability from the measurements, the statistical characterization, and the modeling is rather challenging [80], [81]. In [82], single-bounce scattering is assumed for both fixed and moving scatterers. The high mobility of the transmitter, the receiver, and the surrounding vehicles results in time-variant angles of departure and angles of arrival (AOAs). This fact makes the model nonstationary. A nonstationary wideband geometry-based stochastic model (GBSM) for MIMO under HST channels is presented in [83]. In [84], the wideband LOS MIMO channel models under HSR scenarios were investigated, and the analysis was based on a training and communication scheme employing signaling over orthogonal short-time Fourier (STF) basis functions, which STF signaling naturally relates sparsity in delay Doppler to coherence in time and frequency. A novel wideband MIMO channel model, which is referred to as the *structured model*, based on the eigenvalue decomposition of the wideband channel correlation matrix is presented in [85]. A GBSM channel model based on the tapped delay line (TDL) for wideband MIMO mobile-to-mobile Ricean fading channels is proposed in [86], which has the ability to study the impact of the vehicular traffic density on channel statistics with different time delays.

An interesting issue for LOS MIMO is the maximization of the channel capacity. Under the HSR LOS MIMO scenarios, the channel is normally rank deficient owing to the correlated mutipath. To overcome this problem, the reconstruction of the antenna array can be employed, where the antenna elements are positioned to preserve orthogonality, hence maximizing the channel rank [87]–[91]. To investigate the characteristics of the LOS MIMO system, a suitable channel model is required. It is common for an LOS MIMO channel response matrix to be modeled as

$$H = \sqrt{\frac{K}{K+1}} H_{\mathrm{LOS}} + \sqrt{\frac{1}{K+1}} H_{\mathrm{NLOS}} \tag{2}$$

where H denotes the LOS MIMO channel response matrix, modeled by the TDL model. H_{LOS} is the channel coefficient corresponding to the free-space responses between all elements. H_{NLOS} is the NLOS channel coefficient due to reflection, diffraction, and scattering from the transmission environment. K represents the Ricean K-factor converted to linear scale. The validity of the maximum capacity criterion applied to realize the LOS MIMO channel is investigated for HSR scenarios [63]. In [62], a versatile methodology for maximizing LOS MIMO capacity at any operating signal-to-noise ratio is presented. Numerical results demonstrate that, by simply adjusting antenna spacing as a function of the distance, the orientation, and the spacing of the arrays, significant capacity gains are achievable.

D. T2T Communication

Train-to-train (T2T) communication is proposed as another auxiliary safety-guaranteed measure for HSR communication. It is first presented by Garcia *et al.* [92]. This idea was originally from the automatic identification system, the traffic alert and collision avoidance system, and the car-to-car communication system. In [92], the authors described an overview of the state of the art in railway collision avoidance for maritime transportation, aircraft, and road transportation, proposing a channel model for direct T2T communication appropriate for 400 MHz. Although the presented system has gained some progress in physical layer design, it only supports the train operation velocity lower than 200 km/h at 400 MHz, which is

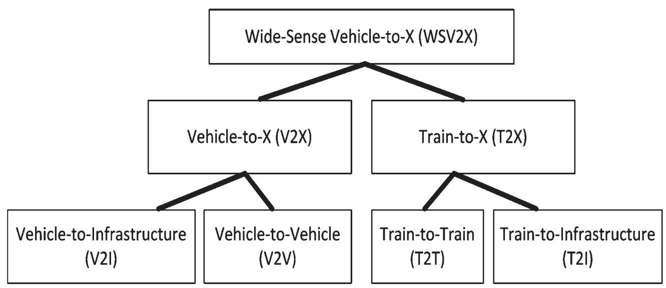


Fig. 13. Block diagram of the constitution of the concept of WSV2X.

not suitable for the HSR with the moving speeds over 300 km/h at 900 MHz.

Different from the traditional views, Fig. 13 gives a block diagram of a more general and comprehensive concept of wide-sense V2V (WSV2X), which is defined by including not only V2V and V2I communications but also train-to-X (T2X) communications constituted of T2T and train-to-infrastructure (T2I) communications. The idea behind the WSV2X communications is the deployment of wireless communication technology in vehicular and railway networks. In this manner, the vehicles, trains, and infrastructures build up a wireless network enabling them to exchange controlling and traffic information such as road obstacles and accidents via the wireless communication links. Over the past few years, V2X and T2I, respectively, have gained popularity in their attempts to improve road safety and railway safety. However, the development of the T2T channel is not so booming as the other components (V2V, V2I, and T2I) of WSV2X; thus, very limited publications can be found, and many technical challenges still remain in T2T communications. For instance, there is only the T2T channel information at 400 MHz, but not at 900 MHz for GSM-R or 1800 MHz for LTE-R or 2.4 GHz for CBTC.

E. Other Key Technologies for Future HSR Development

Composite Transportation: The concept of composite transportation has been developed in recent years, which means that the future intelligent transportation network will take the HSR, the subway, and the road as a whole transportation network. For instance, GSM-R network and WiFi technology are used for HSR and subway train-to-ground communications, respectively. However, the next-generation train-to-ground communication system for both HSR and subway will be based on LTE/LTE-A system. Just as the architecture development team from the Research Innovation Technology Administration said in their report [93], wireless communications will be the most enabling technologies in the composite transportation network. How to design the communication network architecture and related key technologies of different layers will be a challenging task.

Multipath Birth–Death for Combined Scenarios: Along the HSR lines, there are many combined scenarios, for example, the tunnels and the viaducts, the cuttings and the train stations [94], [95], and the viaducts and the crossing bridges [96]. Serious fading may occur under the combination of these scenarios. Therefore, it is of importance to conduct the research on the multipath birth–death for these combined scenarios. Also worthy of study is the determination of the *demarcation points* of the multipath birth–death for these combined scenarios.

SON for Railway: Another advanced and important key technology for LTE-R is the self-organizing network (SON). With this technology, LTE features will be available for managing, configuring, maintaining, and optimizing the LTE-R communication network [97]. Intensive research activities are currently running, for example, in the European FP7 project SEMAFOUR [98], for public heterogeneous cellular networks. Within the scope of these projects, the aspects of users with high mobility are investigated. A future research direction for LTE-R will be in the area of developing SON algorithms dealing with specific aspects of HSR. Examples are the optimization of handover parameters, operations of heterogeneous networks consisting of GSM-R and LTE-R, as well as mechanisms to guarantee a robust and reliable operation.

Internet of Things for Railway: Sometimes, the debris flow, the broken bridges, the subsidence, and the serious weather conditions will have great influence on the train operation safety. Hence, it is a good idea for future HSR development to equip the railway with Internet of Things to predict and avoid these coming accidents. For instance, Japan has developed the earthquake warning system for her HSR systems [99], [100].

Social Network Application for HSR: Social networks such as Facebook, Twitter, LinkedIn, and ResearchGate have been widely used in peoples' everyday life. They facilitate the information transfer and communications between people. We have discussed how to implement social networks for HSR services [101], for example, how to book a train ticket, how to deal with the emergencies on the train, and how to know the tourism attractions and local customs where the train passes. All these can be realized with the utilization of the social network on the train. Then, how to design the architecture and key technologies of such social network and how to realize the intelligent management of the social network on the train remain to be an uneasy task.

Vacuum Maglev Train: It is estimated that the moving speeds of the vacuum maglev train is from 600 to 3000 km/h. The pipeline carrying the train is considered to be vacuum in theory, although, we should note that this is often an ideal condition. Then, designing the key technologies for such a new system and understanding the channel conditions in practice remain to be a challenging task [102].

Security for HSR: This will definitely be a key point for future development of HSR. The security of the train control data is very crucial, particularly for the WiFi-technology-based train control data transmission system, where the unlicensed frequency band is used. Up to now, there has been few research on the security of train operation control data and the user information security for HSR [103].

Fifth-Generation Communications for HSR: The research for the 5G communications system is now on its way. The European Union, the United States, Korea, China, and Japan have developed their organizations for 5G development. HSR scenarios have been recognized as one of the typical scenarios for 5G [60]. Therefore, related key technologies such as massive MIMO technique [104] and the corresponding channel modeling should be paid more attention.

V. Conclusion

HSR is developing very quickly, particularly in France, Germany, Japan, Spain, and China. The United States is ready to develop its first HSR in California. Safety, reliability, high efficiency, environment friendliness, comfort, and humanization are the goals of future HSR development. For this application background, we described in this paper some challenging key points on wireless communications for HSR scenarios.

The differences between communications under HSR scenarios and that of public land mobile communication networks were discussed in detail. Particularly for the broadband communication systems, there are still many constraints such as the required working frequency band versus very limited frequency resource, the nonstationary channel and the Doppler effects deteriorating the performance of OFDM-based wireless access methods, the LOS sparse channel restricting the benefit from MIMO techniques, and complex propagation scenarios complicating the mobile channel. Hence, to provide the broadband wireless services in such a high-mobility environment, additional research is required, such as high-resolution analysis in the time/space/frequency domain, quantification of propagation path life and evolving path trajectories, coherence of environments, dynamics of channel responses, handover schemes, and fast power control under high-mobility environments. These are very meaningful for future HSR development.

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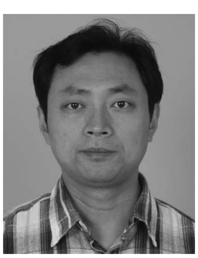

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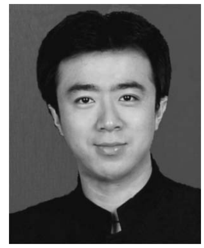

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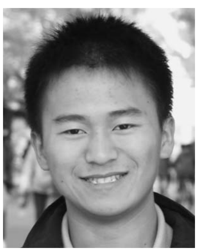

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