Ruisi He, Bo Ai,
Gongpu Wang, Ke Guan,
Zhangdui Zhong,
Andreas F. Molisch,
Cesar Briso-Rodriguez,
and Claude Oestges

High-Speed Railway Communications

From GSM-R to LTE-R

High-speed railways (HSRs) improve the quality of rail services, yield greater customer satisfaction, and help to create socioeconomically balanced societies [1]. This highly efficient transport mode creates significant challenges in terms of investment, technology, industry, and environment. To handle increasing traffic, ensure passenger safety, and provide real-time multimedia information, a new communication system for HSR is required. In the last decade, public networks have been evolving from voice-centric second-generation systems, e.g., Global System for Mobile Communications (GSM) with limited capabilities, to fourth-generation (4G) broad-band systems that offer higher data rates,

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e.g., long-term evolution (LTE). It is thus relevant for HSR to replace the current GSM-railway (GSM-R) technology with the next-generation railway-dedicated communication system providing improved capacity and capability.

With the rapid development of HSRs, a reliable broadband communications system is essential for different HSR components, such as train control and safety-related communications. Since 2014, a project of the International Union of Railways or Union Internationale des Chemins de Fer (UIC), known as the Future Railway Mobile Communication System (FRMCS), has started to assess and shape the future of HSR mobile communications and to identify suitable candidate technologies to use once the currently used GSM-R has become obsolete. HSR applications have strict requirements for quality-of-service (QoS) measures, such as data rate, transmission delay, and bit error rate (BER). Due to these factors as well as a desire to use mature and low-cost technology, HSR communications generally use off-the-shelf technologies and add applications to meet specific services and demands. GSM-R [2] is a successful example, based on the GSM standard and used on over 70,000 km of railway lines (including over 22,000 km of HSR lines) all over the world [3].

The GSM communications systems are being decommissioned as the public communication market is evolving toward the Third Generation Partnership Project (3GPP) LTE [4]. As a consequence, GSM-R also has a foreseeable end to its lifetime. A new system is thus required to fulfill HSR operational needs, with the capability of being consistent with LTE, offering new services but still coexisting with GSM-R for a long period of time. The selection of a suitable wireless communication system for HSRs needs to consider such issues as performance, service attributes, frequency band, and industrial support. Compared with third-generation (3G) systems, 4G LTE has a simple flat architecture, high data rate, and low latency, making it an acknowledged acceptable bearer for real-time HSR applications. Fifth-generation (5G) systems, although currently discussed in 3GPP, will be available only after 2020 and, therefore, are not suitable for the HSR time frame [5]. In view of the performance and level of maturity of LTE, LTE-railway (LTE-R) will likely be the next generation of HSR communication systems [6], [7], and the future vision for HSR wireless technologies will thus rely on it.

A schedule of standardization and establishment of LTE-R is shown in Figure 1(a). The UIC is expected to

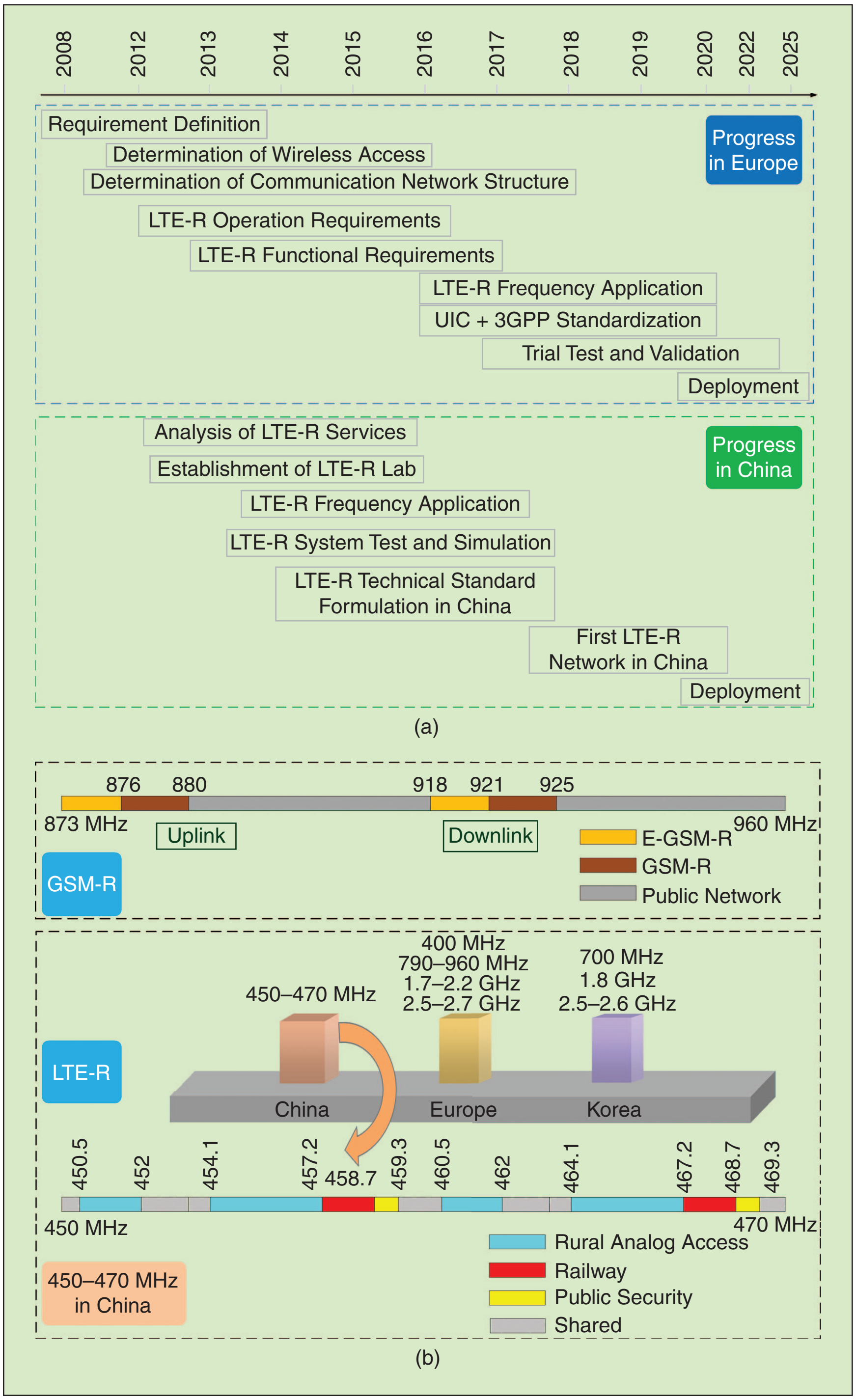

FIGURE 1 (a) The time frame of LTE-R in Europe and China. (b) The allocation of frequency bands.

complete operation and functional requirements determination by 2017. In China, the development of LTE-R also has been widely discussed and scheduled by the government. The first LTE-R network of China is scheduled for 2020; a time frame of LTE-R in China is presented in Figure 1(a).

With the rapid development of HSRs, a reliable, broad-band communications system is essential for different HSR components, such as train control and safety-related communications.

GSM-R

GSM-R System Description

GSM-R is essentially the same system as the GSM but with railway-specific functionalities. It uses a specific frequency band around 800/900 MHz, as illustrated in Figure 1(b) [8]. In addition, the frequency bands 873–876 MHz (uplink) and 918–921 MHz (downlink) are used as extension bands for GSM-R on a national basis, under the name Extended GSM-R (E-GSM-R).

GSM-R is typically implemented using dedicated base stations (BSs) close to the rail track. The distance between two neighboring BSs is 7–15 km; in China, it is 3–5 km because redundancy coverage is used to ensure higher availability and reliability. GSM-R has to fulfill tight availability and performance requirements of the HSR radio services. Table 1 summarizes some key parameters of GSM-R systems.

GSM-R Services

The GSM-R network serves as a data carrier for the European Train Control System (ETCS), which is the signaling system used for railway control. The ETCS has three levels of operation and uses the GSM-R radio network to send and receive information from trains. On the first level, ETCS-1, the GSM-R is used only for voice communications. On the other two levels, ETCS-2 and ETCS-3, the GSM-R system is used mainly for data transmissions. The GSM-R is very relevant to ETCS-2 and ETCS-3, where the train travels at a speed up to 350 km/h, and it is thus necessary to guarantee a continuous supervision of train position and speed. When the call is lost, the train has to automatically reduce the speed to 300 km/h (ETCS-1) or lower. The most typical HSR-specific services offered by GSM-R are as follows [9].

1) *Voice group call service (VGCS):* VGCS conducts group calls between trains and BSs or conducts group calls between trackside workers, station staff, and similar groups.
2) *Voice broadcast service (VBS):* The BS broadcasts messages to certain groups of trains, or trains broadcast messages to BSs and other trains in a defined area. Compared to VGCS, only the initiator of the call can speak in VBS, and the others who join the call can only be listeners. VBS is mainly used to broadcast recorded messages or to make announcements in the operation of HSR.
3) *Enhanced multilevel precedence and preemption (eMLPP):* eMLPP defines the user's priority and is used to achieve high performance for emergency group calls.
4) *Shunting mode:* Shunting mode provides an effective means of communication to a group of personnel who are involved with a shunting operation, which

Table 1 *System parameters of GSM-R, LTE, and LTE-R.*

Parameter	*GSM-R*	*LTE*	*LTE-R*
Frequency	Uplink: 876–880 MHz; downlink: 921–925 MHz	800 MHz, 1.8 GHz, 2.6 GHz	450 MHz, 800 MHz, 1.4 GHz, 1.8 GHz
Bandwidth	0.2 MHz	1.4–20 MHz	1.4-20 MHz
Modulation	GMSK	QPSK/M-QAM/OFDM	QPSK/16-QAM
Cell range	8 km	1–5 km	4–12 km
Cell configuration	Single sector	Multisector	Single sector
Peak data rate, downlink/uplink	172/172 Kbps	100/50 Mbps	50/10 Mbps
Peak spectral efficiency	0.33 bps/Hz	16.32 bps/Hz	2.55 bps/Hz
Data transmission	Requires voice call connection	Packet switching	Packet switching (UDP data)
Packet retransmission	No (serial data)	Yes (IP packets)	Reduced (UDP packets)
MIMO	No	2 x 2, 4 x 4	2 x 2
Mobility	Max. 500 km/h	Max. 350 km/h	Max. 500 km/h
Handover success rate	≥ 99.5%	≥ 99.5%	≥ 99.9%
Handover procedure	Hard	Hard/soft	Soft: no data loss
All IP (native)	No	Yes	Yes

ALTHOUGH THE POPULARITY OF GSM-R IS STILL GROWING, INCREASING INTERFERENCE FROM PUBLIC NETWORKS IS HAMPERING THE USE OF GSM-R WHILE THE ASSIGNED RADIO FREQUENCIES LIMIT ITS CAPACITY.

regulates and controls user access to shunting communications (a link assurance signal used to give reassurance to the train driver).

5) *Functional addressing:* A train can be addressed by a number identifying the function for which it is being used, rather than a more permanent subscriber number.
6) *Location-dependent addressing:* Calls from a train to certain functions can be addressed based on the location of the train as the train moves through different areas of BSs.

GSM-R Limitations

Although the popularity of GSM-R is still growing, increasing interference from public networks is hampering the use of GSM-R, while the assigned radio frequencies limit its capacity. Several limitations are summarized in the following.

1) *Interference:* The interference between GSM-R and other public networks increases because both railway and public operators want to have good coverage along the rail tracks. Instead of cooperating in network planning, railway and public operators fight for the coverage. The interference could result in severe impairment of voice and data communications as well as network loss over several hundred meters of track. Theoretically, such interference can be avoided if public operators do not use frequency bands adjacent to those of GSM-R for the areas close to rail tracks; however, this is not well implemented in practice. In the future, interference may increase owing to the growth of GSM-R network deployment and the potential growth of public networks.
2) *Capacity:* The 4-MHz bandwidth of GSM-R can support 19 channels of 200-KHz width. This is sufficient for voice communication, as voice calls are limited in time and do not occupy resources continuously. However, the current capacity turns out to be insufficient for the next-generation railway system, where each train needs to establish a continuous data connection with a radio block center (RBC), and each RBC connection needs to constantly occupy one time slot. The radio capacity can be increased by using more spectrum resources.
3) *Capability:* As a narrow-band system, GSM-R cannot provide advanced services and adapt to new requirements. The maximum transmission rate of GSM-R per connection is 9.6 kb/s, which is sufficient only for applications with low demands; message delay is in the range of 400 ms, which is too high to support any real-time application and emergency communication [10]. The future services of HSRs such as real-time monitoring require a wide-band system to have larger data rate and short delay.

Due to the above limitations, GSM-R must eventually evolve to eliminate revealed shortcomings [11]. LTE-R, which could be based on the LTE standard, is a likely candidate to replace GSM-R in the future for the following reasons.

1) LTE has many advantages over GSM in terms of capacity and capabilities.
2) As a fully packet-switched-based network, LTE is better suited for data communications.
3) LTE offers a more efficient network architecture and thus has a reduced packet delay, which is one of the crucial requirements for providing ETCS messages.
4) LTE has a high throughput radio access, as it consists of a number of improvements that increase spectral efficiency, such as advanced multiplexing and modulation.
5) LTE is also a well-established and off-the-shelf system and provides standardized interworking mechanisms with GSM.

LTE-R

LTE-R System Description

To provide improved and more efficient transmission for HSR communications, it is vital to consider frequency and spectrum usage for LTE-R. HSRs are important strategic infrastructure, and, in some countries, this argument is being leveraged to convince governments that large spectrum chunks need to be allocated specifically for it. Some industry bodies, including the European Railway Agency (ERA), China Railway, and UIC, are working to secure spectrum allocation for HSR use. Currently, most LTE systems work at the bands above 1 GHz, such as 1.8, 2.1, 2.3, and 2.6 GHz, although 700–900-MHz bands are also used in some countries. Large bandwidth is available in the upper bands, giving a higher data rate, whereas lower frequency bands offer longer distance coverage. Figure 1(b) summarizes the possible frequency bands for LTE-R in China, Europe, and Korea. As a high-frequency band has larger propagation loss and more severe fading, the radius of an LTE-R cell would be <2 km [due to the strict requirement of signal-to-noise ratio (SNR) and BER in HSR], leading to frequent handovers and a requirement of substantial investment for higher BS density. Therefore, the low-frequency bands, such as 450–470 MHz, 800 MHz, and 1.4 GHz, have been widely considered. The 450–470-MHz band is already well adopted by the railway industry; therefore, dedicated bandwidth for professional use can still be allocated from local regulators. Furthermore, the carrier aggregation capability of LTE will permit the use of different bands to overcome problems of capacity. Figure 1(b) presents the detailed frequency allocation of 450–470 MHz in China [12], and it is feasible to allocate enough bandwidth for LTE-R within this band. In Europe, the FRMCS of UIC would like to build on the current GSM-R investment by reusing the existing mast sites, which could save as much as 80–90% of the cost of a network. Railways are also concerned about continuing to make use of their GSM-R masts, and, therefore, a spectrum allocation under 1 GHz is more cost effective in Europe. However, the selection of frequency band depends on government policy and differs by country.

Standard LTE includes a core network of evolved packet core (EPC) and a radio access network of Evolved Universal Terrestrial Radio Access Network (E-UTRAN). The Internet protocol (IP)-based EPC supports seamless handovers for both voice and data to cell towers, and each E-UTRAN cell will support high data and voice capacity by high-speed packet access (HSPA). As a candidate for the next-generation communication system of HSR, LTE-R inherits all the important features of LTE and provides an extra radio access system to exchange wireless signals with onboard units (OBUs) and to match HSR-specific needs. The future architecture of LTE-R according to [4] is presented in Figure 2, and it shows that the core network of LTE-R is backward compatible with GSM-R.

Compared with the public LTE networks, LTE-R has many differences, such as architecture, system parameters, network layout, services, and QoS. The preferred parameters of LTE-R are summarized in Table 1, based on the future QoS requirements of HSR communications. Note that LTE-R will be configured for reliability more than capacity. The network must be able to operate at 500 km/h in complex railway environments. Therefore, quadrature phase-shift keying (QPSK) modulation is preferred, and the packet number of retransmission must be reduced as much as possible.

LTE-R Services

HSR communications intend to use a well-established/off-the-shelf system, where some specific needs should be defined at the service level. As suggested by the E-Train project [6], LTE-R should provide a series of services to improve security, QoS, and efficiency. Compared with the traditional services of GSM-R, some features of LTE-R are described.

1) *Information transmission of control systems:* To enable compatibility with the ETCS-3 or the Chinese Train Control System Level 4 (CTCS-4), LTE-R provides real-time information transmission of control information via wireless communications with a <50-ms delay. While the location information of the train is detected by a track circuit in ETCS-2/CTCS-3, in ETCS-3/CTCS-4 and LTE-R, the location information of the train is detected by RBC and onboard radio equipment. This improves the accuracy of train tracking and the efficiency of train dispatchment. LTE-R also can be used to provide information transmission for future automatic driving systems.
2) *Real-time monitoring:* LTE-R provides video monitoring of front-rail track, cabin, and car connector conditions; real-time information monitoring of the rail track conditions (e.g., temperature and flaw detection); video monitoring of railway infrastructures (e.g., bridges and tunnels) to avoid natural disasters; and video monitoring of cross tracks to detect freezing at low temperatures. The monitoring information will be shared with both the control center and the high-speed train in real time, with a <300-ms delay. Although some of the aforementioned surveillance can be conducted by wired

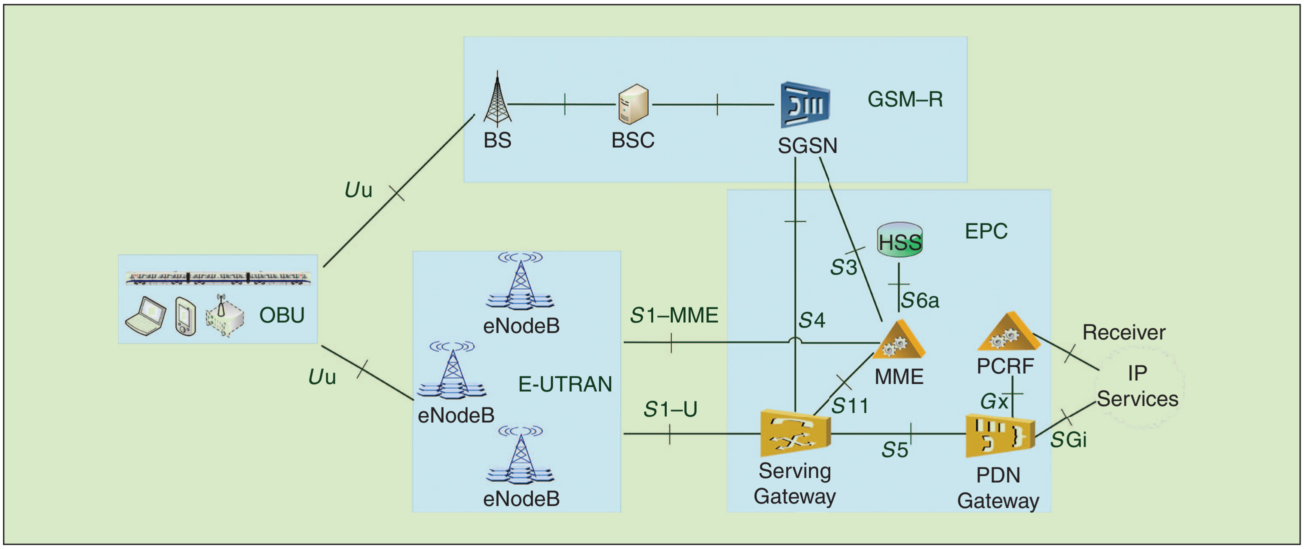

FIGURE 2 The LTE-R architecture for HSR communication. BSC: BS controller; HSS: home subscriber server; MME: mobility management entity; PCRF: policy and charging rules function; PDN: packet data network; SGSN: serving general packet radio service (GPRS) support node.

communications, the wireless-based LTE-R system is more cost effective for deployments and maintenance.

3) *Train multimedia dispatching:* LTE-R provides full dispatching information (including text, data, voice, images, video, etc.) of drivers and yards to the dispatcher and improves dispatching efficiency. It supports rich functionalities, such as voice trunking, dynamic grouping, temporary group call, short messaging, and multimedia messaging.
4) *Railway emergency communications:* When natural disasters, accidents, or other emergencies occur, establishment of immediate communications between accident site and rescue center is required to provide voice, video, data, and image transmissions. Railway emergency communication systems use the railway private network to ensure rapid deployment and faster response (with a <100-ms delay) compared with GSM-R.
5) *Railway Internet of Things (IoT):* LTE-R provides the railway IoT services, such as real-time query and tracking of trains and goods. It helps to enhance transport efficiency and extend service ranges. Moreover, railway IoT could also improve train safety. Most of today's trains rely on trackside switches located in remote areas. With the IoT and remote monitoring, it is possible to remake trackside infrastructure from switches to power lines, which could automate many of the routine safety checks and reduce the costs of maintenance.

In addition to the features listed previously, some other services of LTE-R should be included, such as dynamic seat reservation, mobile e-ticketing, and wireless interaction of passenger information. Figure 3 summarizes the future possible services provided by LTE-R, which is based on the technical reports of the UIC, China Railway, and ERA. It is noteworthy that broad-band wireless access for passengers inside high-speed trains is not provided by LTE-R because of its limited bandwidth. Some candidates for broad-band wireless access for train passengers have been discussed, such as Wi-Fi, Worldwide Interoperability for Microwave Access (WiMAX), 3G/4G/5G, satellite communications, and radio-over-fiber (RoF) technology [13].

LTE-R Challenges

There are several challenges associated with LTE-R.

1) *HSR-specific scenarios:* In the LTE standard of [14], a channel model for HSR is presented that only includes two scenarios, open space and tunnel, and uses a nonfading channel model in both scenarios. However, as indicated by [15], the strict demands (high velocity,

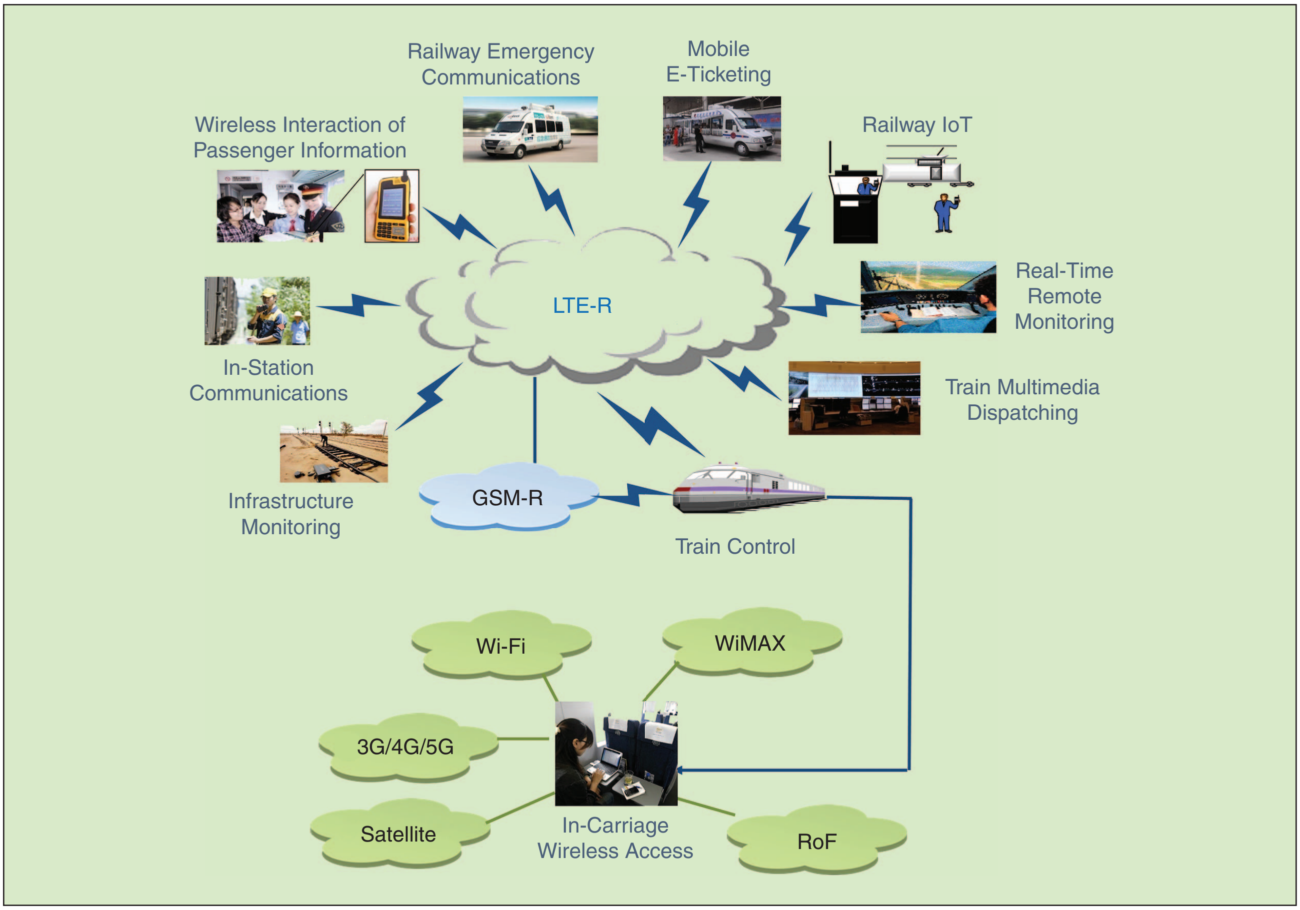

FIGURE 3 The LTE-R services.

rail track flatness, etc.) of HSRs lead to many HSR-specific environments, such as viaducts, cuttings, and tunnels. The propagation characteristics in those scenarios are distinct from traditional cellular communications and may significantly impact the system performances of GSM-R and LTE-R. In the past, some measurements were conducted to characterize the HSR channels for GSM-R band, and a scenario-based path loss and shadow fading model has been proposed in [16] and [17] for GSM-R at 930 MHz. However, this work is still ongoing, and many scientific issues are yet to be solved at LTE-R band, e.g., propagation loss, geometry distribution of multipath components (MPCs), and two-dimensional/three-dimensional angular estimation in those HSR-specific environments. It is necessary to develop a series of channel models for the link budget and network design of LTE-R, and extensive channel measurements are needed.

2) *High mobility:* High-speed trains usually run at a speed of 350 km/h, and LTE-R is designed to support 500 km/h. The high velocity leads to a series of problems. First, high velocity results in a nonstationary channel because, in a short time segment, the train travels over a large region, where the MPCs change significantly. Characterization of nonstationary is of special importance as it affects the BER in single-carrier and multicarrier systems. Second, high velocity leads to a shift of the received frequency, called the *Doppler shift*. For example, if the frequency is 2.6 GHz, the maximum Doppler shift at 350 km/h is 843 Hz, whereas it is only 24 Hz for a pedestrian mobile speed of 10 km/h. The large Doppler shift leads to phase shift of the signal and can impair the reception of angle-modulated signals. However, because the high-speed train mostly moves along a scheduled line with a known speed, it is possible to track and compensate for the Doppler shift by using the real-time recorded information of speed and position. Third, a large Doppler spread is expected in HSR environments owing to the high velocity. For LTE-R (broad-band system), Doppler spread typically leads to loss of signal-to-interference-plus-noise ratio and can hamper carrier recovery and synchronization. Doppler spread is also of particular concern for orthogonal frequency division multiplexing (OFDM) systems, because it can corrupt the orthogonality of the OFDM subcarriers. Several approaches such as frequency-domain equalization and the intercarrier interference self-cancellation scheme should be considered [18].

3) *Delay spread:* Delay dispersion leads to a loss of orthogonality between the OFDM subcarriers, and a special type of guard interval, called the *cyclic prefix* (*CP*), should be employed. The delay dispersion determines the required length of CP. LTE supports both short (4.76 ms) and long (16.67 ms) CP schemes. For the short CP scheme, the corresponding maximum difference of path length between two MPCs is 1.4 km. Because railway communications aim to provide linear coverage, directional BS antennas with main lobes along the rail track are widely used, so transmit power is focused on the narrow-strip-shaped regions. Intuitively, we would anticipate that the short CP scheme is sufficient for LTE-R. This is especially true because high-speed trains mostly travel in (semi)rural/suburban environments, where there are few scatterers. However, in some special environments with rich multiple reflections, such as cuttings, a large delay spread is expected (note that a measurement-based validation is required), and the long CP scheme should be used. Another example for large delay spread occurs in the presence of mountains along the rail track [19], especially before and after the train enters and leaves tunnels. More measurements are required to address the behaviors of delay spread in HSR environments, and the CP needs to be adjusted to the environment, just as with general LTE.

4) *Linear coverage:* In HSRs, linear coverage with directional antennas along the rail track is used, where the directional BS antennas orientate their main lobe along the rail track so that it is power efficient. The linear coverage brings some benefits, e.g., with the known location of a train, it is possible to design distance/time-based beamforming algorithms with good performance. However, it is noteworthy that the link budget and performance analysis of linear coverage are different from the circular cell of cellular systems, e.g., for the determination of the percentage of coverage area. It is well known that, due to the effect of shadow fading, some locations within the coverage area will have a received signal below a particular threshold. Computing how the boundary coverage relates to the overall percentage of coverage area is very useful for link budget and network planning. In Figure 4, we compare the determination of percentage

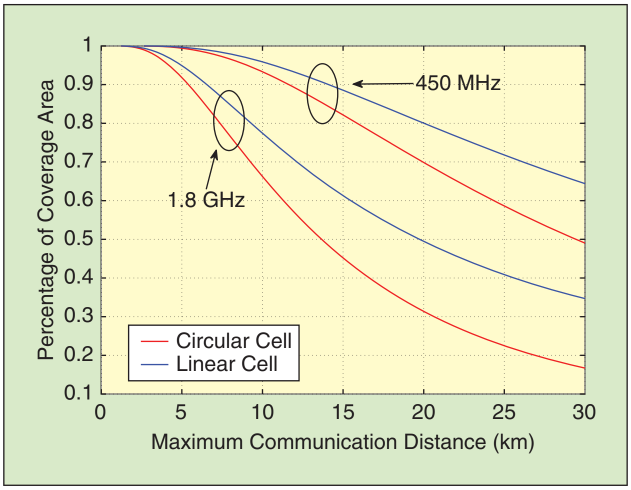

FIGURE 4 The coverage area predictions for HSR linear cell and cellular circular cell.

of coverage area for linear and circular cells [20] using the Hata-based link budget model, where we can see that the linear coverage in HSRs generally has a higher percentage of coverage area. This should be carefully considered when designing LTE-R networks to avoid an overdeployment of BSs.

5) *Sparse multipaths:* Sparse multipath channels represent a sparse distribution of resolvable paths in the angle-delay-Doppler domain. As in some open areas of HSRs, for example, viaducts and rural areas, there are few scatterers. The linear coverage of HSR also reduces the number of the scatterers that can be seen by transmitters/receivers. It is possible to have a sparse multipath channel in those environments. However, support for multiple-input, multiple-output (MIMO) transmission will be an integral part of LTE-R. The performances of multiantenna solutions, such as spatial diversity and spatial multiplexing, depend on the scattering richness in the environments. If the HSR channel turns out to be sparse in those open areas, the clear line of sight and few scatterers lead to a strong correlation between the signals of two antennas and reduce both diversity and spatial multiplexing gain. There is an indication that, in certain sparse environments, a reconfigurable antenna array [21] can improve system capacity.

6) *Impact of train car:* A high-speed train usually is over 200 m long and made of metal. The static high-speed train acts as a scatterer with strong reflection and increases the delay spread, whereas the dynamic nature of the high-speed train significantly increases the nonstationary aspect of channels. The large metal roof of the train also increases reflections and scatterings near the transmitters/receivers and significantly affects the pattern of the transmitters/receivers antenna on the roof. Moreover, propagation into the interior of the high-speed train leads to large penetration loss and reduces the SNR. The coverage inside the train car could be improved with moving relays, similar to femtocell access points.

GSM-R and LTE-R Coexistence

As GSM-R support by suppliers is committed until at least 2028 and the UIC has been working on the succession of GSM-R since 2009, the coexistence between LTE-R and GSM-R is expected to last for a long time.

1) *Business level:* LTE-R needs to support the traditional applications of GSM-R, such as group call service, broadcast service, and functional addressing. The multimedia broadcast multicast service of LTE, which is designed to provide efficient delivery of broadcast and multicast services, would be a possible solution to provide group call and broadcast services. The session initiation protocol (SIP) is a protocol for controlling multimedia communication sessions, and SIP addressing could possibly be used to provide functional addressing in LTE-R.

2) *Terminal level:* The future HSR terminal should support both GSM-R and LTE-R. A multimode mobile terminal with low complexity is a possible solution. Its disadvantages, such as high power consumption and

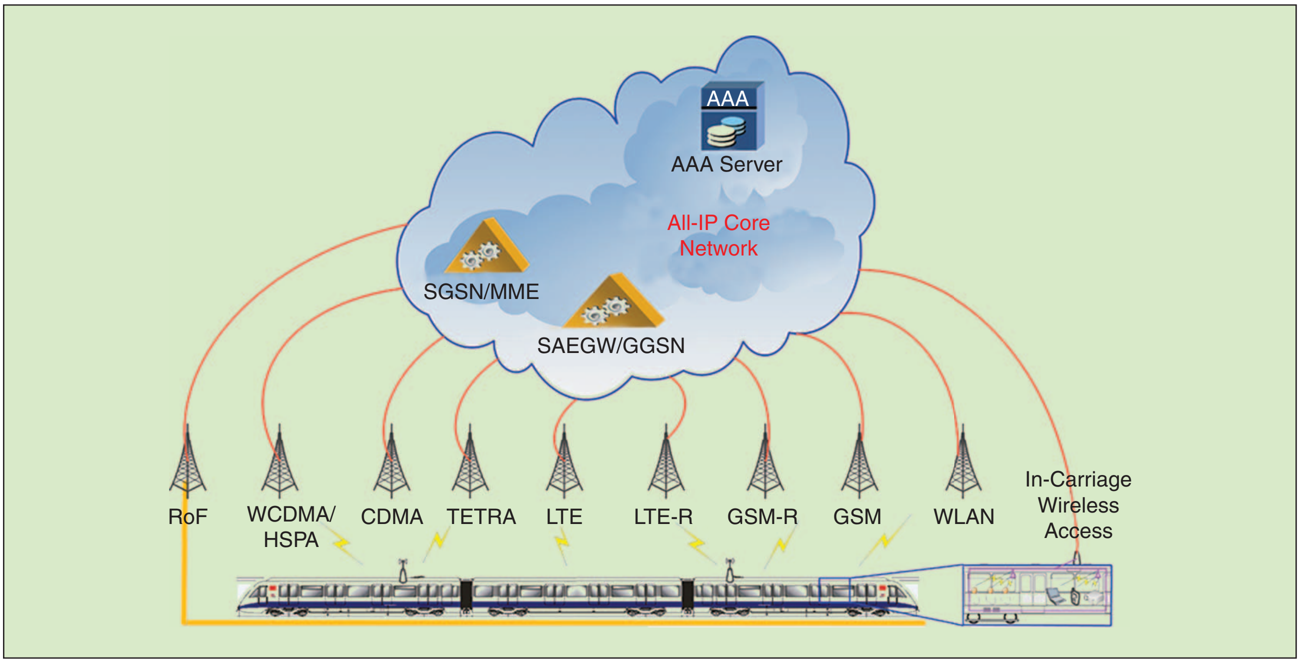

FIGURE 5 The future all-IP core network for HSR scenario. AAA: authentication, authorization, and accounting; CDMA: code division multiple access; GGSN: gateway GPRS support node; MME: mobility management entity; SAEGW: system architecture evolution gateway; WCDMA: wideband CDMA.

large size, are not problems for the HSR communication system.

3) *Access network level:* Direct coexistence of an access network between GSM-R and LTE-R would be difficult because they use different access technologies. It is possible for the two networks to share sites at the first step and use software-defined radio in the evolution from GSM-R to LTE-R.
4) *Core network level:* As pointed out by the UIC E-Train report [6], IP technology is the basic technology used for converging network capability. The goal of the HSR core network is to achieve an all-IP core network, which is illustrated in Figure 5, where GSM-R, LTE-R, wireless local area networks (WLANs), and Trans-European Trunked Radio (TETRA) are all connected to the core network. The all-IP core network supports end-to-end IP connectivity, distributed control and services, and gateways to legacy networks, where wireless BSs can be connected to the all-IP core network via IP. The mobile switching center, home location register, and authentication center of GSM-R will be replaced with the server and database of LTE-R, and the protocol of signaling networks will be replaced with IP. The whole network will evolve from a vertical tree structure to a distributed routing structure.

Conclusions

This article provides an overview of HSR-dedicated communication systems. The current narrow-band GSM-R is presented and its limitations are discussed. LTE-R, which is a likely candidate for next-generation HSR communications, is introduced. LTE-R will be a special configuration of LTE. LTE-R has the ability to fulfill railway requirements, and it will work as a cooperative network for railway operation and services. The possible system parameters and services of LTE-R are described, and some challenging issues are discussed. Finally, coexistence between GSM-R and LTE-R is addressed. LTE-R offers highly competitive performance and provides a good foundation for further evolution. Despite this advantage, LTE-R has to be explicitly evaluated to further prove that it is able to fulfill the requirements of HSR, for example, propagation characteristics and cell coverage at LTE-R band, the support of high mobility, and system capacity and capability. Hence, more investigations of LTE-R are needed.

LTE-R HAS THE ABILITY TO FULFILL RAILWAY REQUIREMENTS, AND IT WILL WORK AS CORPORATIVE NETWORK FOR RAILWAY OPERATION AND SERVICES.

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Author Information

Ruisi He (ruisi.he@bjtu.edu.cn) received his B.E. and Ph.D. degrees from Beijing Jiaotong University (BJTU), China, in 2009 and 2015, respectively. He is an associate professor with the State Key Laboratory of Rail Traffic Control and Safety, BJTU. His research interests include radio propagation, long-term evolution-railways, and fifth-generation communications. He serves as the Early Career Representative of Commission C, International Union of Radio Science (URSI), and he received the URSI Young Scientist Award in 2015.

Bo Ai (boai@bjtu.edu.cn) received his M.S. and Ph.D. degrees from Xidian University, China, in 2002 and 2004, respectively. He is a full professor and Ph.D. degree candidate advisor with the State Key Laboratory of Rail Traffic Control and Safety at Beijing Jiaotong University, China. He is the deputy director of the State Key Laboratory of Rail Traffic Control and Safety. He has authored/coauthored six books and published over 230 academic research papers. He holds 21 invention patents. He is an Institution of Engineering and Technology fellow. He is an associate editor of *IEEE Transactions on Consumer Electronics* and an editorial committee member of *Wireless Personal Communications*.

Gongpu Wang (gpwang@bjtu.edu.cn) received his B.E. degree in communication engineering from Anhui University, China, in 2001; his M.S. degree from the Beijing University of Posts and Telecommunications, China, in 2004; and his Ph.D. degree from the University of Alberta, Edmonton, Canada, in 2011. From 2004 to 2007, he was an assistant professor in the School of Network Education, Beijing University of Posts and Telecommunications. He is an associate professor at the School of Computer and Information Technology, Beijing Jiaotong University, China. His research interests include wireless communication theory and signal processing technologies.

Ke Guan (kguan@bjtu.edu.cn) received his B.E. and Ph.D. degrees from Beijing Jiaotong University (BJTU), China, in 2006 and 2014, respectively. He is an associate professor at the State Key Laboratory of Rail Traffic Control and Safety and the School of Electronic and Information Engineering, BJTU. In 2015, he was awarded a Humboldt Research Fellowship for Postdoctoral Researchers. He was the recipient of a 2014 International

Union of Radio Science Young Scientist Award. His current research interests are the measurement and modeling of wireless propagation channels for high-speed railway communications and future terahertz communication systems. He has authored/coauthored over 70 research papers in international journals and conferences.

Zhangdui Zhong (zhdzhong@bjtu.edu.cn) received his B.S. and M.S. degrees from Beijing Jiaotong University (BJTU), China, in 1983 and 1988, respectively. He is a professor at BJTU and a chief scientist with the State Key Laboratory of Rail Traffic Control and Safety, BJTU. He is also a director of the Innovative Research Team of the Ministry of Education and a chief scientist with the Ministry of Railways in China. His research interests include wireless communications for railways, control theory and techniques for railways, and Global System for Mobile Communications-Railway. He received the Mao Yisheng Scientific Award of China, the Zhan Tianyou Railway Honorary Award of China, and the Top Ten Science/Technology Achievements Award of Chinese Universities.

Andreas F. Molisch (molisch@usc.edu) received the Dipl. Ing., Ph.D., and Habilitation degrees in wireless communications from the Technical University of Vienna, Austria, in 1990, 1994, and 1999, respectively. He is a professor of electrical engineering at the University of Southern California, Los Angeles, where he is also the director of the Communication Sciences Institute. His research interest is wireless communications, with emphasis on wireless propagation channels, multiantenna systems, ultrawide-band signaling and localization, novel cellular architectures, and cooperative communications. He is the author of four books, 18 book chapters, and more than 450 journal and conference papers and holds 80 patents. He is a Fellow of the IEEE, National Academy of Inventors, American Association for the Advancement of Science, and the Institution of Engineering and Technology; a member of the Austrian Academy of Sciences; and the recipient of numerous awards.

Cesar Briso-Rodriguez (cesar.briso@upm.es) received his Eng. and Ph.D. degrees in telecommunications engineering from the Universidad Politécnica de Madrid (UPM), Spain, in 1996 and 1999, respectively. He was awarded the prize for the Best Ph.D. in Global System for Mobile Communications by the Spanish Association of Telecommunication Engineers. Since 2005, he has been a full professor at the Escuela Técnica Superior de Ingenieros de Telecomunicación of the UPM. His research activities are focused on the design and development of high-frequency communication systems for complex environments.

Claude Oestges (claude.oestges@uclouvain.be) received his M.S. and Ph.D. degrees in electrical engineering from the Université catholique de Louvain (UCL), Louvain-la-Neuve, Belgium, in 1996 and 2000, respectively. He is a research associate with the Belgian Fonds de la Recherche Scientifique, Brussels, and a professor in the Electrical Engineering Department, Institute for Information and Communication Technologies, Electronics and Applied Mathematics, UCL. He also serves as an associate editor for *IEEE Transactions on Antennas and Propagation* and *IEEE Transactions on Vehicular Technology*. He is the author or coauthor of two books and more than 170 journal papers and conference communications and was the recipient of the 1999–2000 Institution of Engineering and Technology Marconi Premium Award and the 2004 IEEE Vehicular Technology Society Neal Shepherd Award.

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