Received 5 September 2021; revised 6 October 2021; accepted 15 October 2021. Date of publication 19 October 2021; date of current version 2 November 2021.

Digital Object Identifier 10.1109/OJCOMS.2021.3121313

Hyperloop Communications: Challenges, Advances, and Approaches

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This work was supported by KAUST.

ABSTRACT High-speed rail (HSR) communication has always been an attractive research topic with the continuous progress of transportation systems and communication technologies. Recently, Hyperloop has emerged as a candidate for very high-speed transportation systems. Because of its outstanding potential, Hyperloop can usher in a new transportation era with several attractive features. Developing suitable communication system solutions is crucial to bring this promising technology closer to reality. In addition, the Hyperloop communication system is essential to support monitoring-and-controlling services and deliver communication services inside its capsules/pods. Throughout this article, we overview Hyperloop technology and discuss its general characterization to recognize and estimate its relative position among the current HSR communication systems. Then, we investigate different attributes of the communication system, including network architecture, quality-of-service (QoS) requirements, and critical challenges to implement a reliable communication system. With the high speed of the capsule/pod and the system's unique structure, severe Doppler effect and frequent handover may considerably affect the operation of the communication system. Because Hyperloop is a recent development, it is necessary to study the existing HSR communication technologies to determine whether they can establish robust communication links for the Hyperloop system and deliver data with the required QoS. Furthermore, we provide technical details of the current HSR technologies and related research. Subsequently, we present the recent advances in the Hyperloop communication system with classification depending on whether it is a radio-, network-, antenna-, or software-based solution. Finally, we propose future research directions that can promote an improved communication performance.

INDEX TERMS Hyperloop communications, high-speed rail communications, vacuum tube communications, vehicular communications.

I. INTRODUCTION

TRANSPORTATION has been one of the main pillars of civilization growth during different eras, beginning from the invention of wheels and boats as well as steam trains to high-speed railways and supersonic aircrafts. Communication technology is another essential pillar that supports several aspects of life, including transportation, and has helped to achieve remarkable breakthroughs. Railway systems have likewise reaped countless advantages from the evolution of communication systems when they are efficiently integrated. The transportation of cargo and people requires reliable and robust communication systems to improve performance, increase profit, and avoid hazardous events. Throughout its development, the role of communication technologies in railway systems has evolved from simple control to more advanced applications such as monitoring, automatic control, automated train operation, and seamless Internet connection [1]. After the introduction of electrical power on a commercial scale in 1882, the first electrical control system was created at the end of the nineteenth century and Lemp Hermann patented a reliable electric drive control system in 1914 [2]. A major breakthrough was introduced in

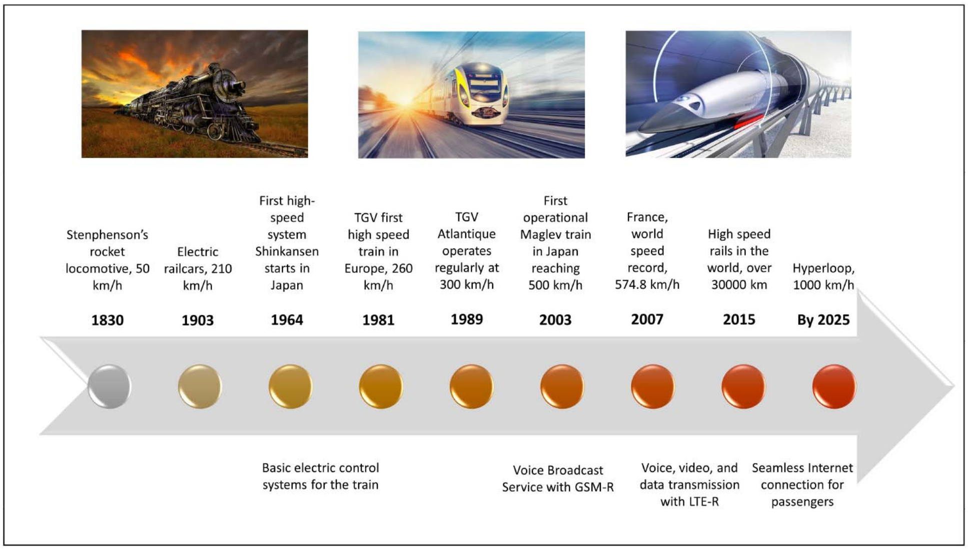

FIGURE 1. Evolution of railway systems and communication services.

the late 1990s with the standardization of Global System for mobile communications—railway (GSM-R) [3]. In Europe, the long-term evolution for railways (LTE-R) requirements were defined in 2008, and the LTE-R technology is expected to be completely operational around 2025. Current communication technologies used to ensure train to trackside connection are either analog or digital, offering different services such as voice, train control and information, maintenance and emergency services [4]. Currently, these services are intended for train radio such as voice and control applications, train positioning using radar technologies, or train remote surveillance [4]. The objective of future railway communication systems is to provide seamless high-speed Internet connection for passengers and ensure low latency and intelligent network for train-to-ground communications. The department of transport in the U.K. expects to offer a WiFi speed of 1 Mbps to passengers [5]. In order to achieve these connectivity goals, transportation organizations must cooperate with different broadband service providers to develop a strategy ensuring a reliable end-to-end connectivity. More details about the evolution of railway systems are provided in Fig. 1.

We are witnessing the beginning of a new era of land transportation, being ushered in by Hyperloop, which represents a great leap toward achieving supersonic speed similar to the speeds of aircrafts [6]. The Hyperloop is a mode of transport that aims to leverage pressurized tubes, electric propulsion, and magnetic levitation to allow a passenger vehicle known as a pod to travel through a tube with reduced drag forces and relatively free of air resistance and friction. The pod can attain aircraft-like speeds [7]. In fact, Hyperloop is expected to attain speeds of 1200 km/h [8]. The concept of vacuum trains was initially proposed by the American engineer Robert Goddard in 1910, but he did not build a prototype [9]. In 2013, Elon Musk, the founder and chief executive officer (CEO) of SpaceX, published his famous white paper Hyperloop Alpha. He elaborated on the concept of Hyperloop, proposing a route between Los Angeles and San Francisco and providing technical details about the pod and tube design [7]. The development and implementation of Hyperloop are of broad and current interest for a wide range of researchers belonging to different areas. Similar to Hyperloop, Maglev trains run at tremendous speeds reaching 600 km/h [10]. In their case, magnetic levitation is applied to eliminate the surface friction, considerably increasing the velocity. The Shanghai Maglev train is known to reach a maximum speed of 430 km/h [11]. It is considered to be the land transportation system closest to Hyperloop in terms of the technology used and speed attained.

Hyperloop systems will bring countless benefits to the global society when brought to reality as a part of international transportation. For instance, it will enable workers to commute over longer distances and within less time between major cities across the globe, availing the hiring process and promoting tourism [12]. Moreover, because Hyperloop consumes electric power, it can be operated using sustainable energy sources, considerably reducing the environmental impact in comparison with other modes of transportation [13]. Therefore, Hyperloop will be one of the most promising reliable alternatives for future transportation with improved performance efficiency and a high degree of sustainability [14]–[16]. However, people are still skeptical about the user experience inside a fast-moving pod enclosed in a tube and its low capacity. The Hyperloop is also subject to prejudices concerning security-related matters such as dealing with emergency evacuations, terrorist attacks, and natural disasters [17], [18], despite Elon Musk confirmation regarding its safety and resistance to natural disasters such as earthquakes [7].

Since 2013 when Elon Mask initially conceived the idea of Hyperloop, several attempts have been made to realize it, and companies are racing to build a reliable,

FIGURE 2. Approximate locations of the proposed routes for Hyperloop transportation.

functional Hyperloop train system [7]. Hyperloop One [19], Hyperloop transportation technologies (HTT) [20] and other companies carry out ongoing research efforts to uphold Hyperloop HSR. Recently, Zeleros has raised a cooperative fund of $7.79 million as an investment to develop an integral Hyperloop vehicle [21]. In 2017, a complete Virgin Hyperloop One capsule and tube were built, which could attain a speed of 387 km/h over a 500-m-track long, after more than 400 tests [19]. A full-scale Hyperloop system was built by HTT in 2019 in Toulouse, France, and tests were performed out to integrate all the system components [22]. Moreover, a long-term project, namely, the 10000-km-long Europe Hyperloop Network, was launched by Hardt Hyperloop [23] in 2019 to connect European countries. The first Hyperloop journey of Hyperloop Virgin with human passengers was carried out in the Nevada desert with a speed exceeding 160 km/h [24]. Moreover, the Hyperloop prototype in South Korea has reached a speed of 1000 km/h [25]. With regard to Hyperloop rail networks, several routes are envisaged for Hyperloop installation. Some of the possible routes are Chicago-Pittsburgh (United States), Glasgow-Liverpool (United Kingdom), Toronto-Montreal (Canada), Jeddah-Riyadh (Saudi Arabia) and Seoul-Busan (South Korea) [19], [26]. Several simulations have been performed to validate these possibilities [27], [28]. The approximate locations of some proposed routes are shown in Fig. 2.

Hyperloop is a complex transportation system that combines the three functionalities of levitation, guidance, and propulsion. The Hyperloop system is unique because all the existing systems use at most two of these functionalities [29]. Monitoring the different tasks involved and situations faced in a Hyperloop system lies within the functions of the communication system. Therefore, a reliable and efficient Hyperloop transportation system depends on a reliable and efficient communication system when the two systems are properly integrated. Hence, we need to investigate the advances and different projects supporting HSR communications. Conventionally, GSM-R is the technology upholding most railway communication systems. The European rail traffic management system (ERTMS) is the standardized system for automatic protection and management of signaling for railways by the European union (EU), directed by the European union agency for railways (ERA). It is an umbrella that combines GSM-R, which is the radio system that provides voice and data communication and European train control system (ETCS), which is the automatic train control system [30]. As described by the international union of railways (UIC), the ETCS is a signaling and control system widely adopted in Europe. It maintains efficient and safe command of rail operations and defines communication protocols [31]. In 2014, a new project that will enable and embrace ERTMS was launched by the UIC. This project is called the future railway mobile communication system (FRMCS) and it will further digitize railway services [32]. FRMCS is considered to be a promising successor of GSM-R and the heir to future worldwide rail communication. It is considered capable of meeting the new requirements of interoperability and high QoS and represents a standard compatible with the existing regulations. It will

TABLE 1. Comparison of projects supporting HSR communications.

	GSM-R	ETCS	ERTMS	FRMCS
Project nature	Wireless communications standard for railway communication	Automatic train protection system that continuously monitors and checks the train speed	Software based system for control, command, signalling and communication/ adopted by the European Union as a standard	Successor to GSM-R / considered to become the global standard for railway communications
Goal / Functions	Part of ERTMS / provides train to trackside connectivity / provides voice and data services	Part of ERTMS/ controls speed limits / exchanges information with the vehicle for safety and effective control / replaces incompatible systems currently adopted by the EU	Combines GSM-R and ETCS / improves interoperability between trains in Europe / manages signaling and train speed	Supports services for current and future rail / targets the 3GPP 5G technology / promotes rail services digitalization / provides futuristic passenger services
Launching date	Specifications concluded in 2000	First Baseline (main version) in 1996	Founded in 1998	available by 2022

enable innovative services, minimize communication latency and boost safety and efficiency [33]. Expected to be available by 2022 [34], FRMCS shall meet the communication requirements of railway systems, achieve seamless connectivity with public operators and different networks (mobile and fixed), and ensure the integrity, reliability, and flexibility of the communication system [35]. Because one of the key user requirements of FRMCS is to be flexible and capable of accommodating futuristic applications, this revolutionary project may enable Hyperloop communication in the future. For further clarity, the differences between the projects described in this section are presented in Table 1.

Several research works have been conducted to push the scientific progress of Hyperloop communication system and bring it closer to reality. A reliable communication system capable of monitoring the pod and tube with minimum latency and high signal speed is critical for ensuring the proper and safe operation of Hyperloop. Owing to its novel and specific structure, strong and efficient supervision by the control center is essential to guarantee safety and to reap maximum benefit from Hyperloop potential. The very high speed of the capsule leads to two major issues, namely, frequent handovers and severe Doppler effect. Hence, the design of the communication system is challenging, and transmission errors may result in alarming consequences related to passengers' safety.

In this paper, we provide a detailed overview and analysis of Hyperloop communication systems, including the existing technologies, the related challenges and the research work conducted to achieve a functional and reliable communication system for Hyperloop. Throughout this study, we introduce and refer to some technologies used in HSR communication systems in general and investigate their potential use in the Hyperloop case. The remainder of this paper is organized as follows. Section II provides general information about the operation of Hyperloop system and its components. In Section III, we present Hyperloop communication system, including the communication network architecture, QoS requirements, and challenges. Section IV provides an insight into the existing HSR technologies and their opportunities to support Hyperloop communication. Then, Section V provides details regarding research advances in Hyperloop communication and the different solutions proposed to overcome the challenges faced by the system in Section V. It also suggests possible future research directions from a communication point of view to further boost the activities for accomplishing a full-scale Hyperloop transportation system. Finally, the conclusions of this paper are presented in Section VI.

II. OVERVIEW OF HYPERLOOP SYSTEMS

Herein, we present an overview of the Hyperloop transportation system, including its physical structure and the fundamental concepts associated with its operation. It is essential to understand the Hyperloop system architecture for defining the required communication services, requirements, and challenges to guide the researchers in proposing appropriate communication solutions.

A. HYPERLOOP STRUCTURE

According to the first Hyperloop version envisioned by Elon Musk in [7], Hyperloop consists of a sealed vacuum tube within which a capsule or a pod,[1] levitates and moves at a very high speed. This innovative transportation system has several advantages due to its unique design. In addition to being faster and safer than traditional transportation means, Hyperloop is also self-powered and environmentally sustainable, consuming renewable energy [7], [36]. Solar panels can be mounted on top of the tube to provide sufficient energy for operating the system, and batteries can be used to store power for later use [36]. Simulations were conducted [37] to investigate the energy consumed by Hyperloop as a function of the speed of the pod and pressure inside the tube and to optimize the pressure in order to minimize energy

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[1] The terms pod and capsule are used interchangeably.

usage. Energy requirements for Hyperloop operation were also studied in [38], [39]. Musk stated in his white paper that overall, a Hyperloop system requires an average power of 21 Megawatts, which is considerably less than the annual production of the mounted solar panels [7]. Regardless, an expert in Maglev trains suggested that Hyperloop system with pressure pumps and a propulsion system cannot be powered only by solar energy [40].

The two main components of Hyperloop are the tube and the capsule, which can carry 25 to 40 passengers [41]. Two twin tubes are mounted on top of elevated pillars for onward and backward travel. Aerodynamic drag is the main force that restrains the motion of the train and is proportional to the square of its speed. Therefore, the power required to maintain a certain speed is proportional to the cube of this speed [42]. The elimination of this drag force will notably reduce power consumption. For this reason, the idea behind Hyperloop was to travel in a nearly vacuum environment, where pressure is negligible [43]. The tube is an evacuated cylinder with a diameter of approximately 3 m and is made of steel with or without concrete [44]. The capsule is optimally designed to levitate and float inside the tube, enhancing its speed and performance. An example of Hyperloop train is shown in Fig. 4.

B. HYPERLOOP OPERATION

To maintain the motion of Hyperloop at the predefined speed, the system relies on three fundamental operations:

- **Levitation:** Hyperloop does not need wheels to move forward. Suspension or levitation allows the pod to float inside the tube, counteracting the effect of gravitational acceleration. There are two main ways to maintain the pod suspended in the air, namely, magnetic levitation and air bearing. Magnetic levitation, used in the Maglev [45], relies on magnetic fields using superconducting electromagnets. In this case, the support that maintains the pod flying in the air are magnetic fields. The air bearing technology, which was adopted by Elon Musk in his prototype [7] and by the authors of [38], happens when fixed and moving surfaces are separated by pressurized air, being able to lift the weight of the moving surface. Thus, the cushion of air allows the pod to float above the rail [46]. In both levitation scenarios, gravitational acceleration is compensated and the pod does not undergo ground friction, resulting in the tremendous increase of its speed [7], [47].
- **Evacuated Environment:** The pod travels in a low-pressure vacuum-sealed tube enabling land transportation to approach sonic speeds. Since atmospheric pressure restricts the motion of objects, the idea was to eliminate the air creating an almost air-free environment and therefore, drastically reducing the pressure. Thus, a higher level of air lubrication can be achieved [48]. This framework can be realized by pumping the air out of the tube. Devices called vacuum pumps remove the air from the sealed tube to maintain the desired atmospheric pressure and deal with gases leakage that eventually occurs along the tube from connections. These vacuum pumps are placed along the connected tubes at discontinuous locations [7], [37], [43]. The optimal pressure must be computed since higher pressure inside the tube requires less energy for the pumping system but at the same time, drag forces increase and therefore, energy required for propulsion increases [49].
- **Propulsion:** Classic ground transportation systems require continuous and uninterrupted propulsion to maintain their motion. Propulsion is the action of pushing objects forward as a result of thrust generated by dedicated engines [50]. In the case of Hyperloop, only intermittent propulsion along the route is needed owing to the levitation and evacuated tube that keep the train in motion for a certain distance without the need to an external driving force. An electric linear motor system, powered by solar panels [7], is used to propel the pod and keep it running at the intended speed that can reach 1200 km/h. The propulsion system is fully electric and does not use any fossil fuels [51] which further supports the sustainability of Hyperloop. Several research papers studied the propulsion system that can counteract air-resistance [52], [53].

III. HYPERLOOP COMMUNICATION SYSTEM SPECIFICATIONS

Considering the very high speed and unique structure of Hyperloop, the performance of the communication system is essential for the safe, secure, and proper operation of the train. In this section, we propose a general network architecture expected to satisfy the requirements of Hyperloop communication. We provide details of the QoS requirements and the challenges faced by Hyperloop communication system. Before delving into technical details, we present a taxonomy diagram (Fig. 3) that provides information about different aspects of Hyperloop communication.

A. NETWORK ARCHITECTURE

The particular structure of Hyperloop as a combination of a train and a tube certainly makes its communication network architecture different from those of the conventional HSR systems, even the Maglev train that travels at very high speeds. Because the tube is partially or wholly made of steel, an external signal will not be able to penetrate its walls without significant losses. Hence, a direct link between an external base station (BS) and the pod is inconceivable. Subsequently, a suitable design of communication links, that takes into consideration the unique structure of Hyperloop, is necessary to establish successful train-to-ground communication.

Being a branch of HSR systems, Hyperloop communication network eventually inherits the general structure of the conventional HSR networks but with some adjustments to fulfill the specific requirements of Hyperloop. Because the tube that surrounds the train may block

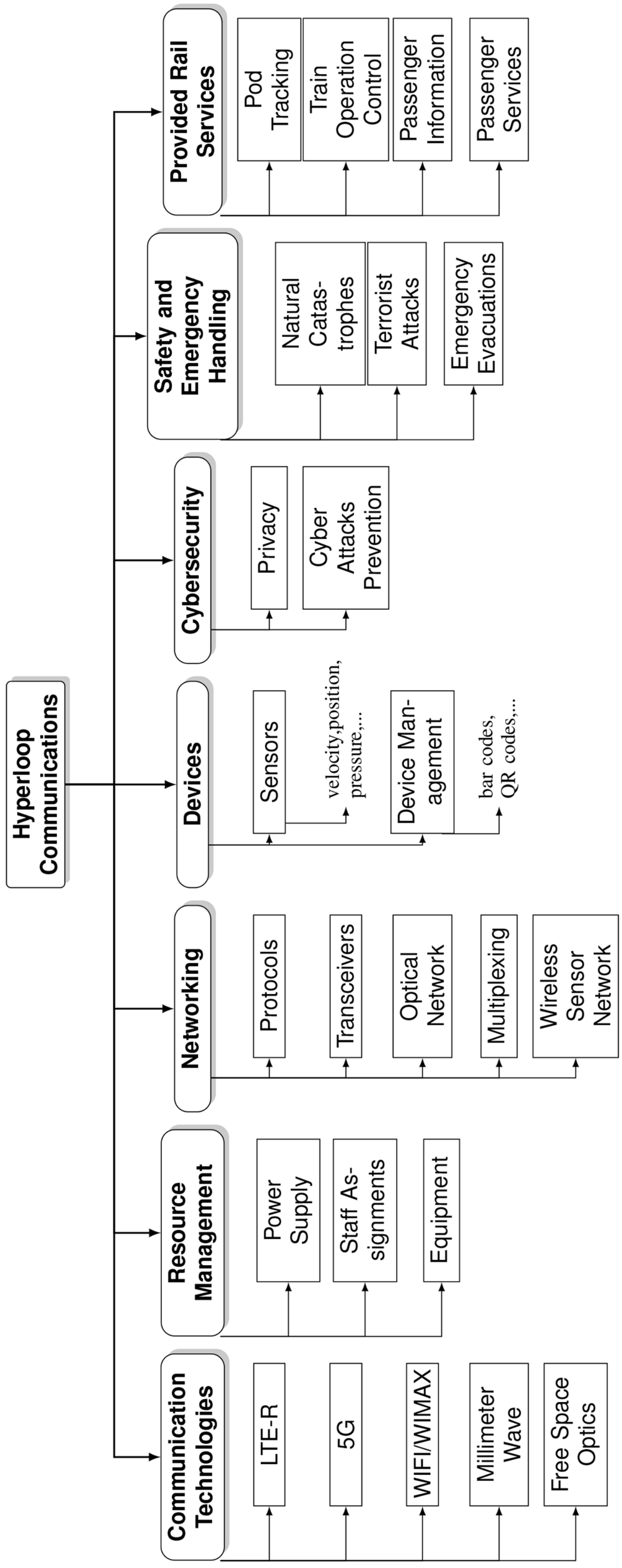


FIGURE 3. Taxonomy of Hyperloop communications.

any upcoming signal, Hyperloop network must consider the need to establish a reliable communication between the pod and the outside world. We depict, in Fig. 5, the general architecture of Hyperloop communication network.

This network can be divided into three main parts to tackle the following tasks.

- *Communication between the pod and user equipment (UE):* The passengers and train control unit can acquire connection and access the network through the train access terminal (TAT) placed inside the pod.
- *Communication between the tube and pod:* Antennas are placed on the pod and communicate with access points (AP) placed inside the tube on the ceiling. This wireless link is established considering the range of both receive and transmit antennas and the adopted technology.
- *Communication between the tube and core network:* The APs placed inside the tube are connected to the core network via wired or wireless links. Relay nodes can be placed on top of the tube [54] or away from the tube [55], and they communicate with the tube via wired links.

To establish these three communication links, the network architecture must be conceived according to the HSR broadband communications specifications, in general, and to Hyperloop in particular.

The network is divided into four main layers.

- **Core Network** The core or backbone network is the part that binds and interconnects different participants of the network. Usually, user expectations from core networks mainly include low congestion, short delays, high availability and adaptability to future applications [56]. In the case of HSR systems, data and services processing is performed at the core network level, which holds the contribution of the global Internet and service providers or railway stakeholders (entities sharing and contributing in the management of railway activities) [57]. One of the main functions of this network is handover processing, which is executed through the mobility management entity (MME) in the case of LTE networks [58].
- **Aggregation Network** The aggregation network is the part of the network responsible for gathering, organizing, and forwarding data flows between access and backbone networks [59]. It represents a junction in the network where upcoming packets are transmitted to their destination following a packet switching process. The two main contributors of the aggregation network are the packet data network (PDN) and serving gateway (SGW) [60]. Technologies such as ADSL, IEEE 802.11, Ethernet and optical fibers can be used in the aggregation network [61].
- **Access Network** The access network represents the frontline of the network. It is directly connected to the UE, i.e., the Hyperloop train in this case. It is responsible for transmission and reception of the signals, coding/decoding, modulation/demodulation [61]. Depending on the adopted technology, these functions may be executed

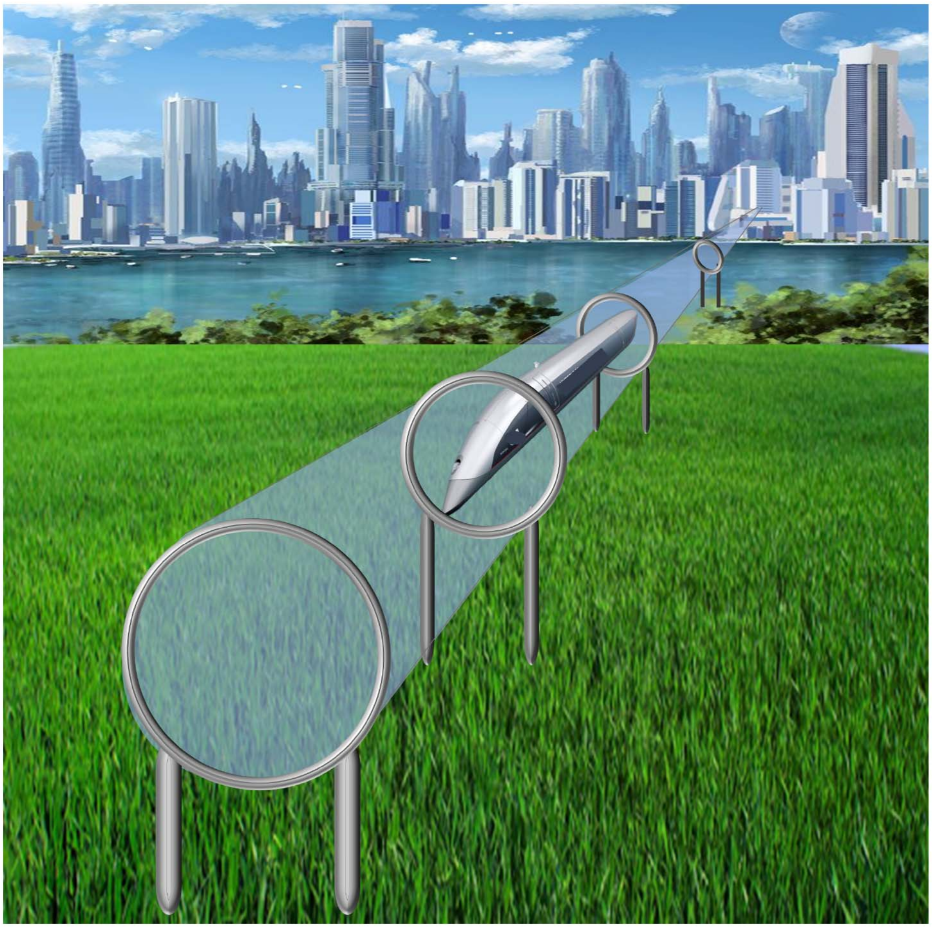


FIGURE 4. Hyperloop prototype.

in one unit or may be distributed among units. In the general case of HSR systems, this network operates using various technologies mainly, satellite communications, wireless data and cellular networks.

- **Hyperloop Network** As previously mentioned, Hyperloop is composed of the tube and the traveling pod. Therefore, Hyperloop inner network is rather different than the conventional HSR systems. The communication between the access network and the tube can be wireless or wired (for, e.g., using optical fiber) to meet the requirements of fast communication and short delays. Antennas will be placed on the ceiling of the tube and communicate with one or two antennas placed on top of the pod to assist and alleviate the handover process: a rear and a front antenna. The signals originating from the train control unit and the personal devices of passengers are received by the TAT placed inside the pod to avoid attenuation if transmitted through the pod walls.

B. HYPERLOOP-TO-GROUND COMMUNICATION SERVICES

As in conventional HSR systems, the traffic is distributed into two main comprehensive service categories [62].

- **Train Operation Control Services:** This category includes signals related to all aspects and elements of train operation (e.g., train command, mobility management, safety, status tracking, signaling, resource allocation, information processing, video surveillance, and passenger information [55], [62]). Some of the important services belonging to this class are as follows.

  - Train control and monitoring system (TCMS) [57]: This system is of great importance because it supervises the overall operation and safety of the train. It is a control and signaling system in which trackside equipment is installed and connected to Hyperloop. Messages are regularly exchanged with this equipment to supervise the train operation and safety. Wireless sensor networks (WSNs) are deployed to follow all parameters that determine whether the train is functioning properly [55]. Similarly, the tube environment and infrastructure of the train are closely monitored. This sensor network can include a variety of devices such as pressure and temperature sensors, cameras, RFIDs, and speed detectors.

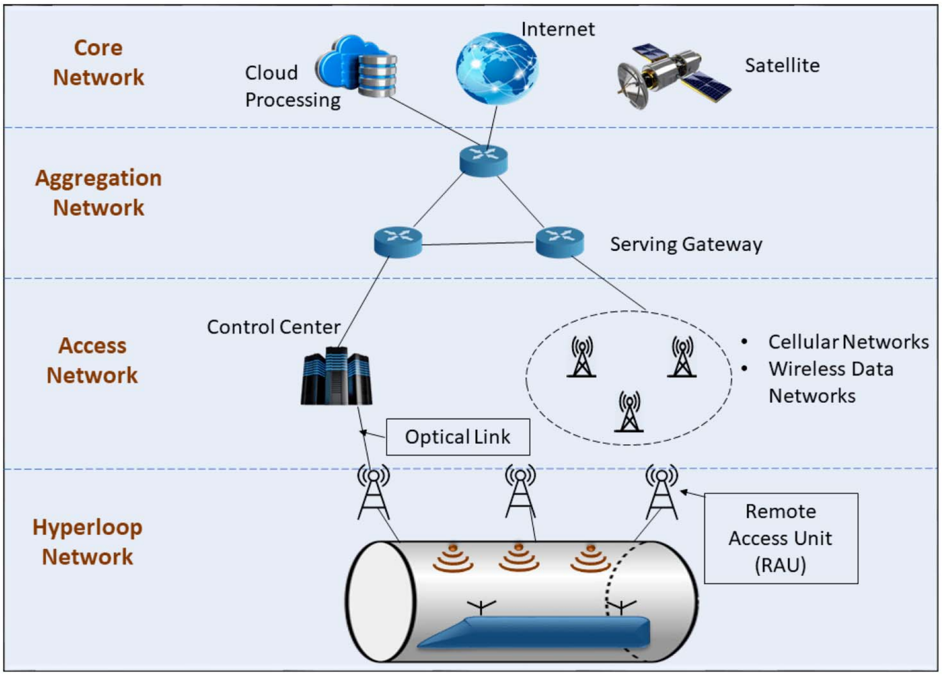


FIGURE 5. Network architecture for Hyperloop communications.

  - Traction control system (TCS): This system tracks the position and speed of the pod [55]. In the case of Hyperloop, this system plays a key role in train operation since the motion of the pod is governed by a sophisticated mechanism involving all three functionalities propulsion, levitation and vacuum environment.
  - Staff voice communication: This system ensures fluent information circulation among the staff involved in train operations. The staff members can be drivers, maintenance personnel, employees at the control center, employees charged with emergency situations, etc. This exchange of information helps to track all operations and situations to ensure safety. Staff members should be able to initiate voice communications at any moment among themselves without any interruptions or delays [63], [64].
  - Passenger information system (PIS): This system provides the necessary information to passengers and represents their main interface. The services provided are essentially information about arrival and departure times, possible delays, and weather forecast [57].
  - Closed-circuit television (CCTV): The CCTV system is a video surveillance system in which several cameras are placed inside the pod to closely supervise and monitor the situation [57]. The staff in charge can check the status of passengers, their seats, any acts of violence and adherence to safety instructions. Facial recognition may also be used to accelerate the process of passenger identification when needed.
- **Passenger Services:** This category includes signals related to services such as Internet Access, gaming, and video streaming provided to onboard passengers. These onboard entertainment services are of great importance in the case of Hyperloop, because the pod is a completely sealed environment and user experience is debatable.

The communication systems for HSR are generally more demanding in terms of QoS than the public land mobile network (PLMN) because of the additional critical services related to safety and monitoring that have to be provided by the HSR communication system [65]. The QoS demands are more stringent in the case of Hyperloop owing to its specific architecture and environment and their corresponding extra requirements. The aforementioned services must be considered when discussing the QoS of Hyperloop communication system. In fact, requirements in terms of data rates, priority and response time differ between services. For example, short delays are crucial for some applications such as video surveillance and train monitoring; however, passenger services are more demanding in terms of data rates and tolerant to transmission delays [55]. Several performance metrics have to be considered when evaluating the functioning of the train's communication system. Precisely, transmission delay is crucial for instantly tracking the train status to ensure a safe trip. Bit error rate (BER) and throughput are other performance indicators. For passenger safety, tolerance to transmission errors should be significantly low; in other words, signals

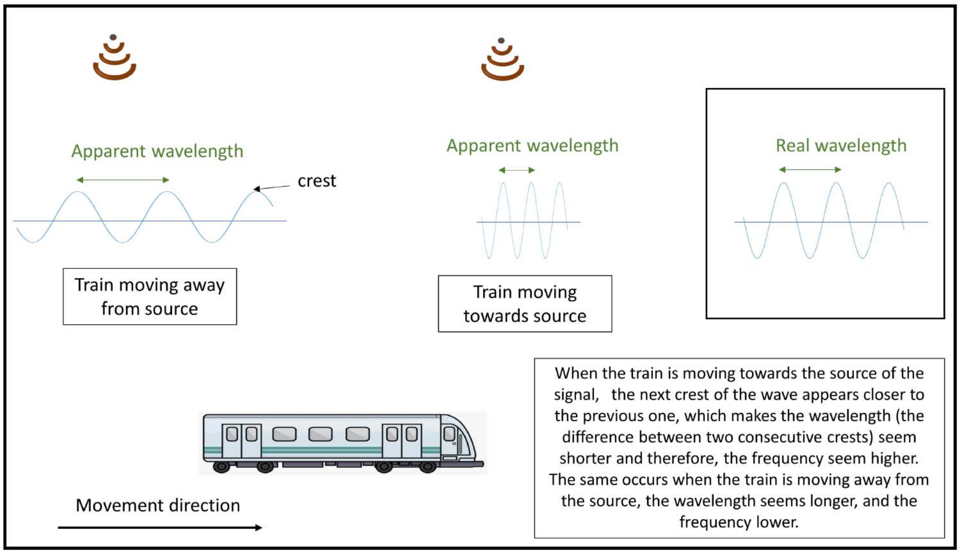


FIGURE 6. **Illustration of the Doppler effect in a high-mobility scenario.**

related to the train operation control are prioritized with very low BER. On the other hand, signals related to passenger entertainment require high data rates but lower priority.

Accordingly, Hyperloop communication system must meet different QoS requirements depending on the provided service. The authors of [55] reported the key performance indicators (KPIs) values for successfully conducting Hyperloop services.

C. CHALLENGES OF HYPERLOOP COMMUNICATION

As a result of the specific configuration and circumstances associated with Hyperloop operation, several challenges have to be resolved to ensure the proper functioning of its communication system. Therefore, before delving into any system design, listing and detailing these challenges are crucial to solving them one by one through practical solutions.

- **Doppler Effect**: The high traveling speed of Hyperloop results in a severe Doppler effect, especially if the communication system is broadband [66]. The estimation and mitigation of the Doppler effect in vehicular communications in general and in HSR systems in particular, are frequently addressed topics [67]–[70]. When the system uses orthogonal frequency division multiplexing (OFDM), signal distortion caused by Doppler shifts is larger as the system is susceptible to carrier frequency offset [69]. In this case, the orthogonality condition of different carriers is violated, resulting in intercarrier interference (ICI) [71]. The high mobility of Hyperloop leads to a fast time-varying channel [72] because of the larger Doppler spread introduced. In fact, fast-varying channels are characterized by a short coherence time. Coherence time is defined as the time duration over which the channel impulse response can be considered as flat or not varying. The Doppler spread is inversely proportional to the coherence time [73] and is defined as the difference between the maximum and minimum Doppler frequency shifts faced by different paths. It characterizes the spectral broadening encountered by the wireless signal in a multipath channel. Therefore, as mobile velocity increases, Doppler spread increases and the coherence time of the channel decreases. Thus, the channel becomes time-varying. Symbol duration must be less than the minimum coherence time to avoid channel distortion (variability) within symbol time. At the receiver side, Doppler shift is estimated and the sampling frequency is adjusted to compensate for the ongoing signal distortion. However, this task becomes complicated because of the aforementioned reasons [74]. Illustration of Doppler effect is shown in Fig. 6.
- **Frequent Handover**: In the case of high mobility networks, handover is one of the immediate and inevitable effects faced by the system. For this reason, it was widely examined in the literature, mainly for HSR systems [75]–[78]. Because Hyperloop can reach speeds of 1200 km/h, handovers become more frequent and must be performed in a very short time to avoid additional delays and performance decline. Additionally, APs are installed at close intervals inside the tube, aggravating the situation. In addition, group handover is another phenomenon occurring in railway communications. Group handover occurs when several users in a given vehicle attempt a handover process simultaneously upon reaching the cell boundary [79]. This exhaustive process may overburden the network and create severe congestion. Owing to the high speed of Hyperloop, group handover is accentuated and more frequent.
- **Special Propagation Environment**: Several challenges arise from the specific propagation environment of Hyperloop (i.e., the pod traveling inside the tube).

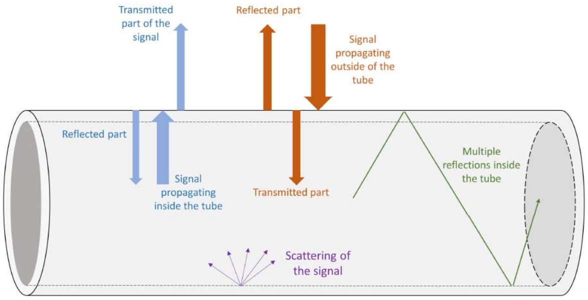


FIGURE 7. Propagation of signals in the tube environment.

However, more challenges arise from this specific propagation environment. First, penetration loss in the walls of the tube must be taken into account. Eventually, these losses depend on the construction materials of the tube and the frequency of the transmitted signal. Other propagation characteristics arise from the different wireless environment inside the vacuum tube and the construction materials of the tube. The wave encounters reflections and scatterings on the walls of the tube, especially if the tube is made of steel, which is a highly reflective material. However, the wave does not undergo losses caused by the molecular attenuation or water vapor. Moreover, interference from outside can occur if the interfering signal can penetrate the tube. The mentioned propagation characteristics are depicted in Fig. 7.

- **Strict QoS Requirements**: The slightest errors in the Hyperloop communication system can be fatal and can put the safety of passengers at high risks. Therefore, the QoS represented as BER, signal-to-noise ratio (SNR), delays, packet loss rate, throughput, etc., must be optimized mainly among the signals related to the train operation and status. Ultra-reliable low latency communications (uRLLC) was one of several possible directions defined by the international telecommunication union (ITU) to serve HSR communication [80] since it is vulnerable to transmission delays. Similarly, the Hyperloop communication system is not tolerant to transmission delays, which is accentuated by the very high speed of the pod and the resulting fast fading communication channel. Furthermore, the Hyperloop communication system is a wideband system because the diversity of applications requires high data rates and large available bandwidth.

Challenges faced by Hyperloop communication system are depicted in Fig. 8.

A comparison between Hyperloop and HSR challenges is provided in Table 2.

IV. OPPORTUNITIES OF HSR TECHNOLOGIES TO SUPPORT HYPERLOOP

In this section, we present existing technologies that serve HSR communication systems and attempt to determine the opportunities that they provide to support Hyperloop communication.

TABLE 2. Comparison of the challenges in HSR and Hyperloop communications.

	Hyperloop	HSR
Doppler effect	Severe	Moderate
Frequent Handover	Severe	Moderate
Propagation through the tube	Yes	No
Strict QoS requirements	Very strict	Strict

A. EXISTING HSR TECHNOLOGIES

The existing technologies can be classified as cellular networks (GSM-R and LTE-R), satellite networks, and wireless data networks (WiFi and WIMAX).

1) **GSM − R** GSM-R is basically the extension of GSM technology assigned to support rail communications using dedicated BSs. It brought several advantages over the traditional analog system used in railways, mainly in terms of voice and data communication, and provides a better handover scheme; further, it can be used over longer distances. This narrowband technology was largely adopted in China, Europe, and the U.S. [62]. However, GSM-R suffers several weaknesses related mainly to its limited bandwidth, the latter may be sufficient for voice communications but is unable to handle sustained connections for more applications. With a maximum data rate of 9.6 kb/s per connection, data-consuming services of HSR cannot be provided by GSM-R [81].
2) **LTE − R** Promoting efficient HSR systems requires the use of wideband low-latency technologies for better passenger experience and safety. Therefore, as GSM-R is expected to become obsolete, the 3GPP LTE has low latency and high data rates and thus, is emerging as a preferred technology to uphold HSR communication [82]. LTE-R is known to provide a variety of services, including real-time monitoring, multimedia services, and emergency services [81]. LTE-R, being a 4G protocol, is suitable for HSR systems that require broadband communication and low latency. These services include multimedia delivery, emergency signal handling and IoT, improving the railway services and safety [81]. For instance, LTE-R showed noticeable performance in satisfying data integrity and delay requirements of ETCS [83], [84]. Currently, GSM-R and LTE-R are the best-known standards for HSR communication systems, and LTE-R is envisioned to replace GSM-R for faster wideband communication [81].
3) **WIMAX/WiFi** Both WiFi and WIMAX can be adopted to support railway communication [62], [85]–[87]. These technologies are essentially considered to provide in-train wireless access because of their short coverage. On the other hand, they can provide high-capacity service with low packet loss. However, the authors

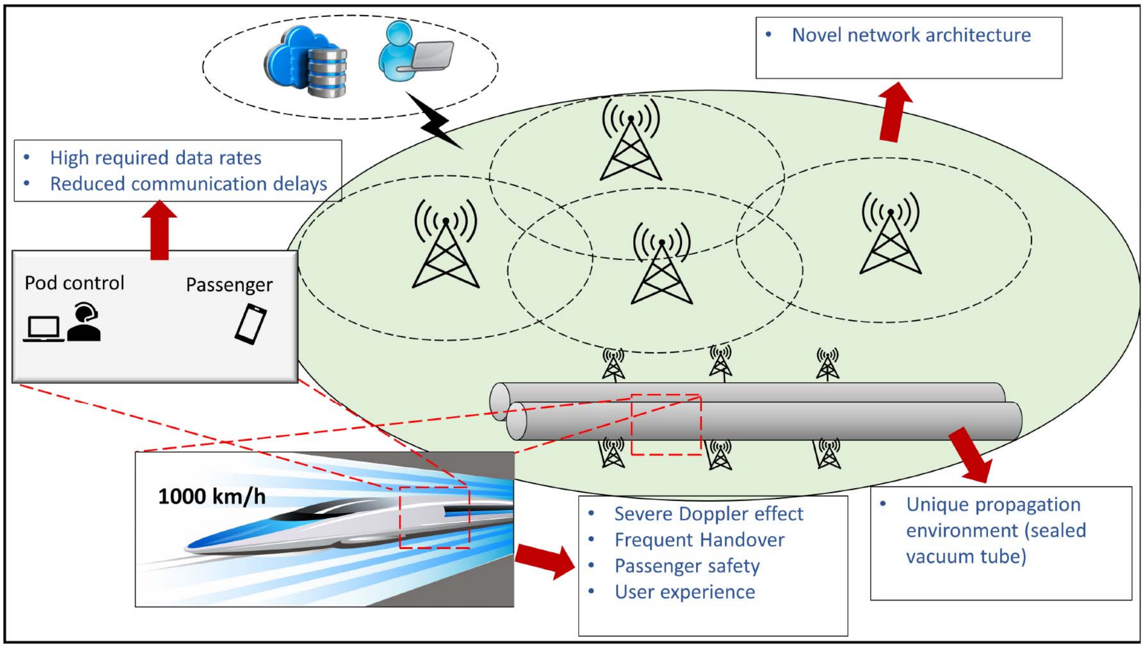


FIGURE 8. Challenges faced by Hyperloop communication system.

TABLE 3. Wireless technologies applied in Railway systems.

	GSM-R [81]	LTE-R [81]	IEEE 802.11	WIMAX	Satellite [62]
Frequency	885-889 MHz (UL) 930-934 MHz (DL)	450, 800, 1400 and 1800 MHz	2400/5000	2.3/2.4/2.5/3.5 GHz	-
Bandwidth	0.2 MHz	1.4-20 MHz	20 MHz	20 MHz	-
Maximum Data Rate (UL)	170 kbps	10 Mbps	54 Mbps	100 Mbps	1 Gbps
Maximum train speed	500 km/h	500 km/h	100 km/h	400 km/h	500 km/h
Handover success rate	>99.5%	>99.9%	-	-	99.5%
Modulation	GMSK	QPSK/16QAM	QPSK, QAM	QPSK, 16-QAM and 64-QAM	FSK-PSK
Mature technology	yes (obsolete by 2025)	setting up standards	yes	yes	yes

of [62] recommended WIMAX over WiFi because of the longer coverage of the former. A combination of WIMAX and radio-over-fiber (RoF) technologies was proposed in previous studies [86], [88], [89].

4) **Satellite Communications** Satellite communications are also considered a suitable candidate to connect trains to the global network, especially because of its advantages in rural areas [90], [91]. Satellites represent a flexible and adaptable solution that can provide broadband connection to large geographic surfaces [92]. However, several limitations should be considered, mainly the need to maintain a line-of-sight (LoS) between the satellite and the ground receiver (i.e., the train or BS), the need for highly directive antennas with good pointing and steering abilities and connectivity interruption in out-of-visibility areas. The French rail company Société Nationale des Chemins de Fer (SNCF) considered using Galileo, Europe's satellite navigation system, in the future trending of ERTMS [93].
5) **5G Next Radio** (**NR**) HSR communications are considered one of the most important axes of the 3GPP 5G NR [94]. It is considered to be the global standard for 5G networks access mode. The main QoS requirements of this radio access technology are to support high mobility, large throughput, and short latency [95]. Millimeter-wave 5G networks will bring countless benefits to HSR communications providing generous bandwidth and high data rates for passengers and HSR services [94]. Regardless, 5G NR can cater to a maximum mobile speed of 500 km/h, as specified in the 3GPP technical report on 5G scenarios and requirements [96].

A comparison of system parameters is presented in Table 3.

B. CAN HSR TECHNOLOGY SUPPORT HYPERLOOP COMMUNICATION?

Commonly, off-the-shelf technologies are used to support HSR communication with some supplementary features and functions to assist HSR peculiar services and needs [81]. However, it must be further explored whether this approach is applicable for Hyperloop communications.

As explained before, the high velocity of the moving pod results in a time-varying channel. Thus, typical communication systems are unable to handle it because the symbol duration is defined according to the channel coherence time. The coherence time T_c must be longer than the symbol duration T_s, i.e., $T_s < T_c$ to prevent signal distortion within symbol time. According to [97], the coherence time can be approximately, expressed as

$$T_c = \frac{0.423}{f_{\mathrm{D,max}}}, \tag{1}$$

where $f_{\mathrm{D,max}}$ is the maximum Doppler shift expressed as [98]

$$f_{\mathrm{D,max}} = \frac{vf_c}{c}, \tag{2}$$

where f_c is the frequency of the transmitted signal, v is the velocity of the train and c is the speed of light.

To better illustrate the matter, for LTE systems as an example, each symbol has a duration of $T_s = 0.5\ ms$ [99]. If we consider $f_c = 1800\ MHz$ (Table 3), the maximum allowed vehicle speed is expressed as

$$v_{\max} = \frac{0.423c}{T_s f_c} \simeq 500 km/h. \tag{3}$$

Going beyond this train speed results in a distorted signal at the receiver.

For this reason, current technologies cannot support the expected high velocity of Hyperloop trains that can reach 1200 km/h and the severe Doppler requirements arising from this speed.

Frequent handovers represent another issue that needs to be considered for judging the eligibility of a technology to uphold Hyperloop communications. It is known that the delay between two successive handovers must be greater than 100 times the handover delay. For a pod traveling at a speed of 900 km/h (the average speed of Hyperloop) and a cell radius of 500 m, the time interval between two handovers is 4 s. In this case, the handover delay must be less than 40 ms. However, current HSR communication links exhibit a handover delay of 100 ms to 1 s [55]. Moreover, satellite channels are known to have long uplink and downlink propagation delays of up to 500 and 600 ms, respectively [100] while Hyperloop communications cannot tolerate latency, and the train control system requires a delay of approximately 1 ms [55].

In conclusion, as stated in Table 3 and in [55], current technologies cannot be applied to Hyperloop communications unless appropriate solutions are provided to overcome the encountered issues. Therefore, off-the-shelf technologies are unsuitable to satisfy various requirements of Hyperloop communication system.

Nevertheless, some technologies may be able to support part of the network. For instance, WiFi and WIMAX are last-mile access technologies for wireless networks and can be advantageous if adopted inside the pod to provide in-carriage wireless access. Moreover, with novel network architectures, the speed limitation of some technologies, such as LTE-R, can be overcome by installing fixed remote antenna units (RAUs) along the rail and using wired connections between the RAU and tube as in [55].

C. CANDIDATE TECHNOLOGIES FOR HYPERLOOP COMMUNICATION

While existing technologies used in HSR communications are not qualified to adhere to Hyperloop requirements, some novel technologies can be investigated and adopted to enable Hyperloop communications.

- **Millimeter − wave and THz Technologies** Millimeter-wave systems are considered a convenient and advantageous candidate for HSR wideband communication systems in general and Hyperloop in particular [11], [101]–[105]. For instance, the communication of the Shanghai Maglev Train used the millimeter-wave 35 Hz band to develop the wireless communication system [11]. Since the related commercial products (wave generators, transceivers, oscillators, etc.) are suitable for 5G and already available for millimeter-wave technology, its deployment becomes smooth. We can learn several insights after applying the millimeter-wave technology in HSR systems, such as its applicability in tunnel scenarios with faster communication links [106]. On the other hand, the THz technology is expected to be a 6G wireless technology where the frequency band between 0.1 and 10 THz is utilized, enabling real-time transmission of higher than 100 Gbps. The THz band is a rarely explored frequency resource that captures outstanding advantages over conventional radio frequencies and can achieve tremendous data rates with an appropriate system design [107], [108]. However, THz radiations undergo severe pathloss caused by molecular absorption [109]. Nevertheless, in the case of Hyperloop, the tube environment is a vacuum which considerably suppresses the molecular absorption. Although the Millimeter-wave also suffers from molecular absorption, the shorter wavelength of THz waves results in severe pathloss, frequency selectivity, and scattering effect, shorter transmission distance and more complexity on the transceiver design [110], [111]. Nevertheless, tremendous data rates can be achieved by THz systems due to their larger bandwidth compared to lower frequency bands [109]. Also, the high mobility of the train requires ultra-fast beamforming techniques, which is a design challenge for the train-to-infrastructure scenario in HSR communications in general. In the case of Hyperloop, since the

TABLE 4. Research directions in Hyperloop communications.

Solution	Details	References
Antenna-based solutions	This category describes efforts to provide solutions that rely on antenna configurations that can address one or more Hyperloop communication challenges	[55], [115]–[117]
Radio-based solutions	This category describes solutions that deal with radio access, cell configurations and channel characterization.	[55], [118]–[121]
Network-based solutions	This category defines different network architectures proposed to provide a reliable communication to Hyperloop.	[54], [55], [116], [120], [122]–[124]
Software-based solutions	This category describes software, programs or any computer solutions to deal with different tasks executed by Hyperloop communication system.	[125]

tube-to-infrastructure communication will be, in most cases, served through optical links, this challenge arises in the communication between the tube and the pod, with additional constraints related to the ultrasound speed of the train and the specific tube environment. When antenna arrays are used, millimeter-wave and THz technologies have the advantage of compact sizes and, therefore, the possibility of easier integration of large numbers of antennas inside the tube. In fact, THz systems have a higher advantage in this regard because of the smaller antenna elements. Nonetheless, the use of large numbers of analog/digital converters and power amplifiers per antenna introduces additional costs when using digital beamforming [112]. For this reason, hybrid beamforming alleviates the cost of THz and Millimeter-wave front ends and reaps the benefits of both analog and digital beamforming techniques [113].

- **Free – Space Optical (FSO) Technology** FSO is another attractive candidate wireless technology that can assist Hyperloop communications due to its numerous merits. This license-free technology can transmit tremendous data rates over long ranges. It is a low-latency communication, immune to electromagnetic interference and can be easily deployed [114]. Furthermore, FSO transceivers are already available in the market. As a potential setup for Hyperloop, optical photodetectors can be installed along the tube. Laser beams originating from the train can be directed towards these detectors. This setup has the convenience of a single beam, point-to-point connection. At the same time, the design faces the challenge of alignment between the laser and the photodetector. Mechanical steering cannot be adopted because of the very high speed of the train. However, novel and adaptable solutions can be proposed to cope with the shortcomings of existing transceivers in the unique environment of Hyperloop.

V. ADVANCES IN HYPERLOOP COMMUNICATION

Developing robust communication system solutions for Hyperloop transportation systems is a new research area that requires appropriate research directions to be defined for tackling the expected limitations. Frequent handovers and severe Doppler shifts are among the limitations that have been discussed and studied. In this section, we classify the possible research directions for Hyperloop communication into four categories: Antenna-based solutions, radio-based solutions, network-based solutions, and software-based solutions (see Table 4).

A. ANTENNA-BASED SOLUTIONS

The impact of transmitting and receiving antennas is undeniably critical to the Hyperloop communication system performance. Antennas represent the interface between the wave propagating through the air and the electrical signal carrying information. In terms of characteristics, antennas are identified by the resonance frequency, operating bandwidth, directivity/gain, radiation pattern, and polarization. Therefore, the antenna performance directly affects the signal strength, allowable bandwidth, and transmission direction. The antenna of Hyperloop communication systems has been thoroughly studied as one of the communication features between the Hyperloop and trackside [55], [115]–[117]. The challenges in antennas implementation and design in Hyperloop vary from regular challenges to those more related to the specific environment and requirements of Hyperloop. Large bandwidth is an important asset for supporting the high data requirements of Hyperloop. Similar to other wireless application scenarios, the antenna radiation efficiency is crucial and is defined as the ratio of the radiated power to the power fed to the antenna by the transmitter [126]. As Hyperloop faces severe Doppler effect, antenna-based solutions can be provided to mitigate the shift by controlling the propagation characteristics. Moreover, antenna directivity is important to maintain the alignment between the antenna of the pod and the antennas placed along the tube. To improve the performance of the antenna system, antenna arrays can be used to achieve more flexibility and to increase the SNR. The antenna size must be carefully selected to accommodate the array within the limited space of the tube. Generally, the antenna size and shape are crucial attributes considering the specific environment

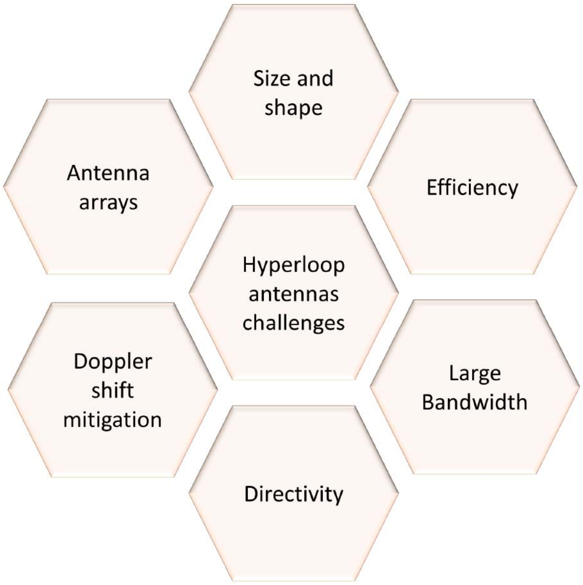


FIGURE 9. Main challenges related to the antenna used for Hyperloop communications.

and space as well as structural constraints of Hyperloop. The challenges are summarized in Fig. 9.

Research has focused on antenna-based solutions that can cope with Hyperloop communication constraints, especially the severe shift in frequency caused by the Doppler effect. Deciding on suitable antenna categories and configurations is one of the most critical challenges associated with Hyperloop system design. The used antennas must have a large bandwidth to convey the high data rates needed for different services of Hyperloop communication. Furthermore, the waveform and propagation direction can help address the Doppler effect as in [117]. Recently, considerable efforts have been made to develop antenna-based solutions to address the challenges faced in Hyperloop communication towards achieving a successful design [55], [115]–[117].

One solution to overcome the Doppler effect, which can drastically worsen the QoS, is to control the propagation direction for suppressing the Doppler shift. Leaky waveguides, also called as slotted antennas, are the commonly used antennas in Hyperloop communication system to suppress Doppler shift. As described in [127], a leaky waveguide is a type of antenna consisting of a waveguide that leaks a part of its power along its length. This type of antenna captures several advantages such as simplicity of design and installation, a flexible radiation pattern, and suitability for millimeter-wave [128]. In this context, a leaky waveguide solution to be installed on the Hyperloop tube ceiling was proposed to overcome the Doppler effect [115], [116]. The radiation direction of this antenna is considered to be orthogonal to the direction of motion of the train, as shown in Fig. 10. Simulation results show that the field distribution undergoes fluctuations in the tube vicinity and passengers experience flat signal coverage with uniformly distributed phase.

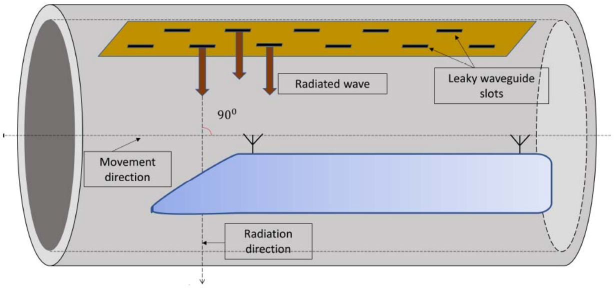


FIGURE 10. Configuration of the vacuum tube with a leaky waveguide.

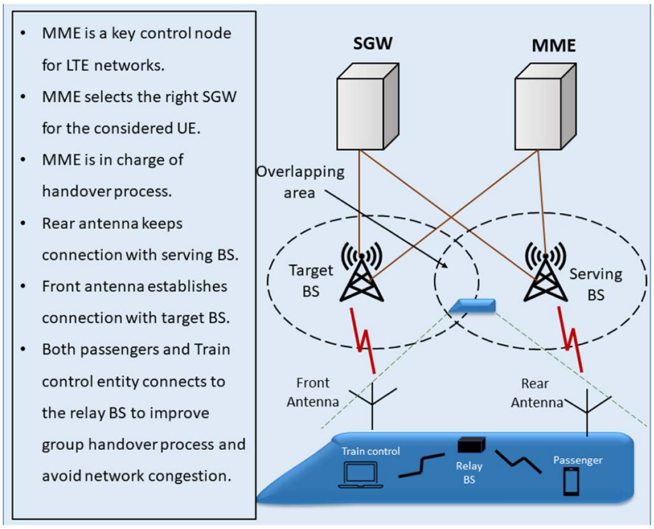
In [117], helical distribution was adopted as the fundamental concept. First, helical antennas are made of a wire with a helical shape. These antennas have several advantages such as high directivity, large bandwidth, simple design and especially the ability to achieve a circular polarization [129]. Circular polarization reaps several benefits over linear polarization, especially its ability to capture upcoming reflected waves in all planes. In [117], novel structures were proposed to reduce the impact of Doppler shift on the system performance. The first structure relies on a number of directional antennas that create a helical distribution. When combining the signals received by the antennas placed at both ends of the pod, the Doppler shift becomes a real value instead of a complex value, indicating that only the amplitude of the signal will be affected. The second structure relies on an antenna placed on the train and rotates around the axis of the tube, and a leaky waveguide with slots having a helical distribution is installed around the tube wall. When considering specific rotation velocity and radius, the structure can control the angle θ defined by the radiation direction and movement direction by keeping it as close as possible to 90^0. Results show that the Doppler shift is reduced compared to its maximum value, as expressed in (2).

To better understand the structure of leaky waveguides, Fig. 10 provides a simple model of leaky waveguide as presented in [116] to efficiently suppress the Doppler effect.

To efficiently use leaky waveguides, two structures were proposed to avoid penetration loss when the UE inside the pod communicates with the leaky waveguides placed on the ceiling of the tube [55]. The first structure relies on the use of a relay station. UEs communicate with an AP connected with a wire to the relay node, which forwards the signals to the leaky antennas. The second structure uses leaky lenses placed on the roof of the pod to allow a direct link between the UE and leaky waveguide. The lens can be tuned to obtain a uniform distribution.

B. NETWORK-BASED SOLUTIONS

Hyperloop communication performance is considerably affected by frequent handovers, resulting from the extremely high velocity of the pods and the short distances between BSs. Network-based solutions can mitigate the handover challenge similar to the approaches adopted in HSR



- MME is a key control node for LTE networks.
- MME selects the right SGW for the considered UE.
- MME is in charge of handover process.
- Rear antenna keeps connection with serving BS.
- Front antenna establishes connection with target BS.
- Both passengers and Train control entity connects to the relay BS to improve group handover process and avoid network congestion.

FIGURE 11. Some handover techniques adopted in LTE networks.

systems [75], [77], [78], [130]. In HSR systems, it is necessary to avoid simultaneous group handover through a single handover by connecting all passengers to a relay BS inside the pod. This approach helps to reduce the time required for the whole operation. The proposed solutions usually rely on mounting two antennas on top of the train, i.e., one at the front to connect to the target BS and one at the rear to keep the communication with the serving BS to avoid any data transfer interruption, as shown in Fig. 11. In this regard, the LTE control node MME is in charge of users' identification and authentication and assists the handover process [131].

Moreover, some network architectures were proposed to establish communication links with reduced handover delays. The distributed antenna system (DAS) is commonly used in HSR communication scenarios, in conjunction with RoF, to overcome handover challenges and is considered to be among efficient approaches [132]–[134]. In this architecture, several RAUs are associated to the same control unit (CU), and are interconnected in a ring topology through optical fiber. The RAU executes simple tasks, mainly up/down conversions and filtering, while most heavy computations are executed at the CU level. Therefore, when the train is moving between RAUs associated to the same CU, no handover is required, which reduces the handover rate [135]. Other schemes adopted in HSR systems to reduce handover delay and frequency are detailed in [135].

On the other hand, cloud radio access network (CRAN) is considered to be a promising architecture for broadband wireless communication. In conventional radio access networks, each BS, covering a specific area, performs processing tasks and then transmits the signals to the core network via a backhaul link. However, CRAN introduces a higher level of cooperation between the BSs via a distributed paradigm [136]. IN CRANs, the baseband unit (BBU) performs digital baseband processing, whereas the remote radio unit (RRU) executes radio functions [137]. It is worth mentioning that the LTE-R network also relies on a similarly distributed network architecture [138]. The main operational concept associated with CRAN is the centralization of all computational tasks at the cloud level in a data center, which is a shared pool among multiple BBUs. The CRAN architecture has numerous advantages over the traditional architecture where baseband and radio operations are performed in the BS. Powerful data centers are used, making it possible to execute heavy operations and extensive computations to accomplish advanced applications and technologies. Moreover, sharing the same pool promotes efficient resource sharing, and energy-saving [139], [140]. Therefore, the provided services become faster and more flexible [141].

In the case of Hyperloop, not all traditional architectures can effectively handle the vacuum tube communication because of several peculiarities stated before. Therefore, many research works explored some novel architectures that should support the Hyperloop operations effectively. In this context, distributed BSs were utilized in [124] with RRUs and BBUs. The handover process takes advantage of the stations' linear deployment, making the prediction and switching to the next RRU faster. The CRAN architecture was used in vacuum-tube flying trains based on a moving cell scheme as in [55], and [122]. The architecture shown in Fig. 12 is the CRAN architecture in the vactrain[2] scenario proposed in [55] and [116]. It is composed of three main parts: the RAUs, optical transmission network, and pool of BBUs in a data center cloud. The handover process in this scenario is executed at the optical level instead of considering successive connections/disconnections at the BSs inside the tube. Hence, the handover delay is reduced to 5 ns. Additionally, CRAN was adopted in [120] where several antenna units were integrated into a logical cell to reduce the number of handovers during the train trip.

To benefit from the 5G network, in [54], a 5G network architecture was proposed to serve the needs of Hyperloop communication via network slicing to multiplex independent end-to-end networks that fulfill multiple applications requirements. In this architecture, eNodeBs are placed on top of the tube connected to leaky waveguides operating as antennas.

To avoid the Doppler spread caused by RF signals, an optical wireless communication (OWC) scheme was adopted in [123] where optical access points are mounted on the top of the tube connected to an optical fiber backhaul. Communication redundancy is utilized to increase the system's reliability. It was shown that OWC outperforms RF schemes in terms of BER, especially for very high train speeds.

C. RADIO-BASED SOLUTIONS

Several techniques have been proposed to deal with frequent handovers faced by systems with high mobility [135],

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[2] Vactrain is another term for vacuum tube train.

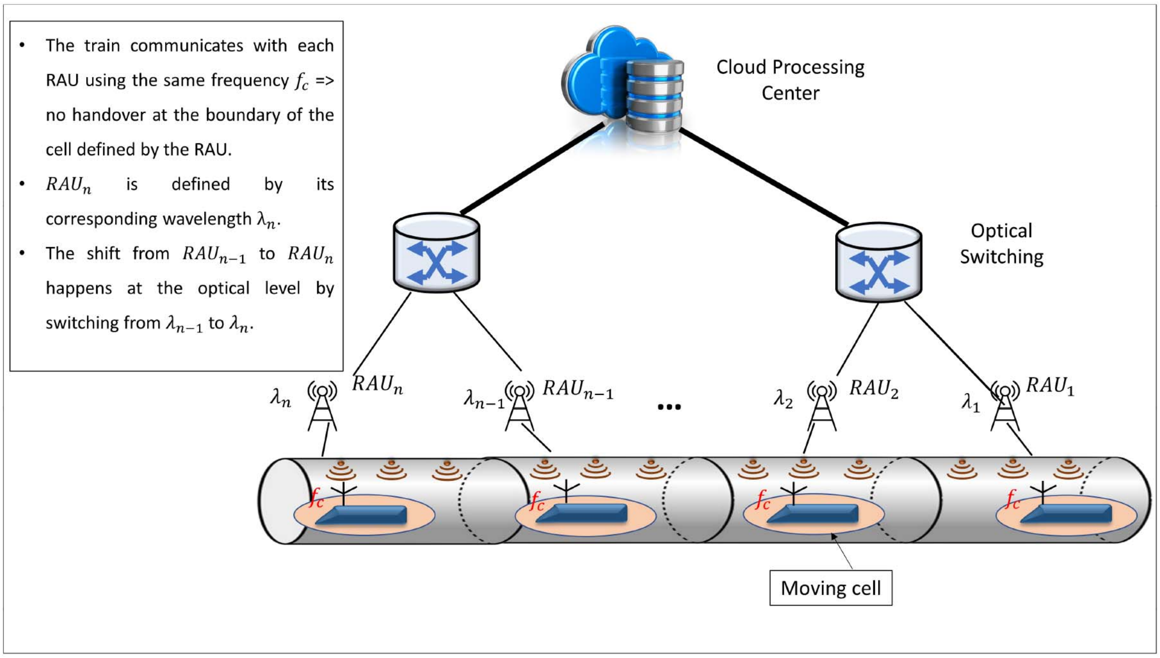

FIGURE 12. **CRAN system architecture for Hyperloop communications.**

including HSR systems. In this context, some researchers have opted for solutions based on radio access. The moving cell approach is a widely adopted technique, where a virtual moving cell with the train is used to avoid handover. The key concept of the moving cell is to allow the BS mobility with the vehicle in the same direction, and speed [142]. In other words, the train will connect to successive BSs using the same radio frequency and, therefore, avoids the time-consuming actions of disconnection and connection to BSs. The train's transceiver sends a signal to the RAUs using a fixed frequency. A central BS connected to the RAUs through optical fiber has instant knowledge of the train's location. The RAU transmits this information signal to the BS over an optical fiber. Using wavelength division multiplexing (WDM), several RAUs are connected to the BS with the same optical link, and each RAU has a specific wavelength. Here, the train transmitter receives information using the same frequency and does not perform a handover process to connect with each RAU. Optical switching will replace the handover at each RAU boundary, which drastically reduces the time consumption. Being efficient and simple to implement, this approach was extensively adopted in HSR communications [134], [143], [144]. Nevertheless, the moving cell approach may be limited to some mobility scenarios because it is constrained by the prior knowledge of the mobile speed and direction of movement.

As far as Hyperloop communication is concerned, the topic is emerging, and researchers are considering various directions. Due to its merits, the moving cell approach was the leading and prevalent approach that was initially adopted [55], [118] to reduce the handover delay. In [55], the moving cell was implemented jointly with CRAN, wherein computational tasks were centralized in a shared pool to reduce delays and support complex operations. Instead of executing handovers at each RAU boundary, an optical switching allows the connection to the active RAU. The handover delay can be drastically reduced using this approach. The overall architecture is shown in Fig. 12. In contrast, the authors of [118] applied the moving cell approach differently. They used the sliding window method for maintaining a constant distance between the BS and the UE. The BS is virtually moved along the movement direction of the vehicle. A dedicated cell is formed with some antennas in each time interval, where at least one antenna is involved in two consecutive time intervals. The moving cell approach is the core technology of the sliding window method and exhibits the shortest handover delay among other schemes with a handover success probability of 0.99.

Channel modeling is another critical part of the system design. It is influential on both the proper design and the performance analysis. Accurate channel characterization provides insights into appropriate resource allocation and conclusive performance analysis, which expands the opportunities to achieve a reliable, efficient, and safe communication system. Regarding channel modeling in Hyperloop, the authors of [119] used propagation graph modeling to characterize the wireless channel inside the vacuum tube. The graph modeling approach allows representing transmitter, receivers, and scatters as vertices and propagation characteristics between them as edges [145]. The LoS, first-order, and second-order reflected waves are used to model the channel impulse response (CIR) accurately. Also, the radio environment of a multiple-input multiple-output (MIMO) wideband system was emulated to provide virtual data representation

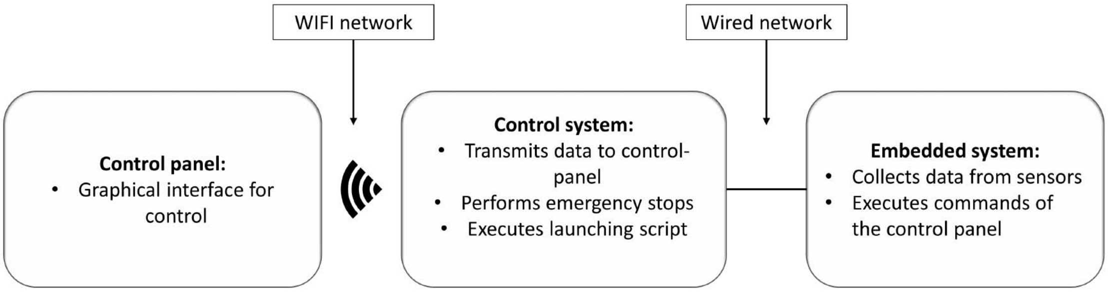

FIGURE 13. Software system overview.

of the channel for a specific tube geometry and train speed. Different KPIs such as the Doppler spread and the number of multipath channels were used to characterize the communication channel. Propagation graph channel modeling was also adopted in [120] to represent the channel when the DAS system is considered. The authors estimated the radio coverage of a slot from a leaky waveguide and the radio coverage between two cells. The channel gain was computed in [121] using the geometry-based deterministic models and considering LoS and first-order (or single-bounced) components. Each single-bounced component is considered to follow the Lambertian scattering model as Model 1 in [146], where the amplitude of the signal is computed as follows,

$$E_s = E_{s,\max} \cos(\theta), \tag{4}$$

where $E_{s,\max}$ is the maximum amplitude at the normal direction of the reflecting surface and θ is the angle between the scattered wave and the normal direction of the reflecting surface. Results show that the major contribution to the received signal comes from the scatters around the transmitter and receiver and provide suitable statistical distributions of the azimuth and elevation angle of arrivals of the scattered waves.

D. SOFTWARE-BASED SOLUTIONS

A comprehensive software solution that interconnects and integrates all components of the communication system is necessary to ensure the well-coordinated and smooth operation of the Hyperloop system. Wireless sensors networks are used to keep track of parameters such as temperature and speed of the pod, and transmit data to the control system. Furthermore, emergency interruptions can occur because of external or internal incidents and the software must be able to deal with the situation with minimum delays. On the other hand, the driver can access the user interface to control the pod, track the system performance and communicate with other drivers and agents.

As in [125], the system can be classified into three main parts, i.e., embedded system, control system and control panel, with appropriate communications links. An overview of the system architecture provided in [125], is shown in Fig. 13. In a competition conducted by SpaceX in 2015-2018, the team from Waterloo University developed a software system to assist Hyperloop operation at the launch phase. In [125], the authors presented a software that allows to control the pod during launch. The system must be able to accurately determine the location of the pod and efficiently command its operation. Results showed that the developed system was capable of executing control commands, gathering distributed data from sensors and accurately evaluating the launch performance.

E. FUTURE DIRECTIONS

Numerous research directions are yet to be explored to design and build a reliable train-to-ground communication system that can meet the specific requirements of Hyperloop. A wideband uRLLC system is crucial to realize high data rates and low latency for different services [92], [147]. In this section, we present some promising research directions suitable for Hyperloop communications.

Service requirements: Hyperloop proper operation requires strict service requirements in terms of delays, transmission errors, and data rates. This challenge needs to be addressed because it can compromise the performance of the system and the safety of passengers. Therefore, we need to design a system that can answer the particular requirements of Hyperloop where the required transmission delay and BER for some critical services can reach 1 ms and 10^{-6}, respectively [55]. Moreover, millimeter, THz and optical waves are convenient candidates that can considerably increase the bandwidth and therefore, reduce the latency. However, deploying millimeter-wave and THz is challenging. They suffer high atmospheric absorption and severe scattering because the wavelength has roughly the same dimensions as water drops and surface imperfections. Another challenge is signal penetration, causing loss of information when propagating through obstacles. Therefore, an accurate system model and adequate design are necessary, where MIMO and massive MIMO are interesting techniques to be investigated. Moreover, FSO can be deployed inside the vacuum tube and thus efficiently reaping the benefits of this technology. Through FSO, considerably high data rates and very low-latency communication can be realized [148], making it particularly beneficial for Hyperloop communications. This technology is inherently secure and has a high reuse factor thanks to the confinement of the narrow light beam. Light-emitting diode (LED) or laser can be used to transmit signals over a large bandwidth [149], [150]. However, Hyperloop pod is in motion with very high speed, resulting in pointing and tracking errors and even communication outage. The system design is challenging. In this case, steering the light beam is necessary. However, this setup may increase the overall cost of the system considerably.

Channel models: Another challenge is related to the lack of suitable channel models that can accurately characterize the propagation environment inside the tube, especially with the very high speed of the pod, which makes it different from traditional mobility scenarios. Statistical models need a database obtained through extensive field measurements, which have not yet been conducted to the best of our knowledge. Therefore, addressing this challenge is a priority to allow accurate future systems designs. Although deterministic models using ray-tracing techniques, for example, prove useful to predict the wireless channel, reliable statistical channel models must be developed and confirmed through measurements and real-world system experiments. Therefore, field measurements that parametrize the models are another challenging task because of the high speed of the train, the tube structure and the special conditions of operation (mainly the evacuated environment). A large amount of data will be collected and stored in databases to be used as a reference for future research efforts in Hyperloop communications to reduce the computational complexity.

Handover and Doppler effect mitigation: As mentioned earlier in the paper, frequent handover and severe Doppler shifts are two main outcomes of Hyperloop sonic speed. Although some researches have been conducted to face these issues, we envision further efforts in these areas because of the lack of simulations and experimental results. Fast handover algorithms are needed to meet the speed of the movement and the successive connections/disconnections. Moreover, techniques to cancel Doppler shift or harness its benefits can be used, such as Doppler diversity or intelligent reflecting surfaces (IRS). IRS is a revolutionary technology in radio propagation because they are capable of controlling incident waves. It is considered as a 6G technology, portraying smart environments that will increase energy and spectrum efficiency and immensely improve wireless communications. They can tune the frequency of the incident wave. This feature can be used to reduce or even cancel the Doppler shift by adjusting the frequency to its desired value. Moreover, non-coherent differential spatial modulation (SM) can be utilized to mitigate Doppler shifts [151]. Non-coherent scheme bypasses channel state information (CSI) estimation, unlike coherent SM that relies on prior knowledge of CSI, resulting in estimation overhead and performance degradation [152]. The non-coherent scheme can be helpful to design systems for Hyperloop communications robust to high Doppler shifts.

Hybrid architecture: Hyperloop communication system will combine different technologies since the overall network is divided into different portions with different characteristics. A heterogeneous network will be put in place where several issues may be encountered, such as user experience, interoperability of technologies and deployment complexity. Availability and scalability are two major aspects of Hyperloop communication network. Future research directions in Hyperloop communications include, furthermore, the investigation of several technical aspects such as optimal positioning of APs, efficient radio resource management, and instant tracking of the train location.

Optical networks are considered among the preferred solutions due to their high throughput and short delays [153]–[156]. Optical fibers can serve in the tube-to-ground portion of the network, while wireless optical communication can be established inside the tube. Several technologies may be considered, such as LiFi and FSO. The optimal design of the network is a challenging future direction, where the positions of stations and relays, the modulation of the optical signal, multiplexing schemes must be considered, especially in the presence of some limitations such as the short ranges of optical signals and the high implementation cost.

MIMO systems and precoding techniques: Precoding techniques are becoming a tempting research topic that helps to relieve the complexity of MIMO and massive MIMO systems that require large numbers of radio frequency (RF) chains and antennas [157]. For instance, hybrid beamforming (HB) is a combination of analog (AB) and digital beamforming (DB) with a reduced number of RF chains compared to the DB [113]. In AB, phase-shifters are used to form a dedicated beam towards the desired direction [158]. On the other hand, DB relies on baseband processing and requires an RF chain (with power amplifier, analog-to-digital converter$\cdots$) for each antenna element with increased cost and energy consumption [113], [159]. HB is an energy-efficient solution that mimics the performance of DB [160]. Considering spatial restrictions on the communication and electronic devices inside the tube, HB is a promising scheme that can be utilized to avoid cumbersome cables and devices inside the tube with reduced power consumption, while maintaining DB-like performance. Furthermore, multi-cell coordination is considered a key technique to manage inter-cell interference where joint signal processing is executed between BSs to share useful information (CSI and/or user data). This scheme allows the use of interference channels to transmit useful information, reduce inter-cell interference and maximize the throughput [161]. Cell cooperation is proven to be an efficient technique to improve the performance of wireless communications depending on the proposed level of cooperation [162]. The wireless access points installed inside the tube form adjacent cells and can benefit from cell coordination to ensure seamless transitions (handoffs) and achieve higher data rates. Future research efforts can further promote the use of cell cooperation in Hyperloop systems, especially that a huge complexity is imposed on CSI estimation and tracking in fast fading time-varying channels [74].

VI. CONCLUSION

The challenges associated with Hyperloop communication system considerably differ from those associated with conventional HSR systems, resulting in communication scenarios and events unfamiliar to the HSR communication community. The specific design of the train, tremendous speed requirements, and modern services expected by passengers make the task of designing a thorough and efficient communication system extremely challenging.

In this paper, we present a comprehensive study of Hyperloop communication system and different research work conducted to address several encountered challenges. We also propose potential solutions that can efficiently serve Hyperloop. Recent research has led to various solutions ranging from antenna design and network architectures to radio solutions that can adequately cope with the specific structure of Hyperloop. Leaky waveguide antenna designs are frequently proposed to reduce the Doppler shift, while studying the near and far fields of the antenna. Further, radio solutions that adopt moving cell approach to considerably reduce the number of executed handovers have also been explored. Similarly, network architectures such as DAS and CRAN were considered to reduce handover delay by adopting a centralized architecture combined with optic fibers.

Future research should focus on bringing together candidate technologies into a cooperative homogeneous solution and develop a complete Hyperloop communication system. Several technologies such as millimeter and THz waves, FSO, UAVs, MIMO and other techniques must be investigated for Hyperloop communication [150], [163], [164].

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