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EMI and IEMI Impacts on the Radio Communication Network of Electrified Railway Systems: A Critical Review

Yejing Fan, Li Zhang, *Senior Member, IEEE,* Kang Li, *Senior Member, IEEE*

***Abstract*—The electrified railway system has been rapidly rolled out in many countries and regions in the past decades, along with the transportation decarbonization agenda. The latest development in power electronics and electrical railway systems has increased the risks of electromagnetic interference (EMI) and intentional EMI (IEMI) emissions, introducing new challenges to the railway radio communications network. It is vital to have a robust and reliable railway communication network that can be resistant and immune to these interferences for the safe and efficient operation of modern railway systems. Yet, the source and new features of EMI and IEMI emerging along with the latest technological development have not been thoroughly investigated and understood. This review paper aims to fill the research gap. First, railway communications systems are introduced. The EMI and IEMI are discussed at the whole system level, and the corresponding impacts on the signaling and communication systems are reviewed comprehensively. Current electromagnetic compatibility (EMC) methods are surveyed, and challenges of tackling the impacts of EMI and IEMI on the signaling and communication systems are discussed. Finally, future research directions are outlined.**

***Index Terms*—electromagnetic interference (EMI), intentional EMI (IEMI), electrified railway systems, radio communication networks, and electromagnetic compatibility (EMC).**

I. INTRODUCTION

CLIMATE change is one of the biggest challenges facing the mankind today [1]. To meet the Paris agreement adopted by 196 parties worldwide in 2015 [2], the roadmaps to decarbonization will need to increase the prominence of low-carbon power generation and reduce fossil fuel consumption in all sectors. Transportation is the largest emitting sector, largely due to the excessive use of internal combustion engine-based vehicles and inadequate public transportation arrangements. Hence, to grow public transportation such as railways has become a major strategic priority worldwide [3], [4]. The electrified railway has entered into a period of rapid development worldwide as a sign of transportation decarbonization [5]–[10]. To achieve the net-zero target by 2050, the UK Network Rail has targeted to phase out diesel-only trains by 2040 [11]. The Swiss rail network has become the only fully electrified network in the world, and railway electrification in other countries and regions also has constantly increased in the past decades. Alternative energies such as hydrogen fuel cells, batteries, solar energy, and biomass have been applied to the railway network [12]–[15]. The introduction of electro-diesel bi-mode or hydrogen trains, with electricity generated from nuclear or renewable resources, has been considered a viable alternative solution as they can reduce fuel consumption by 20% [16], [17].

Today, there are different electrified transportation systems, e.g., trams, light rails, and maglev trains. Significant investments have been made in high-speed railway (HSR) worldwide in the last decades. According to a recent report on the growth of HSR published in 2020 [18], the global high-speed network in operation reached 52,418 kilometers, of which 35,740 kilometers are operated in China, representing over two-thirds of the global total. Furthermore, some new transportation models, such as the Hyperloop and electric road system, are also explored. Fig.1 shows five typical types of electrified transportation, and depending on their power supply, different levels of electric and magnetic fields are generated.

As railway electrification grows, the railway environment of railway tracks is increasingly exposed to the magnetic and electric fields generated from trains, railway power supply systems, nearby electric power transmission lines [19], and other sources [20]. Also, the increase in traffic flow, higher speed, larger capacity, and heavier axle loads require more powerful engines and electronic devices [21]. The complexity of the railway system is higher than ever before. There are two specific ways to deliver the energy: radiated emission is EM energy that propagates in the open space, while conducted emissions travel through a conductive medium. As a result, the radiated and conducted EM emissions from railway systems increase over time. According to the statistics, as many as 70% of the Swedish railway infrastructure system faults originate from the EMI [21]. Hence, it is vital to tackle the EMI occurring in railway systems.

On the other hand, along with the rapid development of the railway industry, conventional railway signaling systems based on color light signals and train location detection with track circuits are gradually replaced by modern signaling systems with Radio Block Center (RBC) [22]. The evolution of Global System for Mobile Communications-Railway (GSM-R), Long-Term Evolution-Railway (LTE-R), and 5G-Railway (5G-R)

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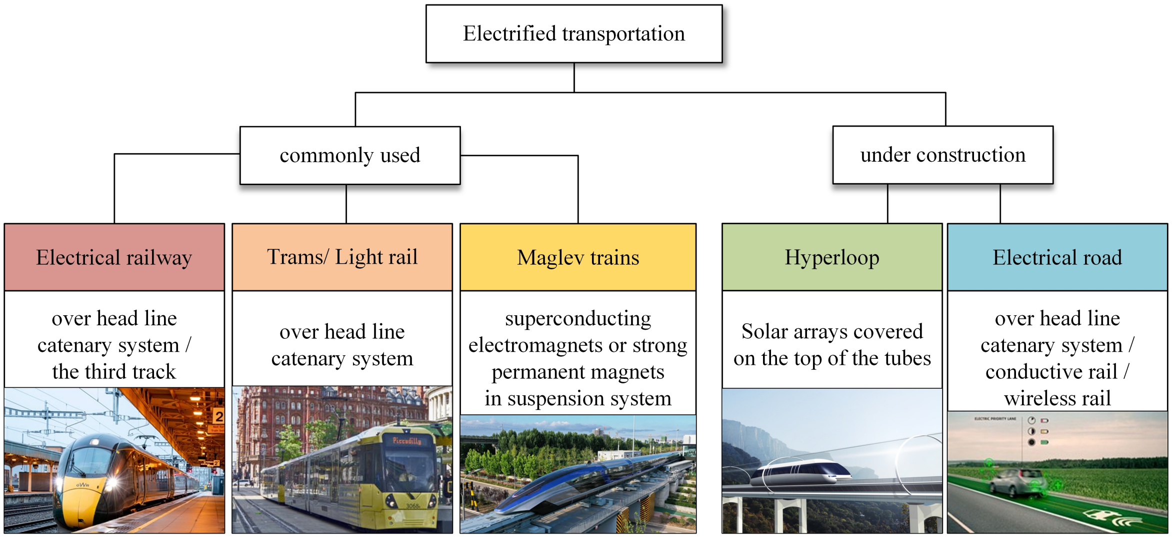


Fig. 1. The diagram of commonly used and under construction electrified transportation system

enable more advanced services to improve efficiency, safety, reliability, and profit [23]–[25]. However, this evolution leaves new forms of vulnerability to EM disturbances characterizing the railway environment [26]. Generally speaking, radio communications can provide railways with three types of services: safety-related services to support train movement, non-safety-related operational services, and internet access by onboard passengers [25]. The advantages of radio communications ensure safer movements of trains at higher speeds with increased passenger capacity, a better quality of services, and a reduced number of trackside equipment. This paper primarily focuses on signal transmission and communication networks related to railway operation safety. The disturbance from EMI may cause sensor and signal failures, Automatic train protection (ATP) failures, and radio module system errors. Moreover, the intentional EMI, a potential terrorism-related threat, must be detected in time to ensure safety and security [27]. Therefore, analyzing the characteristics of EMI and IEMI and finding EMC methods is of great importance for the design, construction, and operation of railway systems.

Although extensive research has been conducted on the EMC, they generally focused on suppression techniques or are unsuitable for railway communication systems. In particular, the ”Shift2Rail Plan” shows that future rail implementations require intelligent traffic management, with Gb/s transmission data rate, ultra-reliability, *ms*-level delay, and interconnected traffic at over 500-km/h train speed which heavily relies on radio communications [28]. Therefore, it is urgent to envisage an immunity testing solution that evaluates the telecommunication system behavior against EMI in the railway system.

This paper aims to provide a systematic review of the EMI and IEMI issues and their impacts on railway communications systems and outline future research directions, including EMI and IEMI modeling, detection, and mitigation. Existing research lacks the investigation of the EMI and IEMI impacts on signal transmission at a system level. Also, the electric multiple units (EMU) on the train are complicated systems with various electrical and electronic devices, so it is hard to investigate the interactions of the EM environment and EMU. Therefore, network-based models are proposed to fill the gaps. They capture the EMI path along the EMU by identifying the category of the EMI sources and the coupling methods. The main contributions of this paper are summarized below:

(1) The evolution of railway communication networks is reviewed from the current GSM-R, LTE-R, to the future 5G-R.
(2) The EMI and IEMI issues are surveyed systematically aided with network-based models.
(3) The existing EMC methods for the communication network are comprehensively reviewed. Future challenges and research directions are presented, including EMI and IEMI modeling, detection, and mitigation through combining advanced communication technology with AI.
(4) The analysis framework can be extended to a broad range of electrified transportation modes.

The rest of this paper is structured as follows. The overview of the railway communications system, EMI and IEMI impacts, and existing EMC methods are surveyed in Sections II and III, respectively. Section IV introduces the system-level network-based modeling method and reviews four types of EMI and IEMI issues. Section V discusses future challenges and research directions. Finally, Section VI concludes the paper.

II. OVERVIEW OF THE RAILWAY COMMUNICATION SYSTEMS

A. Current Railway Communication System

European Railway Traffic Management System (ERTMS) standard is a modern communication-based signaling system used worldwide and composed of two main components: the European Train Control System (ETCS) and the GSM-R system. There are three ETCS levels: ETCS-Level1, ETCS-Level2, and ETCS-Level3. Fig.2 shows their evolution and functions, where a fully digital radio-based train system will increase railway capacity and decrease trackside equipment.

The details of the three levels can be found in [29]. The ETCS can automatically control the train's speed if necessary, and each level of ETCS relies heavily on using GSM-R.

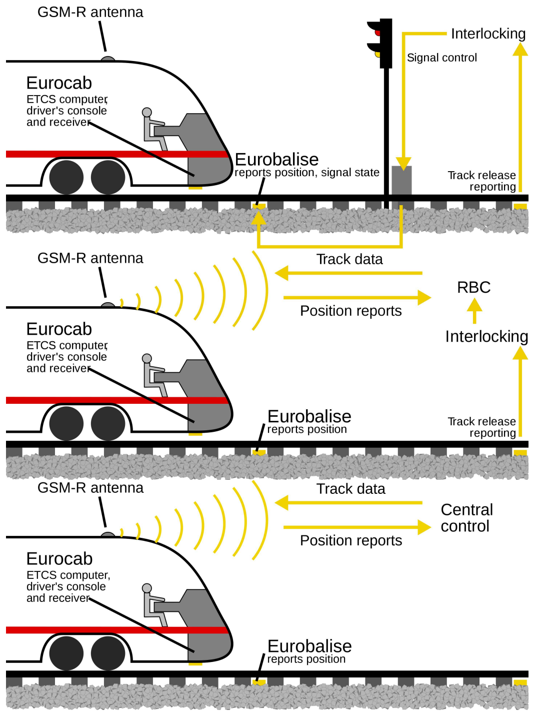


Fig. 2. Evolution and functions of three ETCS levels [30]

The communication performance should meet the International Union of Railways (UIC) standard or specification's reliability, availability, maintenance, and safety (RAMS). The train must be reliably connected to the RBC [31], via which the train continuously sends data to the RBC to exchange movement authority (MA) messages. It must be bidirectional with high uplink/downlink data rates and low latency during the HSR operation [32]. This connection has a high priority, and if the modem connection is lost without updated control for more than 20s, the train stops automatically [33].

GSM-R is based on the GSM cellular radio standard with specific railway modifications. It has been developed to ensure robust vocal exchanges, signal transmission, and stand EMI. Moreover, the GSM-R is included in the Euroradio protocol, which is specific to the railway and managed with the altered received information, notably by resending some altered bursts until good reception [29]. Such a robust communication system is essentially motivated by the severity of the railway EM environment. However, the GSM-R technology developed in the 1990s shows the limitations now, considering the foreseen evolution of ETCS level and additional functions like Automatic Train Operation (ATO). In addition, the HSR generates a critical demand for high data-rate railway communication services for both train operations and passengers. To satisfy the ever-increasing requirements, future railway communication systems, like LTE-R and 5G-R, have attracted much attention in recent years [34]–[36].

B. Future Railway Communication Technology

The Future Railway Mobile Communication System (FRMCS), launched by UIC in 2012, is the successor of the GSM-R systems to become a worldwide standard for the railway industry [37]. The FRMCS based on LTE technology with the evolution towards 5G is growing its presence. The main goals of FRMCS are to digitalize railway operations completely, support an increasing level of ATOs, enable a wide range of new applications, and embrace the application of 5G in the railway industry.

LTE-R is a promising railways technology and has many advantages over GSM-R regarding capacity, throughput, and radio access related to spectral efficiencies such as advanced multiplexing and modulation. The details of system parameters can be found in table I. Moreover, it has better interference resistance, priority protection mechanism, good maintainability, and high system reliability [38]. Also, LTE has a simple flat network architecture for real-time HSR applications, which is one of the essential requirements for providing ETCS messages. In Europe, FRMCS prefers to build on the current GSM-R by reusing the existing mast sites for the 80-90% cost saving [39]. Therefore, the HSR core network aims to achieve an all-IP core network where GSM-R, LTE-R, wireless local area networks (WLANs), and Trans-European Trunked Radio (TETRA) are all connected to the core network.

5G communications brings new opportunities through enabling key techniques, including millimeter-wave (mm-wave) spectrum, massive multiple-input and multiple-output (MIMO), nonorthogonal multiaccess (NOMA), device-to-device communication (D2D), ultra-dense heterogeneous networks (UDHN), and network slicing [40]. Driven by 5G, many technologies have promising application potentials. Previous research tends to group the 5G railway applications into

TABLE I
SYSTEM PARAMETERS OF GSM-R, LTE-R, 5G-R

Parameter	GSM-R	LTE-R	5G-R
Frequency	Uplink: 876- 880 MHz; Downlink: 921- 925 MHz	450 MHz, 800 MHz, 1.4 GHz, 1.8 GHz	1.9GHz
Bandwidth	0.2 MHz	1.4-20 MHz	$\geq$100 MHz
Modulation	GMSK	QPSK/16- QAM	16- QAM/OFDM/NOMA
Cell Range	8 km	4-12 km	1.6-5km
Peak Data Rate, Downlink/Uplink	172/172 Kbps	50/10 Mbps	20/10 Gbps
Peak Spectral Efficiency	0.33 bps/Hz	2.55 bps/Hz	20bps/Hz
Latency	400ms	50ms	$\leq$1 ms
Mobility	Max. 300 km/h	Max. 500 km/h	Max. 500 km/h

TABLE II
RAIL SCENARIO, 5G CATEGORIES, KEY TECHNOLOGIES, AND APPLICATIONS IN RAIL

Rail scenarios	**Scenario slice**	**5G categories**	**Key technologies**	**Application in Rail**
Automatic Train Operation Intelligent dispatching Intelligent maintenance	ubiquitous perception	massive machine-type communications (mMTC)	NOMA D2D Network slicing	IoT Blockchain
	self-learning intelligence	ultra-reliable low latency communications (uRLLC)	D2D UDHN	Edge computing Big data AI
	immersive interaction	enhanced mobile broadband (eMBB)	mm-wave massive MIMO NOMA D2D	Virtual reality Digital twin

several categories from location or the business perspectives [41], [42]. However, the railway is a complicated system, and many scenarios may demand more than one of the 5G categories, which are eMBB, uRLLC, and mMTC [43]. The common features of railway 5G applications are summarized in table II, where the railway scenarios are sliced into three layers corresponding to the 5G technological categories.

Among the three main usage scenarios, the future railway radio communication system is closely related to the URLLC, which provides high-data-rate and reliable train operation and passenger experience services. UIC prefers 5G as a successor of GSM-R, which is supported by many telecom providers and major European railway operators. According to [44], FRMCS will coexist with GSM-R at the 900MHz band to ensure interoperability until 2035. However, uncertainty exists if broadband mobile communication techniques are directly applied to HSR. Three main challenges need to be addressed before the deployment according to [41], [43], [45]:

- Radio Wave Propagation Mechanism in HSRThe performance of wireless systems and technologies is limited by the propagation channels [46]–[49]. Radio channel modeling, describing how the channel fading behaves in a given scenario, is the foundation of designing and evaluating wireless systems and transmission technologies. Concerning the future HSR communication systems, the authors in [35] proposed three propagation channels: multi-link channels, massive MIMO channels, and mm-Wave channels. These channels have various propagation characteristics and exhibit space-time-frequency non-stationarity. Moreover, the future HSR channel modeling should possess learning ability by applying AI to establish general models that can be tailored to suit different scenarios, frequency bands, and antenna sizes.
- Data Transmission Mechanism under High Mobility 5G-R may experience problems such as frequent handover, Doppler effect, penetration loss in mmWave frequency bands, smaller cell range, significant speed increases, and the closed design of the train carriage. Therefore, to maintain the high spectral efficiency offered by 5G and provide better service, the HSR wireless communication network architecture needs to transform from the traditional cellular network to a heterogeneous cellular network (HCN) [50]–[52]. To reduce frequent handovers and provide seamless connection, cell combining is employed [35]. Also, 5G New Radio (NR), developed by 3GPP, adopts several novel schemes to alleviate handover issues, e.g., multi-transmission reception point (TRP) schemes, conditional handovers, and dual active protocol stack (DAPS) [44]. Some recent studies consider the mobility and handover management with novel machine learning (ML)-based methods [53]–[58].
- Wireless Resource management mechanism for HSR
For new applications in smart rail, real-time management for HSR needs more powerful computation capabilities and lower processing latency. Multi-access edge computing (MEC) has emerged as a key technique in 5G, which extends cloud computing to the edge of the network closer to users [59]. Future edge computing is to make distributed resource scheduling decisions related to computation offloading and data management [60]. There have been some analyses on combing MEC and communication systems in the HSR system. Train communication systems offload their computation-intensive and delay-sensitive tasks to the edge servers, which can improve broadband wireless communication service performance [61]. The computing tasks of users can be executed locally, offloaded to the edge servers deployed at the roof of the train, or to the rail-side base station (BS). Some research proposes to optimize the joint resource allocation and computation offloading subject to energy consumption constraint [62], [63]. In addition, federated learning is well suited to edge computing to share knowledge without compromising user privacy [64], [65]. Moreover, with edge computing, big data, AI, and uRLLC of 5G can maximize the utilization of data and generate smarter models, thus providing self-learning intelligence for railways.

Among all the challenges, security is the most crucial for the 5G-R system to guarantee high-level security to prevent the trains' and passengers' data from any possible security attack, such as unauthorized access, transmission disruption, and intentional modification. The future railway communication system should provide more options beyond train-to-ground communication. Recently, train-to-train communication has been proposed for a well-integrated part of the 5G overall wireless-access solution [66]. It can be considered as an auxiliary train control system between two trains to avoid possible accidents without using BS and extends coverage beyond the reach of conventional infrastructure [67], [68]. With higher efficiency and a briefer system structure, it is an ideal way to help transmit warning signals directly to the vicinity, avoid many subsystem interfaces in train-to-ground communications, and be an emergency communication tool when the train-to-ground communication links fail. Therefore, it is also necessary to consider the possible impacts of EMI and IEMI on train-to-train communication. If the security concern is not solved correctly, the attackers may quickly identify vulnerabilities and launch attacks, e.g., IEMI. Consequently, new security issues may emerge from time to time as a price of the revolution of railway radio communication networks.

III. CHARACTERISTICS OF EMI AND IEMI

Generally, a typical electrified railway train operation system comprises various sub-systems, such as traction power supply, radio communication, and catenary systems [69]–[71]. Each sub-system could be a source to affect others or a victim.

A. EMI and impacts

Numerous sources of unintentional EM radiation occur naturally, such as lighting, relays, electric motors, and digital systems. They are either from natural phenomena or onboard train equipment. Fig.3 shows several of these EM environments qualitatively, along with the narrowband and wideband EMI and IEMI threats [72]. It is noted that the high-power electromagnetic (HPEM) spectral components have a broad spectrum of up to several GHz. Therefore, railway communications, whether current GSM-R or future LTE-R/5G-R, might be impacted by EMI. EMI may also affect electromechanical systems, people, and equipment near rail vehicles. Moreover, the risk distance of EMI varies depending on the specific situation, e.g., viaduct, cutting, or tunnel.

B. IEMI and impacts

IEMI is a potential threat of EM attacks related to terrorism and crime in modern railways. It is referred to as EM weapons, including high-power microwave, high-altitude nuclear, and ultra-wideband EM pulse. The EM pulse from such EM weapons can be coupled into the equipment of a railway system in various ways, and the radiation distance ranges from 100m to several kilometers [27].

Although in most countries, an attack on commercial interests for ‘entertainment’ is against the law, and the attackers’ motives may vary, many radio jammers are sold on the market. The number of emitters is increasing rapidly. Some emitters employ very high-power levels; others, such as digital systems, use faster digital electronics and become more efficient radiators than unintentional EM energy [29]. They can be battery-operated, pocket-size, or more powerful. As illustrated in Fig.3, they operate between several hundred megahertz to a few gigahertz. Most of them operate by sweeping the covered frequency band very quickly. Thus, their instantaneous frequency varies as a linear function of time [73]. In addition, unlike the high-power sources, low power is more difficult to detect and identify when and after the jammer is switched off. It occurs more likely as an anonymous attack. Therefore, the study of low-power IEMI characteristics is also indispensable.

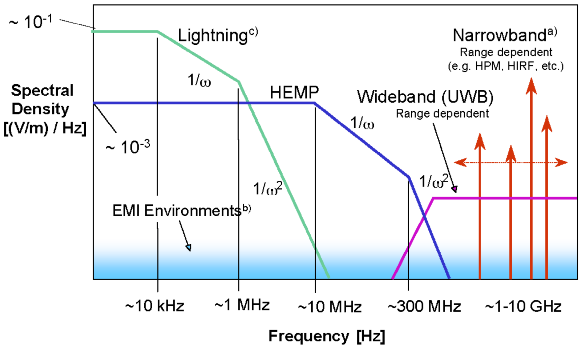


Fig. 3. Frequency spectrum of various EMI and IEM [72]

C. EMI and IEMI waveform classification

The waveform descriptions are considered to analyze the inner characteristics of EMI and IEMI impacts on the spectrum level. Compared to unknown sources, it is straightforward to figure out the parameters of a jammer generator because this waveform is generated using devices with published characteristics on the market. Therefore, the IEMI aimed at the particular protocol and allocated bands can be classified according to their temporal characteristics and frequency. Three main classifications are summarized and shown in Fig.4. After classification, it is possible to detect the disruption of railway signaling and deduce with an adequate measure [74].

- Ultra wideband (UWB) jammer

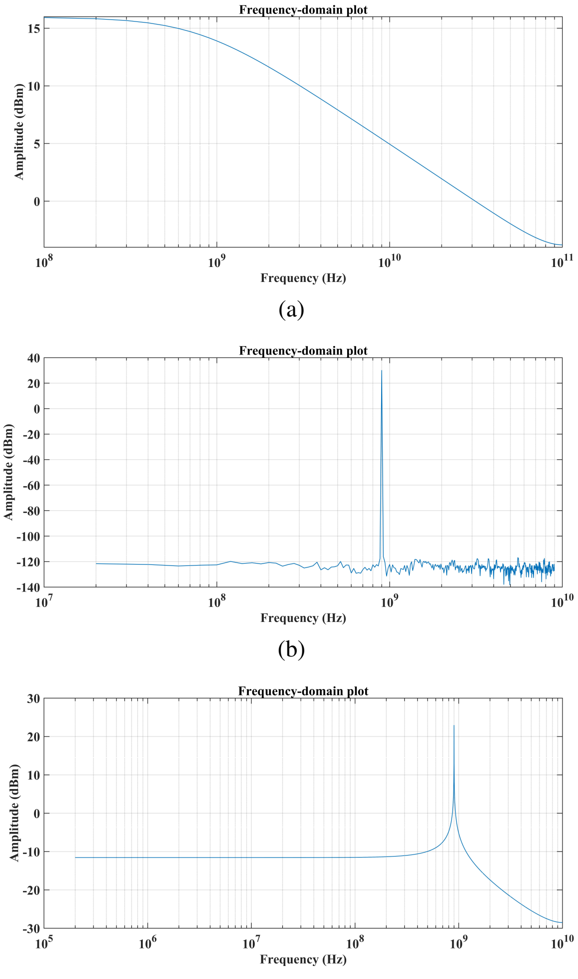
The UWB jammer source produces transient pulses of short duration while generating a broad spectrum covering a frequency range from GSM-R to 5G-R. While the wideband threat could simultaneously produce energy over a wide range of frequencies, the energy associated with the short-duration pulse is, therefore, limited. For this reason, it is difficult to create permanent damage with this type of disturbance. Nevertheless, if the amplitude is continuously increased and repetitively imposed on the communication system, the possibility of damage increases [74].

- Narrowband jammer

Unlike the UWB jammer, the narrowband threat usually has high power and energy for system vulnerabilities because the energy is delivered in a narrow frequency band. Therefore, the malfunctions with narrowband waveform observed in the systems often permanently damage the devices. Fig.4(b) illustrates an example of 900 MHz narrowband interference. A variable frequency oscillator sweeps quickly and repeatedly in a few microseconds [72].

- Broadband damping sinusoidal jammer

The Broadband damping sinusoidal jammer combines specific signal characteristics of UWB and sustained sinusoidal signal. This type of waveform represents a reasonable compromise that can cover all allocated frequencies to a radio system and maximum energy concentrated around the center frequency. Fig.4(c) represents the frequency of broadband damping sinusoidal covers a wide range and centers at 900MHz.



(a)

(b)

(c)

Fig. 4. Frequency-domain graphs of the jammer. (a) UWB (b)Narrowband (c)Broadband Damping Sinusoidal

D. EMC and Standards

The natural and EM environments in different countries are very different, which may lead to EMC's different design solutions. Referring to the impacts on the transport systems, four states of the system's operation can be classified [75]:

- the acceptable level of interference was not exceeded, and the system remains in operation.
- the devices automatically eliminate the interference.
- the system transit to partially functional.
- the system is damaged and malfunctioning.

Implementing EMC in railway systems becomes a challenging issue, and the existing work analysis with comparison for EMI and IEMI is shown in table III. The International Electrotechnical Commission (IEC), a worldwide, independent, non-profit membership organization, develops globally relevant International Standards for electrical and electronic technologies. IEC's immunity follows the standards on Electrostatic Discharge (ESD) [76]. Immunity examines the ability of a system to operate correctly under the presence of intentional and unintentional EMI. According to the European Integrated Railway Radio Enhanced Network (EIRENE) specifications, the antenna has minimum operationally acceptable received power -95dBm and received coverage level 95% of the time and the space [77]–[79]. The signal transmission is disturbed when the interference is beyond the immunity level.

Based on the analysis of the status quo of the EMC related to the communications systems, some new EMC design methods need to be developed, such as inhibiting interference sources, cutting off transmission routes of EMI, and improving the EMI resistance of the signal receiver [97]. In EMC design, field measurement and tests with software and hardware tools also should be conducted [98]–[102]. In addition, the construction and implementation for mitigating EMI and IEMI should be economical and environmentally friendly. It is urgent to envisage an immunity testing solution at the physical layer against EMI in the railway system.

IV. ANALYSIS OF EMI AND IEMI ISSUES ON SIGNAL TRANSMISSION

A. Network-based modeling Method

1) Model description: Traditional approaches could effectively decompose the complex system into equivalent circuits or simplified parts. However, when the methods are applied to complicated systems like railway systems, many limitations are shown in table III. Therefore, a topological network with edges and nodes is proposed to describe the EM coupling and connection between the sources and equipment.

The problem in the system refers to the process in which the EM disturbance sources affect the normal operation of the corresponding parts through the transmission coupling relationship within the system. Fig.5 shows the analogy between the EMC problem and the network with four parameters [83], [84]. It is a directional network formed by nodes and corresponding connection edges representing the coupling relationship. Each node can represent the elements of EMI events, such as EM disturbance sources, sensitive devices, and vulnerable equipment. The edge indicates the propagation path where an EM disturbance source affects the target equipment through a particular coupling node.

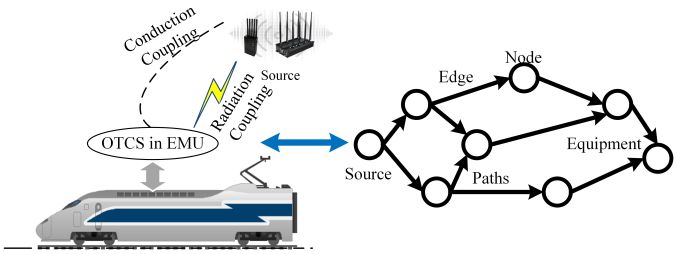


Fig. 5. An analogy between the EMC problem and network [84]

The core function of the On-board Train Control System (OTCS) equipment is to supervise the speed of EMU in real-time and automatically control the braking system to prevent the train from over-speeding [84]. The EMUs are distributed on the train's roof, interior, and bottom. Correspondingly, OTCS equipment that controls the train operation is distributed

TABLE III
ANALYSIS WITH COMPARISONS OF EXISTING WORK ON EMI AND IEMI

	Topics	**Contents**	**Limitations**
EMI	Measurments	IEC 61000-4 series: basic EMC standards for testing and measurement techniques of electrical and electronic equipment [77]–[79]	only evaluate the current levels of the immunity requirements with peak detectors [80]
		EN 50121-4: the emission and immunity of the EMC of signaling and telecommunications apparatus [81]	not specific to the railway domain or the field of telecommunications [82]
		Japanese standard JIS E5006, and Chinese standard GB/T 24338 and GB17626.3	do not specify basic personal safety requirements for apparatus under fault conditions [77], [78]
	Modeling	lumped equivalent circuits and transfer functions like EM topology [83], [84]	cannot cover the frequency range, obtain proper transfer functions, and add any new parameters
		EMI issue from Pantograph-Catenary Arcing (transient disturbance EMI issue) [29], [85], [86]	the only model construction for EMI issue and only based on GSM-R communication system
	Mitigation	suppression techniques, including passive filter, Wheatstone bridge balance, active filter, and optimized modulation, related to hardware electrical equipment [87]–[90]	unsuitable for the railway domain or the field of telecommunications
IEMI	Detection	statistics-based and threshold detection (capture the temporal and spectral information with time and frequency analysis) [91]–[94]	cannot analyze multiple indicators and distinguish attacks in real time
		classification methods, either binary or multiple classifications [95]	efficiency is low and needs a long processing time with a huge amount of data
	Mitigation	increasing transmitted power to increase SIR, switching from the train front antenna to the train rear antenna to increase attenuation, and using a high front-to-back ratio train antenna [73]	Mainly physical methods to mitigate the impact and lack consideration about the specific telecommunication field in the railway systems [26], [96]

in the above three spaces. Therefore, each disturbance generated in the EM environment interacts with the EMU and ultimately interferes with the OTCS equipment in HSR, as illustrated in Fig.6. Each node in the EMI network model has a one-to-one match, and each path from a source to a device can be represented as an EMI event. Therefore, all EM interactions are mapped into a complicated network.

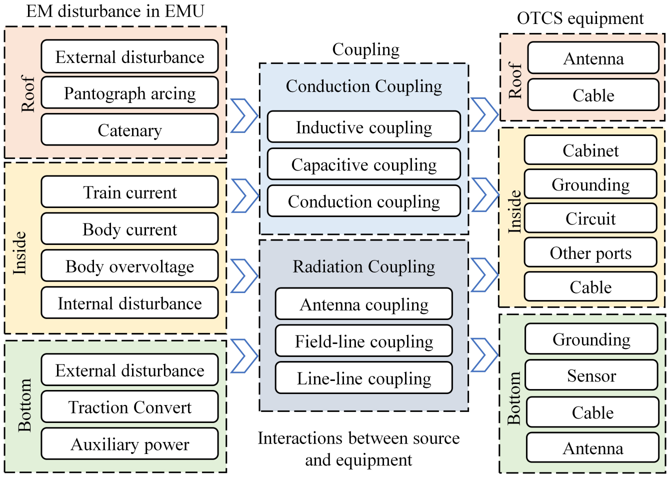


Fig. 6. The EM interactions between EMU and OTCS [84]

2) The definition and form of the node: The form of nodes is defined in table IV. The parameters of the nodes, such as the amplitude, frequency, and module function, can be obtained through simulation, computations, or measurements. Two kinds of EM disturbance nodes in the HSR are the radiated disturbance node and the conducted disturbance node. The virtual node can be used to determine the coupling relationship between the disturbance source and the module nodes. On the other hand, it can reduce the complexity of the network by reducing the cross among the connection edges from the disturbance nodes to the equipment nodes.

TABLE IV
THE FORM OF THE NODE

No.	Node	Form	EMC Elements
1	Disturbance node	⭘	Radiation source
2	Disturbance node	⊙	Conduction source
3	Virtual node [1]	○	Radiation coupling
4	Virtual node	●	Conduction coupling
5	Module node	◉	Equipment

[1] The connections between disturbance and equipment.

3) The definition and form of the edge: EM energy is coupled into systems in two main paths: front door coupling and back door coupling [103]. Front door coupling is the energy that uses available ports intended for the propagation of EM energy and communication with the external environment, e.g., antennas or power sockets. It can cause interference in-band and out-of-band through the ports used for coupling. Back door coupling is the EM energy that uses ports and paths generally not intended for communication with the external environment, e.g., through walls, small apertures, or coupled onto cables. Considering the coupling process of the EM disturbance in the EMC network domain, the connection relationship between the source and equipment can be divided into two categories: conduction and radiation coupling. The former includes direct conductive coupling, capacitive coupling, and inductive coupling. The latter contains antenna coupling, field line coupling, cable coupling, and crosstalk [83]. The form of the edge is defined in table V. The physical connection and the signal connection are distinguished from the form of the network structure.

TABLE V
THE FORM OF THE EDGE

Edge	Form	Explanation
Physical connection	◉←——→◉	Contact by metal (ground)
Coupling connection a [1]	●——→◉	Conduction coupling
Coupling connection b [2]	○- - - -→◉	Radiation coupling
Signal connection	◉← · →◉	Wire transmission (unidirectional or bidirectional)
	◉←- - -→◉	Wireless transmission

[1] The edge between the source and coupling nodes are the same with coupling connection. [2] Field-line couplingand inductive or capacitive coupling (crosstalk) are classified as this form for simplicity.

Each EMI event corresponds to an interactive relationship, and all EMI events form a complex network of connections. Due to the complexity of the source and coupling mechanism, all possible situations should be considered to find the path. The complete network model can be found in [83], [84]. However, the EMI events may not occur simultaneously due to different scenarios. Therefore, the study of each EMI event relies on the case study in the following sections.

B. EMI Issues from Pantograph-Catenary Arcing

When a spark occurs between the catenary and the pantograph, transient disturbances are produced on the antenna fixed on the train roof. A typical EMC model with a pantograph and antenna on the same carriage is shown in Fig.7 and Fig.8. For the radiation coupling between the pantograph arcing and antenna, the train roof and catenary contact wire are the essential components of the model.

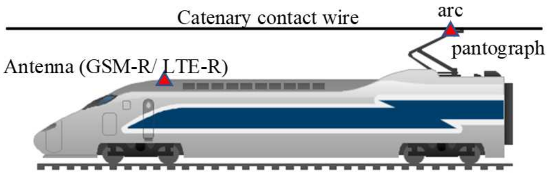


Fig. 7. A typical model of train with pantograph and antenna

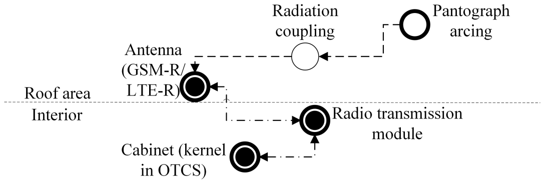


Fig. 8. EMC network model of pantograph arcing and antenna with actual location

Two kinds of radiation coupling are related to the pantograph: contact wire and the train roof. One is direct radiation from the arc itself, and the other is the secondary radiation generated by the induced current in the pantograph and contact wire. The disturbance electric field generated by the induced current on the train roof can also be categorized into radiation and induction fields. Thus, the total disturbance electric field can be calculated by the electric radiation field and the induction field.

The transient disturbances mainly occur in HSR and can be differentiated by the power, the rise time, the duration, and the repetition rate [85]. The existing EMI impact for this type of disturbance is mainly based on the measurements from the test equipment, and the EMI model constructions primarily focus on the GSM-R communication system. According to the measurement, the power of the transients generally depends on the maximal amplitude. It can reach an amplitude of up to -40dBm. The distribution of the rise times and duration share some common aspects, with the rise times inferior to $1ns$ and the duration inferior to $20ns$ [86]. It means that the duration of each measured transient event is considerably shorter than the transmission duration of a bit in the GSM-R system (3.7μs). Thus, in [33], the authors assume that each time a transient occurs, it can disturb only 1 bit. Consequently, the impacts of the disturbances can be quantified as Bit Error Rate (BER), and the quality of the received signal can be linked to transient noises. Moreover, the transient disturbances can vary significantly depending on the operating conditions (the train speed, the supply line power, the age of the pantograph and catenary, and the weather conditions). The analysis in [104] shows that the train speed affects the intensity of the electric field of the pantograph-catenary arc by impacting the radiation power. It reveals that the faster the train speed, the stronger the electric field, which means that increasing the train speed leads to stronger EMI. Therefore, the time interval between the successive transient events, also called the repetition rate, cannot be extracted as a typical value. It is considered a variable parameter for immunity testing [33].

According to the frequency analysis in [85], [105], [106], the high-power catenary system's primary EM transient interference is a pulse extended to 1GHz, covering the GSM-R and the future LTE-R, 5G-R frequency bands. To validate whether the interference will degrade the radio transmission module and affect the communication performance, the relationship between the throughput and Signal to noise ratio (SNR) is simulated with Physical Downlink Shared Channel (PDSCH) in MATLAB [84]. It is based on the File Transfer Protocol to measure the throughput of the LTE-R system in an experimental HSR line in Shenyang, China. The throughput decreases when the disturbance is generated by pantograph arcing. Therefore, the feasibility of the first EMC model is validated.

The relationship between BER and SNR in [21] shows that the simulation results agree closely with the theoretical but are slightly higher than the theoretical result. The main reason is that the interferences in simulation include high amplitude interference from pantograph arching and low amplitude interference from power electronics. The traction system and auxiliary power like transformer and inverter may generate EMI and will be discussed in the next section.

C. EMI Issues from Train onboard Power Electronics

Power electronics is a power processing system with electronic circuits based on Pulse Width Modulation (PWM) technique. A power switch is ideal for handling unlimited current and voltage for straightforward analysis at a low-frequency level. However, for practical considerations and high-frequency operation, three main issues may occur losses, EMI, and harmonics. In a power converter, efficiency is one of the main concerns [107]. The main part of a total loss, i.e., switching loss, must be reduced to increase efficiency. The switching loss can be reduced by decreasing the switching time, but fast switching increases voltages ($\frac{dv}{dt}$) and currents ($\frac{di}{dt}$) during switching transient, which aggravate EMI noise [107]. Due to significant over-voltage and leakage current generated by fast switching and stray components of the power electronic systems, it is a trade-off between EMI and losses [107]. Also, the output voltage or current generated by the PWM control system has harmonics around the switching frequency. While increasing the switching frequency decreases output ripple magnitude, reduces low order harmonics, and reduces the size and cost of passive filters, the drawback is more switching loss and EMI noise. Therefore, it is a trade-off between quality and losses [107]. The research in [108] analyzes the power-stage switching functions related to EMI noise emission. It is concluded that the EMI emission from a power electronic system is determined by two fundamental switching transitions when the switches turn on and off: positive-going and negative-going transitions. However, few studies have used a system model to describe the EMI emission impacts on radio communication networks.

Power electronic systems have developed rapidly in the railway, and many applications have been introduced into the traction systems to control a power converter to provide adjustable DC or AC voltage for different loads [87]. The sources of EMI derived from the power electronics in EMU can be categorized into two major parts: traction power supply system and traction propulsion system. The conducted and radiated EMI is generated by the complicated structure of traction systems, such as a two-cell H-bridge boost, active converters, and parasitic capacitance. As shown in Fig. 9, the commonly used AC traction system includes a three-phase grid received by a pantograph, high-voltage cable, main traction transformer, rectifier, inverter, and AC propulsion motor. Fig. 10 shows the EMC network model of power electronic systems with actual locations. The train collects electrical energy from sliding contact with a power supply line from an overhead line. The current passes through the traction system to provide power for the power control unit and propulsion systems. The traction system, auxiliary power, and ground system are connected by a metal connection. This electromechanical system may be affected by the conduction coupling source with fast-changing of voltage ($\frac{dv}{dt}$) through the path 'pantograph–traction transformer–traction converter–power line–ground device.' It shows that the frequencies range from 9kHz to 30MHz [87], which is far less than the radio communication system frequency spectrum, and many studies have focused on developing techniques to reduce the conducted EMI noise from power electronic converters [109].

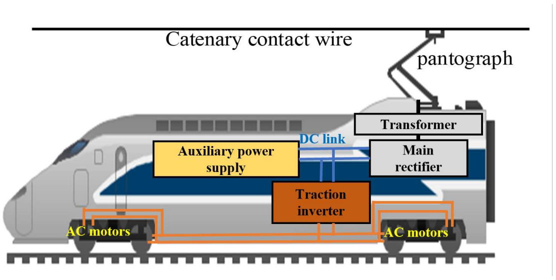


Fig. 9. A typical model of train with the power electronic system

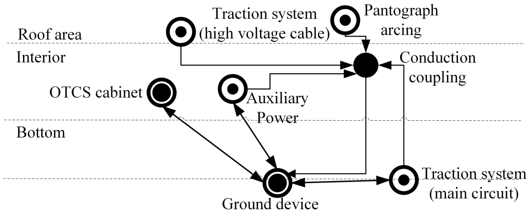


Fig. 10. EMC network model of power electronic systems with actual locations

The situation becomes worse when the wide-bandgap (WBG) power semiconductor, e.g., silicon carbide (SiC) and gallium nitride (GaN), including power diodes and active power switches with high-efficiency and high-density design compared to Si devices, have been widely applied in power electronics applications [110]. The WBG devices have three advantages: smaller reverse recovery current and time, fast-switching speed, and high-frequency operation. However, they generate both conductive and radiative EMI, especially high-frequency EMI [111]. The conductive EMI frequency at measurement minimum range is from 150 kHz to 30 MHz and is related to switching speed, switching frequency, and the impedance of the EMI propagation paths. The details of emission sources of the Common Mode and Differential Mode model and reduction techniques are presented in [110]. Also, the passive methods of suppressing conducted EMI noise are designed and studied in [112]. In terms of the radiative EMI, it is introduced and classified as near-field coupling and far-field radiation. In [111], the solution to reduce EMI by shifting EMI peaks to the most effective bandwidth of a filter by reprogramming the FPGA is discussed.

The radiation coupling from the traction system and auxiliary power at the bottom of the train may also affect the speed sensor in the speed and distance processing unit in OTCS, leading to an over-speed problem. Also, this radiation coupling may cause the track circuit receiver and compact antenna unit in the Blaise Transmission Module (BTM) to fail to acquire the MA information and calculate the train's location. There is also a radiation coupling path from auxiliary power and traction system power cables to the driver-machine interface (DMI) cable, which is the metal physical connection between the DMI and the kernel of OTCS inside the train, as illustrated in Fig. 11 and Fig. 12. The DMI displays the driver information, such as control orders, equipment status, and driving strategies. The driver will process this information to control the EMU. The kernel in OTCS is installed in the ATP cabinet with power and ground connection with the EMU. The DMI and kernel in OTCS are connected by a metal physical connection cable. According to the layout described in [84], the factory workers designed to lay this metal physical connection cable inside the train closely parallel to the power cable of auxiliary power to save space. However, from measurement in [21], the disturbance in power cables is the potential source to impact this metal physical connection cable, leading to communication interruption error, and the emergency brake signal is given to stop the train. From the simulation results verified in [84], this EMI event would affect the communication between the DMI and kernel of OTCS.

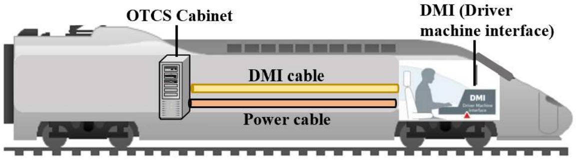


Fig. 11. A typical model of train with DMI and OTCS Cabinet

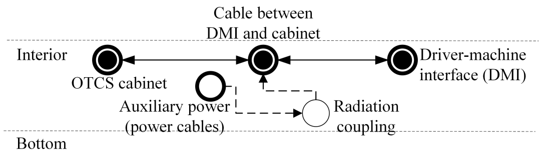


Fig. 12. EMC network model of DMI and OTCS Cabinet with actual location

D. EMI Issues from Public Cellular Network

Apart from the significant EM interferences on the antenna generated from pantograph-catenary arcing and the train on-board power electronic systems, some interferences can be considered permanent interferences from adjacent public bandwidth of BS and cellular network [29], [33]. Some early research presents the relationship between the antenna fixed on top of a train and the public GSM BS shown in Fig.13. When the public GSM BS and user numbers increase rapidly in the vicinity of a city, the first public GSM channel (925.2 MHz) can induce an EMI on the closest downlink GSM-R frequency channel (924.8 MHz) with a variation of the measured amplitudes up to -75 dBm. Meanwhile, the GSM-R signal level can decrease to a minimum of -92 dBm. Therefore, it proves that this interference is a severe threat to disturb a GSM-R transmission.

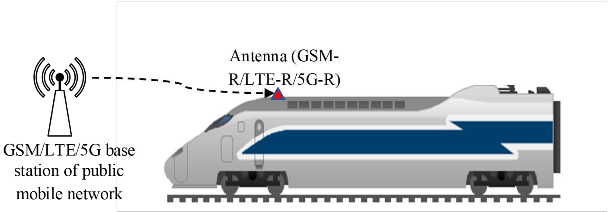


Fig. 13. A typical model of train and public mobile network

In terms of the conventional GSM cellular networks, the self-interference of the system, such as co-channel interference, adjacent interference, and alternated interference, must be analyzed and mitigated [50]. The signal generated from another BS operating in the same channel or using carrier frequencies in the vicinity of the desired transmission is the most important source of interference for a BS [82]. As the HSR wireless communication network architecture will transform from the traditional cellular network to HCN, interference has become an inevitable problem. With the increase of BS, communication link density, and complexity at the network level, signal interference is becoming more serious in the 5G heterogeneous ultra-dense network system [51], [113].

E. Intentional EMI (IEMI)

As described in Section III, IEMI in modern railways is considered a potential threat of EM attacks related to terrorism and crime [27]. It becomes easier to disturb critical systems through telecommunication devices because small and discreet equipment can be easily accessible to the public [114]. Depending on the location of IEMI, on the ground, or embedded in the train, its impacts may be different. Two cases are considered in this section: the IEMI device is inside the train or on the ground between BS. Generally, devices with power limited to 1W are considered inside the train and on board. The high-power devices are used on the ground because they are bulky and often require an external power supply [74]. It is a preliminary comparison between the signal and interference power levels in the railway communication network. The assumption is that when the IEMI power level is comparable with the useful power level, there is a detrimental impact.

The first case is that the IEMI device is present inside the train, which is portable and has a limited power level. Considering the IEMI transmitted from the train in a passenger's pocket to interfere with the antenna, as shown in Fig.14, it might stop the train potentially if the modem connection is lost without updated control [73]. The signal received by the train antenna from the IEMI will be stable if the passenger does not move on the train. Due to the interactions of radio-frequency signals in the fading conditions, the received power of the train antenna will decrease with the increased distance between the train and BS.

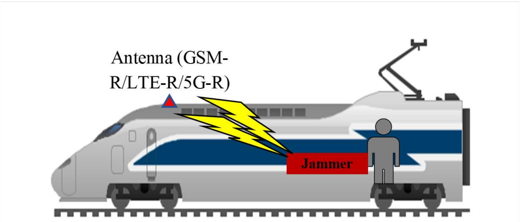


Fig. 14. IEMI signal transmitted inside the train to the roof train antenna

According to the measurement [74], the IEMI device generates a power of +30dBm at a frequency of 940 MHz. After the propagation loss and additional attenuation due to the train's structure, the level received by the train antenna becomes -42dBm (10m away from the device) and -62dBm (100m away from the device). Compared to the dynamics GSM-R signal power level received by the antenna between -95 and -20dBm, when the train leaves a critical communication area (below the red line), the IEMI power is larger than the power of the useful signal, as shown in Fig.15. Suppose the IEMI signal power is to jam all the allocated downlink channels. In that case, the radio communication may be significantly affected, and the train operation system will trigger the emergency brake due to the loss of updated control command.

The second case is where the IEMI device is placed on the ground along the tracks, near a BS or halfway between two BS, as shown in Fig.16. It can continuously disturb the radio receiver and transmitter located in the BS, no matter the trains

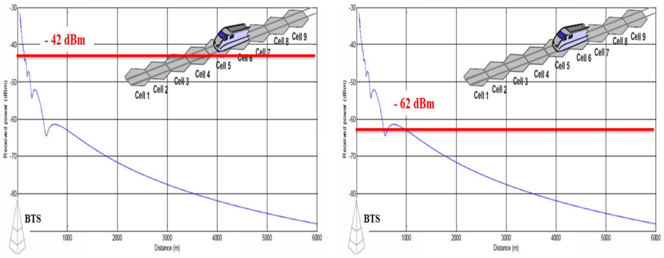


Fig. 15. Power level received from the BS compared with IEMI device [74]

are present or not. In this case, the IEMI received by the BS remains constant, and the detection methods can be used to identify the location close to the BS [74]. However, the signal received by the train antenna from the BS and IEMI are both dynamic during the operation, so the cover design of the BS is crucial. In particular, the received signal strength of the train is the lowest during the overlapping area between two cells because the handover operation between consecutive cells is also carried out. The case will get worsened in 5G-R and HSR due to frequent handover with smaller cell ranges and higher train speed. Therefore, if the IEMI device is placed between two BS, the impacts of the jammer on BS communication to the train can be particularly significant.

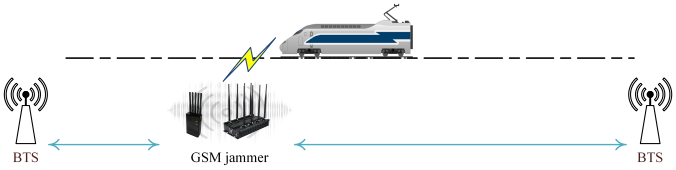


Fig. 16. IEMI device placed on the ground along the track

In addition, GSM-R antennas are generally multi-band antennas and are not selective around the frequency bands dedicated to the railway. They can thus receive GSM-R in-band and out-band IEMIs. Reference [104] showed that out-band EMIs observed in the railway environment could severely threaten the low noise amplifier (LNA), which is to amplify the weak signals captured by the antenna installed at the GSM-R receiver. Such component is susceptible to IEMI, which can permanently damage the system.

F. Overall Impacts of EMI and IEMI on Signal Transmission

Fig.17 summarizes the impacts of all four EMI types on the signal transmission in the electrified railway, including the transient EMI, EMI from power electronics, permanent EMI, and the intentional EMI from artificial noise. Thanks to the more advanced technological development related to the railway systems, such as power electronics, the impacts on signal transmission in the railway system are more severe. As the railway industry develops rapidly, the communications network in the railway system also needs to improve its resilience against EMI and IEMI. Therefore, creating a holistic and effective EMI mitigation mechanism is crucial.

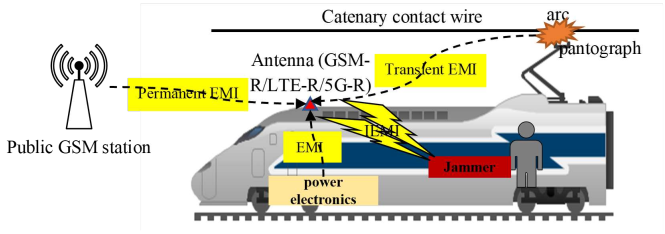


Fig. 17. Four types of EMI (Transient and Permanent EMIs, EMI from power electronics, and IEMI) received by GSM-R antenna

V. FUTURE CHALLENGES AND WORKS

Recent progresses on current and future railway communication systems and technologies, evolution from GSM-R to 5G-R, have been surveyed in Section II. The impacts of EMI and IEMI, including new security issues, have been analyzed. Hence, the potential challenges must be addressed before implementing the railway communication network.

Various advanced technologies have been commercially utilized in public communications networks. Among them, artificial intelligence (AI) is a promising technology that can be applied to different fields [115]. As part of the smart city initiatives, the future electrified railway, e.g., the massive development of HSR worldwide, can take advantage of the latest progresses in AI. For example, ML [116]–[118], such as multi-agent reinforcement learning algorithm, deep neural network (DNN), and Bayesian optimization algorithm (BOA), have been used in EMI and IEMI prediction, optimization, and localization in railway systems. As shown in Fig.18, the research on EMI and IEMI in the railway communication network, including accurate modeling, real-time detection and prevention, and effective mitigation, needs to be considered holistically. Therefore, future works are discussed in the following sections, and the potentials of AI applications are highlighted in particular.

A. EMI and IEMI modeling and analysis

The source and impacts of EMI and IEMI have been thoroughly investigated, from the inherent characteristics of the spectrum to the systematic review of railway signal transmission in this paper. Once the measurement data of typical EMI and IEMI sources are available, it is necessary to develop a mathematical model to relate the EM interference to the radio immunity of the communications network. Current modeling effort is focused on the empirical distributions using real scenario measurements, or in an emulation platform such as the zero-on-site-testing approach [86], [119], [120].

Integrating multiple sources of EMI and IEMI into a typical mathematical model is a challenging topic for future modeling works. Reasonable assumptions are required to combine the key characteristics of different sources, and it is hard to find a good compromise. The aim is to develop a proper model to integrate the multiple EMI sources from rolling stock, power electronics systems, public cellular networks, and even intentional EMI discussed in the previous sections. Also, due to the surrounding geographical environments, different

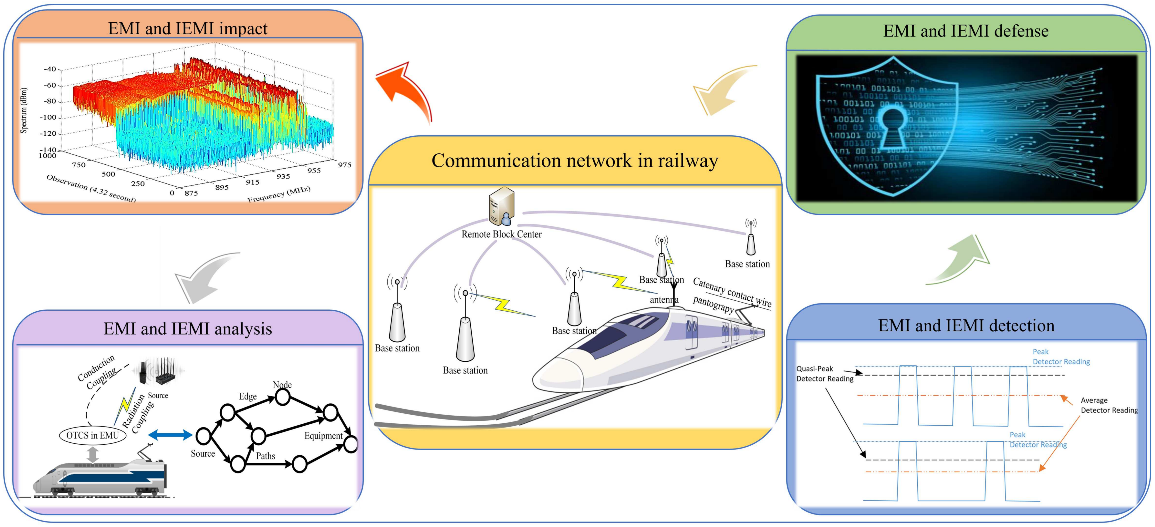


Fig. 18. The research framework of EMI and IEMI on radio communication network

scenarios can be considered during the train operation, such as open space, viaduct, tunnel, and stations [121], [122]. With the help of ML techniques, e,g, data-driven model, adaptive classification algorithms, the EMI and IEMI models will evolve when new unknown scenarios occur. Therefore, the models can keep updated regularly [123].

In addition, the evolution of the railway communication networks (the coexistence of GSM-R and LTE-R and the future intelligent railway implementation of 5G-R) is under construction. The model should be flexible and easily compatible with different communication networks in GSM-R, LTE-R, and even 5G-R.

B. EMI and IEMI Detection

As discussed in the previous section, IEMI has increased in recent years. According to [124], the vulnerability of 5G wireless systems to IEMI is analyzed in detail. Although 5G NR can enhance the resilience of wireless cellular networks to jamming attacks due to its flexible and dynamic resource allocation, 5G NR is still far from being secure against jamming attacks. It is difficult to predict when and where the IEMI occurs compared to EMI. Therefore, real-time detection is highly required to distinguish IEMI from the EMI model.

Current IEMI detection methods cannot analyze multiple indicators and attacks simultaneously based on statistics-based detection and threshold detection [91]–[94]. The research in wireless communications systems has led to the development of different classification methods, either binary or multiple classifications. The binary classification, for example, can distinguish whether the incoming EMI or IEMI is tolerable for the communication system [95]. Recently, jamming attacks have been classified into four types: constant jammers, random jammers, deceptive jammers, and reactive jammers [125], [126]. Among them, the reactive jammer is special compared to the other three active jammers. It presents a smarter and more power-efficient approach and can sense the communication channel to update its attack strategies. Therefore, the reinforcement learning method can be introduced to detect the jammer in such a dynamic environment. Other ML algorithms such as random forest, support vector machine, and neural network are also investigated [127]–[129]. However, the above analysis is conducted on general public cellular networks. It is yet a long way to implement in the railway wireless communications network.

Monitoring IEMI in real-time is crucial and valuable in the industry. If remote condition monitoring is used widely, operators can reduce the cost of labor and check the operation whenever and wherever needed for free. Future smart infrastructure should also have the functionalities of predicting the risk timely from the varying environment with source reconstruction and advising to take action before a critical problem occurs [116].

C. EMI and IEMI Mitigation

Based on the EMI and IEMI detection, the mitigation will be more effective if jamming is monitored sufficiently early or predicted in specific scenarios. For instance, the transmitted power can increase once the jamming condition is detected to save energy during regular operation and manage the interference in real time before the connection is lost. However, most existing methods do not consider smart jammers, while trains can be considered as multi-agents operating in a complex and dynamic EMI environment in the railway system. Therefore, future works for EMI and IEMI mitigation schemes can be developed from the transmitter and receiver sites with the aid of ML algorithms. For instance, in wireless communication [130], the transmitter deliberately takes wrong actions and adapts the level of defense to mislead the IEMI into prediction errors. This proactive approach can potentially be applied to the railway communication system. Furthermore, the flexibility of the analysis methodology and the prevailing existence of EM disturbance make it naturally appealing to extend the investigations to broad transportation scopes, such as maglev trains, hyperloop, and electric road systems.

D. Communications System's Resistance to EMI and IEMI

Apart from the reactive methods against EMI and IEMI, some recent papers consider the inherent characteristics and enable systems to be more resilient to internal or external constraints [96]. Further, some advanced technologies such as massive MIMO and distributed antenna technology can be implemented in the system architecture design [131]. For instance, cell-free massive MIMO, employing a large number of distributed access points with antennas over a wide area, is a promising solution [132]–[136].

VI. CONCLUSION

This paper has presented a systematic review of the impacts of EMI and IEMI on signal communication in electrified railway systems, along with the broad background of transportation decarbonization and the current and future electrified transportation in the railway system. Also, the evolution of railway communications ETCS levels is surveyed together with the development of the communication network. GSM-R is currently deployed, and LTE-R will co-exist and move toward the 5G-R. To ensure the safety of railway operations, the EMI and IEMI issues are modeled with network-based and system-level analysis, representing the elements on the train nodes and edges. It clearly shows the source of EMI and IEMI and their impacts on signal transmission. Furthermore, the existing EMC methods related to the communication network are discussed on their limitations, and the challenges such as modeling, detection, and mitigation are presented. Future works have outlined the potential research directions, such as combining advanced communication technology with AI to improve the EMI and IEMI resistances of signal transmission and communications networks.

With the continual development of railway electrification, the EMI and IEMI are becoming severe issues. EMC related to signal transmission needs to be improved in the design and application to ensure safe operation. This review paper aims to bridge the knowledge gaps in the impacts and mitigation of EMI and IEMI in railway communications networks.

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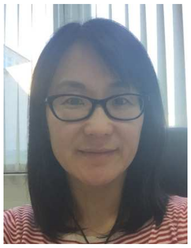

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