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A survey on advanced transmission technologies for high bandwidth and good signal quality for high-speed railways

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ABSTRACT

A high-speed railway (HSR) has gained very high popularity for passengers due to the fast, reliable, economical and convenient during traveling a very long-distance journey. The demand for advanced broadband services such as watching 4K movies, cloud computing and online gaming, has exponentially increased for travelers on the high-speed train (HST). The HST can't provide good bandwidth to facilitate these services for travelers via existing technologies such as cellular networks and satellite networks because of frequent handoffs, high penetration and fading. So, the bandwidth degrades dramatically due to these issues. Research workers have developed proposals to handle these problems by advanced transmission technologies for HSR. Until now, various transmission schemes have been suggested by research works with the focus for either high bandwidth or signal quality improvement. This paper presents a survey on advanced transmission technologies for high bandwidth and good signal quality. In this paper, a comprehensive survey of the appropriate literature published that concentrate on advanced transmission methods in HSR communications in getting higher bandwidth efficiency and maximize the signal quality is presented. Advanced transmission method can be categorized into orthogonal frequency division multiplexing (OFDM), multiple-input multiple-output (MIMO) and radio-over-fiber (RoF).

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1. INTRODUCTION

The communication demand of smart devices based on the fourth-generation (4G) mobile communication system from anywhere and anytime to the internet, providing advanced multimedia services such as online gaming, high-definition television (HDTV) and peer-to-peer social cloud computing, and industrial internet of things (IoT), is growing rapidly [1]. While more than 80 countries have started 4G mobile communication services. Now, the fifth-generation (5G) mobile service has been practically implemented [2], [3]. However, these demands for fast-moving users, especially travelers on HSTs for long-distance journeys, have become challenging for network operators over the traditional cellular wireless network due to low throughput and high-latency.

HSR has been evolved exponentially as a fast, very convenient and green transportation system. It will turn into the pattern of future of railroad transportation around the world. Besides, gigabit-level communications and advanced next-generation communication systems are requirements to facilitate the broadband wireless communications for HSTs. However, wireless communication systems, such as broadband wireless access systems like the Worldwide Interoperability for microwave access (WiMAX), satellite communications, and 4G mobile communication, have been applied for the current railway communication systems (RCSs) utilized for travelers [4].

A high-speed network must be constructed to overcome several issues, such as frequent handoffs, fading, and high penetration loss. In a cellular-based communication network, incorporating WiMAX at the front end to communicate with the antenna of mobile-user, adequate bandwidth more than 20 Mbit/s within the cell's radio coverage area up to 1-2 km could be achieved. Although HSTs such as a Maglev-system-based train at a speed of 500 km/h or even the Japanese Shinkansen Bullet Train at a speed of 300 km/h, cross the coverage area of the cell within just 10 sec. Therefore, the frequent handover process occurs, in which the changing of remote antenna units (RAUs) is performed fastly within a short time like hundred of milliseconds. Finally, the effective throughput degrades dramatically [5]. Moreover, using a linear-cell-based RoF network, penetration losses and fading signals can be reduced dramatically because the radio signals propagate through the RAU and train antenna unit (TAU). Therefore, there is no direct transmission between the RAU and mobile terminal (MT) [6]. In order to resolve the frequent handovers problem, there are many advanced transmission technologies such as OFDM, MIMO and RoF technology. These transmission technologies will be described in the following sections.

2. HIGH-SPEED RAILWAY COMMUNICATION

HSRs have been evolved exponentially worldwide in developed countries such as America, UK, Europe, and China. HSR because of its big advantageous, for example, very fast, reliable, convenient and very economical during traveling a very long distance [5]. As per the latest report related to railway track [6], [7], America has planned a railway track for HSR, and China has installed a high-speed rail track of 36,000 km in August 2020 and has announced to expand the railway track length 70,000 km by 2035. With the increasing continuously development of HSR in recent years, the problem of the safety of train operation is taking an interest impressively because the control of train operation is very important part in the safety of train operation and is known as heart of HSR communications. A standard has been designed to control of train operation center by european train control system (ETCS) [8], [9]. So as to make ETCS work better, international union of railway (UIC) used the Global System for mobile communications for railway (GSM-R) [10].

In HSR communications, GSM-R has been broadly utilized and can keep up a reliable connection between the ground and the train. Despite these benefits, it has some significant deficiencies, for example, inadequate capacity and limited bandwidth for internet services [11]. Only the bandwidth of 200 kbps was achieved by using the gaussian minimum shift keying (GMSK)-time division multiple access (TDMA)-based GSM-R network for HSR [12]. However, Next-generation wireless communications dedicated to HSR communications known as long-term evolution for railway (LTE-R) is introduced in [13], [14]. Also, It has been decided in the 7th world congress especially for HSR [15]. It can control data transmission, for example, safety and track diagnostic type information during train operation [16]. Also, It can provide more services to passengers such as internet access, advanced multimedia services [17]. The maximum bandwidth of 10 Mbps was achieved using by 64-quadrature amplitude modulation (QAM)-OFDM-based LTE-R network for HSR [15]. Whereas the maximum bandwidth of 2 Mbps is attained using by frequency shift keying (FSK)/phase shift keying (PSK)-based satellite network for HSR [18].

To upgrade the capacity of HSR especially in wireless communication for getting high bandwidth and good signal quality, the upcoming newly HSR communication networks are required to provide compatibility among various networks and radio access technologies such as cellular network, satellite network and wireless data network so that hundreds of users during traveling by the train can access simultaneously [19], [20]. So, we can increase spectral efficiency and aggregate capacity by architectural enhancement including advanced transmission technologies such as MIMO, OFDM, and RoF. However, the need for the wireless technology of HSR is exponentially increasing, for instance, the requirements of wireless links in [21] are estimated which is 65 Mbps per train. To additionally mitigate the logical inconsistency between the expanding demand and restricted transmission capacity of wireless technology of HSR, it is important to actualize radio resource management (RRM) to upgrade the efficiency of resource utilization and improve quality of service (QoS) enhancement. Nonetheless, the customary RRM techniques such as resource allotment, power control and handover process, for existing mobile communications may not be productive in HSR networks because of the subsequent challenges, which firmly identified with the attributes of the HSR conditions. Table 1 explains a comparison of HSTs with multiple aspects of maximum train speed, maximum train length and applied transmission technologies.

2.1. High mobility

The development of wireless communication technologies from the last twenty years creates many new opportunities for supporting onboard trains. For instance, passengers in a stationary train can access the internet easily using the existing cellular network within the same coverage of the cell. But the issue comes when the train starts to travel at high speed from the current cell to a new targeted cell within a very short time and similarly passes to other cells. Then, it needs several handovers in a very short time. Consequently, it will give rise to frequent handover and reduce the throughput dramatically. In [22], as per given cell size up to 1-2 km, one handover takes 10-20 seconds when the train travels with a speed of 350 km/h. That is the main challenging problem to resolve the frequent handover in HSR wireless communications. Moreover, another problem for a high-speed train is a large Doppler shift and small coherence time due to fast relative motion between the train and the ground. In [21], a Doppler shift of 945 Hz at 2.1 GHz is recorded at a very high speed like 486 km/h of the train in China. Therefore, it is compulsory to consider March 18, 2016 DRAFT 3 that is inter-carrier interference and the fast-varying channel particularly for OFDM when performing resource allocation for HSR communications.

2.2. Unique channel qualities

The moving train experiences various situations such as tunnels, viaducts, and cuttings, considering various channel propagations properties [23], which cause that the characteristics of HSR channels can’t be described accurately by a single channel model. This is the big challenge for RRM methods and should be flexible for various scenarios along the railway track including different channel models. Moreover, in the case of the viaduct scenario, the line-of-sight (LOS) component is much more practical than the multi-path components because the propagation loss depends on the distance between the train and the base station (BS) [24].

Table 1. Applied transmission technologies for HSTs

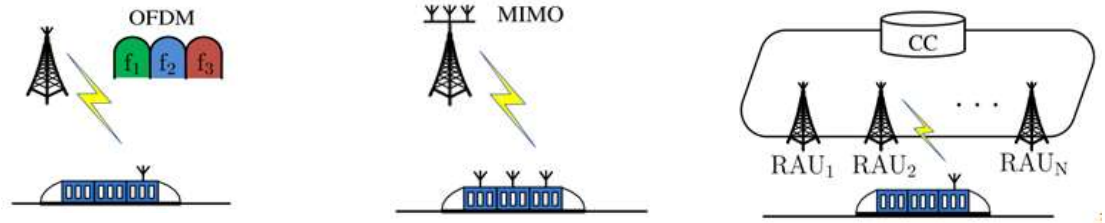
High-Speed Trains (HSTs)	Country	Avg. Speed (km/hr)/Max. Speed (km/hr)	Max. Train Length (m)	Wireless Technologies	References
TGV-POS	France	320/574.8	208	GSM-R/Satellite	[25]
AVE Class 103	Spain	310/403.7	206	GSM-R	[26]
ICE 3 class 403	Germany	330/368	201-439	GSM-R, Radiating Cable, Wi-Fi	[27]
ETR 500	Italy	300/362	328	GSM-R, Radiating Cable, Wi-Fi	[28]
KTX-I	South Korea	330/360	389-550	Automatic Train Control, Wi-Fi	[29]
Eurostar	France, Spain, England	300/334.7	387-443	GSM-R, Wi-Fi, WiMAX	[30], [31]
N700 Shinkansen	Japan	275/332	400	Radiating Cable	[32]
THSR 700T	Taiwan, China	300/320	304	RoF, WiMAX	[27]
Acela	USA	240/265	203	GSM-R, Wi-Fi	[33]
Pendolino	Finland	250/280	276	WiMAX	[34]

3. ADVANCED TRANSMISSION TECHNOLOGY

With the increasing demand of advanced multimedia services for travellers, the HSR wireless communications need to upgrade the existing technology with advanced transmission technology such as OFDM, MIMO and RoF, in order to improve transmission capacity for getting high data rates. These technologies can be efficiently used as shown in Figure 1.

3.1. OFDM

OFDM is a dominant transmission technique for higher data rate services such as voice, multimedia, and data, over wireless communication. It has been widely used in LTE on railway and all latest Wi-Fi standards [35], [36]. The basic purpose of this technique is to remove fading and inter-symbol interference (ISI) caused by multipath propagation. It provides very high spectral efficiency means that more data services. The basic principle of OFDM is to allocating the subcarriers dynamically to different users and picking the best possible options such as modulation and coding scheme adaptively. In case of best pairing for MIMO, it works perfectly.



(a) OFDM technology (b) MIMO technology (c) RoF technology

Figure 1. Advanced transmission technologies for HSR

Given this effective rundown of characteristics, OFDM technology is the irrefutable leader for future HSR communications [37], [38]. But, it has some drawbacks in HSR environment. First, more prominent disadvantage is Doppler shift that badly effects the orthogonality of the subcarriers because of high mobility. Consequently, the inter-carrier interference (ICI) prominently degrade capacity and link performance of HSR communications. In case of resource allocation for HSR, it can't be ignored. However, the influence of ICI can be reduced by channel estimation and equalization in LTE-R systems with RAUs [39], [40]. Recently, another latest technique is a fundamentally distinct OFDM based transmission scheme known as time-frequency training OFDM, which is used for high speed mobile environment [37]. It has high spectral efficiency than the standard cyclic prefix OFDM. Besides this benefit, its performance is highly reliable over fast fading channels. More recently, OFDM signal centered at intermediate frequency (IF) of 7GHz having channel bandwidth up to 6 GHz has been used in fiber-wireless (FiWi) network for HSR [41].

Second, OFDM has also the peak-to-average power ratio (PAPR) problem, which effects the efficiency of power amplifier and the resolution of signal conversion. But, it can be largely overcome by using different techniques such as signal precoding technique [42] and the pilot-assisted technique [43] when we implement OFDM technology practically on HSR communications. Recently, another very popular technique is a Non-OFDM (N-OFDM) [44] that can be used in HSR communication because of its ability to reduce the effect of Doppler frequency shifts of sub-carriers during the fast-moving train. Although, the complexity of demodulating N-OFDM signals is higher than OFDM.

3.2. MIMO

With the increasing demand of smart devices on HSR communications, we can't get more bandwidth using single-input single-output (SISO) technology. MIMO technology has gained very high attraction especially in ground-to-train communications [45]-[50]. Recently, the multiple-input single-output (MISO) having 2×1 receiver diversity scheme has been used in linear-cell-based FiWi network using W-band (75-100 GHz) for HSR [41].

MIMO technology is widely used in wireless communications such as 4G LTE, Wi-Fi, and WiMAX. The function of this technology is to send or receive data practically more than one data signal at the same time using multiple antennas at the transmitter and the receiver. But it exploits multipath propagation. There are many techniques such as transmit diversity, pre-coding, and spatial multiplexing, that can enhance the system bandwidth efficiency and the signal quality.

Nevertheless, wireless channels are profoundly corresponded with strong LOS because of scatters and few multipaths in HSR conditions. The presence of the LOS part is viewed as a restricting element for MIMO technology because of lower multiplexing gain contrasted and the predominant Rayleigh blurring channel [51]. Along these issues, the customary spatial multiplexing and diverstiy techniques of MIMO can't be legitimately implemented in HSR conditions.

However, to overcome these issues, some advanced schemes have been suggested using MIMO technology for HSR communications. Firstly, a multiple-group multiple-antenna (MGMA) scheme, which is addition of the LTE specification, is presented in [45] using 3-D modeling of the LOS MIMO channel for HSR viaducts. The purpose of this technique is to enhance the capacity of the LOS MIMO channel by tuning the weights among MGMA arrays. Secondly, a beamforming platform in which the direction of transmitter antenna is changed towards the receiver antenna of a HST with the helping of global positioning system (GPS) information is experimently proposed in [46] to increase the signal quality and decrease the interference. Moreover, the algorithm of distributed beamforming with the helping of real-time GPS information is proposed in [47]. Finally, by taking the benefits of both OFDM and MIMO technologies in HSR communication has been suggested in [49], [52] to improve the spectrum efficiency.

Recently, besides these modified schemes, researchers are taking interest in massive MIMO systems [53], [54] that use a very high number of antennas at transmitter and receiver to provide high bandwidth and high spectrum efficiency, especially for HSR communications because of large size of the train. Keeping this advanced system, many methods are adopted such as a two-antenna configuration [22], [55], 3-D based massive MIMO [56], and massive MIMO based adaptive multi-stream beamforming scheme [57]. Basic working principle of RoF technology as shown in Figure 2.

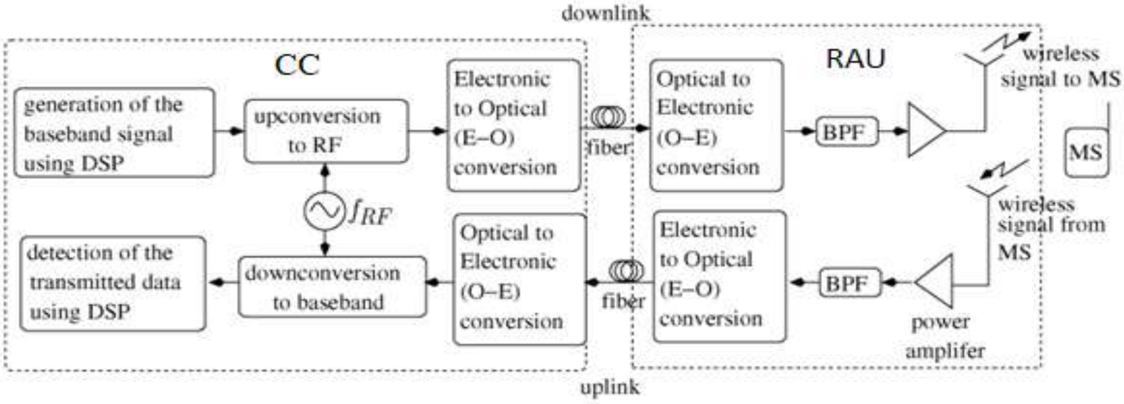


Figure 2. Basic working principle of RoF technology

3.3. RoF

Radio over fiber technology is a very impressive solution to facilitate the broadband RAUs in which radio-frequency (RF) signals are sent over fiber link to provide wireless communication services. Normally, the transmission of RF signal over fiber link is used for other applications such as satellite base stations and cable television networks. However, the researchers are taking an extraordinary interest in the backbone of cellular networks (4G/5G) and HSR networks [41], [58] because of several advantages of RoF transmission to construct micro or pico cellular radio architecture. One significant favorable advantage is that very low alteration is required at BS as shown in Figure 1 (c), where the RF signal from centralized center (CC) propagates through the fiber link to RAU and communicates with the mobile station (MS) through the wireless link and vice versa for uplink communication, there is no need to perform extra activities at RAU such as all signal processing, modulation stages, and digital signal processing (DSP) coding except such as band-pass filter (BPF) and power amplifiers. So, this is a very cost-effective way to put up micro or pico radio cells because all extra stages are performed at CC [59]. The basic working principle of RoF technology is briefly shown in Figure 2.

Moreover, Figure 3 shows wavelength-division-multiplexing (WDM)-based RoF-millimeter-wave (MMW) network especially designed for HSR communications. Using this network, all RAUs are handled and monitored by the same control station (CS). They are linearly installed along the railway track and are interconnected with multiplexer and CS by fiber links. There is no requirement to perform the handover process remaining under the same CS when the HST travels from one RAU to the next RAU because all RAUs perform as repeaters by using the “moving frequencies” or “moving cells” concept. Only the handover process starts when the train moves from one CS to the next CS. Therefore, the RoF scheme can dramatically reduce frequent handovers. The dropped calls can be reduced by using this scheme in HSR communications [41], [60]. In addition, a distributed antenna system (DAS) has been applied experimentally in HSR communications to give good signal quality and spectral efficiency [61]. Furthermore, to achieve a high data rate for fast-moving users, millimeter-wave bands such as E-band (60-90 GHz) and W-band (75-100 GHz) as a carrier-frequency are experimentally proposed for wireless backhaul network such as RAUs and TAU [36], [41], [58], [60] due to its large available bandwidth and low atmospheric attenuation. The problem arises when we talk about the distance at such high frequencies between RAUs and TAUs. Therefore, we can increase the coverage area of RAUs and TAUs by using high gain, high directivity antennas, and high-output-power amplifiers [60]. Table 2 shows the summarized comparison of deployed access technologies.

Table 2. Summarized comparison of deployed access technologies in HSR

Access Network	Bandwidth	Working Frequency	Modulation/Multiplexing/ MIMO	Technology Maturity	Comments/References
GSM-R	< 200 kbps	800-900 MHz	GMSK/TDMA	Until 2025	[12]
802.11	15 Kbps	2.4/5.8 GHz	QAM	Mature	[62]
WiMAX	DL: 42 Mbps UL: 14 Mbps	2.3/2.4/2.5/3.5 GHz	16-QAM	Mature, decreasing	[62]
LTE-R	>10 Mbps	400 – 3.5 GHz	64-QAM/OFDMA 2 × 2 MIMO	Emerging and offered	As per simulation [15]
Satellite	DL: 2 Mbps UL: 0.5 Mbps	Limited	FSK/PSK	Mature, But very costly	[18]
WiMAX-RoF	DL: 3.3 Mbps UL: 1.2 Mbps	2.5 GHz	16-QAM-OFDM	Not yet deployed	As per simulation [63]
0IFoF-FiWi-MMW	DL: 20Gbps UL: 10 Gbps	IF: 7 GHz RAU: 90 GHz TAU: 90 GHz	16-QAM-OFDM 2 × 1 MISO	Field Trial Test	As per practical [41]

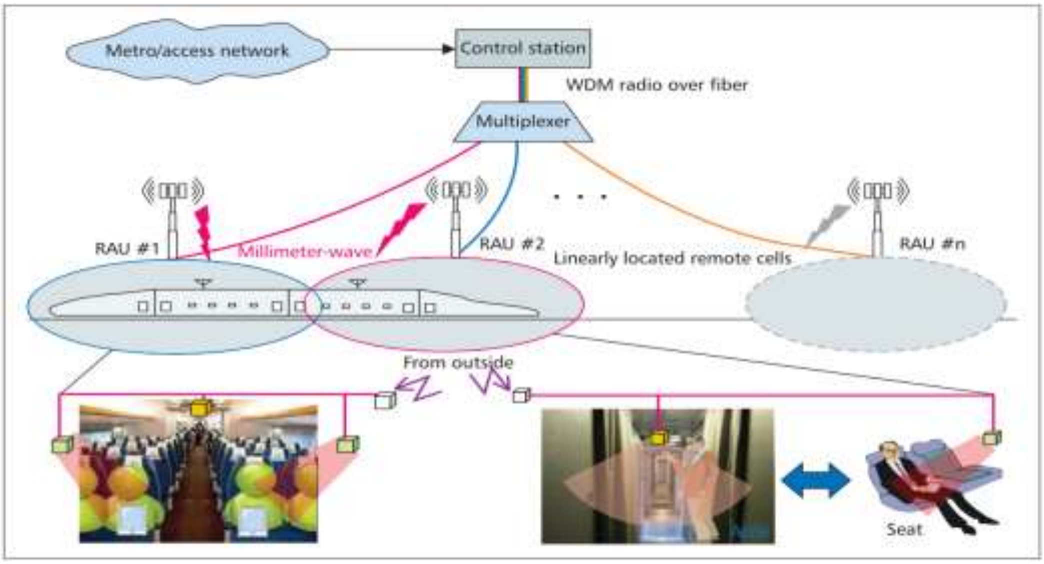


Figure 3. WDM based RoF-MMW and linearly installed cell system for HSR communications

4. CONCLUSION

This paper studied published literature with the focus to increase bandwidth as well as better signal quality particularly via advanced transmission technologies in the HSR communication network. We studied thoroughly the very latest three transmission technologies such as OFDM, MIMO and RoF, to overcome multiple problems such as frequent handovers, high penetration loss and fading, which affect the throughput dramatically. These technologies are discussed while keeping the HSR communications perspective. Based on the survey, advanced transmission technologies in HSR communications that have been discussed by research works are focused on the bandwidth without combining these technologies efficiently. Due to this research gap, combining these technologies to get higher bandwidth in HSR communications will be chosen for future work because of good spectral efficiency.

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