High-Speed Railway Communications: from GSM-R to LTE-R

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Abstract: To handle increasing traffic, ensure passenger safety, and provide real time multimedia information, a new communication system for high-speed railway (HSR) is required. In the last decade, public networks have been evolving from voice-centric 2G systems, e.g. Global System for Mobile Communication (GSM) with limited capabilities to 4G broadband systems, e.g., Long Term Evolution (LTE) that offer higher data rates. It is thus relevant for HSR to replace the current GSM-Railway (GSM-R) technology with the next generation railway dedicated communication system with improved capacity and capability. This article gives a brief review of the current GSM-R performance, followed by a discussion of its limitations. Then, the LTE-Railway (LTE-R) is introduced as the candidate for the next generation HSR dedicated communication system. System architecture, parameters, and services for the LTE-R network are presented and some challenging technical issues are discussed. Finally, the coexistence between GSM-R and LTE-R is addressed.

1. Introduction

High-speed railways (HSRs) improve the quality of rail services, yield greater customer satisfaction, and help to create socio-economically balanced societies [1]. This highly efficient transport mode creates significant challenges in terms of investment, technology, industry, and environment.

With the rapid development of HSRs, a reliable, broadband communications system is essential for different HSR components such as train control, safety-related communications, etc. 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 Global System for Railway Communication (GSM-R) has become obsolete. HSR applications have strict requirements for Quality of Service (QoS) measures such as data rate, transmission delay, Bit Error Rate (BER), etc. Due to these factors, as well as a desire to use mature and low-cost technology, HSR communications generally uses off-the-shelf technologies and add applications to meet specific services and demands. GSM-R [2] is a successful example, which is based on the GSM standard and has been used on over 70,000 km of railway lines (including over 22,000 km HSR lines) all over the world [3].

The GSM communications systems are decommissioned as the public communication market is evolving towards 3GPP Long Term Evolution (LTE) [4]. As a consequence, also GSM-R has a foreseeable end of its lifetime. A new system is thus required to fulfil HSR operational needs, with the capability of being consistent with LTE, offering new services, but still co-existing with GSM-R for a long period of time. The selection of a suitable wireless communication system for HSRs needs to consider performance, service attributes, frequency band, and industrial support, etc. Compared with 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. 5G, while currently discussed in 3GPP, will be available only after 2020 and thus is not suitable for the HSR timeframe [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). UIC is expected to complete operation and functional requirements determination by 2017. In China, the development of LTE-R has also been widely discussed and scheduled by the government. A time frame of LTE-R in China is presented in Figure 1(a), and the first LTE-R network of China is scheduled for 2020.

This article aims to review and discuss the features and key challenges of LTE-R in future HSR communications. The current GSM-R system is introduced in the next section. Then some challenging issues of LTE-R and its co-existing with GSM-R are discussed. The final section concludes this article.

2. GSM-R

This section introduces GSM-R system, presents some typical rail specific features, and discusses some limitations.

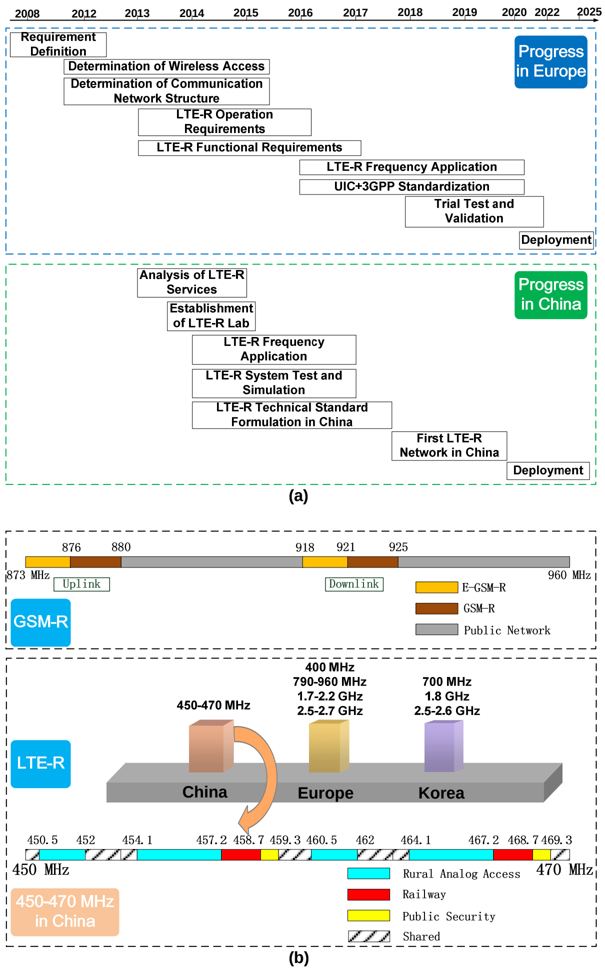

Figure 1 *(a) Time frame of LTE-R in Europe and China. (b) Allocation of frequency bands.*

2.1 System Description

GSM-R is essentially the same system as the Global System for Mobile Communications (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 also 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; whereas in China, it is 3-5 km since redundancy coverage is used to ensure higher availability and reliability. GSM-R has to fulfil tight availability and performance requirements of the HSR radio services. Table 1 summarizes some key parameters of GSM-R systems.

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	Multi-Sector	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	2x2, 4x4	2x2
Mobility	Max. 500 km/h	Max. 350 km/h	Max. 500 km/h
Handover Success Rate	⩾ 99.5%	⩾ 99.5%	⩾ 99.9%
Hanover Procedure	Hard	Hard/Soft	Soft: No data loss
All IP (native)	No	Yes	Yes

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

2.2 Services

GSM-R network serves as a data carrier for the European Train Control System (ETCS), which is the signaling system used for railway control. ETCS has 3 levels of operation and it uses the GSM-R radio network to send and receive information from trains. On the first level, i.e., 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. We briefly discuss in the following the most typical HSR-specific services offered by GSM-R [9]:

1) Voice Group Call Service (VGCS): this 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) Multi-Level Enhanced Precedence and Pre-Emption (eMLPP): this defines the user's priority and is used to achieve high performance for emergency group calls.

4) Shunting Mode: The purpose of shunting mode is to provide an effective means of communication to a group of personnel who are involved with a shunting operation. This application regulates and controls user access to shunting communications. Shunting communication is a Link Assurance Signal (LAS) that is 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.

2.3 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 as follows.

1) Interference: The interference between GSM-R and other public networks increases due to the fact that 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 speaking, 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 narrowband system, GSM-R cannot provide advanced services and adapt to new requirements. The maximum transmission rate of GSM-R per connection is 9.6 kbit/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 new services of HSRs such as real time monitoring require a wideband system to have larger data rate and short delay.

Due to above limitations, GSM-R must eventually evolve in order to eliminate revealed shortcomings [11]. LTE-R, which could be based on LTE standard, is a likely candidate to replace GSM-R in the future for the following reasons: i) LTE has many advantages over GSM in terms of capacity and capabilities; ii) as a fully packet-switched based network, LTE is better suited for data communications; iii) 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; iv) LTE has a high throughput radio access as it consists of a number of improvements that increase spectral efficiency such as the advanced multiplexing and modulation; and v) LTE is also a well-established and off-the-shelf system, and provides standardized interworking mechanisms with GSM.

3. LTE-R

This section presents the system parameters and possible services of LTE-R. Some challenging issues of LTE-R implementation are further discussed.

3.1 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 needs 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 system works at the bands above 1 GHz, such as 1.8 GHz, 2.1 GHz, 2.3 GHz, 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 a LTE-R cell would be less than 2 km (due to the strict requirement of signal-to-noise ratio (SNR) and BER in HSR), leading to a requirement of substantial investment for higher BS density, and frequent handovers. Therefore, the low frequency bands such as 450-470 MHz, 800 MHz, and 1.4 GHz have been widely considered. Especially the 450-470 MHz band is already well adopted by the railway industry, therefore, dedicated bandwidth for professional use can still be allocated from the 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 re-using 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, 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 for different countries.

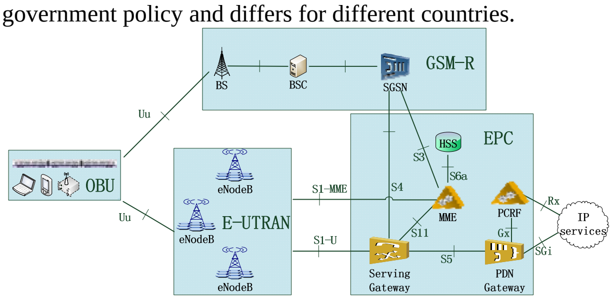

__Figure 2__ LTE-R architecture for HSR communication. SGSN: serving GPRS support node.

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 extra radio access system to exchange wireless signals with Onboard Board Units (OBUs) and to match HSR specific needs. The future architecture of LTE-R is presented in Figure 2 according to [4] and it shows that the core network of LTE-R is backwards-compatible with GSM-R.

Compared with the public LTE networks, LTE-R has many differences such as architecture, system parameters, network layout, services, QoS, etc. 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 speed in the 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.

3.2 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 as follows:

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 less than 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.

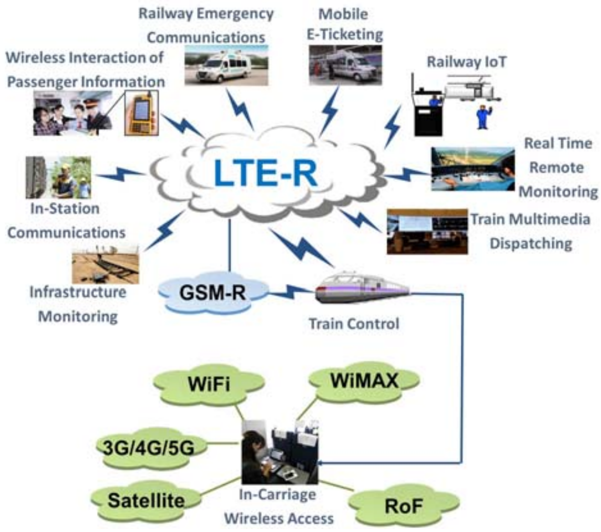

__Figure 3__ LTE-R services.

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 less than 300 ms delay. Though some of the above surveillance can be conducted by wired communications, the wireless-based LTE-R system is more cost-effective for deployments and maintenances.

3) Train multimedia dispatching: It 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, etc.

4) Railway emergency communications: When natural disasters, accidents or other emergencies occur, it is required to establish communications quickly between accident site and rescue center 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 less than 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 the remote areas. With the IoT and remote monitoring, it is possible to remake trackside infrastructure from switches to power lines. This could automate many of the routine safety checks and reduce the costs of maintenances.

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

3.3 Challenges

1) HSR-specific scenarios: In the LTE standard of [14], a channel model for HSR is presented, which only includes two scenarios: open space and tunnel, and [14] uses a non-fading channel model in both scenarios. However, as indicated by [15], the strict demands (high velocity, rail track flatness, etc.) of HSRs lead to many HSR-specific environments, such as viaducts, cuttings, tunnels, etc. The propagation characteristics in those scenarios are distinct from the 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] [17] for GSM-R at 930 MHz. However, this work is still ongoing and many scientific issues have not been solved at LTE-R band yet, e.g., propagation loss, geometry distribution of Multipath Components (MPCs) and 2D/3D 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: i) High velocity results in a non-stationary channel, because in a short time segment the train travels over a large region, where the MPCs change significantly. Characterization of the non-stationarity is of special importance as it affects the BER in single-carrier and multicarrier systems. ii) 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, since 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. iii) A large Doppler spread is expected in HSR environments owing to the high velocity. For LTE-R (broadband system), Doppler spread typically leads to loss of signal-to-interference-plus-noise ratio (SINR) and can hamper carrier recovery and synchronization. Doppler spread is also of particular concern for Orthogonal Frequency Division Multiplexing (OFDM) systems, since 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 us) and long (16.67 us) CP schemes. For the short CP scheme, the corresponding maximum difference of path length between two MPCs is 1.4 km. Since railway communications aim to provide linear coverage, directional BS antennas with main lobes pointing to along the rail track are widely used, so that 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 since 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 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.

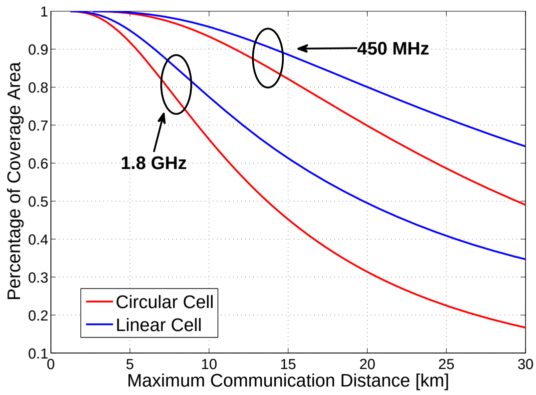

Figure 4 *Coverage area predictions for HSR linear cell and cellular circular cell.*

4) Linear coverage: In HSRs, linear coverage with directional antenna 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 is different from the circular cell of cellular system, e.g., for the determination of 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 of the 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 over-deployment 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, e.g., viaduct, and rural areas, there are few scatterers. The linear coverage of HSR also reduces the number of the scatterers that can be seen by Tx/Rx. 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 multi-antenna solutions such as spatial diversity and spatial multiplexing depend on the scattering richness in the environments. If the HSR channel turns to be sparse in those open areas, the clear LOS and few scatterers lead to strong correlation between signals of two antennas, and reduce both diversity and spatial multiplexing gain. It has been indicated that in certain sparse environments 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 non-stationarity of channels. The large metal roof of the train also increases reflections and scatterings near the Rx, and significantly affects the pattern of the Rx antenna on the roof. Moreover, propagation into the interior of the high-speed train leads to large penetration loss and reduces SNR. The coverage inside the train car could be improved with moving relays, similar to femtocell access points.

4. GSM-R and LTE-R Coexistence

As GSM-R support by suppliers is committed until at least 2028, and UIC has started the work on the succession of GSM-R since 2009, it is expected that the co-existence between LTE-R and GSM-R will last for a long time. This can be elaborated from several aspects:

1) Business level: LTE-R needs to support the traditional applications of GSM-R, such as group call service, broadcast service, functional addressing, etc. The Multimedia Broadcast Multicast Service (MBMS) 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 the SIP addressing would be a possible solution to provide functional addressing in LTE-R.

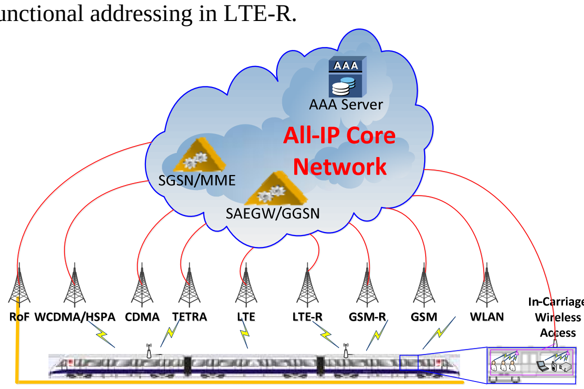

Figure 5 *Future all-IP core network for HSR scenario. MME: mobility management entity, SAEGW: system architecture evolution gateway, GGSN: gateway GPRS support node. AAA: authentication, authorization, and accounting.*

2) Terminal level: the future HSR terminal should support both GSM-R and LTE-R. A multi-mode mobile terminal with low complexity is a possible solution, whose disadvantages such as high power consumption and large size are not problems for the HSR communication system.

3) Access network level: direct coexistence of access network between GSM-R and LTE-R would be difficult since they both use different access technologies. It is possible for the two networks to share sites at the first step and use software defined radio (SDR) 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 (WLAN), 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 base stations can be connected to the all-IP core network via IP protocol. The mobile switching center (MSC), home location register (HLR), and authentication center (AUC) of GSM-R will be replaced with the server and database of LTE-R, and the protocol of signaling network will be replaced with IP protocol. The whole network will evolve from vertical tree structure to distributed routing structure.

5. Conclusion

This article provides an overview of HSR dedicated communication systems. The current narrowband GSM-R is presented and its limitations are discussed. LTE-R, which is a likely candidate for the next generation HSR communications is introduced. LTE-R will be a special configuration of LTE. It has the ability to fulfill railway requirements and it will work as corporative network for railway operation and services. The possible system parameters and services of LTE-R are described and some challenging issues are discussed. Coexistence between GSM-R and LTE-R is finally 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, e.g., propagation characteristics and cell coverage at LTE-R band, the support of high mobility, system capacity and capability, etc. Hence, more investigations of LTE-R are needed.

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