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Mobile 5G Network Deployment Scheme on High-Speed Railway

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Abstract: The fifth-generation (5G) wireless communication has experienced an upsurge of interest for empowering vertical industries, due to its high data volume, extremely low latency, high reliability, and significant improvement in user experience. Specifically, deploying 5G on high-speed railway (HSR) is critical for the promotion of smart travelling such that passengers can connect to the Internet and utilize the on-board time to continue their usual activities. However, there remains a series of challenges in practical implementation, such as the serious Doppler shift caused by the high mobility, the carriage penetration loss especially in the high-frequency bands, frequent handovers, and economic issues. To address these challenges, we propose three schemes in this article to improve the coverage of 5G networks on the train. In particular, we provide a comprehensive description of each scheme in terms of their network architecture and service establishment procedures. Specifically, the mobile edge computing (MEC) is used as the key technology to provide low-latency services for on-board passengers. Moreover, these three schemes are compared among themselves regarding the quality-of-service, the scalability of service, and the related industry development status. Finally, we discuss various potential research directions and open issues in terms of deploying 5G networks on HSR.

Keywords: high-speed railway; mobile edge computing; mobile 5G; picocell base station

1 INTRODUCTION

The emergency of high-speed railway leads to the reconstruction and redistribution of population and industry, while bringing a significant impact on economy development, including tourism and freight industries. Moreover, Ai, B. (2015) [1] emphasized that high-speed railway (HSR) had brought huge convenience for passengers with high punctuality, rapid transit, and comfort services, while consuming less energy and producing less air pollution compared with cars and airplanes. Therefore, the future development of the railway is highly desired to evolve into a new era where infrastructure, trains, travellers, and goods will be increasingly interconnected to provide high comfort, with optimized door-to-door mobility at higher safety. Meanwhile, Osseiran, A. (2016) [2] and Ai, B. (2020) [3] also reported that HSR is expected to evolve into a new era for providing smart travelling services in the near future. In particular, passengers would enjoy their journey by utilizing the on-board time for their business-as-usual activities, such as watching high-quality videos, engaging low-latency online gaming, working via remote access to office clouds, real-time meetings, and participating in online courses. Especially, Ai, B. (2020) pointed out that 5G technologies could be a promising solution to dealing with the design challenges on high reliability and high throughput for HSR communications. Thus, to realize such services, the evolution of the 5G mobile communication is expected to be deployed on HSR for enhanced connectivity, real-time responses, and innovative experiences on-board.

The first standardized train communication system was based on Global System for Mobile (GSM) technology, which was deployed worldwide. Its extension to the railway service, namely GSM-Railway (GSM-R), is capable of providing voice and data services for train control. However, GSM-R has limited capability. The peak data rate of GSM-R is only 172 kb/s with latency on the order of 400 ms [4]. From the users' perspective, Gonzalez-Plaza, A. et al. (2017) [5] reported that 5G had made an incredible step forward, especially in audio-visual experience, interactivity, and scene expansion. Therefore, 5G systems will be needed to replace old GSM-R and dedicated systems for HSR signalling.

The most recently developed wireless standard, 5G NR, is designed to flexibly support diverse use cases and deployment scenarios having quite different requirements and properties, including very high mobility scenarios such as the high speed train [6]. 5G integrates big data, artificial intelligence (AI), cloud computing, the Internet-of-Things, and other technologies to enhance the quality of service to end users [7]. With its commercialization, Wong et al. (2017) [8] indicated that 5G had opened up a new world by providing unprecedented wireless services. Also, 5G terrestrial and satellite technologies will provide high data rate services to passengers. For example, Ghoshal, M. et al. (2022) reported that 5G could support not only the transmission of ultra-high-dimensional videos, but the commercial applications based on virtual reality (VR) and AI [9]. Moreover, Sandeepa et al. (2022) [10] mentioned that the concept of 5G cloud gaming breaks the limits of terminals, greatly improves the user mobility, and promotes the development of VR/augment reality (AR), somatosensory and interactive game devices. Furthermore, 5G effectively alleviates the technology bottleneck of VR and enriches the reading scenes, contents, and presentation forms of VR books, which undoubtedly creates a significant change in people's lifestyles. M. H. M. Sambas et al. (2019) [11] and Ashraf, S. A. et al. (2022) [12] tested the performance of 5G new radio for FRMCS, and found that 5G new radio can well meet the requirements of FRMCS. China has released a strategy to strengthen national transportation and promote the development of digital and intelligent railways based on 5G technology. In addition, China has realized the world's first 5G full-coverage high-speed railway in early 2022 (a total of over 300 base stations are built along the whole line of Beijing-Zhang railroad), which effectively solves the problems of signal penetration loss of the car body through technological innovations such as 5G slicing, dedicated high-speed railway network, carrier aggregation, super uplink and Unicom telecommunication sharing. Meanwhile, in the reports of Strinati, E. C. et al. (2018) [13] and Noh, G. et al. (2019) [14], real-world implementations of high speed train communication, which can achieve higher than 1 Gb/s data rate, where millimeter-wave (mm Wave) bands are employed to utilize a large amount of bandwidth. Therefore, providing 5G services for railway tourism can significantly promote the service level of HSR and consequently reshape the traffic pattern [15].

In recent years, a series of 5G deployment challenges have been discussed, Shafi, M. et al. (2017) [16] discussed site deployment and antenna arrays deployment, these challenges further trigger an increasing amount of research efforts for tackling 5G-related research problems. For example, Alsharif, M. H. et al. (2017) [17] researched the evolution towards 5G wireless networks, and pointed out that small-cell was considered to be an efficient and feasible solution for ensuring 5G indoor coverage. In addition, so far, many countries have not even allocated 5G dedicated frequency bands, and operators are promoting 5G-R public-private network integration solutions [18]. At the same time, railway industry is still actively striving for the private frequency of 5G-R networks. It is expected that the bandwidth that can be allocated to 5G-R will be smaller than that of the 5G public networks, which is an important factor affecting the performance of 5G-R [19].

To our knowledge, only a few studies have investigated the deployment of 5G networks on HSR carriage, as the indoor and high mobility characteristics bring further difficulties for implementing 5G in practice. In particular, the propagation and penetration losses, especially in the high-frequency bands, are fundamental problems to be solved. Moreover, Jiang, D. et al. (2017) [20] addressed the importance of Doppler shift and frequent group handovers. Therefore, the serious Doppler shift and frequent group handovers caused by the high mobility should also be taken into account. Consequently, it is still a pressing issue to deploy 5G on HSR without significant degradation of user experience.

Motivated and inspired by the unique challenges and opportunities brought by 5G and HSR, this article aims to provide high-quality 5G services for passengers, which sheds light on the potential research in this field. In particular, we first provide an overview on the unique challenges toward wireless coverage for HSR. We then propose three schemes to provide complete 5G coverage on HSR by using the mobile picocell base station (BS), the digital repeater, and the analog repeater methods, respectively. Moreover, a comprehensive description of each scheme is given in terms of the network architecture and session procedures. To further demonstrate the performance of the proposed schemes, we draw a comparison among the discussed schemes by evaluating their quality of service (QoS), scalability, and industry development status. Finally, potential research challenges and some future directions in terms of 5G network deployment on HSR are envisioned.

2 CHALLENGE IN PROVIDING 5G SERVISE ON HSR

With the development of HSR, the provision of high-quality services based on telecommunications still face various technical challenges, especially those caused by the high mobility and severe path loss. In the following, we point out the main challenges to be resolved [21].

2.1 Doppler Shift

The Doppler effect is a well-known phenomenon caused by the relative motions among radio sources, receivers, and the medium. In the HSR scenario, a fast-moving train introduces very high mobility relative to ground terminals/transceivers. Notably, the higher speed of the train, the more pronounced the Doppler effect is, which leads to a radical deterioration of the communication system reliability. For instance, for an HSR with a maximum speed of 500 km/h, it would induce a Doppler shift of 1620 Hz at a carrier frequency of 3.5 GHz. Specifically, the Doppler effect imposes a serious impact on the carrier frequency offset, which may introduce severe inter-carrier interference in 5G, where orthogonal frequency division multiplexing (OFDM) is adopted [22]. Therefore, the Doppler effect problem plays a crucial role in 5G-enabled HSR communications.

2.2 Frequent Group Handovers

The group handover problem occurs when the on-board mobile user equipments (UEs) switch their connections from one BS to another one simultaneously as a certain number of UEs are always concentrated in one train and moving forward to one direction. This creates a signalling message storm and generates a large number of processing demands for wireless links and network components [23]. Moreover, considering the use of the high frequency spectrum in 5G, the interdistance among BSs shrinks that leads to a more frequent group handover compared with the counterpart in 4G. For example, given a cell size of 300-500 meters and each building base band unit (BBU) supporting at least 6 remote radio units (RRUs) or active antenna units (AAUs), an HSR of 350 km/h experiences a group handover every 18-30 seconds. Such frequent group handover may seriously overload the system that reduces the system throughput, spectral efficiency, and service quality bringing another obstacle to deploying 5G networks on HSR.

2.3 High Penetration Loss

It is noted that the penetration loss increases with the signal carrier frequency. Also, microwave signals may experience excessive energy loss after penetrating the metallic carriage. In addition, the penetration loss is further increased when the incidence angle between the BS and the train is small. As a result, the signal transmitted from the trackside BS into the train is severely attenuated, especially due to the carriage penetration loss on the 5G high frequency spectrum band. Therefore, the high penetration loss needs to be resolved for improving the quality of 5G services on HSR.

In order to effectively circumvent the performance losses caused by the three aforementioned challenges, this article presents three new strategies based on the 5G frequency spectrum band namely, the mobile picocell scheme, the digital repeater scheme, and the analog repeater scheme. To highlight the advantages and disadvantages of each scheme, we then conduct a comprehensive comparison.

3 MOBILE PICOCELL SCHEME

Picocell BS is typically used to extend communication coverage and to increase the accommodation of wireless devices [24]. Benefited by its high flexibility, simple implementation, and satisfactory performance, we investigate the deployment of a mobile picocell BS in the carriage for HSR to boost the overall energy and spectral efficiencies [25]. Besides, the customized user plane function (UPF) and MEC are also mounted on the HSR to enable caching of popular resources and local offloading.

3.1 Network Architecture

The typical 5G mobile picocell architecture illustrated in Fig. 1 comprises the train networks and the ground networks. They collectively provide end-to-end high-quality communications. Specifically, the train network includes mobile picocell BSs, Ethernet systems, switches, MEC, UPF, and mobile relays. The ground networks include the trackside BSs, the 5G core network (5GC), servers, and the bearer network. Note that the Internet protocol security (IPSEC) gateway is deployed in the 5GC to establish virtual private network (VPN) tunnels. In the following, we specify the main components of the train network architecture.

Mobile Relays: It is in charge of the train-to-ground communication. All packets from the train are transmitted over the Internet via the designated mobile relay. By establishing a VPN tunnel between the mobile relay and the IPSEC gateway, the 5G data can be transferred securely and reliably. Moreover, we note that the antennas of the mobile relay are equipped outside the carriage, which could effectively address the path loss issue caused by carriage penetration.

Mobile Picocell BSs: The 5G radio access network on the train consists of various mobile picocell BSs that connect UEs to the 5GC. It is noted that each mobile picocell BS connects to the 5GC through the mobile relay and the IPSEC gateway. Moreover, the train backbone network provides connections among mobile picocell BSs in one train over at least the 10 Gigabit Ethernet to guarantee smooth communication services.

3.2 Registration Procedures

To set up the end-to-end communications between the UEs on the train and the corresponding service servers, the mobile relays have to register to the 5GC and then establish a VPN tunnel between them and the IPSEC gateway using the IPSEC protocol. The mobile picocell BSs subsequently register to the 5GC through the VPN tunnels. Next, each UE can register to the 5GC and then be ready for the 5G services. In the following, we detail the registration procedures.

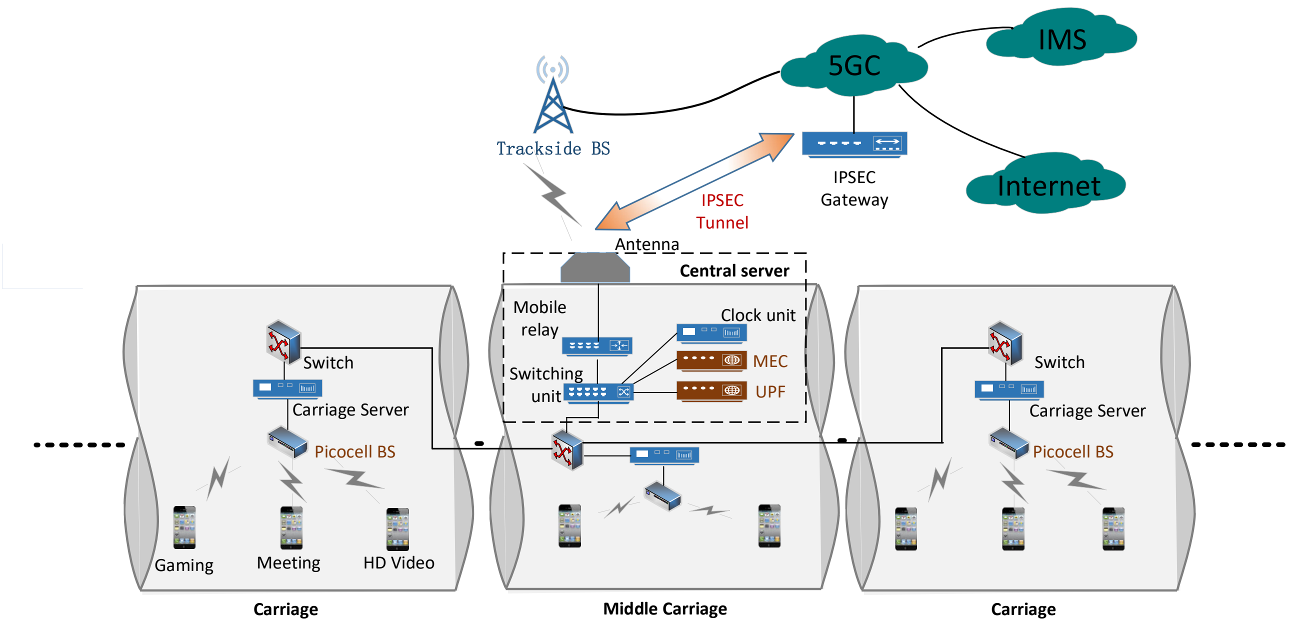

Figure 1 Mobile picocell network architecture

3.2.1 Mobile Relay Registration

The registration procedure of the mobile relay is similar to the 5G standalone access registration one, which is to obtain authorization, to enable mobility tracking, and to enable reachability. To this end, the mobile relay first performs a random access procedure to initiate communications with the trackside BS using the radio resource control (RRC) protocol. Then, the mobile relay sends a registration request to the 5GC. Next, the 5GC authenticates the mobile relay, which indicates that the non-access stratum (NAS) level security is established. After that, the 5GC and mobile relay perform a device authentication procedure to protect against the use of stolen devices. During the whole registration procedure, the core network elements conduct corresponding interactions. After receiving the registration acceptance signal, the mobile relay has successfully registered to the 5GC.

3.2.2 IPSEC Tunnel Establishment

IPSEC provides a dedicated VPN tunnel for mobile picocell BSs to enable secure transmission from the HSR to the IPSEC gateway. The mobile relay and the IPSEC gateway at the ends of the tunnel are IPSEC peers. Besides, the trackside BSs together with the 5GC play the role of routing and forwarding. The tunnel establishment procedure can be mainly divided into two phases:

Phase 1 is to set up a secure encrypted channel. To this end, three main steps are conducted between the two peers, i.e., the mobile relay and the IPSEC gateway. First, they negotiate and confirm a security proposal. Then, they exchange credentials. Finally, they identify each other and specify their respective communication counterparts.

Phase 2 is to negotiate an IPSEC security association between the peers. After that, the tunnel is successfully established.

3.2.3 UE Registration

The registration procedure of the on-board UE is similar to that of the mobile relay. The difference is that the UE registration is performed after the mobile relay registration is completed. In addition, the UE needs to establish an RRC connection with the mobile picocell instead of the trackside BS.

After registration, the on-board UEs would enjoy a variety of rich 5G services, such as Ultra high-definition video, cloud gaming, business meetings, etc. In the following section, we take the data service as an example to describe the on-board 5G services benefited by the mobile MEC.

3.3 Data Service Procedures

The UPF is the anchor of interconnection between the mobile infrastructure and the data network. It plays a key role in the integrated MEC deployment of the mobile 5G networks. From the MEC system perspective, the UPF can be seen as a distributed data plane that directs user plane traffic to the targeted MEC applications in the data network.

Since the customized UPF and MEC are deployed on the HSR, data service procedure of the on-board UE is different from that of the terrestrial UE. Fig. 2 illustrates the key procedures. Specifically, it can be typically divided into two phases: the signalling-plane procedure and the user-plane procedure.

In terms of the signalling-plane, the on-board UE first establishes an RRC connection with the mobile picocell BS. Then, the mobile relay forwards the session establishment request to the 5GC via the IPSEC tunnel. When the 5GC verifies the mobile picocell information, it selects the UPF on the same train through the pre-configured correspondence to establish the connection. Subsequently, the 5GC notifies the mobile picocell BSs and the corresponding UEs for session requirement. Finally, the 5GC performs the connection modification process with the UPF. At this point, the signalling-plane procedure ends and the users could request data services through the corresponding UPF.

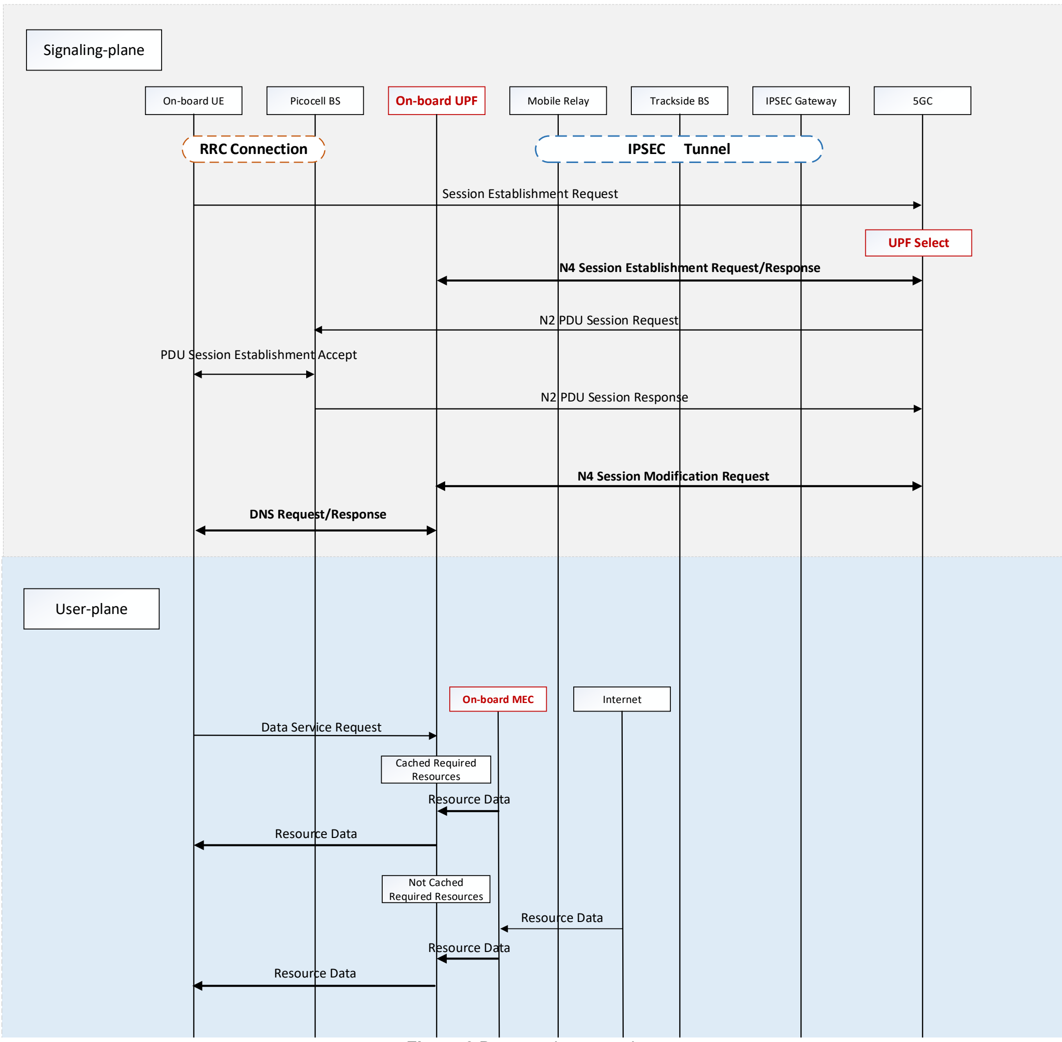

Figure 2 Data service procedure

On the other hand, in the user-plane, the domain name system (DNS) requests from the UE are sent to the UPF when the MEC is available. Then, UPF performs DNS resolution and returns back the result. Later, the UE sends a service request to the MEC. If the MEC has the required resources in its local cache, it directly delivers the data. Otherwise, the MEC takes the data from the external network and sends it back to the UE.

As the MEC is deployed on the HSR, the frequent handover and the high penetration loss issues are completely addressed. Therefore, users could enjoy high quality and low-latency 5G data services. In addition, due to the integration of networking, computing, and storage capabilities, MEC can satisfy many other service requirements: For example, popular short videos and hot news can be pre-stored on MEC, which reduces transmission delay and improves user experience. Besides, game developers can use MEC to achieve fast download and network speed up of their games. Moreover, the online lessons and webcasts can be cached in advance so that passengers can enjoy a smooth viewing experience.

4 DIGATAL REPEATER SCHEME

In this section, we specify the digital repeater in terms of the network architecture and the service establish procedures.

4.1 Network Architecture

Fig. 3 provides the network architecture of the digital repeater scheme, which is comprised of the train roof antenna, the digital repeater head-end unit, the digital repeater remote units, the Ethernet network, and several in-train antennas.

Train roof antenna: The external antenna installed on the outside of the carriage to avoid penetrating loss.

Digital repeater head-end unit: In the downlink, it receives the signal from the trackside BS and converts it to digital signal for transmission to the remote unit. In the uplink, it restores the digital signal from the remote unit to the radio frequency (RF) signal and sends it to the trackside BS.

Digital repeater remote unit: In the downlink, the digital signal from the head-end unit is restored to RF signal and sent to the on-board UE. In the uplink, the received UE signal is converted into digital signal and transmitted to head-end unit.

In-train antenna: Connect the digital repeater remote unit for signal coverage in the carriage.

Ethernet network: Use 10 Gigabit Ethernet cable instead of single-mode dual-core optical fiber to connect the head-end unit and the remote unit.

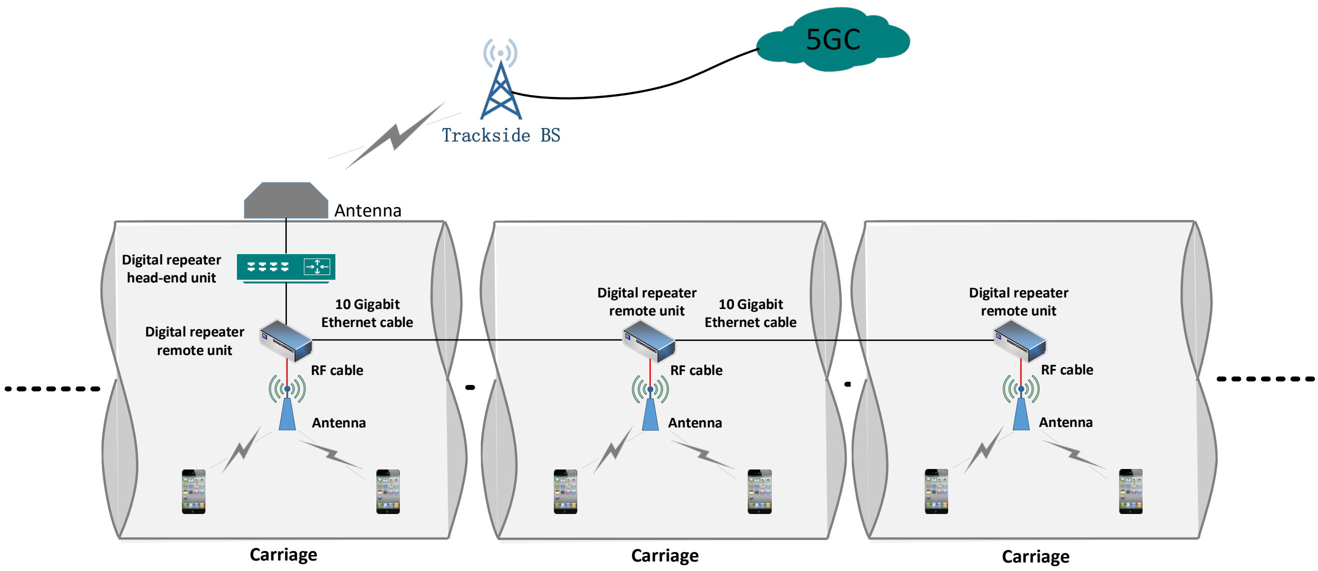

Figure 3 Digital repeater network architecture

4.2 Data Service Procedures

Different from the mobile picocell, the digital repeater acts as a relay between the UE and the trackside BS. User data is transparently transmitted. The voice, data, video, and other services are achieved by the trackside BS. The registration and data service procedures are the same as those of the ground terminals.

5 ANALOG REPEATER SCHEME

Different from the digital repeater, which can reconstruct the signal, analog repeater only amplifies the RF signal and transmits directly through the coaxial cable.

5.1 Network Architecture

The analog repeater scheme illustrated in Fig. 4 consists of the train roof antenna, the repeater host, the repeater slave, the in-train antenna, and the coaxial cable.

The host is typically installed in the middle carriage and intends to amplify the signal received by the train roof antenna. Then, the amplified analog signal is relayed to the slave equipped in each carriage through the coaxial cable. The slave is for further relaying and amplifying analog signals. Each slave connects to an in-train antenna for 5G coverage.

5.2 Service Establishment Procedure

Similar to the digital repeater, the analog repeater acts as a relay between the trackside BS and the on-board users. As an extension of the trackside BS, it works at the physical layer and can carry basic telecommunication services such as telephone service, data service, and short message service.

5.3 Downlink Signal Coverage Estimation

Due to the cable loss between adjacent carriages, the analog repeater needs sufficient amount of input power to ensure a certain level of the output power. Basically, in low and mid-bands, i.e., FR1, 5G typically can use up to 100 MHz of bandwidth as a single carrier. We note that the length of each carriage is typically 30 meters and $1/2$ feeder coaxial cable is commonly used between adjacent carriages. Specifically, the cable, coupling, power divider, and the other insertion losses at the 3.5 GHz band are typically 24 dB per 100 m, 10 dB, 3 dB, and 1 dB, respectively. In terms of the center carriage without cable loss, taking into account the coupling loss, the power divider loss, and the other insertion loss, the total loss is 14 dB. Assuming the maximum power gain of the system is 100 dB, if the output power reaches 20 dBm/100 MHz, the input power of the forward antenna is at least –66 dBm/100 MHz, i.e., 20 dBm/100 MHz – 100 dB (system gain) + 14 dB (total loss) = –66 dBm/100 MHz. Moreover, the theoretical noise floor level of the 100 MHz system is –174 (spatial thermal noise) + 100 (system gain) + 6 (noise figure) + 80 ($10\lg 10^8$ Hz) = 12 dBm/100 MHz. This indicates that the theoretical SNR is 8 dB. Furthermore, based on the 5G frame structure, each 100MHz bandwidth contains 273 resource blocks with subcarrier spacing of 30 kHz, i.e., $N_{\mathrm{RB}} = 273$ [26]. Consequently, the reference signal received power (RSRP) is –66 dBm/100 MHz $- 10\log_{10}(12 * N_{\mathrm{RB}}) = -101.15$ dBm.

In Tab. 1, we list the loss, signal, and noise levels of each carriage in the analog repeater scheme. We note that in the third carriage, the SNR of the signal radiated from the trackside BS is already close to that of the analog repeater, which means that the analog repeater not only brings no advantages, but also leads to a channel deterioration due to co-channel interference. Therefore, a set of analog repeaters with power dividers can only cover up to seven carriages. For a HSR with sixteen carriages, at least three sets of analog repeaters are necessary to achieve 5G coverage.

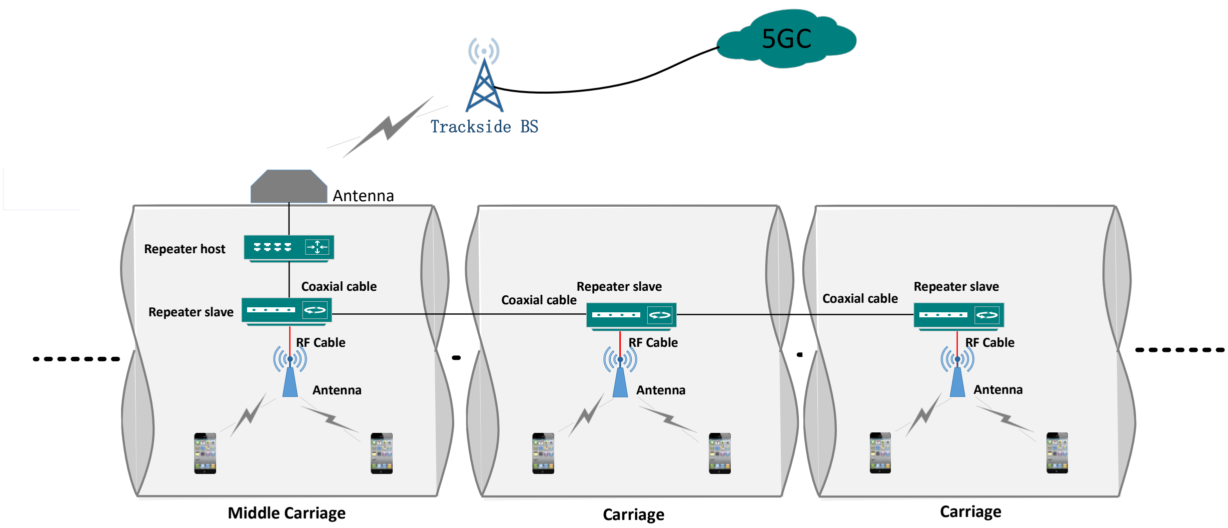

Figure 4 Analog repeater network architecture

Table 1 Signal coverage of each carriage in the analog repeater scheme

	Center carriage	First level cascade	Second level cascade	Third level cascade	Fourth level cascade
Cable loss / dB	0	7.2	14.4	21.6	28.8
Coupling loss / dB	10	10.5	11	11.5	12
Power divider loss / dB	3	3	3	3	3
Other insertion loss / dB	1	1.5	2	2.5	3
Comprehensive loss / dB	14	22.2	30.4	38.6	46.8
Noise figure / dB	6	6	6	6	6
System gain / dB	100	100	100	100	100
Downlink noise level of repeater / dBm/100 MHz	12	12	12	12	12
Downlink signal level of repeater / dBm/100 MHz	20	20	20	20	20
Downlink SNR of repeater / dB/100 MHz	8	8	8	8	8
Forward antenna input RSRP / dBm	–101.15	–92.95	–84.75	–76.55	–68.35
Macro station radiation signal level / dBm	–131.25	–123.05	–114.85	–106.65	–98.45
acro station radiation noise level / dBm	–114	–114	–114	–114	–114
Macro station radiation signal-to-noise ratio / dB	–17.25	–9.05	–0.85	7.35	15.55

5.4 Scheme Comparison

In this section, we discuss a comprehensive comparison among the proposed three schemes in terms of QoS, scalability of service, implementation challenges, and state of the art. For the sake of convenience, we provide a brief comparison in Tab. 2.

5.4.1 Quality of Service

Comparing with general scenarios, the challenges specified for 5G coverage in HSR typically include penetration loss, Doppler shift, mobility management, limitations for network capacity, and interference. In response to these issues, the QoS of these schemes is comparatively presented as follows:

5.4.1.1 Carriage Penetration Loss

These three schemes all aim to address this problem. In terms of the mobile picocell scheme, the mobile relay serves as the terminal to access the trackside network and the path loss caused by carriage penetration is thoroughly tackled by the antenna installed outside the carriage. Similarly, analog and digital repeater schemes resolve this problem in the same manner. However, the analog repeater amplifies the background noise while amplifying the signal, which results in further SNR deterioration.

5.4.1.2 Doppler Shift Resistance

In general, these three schemes are not directly addressing the Doppler shift problem. Notably, the resource data is transmitted directly from the on-board MEC to the UE in the mobile picocell scheme, thus avoiding the Doppler shift in the user plane.

5.4.1.3 Mobility Management

We note that only the mobile picocell scheme could effectively solve the problem, as the handover occurs only at the mobile relay when there is access to another trackside BS instead of at the on-board users. The on-board users just access to the mobile picocell BSs and hence avoid frequent group-switching between the trackside BSs. Different from the mobile picocell scheme, the Digital repeater scheme and Analog repeater scheme could not address these problems, thus have invalid mobility management.

5.4.1.4 Network Capacity

All schemes improve the network capacity by avoiding penetration loss. The mobile picocell scheme can satisfy the UE's business requirements by using MEC and relieves the pressure of limited train-to-ground communications. In addition to that, in the mobile picocell scheme, the train network transmits application layer data, while the remaining two schemes transmit much larger physical layer data. Therefore, the mobile picocell scheme has the best performance in terms of network capacity among the three schemes. In terms of the digital repeater scheme, the transmission loss is low and hence the QoS performances are generally similar on each level. Meanwhile, it can provide a digital physical channel and a digital trunk interface of the switch, enabling users to exchange voice and other information with users on the public telephone network. As regarding to the analog repeater scheme, the transmission loss and the background noise are relatively high, and the damages increase with the number of carriages.

5.4.1.5 Interference Management

The mobile picocell scheme effectively avoids cochannel interference by advanced resource management mechanism and is free from self-excitation and delay dispersion problems. The repeater schemes work in the same frequency coverage within the carriages. This causes cochannel interference and hence affects the network quality. In addition, the repeater may further cause self-excitation and delay dispersion interference.

5.4.2 Service Scalability

The mobile picocell scheme has a better scalability than the ones with repeaters. This is due to the fact that it can provide more extension services for railway services and third-party application service. Compared with other two schemes, mobile picocell scheme can enable computing, storage, and low-latency and high-bandwidth communications by providing various MEC-based services for railroad systems and third-party applications. The repeater only plays the role of signal relaying and amplification, it does not have the capability for offering extra service. Besides, the repeater schemes require the assessment of the installation environment, and the low resource integration rate makes it difficult for practical implementation. Moreover, mobile picocell scheme supports IP bearer, adaptive wireless parameter configuration, simplified management, and coverage of smaller areas. And mobile picocell scheme is used for blind and heat compensation in public areas, and the power is generally 125 MW to 500 MW.

5.4.3 Industry Development Status

We comparatively discuss three schemes from technical and business perspectives. From a technical and business perspective, the two repeater schemes and the mobile picocell scheme have their advantages and disadvantages. From the business point of view, the repeater schemes and Analog repeater scheme have been widely commercialized with slightly different implementation, while the mobile picocell has not yet been realized. From a technical perspective, the picocell technology is sophisticated and the analog-to-digital conversion technology of the repeater is mature. Nevertheless, the Ethernet-based digital technology is still immature for real-time signal transmission.

Overall, after technical comparing, Mobile picocell schemes have more advantages compared with the other two schemes. In general, Mobile picocell schemes have better Doppler shift resistance, mobility management, network capacity, interference management, as well as scalability of service, while still need to be improved in commercialization. Therefore, Mobile picocell BS scheme has the advantages regarding high-quality 5G services provision.

Table 2 Technical comparison

		Mobile picocell scheme	Digtal repeater scheme	Analog repeater scheme
Quality of Service	Penetration loss resistance	Best	Best	good
	Doppler shift resistance	Effective	Invalid	Invalid
	Mobility management	Effective	Invalid	Invalid
	Network capacity	Best	Better	good
	Interference Management	Effective	Invalid	Invalid and negative effect
Scalability of Service	Railway service expansion	Effective	Invalid	Invalid
	Third-party application service extension	Effective	Invalid	Invalid
State of art	Key technology	Mature	Partially mature	Mature
	Commercialization	Immature	Mature	Mature

6 OPEN ISSUES AND CHALLENGES

The 5G deployment on HSR is a key issue to promote the development of railway and unlock its potential issue. Despite the fruitful research in this area, there are a variety of challenges to be tackled. In this section, we provide a list of open issues and challenges for future works.

6.1 Smart MEC

MEC is one of the most critical pieces of 5G key technology. Deploying MEC close to the terminal enables low latency and high efficiency of services [27]. Besides, MEC also has excellent computing and storage capabilities [28]. As such, how to make use of these excellent features to provide high quality services is the key point of future 5G research. Especially, the combination with new technologies such as deep learning can provide a boost to 5G communication, such as load balancing and traffic analysis, etc.

6.2 Ultra-High Speed Adaptability

Along with the development of vacuum tube maglev trains, future 5G systems will need to be further evolved to support train speeds of up to 1000 km/h. Current 5G systems are incapable of resolving the very high Doppler shifts [29]. Thus, the network structure, signal waveform and frame structure need to be redesigned.

6.3 New Service Scenarios

While ensuring QoS for train-to-ground 5G services and improve travel experience for passengers, additional train communication scenarios, such as vehicle-to-vehicle, inter-vehicle, and intra-vehicle [23, 30], still need to be supported in future research.

7 CONCLUSION AND OUTLOOK

This article provided an overview and comprehensive discussions on the deployment of 5G especially for HSR, which is the key to improve travel experience for passengers. First, the challenges of deploying 5G on HSR were fully explored. Then, three schemes, i.e., the mobile picocell BS, the digital repeater, and the analog repeater, were proposed to provide 5G coverage. Moreover, we analyzed the network architecture and service establishment procedure of each scheme. Particularly, the on-board customized UPF and MEC are deployed in the picocell BS scheme to provide ultra-low latency and high reliability services. Furthermore, we further provide technical comparison of three schemes from the perspectives of service quality, service scalability and industry development status, and we further unveiled that the mobile picocell BS scheme has the advantages regarding high-quality 5G services provision. Finally, some potential research directions were envisioned, and we provide a list of open issues and challenges for future works from the perspectives of smart MEC, ultra-high speed adaptability and new service scenarios.

Through the above review and introduction, it can be seen that 5G technology will penetrate into all aspects of intelligent HSR in the future, thus effectively supporting the realization of intelligent HSR. In the future research, the mobile communication system of high-speed railway will continue to consider the establishment of a reliable communication network to achieve continuous online reliable transmission of high data rate at high mobile speed and the integration of network, computing and storage resources, so as to promote the further development of intelligent HSR.

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