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TOPICAL REVIEW

Enabling Network Technologies For Flexible Railway Connectivity

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ABSTRACT Today's rail industry deploys innovative applications for real-time monitoring of trains and railway infrastructures and remote control of trains to enhance the safety and security of passengers and train operation. These applications can require multiple constraints satisfactions in terms of latency, data rate, reliability, coverage, mobility, security, *etc*. In order to meet the desired quality of users' (trains, passengers, controllers, *etc.,*) experience, it is essential to apply and combine various enabling wireless technologies for the railway communications architecture such as end-to-end (from the cloud hosting applications to the user client, traversing communication network infrastructure) Network Slicing (NS), Software Defined Network (SDN), Network Function Virtualization (NFV), Multi-access Edge Computing (MEC), Blockchain, Artificial Intelligence (AI) tools, *etc*. This paper aims to propose a global unified control framework to automatically compute deploy, and manage necessary resources on the different network infrastructures (cloud, core, transport, and multiple-access networks). In this context, this article proposes the first study in the railway sector to link application constraints and enabling technologies. After a brief overview of the railway context, the main applications requirements, and the technologies that could be applied, we propose a high-level architecture for railway applications incorporating the various technologies identified: MEC, NFV, SDN, AI tools, and Blockchain. We also study the impact that these different technologies could have on existing rail applications and identify the challenges and future directions for rail networks in the era of 5G and future 6G.

INDEX TERMS Railway, 5G, network slicing, quality of service (QoS), AI, edge computing, quality of experience (QoE).

I. INTRODUCTION

The railway transportation sector is undergoing profound transformations through digitalization and emerging wireless technologies to provide new services and improve passenger comfort while increasing the security and safety of train operation. To modernize rail communications, the Future Railway Mobile Communication System (FRMCS) is under development at the European level to migrate mission-critical railway communications systems from narrowband Global System for Mobile Communications-Railways (GSM-R) to broadband 5G-based systems for railways to offer a wider range of services [1]. In the early 2010s, LTE-Railways (LTE-R) was considered the candidate technology for evolving the railway communication system. Unfortunately, it was found that the LTE-R system is no longer

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suitable because of the requirements of railway services in terms of ultra-reliability and massive connectivity for future railways. Therefore, to satisfy high reliability, low latency, massive connectivity, and enhanced security requirements for intelligent railway applications, a 5G for Railways (5G-R) communication system is being developed. 5G-R is a promising solution for further intelligent railways and a critical enabler for FRMCS. The main difference between 5G and 5G-R is the transmission performance in the context of railway mobility. It has been found that 5G-R improves performance compared to the 5G. The 5G-R system supports a reliability rate of 99.9999% and a handover success rate greater or equal to 99.9%. In comparison, the public 5G system supports a reliability rate of 99.999% and a handover success rate that varies between 90-95% [2]. Furthermore, as 5G, 5G-R has under its umbrella several cutting-edge enabling technologies, such as SDN, NFV, NS, MEC, and AI, that arouse interest in rethinking a new architecture of railway communication networks.

In addition to FRMCS, other technologies such as satellite communications and other wireless technologies (WiFi, ITS-G5, LPWAN [3], *etc.,*) will also find their place in these future railway communication systems architecture thanks to the concept of adaptable communications [4]. They will support different use cases and guarantee the QoS of applications and the QoE requirements [5]. This will open the door to many new rail safety-related or non-safety-related applications such as autonomous train control, virtual train coupling, remote driving, and IoT applications (*e.g.,* freight operation management, freight tracking, predictive maintenance, *etc.*) [6]. Enhancing railway transportation with these latest-generation communication technologies enables rail operators and infrastructure managers to take on the following challenges: improve safety and security, reduce operation and maintenance costs while increasing capacity, efficiency, and competitiveness, and reduce greenhouse gas emissions).

The railway communication systems transition to new generations of networks comes with the challenges of deploying Multi-Radio Access Technologies (Multi-RAT) such as cellular (advanced 5G or 6G), satellite, Wi-Fi, and LPWANs. Another challenge is to integrate into the rail communication network architecture the cutting-edge enabling technologies such as SDN, NFV, NS [7], [8], MEC [9], Blockchain [10], AI [11], [12]. Integrating some or all of these technologies could offer an advantage in terms of performance, flexible maintenance and management, cost reduction, flexibility, and scalability of railway communication networks. These solutions could also provide various QoS for railway service users in two aspects: Railway transport safety and information communication security. From railway safety aspects, MEC ensures the reduction of latency and the offloading of the network, which increases the responsiveness time of applications for the safety and comfort of railway users. In the same context, SDN and NFV provide latency reduction, efficient bandwidth management, fine-grained service management, flexibility, and real-time service redefinition to enhance safety-critical application performance. NS ensures network deployment and updates flexibility and performance improvement. AI enhances passengers' comfort and train safety by enabling communication systems to perform IoT data analysis, railway traffic predictions, process automation, and performance improvement. From an end-to-end network communication security, blockchain technology provides fairness, user data protection, and application protection from end-to-end network communication security and user data safety. AI helps detect intrusion and manage threats. MEC guarantees user privacy preservation by enabling local computation of railway users' data. NS also enhances network security by allowing the virtual isolation of network slices over a single network infrastructure.

Recent works have been focused on fostering modern railway communication services efficiency by leveraging these 5G cutting-edge technologies. Some experimental works in this direction have been proposed. Given this, authors in [13] present SDN, NFV, MEC, and AI tools as emerging technologies and explore how they could be leveraged to revolutionize both railway communications and railway system operations. Authors in [14] discussed and proposed the adoption of the SDN/NFV Framework in railway control networks. In addition, they explored some possible directions considering service orchestration and edge-based NFV services. In the same context, authors in [15] studied the possibility of applying the SDN-based slicing and network resource distribution in train-to-ground railway communication. Finally, authors in [16] focused on throughput maximization in MEC networks for high-speed railways.

Despite the previous works that aim to apply emerging technologies to railway communication networks, little effort has been made to provide a comprehensive survey showing the optimal use of these new technologies based on the different requirements of railway applications. This paper analyses a multi-RAT architecture for railway connectivity integrating emerging technologies such as SDN, NFV, Network Slicing, and MEC. We also consider the integration of AI tools and Blockchain tools in the architecture. The potential benefit of emerging technologies for existing railway applications is studied as well as the open challenges and future directions. Compared to our work, table 1 highlights the technologies considered in other railway surveys.

Our contributions can be summarized as follows:

- We provide a brief overview of the main communication applications in the rail domain and their characteristics, and discuss the enabling technologies that could be applied;
- We propose and present a description of a high-level network architecture integrating identified enabling technologies;
- We analyze potential applications of enabling technologies to existing railway applications;

TABLE 1. Comparison of existing surveys in the railway domain.

Surveys	MEC	SDN	NFV	NS	Blockchain	AI
[17]		✓	✓		✓	✓
[13]	✓	✓	✓			✓
[14]	✓	✓	✓			
[15]		✓				
[16]	✓					
Our survey	✓	✓	✓	✓	✓	✓

- We identify open challenges and future directions in the field of railway communication networks in the 5G and 6G era.

The remainder of this paper is organized as follows: Section II briefly describes the railway infrastructure from a physical and technological point of view. Section III proposes a new railway communication system architecture, describes 5G enabling technologies, and shows their benefits for railway applications. On this basis, Section IV identifies the main future directions for the research in the railway context. Finally, Section V summarizes the contributions of this paper.

II. BACKGROUND

This section describes the main elements related to the railway environment and its current and future developments. It is divided into three subsections: 1) Railway environment, 2) Railway applications and their constraints, and 3) Leading enabling technologies that could be integrated with the railway architecture.

A. RAILWAY COMMUNICATION ARCHITECTURE

In this section, we present the main elements of railway physical infrastructure, communication systems architecture and the types of communication available.

1) PHYSICAL RAILWAY INFRASTRUCTURE

The railway's physical infrastructure includes all the fixed facilities allowing train traffic. There are three types of infrastructure:

- Installations that include the following facilities:
  - Railway tracks and switch points: A running path for trains made up of two iron rows of rails whose spacing is kept constant by fixing them to sleepers placed on the ballast or concrete;
  - Railway rolling stock: The equipment designed to operate or move on railway tracks. These equipment are trains, locomotives, railcars, track units, *etc*.
  - Catenaries: An external overhead power source line for electric trains' power supply. The train collects electric power from catenaries, which serves as traction power for train movement and auxiliary power for Heating, Ventilation, Air Conditioning (HVAC), compressors, lights, *etc*.
  - Signaling and communication equipment developed to optimize safe train operations but also for passenger services.
- Buildings for railway operations mainly correspond to train stations and traffic control centers. These are the control and interaction points between the train and the outside world;
- Artworks include all the structures required to build the rail network. These are bridges, tunnels, retaining walls, viaducts, *etc*.

2) RAILWAY COMMUNICATION SYSTEMS

Communications in the railway domain provide safety and non-safety rail applications. The communication between trains and their environment motivated much research and industrial implementations. Therefore, in the 2000s, the European Train Control System (ETCS) developed GSM-R, a wireless communication standard based on GSM cellular technology. GSM-R enabled mission-critical train communications and interoperability in Europe. Today, GSM-R is no longer efficient and must be abandoned in 2030 and replaced by the international railway communication standard FRMCS, known as the successor of GSM-R [1]. FRMCS introduced 5G in railway communications and this is an opportunity to combine cellular networks with other wireless technologies to provide numerous rail applications and to explore the use of 5G enabling technologies such as MEC, SDN, NFV, NS, AI tools, and Blockchain to improve rail network application performance. The railway communication applications have different requirements that a single access technology cannot satisfy. These requirements are depicted in table 2. Railway operators have deployed diverse wireless access technologies like cellular [18], satellite [19], LPWANs [20], and Wi-Fi [21] for different needs. These technologies still need to be combined in a Multi-RAT architecture for efficient rail communication.

In this context, the train's communication systems architecture can be segmented into three parts: the terrestrial communication systems, the non-terrestrial or satellite communication systems, and the railway user part, as depicted in Fig 1. The terrestrial communication systems is an environment where we can use many terrestrial access technologies such as Wi-Fi, cellular technologies (LTE-R, 5G-R, 5G, 6G), and LPWAN (LoRa, NB-IoT, Sigfox, *etc.*). The non-terrestrial communication system is a satellite communication system that allows trains to access the core network through a satellite station on the ground. Finally, the railway user part is the railway environment composed of trains, other vehicles, sensors, smart infrastructure, and gap fillers. Railway users can be passengers, trains, cars, sensors, or an infrastructure using either terrestrial or non-terrestrial technology to communicate. Gap fillers are a kind of relay in the case of Non-line of Sight. For example, a train moving under the tunnels can lose the connection and could rely on gap fillers to ensure the continuity of the connection. All

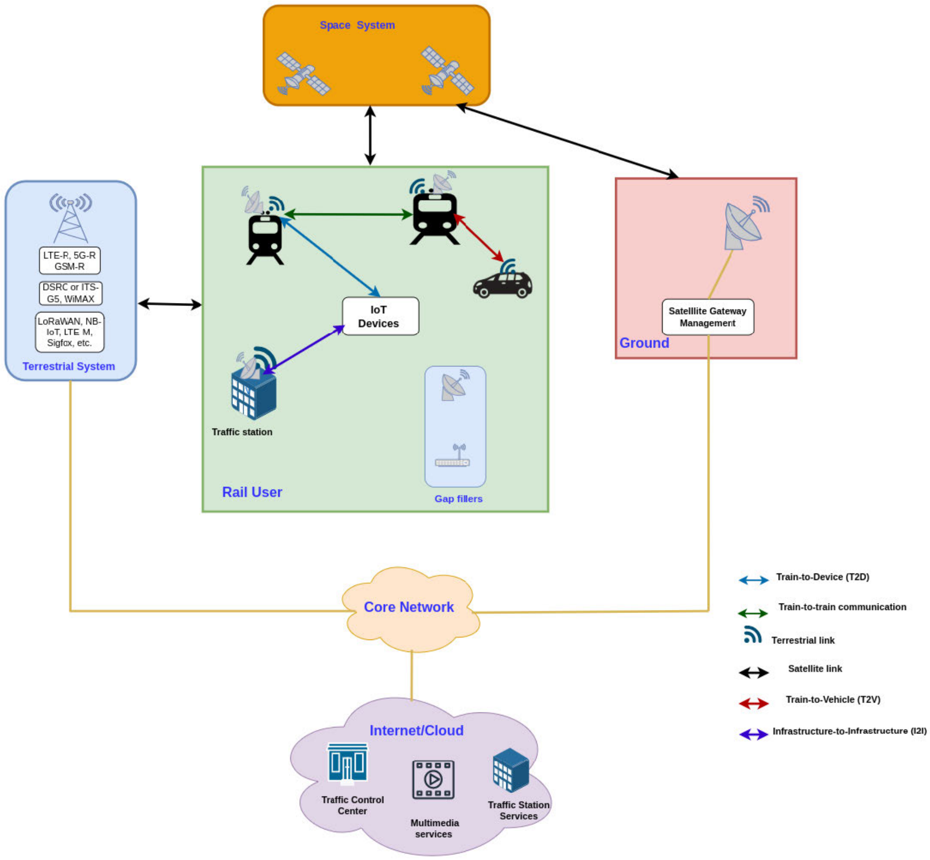

FIGURE 1. **Railway communication system architecture (Terrestrial + Space).**

these described segments have access to the cloud services (traffic station services, traffic control services, Multimedia services *etc.,*) through the core network, which is a set of interconnected routers and switches.

3) TYPES OF COMMUNICATIONS

Various types of communications are made possible by the railway communication architecture described so far:

- Train-to-Ground (T2G): This type of communication corresponds to the bidirectional communication between train on-board units and the wayside access points or gateways or base stations. In the case of mission-critical applications, it could require a very high level of reliability and resistance to high speed but the throughput is not necessarily high. With the development of full automation of trains, new requirements such as high data rate and low latency (less than 100 ms) are defined [22], [23];
- Train-to-Train (T2T): Train-to-train communication involves interconnecting the networks embedded in the trains but also communicating between trains in the same area. The objectives can be multiple: 1) to manage critical situations following or immediately before an accident; 2) to implement train platooning solutions relying on wireless connectivity [24], [25];
- Device-to-Infrastructure (D2I): This type of communication ensures the real-time connection between railway infrastructure and IoT devices. It can consist of data forwarding between the IoT infrastructure (*e.g.,* cameras) and APs installed on the train, rail stations, and along the railway tracks' side [5], [26];
- Train-to-Device (T2D): This type of communication concerns the communication between the train and the internal and external IoT devices to perceive and understand its immediate environment. For example, a train system can collect data from wireless sensor networks along the rail infrastructure and forward it to the control center [27].
- Train-to-Car (T2C): This communication corresponds to the communication between cars and trains, mainly at level crossings or urban scenarios to avoid collisions [28].

B. RAILWAY APPLICATIONS REQUIREMENTS

Railway applications are usually classified into two main categories in railway networks: safety and non-safety related. However, the emergence over the last decade of the Internet of Things and the multiplication of sensors and potential

TABLE 2. Railway applications and their specific requirements.

Scenario / Use case	End-to-end latency	Reliability	speed limit	user experience data rate	Payload size	Area traffic density	Service area dimension	Safety-critical application
Voice applications								
On-train outgoing voice communication from the train driver to the controller (s) of the train	$\leq$100 ms	99,9%	500 km/h	100kbps up to 300kbps	small	up to 1Mbps/line km	200km along rail tracks	✓
On-train incoming voice communication from the controller towards a train driver	100 ms	99,9%	500 km/h	100kbps up to 300kbps	small	up to 1Mbps/line km	200km along rail tracks	✓
Multi-train voice communication for drivers including ground user(s)	100 ms	99,9%	500 km/h	100kbps up to 300kbps	small	up to 1Mbps/line km	200km along rail tracks	✓
Railway emergency voice communication	<200 ms	>99,99 %	160 km/h	200 kbit/s	–	–	50 km x 200 m	✓
Data Applications								
Cooperative Awareness Messaging (level crossing use case)	100 ms	99,999 %	NA	NA	800 bytes	NA	up to 1 km along road or rail tracks	✓
Decentralized Event Notification Messaging (level crossing use case)	100 ms	99,999 %	NA	NA	*leq* 800 bytes	NA	up to 1 km along road or rail tracks	✓
Automatic Train Protection Communication	<100 ms	99,999 %	160 km/h	200 kbit/s	200 bytes		50km x 200 m	✓
Automatic Train Operation Communication	<100 ms	99,999 %	160 km/h	200 kbit/s	200 bytes		50km x 200 m	✓
On-train telemetry communications (TCMS)	<100 ms	>99,9999 %	- (note5)	1 Gbit/s	–	–	3 m x 1 m	✓
On-train remote equipment control (TCMS)	<100 ms	>99,9999 %	- (note5)	1 Gbit/s	–	-	3 m x 1 m	✓
Non-critical real-time video (BC, HU, DE)	1 to 18 s	1-2,5%(packet loss)	-	1.5Mbps (video)	NA	NA		✗
Transfer of CCTV archives	–	–	∼0 km/h	1 Gbit/s	–	–	train station	✗
Passenger Information System (PIS)	NA	NA	NA	NA	NA	NA	NA	✗
Remote Control of engines (remote vision application)	NA	–	NA	NA	NA	NA	NA	✗
Critical video communication for observation purposes	100 ms	99,9%	500 km/h	10Mbps	Medium	Up to 1 Gbps/km	200km along rail tracks	✓
Very critical video communication with a direct impact on train safety	100 ms	99,9%	500 km/h	10Mbps up to 20 Mbps	Medium	up to 1Gbps/km	200km along rail tracks	✓
	10 ms	99,9%	$\leq$40 km/h	10Mbps up to 30 Mbps	Medium	up to 1Gbps/km	2km along rail tracks urban or station	✓
Standard data communication	500 ms	99,9%	$\leq$500 km/h	1Mbps up to 10 Mbps	Small to large	up to 100Mbps/km	100 km along rail tracks	✗
Critical data communication	500 ms	99,9999%	$\leq$500 km/h	1kbps up to 500 kbps	Small to medium	up to 10Mbps/km	100 km along rail tracks	✓
Very Critical data communication	100 ms	99,9999%	$\leq$500 km/h	100kbps up to 1 Mbps	Small to medium	up to 10Mbps/km	200 km along rail tracks	✓
	10 ms	99,9999%	$\leq$0 km/h	100kbps up to 1 Mbps	Small to medium	up to 100Mbps/km	2 km along rail tracks	✓
Messaging	–	99,9%	$\leq$500 km/h	100kbps	Small	up to 1Mbps/km	2 km along rail tracks	✗
Control of automated train	<100 ms	99,999 %	160 km/h	200 kbit/s	200 bytes	–	50km x 200 m	✓
CCTV communication service for surveillance cameras	<500 ms	>99,99 %	160 km/h	2 Mbit/s	–	–	50 km x 200 m	✓
Train coupling	<100 ms	>99,9999 %	- (note5)	1 Gbit/s	–	–	3 m x 1 m	✓
CCTV offload in train stations	–	–	∼0 km/h	1 Gbit/s	-	–	train station	✗
Multimedia and entertainment solutions	1 to 18 s	1-2,5%(packet loss)	–	0.13Mbps(audio), 1.5Mbps (video)	–	–		✗
IoT Applications for Internet of Smart Trains								
Freight operation management	50 to 100 ms	9.999 et 9.9999	<5 km/h	–	40 to 100 bytes	10000 devices/plant	100 to 500 m	✗
Freight Tracking	–	–	–	–	–	–	–	✗
Intelligent power supply	3 to 20 ms	9.999999	0	–	80 to 1000 bytes	10 to 2000 devices/km²	**A few m to km**	✗
Smart metering	3 to 20 ms	9.999999	0	–	80 to 1000 bytes	10 to 2000 devices/km²	A few m to km	✗
Predictive maintenance(Real-time re-scheduling, Analytics, Rail-support system)	50 to 100 ms	9.999 et 9.9999	<5 km/h	–	40 to 100 bytes	10000 devices/plant	100 to 500 m	✓
Advanced monitoring of assets	50 to 100 ms	9.999 et 9.9999	<5 km/h	–	40 to 100 bytes	10000 devices/plant	100 to 500 m	✗

use cases has led to a sharp increase in the number of applications that can be envisaged in a railway context. For this reason, we have decided to classify the applications in this section into three categories corresponding to the decomposition commonly used for cellular communication networks: voice, data, and IoT. To comply with railway standards, Table 2 specifies whether each application is critical or not. In addition, the main requirements of these applications are also summarized in the table, based on data extracted from various research studies and deliverables of European Projects: [5], [29], [30], [31], [32].

1) VOICE APPLICATIONS

Voice applications are a class of applications using voice to transmit mission-critical information. These mission-critical communication applications are used for ground-to-ground, shunting, and banking communications to coordinate train operations to avoid collisions [33]. Voice application scenarios involve the railway traffic stakeholders such as drivers, controllers, and train users. Calls are coming from the driver to the controllers and vice versa to allow them to exchange rail traffic safety-related information, an emergency voice communication always coming from the controllers to warn drivers about danger, and finally a multi-train-voice communication, a kind of group communication for drivers which can include other railway users.

Both 5G and 5G-R can provide voice application communications. However, due to their limited coverage and weak signal in some rural areas, using satellite networks [34] for voice communications could provide permanent signal coverage for long-distance trains. In addition, various 5G-based positioning combined with satellite navigation systems can realize high-precision positioning for trains.

2) DATA APPLICATIONS

Data applications are the category of applications using the Internet to exchange data between train controllers, drivers, operational centers, and passengers [35]. There are different domains of action of these applications such as the train protection domain, train automation and remote control domain, train surveillance domain, and passenger information domain. The train protection applications are intended to protect the train from accidents by analyzing the external inputs to actuate security maneuvers such as automatic braking, and speed limitation; they also automate the train operations. These applications are automatic train protection communication and very critical video communications with a direct impact on train safety. Train automation and remote control include applications such as automatic train operation communication, on-train telemetry communications, on-train remote equipment control, remote control of engines, and train coupling control. This group of applications enables distributed power sending signals to the remote units via radio or infrared signals transmitted from a device and allows to take control of train equipment remotely. Then there are surveillance domain applications which are Closed Circuit Television (CCTV) and transfer of CCTV archives. CCTV application in railways aims to provide a video surveillance system by transmitting high-resolution images or videos within and outside the train during the train operation for train station surveillance and infrastructure monitoring. The passenger information domain application is the Passenger Information System (PIS) and it concerns all the information that passengers need before, during, and after the journey (*e.g.,* the route of the journey, purchase tickets online, the journey schedule *etc*). This domain also includes, infotainment applications (*e.g.,* video conferencing, chatting on social media, playing music, *etc*). Finally, we have a messaging application which is a kind of short messaging via Internet Protocol between train drivers and controllers.

The requirements of these data applications are complex and diverse. Therefore the implementation of these applications is made possible thanks to the communications technologies mentioned in the subsection II-A2 that support various data communication services. 5G-R is the leading technology among those technologies. The 5G-R network dedicated to railway communications is mainly developed to meet the requirements of railway users in terms of broadband and high data rate services [2], [36]. Due to its characteristics of high-frequency bands and reduced coverage capacity, 5G-R is not suitable for railway line coverage but for communication within railway hotspot areas such as inside the train and rail stations. The future railways' challenges to ensure reliable and available wireless connectivity covers several scenarios, such as continuous coverage along railway lines and stations, monitoring of ground infrastructure, and broadband applications for intelligent trains. Thus, 5G-R is positioned as the key technology in the future railway communication because it offers a wide range of new digital railway services. 5G-R leverages 5G techniques such as network virtualization, Multiple-Input Multiple-Output (MIMO), and Millimeter-Wave (mmWave) to support various data application requirements.

- **Centralized and distributed Massive MIMO:** MIMO technique first, improved cell edge coverage: In cellular communications, the closer the end user gets to the base station, the stronger the signal becomes, and the further away from the base station and towards the edge of the cell, the weaker the signal becomes. Thus, massive MIMO is a technique that allows spatially directing transmissions to concentrate the signal energy toward the end user. This allows for improved performance at the edge of the cell. Secondly, MIMO improves throughput thanks to spatial multiplexing with MU-MIMO, which allows wireless systems to communicate simultaneously with multiple user devices using the same time-frequency resources. Thus, centralized massive MIMO can provide narrow beams with high gain for high-speed train transmissions to improve system capacity. Furthermore, a distributed massive MIMO, which consists of deploying access points along the railway and forwarding data to the central processing unit via fronthaul links, is a promising solution to cope with the rail users' communication quality degradation issues caused by the users' frequent handover and rapid movement [8], [37];
- **Millimeter-Wave (mmWave):** Spectrum scarcity is one of the main problems that still need to be solved entirely for railways. This prompted the exploration of mmWave frequencies utilization in railway communication [38]. mmWave is the high band of 5G that operates on the highest frequencies used in 5G, ranging from 24 GHz to 100 GHz. The advantage of this technology is that it offers a massive amount of bandwidth, which in turn can support transmission peak data rate of several gigabits-per-second for massive 5G-R applications. The disadvantage is that these high frequencies are short-range by nature because they cannot penetrate obstacles such as walls and foliage easily. This requires the deployment of a much larger cellular infrastructure to ensure coverage. Therefore, to face the huge penetration loss and attenuation challenges, the beamforming technique is leveraged to realize high-gain mmWave transmission, and according to the 3GPP TR 38.854, the repeater nodes on top of the train can also be used to improve transmission signal strength. However, mmWave practical implementation faces key challenges, such as the rapidly time-varying channel in high-mobility scenarios and random blockage events in complicated scenarios. In addition, experiments showed that the mmWave network performance decreases with train moving speed due to the Doppler effect [39].

According to the complexity and diversity of future railway applications, future railway communications should be adaptable and able to support multiple access technologies with bearer independence. Thus, the coexistence of advanced wireless technologies in railway communications is important to meet railway operators' expectations. It involves the integration and cooperation of the 5G-R and the advanced aforementioned wireless access technologies such as satellite, WiFi, and DSRC or ITS-G5. 5G New Radio offers a multi-RAT platform to integrate these wireless technologies via its radio interface.

- **Dedicated Short-Range Communications (DSRC):** Shortly, railway transport communication systems will merge with road transport communication systems to form an integrated intelligent transport system. Therefore, 5G-R can integrate DSRC or ITS-G5 V2X technology to support T2V communication and provide a fully connected rail-road transport infrastructure. DSRC is a wireless technology based on the IEEE 802.11p standard, used in the USA as the primary protocol for Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications [40]. This solution in Europe is known as Intelligent Transport System-G5 (ITS-G5). Both protocols are key technologies in Intelligent Transportation Systems (ITS) and operate at the licensed 5.9 GHz band. They can be used within train environments to enable train and vehicle safety communications to avoid collisions at rail-road unmanned crossings or urban tramway scenarios. [28];

- **Wi-Fi:** Nowadays, smartphones and augmented reality applications become pervasive. As a result, rail operators equip their trains and railway stations with public Wi-Fi networks to provide Wi-Fi coverage to train passengers and pedestrians moving around the railway stations. Wi-Fi networks offer multimedia services (information, games, video streaming *etc*) to passengers and railway station pedestrians [41].

3) INTERNET OF THINGS APPLICATIONS

Nowadays, the railway industry is leveraging IoT opportunities to enhance train safety, energy efficiency, and comfort. IoT allows rail traffic operators to embed advanced sensors on mediums like locomotives, train tracks, and platforms to lower maintenance costs and energy consumption to ensure that the traffic is safe, reliable, and seamless [6]. Among the rail IoT applications, we can enumerate the smart infrastructure, a WSN system used to monitor train operations to decrease the risk of train collision, derailment, terrorism, and failure in the wagons. Among the monitored infrastructure, we can list tunnels, bridges, viaducts, rail gaps, *etc*. Applications such as predictive maintenance, energy efficiency, and advanced assets monitoring collect data from WSN and perform data analysis algorithms on collected data to prevent or predict events related to railway traffic safety and optimize resource use. The last IoT application but not the least is the freight information system which allows the use of GPS-equipped sensors to help rail operators in real-time freight movement tracking.

One of the underlying 5G-R cutting-edge techniques is the mMTC for railways also, called Railway IoT, to implement railway IoT application communication. Besides, 5G-R railway IoT, there is the Long Range Wide Area Network (LoRaWAN), another promising IoT technology tailored to support railway IoT applications.

- **5G-R Railway IoT:** IoT in railways automates equipment monitoring by using smart sensors, cameras, and machine vision controls to collect data on tracks, locomotives, trains, and equipment. 5G-R Railway IoT will shortly be crucial to equip massive sensors for comprehensive situation awareness. Since massive IoT sensors are generally less power-hungry and have low power, grant-free random access could be used to reduce signaling overhead. Conventional multiple access schemes cannot support reliable grant-free random access for massive sensors to optimize radio resources. Therefore, non-orthogonal multiple access (NOMA) is leveraged to achieve larger user device access numbers. According to the [42], among the NOMA schemes, tandem spreading multiple access (TSMA) can effectively realize reliable grant-free random access for massive railway IoT devices.
- **Long Range Wide Area Network (LoRaWAN):** LoRaWAN is an LPWAN communication protocol that uses LoRa (Long Range), a wireless access technology used to collect data from IoT infrastructure and send it to the remote IoT platforms [43]. In the context of smart railways, LoRaWAN is one the best candidate technologies because it offers low power consumption, long battery life, and cheap IoT sensors tailored to railway intelligent monitoring requirements. LoRaWAN technology can be applied to railway IoT applications for predictive maintenance, remote freight tracking, smart metering, intelligent power supply, and advanced monitoring of assets. Its use can be extended to other applications related to train operations such as track monitoring, supervision of train doors, pressure in air conditioning units *etc.*. One of the practical use cases of LoRaWAN in the railway industry is that of the French National Railway Company (SNCF), which is deploying IoT technologies using LoRaWAN communication protocol to centralize and send the data measured by onboard sensors to the railway monitoring and maintenance centers. Thus, many sensors onboard SNCF trains collect data on the state of each wagon and other facilities and forward the data to the centralized IoT platforms through LoRaWAN technology [44].

C. ENABLING TECHNOLOGIES

In this section, enabling technologies for future railway applications are introduced: MEC, SDN, NFV, NS, Blockchain, and AI.

1) MULTI-ACCESS EDGE COMPUTING (MEC)

MEC represents a transformative paradigm in network architecture by bringing computation and data storage closer to the edge of the network infrastructure [45]. This architectural shift is driven by the need for reduced latency and enhanced real-time processing capabilities, which are critical for emerging technologies like augmented reality, autonomous vehicles, and the IoT. MEC operates by distributing computing resources to edge locations, extending the Cloud closer to end-users and connected devices. This proximity not only reduces latency but also minimizes backhaul traffic, optimizing the utilization of network resources. MEC's benefits extend to various sectors, including telecommunications, healthcare, and industrial automation. Telecom operators can offer low-latency services, while healthcare providers can support remote patient monitoring and real-time diagnostics. In industrial settings, MEC facilitates responsive automation and predictive maintenance. However, MEC only offers finite computing resources at the edge, and interactions with Cloud Computing (CC) are crucial [46]. By seamlessly integrating MEC with the Cloud, organizations can overcome these limitations. Cloud computing provides unlimited data storage and computation resources, enabling MEC to offload tasks to the Cloud when local edge resources are insufficient. This synergy between MEC and the Cloud creates a robust ecosystem where real-time processing occurs at the edge. In contrast, the Cloud offers scalability and extensive resources, ensuring that even the most demanding applications can be efficiently supported.

Some research studies have focused on the application of MEC in railway communications. Xu et al. [16] investigated the impact of handovers on high-speed railway communications and proposed a graph-based model to portray the resource availability in the network. Furthermore, they have defined a heuristic algorithm to find a set of single-source-single-destination delay-constrained shortest paths in a series of auxiliary graphs. In [47], authors proposed an edge computing-aided real-time detection framework for traction systems in high-speed trains. Moreover, Wu et al. [48] combined edge computing, deep learning, and IoT technology to build a 3D model of railway station equipment and real-time data collection and analysis. The built model can propose a reasonable line planning scheme to provide a reliable basis for engineers to plan railway transportation lines and improve design efficiency. These different research works, therefore, show the relevance of integrating this technology into the railway environment.

2) SOFTWARE DEFINED NETWORKING (SDN)

SDN is also an enabling technology for future railway applications. It decouples the network's control plane from the data plane [49]. In traditional networks, control functions are tightly integrated into individual network devices (routers) using distributed algorithms, limiting flexibility and manageability. On the other hand, SDN centralizes network control through a logically centralized component known as the SDN controller [50]. This controller has a global view of the network and can programmatically instruct network devices, such as routers and switches, on forwarding data. Different tools/languages/protocols, including OpenFlow and P4, can enable this management [51]. By separating the control and data forwarding functionalities, SDN offers several benefits. It enhances network agility, allowing for dynamic and global reconfiguration of network resources to adapt to changing traffic patterns (*e.g.,* traffic redirection). SDN also simplifies network management, reducing operational complexity through centralized control and automation. Additionally, it improves network scalability, making it easier to accommodate growing demands (*e.g.,* efficient load balancing).

In the same context of applying SDN to the railway communication networks, Franco et al. [52] designed a railway-to-ground communication architecture based on the 5G SDN enabler and on-the-transport level redundancy technique multipath TCP (MPTCP) to provide an adaptable and multi-technology communication service while enhancing the network performance of current rail systems. To enhance the robustness of the control network for Chinese Train Control System Level-3 (CTCS-3), the authors in [53] proposed a centralized ring redundant link failure failover management scheme based on a software-defined networking architecture using an OpenFlow protocol and a POX controller. In [54] Gopalasingham et al. proposed the architecture and use cases of an SDN-controlled mobile backhauling framework for a train-to-wayside communication system for the first time. Furthermore, they have discussed how the proposed architecture can efficiently handle mobility management and provide QoS for different onboard services. In addition, the coexistence of railway and road services by sharing the same telecommunication infrastructure using SDN-based slicing has been explored. Based on the ONOS SDN controller, Singh et al. [55] provide detailed instructions for creating network topology using Mininet-WiFi that can mimic real-life coexistence scenarios between railways and roads.

3) NETWORK FUNCTION VIRTUALIZATION (NFV)

NFV brought a significant shift in network architecture [56], wherein traditional network functions are transformed into software-based virtual instances. This innovation allows these Virtualized Network Functions (VNFs) to be deployed on standard servers, optimizing resource utilization and substantially reducing hardware costs. Routing, load balancing, and firewalling are some examples of potential VNFs. The advantages of NFV extend to service providers as it enables the rapid deployment and scaling of network services, significantly enhancing agility in adapting to evolving network demands. Operating at its core, NFV replaces dedicated hardware appliances with VNFs, which can be dynamically orchestrated (NVF orchestrator [57]) and scaled to maximize network performance, resource allocation, and cost-effectiveness. This transformation streamlines operations and paves the way for innovative and efficient network management strategies. Besides, research has been conducted into the benefits that NFV offers to modern railway communications systems. In [7] authors address some ICT challenges to support future railway systems. Based on NFV and SDN, they proposed a dynamically re-configurable advanced communication platform enabling connectivity between various monitoring devices and computational resources through a heterogeneous network infrastructure. The benefits of the proposed platform in the end-to-end service delay and power consumption are quantified over the 5G Bristol open network topology. Moreover, Ruscelli et al. [14] have discussed and proposed adopting the SDN/NFV framework in railway control networks. In particular, some possible promising directions of investigation are drawn considering service orchestration and edge-based NFV services.

4) NETWORK SLICING (NS)

NS is a fundamental concept in the FRMCS network architecture and is prominent within 5G enabling technologies. The

5G-R, built on 5G technology, has the overarching objective of enhancing railway services and improving communication performance for operational and passenger-centric applications. However, network resources and the amount of spectrum assigned to FRMCS may likely not be enough to meet all of the railway industry's requirements. This is where NS comes into play to allow communication service providers (CSPs) to simultaneously deliver the required service capacity and stringent service level agreements (SLAs) for railways. Therefore, The 5G-R network can use the same network infrastructure to implement multiple network slices to develop a comprehensive end-to-end network slicing of the railway-dedicated communication network. Rail applications with different requirements, such as train coupling, emergency communications, high-definition video surveillance, automatic train operation, and railway IoT, can use customizable network services to guarantee the expected QoE. Thus, in a railway context where applications have diverse QoS requirements, some applications need high data reliability and low data rate while others need ultra-low latency and a high data rate. To guarantee QoS in the railway communication network environment, NS seems to be the best solution capable of satisfying each application requirement while using the same hardware and software infrastructure. Three main classes of services are defined in 5G: URLLC, evolved Mobile Broadband(eMBB), and massive Machine-Type Communication (mMTC) [58]. In connected trains, the three main services have to coexist *e.g.,* URLLC is tailored to critical safety applications, eMBB for railway multimedia applications, and mMTC corresponds to train and infrastructure monitoring applications. In this context, it is difficult for a single Radio Access Technology (RAT) to offer these services. Besides the variety of services, 5G and 6G come with some RATs under their umbrella, such as Cellular Networks, DSRC or IEEE OCB (known as ITS-G5 in Europe), and LPWANs (*e.g.,* LoRaWAN, NB-IoT). Therefore, NS in the 5G context is the promising solution that could provide many kinds of network slices tailored to the railway transportation service specific requirements: eMBB, URLL, and mMTC *etc.,* in a Multi-RAT architecture [59]. NS enables network isolation, thus making the network more robust against attacks. Implementing network slicing in the railway domain under 5G could face many challenges, such as ensuring the continuity of QoS in the context of Multi-operators (*i.e.,* how to maintain QoS once the train shifts to another operator radio access technology [60]).

5) BLOCKCHAIN

From a security perspective, Blockchain could appear as a required technology for future railway applications [61]. Blockchain relies on a decentralized and distributed ledger system. It records transactions (data, certificates, *etc.,*) across a network of computers (Blockchain nodes), ensuring transparency, security, and immutability. Unlike traditional centralized systems, where a single entity controls the ledger, Blockchain operates on a peer-to-peer network. Each participant, or node, holds a copy of the entire Blockchain. Transactions are verified and added to blocks through a consensus mechanism, often using complex cryptographic algorithms, which makes the system resistant to fraud and tampering [62]. This combination of decentralization, cryptography, and consensus mechanisms extends the applicability of Blockchain beyond finance, finding uses in supply chain management, healthcare, voting systems, transports, and various other domains where secure and transparent record-keeping is essential.

Like previous enabling technologies, research has also focused on the potential use of Blockchain in railway applications. Thus, Naser in [61]conducted a literature review using blockchain in different industries, particularly IoT applications, and in the railway context. Opportunities and challenges that blockchain technology can offer for the railway industry have been outlined. To overcome some of the adoption rate barriers in the railways, the author has developed a solution called inspector, which is a speech recognition and mobility-based interface that can be utilized across different transport organizations, which can help in the data collection and pave the way for blockchain applications. The article of Liang et al. [63] focuses on the current prospects, case studies, and future challenges of blockchain-empowered urban rail transit (URT). Furthermore, a concrete case study of using blockchain in a distributed authentication scheme for URT is described. Test results showed that the proposed blockchain-based distributed authentication scheme can enhance the security of the train control system without sacrificing communication performance. Preece et al. [64] introduced a novel digital ticketing platform using blockchain technology in railway ticketing systems. IBM's Hyperledger Fabric framework designs an architecture that distributes the tickets across all participating organizations. In [65] the author leveraged blockchain technology for railway traffic conflict resolution. To ensure both operator and passenger satisfaction, he proposed a novel blockchain-enabled virtual coupling of automatic train operation fitted mainline trains for railway traffic conflicts. Based on the simulation results, the author showed that the significant advantage of the proposed study is that it can be an overlay to the existing European Railway Traffic Management System Level-2.

6) ARTIFICIAL INTELLIGENCE (AI):

AI tools will also play an important role in the flexibility of railway connectivity [66]. It is a transversal tool that can be applied to all the technologies described above and to the different levels of the architecture. Many tools are available today for implementing AI solutions: fuzzy logic, decision trees, Machine Learning, Deep Learning, *etc*. The level of performance of these tools varies, but their objective is the same: to offer the possibility of automating one or more decision-making processes. The reduction in costs associated with computing power today makes it possible to deploy AI solutions at different levels: in the network core, at the network edge, or even at the level of the terminals themselves. Therefore, numerous potential applications can correspond to any of the technologies already described in this section. Consequently, we can imagine using such approaches to optimize network operation and automate redefinition in real-time (complementary to SDN and NS). Similarly, the management of available resources, both for network functions (NFV) and applications (MEC), could also be improved through intelligent decision-making processes. AI tools could also play an important role in security solutions (Blockchain), particularly in detecting anomalies or intrusions. In summary, AI's integration into network management could be a pivotal development, offering efficiency, security, and scalability [67].

In addition to the above, many field examples show that AI improves railway safety and passengers' comfort by minimizing the risk of human error. As railway systems are modernized, automated signaling systems, including driverless trains, are being adopted with AI integrated with IoT to improve safety and efficiency. Equipped with AI-powered cameras, these AI systems can capture images and data to identify obstacles that allow operators to take maintenance and corrective measures in real time. They can also review track conditions and inform operators of any anomalies that affect safety and prevent potential derailments. Thus AI is involved in improving the safety and experience of passengers and operators. A recent example is the Namo Bharat, an Indian Electric Multiple Unit (EMU) train designed by the French rolling stock manufacturer Alstom to reduce travel time by 40% i.e. from 100 to 60 minutes, thereby allowing passengers to spend less time thanks to AI, which is being leveraged in train safety, planning, and speed management. Based on real-time data analysis, AI algorithms can adjust train schedules to account for unforeseen disruptions or changes in passenger demand. Another example is the SNCF, which uses AI-based predictive maintenance on Transilien commuter trains in the Paris region (SNCF, 2024). Furthermore, some research has focused on the use of AI in the railway communication system. Authors in [68] investigated a high-speed smart railway network power allocation algorithm based on multi-agent deep recurrent deterministic policy gradient (MADRDPG). Numerical results show that the performance of the MADRDPG-based method significantly outperforms existing state-of-the-art methods in terms of spectrum efficiency and execution latency. In the same context of smart high-speed railways Zhou et al. in [11] proposed Conv-CLSTM, a novel spacial-temporal channel prediction model that combines the convolutional neural network (CNN) and convolutional long short-term memory (CLSTM). The model is evaluated in terms of prediction accuracy and space and time computational complexity. The evaluation results show that the proposed model has high prediction accuracy but acceptable computational complexity.

III. A RAILWAY ARCHITECTURE INTEGRATING 5G ENABLING TECHNOLOGIES

A. ARCHITECTURE OVERVIEW

We propose the following railway communications architecture depicted in Fig. 2. The design should meet the requirements and challenges described in the previous sections. This architecture also supports enabling technologies to coordinate, manage, and optimize railway network resources. The architecture is divided into three layers: 1) the infrastructure layer, 2) the control layer, and 3) the application layer. An overview of this architecture is shown in Figure 2 and the various components are presented in the following sub-sections.

1) INFRASTRUCTURE LAYER

The railway telecommunication infrastructure can be split into three main parts: the Multi-access radio, which comprises satellite or terrestrial communication systems and end devices, the backhaul/core network, and the cloud. The access networks enable communications between end-user devices such as trains and rail users to a wide area network that gives access to Cloud-based rail and business applications. To access the cloud services, the access network environment is made of multi-access radio technologies that provide reliable and high-speed connections, making the access networks an important component of the infrastructure layer. The used wireless access technologies are cellular (4G, 5G) [2], [72], [73], the WiFi (ITS-G5) [28], the satellite [74], [75], and LoRaWAN. These technologies' main characteristics are summarized in Table 3 [76], [77], [78], [79], [80], [81]. Each technology has a base station or an access point to relay information from the end devices to the cloud through the transport and core networks. Communication links between trains and base stations can be direct (T2I) or indirect (T2T), meaning a train can use multi-hop communication (a train using other trains as relays) to access the network. Direct communication between trains (T2T) without infrastructure or APs could be considered using 5G PC5 communication links. In addition, railway communication systems may be combined with road communications systems to form an integrated network that leverages sidelink communication technologies such as ITS-G5 or 5G PC5 for Train-to-Vehicle (T2V) communication around rail-road intersection areas.

Therefore, trains are considered end devices that communicate with each other, as well as the infrastructure and surrounding objects such as IoT devices. LoRaWAN [82] technology is deployed to assure railway secure IoT communications. IoT communications are crucial for modern railway communications because IoT devices are facilities for rail in-train and outside-train environment-sensitive data collection. The collected data is related to the train speed, position, ambient temperature, engine status, level crossing status, track conditions, freight tracking, *etc*. Furthermore, the access technologies provider can be a public or private entity. In our architecture, the use of Software Defined

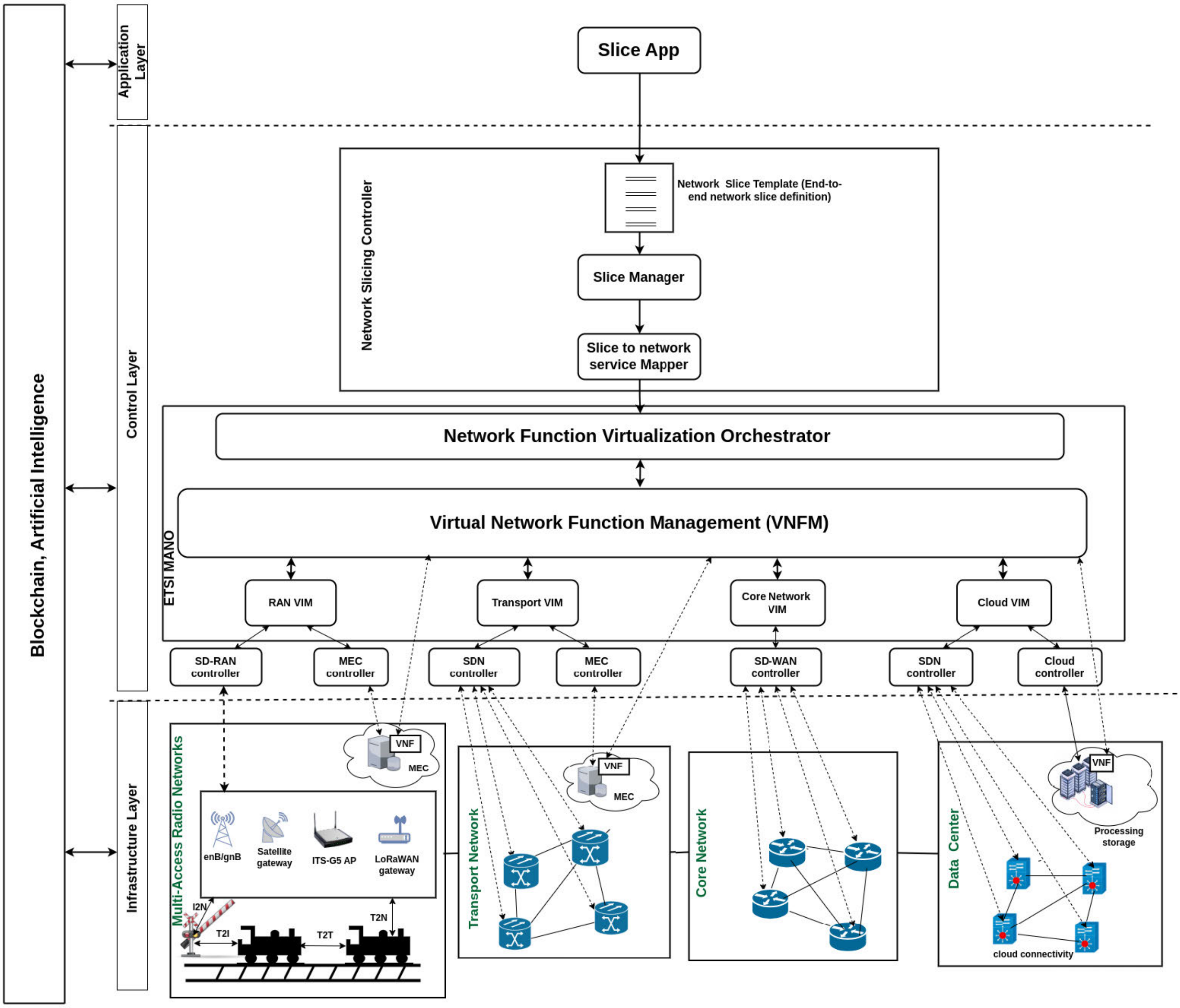

FIGURE 2. Network slicing for railway communications with unified SDN/NFV control framework.

Radio (SDR) [83] and other open hardware platforms can be considered an alternative means to create private rail networks for transmitting and receiving radio signals, giving more flexibility in network configurations.

As mentioned above the aim of these wireless communications is to give access to the rail cloud-based applications hosted in a data center. The data center is a set of networked computer servers hosting railway remote applications and traffic management service applications. Connected trains can therefore exchange data with cloud application servers containing useful information for rail traffic. Applications such as remote monitoring, traffic management services, voice and video communication applications, and multimedia services for train users are accessible to the train and traffic monitoring services from data centers via the Internet. Depending on the rail operator, the cloud domain can be private, public, or hybrid [84].

2) CONTROL LAYER

Above the infrastructure layer, the control layer consists of the ETSI Management and Orchestration framework (MANO), multiple heterogeneous SDN controllers, and the network slicing controller:

- **ETSI MANO**: To provide NFV management and orchestration functionalities, we use an ETSI MANO [85] within the control layer of our architecture. The MANO aims to perform configurations and optimize virtual and physical resources to guarantee QoS requirements for each slice. It includes:
  - **VNFs:** VNFs represent virtual network functions deployed on commodity hardware (*e.g.,* virtualized switches, routers, and firewalls);
  - **NFV Infrastructure (NFVI):** NFVI is a set of physical infrastructure (compute, storage, and

TABLE 3. Main characteristics of wireless access technologies that could be applied to rail.

Technology	Max Range	Data Rate	Enabled Topology	Bandwidth	Max Latency	Usage	RAN Manager	Open Hardware Platforms	Rail Applications
WiFi [69]	Up to 1 km	up to 1300Mbps	star	320 MHZ	40 ms	Access points, User equipment	Public	PC + Wifi card, PC + SDR	CCTV communication service for surveillance cameras, Multimedia and entertainment, Passenger Information System (PIS), Transfer of CCTV archives
LoRaWAN [70]	Urban: 5 km, *rural: 15 km	0.3–50 kbps	Star-of-Stars	125-500KHz	<400 ms	Sensors, Gateways	Private	PC+ Dragino LG308 +Arduino Transceiver Shield	Predictive maintenance, Freight tracking, Smart metering, Intelligent power supply, Advanced monitoring of assets
5G [71]	Up to 12 km	Up to 20 Gbps	Cloud-based star topology	50-400MHz	1-10 ms	Train, gnBs, Sensors	Public, private	ETTUS USRP + B210 or X210 Boardand and OAI SIMcard	Train coupling, Automatic Train Protection, Railway emergency voice communication, Automatic Train Operation, On-train remote equipment control, Remote Control of engines, Critical video communication for observation purposes, Control of automated trains, Very critical video communication with a direct impact on train safety, Very Critical data communication, Multimedia and entertainment, Predictive maintenance, Advanced monitoring of assets, Freight operation management, Intelligent power supply
5G-R [2]	Up to 6km	Uplink: 50 Mb/s Downlink: 200 Mb/s	Cloud-based star topology	10–20 MHz; possible 100 MHz at higher frequency bands	50–500 ms	Railway Infrastructure	Private	–	Train coupling, Railway emergency voice communication, Automatic Train Protection, Automatic Train Operation, On-train remote equipment control, Remote Control of engines, Critical video communication for observation purposes, Control of automated trains, Very critical video communication with a direct impact on train safety, Very Critical data communication, Multimedia and entertainment, Predictive maintenance, Advanced monitoring of assets, Freight operation management, Intelligent power supply
ITS-G5 [71]	Up to 1 km	3-27 Mbps	Mesh	10 MHz	50 ms	Trains, Roadside Units	Public, Private	–	Cooperative Awareness Messaging (Level crossing warning)
Satellite [69]	36000 km (Geostationary orbit) 500-2000 km (Low Earth Orbit)	Up to 1Gbps 50-400Mbps	Star	C, Ku, Ka bands (4-30 GHz) Ku, Ka, V bands (12-75 GHz)	800-1600 ms 40-150 ms	Trains	Public	–	Messaging, Standard data communication, On-train outgoing voice communications, Multi-train voice communication for drivers including ground user(s), Railway emergency voice communication

networking) and software where VNFs are deployed, managed, and executed [86];

- **VIM:** is responsible of controlling and managing NFVI resources. Available VIM solutions include OpenDayLight [87] and ONOS [88] as SDN controllers, OpenStack [89] and Amazon Web Services (AWS) [90] as cloud operating systems;
- **VNF Manager (VNFM)** responsible for configuration and lifecycle management (instantiation, update, scaling, and termination) of VNF instances running on top of virtual machines or containers;
- **NFV Orchestrator (NFVO):** NFVO also known as an NFV network service orchestrator is responsible for the orchestration of NFVI resources across multiple VIMs and lifecycle management of network services to deliver end-to-end connectivity (service function chains) and network slices.

In addition to the aforementioned functional blocks, ETSI MANO comprises four repositories to store management and orchestration data [91]. These repositories are **NFV Service** a set of predefined templates which specify the procedures of service on-boarding, creation, and termination; **NFV Instance** stores information related to virtual network functions and services; **NFVI Resource** is used to store all information regarding the NFVI; and the **VNF Catalogue** a set of templates that describe the attributes of VNFs.

- **SDN Controllers:** SDN enables the separation of the control plane from the data plane by moving the control capability to a centralized entity called the SDN controller. This makes switches and routers behave as simple forwarding devices, whose actions are programmed SDN controllers through protocols such as OpenFlow [92]. In the field of connected trains, where the network topology changes very fast due to the speed of communicating nodes, SDN technology offers considerable advantages in routing path selection, connectivity situations, and frequency or channel selection [52]. This may involve establishing connections between different access network elements, managing IoT communications, or even communications within the satellite network. In this architecture, SDN controllers are allocated to manage specific network segments, such as the fronthaul, backhaul, core, and data center. First, an SD-RAN is assigned to manage the access networks. SD-RAN is a centralized unit that detaches the monolithic RAN control and enables cooperation among RAN components such as base stations. A centralized SD-RAN controller offers flexibility in RAN resource allocation. Depending on the current spreads of the end users across base stations and their channel status, the SD-RAN controller can reallocate resources accordingly. Hence, compared to the traditional RAN approach, a centralized SDN-RAN approach improves performance (i.e. maximizes throughput) as it allows for optimal allocation decisions [93], [94], [95]. Secondly, SDN controllers are deployed at the transport network domain and within the cloud to flexibly manage the transport network and cloud connectivity (data center) data flows [96], [97]. Finally, an SD-WAN controller is assigned to the core network (Wide Area Network) to manage data flow at that network segment. Given that WAN is a large network, deploying an SDN controller requires partitioning the network into geographically smaller networks for privacy, scalability, security, deployment, and other reasons.
- **Cloud Controller:** The cloud controller manages services such as system-wide arbitration of resource allocation, handling authentication, governing of persistent

data and system user, and protocol translation for user-visible interfaces. It supports the lifecycle of service orchestrator and service instances such as runtime, deployment, and provisioning. Thus, the Cloud controller provides the Cloud service manager and service orchestrater APIs to interact with the underlying infrastructure [98]. As for *MEC controller*, it plays the same role as the cloud controller but at the edge cloud.
- **Network Slice Controller:** The slice controller provides a framework for slice template definition, processing, mapping, and managing the slice's life cycle. It takes slice creation specification from the *Slice App* as input, processes it, and sends it as an output to the MANO orchestrator. It comprises network slice templates, a slice manager, and the slice-to-network service mapper.

3) APPLICATION LAYER
The application layer is the topmost layer in the proposed architecture. This layer provides interfaces to interact with the bottom layer (control layer). It aims to provide an application programming interface to configure and automate the slice creation. Therefore, it allows the slice owner to provide a high-level description of the environment he needs by specifying the physical, virtual, or emulated resources, and connectivity between the components and the required VNFs. This is done using the end-to-end network slice definition API.

B. ARCHITECTURE IMPLEMENTATION
After presenting the different layers of the proposed architecture in section III-A, this section aims to understand how the different technologies identified (MEC, SDN, NVF AI tools, Blockchain) can be deployed at the different layers of this architecture to ensure optimal operation.

1) COMPUTING SERVERS DEPLOYMENT
MEC servers are deployed closer to the end nodes (trains, passengers, mobile phones, *etc.,*) in all nodes with computing power. They can be placed inside the trains, in the mobile and satellite base stations, and in the core network. Different MEC deployments may involve different constraints. For example, deploying MEC servers in a satellite will consume more power and reduce the satellite lifecycle, given that satellites have limited energy. To comply with limited energy constraints, an edge server in a satellite will have very little computing power. On the other hand, in areas with poor coverage, this may be a solution that allows the train to offload data processing. For the terrestrial system, the computing power used for trains could be deployed inside the train or at specific base stations. In this context, the cost could be a limiting factor because it would require the operator to deploy base stations equipped with MEC everywhere. Finally, we can also leverage MEC technology in the core network. Deploying MEC servers in the core increases not only computing power consumption and latency because the core network is usually located far from the end nodes. Therefore, multi-layered edge computing architecture aims to find a compromise between all these deployment types to provide continuous computing capacity for the train [47], [99];

2) QUALITY OF SERVICE (QOS) MANAGEMENT
Each level or layer of the network must be able to meet the different QoS requirements of applications. The network slices concept is suitable for this architecture and capable of delivering various QoS solutions to meet this challenge. Network slices we would like to implement span the whole network protocol stack from underlying hardware up to the VNFs and applications running on top. We consider a network slice as a set of appropriately configured network virtual functions, network applications, and the underlying physical and cloud infrastructure (physical, virtual, emulated resources, *etc.,*) packed together to meet specific use case requirements. More details on network slicing towards 5G and 6G networks are given in [100] and [101].

To meet the railway applications' QoS requirements, three types of end-to-end logical networks or slices can be orchestrated on top of the physical infrastructure to enable efficiency spectrum and resource allocation tailored to each application category. The first slice will provide URLLC service to railway safety-critical applications such as Automatic Train Protection communication, Automatic Train Operation communication, Very critical data or video communication, automated train control, train coupling, *etc.* The second slice will be in charge of IoT applications to satisfy mMTC QoS requirements. Applications involved in this type of slice are predictive maintenance, smart metering, freight operation management, intelligent power supply, and advanced assets monitoring. The third slice will provide eMBB service to non-safety applications such as Multimedia and entertainment, Passenger Information Systems, transfer of CCTV archives, standard data communication, remote control of engines, *etc.*

It is to define slices at the RAN level to respond to the QoS requirement at the radio access level, then slices at the edge level for QoS provisioning at the edge, then at the core layer of the network, and finally at the cloud layer to manage cloud applications access QoS requirements. This will make it possible to manage the provision of QoS at each network layer. Depending on the required quality of service and the targeted layer, the operator can decide which part of the network should be partitioned. The slicing architecture could be distributed, i.e., a slicing that covers the end-to-end network with a general orchestrator that manages the local orchestrators. The local orchestrator is in charge of a certain layer slice management and submits slice creation requests to the general orchestrator, which is responsible for adding the created slice to the network. So, it coordinates all the slices and is responsible for updating them.

3) SECURITY SERVICE MANAGEMENT

Blockchain is a cross-layer technology applicable to infrastructure, control, and application layers in the proposed architecture. It is a relevant solution for providing security even without connectivity or in the presence of different heterogeneous/competitive systems (*e.g.,* multiple operators) [102]. However, Blockchain can impose constraints in terms of data storage and processing, both to guarantee consensus and to maintain stored information. As a result, deploying this technology does not seem feasible at all levels. For example, deploying the technology in the satellite segment seems complex, given this environment's energy, processing capacity, and communication constraints. The preferred levels, therefore, appear to be the cellular access network, which can guarantee distributed security [103], [104], [105], the core network, and the upper layers of the satellite system. The idea is, therefore, to propose a Blockchain architecture that 1) enables information to be processed as low down the architecture as possible to guarantee a high level of security and 2) combines different types of deployment depending on the type of need and potential constraints in terms of number of users, latency, and so on. Today, private or consortium blockchains such as Hyperledger Fabric seem to be the most suitable for railway communication networks. Indeed, this approach could enable the rail operator and its partners (network operators involved in communications, for example) to determine which nodes can be integrated into the Blockchain network to secure the network. As a result, consensus between the various network nodes can be one of the protocols commonly used in private networks, such as Practical Byzantine Fault Tolerance (PBFT). Another important point is that the multi-layer (Cloud, Edge, *etc.,*) and multi-application (real-time or not) rail environment will require considerable thought to be given to positioning Blockchain nodes. Those reserved for system security will find their place in the Cloud or Edge layer to guarantee their operation. However, real-time data validation may, for specific applications, need to be deployed on terminal equipment. Similarly, data updating and retrieval could be carried out directly at the base station level for applications such as communication channel management. Work from the vehicular environment could be used for this type of application.

4) SOFTWARE-BASED SERVICE DEPLOYMENT

Several VNFs in railway communications, such as switching functions (routers, Broadband Network Gateway), security functions (firewall, intrusion detection systems, virus scanners), Service Prioritization Function (SPF), Remote Control Function (RCF), Video DECoding function (V-DEC), load balancing function, *etc*, can be deployed on generic hardware at the rail user segment, terrestrial segment, or space segment; or at the core network or cloud layer. These will, therefore, replace the network functions usually deployed in specific equipment: routers, switches, firewalls, load balancers, *etc*. NFV can be useful at all levels. We can virtualize a satellite, a core router, and the functions of a base station. This allows for simpler scaling up for the operator and immediate updating of different functionalities. Introducing NFV in railway networks enables flexibility and scalability in network management and dramatically reduces network resources, capital, and operational expenditures. It also offers an advantage in addressing the challenge of managing and operating complex and heterogeneous railway network infrastructure [7], [106];

5) DECISION-MAKING PROCESS MANAGEMENT

Instead of relying only on cloud facilities for data process automation and analytics, artificial intelligence or machine learning programs can be installed in the train's onboard servers or edge servers to enable latency-sensitive decision-making. The potential applications of AI tools today seem unlimited and can be applied to any application. As a result, using this technology at all levels of architecture is the approach that will eventually emerge. As shown in [66], [68], and [107], many railway applications involve AI. AI tools could be applied to the infrastructure, control, and application layers in the proposed architecture, which makes it a cross-layer technology.

C. APPLICATION OF ENABLING TECHNOLOGIES TO EXISTING RAILWAY APPLICATIONS

Having presented the integration solutions considered in the architecture for the various technologies in section III-A, the idea now is to look at the potential benefits and uses of these technologies. A summary of the use of the emerging technologies for railway applications is provided at the end of the section in Table 4.

1) COMPUTING SERVERS USE CASES

The proposed data processing architecture appears to have two potential applications for railway applications:

- Multimedia Service Provisioning: This corresponds to any multimedia service, whether in 1) upload (video and image data compression) or in 2) download (Content Caching). In case 1), Edge Computing will primarily aim to reduce the amount of information passing through the core network of the railway communications infrastructure. This will maximize the available bandwidth and avoid congestion leading to latency. Data compression algorithms will be implemented at the Edge to achieve this goal. In case 2), the idea will be to bring the service as close as possible to the end-user, for example, Augmented Reality for both train driver and passenger applications. The idea will, therefore, be to store relevant content at edge level before use, depending on the current scenario (*e.g.,* breakdown and provision of pertinent information to the person on the train) or the popularity of content aimed at passengers. Remote Driving (video transmission to remote operator), CCTV (case 1), and Multimedia and entertainment solutions (case 2) are examples of applications in this context [108], [109];

- Data Processing: This concerns any raw data collected from the train sensors and cameras, which are filtered, sorted, processed, analyzed, and then made quick decisions on a local edge server instead of forwarding raw data to a server located in the cloud. This will avoid overloading the core network data traffic, which frees communication links to other safety-critical applications such as remote driving and control. It also offloads resources for non-critical applications communication (*e.g.,* passenger applications). This will reduce latency and optimize the utilization of available bandwidth and resources. This service benefits freight trains, given that it is well suited to rail IoT applications such as smart metering, advanced monitoring of assets, and autonomous train control [45], [110].

2) NETWORK MANAGEMENT USE CASES

The proposed SDN architecture could offer two types of services for railway communications scenarios:

- Network Optimization: This type of service may be provided by the various SDN controllers. They manage flow control for the network to improve network management and application performance. The SDN controller dynamically injects data transfer policies into the switches. Using the SDN controller will enable rail networks to be managed dynamically to ensure load balancing, network resilience in the event of failure, and prioritization of data traffic, optimizing network hardware resources and application performance. This is true regardless of the type of access network considered and can also be used at the IoT level. Such network performance optimization is beneficial because it guarantees efficient bandwidth management, low latency, fine-tuned service management, and flexible, real-time service redefinition. All railway applications, especially those with high latency requirements, can benefit from this service [111], [112];
- QoS Management: The ability offered by SDN to manage traffic flows (network optimization) is also associated with another possibility: that of finely managing data flows (by application, by the user, by packet, *etc.,*) and thus reserving resources for each of these flows. This means that SDN technology can dynamically manage different applications' QoS requirements to guarantee their latency or bandwidth needs. Such a property would be particularly beneficial for mission-critical applications, for which sufficient resources must be systematically reserved, particularly in emergency scenarios [111], [113].

3) SOFTWARE-BASED DEPLOYMENT USE CASES

NFV and Network Slicing integration in the railway architecture could provide two main services to railway networks:

- Network Functions Lifecycle Management: This service is related to the NFV concept, which replaces network appliance hardware with Docker containers installed on a Docker engine. This allows VNFs to be managed flexibly. It provides network function lifecycle management, given that scaling the network architecture with Docker containers is more accessible, flexible to manage, and does not require additional hardware purchase. Docker containers can be installed on servers on an edge or a cloud layer to implement dynamic updates, deployment, and dynamic scalability management. The advantages of this service for railway applications are the flexibility of updates and deployment, virtual isolation over a single infrastructure, and cost reduction (capital expenditure - CAPEX and operational expenditure-OPEX) [114], [115]. This can be beneficial for all rail applications.
- QoS Management: Just as SDN enables network management, NFV enables the management of the physical infrastructure and the allocation of resources to the various services deployed. Depending on the needs and priority level of a given application, it is possible to allocate a variable quantity of resources to it: storage, computing, memory, and so on. NFV, therefore, offers a flexible solution for managing the resources available and is thus able to guarantee the smooth operation of railway applications, especially critical ones, even in a context of performance degradation (*e.g.,* server failure) [116];

4) DECISION-MAKING PROCESS USE CASES

Regarding security, we can leverage Blockchain, SDN, NFV, NS, and AI for the following services:

- Network-based security: From the network security point of view, the SDN controller offers the possibility of filtering packets or data generated by specific users/applications (possibly intelligently by integrating AI tools or other algorithms). This provides security services such as malicious packet dropping and firewalling to all railway applications [117], [118];
- Application-based security: NFV aims to ensure service isolation - physical resources are reserved for a given application and cannot be used by another application. As a result, the fact that virtual equipment dedicated to a given application is attacked should not, in theory, have any impact on equipment belonging to other subnetworks. This isolation can reinforce the security of the railway architecture as a whole. What's more, the ability to update the various services deployed via NFV orchestration also constitutes a rapid and effective solution if a vulnerability or threat is detected. NFV could enhance the security of the entire system [119];
- Blockchain - a global security solution: While SDN and NFV technologies focus on specific networks and hardware levels, Blockchain can be seen as a global solution for securing rail communication networks.

Let's consider a rail operator on its own. Blockchain can enable it to manage its infrastructure in a distributed way, whether this involves managing routing tables for its routers with secure updating (thus usable in the SDN service), updating its application services (therefore usable in the NFV service), or allocating resources, processing edge data and merging operator data. This distributed management can eliminate the need for a single point of failure in the network and thus provide a better response to attacks and potential failures. It may also provide a solution for enabling data access even in the event of a temporary loss of connectivity (deployment of Blockchain nodes within network edge servers). Blockchain can therefore guarantee the security not only of data storage but also of data processing and updating by relying on the Smart Contracts supported by most existing technologies, especially those designed for private use cases [120]. However, the full potential of Blockchain becomes apparent when we consider rail networks as a whole: potentially hosting different operators (cellular networks, IoT networks, satellite networks) who may need to reach agreements. Such a situation may arise when 1) these operators share the same base stations, and the allocation of resources to each of them needs to be dynamically redefined (*e.g.,* at a border), 2) when the operation of the rail operator's network relies on nodes outside its infrastructure (satellites, for example), 3) when the railway operator needs to extend connectivity and 4) when the railway operator is not able to provide enough computing/storage resources [121]. In this context, the implementation of a solution enabling the various operators to reach an agreement seems essential: Blockchain is then a relevant answer. It can allow each operator to keep control of these resources while also ensuring that other operators do not try to manipulate the resources allocated, the price set, or the Quality of Service offered. As a result, it enables agreements between operators to be reached efficiently, securely, in real-time, and automatically (using smart contracts). This comprehensive solution for rail network security enables rail operators to secure both their internal network (data processing, storage, and transmission) and external communications (exchanges with other operators). The potential of this technology, now increasingly used in conjunction with AI tools [122], is therefore great.

5) DECISION-MAKING PROCESS USE CASES

AI is a generic or umbrella technology that can be applied to all the cases described in this section. It makes it possible to analyze data, which is useful for any kind of service requiring a decision-making process. Machine learning/Deep Learning/Reinforcement Learning algorithms can process data on the servers located at the edge or cloud level of the network for quick decision-making. For instance, data analysis services are useful for rail applications, as they use data from WSNs to automate train operations and control them. The advantages of including such services within the railway network applications architecture are data processing automation, application performance improvement, and real-time system updates [66] [121], [123].

6) ENERGY CONSUMPTION

The proposed architecture leverages network abstraction to provide a diverse number of rail services and optimizes network infrastructure energy consumption. Virtualization enables railway network operators to use fewer servers at the edge, core, and cloud levels, thus decreasing electricity consumption. One of the key components of the proposed network slicing framework 2 to improve resource allocation and energy efficiency is the installation of heterogeneous networks. In the same vein, Ho et al. showed in their work [124] how virtualized wireless heterogeneous networks optimize energy efficiency.

IV. FUTURE DIRECTIONS

In this section, we identify four future directions that appear to us as significant challenges that must be considered to enable the advent of 5G railway networks.

A. TECHNOLOGIES INTEGRATION IN THE RAILWAY ARCHITECTURE

Railway communication architecture, particularly FRMCS, is currently being specified and validated and includes elements specific to the railway environment. One example is the TOBA box, an onboard unit deployed within trains or its infrastructure counterpart [125]. Because of these specificities and the need to standardize the proposed solutions, integrating the above-mentioned technologies into the railway infrastructure could prove complex, requiring a great deal of upstream work. However, initial work in this direction has already begun, as illustrated by the European projects 5G-VICTORI and 5GRAIL integrating Edge Computing into the FRMCS architecture [126], [127]. The introduction of other technologies, notably AI tools and NFV, is currently being studied. Given the advantages presented in this article, the different technologies listed could also prove relevant (SDN, Blockchain), for example, in the core network, as has already been implemented in other fields such as data center [128]. For example, the prospects for cooperative studies in this field and the evaluation of different deployment types for edge servers are essential issues.

B. EXTENDING NETWORK CONNECTIVITY

This is another primary objective. Indeed, many future applications envisaged for railways involve continuous communication with the train, remote control, and signal management, which are just two examples. However, in areas with poor network coverage, such as suburban or rural areas, such continuity of service may be challenging to guarantee by relying solely on the rail operator's infrastructure. For

TABLE 4. Deployment of enabling technologies within the railway architecture.

Framework Layers		Enabling Technologies					
		Network Slicing	Software Defined Network	Network Function Virtualization	Edge: MEC	Artificial Intelligence	Blockchain
Infrastructure Layer	RAN	-Bandwidth reservation -Access scheduling -Network service prioritization	Control Access Points (APs)	Offloads network functions on the edge servers	-Data processing (local decision making, data caching, data fusion, data reduction) -Multi-media service provisioning (video and image data compression, content caching)	-Intelligent resource management -Decision making processing -Intrusion detection -Threats management -Risk assessment	-Access security (access control) -Transaction security -Data Sharing security (data traceability, monitoring and accountability) -Distributed data sharing and storage -Cross-chain and heterogeneous network interaction
	Transport	-Traffic scheduling -Resource allocation -Service prioritization -Slices isolation -On-the-fly security tools deployments	-Control Switches -Resource reservation	Virtualizes transport network functions			-Supply Chain management -Identity and access management -Data management and storage
	Core		-Control routers data traffic -Dynamically allocate resources -	Virtulizes the core network functions	N/A		
	Cloud		Cloud resource control and reservation	-Cloud network functions virtualization -Offloads network functions on the cloud servers	N/A		-Cloud applications data protection -Supply Chain management -Passengers payment processing and financial transactions -Identity and access management -Data management and storage
Control Layer		-Slice Management -Slice-to-network mapping	N/A	N/A	N/A	Automate the end-to-end network slice configuration	-Slice creation request authentication -Slices data storage
Application Layer		Slice definition	N/A	N/A	N/A		-Slice application security

this reason, as mentioned above, integrating new radio access technologies seems essential: satellite, LPWAN, ITS-G5, *etc*. A complementary approach could be to use point-to-point communications (via trains, cars, drones, or other terminal equipment) to enable the train to access an access network via several hops. In this context, optimal use of available resources is essential. To achieve this, two visions can be considered: 1) an operator-centric vision involving the definition of global network management solutions via SDN, for example, [129], or 2) a train-centric vision with optimal selection of the radio access technologies available at any given time, according to the needs of the various applications in operation [130]. Due to the limited amount of work in the rail sector, the need for proposals in this area is considerable.

C. ENABLING COLLABORATION BETWEEN MULTIPLE OPERATORS

Collaboration between multiple operators could also be a solution to extend network continuity. For example, if a railway operator could use the computing or communication capacities of a conventional network operator's base stations at specific points, this could extend its coverage capacity, guaranteeing the smooth running of critical applications. Integrating it into the railway communication architecture and standardization would require careful thought. In this area, work is already in progress, such as the idea of Edge Computing Federation [131], which can guarantee service continuity by establishing links between the core functions (User Plane Function in particular) of different 5G network operators. However, such ideas have not yet been considered in the railway environment. More work is needed to ensure collaboration between different operators in a multi-technology railway context. Blockchain could be seen as an interesting solution in this context. Indeed, its application has already been considered in other environments (classic cellular networks and the Internet of Things in particular) to implement secure exchanges between operators without implementing a centralized solution [132], [133]. In the railway context, we could therefore imagine its application at different levels: fair and efficient distribution of tasks between different edge servers/orchestrators managed

TABLE 5. Definitions of abbreviations.

Abbreviations	Definition
AI	Artificial Intelligence
CCTV	Closed Circuit TeleVision
CPU	Central Processing Unit
FRMCS	Future Railway Mobile Communication System
GSM	Global System for Mobile Communications
GSM-R	GSM-Railways
IoT	Internet of Things
ITS-G5	Fith-Generation wireless communication for Intelligent Transportation System
LoRa	Longe Range
LPWAN	Low-Power Wide Area Networks
LTE	Long Term Evolution
MEC	Multi-access Edge Computing
NFV	Network Functions Virtualization
SD-RAN	Software Defined Radio Access Network
QoS	Quality of Service
URLLC	Ultra Reliable Low Latency Communications
RAN	Radio Access Network
SDN	Software Defined Network
SD-WAN	Software Defined Wide Area Network
T2C	Train to Car
T2D	Train to Device
T2G	Train to Ground
T2T	Train to Train
T2V	Train to Vehicle
V2X	Vehicle to Everything
eMBB	enhanced Mobile Broadband
URLLC	Ultra-Reliable Low-Latency Communication
mMTC	massive Machine Type Communication
VNF	Virtualized Network Functions
NS	Network Slicing
ETSI	European Telecommunications Standards Institute
MANO	Management and Orchestration
VIM	Virtual Infrastructure Manager
CAM	Cooperative Awareness Message
DENM	Decentralized Event Notification Message
RSU	Road Side Unit
UIC	International Union of Railways
FRMCS	Future Railway Mobile Communication System
5G	Fith-Generation technologies for wireless communications
6G	Sixth-Generation technologies for wireless communications
RFID	Radio Frequency Identification

by different operators, real-time selection of access network according to different criteria (price, Quality of Service, security, etc.), definition of Service Level Agreements between multiple operators and an end-user, etc. The benefits of such an approach would be manifold: no dependence on the operator, enhanced security, and flexibility through the use of Smart Contracts. Depending on the target application, the Blockchain layer could be hosted at different levels of the architecture: Edge, Cloud, public infrastructure, private infrastructure, etc. Work could, therefore, be undertaken to define optimal architectures and frameworks.

D. SETTING UP AN EVALUATION ENVIRONMENT

This point seems essential, regardless of the area of improvement and the technology considered. However, open and accessible research in this field remains limited. Works such as [134] and [135] have proposed initial approaches incorporating some of the elements needed to implement simulation/emulation tools for future-generation rail environments: integration of 5G architecture, reproduction of terminal mobility, multiple access technologies, and integration of edge computing. However, these studies do not include the railway applications described in this work, nor do they reproduce the complexity of this architecture. As a result, the scope of the solutions proposed in these platforms remains challenging to measure. As a result, it is now essential to complete this type of environment by integrating the components specific to the rail environment. This would provide all researchers in the field, both industrial and academic, with a complex and realistic environment in which to evaluate new solutions.

V. CONCLUSION

The emergence of new generations of cellular networks and access networks (dedicated to connected objects, based on satellites, *etc.,*) is opening the door to new applications, including in the railway sector. They are also supported by the development of different network technologies that could be considered to enable flexible railway connectivity: AI tools, Blockchain, SDN, NFV, NS, and MEC.

In this article, we have sought to assess the impact of these technologies on current and future railway applications. To do so, we have highlighted the needs of these railway applications. We also proposed and described a railway communication architecture integrating the identified enabling technologies. The proposed architecture involves the reconfiguration of railway network functionalities to provide low latency, reliability, flexibility, and scalability. Multiple potential use cases have been identified for this architecture in the railway context: service provisioning, QoS, data processing, *etc*. Finally, we have highlighted essential directions today, notably the integration of enabling technologies in railway communication architecture, the extension of network coverage, the definition of architectures implying multiple network operators, and the design of emulation/simulation tools for evaluating solutions in railway networks.

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