Development Trends of Mobile Communication Systems for Railways

Rui Chen Member, IEEE, Wen-Xuan Long, Guoqiang Mao Fellow, IEEE, Changle Li Senior Member, IEEE

Abstract—With the widespread deployment of high-speed railways and the increasing speed of trains, timely and reliable wireless transmission of train control signals and passengers’ mobile Internet access become critical. To meet these demands, mobile communication systems for railways is shifting from narrowband GSM-R to broadband systems. In contrast to GSM-R, broadband LTE-R and 5G-R system could provide more services such as real-time video surveillance, multimedia dispatching and railway Internet of Things (IoT). In this paper, we first briefly review the existing GSM-R system and discuss its limitations. Then, we discuss future development of user demands and various data services, which suggests the key performance indicators of the future mobile communication systems for railways. Afterwards, we survey the recent wireless technologies and network architectures that may be applied in mobile communication systems for railways in the near future. Finally, we summarize the technical challenges of future mobile communication systems for railways and conclude the paper.

Index Terms—Mobile communication systems for railways, GSM-R, LTE-R, 5G-R, heterogeneous integration.

I. INTRODUCTION

In recent years, fast, safe and efficient high-speed railway (HSR) has become one dominant transportation approach. Many countries have developed HSR to connect major cities, including Austria, Belgium, China, France, Germany, Italy, Japan, Netherlands, Poland, Portugal, Russia, South Korea, Spain, Sweden, Turkey, the United Kingdom, the United States and Uzbekistan. Only in Europe HSR crosses international borders. China has 25,000 kilometres of HSR at the end of December 2017, accounting for two-thirds of the world’s total and having reached an annual capacity of over 1.4 billion passengers [1]. Meanwhile, the maximum speed of the bullet train trips between Beijing and Shanghai has been raised to 350km/h in September 2017 [2]. An overview of HRS in service in these countries is given in Table I based on the data from International Union of Railways (UIC) [3] and updated with Google. With the widespread development of HSR and the rising speed of the trains, timely and reliable wireless transmission of train control signals and passengers’ mobile Internet access become more and more important.

Mobile communication systems for railways as an important connection between ground and train is one of the key technologies enabling the successful operation of HSR. The first international mobile communication system for railways standard Global System for Mobile Communications-Railway (GSM-R) provides reliable two-way channels, through which movement authority, temporary speed restrictions and other train control signals are transmitted [4]. GSM-R has been successfully used for several years but can not fulfill all requirements of the railway industry [5]. Mobile communication systems for railways need keeping pace with the development trends of 4G and 5G mobile telecommunication technologies.

In recent years, Long Term Evolution for Railway (LTE-R) system has became a popular research topic [6], since LTE has been successfully commercialized. The first LTE-R network production was implemented in South Korea by Nokia in 2016 [7]. Adoption of advanced physical layer key technologies such as orthogonal frequency division multiplexing (OFDM) and multiple-input multiple-output (MIMO), and network layer key technologies such as all IP packet switching and flat network architecture [8] enables LTE-R network to achieve 100Mbit/s data transmission rate with 20MHz bandwidth and 100ms system delay in high mobility [6]. Thus,

<table>
<thead>
<tr>
<th>Country</th>
<th>In Operation (Km)</th>
<th>Operating Speed (Km/h)</th>
<th>Population Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>25000</td>
<td>350</td>
<td>10.70%</td>
</tr>
<tr>
<td>Spain</td>
<td>3100</td>
<td>320</td>
<td>12.69%</td>
</tr>
<tr>
<td>Germany</td>
<td>3038</td>
<td>320</td>
<td>18.28%</td>
</tr>
<tr>
<td>Japan</td>
<td>2765</td>
<td>320</td>
<td>36.55%</td>
</tr>
<tr>
<td>France</td>
<td>2647</td>
<td>320</td>
<td>12.96%</td>
</tr>
<tr>
<td>Sweden</td>
<td>1706</td>
<td>200</td>
<td>21.41%</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>1377</td>
<td>300</td>
<td>11.99%</td>
</tr>
<tr>
<td>South Korea</td>
<td>1104.5</td>
<td>300</td>
<td>44.57%</td>
</tr>
<tr>
<td>Italy</td>
<td>999</td>
<td>200</td>
<td>18.47%</td>
</tr>
<tr>
<td>Russia</td>
<td>845</td>
<td>250</td>
<td>12.22%</td>
</tr>
<tr>
<td>Turkey</td>
<td>802</td>
<td>250</td>
<td>7.00%</td>
</tr>
<tr>
<td>Finland</td>
<td>609.5</td>
<td>220</td>
<td>1.89%</td>
</tr>
<tr>
<td>Uzbekistan</td>
<td>600</td>
<td>250</td>
<td>9.01%</td>
</tr>
<tr>
<td>Austria</td>
<td>352</td>
<td>230</td>
<td>27.55%</td>
</tr>
<tr>
<td>Belgium</td>
<td>326</td>
<td>300</td>
<td>7.83%</td>
</tr>
<tr>
<td>Netherlands</td>
<td>175</td>
<td>300</td>
<td>11.99%</td>
</tr>
<tr>
<td>Poland</td>
<td>143</td>
<td>200</td>
<td>12.57%</td>
</tr>
<tr>
<td>Norway</td>
<td>64</td>
<td>210</td>
<td>12.44%</td>
</tr>
<tr>
<td>United States</td>
<td>54.6</td>
<td>240</td>
<td>3.73%</td>
</tr>
</tbody>
</table>

This work was supported in part by the National Natural Science Foundation of China (61571350,61301168), the China Postdoctoral Science Foundation, State Key Laboratory of Rail Transit Engineering Informatization (SKLK18-03), State Key Laboratory of Rail Traffic Control and Safety (RCS2016K011). (Corresponding author: Changle Li.)

R. Chen, W.-X. Long and C. Li are with the State Key Laboratory of Integrated Service Networks (ISN), Xidian University, Shaanxi 710071, China, and also with the State Key Laboratory of Rail Transit Engineering Informatization, China Railway FSDI Group Co., Ltd., Shaanxi 710043, China (e-mail: rchen@xidian.edu.cn, wxlong@stu.xidian.edu.cn, clli@mail.xidian.edu.cn).

G. Mao is with the School of Electrical and Data Engineering, University of Technology Sydney, Ultimo, NSW 2007, Australia, and also with Data61, CSIRO, Sydney, NSW 2015, Australia (e-mail: g.mao@ieee.org).
LTE-R system is able to provide more comprehensive railway services than GSM-R such as railway video surveillance and train multimedia dispatching.

However, the 4G system LTE Advanced (LTE-A) can not accommodate some potential railway services including autonomous driving and massive connections of railway Internet of things (RIoT) [6]. Although automatic train operation has long been used in trains, it can not deal with complex and emergency conditions. Thus, to realize autonomous driving, massive connections of RIoT and passengers’s Internet access, 5G communications as a promising solution has been proposed by the International Telecommunication Union (ITU), which will eventually achieve ultra-high peak data rate about 1Gb/s, ultra-low system delay about 1-5ms and 1000 times capacity of existing network. In 2015, ITU defined three major directions for novel 5G application scenarios including enhanced mobile broadband (eMBB), massive machine type of communications (mMTC), and ultra-reliable low latency communications (uRLLC) [9]. Due to high density passengers, high running speed and a large number of sensors, HSR can be considered as a typical scenario demanding development in all three directions. Recently, the world’s largest 5G test network has been deployed in China, and 5G is expected to be commercialized in 2020 [10]. With the rapid deployment of 5G in the coming years, mobile communications for railways are expected to be further enhanced by 5G for railway (5G-R) systems. So far, there are a number of studies on GSM-R, LTE-R networks and 5G techniques, but only limited number of researchers investigated 5G-based railway communication networks.

This paper provides an overview of the current mobile communication systems for railways and analyzes its future development trends and technical challenges. The rest of the paper is organized as follows: in Section II, we briefly review the current GSM-R system and discuss on its limitations; in Section III future development of user demands and various data services are discussed, which suggests the key performance indicators (KPIs) of future mobile communication systems for railways; we survey the recent wireless technologies and network architectures that may be applied in the future mobile communication systems for railways and summarize the technical challenges in Section IV, finally Section V concludes this paper.

II. EXISTING RAILWAY-DEDICATED MOBILE COMMUNICATION SYSTEMS

GSM-R promulgated by UIC is the first international mobile communication system for railways standard [11], which was built on GSM technology and benefits from the economies of scale of its GSM technology heritage, aiming at being a cost efficient digital replacement for those incompatible in-track cable and analogue railway radio networks. GSM-R is typically implemented using dedicated base stations (BSs) close to the railway, with tunnel coverage effected using directional antennae or ‘leaky’ feeder transmission. Thus, the network structure of GSM-R as shown in Fig.1 is essentially the same as GSM except for serving specific railway applications and network architectures that may be applied in the future.

![Network structure of GSM-R](image)

**Fig. 1: The network structure of GSM-R. CS: Circuit Switching; PS: Packet Switching; MSC: Mobile Switching Center; IN: Intelligent Network; HLR: Home Location Register; S-GSN: Serving GPRS Support Node; BSC: BS Controller; BTS: Base Transceiver Station; MS: Mobile Station.**

[12]. GSM-R has 9.6kbit/s data transmission rate in a specific frequency band with duplex frequency separation (In Europe, uplink: 876-880 MHz, downlink: 921-925 MHz; In China and South Africa, uplink: 885-889 MHz, downlink: 930-934 MHz; In India, uplink: 907.8-909.4 MHz, downlink: 952.8-954.4 MHz; In Australia, uplink and downlink using frequencies in 1800 MHz band) [13], supporting moving speed up to 500km/h. Taking GSM-R in China for example, in accordance with the channel allocation of equal spans, there are 21 carrier channels in total with channel serial number ranging from 999 to 1019. Removing the 999 and 1019 channels for separation and protection, 19 channels are actually available, each having a bandwidth of 0.2MHz. The distance between adjacent dedicated GSM-R BSs is 3-5km since redundant coverage is required to guarantee high availability and reliability [14].

The GSM-R network provides an information platform on which multiple services can be developed to meet railway-related communication demands. As illustrated in Fig.2, the service model of GSM-R from bottom up can be divided into four layers: GSM service, Advanced Speech Call Items (ASCI), railway specific services and railway applications. Since GSM-R inherits most of the features from GSM, the services provided by GSM become the basis of GSM-R services. Moreover, GSM-R provides ASCI and railway specific services to meet railway specific communication demands such as Group Voice Call [5]. ASCI consists of Enhanced Multilevel Precedence and Preemption (eMLPP), Voice Broadcast Service (VBS) and Voice Group Call Service (VGCS). Railway specific services contain functional addressing, presentation of functional addressing, access matrix and location dependent addressing. On the basis of ASCI and railway specific service, GSM-R provides a number of railway applications including the transmission of train control information, dispatch order
and radio train number.

Undoubtedly, GSM-R is successful in achieving its initial design goals. Nonetheless, some major limitations have been revealed in recent years, which are summarized as follows.

1) **Low link rate**: Each connection of GSM-R has a maximum transmission rate of 9.6kbit/s, which is not sufficient for image and video services. In addition, the delay of GSM-R is in the range of 400ms, which is too large to provide any real-time interactive services [15]. The connection setup time of GSM-R is in the range of 7s [16], which is too long to provide emergency services that require rapid connection.

2) **Small system capacity**: GSM-R system with the available 4MHz bandwidth can only support 19 channels of 0.2MHz bandwidth per channel, which can not accommodate the rapidly developing railway communications [14]. However, it is difficult to increase the system capacity of GSM-R since adjacent frequency bands of GSM-R have already been occupied.

3) **Few passenger service**: With the development of mobile Internet and the popularity of personal mobile terminals, passengers’ demand for fast and high-quality Internet access has grown significantly. However, GSM-R only provides train dispatching and control services. So far, passengers on the trains access the Internet through public networks along the railway tracks with poor user experience.

GSM-R as the early-generation mobile communication system for railways should evolve further to keep pace with the emerging requirements of HSR and mobile Internet. Otherwise, for railways should evolve further to keep pace with the e-Internet and the popularity of personal mobile terminals, which are summarized as follows.

**III. REQUIREMENTS OF FUTURE RAILWAY MOBILE COMMUNICATION SYSTEMS**

A. **Emerging Services for Future Railways**

With the rising speed and reduced inter-departure time interval of trains, reliable, real-time and comprehensive train control becomes critical. In an era when even airlines are trying to provide Internet access to passengers, it is urgent for railways to provide high quality Internet access service for train passengers. Emerging services of mobile communication systems for railways are summarized as follows.

1) **Real-time video surveillance**: To guarantee the safety of train operations, one of the effective measures is deploying real-time video surveillance system, which provides an “electronic telescope” to the drivers to expand horizon [19]. High-definition cameras will be installed along the railway track. Front-rail track situation will be transmitted to the driver to enable the driver to have enough time to take actions if there is something dangerous in front. At the same time, video services...
can enable other functions such as train multimedia dispatching.

2) **Train-to-train (T2T) direct communication**: At present, critical signals such as train location information are indirectly transmitted through train-to-infrastructure (T2I) communication system among trains. When infrastructure is broken and fail to work, communication among trains is interrupted. Under this scenario, since a train is unable to determine the precise location of other trains on the same track directly and without the assistance of infrastructure, rear-end accidents cannot be entirely avoided. Thus, it is necessary to deploy T2T communication system as the redundant system, which aims at detecting potential collisions and broadcasting prewarning messages to other trains on the same and neighboring tracks when emergency occurs [20].

3) **Train multimedia dispatching**: Currently, dispatching communication systems only provide data and voice information to the dispatcher. Lack of image and video information may cause remote dispatchers unable to know exact state accurately, resulting in low dispatching efficiency. To improve dispatching efficiency, full dispatching information, including data, voice, text, image and video, should be provided by next-generation multimedia dispatching communication system to the dispatcher. For instance, when a disaster strikes, a real-time train multimedia dispatching video should be provided to the dispatcher to ensure that the dispatcher can get the train status visually.

4) **Railway Internet of Things (RIoT)**: Most of railway infrastructures are located in remote areas, which is difficult for on-site check and maintenance. To solve this problem, railway IoT should be developed. The sensing information of railway infrastructures such as bridges, viaducts and tunnels can be collected through various sensors and sent back to the control center [6], [21]. In this way, a number of the routine safety checks can be implemented in the remote control center.

5) **Internet access on high-speed trains**: With the popularity of Internet, providing fast and high-quality Internet access services for passengers on trains become increasingly pressing [22]. Furthermore, wireless Internet should provide coverage for every corner of carriages, where passengers not only can chat on the Internet and browse the Web, but also access real-time HD video for business and entertainment [6].

**B. Performance Indicators of Future Railway Mobile Communication**

As mentioned above, the future mobile communication systems for railways will provide high data rate services, such as real-time video surveillance, train multimedia dispatching and Internet access on high-speed trains, whose data rate may reach tens of Mbps, or even several Gbps. Accordingly, in addition to other measures the bandwidth of future mobile communication systems for railways must be increased to meet the transmission needs of new services. Consider the high-speed Internet access service for example [23], assuming a per-passenger throughput of 0.6Mbps (uplink: downlink=1:5), mobile user penetration rate of 90%, LTE terminal penetration rate of 80%, an activation rate of 70%, and a use rate of Internet access service to be 50%. For example, CRH3 electric multiple units (EMUs) have a total passenger capacity of 1114. It follows that the total passenger throughput of the train is $(0.6 \times 70\% \times 50\%) \times (1114 \times 90\% \times 80\%) = 168.44Mbps$, which far exceeds that can be provided by the existing system bandwidth. Thus, future mobile communication systems for railways must shift from narrowband networks to broadband systems to be able to provide high data rate transmission capability.

**IV. FUTURE RAILWAY-DEDICATED MOBILE COMMUNICATION SYSTEMS**

To represent the railway service space, five typical railway communication scenarios are categorized: T2I communication, T2T direct communication, intra-carriage communication, intra-station communication, and infrastructure-to-infrastructure (I2I) communication [6], as shown in Fig.3. Since wired communications are commonly used among infrastructures and technically not much of a challenge, we mainly discuss the first four scenarios. Considering various railway services and scenarios, the network architecture of future mobile communication systems for railways should be heterogeneous including a variety of access networks operating at different frequency bands.

**A. T2I Communication Systems**

In the next-generation HSR system, image and video services will be provided. With this drastic change in railway communication services, a consequent change in T2I communication network is necessary.

With the widespread commercial use of LTE, LTE-R has already been an international research hot-spot for railway communications. In contrast to GSM-R, the network architecture of LTE-R is relatively flat, as shown in Fig.4. Without more intermediate control nodes (e.g., the BSC in GSM-R), eNodeBs can be connected to network routers directly [12].

1 The CRH3 is a version of the Siemens Velaro high-speed train used in China on the Beijing-Tianjin, Shanghai-Nanjing and other intercity railway lines. It is capable of service speed of 380 km/h.
which could reduce the system delay. Meanwhile, two physical layer technologies OFDM and MIMO can be used in LTE-R. On one hand, multiple parallel independent channels are generated by applying MIMO, where multiple data streams can be transmitted at the same time. Thus, data rate of LTE-R could be improved significantly without increasing bandwidth. On the other hand, the broadband channels are divided into a group of orthogonal flat sub channels by applying OFDM, and MIMO signal can be independently processed in each sub channel, which can maximally eliminate interference. Table II compares the major parameters between LTE-R and GSM-R. Obviously, LTE-R has better network performance and user experience than GSM-R. This means that LTE-R can provide more railway services including video surveillance in key areas (e.g., bridges, tunnels and scissor crossover) along railways and train multimedia dispatching [14]. Besides, the results in [24] indicated that LTE-R can inherit all the existing important railway services including eMLPP, VGCS and VBS. Meanwhile, LTE-R backbone evolved packet core (EPC) can provide support for legacy 3GPP technologies such as GSM-R [25], facilitating smooth evolution of mobile communication systems for railways. Thus, LTE-R is considered as the most likely alternative to GSM-R.

![Diagram](image)

**TABLE II: System parameters of LTE-R and GSM-R.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GSM-R</th>
<th>LTE-R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>900MHz, 800MHz, 1.4GHz</td>
<td>450MHz, 1.8GHz, 2.3GHz, 2.6GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>6MHz</td>
<td>1.4-20MHz</td>
</tr>
<tr>
<td>Peak data rate</td>
<td>CSD 9.6kb/s</td>
<td>Uplink 100Mbit/s</td>
</tr>
<tr>
<td></td>
<td>GPRS 170kb/s</td>
<td>Downlink 100Mbit/s</td>
</tr>
<tr>
<td>Peak spectral efficiency</td>
<td>0.33bps/Hz</td>
<td>2.55bps/Hz</td>
</tr>
<tr>
<td>Mobility</td>
<td>≤ 100km/h</td>
<td>≤ 100km/h</td>
</tr>
</tbody>
</table>

As an heterogeneous integrated network, 5G will be backward compatible with existing wireless communication technologies (e.g., 3G, LTE and LTE-A). This means that 5G is expected to support all existing railway services including ASCI and railway characteristic services, which lays foundation for 5G-R. Besides, compared with traditional MIMO, the 5G core technology massive MIMO can offer more degrees of freedom of wireless channel to support higher data rate [28]. Thus, besides inheriting the benefits of MIMO systems, massive MIMO can improve both the spectral efficiency and the energy efficiency significantly [27], [29], [30]. Moreover, with the aid of cloud system MIMO joint beamforming can focus the radiated energy towards the intended directions to minimize interference and greatly improve the data rate of high-mobility users [31]. Furthermore, the medium access control (MAC) layer design can be simplified by properly deploying massive MIMO systems [32], resulting in reduced system delay. Obviously, the transmission performance of 5G-R can be improved significantly by massive MIMO. In addition, as a candidate technology, instead of OFDM in 5G, the filter-bank based multicarrier (FBMC) may also be used in 5G-R. Since multiple discontinuous unoccupied spectrum resources could be flexibly used by FBMC [33], and the available bandwidth of 5G-R is much larger than LTE-R, a number of railway services that need a great deal of spectrum resources is expected to be provided by 5G-R. Based on the above discussion, due to improvement of network performance and capacity, besides inheriting existing railway services, 5G-R is expected to provide various emerging railway services such as real-time video surveillance along the railway tracks, train multimedia dispatching and massive connections of RIoT, which provides a basis for autonomous driving and remote maintenance. Due to the demands in short time delay for autonomous driving, large data capacity for real-time video surveillance, and a large number of sensing measures for railway IoT, HSR has been recognized as a typical scenario of 5G [34].

As an unlicensed and well known technology, WiFi has become feasible to utilize IEEE 802.11 standard-based wireless technologies for applications desired by the railway industry for improving operations’ effectiveness, monitoring and control, and safety. Some previous work has presented results on evaluation and test of the applicability of WiFi to provide connectivity to trains. The University of Nebraska, funded by a grant from the Federal Railroad Administration...
This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2018.2859347, IEEE Communications Surveys & Tutorials

As railway lines is fixed, train position, running direction and wireless environment parameters present strong regularity. Thus, a comprehensive railway wireless communication systems for railways can effectively improve the spectral efficiency and communication quality. In recent years, researchers from North America and Europe have already tried to apply emerging CR technology into the HSR field [42].

Another solution that is immune to electromagnetic interferences and able to offer large unregulated bandwidth is optical wireless communications (OWC) or free space optics (FSO). Some pioneering investigations on T2I communication using FSO technology were performed in Japan and UK. Specifically, works in Japan are quite advanced and promising for a new option for providing Internet on board trains (18 and references therein). The Railway Technical Research Institute in Japan in collaboration with the Keio University tested three methods: leaky optical fiber, fan-shaped laser beam and laser beam tracking and obtain the conclusion that the laser beam tracking is the most efficient method. It obtains throughput up to 400 Mbps.

CR monitors a set of parameters. If the results fall beyond a certain threshold, CR first attempts to adopt a new conditions from database. If there is no past experience suitable for the current conditions, CR can develop a new strategy and enable it, which is also placed into database [42]. Thus, applying CR to mobile communication systems for railways can effectively improve the spectral efficiency and communication quality. In recent years, researchers from North America and Europe have already tried to apply emerging CR technology into the HSR field [42].

Table III: Summary of different technologies to provide T2I communications.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Throughput</th>
<th>Latency</th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite</td>
<td>&gt;10Mbps</td>
<td>&lt;400ms</td>
<td>Existing infrastructure</td>
<td>Limited throughput, communication failures due to obstacles (tunnels, relief, etc.)</td>
</tr>
<tr>
<td>LTE/5G</td>
<td>&gt;10Mbps</td>
<td>&lt;200ms</td>
<td>Upgradeable infrastructure, low cost</td>
<td>Possible limited coverage, limited throughput</td>
</tr>
<tr>
<td>WiFi</td>
<td>&gt;100Mbps</td>
<td>&lt;100ms</td>
<td>Average throughput, seamless communications</td>
<td>High costs</td>
</tr>
<tr>
<td>RoF</td>
<td>/</td>
<td>&lt;100ms</td>
<td>Low cost, base stations, seamless communications</td>
<td>High costs</td>
</tr>
<tr>
<td>OWC</td>
<td>&gt;10Gbps</td>
<td>&lt;50ms</td>
<td>Very high throughput, seamless communications</td>
<td>Heavy infrastructure needed, influence of atmospheric conditions, very high costs</td>
</tr>
</tbody>
</table>

1553-877X (c) 2018 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.
Besides, 5G has good transmission performance, such as low delay, high reliability and high date rate, which can meet the requirements of T2T communication. Thus, 5G-R will be a strong candidate for railway T2T communications.

To illustrate the scenario of T2T communications more clearly, we plot a diagram in Fig.5. It is expected in 5G-R systems, when infrastructure stops working, an emergency T2T communication network is set up using D2D functionality in a short time, replacing the interrupted T2I communications. Once a T2T communication link is established, adjacent trains on the same track directly connect and communicate with each other, such as Train1 and Train2 in the diagram. Meanwhile, the destination train can use the trains running on neighboring tracks as relays to receive signals from the source train if the source and destination trains are at an unreachable distance apart, such as Train1 and Train4 in the diagram.

C. Intra-carriage Communication Systems

Since densely packed passengers in carriages have to travel for a relatively long time, passengers would be very interested in Internet access service. However, Due to high penetration loss of radio wave through carriage, high Doppler shift, frequent handover and other special features associated with high mobility, Internet access services may be challenged at high speed [50]. Even LTE-R, the latest-generation mobile communication systems for railways, still cannot provide Internet access for passengers due to the limitation of spectrum resources [50]. Hence, the most reliable solution is that passengers connect to APs in the carriage, and these APs connected to antennas outside the metal carriage communicate with infrastructure as relays.

Deploying a WLAN such as WiFi within the carriage is the approach chosen unanimously by all deployed solutions. Some researchers investigate also very recent technologies, such as IEEE 802.11ad or WiGig (at 60 GHz), and the Li-Fi [18]. Furthermore, some preliminary studies were carried out on inside-carriage massive MIMO network in [6], including access modes for the coverage inside the carriage and the type of massive MIMO antennas array.

Fig. 5: The scenario diagram of T2T direct communications.
This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2018.2859347, IEEE Communications Surveys & Tutorials

Fig. 7: The heterogeneous network architecture of mobile communication systems for railways.

D. Intra-station Communication Systems

With the increase of multimedia and real-time services in railway station, the demand for reliable high data rate intra-station wireless communication is growing. However, due to the limitation of spectrum bandwidth and technical standards, GSM-R network only carries part of intra-station voice and data services with low requirements for data rate and delay [51]. Thus, it is necessary to optimize the intra-station wireless communication systems.

As railway hotspot areas, railway stations will become another typical scenario for massive MIMO network [6]. Compared to other higher mobility networks, deploying intra-station massive MIMO network is comparatively easy. As shown in Fig.6, intra-station massive MIMO network comprises of outdoor macro BSs and micro BSs installed inside the station buildings, forming a wireless backhaul. At the macro BS side, different forms of massive MIMO antennas could be deployed by utilizing nearby high buildings. The shape of those antennas can be diverse, including distributed, spherical, cylindrical, and rectangular array, but the most appropriate antenna array shapes in different environments need further investigation.

E. Heterogeneous Network Architecture

In summary, mobile communication systems for railways is expected to be further improved by 5G-R. In our opinion, the continued development of mobile communication systems for railways may be divided into three stages. In the first stage, LTE-R will be gradually deployed, working with GSM-R. GSM-R will be responsible for the transmission of security data related to train dispatching and control, while LTE-R will be responsible for transmission of other non-security data. In the second stage, LTE-R will completely replace GSM-R. Meanwhile, 5G-R will be gradually phased in to provide emergency communication among trains and Internet access inside carriages. In the third stage, a complete 5G-based heterogeneous mobile communication systems for railways will be deployed, which can meet the communication requirements of various railway scenarios, including T2I, T2T, intra-carriage and intra-station.

The heterogeneous network architecture of mobile communication systems for railways is illustrated in Fig.7. The onboard-tier is composed of devices and personal terminals inside the carriage, and the infrastructure-tier is built on the basis of multiple public wireless access networks (e.g., WiFi, 3G, 4G and 5G). However, for most railway scenarios, sparse population distribution results in low coverage of public wireless access networks. Thus, realizing reliable and various services still requires railway dedicated wireless networks (e.g., GSM-R, LTE-R and 5G-R). Each level of the heterogeneous system can realize the decoupling of the control plane and data plane. Data flows forwarded by switches are manipulated by the controller(s) of their own level. By external programming, the system enables the cooperative use of multiple public and dedicated wireless access networks along the railway tracks, and performs advanced distributed space-time data coding techniques [52] and packet classification to satisfy the data rate requirements of different user data flows. A pioneering commercial solution of aggregating multiple air interfaces of networks has been developed for the so-called “networked train” by Nomad Digital [53]. Moreover, the energy efficiency of the heterogeneous network could be further improved with “green” strategies [54]–[57].

The reliability of train dispatching and control services must be strictly guaranteed when passenger services are supported by mobile communication systems for railways. 5G network proposes conception of C/U-plane decoupled architecture, which can be used to ensure the reliability of train dispatching and control services. In the architecture, on one hand, to provide good connectivity and mobility, the C-plane is kept at 3G, 4G and 5G. However, for most railway scenarios, sparse population distribution results in low coverage of public wireless access networks. Thus, realizing reliable and various services still requires railway dedicated wireless networks (e.g., GSM-R, LTE-R and 5G-R). Each level of the heterogeneous system can realize the decoupling of the control plane and data plane. Data flows forwarded by switches are manipulated by the controller(s) of their own level. By external programming, the system enables the cooperative use of multiple public and dedicated wireless access networks along the railway tracks, and performs advanced distributed space-time data coding techniques [52] and packet classification to satisfy the data rate requirements of different user data flows. A pioneering commercial solution of aggregating multiple air interfaces of networks has been developed for the so-called “networked train” by Nomad Digital [53]. Moreover, the energy efficiency of the heterogeneous network could be further improved with “green” strategies [54]–[57].

The reliability of train dispatching and control services must be strictly guaranteed when passenger services are supported by mobile communication systems for railways. 5G network proposes conception of C/U-plane decoupled architecture, which can be used to ensure the reliability of train dispatching and control services. In the architecture, on one hand, to provide good connectivity and mobility, the C-plane is kept at 3G, 4G and 5G. However, for most railway scenarios, sparse population distribution results in low coverage of public wireless access networks. Thus, realizing reliable and various services still requires railway dedicated wireless networks (e.g., GSM-R, LTE-R and 5G-R). Each level of the heterogeneous system can realize the decoupling of the control plane and data plane. Data flows forwarded by switches are manipulated by the controller(s) of their own level. By external programming, the system enables the cooperative use of multiple public and dedicated wireless access networks along the railway tracks, and performs advanced distributed space-time data coding techniques [52] and packet classification to satisfy the data rate requirements of different user data flows. A pioneering commercial solution of aggregating multiple air interfaces of networks has been developed for the so-called “networked train” by Nomad Digital [53]. Moreover, the energy efficiency of the heterogeneous network could be further improved with “green” strategies [54]–[57].
interface, namely, X3 [59]. Considering strict requirements for transmission reliability, train control information is entirely kept at lower frequency bands without decoupling [60]. The user data flow is relegated to higher frequency bands with wider spectrum. As a result, crucial train control information and user data flow are separately transmitted through different nodes, which can avoid the interference from passenger services to enhance the security. Thus, applying C/U-plane decoupling architecture to 5G-R provides a better choice for Internet access service.

Thus, an intelligent control scheme is needed to manage the highly dynamic situation. SDN is a promising scheme, which makes it easier to manage different types of wireless networks [61]. The core concept of SDN is dividing the network into a smart control plane and simple data plane [62]. On one hand, data is forwarded only in data plane; on the other hand, the software-based control plane is regarded as the core of network intelligence, which can be programmed by external applications to manage different types of wireless networks [63], [64]. Thus, the key idea of deploying SDN for high-speed trains is to introduce the programmable layered architecture.

V. 5G-R CHALLENGES

Undoubtedly, the performance of mobile communication systems for railways will be improved significantly by 5G-R. However, as a new research field, 5G-R faces several challenges including propagation characteristics and channel models under various railway scenes, which are described as follows.

Firstly, the biggest challenge for 5G-R is providing network coverage along railway tracks. As a heterogeneous network, 5G supports all-spectrum access, allowing the utilization of both high and low frequencies [65]. Thus, 5G-R could be deployed by utilizing multiple frequency bands. On one hand, to provide good connectivity, the access layer of 5G-R can use high-quality lower frequency bands [66], such as 450-470MHz bands assigned to next-generation mobile communication systems for railways in China. Furthermore, abundant unused spectrum resources between 6GHz and 100GHz can be assigned to provide high data rate transmission capability. However, all-spectrum access faces a series of challenges such as channel measurement and modeling, unified access for low- and high-frequency bands, and the design of radio frequency components.

Secondly, for 5G-based T2T network, the propagation characteristics and channel models are highly dependent on the train operation environment. Meanwhile, the stability of the long-distance communication link is prone to be affected by environment, bad weather and interference. Thus, establishing channel models is a challenging task. To avoid interference between different T2T links, intelligent interference management scheme is indispensable for T2T communications. In addition, due to lack of effective supervision, security of T2T communication is a challenging task. Earlier studies on the security of machine-to-machine (M2M) communication including M2M connection based on trusted environment [67] and secrecy-based access control [68] may be adapted to solve the issues.

Furthermore, in the 5G-R C/U-plane decoupled architecture, since the C-plane and U-plane are inherently relegated into different physical nodes [59], how to synchronize the separated C-plane information with U-plane data is an urgent challenge [69]. Meanwhile, under high mobility scenarios, the trains pass through the overlapping registration areas so fast that the handover procedure may not be completed timely [70], resulting in service interruptions. Thus, how to achieve soft and fast handovers is another challenging task. The latest research on C/U-plane staggered handover [69] may be a feasible method to solve above problem.

In addition, so far, the researches on massive MIMO mainly focus on static channel conditions, and only several researchers investigated on the massive MIMO under high mobility scenarios [71]. Thus, the primary task for applying 5G-R to mobile communication systems for railways is propagation characteristic and channel models for massive MIMO under various high mobility scenarios including T2I communication and intra-carriage Internet access. Besides, inside the train the fundamental infrastructure and the user distributions that have impact on the shadow fading, will affect the deployment of massive MIMO antenna array [6]. Thus, how to deploy antennas array including the antenna numbers, the shapes, and the pitch angles to meet various scenarios and demands is another challenging task for massive MIMO.

Lastly, in the railway station, 5G-R must coexist with the public mobile communication network, the former is used for railway-dedicated communication, and the latter is responsible for recreation purposes such as Internet access for passengers. Thus, how to avoid the serious adjacent channel interference is a main challenge. Besides, considering the features of railway station including semi-closed, dense crowd, and complicated environment, the deployment of massive MIMO antennas may be affected. Thus, designing the optimum massive MIMO antenna array type for railway applications is another challenging task.

VI. CONCLUSIONS

Through presenting future railway services requirement, this paper has shown some opportunities to be brought by 5G-R to mobile communication systems for HSRs. As the first-generation mobile communication systems for railways, GSM-R has to evolve to broadband communication systems to meet the emerging requirements of HSRs. Although LTE-R can provide more comprehensive railway services than GSM-R, it still falls short of supporting some emerging services including autonomous driving, massive connections of RIoT and Internet access for passengers. As a possible future railway communication systems, 5G-R networks are expected to offer highly competitive performance, which will support a number of high data rate railway services not provided by LTE-R. In practice, whether the current GSM-R system evolves gradually from LTE-R to 5G-R or directly to 5G-R depends on the maturity of 5G networks and many other commercial and government policy factors. We envisage that the future mobile communication systems for railways including T2I, T2T, intra-carriage and intra-station communications will be finally
deployed with 5G-R based heterogeneous networks. Moreover, some future potential challenges of 5G-R are discussed.

REFERENCES


---

**Rui Chen** (’08-M’11) received the B.S., M.S. and Ph.D. degrees in Communications and Information Systems from Xidian University, Xian, China, in 2005, 2007 and 2011, respectively. From 2014 to 2015, he was a visiting scholar at Columbia University in the City of New York. He is currently an associate professor and Ph.D. supervisor in the school of Telecommunications Engineering at Xidian University. He has published about 50 papers in international journals and conferences and held 10 patents. His research interests include broadband wireless communication systems, array signal processing and intelligent transportation systems.

**Wen-Xuan Long** received the B.S. degree (with Highest Hons.) in Rail Transit Signal and Control from Dalian Jiaotong University in 2017. Shi is currently pursuing a M.S. degree in Communications and Information Systems at Xidian University. Her research interests include railway dedicated mobile communication systems and radar signal processing.

**Guoqiang Mao** (S’98-M’02-SM’08-F’18) joined the University of Technology Sydney in February 2014 as Professor of Wireless Networking. Before that, he was with the School of Electrical and Information Engineering, the University of Sydney. He has published about 200 papers in international conferences and journals, which have been cited more than 6000 times. He is an editor of the IEEE Transactions on Wireless Communications (since 2014), IEEE Transactions on Vehicular Technology (since 2010) and received Top Editor award for outstanding contributions to the IEEE Transactions on Vehicular Technology in 2011, 2014 and 2015. He is a co-chair of IEEE Intelligent Transport Systems Society Technical Committee on Communication Networks. He has served as a chair, co-chair and TPC member in a number of international conferences. He is a Fellow of IET. His research interest includes intelligent transport systems, applied graph theory and its applications in telecommunications, Internet of Things, wireless sensor networks, wireless localization techniques and network performance analysis.

**Changle Li** (M’09-CSM’16) received the Ph.D. degree in Communication and Information System from Xidian University, China, in 2005. He conducted his postdoctoral research in Canada and the National Institute of Information and Communications Technology, Japan, respectively. He was a Visiting Scholar with the University of Technology Sydney and is currently a Professor with the State Key Laboratory of Integrated Services Networks, Xidian University. His research interests include intelligent transportation systems, vehicular networks, mobile ad hoc networks, and wireless sensor networks.