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

Development Trends of Mobile Communication Systems for Railways

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***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.

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).
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TABLE I: The development of HSR in the world by 2017.

Country	In Operation (Km)	Operating Speed(Km/h)	Population Coverage
China	25000	350	10.70%
Spain	3100	320	12.69%
Germany	3038	320	18.280%
Japan	2765	320	36.55%
France	2647	320	12.96%
Sweden	1706	200	21.41%
United Kingdom	1377	300	11.99%
South Korea	1104.5	300	44.57%
Italy	999	200	18.47%
Russia	845	250	12.22%
Turkey	802	250	7.00%
Finland	609.5	220	1.89%
Uzbekistan	600	250	9.01%
Austria	352	230	27.55%
Belgium	326	300	7.83%
Netherlands	175	300	11.99%
Poland	143	200	12.57%
Norway	64	210	12.44%
United States	54.6	240	3.73%

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, 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

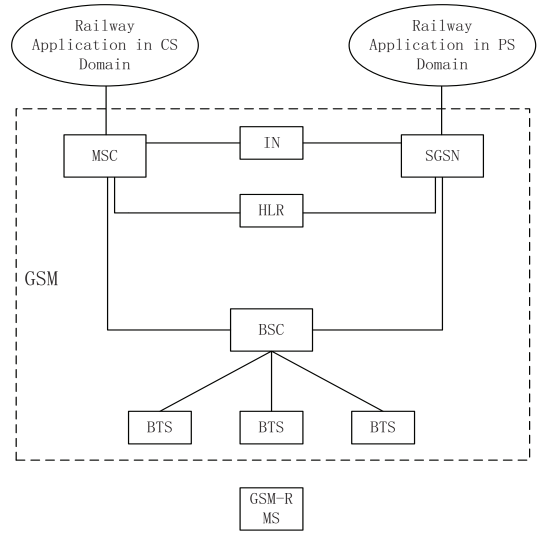

Fig. 1: The network structure of GSM-R. CS: Circuit Switching; PS: Packet Switching; MSC: Mobile Switching Center; IN: Intelligent Network; HLR: Home Location Register; S-GSN: Serving GPRS Support Node; BSC: BS Controller; BTS: Base Transceiver Station; MS: Moble Station.

[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 (ASCIs), 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

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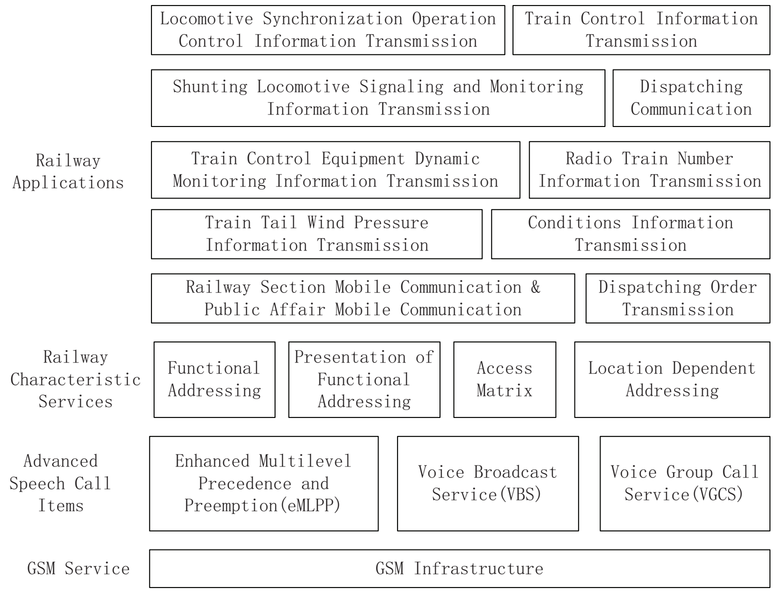

Fig. 2: The service model of GSM-R.

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, mobile communication systems for railways may turn into a bottleneck of railway growth [5]. UIC has announced that the life cycle of GSM-R will end in 2025.

Traditional cellular networks for railway have the main drawback of frequent handovers especially for HSR, which leads to a significant decrease of throughput. To solve the frequent handovers during the passage from one BS to another, Radio-over-Fiber (RoF) scheme is proposed to transfer complicated signal processing functions from the base stations along the railway to a centralized control station [17]. Antennas fed by optical fiber are called Remote Antenna Units (RAU). For communications from the access network to the train, firstly, data are modulated at control station level and sent into optical format to each RAU, and then antenna transforms the optical signal into a radio signal transmitted to the train. For communications from the train to the access network, the closest antenna captures data and perform the same operations. The RoF technology is used in the Shanghai Transrapid, which is a MAGLEV train running up to 500 km/h between the Shanghai airport and the city center around 30km long [18].

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

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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

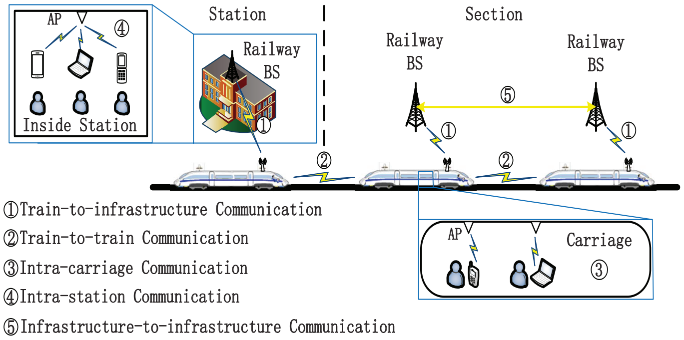

Fig. 3: Typical railway communication scenarios.

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[1] 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 Internet access, 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.

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

Parameter	GSM-R	LTE-R
Frequency	900MHz	450MHz, 800MHz,1.4GHz, 1.8GHz, 2.3GHz, 2.6GHz
Bandwidth	4MHz	1.4-20MHz
Peak data rate	CSD 9.6kb/s GPRS 170kb/s	Downlink 100Mbit/s Uplink 50Mbit/s
Peak spectral efficiency	0.33bps/Hz	2.55bps/Hz
Delay	$\leq 400ms$	$\leq 100ms$
Mobility	500km/h	500km/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.

However, even LTE-A is inadequate to support some potential railway services. For instance, due to limited bandwidth, LTE-A cannot support all-round real-time video surveillance along railway tracks, which is indispensable to automatic driving [6]. Besides, RIoT with the characteristics of massive connections, broad coverage and low power consumption may not be provided by LTE-A. Thus, to achieve the above services, we discuss the possibility of applying 5G to T2I communications. Similar to GSM-R and LTE-R, 5G-R systems will be also based on 5G mobile communication standard but with additional specific railway applications and dedicated frequency bands. As the next-generation communication systems, 5G mobile communication systems have ultra-low system delay of about 1-5ms [26] and ultra-high peak data rate of about 1Gb/s for high mobility. Meanwhile, compared with LTE, 5G systems can achieve 1000 times the system capacity, 10 times the spectral efficiency and 25 times the average cell throughput compared with its 4G counterpart [27]. This means that 5G systems may be able to support a number of high data rate services for HSR scenarios not supported by LTE-R.

As a 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

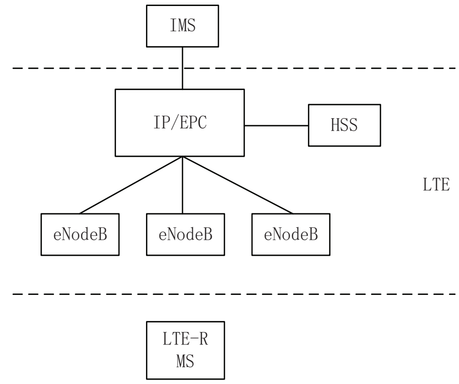

Fig. 4: The architecture of LTE-R. IMS: IP Multimedia Subsystem; EPC: Evolved Packet Core; HSS: Home Subscriber Server; eNodeB: evolved-NodeB; MS: Mobile Station.

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 aboved 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

(FRA), has been studying the feasibility of using 802.11a/b/g-based wireless networks for mobile railway environments [35]. Simulation results have been compared and verified with test bed measurements to analyze the performance of 802.11-based networks for mobile trains. Results and analysis show that even though the system throughput of 802.11 decreases under high mobility, it can still support railway applications if the coverage range is guaranteed. Besides, SNCF, the French National Railway Company, in collaboration with Orange Labs performed some experimental tests relying on 802.11b and g [36]. The tested network was based on 4 access points (APs) located on bridges and pylons, covering an area of 13km in Vendome. Connectivity performance tests were performed showing a network able to support 2 Mbps traffic during the handover across the 4 access points. More experiments were performed in 2010 using the IEEE 802.11n standard, in which two WiFi APs were placed at 6.3 km from each other in France, close to the average distance between two consecutive GSM-R sites, and the throughput up to some tens of Mbps were achieved [37]. In October 2016, ACKSYS Communications & Systems announced the release of a robust wireless backbone AP based on 802.11ac for cost-effective and scalable deployments of trackside networks, which has three independent 802.11ac high-speed radio cards (3 streams) delivering more than 900 Mbps each [38]. Thus, the AP allows the construction of "wireless backbone" to overcome Ethernet cables along tracksides and tunnels: 2 radios can be used to build the wireless infrastructure on the trackside while the 3rd radio is used as local AP to provide communication between the trackside and the train. Since 802.11ax is the successor to 802.11ac and will provide 4 times the throughput of 802.11ac, it is reasonable to believe that as a cost-effective complement future WiFi network may support real-time T2I communications for passengers, crew and railway workers, improving railway operating safety and efficiency.

Besides, due to multiple sources of interference, users competing for bandwidth, and unpredictable occupation [39], efficient management of mobile communication systems for railways is indispensable. Cognitive Radio (CR) is a promising approach to provide better QoS, which can perform bandwidth aggregation, dynamic spectrum allocation and mobility support. As opposed to the traditional wireless network, CR has cognitive ability, which can identify the portions of the spectrum that are unused at a specific time or location through real-time interaction with the wireless environment [40]. Meanwhile, through spectrum management capability, CR can select and reconfigure the best spectrum band and the most appropriate operating parameters [40], [41]. As railway lines is fixed, train position, running direction and wireless environment parameters present strong regularity and predictability. Thus, a comprehensive railway wireless environment database can be established by using CR to collect, analyze and store wireless environment parameters. When trains need to access the mobile communication systems for railways, CR can search the best conditions from the historical data, assigning the best idle frequency band and the most appropriate operating parameters to the train under the current scenario. Meanwhile, during the operations of trains,

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

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

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].

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.

Except for the aforementioned terrestrial mobile communication systems, satellite communications have long been considered to be applied in railway T2I communications in the scenario lacking of terrestrial communication infrastructure such as those sparsely populated areas. Communication satellites provide a vast coverage area, which can enable Internet access in combination with aggregation networks [43]. Despite having a long propagation delay of more than 250 ms and significant cost of implementation, Geostationary Earth

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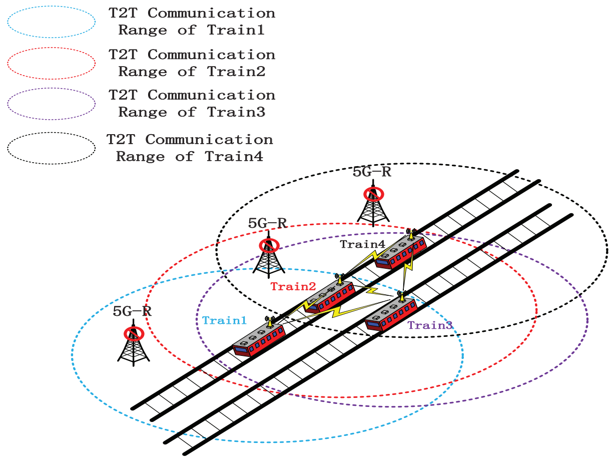

Fig. 5: The scenario diagram of T2T direct communications.

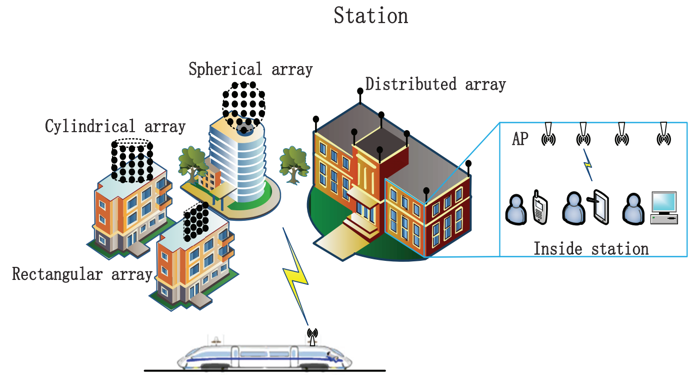

Fig. 6: The schematic diagram of intra-station massive MIMO network.

Orbit (GEO) satellites are most commonly used for train communications. Meanwhile, Ka band is proposed to provide a higher satellite capacity with a lower cost, but studies on Ka band still have to be performed, such as mobility effects and cell changes [18]. However, satellite communications face severe burst errors due to obstacles and mobility. The larger the obstacle, the larger the impact on the signal [42]. Moreover, satellite communication signals have a limited selection of frequency bands and cannot cover non-line-of-sight zones like hilly terrains, bad weather affected zones, tunnels and even densely populated urban areas [44]. Therefore, satellite communications usually act as a "gap-filler" of terrestrial T2I communication systems.

We summarize the pros and cons of different technologies to provide T2I communications in Table III. From the table, we consider that future T2I communications will be mainly based on LTE and 5G, i.e., LTE-R and 5G-R, supplemented by other technologies in different railway sections.

B. T2T Direct Communication Systems

As an assisting role, T2T communication systems maintain the normal communication among trains only through on-board devices when T2I communication network is broken. Since T2T wireless communication often takes place in the sections where trains don't have line of sight among them, the assigned frequency band of the system must have good diffraction property [45]. Meanwhile, with the continuous improvement of train speed and traffic density, available braking time of the train is greatly reduced. Thus, T2T communication has more stringent requirement for delay and transmission rate.

The 5G cellular network is envisioned to be a two-layer network with macrocell layer and device layer [46]. The device layer involves device-to-device (D2D) communications, which allows direct communication among devices without any network infrastructure involved or with limited infrastructure involvement [47]–[49]. Meanwhile, as a heterogeneous network, 5G supports all-spectrum access and is expected to provide frequency band with good diffraction performances. 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.

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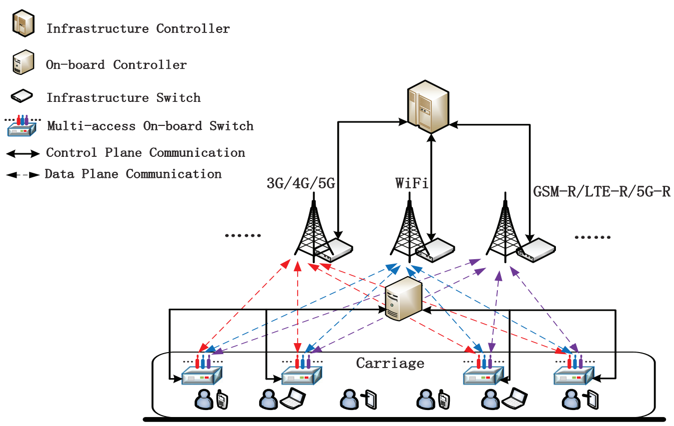

Fig. 7: The heterogeneous network architecture of mobile communication systems for railways.

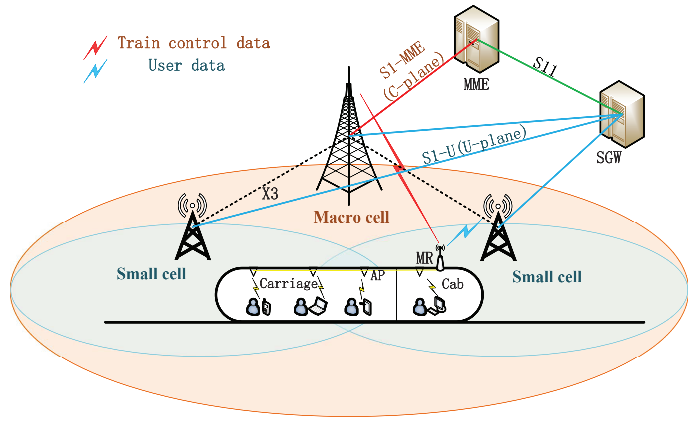

Fig. 8: The C/U-plane decoupled architecture of railway communication systems.

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 macro cells operating at high-quality lower frequency bands; on the other hand, to expand capacity, U-plane is moved to higher frequency bands of the small cells. Since different frequency bands are assigned to macro cells and small cells, there is no co-channel interference between them [58]. As shown in Fig.8, macro cells are connected to both the mobile management entity (MME) and the serving gateway (SGW). Small cells are only connected to SGW without any control functions. Also, macro cells and small cells can interact and synchronize with each other through a newly introduced

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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 indispensible 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 s-cenarios [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

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deployed with 5G-R based heterogeneous networks. Moreover, some future potential challenges of 5G-R are discussed.

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