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ARTICLE TYPE

COMMUNICATION SYSTEMS OF HIGH-SPEED RAILWAY: A Survey

Waled Gheth*¹ | Khaled M. Rabie¹ | Bamidele Adebisi¹ | Muhammad Ijaz¹ | Georgina Harris²¹Department of Engineering, Manchester Metropolitan University, UK²School of Science, Engineering and Environment, University of Salford, UK**Correspondence**

*Waled Gheth, w.gheth@mmu.ac.uk

Present Address

John Dalton Building, Manchester Metropolitan University, Chester St, Manchester M1 5GD

Summary

Modern railway services are required to deliver good quality services to the passenger throughout the whole journey. These include improved performances, safety, and reduce delays. There is also the requirement for in-train customer experience such as infotainment and access to reliable communication systems. The railway industry has employed different types and generations of communication systems in recent times. Signaling systems were used at the early stage of the railway services. Today, communication systems such as the second-generation communication system, also known as the global system for mobile communications (GSM), the Third-generation (3G) and the Fourth-generation (4G) are utilized in the railway industry. In this paper, we present a brief history of railway communication systems, their features and applications. In addition, we discuss the technical challenges and potential solutions of in-train communication systems and how data can be distributed on-board and between the train coaches using state of the art and hybrid communication technologies.

KEYWORDS:

High-speed railway, long-term of evaluation, optical wireless communications, power-line communications, visible-light communications.

1 | INTRODUCTION

High-speed railways (HSRs) offer transport that runs considerably fast in excess of 160 mph for the new lines and in excess to 120 mph for the existing ones. Hence, HSRs can significantly improve the quality of service which in return leads to greater customer satisfaction¹. However, the rapid development of the HSRs brings significant challenges in terms of industry, technology, and investment. For safety reasons and to handle the rapidly increasing traffic, a reliable communication system is required for HSRs. The current HSR communication systems have a foreseeable end to their lifetime and the need of a reliable communications system has become essential. Therefore, the assessment of the future of HSR mobile communication has recently started.

Different parameters are considered for the selection of a suitable system that can fulfill the requirements of HSR operations such as performance, service attributes, frequency band and industrial support. Fourth-generation (4G) broadband systems are one of the proposed systems to replace the current HSR communications systems. These systems, compared with Second-generation (2G) and Third-generation (3G) systems, have more capabilities as they offer higher data rates². Currently, Fifth-generation (5G) systems are still being discussed and will not be available before 2020. Therefore, they are not an option for the HSRs time frame^{2,3}. For their performance and high level of maturity, the 4G long-term of evaluation (LTE), LTE-railway (LTE-R) is more likely to be the most suitable and reliable technology for the next generation of HSR communication systems^{4,5}.

The non-negligible time that people spend commuting on trains can be used for reading electronic book, watching live programs, listening to music and playing video games. Some services, for instant ticketing and seat reservations, operate smart-catering and smart-retail services as well as supporting continuous condition monitoring of in-service rolling stock can be easily provided by using proper communication systems within the train. However, communications within the train is another issue as the electromagnetic waves can be severely attenuated by the metallic coating of the train⁶. Connecting the train to a network then distributing signals within and between coaches by using a proper distribution system could be a preferable scenario for communications inside the train⁶.

In order to achieve broadband services, different reliable communication system that can provide better performance and mobility to the end users can be adapted inside train coaches, such as wireless local area network (W-LAN), power line communication (PLC), optical wireless communication (OWC) services of the visible light communication (VLC), and a communication system which is based on a combination of PLC and VLC. W-LAN, most of the modern communication apparatus can use this system as they have W-LAN interface⁷. Besides W-LAN, femtocells or repeaters of the mobile communication standards themselves can be installed inside the coaches⁷, PLC is another candidate for in train communication. This can be used to achieve broadband services among the interconnected locomotive coaches. The principle of PLC is based on the use of the existing power lines in buildings, utility grid or vehicles to carry data and electricity, simultaneously⁸. This technology has been around for some decades, but it has only been used for limited applications such as, home automation, public lighting and narrow-band tel-remote relay applications. Recently, some studies showed promising results about using the PLC technology on board vehicles (automotive and aircraft). However, PLC might sooner play an important role in communication within the train, but it is still a new field of study⁹. To the best of our knowledge, very limited studies were carried out so far concerning broad-band PLC (BB-PLC) inside trains, particularly on PLC channel characterization^{9,10,11}.

Mobile phone and laptop users can also enjoy broadband services using VLC which has recently matured. This technology can provide a significant range of benefits to the railway industry not only within the trains but inside stations as well; since every source of light on a train or inside a station could be used as a wireless hot-spot^{12,13}. However, some light sources have advantages that made the VLC technology began to be used in various indoors and outdoors applications. Light Emitting Diode (LED) is one of the light sources of the VLC technology which can offer energy efficiency, long life expectancy and low maintenance cost¹⁴. Nevertheless, there are a number of challenges to be overcome and studied before this technology can be fully employed¹².

The paper presents a brief history of railway signaling and the need for a reliable railway communication system that can meet the demand for rail transport. This is followed by an overview of HSR-dedicated communication systems. A comprehensive review of the current GSM-R system is introduced in this paper along with its essential challenges. LTE-R that has the ability to fulfill railway requirements and a likely candidate for next-generation HSR communications is also presented in this paper. The systems parameters and services of both GSM-R and LTE-R are described, and some limitations are discussed. Furthermore, comparisons between public networks and railway networks are made. The authors also present some reliable communication systems that can play a crucial role in the future of railway communication. Moreover, a survey on the communication systems that can be used to distribute signals inside and between train coaches is provided. The paper discusses the advantages and the challenging issues of such in-train communication systems.

The rest of this paper is organized as follows. A brief of history of railway communication is given in Section 2. Section 3 discusses the communication-based train control systems and the description and limitations of the GSM-R and the LTE-R systems. Section 4 presents communication within the train. Section 5 is the future work. Finally, the main conclusions are summarized in Section 6.

2 | BRIEF HISTORY ON THE RAILWAY SIGNALING

The survey of signaling and its development starts from the first purpose-built passenger-carrying railway with haulage by locomotives Liverpool and Manchester Railway which was opened in September 1830¹. At this time the railway was entirely controlled by human signals. This is to ensure that the separation distance between trains is more than the required stopping distance. The concept of 'stopping distance' term is common among people. The highway code shows that about 20 meters is the required distance for a car with 30 mph speed to be completely stopped and it requires three times of this distance if the speed is double¹. The required stop distance for the modern trains even with superior brakes is as high as 1.25 miles as their speed is 200 km/h. To avoid colliding with obstructions and other trains there was a need of disciplines that can ensure a safe

separation of moving trains. In 1830, none of the facilities which are considered today to be essential to operate the trains safely, for instance, telegraphs, telephones, line-side signals, etc, were available¹.

At that time, the signaling systems were totally human-based. The guide-ways were divided into different sections, each section is about two miles, where a stationed railway policemen give hand signals to train drivers at each section. The policemen either give a clear signal to the coming train if there is no train in the section or indicate stop signal if the section is busy. There was one insurmountable disadvantage with this signaling system. If a train fault occurred and it stopped in a position, out of sight between two policemen, the guard of the train had to go back to indicate stop signal to the next train approaching the section.

In the late 1830s, the policemen hand signals were replaced by fixed-line signals. This system has the advantage of being visible to the train drivers from greater distances, where Red indicates 'Stop', Green 'Caution' and White 'Clear' in according to the convention¹. A reliable form of communication was needed between the policemen in each section. Cooke and Wheatstone electric telegraph was the device that would present the required communication between the train policemen. In 1838, policemen used a telegraphic code to send words letter by letter where the telegraph's needle was moved to the right or left to allow messages to be sent and that is how policemen could report the entering and the leaving of the train to/from the section¹.

The electric token system of single-line was used in the 1890s instead of using telegraphic orders¹. Track circuit, used as a practical mean to detect the presence of a train at a certain location. The use of this information would help to protect the train against other trains which are moving towards it. One of its benefits was the ability to control the signals (either power-worked semaphores or color-lights) without human interference. In the last three decades, electronics spread widely into all walks of life¹. Adoption of processor-based interlocking systems was the most significant advance in those decades.

Recently, the demand of rail transport has increased due to many reasons including the growth of population, environmental requirements, urbanization increasing, and trains are more energy-efficient safer; and higher speed than the other land transport. Some studies^{15,16,17}, showed that the rail mark in Europe grew by approximately 28 billion Euro in only five years with an expectation to grow more in the nearest future. This growth needs more modern communication-based signaling system to be installed compared to the previous decades^{18,19}. The technology of the conventional railway signaling is almost 50 years old and it is regarded as the main reason of delays of the trains experienced every day. This explains why these systems are being replaced by new ones^{20,21,22}.

Today, a number of radio-communication-based signaling systems are installed worldwide for mass-transit operations. The use of radio communication makes such systems the first choice of some operators as they offer high resolution and real-time train control information, which consequently would minimize the number of equipment in the track-side and increase the capacity by reducing the distance between the trains in the line^{23,24,25}. Communications-based train control (CBTC) systems are regarded distinct from the European rail traffic management system (ERTMS), as they are specifically used for mass-transit which implies IEEE 802.11 wireless local area network (W-LAN) computer and radio communication for certain frequency bands.

3 | COMMUNICATIONS-BASED TRAIN CONTROL (CBTC) OPERATION

CBTC uses high capacity radio communication for train control information exchanging between the train and the wayside. This would enable both train control functions, automatic train operation (ATO) and automatic train supervision (ATS), and automatic train protection (ATP) subsystems. Simply, the state of the train including speed, direction, and location of the train is sent continuously over the radio connection to the wayside. The traffic control center at the wayside as a part of this system receives the information sent by the trains on the track then calculates two factors: maximum speed and distance that the train is allowed to proceed. The traffic control center also performs many other functions, such as trains scheduling and trains arrival time to destination²⁶. CBTC system contains multiple Wi-Fi APs to ensure a continuous connection. These APs are placed at the track-side in a way that their coverage areas are overlapped. Each AP is then connected to the traffic control center by cable and communicates to the train through a radio connection. However, the installation cost of the cables which connect the APs to the wayside is very high and considered as one of the challenges of this system as it reaches to about 30,000 EUR/Km. The second challenge is the handover process, train ought to be connected to an AP all the time and as it moves should find a new suitable AP. Scanning, authentication, and re-association are the stages of the handover process in according to IEEE 802.11²⁶.

Both scanning and authentication contribute the most to the latency of the process. The study in²⁷ showed that the latency of the scanning stage, the process of finding a suitable AP, is almost ninety percent of the total latency of the handover process. Generally, for latency reducing, active scanning is adapted in CBTC systems in a way that the announcement of searching for APs is proactively made by a node rather than waiting for APs announcement. The study in²⁸ showed that data lost due to radio

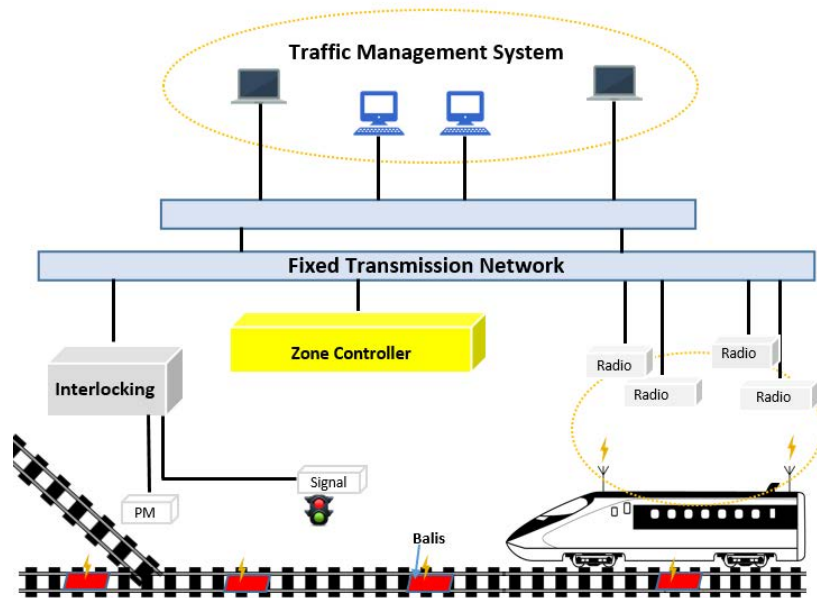


Fig. 1 CBTC system overview.

propagation effects is much less than that caused by the handover as the typical handover time is from 70-120 milliseconds in CBTC. However, two radios or more are installed at each end of the train to ensure a smooth transition, while one of these stays connected to the previous AP the other one switches to another AP.

A combination of devices is used in CBTC to determine the train speed and location such as transponders (“balises”), tachometers, Doppler radar, speedometers, odometers, and geolocation systems such as global positioning system (GPS)²⁹. Based on the information collected by such devices, the wayside traffic controller measures the limit of movement authority (LMA), the maximum speed and distance that the train is permitted to travel and passes it back to the on-board equipment. Based on the information received back from the wayside ATC, the train speed and safety distance are continuously adjusted by the on-board equipment of the automatic train control. As a train passes over transponders which are mounted between rails, the transponders transmit the location information to the train through an antenna fixed under the train. Any inaccuracies in the location that could accumulate when the train travels over a distance will be corrected as soon as the train passes the next transponder²⁹. Fig. 1 presents an overview of the CBTC system.

Real-time information exchange, provided by CBTC systems, explains why these systems would replace the conventional systems. Using this system reduces the headway distance between trains thus the capacity of the line increases and decreasing the number of the track-side equipment required by the previous system, for instance, color light signals and track circuits¹⁹. However, the main problem of using GPS is detecting the accurate location when two trains moving very close to each other on the railway. Also, the CBTC suppliers do not rely on the satellite signals inside tunnels. Moreover, the GPS is controlled by an external authority which makes the suppliers of CBTC hesitant about relying on such a system, thus its utilization in CBTC is supplementary.

As we previously mentioned, the rail tracks in conventional railway are divided into sections. The main purpose behind these sections is to make sure that separation distance between two neighboring trains is enough to stop the train in case of failure. These sections are called blocks and they are protected by a signal, track circuits are installed to determine the movement of the train inside the blocks. The length of any section is dictated by some factors, including the maximum speed of the trains, trains braking capabilities, the busyness of the line and the maximum allowed speed on the same line, etc. If a train is determined inside a block, no other trains are permitted to enter into this block and the entire block is considered as occupied. These blocks are called fixed blocks as their boundaries are fixed, regardless the speed of the train and its braking capability^{29,30}. The simplest way to describe this is that fixed block signaling creates an artificial separation between trains.

Even though the signaling community has been served well by this method for more than a century, the urban growth required a new reliable system to replace it. On the contrary, CBTC uses moving block operation, thanks to the real-time communication which is used to communicate between the train and the wayside. As the location of the train is continuously corrected and

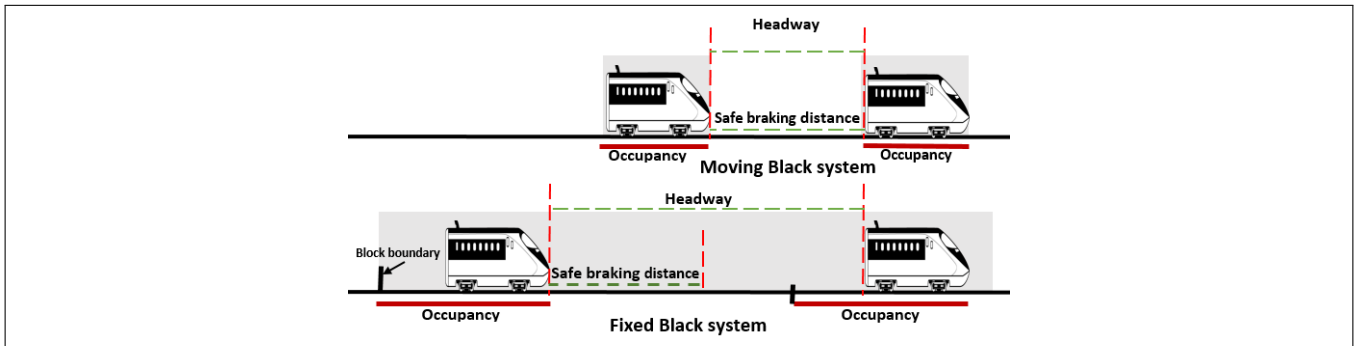


Fig. 2 The difference between fixed and moving blocks.

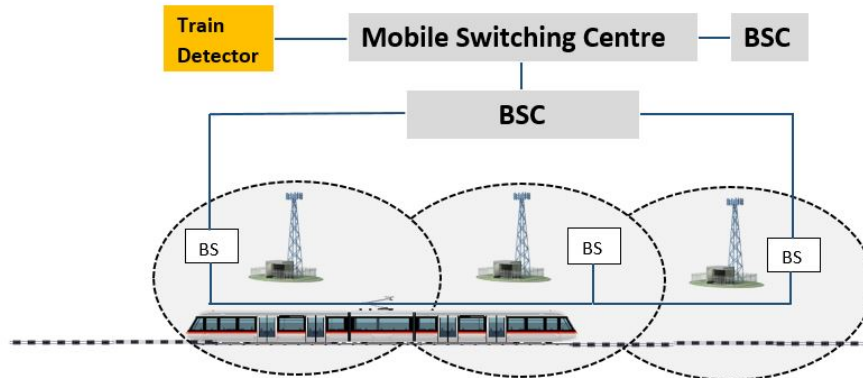


Fig. 3 GSM-R system architecture.

updated, the occupancy block moves with train with no fixed boundaries which allow trains to move closer to each other. The most important benefit of this paradigm is the safe braking distance was not anymore fixed but changeable depending on the speed of the train; if the train is moving at low speed the headway is short and expands as the train speed increases. As seen in Fig. 2, which shows fixed and moving blocks, the headway, the distance between two trains following each other, in the conventional signaling systems is relatively large compared to that in the CBTC systems. This means information, such as location and train speed, might not be received by the following trains within sufficient time. In such scenarios, the emergency brakes should be applied and the manual drive mode ought to be implemented¹⁶.

3.1 | GSM-R

GSM-R is an international wireless communication which has been specifically introduced to European rail companies to replace the conventional railway communication system as well as to ensure that trains can safely travel to different countries without any communications issues³¹. The GSM-R mobile technology is radio network which provides the radio coverage for both commuters and train crew. It is used for voice calls, data transmission and traffic control. In this system, the communication for drivers and signallers is secure as the coverage of the rail network is thorough, including deep cuttings and tunnels³². GSM-R and GSM system are basically the same but GSM-R has railway specific functions based on European standards and specifications².

Each driving cab is equipped with a cab radio to be used by the crew of the train for communication purposes. Dedicated base stations (BSs) are installed beside the railway track to configure the GSM-R system. The distance between any two neighboring base stations is different from country to another depending on the local environment, for instance, it is from 3-to-5 km in China and 7-to-15 km in Europe². The cell range or the area covered by each BS is around 8 km, and the frequency band used by GSM-R system is around 800/900 MHz. However, there are extra frequency bands used in GSM-R on a national basis known as extended GSM-R (E-GSM-R). These frequency bands are 873-876 MHz and 918-921 MHz, the former is for up-link and the latter is for down-link².

The BSs are linked together in groups and controlled by base station controller (BSC). This BSC also provides the connection between the BSs and the mobile switching center (MSC). The MSC is one of the mobile switching subsystem (SSS). The MSC is the network core which is responsible of the connection between the users of the system and managing the mobility of the users. Furthermore, its gateway is in charge of connecting between the GSM-R network and other public networks³³. The second function of the SSS is; the dynamic database and visitor location register (VLR). When the mobile station (MS) moves to a new control area, the home location register (HLR) provides the required data to the new VLR such as location registration, the VLR stores the information of the users which is initiated by the HLR³³. In order to enable the GSM-R system to track the position of the train and provide services to that train, the journey details should be entered into the cab radio of the train by the driver.

The GSM-R system offers different services to its users. Point-to-point and group calls are some of the services which is provided by the system, where the former is a similar to the normal telephone call as it is between two users only, the latter is a group call and using the press to talk (PTT) is required to take part in this call conversation. Every user in the GSM-R area where the group call was aimed at will be connected to the conversation and will be leaving the call when they leave the aimed cell or area. Operational text messages is another service that the GSM-R provides. GSM-R users (drivers, signalers and controllers) can send different types of operational text messages which would improve the communications between them, such as contact signaller, wait, standing at signal and acknowledge. The GSM-R system architecture is shown in Fig. 3.

Even though the GSM-R system is very relevant to the high speed trains and is based on a mature technology, but it has some considerable limitations. Handover is the most crucial issue that can affect the quality of service (QoS) in GSM-R systems³⁴. Mobile-controlled handover, network-controlled handover and mobile-assisted handover are the three strategies of the communication systems. However, the latter where both up-link and down-link signals are involved, is the handover scheme applied in GSM-R³⁵. The GSM-R handover process is controlled by BSC, which initiates the handover whenever the signal strength report received from the MS shows that the signal strength of the target cell is by far stronger than the serving cell³³. The small area covered by each BS and the high mobility of the trains make the handover process in GSM-R systems different and more difficult than that of the GSM systems. This also increases the number of handovers during one voice call or data transmission².

The transmission of the signal in the GSM-R system suffers from shadowing and multi-path effect. In addition to this, transmission in GSM-R networks is affected by the Doppler shift due to the high speed of the MS³⁶. The growth of both GSM-R and public networks has increased the electromagnetic (EM) interference between both networks². The second source of conducted and radiated EM interference is caused by the arcing between the contact wire and pantograph during the current collection process³⁷. This is a common phenomenon in electrified railway systems that predominantly occurs at higher speeds and loads. This interference might cause a significant impairment of communication as well as network loss along the rail tracks³⁸. In order to avoid such interference, and ensure reliable transmission, this problem has been investigated by a number of research^{39,40,41}. A number of solutions are proposed in the literature to eliminate the effect of the EM interference on the performance of the GSM-R systems, such as increasing the coverage level, processing the signal at the receiver and enhancing the receiver part on the trains⁴².

The dedicated frequency bandwidth and circuit-switched based design of the GSM-R limit its capacity. Only 19 frequency channels are available in the allocated 4 MHz bandwidth to the GSM-R systems which leads to some technical issues in providing services to all trains in busy areas at the same time⁴³. In different scenarios such as a high volume of traffic the circuit-switched can not ensure a reliable voice and data transmission at the same time and the need to an alternative approach becomes essential⁴⁴. In such cases, the packet-switched, based on general packet radio service (GPRS) and enhanced GPRS (EGPRS) services, can be used to increase the capacity of the GSM-R systems by improving the use of the frequency spectrum⁴⁴. Capability is considered as another challenge of the GSM-R system. The insufficient transmission rate and the system delay can hardly support any real-time applications and emergency communication⁴³. The gaussian minimum-shift keying (GMSK) modulation scheme used in GSM-R is much less flexible in terms of allocating resources to the users than the orthogonal frequency-division multiple access (OFDMA) used in LTE-R⁴⁵.

Even though the GSM-R continuity is ensured for the next few years, but due to the mentioned limitations, the need of switching to another system which can overcome these limitations is necessary. At the current time LTE-R based on LTE standards might be the preferable candidate to replace the GSM-R system⁴⁴. The deployment of LTE-R systems can improve the performance of the HSR communication systems in terms of capacity and capabilities as it uses a fully packet-switched-based network⁴³. Furthermore, the advanced multiplexing and modulation used by LTE-R can improve the spectral efficiency. Moreover, LTE is also a well established and off-the-shelf system and the coexistence between the previous HRS communication and the LTE-R is predicted to last for some time which is strongly support the move from GSM-R to LTE-R².

3.2 | LTE-R

Due to the required reliability and availability of the railway communication system, public networks have been developing for many years from systems with limited capability such as GSM to systems that can provide better performance in terms of data rates such as LTE^{2,46}. The main aim of these systems was to improve the speed and capacity of wireless networks. For this goal new digital signal processing and modulations techniques were employed at the beginning of the last decade. A further aim was making the system architecture less complicated by redesigning to an IP-based network which can ensure less transfer latency than the previous wireless systems⁴³. Thanks to these reasons, that the LTE-R, which is based on LTE standards, is considered as the best candidate that can replace the current railway communication system at the current time². In this regard, some preliminary recommendations were issued by the international union of railways (UIC) on the feasibility of using standard LTE as the replacement of the current railway communication system⁴³. However, the first LTE-R network is already scheduled to take place in some countries by the beginning of next decade². Fig.4 shows the development history of wireless communication systems from the GSM to 4G. Compared to the GSM-R system, LTE-R system offers a high data rate up to 50 and 10 Mbps

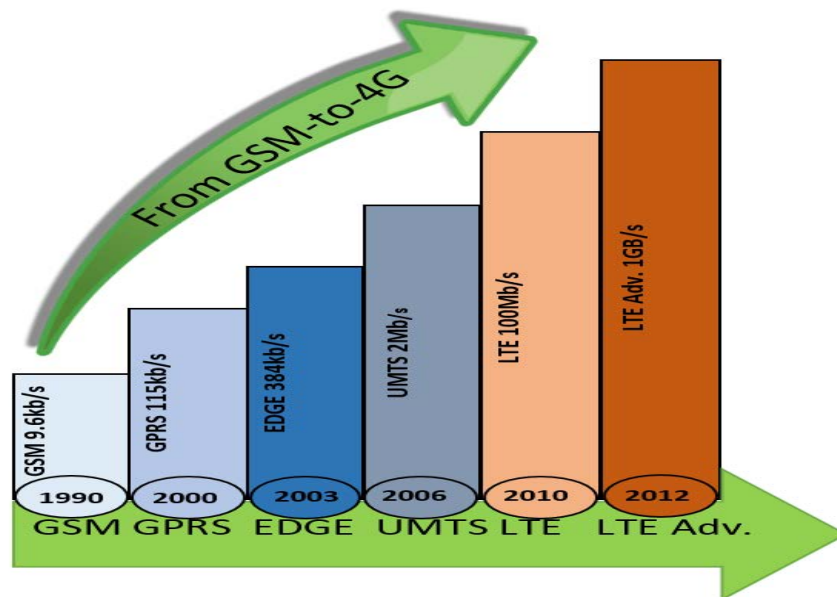


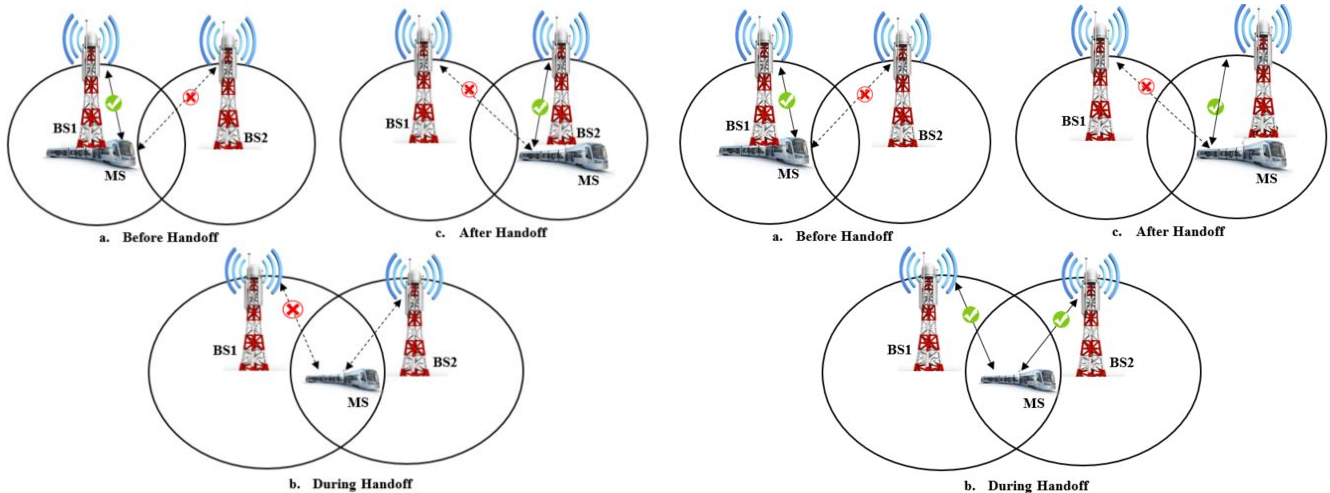
Fig. 4 The development of wireless communication systems from the GSM to 4G.

for down-link and up-link, respectively. QPSK/16-QAM is the modulation scheme used in the LTE-R system, whereas GSM-R uses GMSK modulation scheme. The handover process in GSM-R system is a hard change, that is, the connection of the MS is entirely broken with the current BS before it is being switched to the target BS. This handover technique is also known as break-before-make. Although this process appears seamless to the network users, there is a possibility that a short break in the connection can be easily noticed particularly during high speed movement of the train that causes a frequent handover during one call. Unlike the hard handover that is implemented in GSM-R system, the LTE-R system uses the soft handover between the BSs⁴⁷. Here, the MS is always connected to at least one channel. This process is known as make-before-break as the MS keeps the connection for the previous BS until it gets connected to the target BS. In the downlink direction of the soft handover scenario, when the MS is in the overlapping area coverage of neighbouring BSs, the signals that are received from these BSs are combined at the receiver. However, in the uplink direction, the signals from the BSs are compared frame-by-frame basis, and the best one is selected. Although the make-before-break process is more complex compared to the hard handover process, but it can drastically improve the QoS by reducing the probability of call drop and eliminating the interference⁴⁷. Table 1 shows some characteristics of hard and soft handover processes.

However, this is considered one of the major challenges of the LTE-R system. The system is meant to support high-speed trains up to 500 km/h. The high speed of trains and the small area covered by each BS lead to increasing the number of handovers between the cells in LTE-R network³⁵. To start the handover process in LTE-R system, the user equipment reports the signal

TABLE 1 Characteristics of hard and soft handover processes.

Characteristic	Hard	Soft
Complexity	Less	High
Disruption time	High	Less
Network resources	Uses less	Uses More
Extra radio link	Not required	MS consumes extra radio link
Additional hardware	Not required	More hardware is required–12 km
Packet loss	High	Less

**Fig. 5** Mechanism of Hard Handover.**Fig. 6** Mechanism of Soft Handover.

strength to the serving cell which then decides whether the MS needs to be connected to the target cell or not. If the handover is needed, the current cell sends a handover request message to the target cell then the target one sends acknowledge message if it accepts the handover request. A path switch request or handover notify message is then sent by the target cell to mobility management entity which in turn informs the serving gateway about the change in the path of the MS⁴⁷. Figs 5 and 6 show the mechanisms of hard and soft handovers, respectively.

The perfect use of the frequency and spectrum of LTE-R is vital to consider in order to provide a reliable and efficient communication system for HRS. Currently, 1 GHz, such as 1.8, 2.1, 2.3, and 2.6 GHz are the bands where the most of LTE system work at². Although the availability of bandwidths is higher at high frequencies which gives more data rate, but longer distance coverage can be provided by lower frequency bands. Furthermore, it is known that the propagation loss and fading are considerably larger at higher frequency bands. Therefore, lower frequency bands 450-470 MHz have been widely considered for HRS². The use of this low- frequency band can allow countries reducing the cost of the network by reusing the existing GSM-R mast sites². Table 2 shows some parameters differences between GSM-R and LTE-R.

There are some differences between both public LTE and LTE-R networks, such as the layout of network, architecture, system parameters and QoS. The reliability has more consideration than capacity in LTE-R networks configuration². Although the capacity is less considered than the reliability in LTE-R, the LTE-R cell can serve 27 trains simultaneously at one of the main train stations and the capacity provided by the cell is enough to serve more trains at the same time⁴⁸. The LTE-R network is supposed to be able to operate at a very high speed up to 500 km/h, sometimes in very complex railway environments. A growing number of research works has been contacted to prove that the LTE-R can fulfill the railway requirements^{49,43,50,48}. Simulation

TABLE 2 GSM-R and LTE-R parameters.

Parameters	GSM-R	LTE-R
Up-link frequency	870-880 MHz	450 MHz, 800 MHz, 1.4 GHz
Down-link frequency	921-925 MHz	1.8 GHz
Bandwidth	0.2 MHz	1.4–20 MHz
Modulation	GMSK	QPSK/16-QAM
Cell range	8 km	4–12 km
Maximum mobility	500 km/h	500 km/h
MIMO	No	Only 2x2
Data transmission	Requires voice call connection	Packet switching (UDP data)
Handover procedure	Hard	Soft
Data rate, downlink/uplink	172 Kbps	50/10 Mbps
Peak spectral efficiency	0.33 bps/Hz	2.55 bps/Hz

results and technical analysis of these studies have proven that the LTE-R system is the preferred candidate for the future of the railway communication system⁴⁸.

LTE-R can provide different services that can significantly improve railway services in terms of capacity and passengers. To improve the tracking accuracy, the train location is detected by on-board equipment, this information is then transmitted through wireless communication with a delay time less than 50ms which is considered as a real-time transmission². The system also offers a real-time train, weather conditions and railway infrastructure video monitoring with transmission latency less than 300ms. The LTE-R system provides railway emergency communications in case of any emergencies that can disturb the railway users, such as natural disasters and accidents. In such cases, an immediate voice, video, data communications can be established between the site of the accident and the control center². There are some other services that the LTE-R system can provide to the train commuters, for instance, seat-reservation, electronic-ticketing, and interaction of passenger information².

There are different issues associated with the employment of the LTE-R. The coexistence between the LTE public safety network and the LTE-R network is one of these issues. Basically, public safety network, such as police, firefighters and ambulance, and LTE-R networks use the same frequency bands which are 718-728 MHz and 773-783 for up-link and down-link, simultaneously⁵¹. Therefore, one of the major challenges is how to eliminate radio interference between both networks as both of them are more concerned about reliability and safety⁵¹. High mobility of trains leads to Doppler shift which is a shift of the received frequency and in some cases this might lead to a phase shift of the signal and can impair the reception of angle-modulated signals. However, tracking and compensation are possible for the Doppler shift as trains move with a well-known speed and the position and real-time are recorded².

Propagation loss in the HSR environments, such as cuttings, tunnels, bridges, and train stations can considerably affect the performance of the LTE-R system⁵². Although some measurements were carried out to characterize the channel for such environments, it is essential to develop an appropriate channel model which can perfectly represent the transmission channel in the HSR environments². There are other challenges which should be taken in consideration for the designing of LTE-R system such as large Doppler spread which can cause signal-to-interference-plus-noise ratio degradation and OFDM corruption. Furthermore, delay spread which can lead to a loss of orthogonality between the OFDM sub-carriers and a special category of guard interval. Moreover, linear coverage with directional antennas is used in railway communication systems². Although this type of coverage consumes less power and provides better performance, at some train locations the outage probability is high due to the shadow fading impact². Due to these limitations and the requirement of high-capacity communications for passengers of the next generation of the railway, finding an alternative technology to the current railway communication systems has become necessary. However, the challenges of providing the required services and focusing on QoS, reliability and capacity should be the principal issues of the candidate technologies of the future of the railway communication.

3.3 | The Fifth-Generation (5G) Communications

The maximum capacity of the current communication systems is still insufficient to handle the required data rate for the applications of the future generation of the railway. These applications include high-definition videos, images and important information in real time transmission for train-to-infrastructure, train-to-train and instructions-to-instructions. All of the existing technologies support data rates up to 100 Mbps only. The main reason behind this is that these technologies work frequencies lower than 6 GHz. Therefore, to acquire sufficient bandwidth, the jump to a technology that uses higher bandwidth is essential. However, the interest of implementing a capable system to handle the critical and noncritical communications of the railway has increased⁵³. Both critical and noncritical communications have very specific requirements and any frequent failure of them can affect the service reliability. However, the extremely high frequency (EHF) bandwidth, which is well studied for 5G technology, can tackle the issue of the shortage of frequency band resources.

Although 5G technology is not in the final stage, its final form is expected to be determined by 2020 as the entire industry is working on this task. This technology with its high-data rate is expected to play a crucial role in applications that require more reliable and low-latency communication such as intelligent transportation systems. Technologies including millimeter waves, beam-forming, M-MIMO, small base stations, and full duplex play the essential role in the development of this 5G technology. The 5G networks will be built upon the existing wireless systems including the 2G, 3G and 4G and it aims to retrofit the architecture of the current communication systems (i.e., 4G)⁵⁴. These networks can benefit from the current investment of the 4G networks by expanding their capabilities ensuring that 5G is interoperable with 4G and provides the desired performance for the railway communications.

Latency is one of the items that have been improved in 5G technology which can help enabling some functions that require a quick response such as auto-driving trains. The new technologies that are implemented by 5G aim to reduce the latency in such networks to 1 ms compared to 70 ms of data-transmission latency of the current 4G technology. Thanks to the millimeter waves technology used by the 5G that makes its spectrum bandwidth higher than the existing technologies thus enhances the speed of data transmission and offer better connectivity between the train and the wayside⁵⁴. For example, the available bandwidth of the 5G networks is nine GHz, while only 100 MHz of spectrum bandwidth is available in 4G-LTE networks. The targeted data rate of the fifth generation technology is 20 Gbps, which is achievable with its recommended bandwidth and the implementation of massive MIMO⁵⁴. This makes the 5G technology more reliable to be used for railway communication than the current communication systems.

Even though the 5G technology seems to be the best candidate for the existing railway communication systems, there is a number of challenges to consider. First of all, self-interference cancellation. Looking at the fundamental nature of the fifth generation technology, self-interference can have a considerable effect on 5G networks⁵⁵. Secondly, the power consumption of the overall system. As the fifth generation network utilize larger bandwidth compared to the current technologies which means more data rate thus this technology consumes more energy for data transmission⁵⁶. Furthermore, in multi-Gbps communication networks, data transmission is restricted by the characteristics of data propagation. It was reported that a very-high path loss and attenuation are associated with high frequencies. This should be compensated by either increasing the transmit power or the gain of the receiving antenna⁵⁶. Moreover, due to the nature of the wavelength of the millimeter waves and the railway environment, the transmission can be easily blocked or shadowed⁵⁷.

4 | INSIDE TRAIN COMMUNICATION

The time that people spend commuting on trains can be used for different interesting things, such as reading electronic books, watching live programs, listening to music and playing video games as long as their electronic devices are connected to the internet or communication systems. The required connection can be made into two different scenarios. The first scenario, every single electronic device can be connected to the communication network individually. In this scenario, the transmission to the mobile equipment is highly attenuated by the metallic coating of coaches particularly the modern ones. Furthermore, such communication suffers from the Doppler shift due to the high speed of the train and the high transmission frequency of the wireless networks⁶. In most of the cases, the second scenario is preferable. In this scenario, the train is connected to a public network then the signal is distributed inside the train coaches using a proper distribution system⁶.

Dedicated wireless networks, such as GSM-R and LTE-R, are used to provide trains with different communication services. These two networks are dedicated particularly to support the HSR by providing specific information that can help to monitor and control the traffic of the trains and thus to eliminate train accidents⁶. However, the public networks, such as GSM and LTE

are designed with specific cells overlapping. This overlapping is large enough to make a full handover procedure between two neighboring cells in the HSR system. The main issue of the public networks that they do not provide a network coverage for the entire railway tracks. Particular areas in the railway track, such as remote areas and areas near to the tunnels and bridges usually suffer from holes in the public network coverage. This is because of the lack of customers besides such areas thus public operators do not install their equipment there. Recently, the HSR operators invited the public network operators to provide communication services in such places⁶.

The reliability of in-train communication systems in the second scenario depends on two parameters, receiving equipment and the distribution system inside the train. Generally, a roof-mounted antenna fixed on the train roof works well as a receiving equipment. Various communication systems can be used for signal distribution within the train coaches. W-LAN can be installed in each train coach to distribute signals to the passengers' user equipment (UE)⁵⁸. Furthermore, the technology of VLC that recently has matured is predicted to play a crucial role in the railway industry¹². Moreover, PLC systems have been used for different indoor applications and it can be used for distributing the signals inside the train using the pre-installed power lines⁹. The main issue with PLC systems is that mobile users do not have an access to the power lines. In such cases, cooperative PLC/wireless or PLC/VLC is an option. In this section, we discuss how signal can be distributed within the train.

4.1 | Wireless Access Point

As previously mentioned that the electromagnetic waves are significantly attenuated by the metallic shielding of the train coaches. For this reason, communication between UE on-board and the public networks outside the train can be improved by using a roof-mounted antenna to communicate with the public networks. Then a central distribution system can be installed inside train coaches to communicate between the UEs on-board and the roof-mounted antenna. Almost all of the modernized electronic devices have a W-LAN interface so they can use this system for communication purposes⁶. This system can offer different services, such as internet access and entertainment services to the commuters of the high speed trains with sufficient data rate⁵⁹.

The W-LAN system can be installed either in each coach of the train or one system serving all coaches. However, if the former configuration is installed, then a receiving device (i.e a roof-mounted antenna) is needed to be located in each coach to communicate with the W-LAN on-board and the base stations of the public networks. On the other hand, only one receiving device is needed if the latter system configuration is installed. Then the connection between any two neighboring coaches should be wireless to ease the coaches assembly process at the stations. As mentioned above, a receiving device is located in each coach or only in one coach depending on which way the WLAN system is installed⁵⁸. This device will be responsible for connecting the W-LAN in the train with the outside communication systems. The receiving device should support LTE modem type of functionality and a wire-line to be able to communicate with both outside and in the train systems, respectively⁵⁸. Fig. 7, shows W-LAN system inside a train coach.

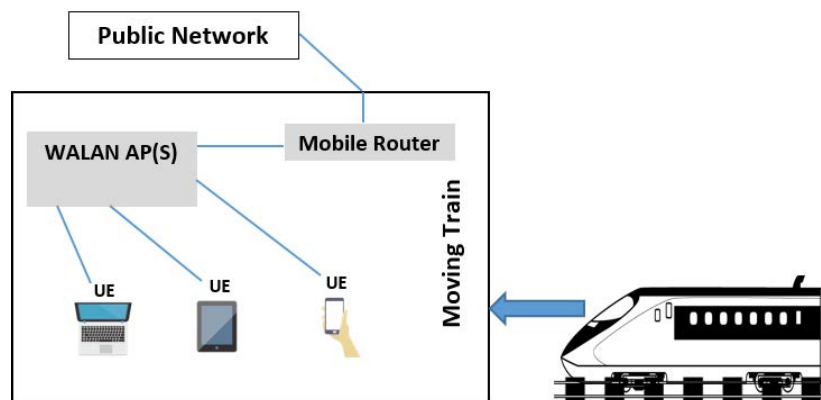


Fig. 7 W-LAN system inside a train coach.

Another installation design is to attach receiving devices to the roof of the first and the last coaches of the train. This installation offers to the commuters a high-capacity access to the public networks and reduces the fixed infrastructure requirements⁶⁰. Furthermore, both of the receiving devices are able to distribute the signal inside all of the train wagons. Therefore, when one

TABLE 3 Main standards of the Wi-Fi IEEE 802.11.

Standard	IEEE 802.11A	IEEE 802.11B	IEEE 802.11G	IEEE 802.11N
Approval date	July 1999	July 1999	June 2003	October 2009
Data rate	54 Mbps	11 Mbps	54 Mbps	600 Mbps
Modulation schemes	OFDM	CCK or DSSS	CCK, DSSS, or OFDM	CCK, DSSS, or OFDM
RF band	5 GHz	2.4 GHz	2.4 GHz	2.4 or 5 GHz
Number of spatial streams	1	1	1	1, 2, 3, or 4
Channel width	20 MHz	20 MHz	20 MHz	20 or 40 MHz

of the receiving devices is out of the public network coverage the other one is still communicating between the UE on-board and the public network. This is particularly in areas that suffer from small holes in the public network coverage, such as short tunnels and bridges⁶⁰. For all of the above-mentioned installations, although the train is in high speed and passenger equipment are in high mobility state relative to the fixed base stations of the public networks, the user equipment is stationary relative to the in-coaches WLAN system⁶. However, different W-LAN types such as Wi-Fi and WiGig can be installed inside train coaches for signal distribution.

The Wi-Fi is a well-known cost effective W-LAN technology. Wi-Fi IEEE 802.11 is the main standard of the Wi-Fi. The different standards of this main one are shown in Table 3. The allowed achievable throughput is 450 Mbps on every available frequency bands (2.4 and 5 GHz) in IEEE 802.11n. This is almost five times the previous IEEE 802.11 main standards⁶¹. Unlike the other main standards of IEEE 802.11, the IEEE 802.11n standard relies on multiple-input-multiple-output (MIMO) technology. Furthermore, The bandwidth, due to the aggregation of channels, is increased from 20MHz for the other main standards to 40 MHz for IEEE 802.11n standard⁶¹. However, the recent Wi-Fi standard which was developed at the beginning of this decade and was approved in the last few years is Wi-Fi IEEE 802.11ac standard. A 500 Mbps is the achievable theoretical throughput of this standard and a 7 Gbps of throughput can be achieved by implementing the MIMO and multiplexing techniques⁶². Although the Wi-Fi technology has a larger transmission range than the Wi-Gi one, the latter provides better throughput.

Recently, the millimeter wave technology, wireless gigabit (Wi-Gi), has gained the researchers' attraction due to the 6 Gbps of throughput that this technology offers to its users. This Wi-Gi is commonly known as IEEE 802.11ad^{63,64}. Both bodies the wireless gigabit Alliance and IEEE 802.11ad have developed the industrial standard of the Wi-Gi which has been issued by IEEE in late 2012. The main aim of this technology is to be used to transfer a high-volume of data with a throughput of around 7 Gbps over a relatively short range. It operates at 60 GHz frequency with 9 GHz bandwidth from 57 to 66GHz which makes the 7 Gbps of throughput is achievable⁶³. In addition to the high-speed data rate offered by the Wi-Gi, it also provides a secure and protected transmission over a short distance with low latency⁶². Table 4 presents a summary of the salient features of 802.11ad.

The main issue of this technology is its very limited transmission range, as its typical transmission distance is 1–10 m. Furthermore, due to its short wavelength at 60 GHz, the transmission is severely affected by the path loss, the loss can be as high as 28 dB^{62,64}. However, this loss can be compensated by increasing the gain of the antenna. This leads to a narrower beam-width of the antenna, which is consequently will require antenna beam-forming. Omni-directional antennas are used by the previous IEEE 802.11 main standards, therefore this was not considered as an issue⁶². An extensive study was carried out by the authors of⁶⁴ on planning and the formation of the Wi-Gi network. Two different network scenarios were investigated in order to extend the coverage of the Wi-Gi network. They concluded that the performance of the Wi-Gi network is affected by different parameters, such as network-load, the percentage of intra-LAN and internet devoted network traffic⁶⁴.

4.2 | Visible Light Communication (VLC)

One of the most significant current discussions in optical wireless communication technologies (OWC) is the light fidelity (Li-Fi) technology. This green technology is predicted to play an essential role in indoor communication applications. Instead of

TABLE 4 Summary of the salient features of 802.11ad.

Characteristic	Description	References
Frequency	60 GHz ISM band	63,64
Throughput	7 Gbps	62
Typical transmission range	1–10 m	63
Antenna technology	Beam-forming is used	62
Modulation schemes	Single carrier and OFDM	62

using radio frequency, the short-range Li-Fi technology is based on the implementation of VLC. The light emits from the low-cost and energy-efficient LEDs is the transmission medium of this technology which makes its potential implementation in HSR due to low complexity and cost effective^{65,66}. The Li-Fi technology is better in terms of data exchanges security compared to the RF one, and it allows high data transmission rates up to 500 Mbps over short distances. This is due to the nature of the non-breached light waves and the line-of-sight (LoS) of propagation of the LEDs lights⁶⁶. Furthermore, this technology offers better performance than that provided by the RF technology. This is because of the non-electromagnetic interference, high transmission power and rich spectrum resources⁶⁷.

Likewise, the other communication systems, the VLC contains three main components, namely transmitter, transmission medium, and receiver. In general, any light source can be utilized as a transmitter. However, LEDs are predicted to replace the other light sources in the future due to its energy consumption performance¹². The LEDs such as white LEDs (WLEDs), which are one of the best light sources that can suit the VLC, are used for illumination and data transmission simultaneously⁶⁸. This type of light sources has a higher expected lifespan compared to the other sources such as incandescent bulbs⁶⁹. This short-range technology uses the portion of the electromagnetic spectrum, which can be seen by the human eye, with wavelengths from 390nm-to-750nm as a transmission medium⁷⁰. At the receiver, the photo-diode detector, the received signal is converted from light into an electrical signal which is then demodulated to the desirable information^{12,71}.

This fast growing technology can offer a wide range of services to the railway operations; such as entertainment, internet facilities (inside trains and underground stations), smart lighting inside train stations and improving railway safety¹². In trains, LEDs can be equipped with transceivers to provide different multimedia facilities and internet services to train passengers¹². Furthermore, using LEDs for providing internet services inside underground stations can help to tackle one of the major issues that face passengers in such areas. Moreover, due to the light sources distribution inside train stations, they can ensure a very seamless connectivity to the moving people and they can be used for in-station positioning and venue navigation¹². On top of that, this technology can be used for ground-to-train communication and reducing the accidents¹².

As an upcoming technology, a number of technical issues should be studied before this technology is fully implemented in the railway industry. First of all, the covered area by each LoS of the LED is relatively small. This is because of the rectilinear propagation of light which leads to frequent horizontal handover when the passenger is moving, thus instability of data reception⁶⁵. During the handover process, the user changes the information with a central unit (CU) which can take up to 3000ms, this leads to a transmission loss⁷². Furthermore, light interference, this is due to the overlapping with the other neighboring light sources and sunlight¹². However, different techniques are proposed in the literature for reduction of such interference^{73,74,75,76}. For example, authors of⁷³ suggested choosing a suitable transmission band, which experiences relatively-less interference by other light-sources, to tackle the effect of this type of interference. The band can be chosen according to different factors, such as distance between the transmitter and receiver, irradiance angle, and incident angle. The results of this study have proven that the suggested technique works efficiently and can improve the performance of the VLC system by tackling the interference issue.

Both communication and illumination practices standards should be considered for the deployment of the VLC technology. This is different from any other communication system and adds the issue of coordination between different regulatory bodies⁷⁷. Integrating the VLC as a new technology in an existing railway industry infrastructure can be a complex and costly task. The RF modulation schemes and the conventional modulation techniques which are used with optical communication cannot be

used with VLC technology due to the flicker and dimming. The complexity of the transmitter and the receiver equalization is another issue in VLC system designing⁷⁷. Another major challenge is to design an adequate transceiver which can be installed in small smartphones and laptops¹². However, providing an up-link by the VLC link can be problematic. Therefore, as the Li-Fi technology does not interfere with the RF one, a cooperative VLC-RF system, where the VLC is used for a down-link and the RF is for up-link, can offer full connectivity and improves the QoS. Nevertheless, such cooperation leads to a vertical handover between the VLC and the RF systems which can cause more instability delay in data reception⁷⁷.

4.3 | Power-line Communication (PLC)

In recent years, there has been an increasing interest in PLC technology. Simply, in this technology, the pre-installed infrastructure of wiring networks of a building or utility grid is utilized for both purposes carrying electricity and data transmission to consumers. This advantage makes the PLCs a cost-effective and competitive technology for in home networking applications⁷⁸. According to its operating frequency this technology is grouped into two different groups, namely narrow-band PLC (NB-PLC) and BB-PLC. NB-PLC (low-frequency PLC) works at frequencies from 3-to-500 kHz and it is characterized by its low-data rate and long-range of transmission.^{79,80,81} For The BB-PLC (high-frequency PLC) performs at frequencies from 1.8 – 250 MHz and it has higher data rate up to 200 Mbps and shorter transmission distance than that of the NB-PLC. The PLCs can also be classified to PLC over alternative current (AC) lines and PLC over direct current (DC) lines depends on the type of the current carried by the power lines.

In PLCs systems, the transmitted data is firstly modulated by modem node then it is injected to the power lines, which represents the transmission medium, to be sent to its destination. At the receiver node, the information signal passes through a filtering process then a demodulation technique to recover the original data⁸². Different modulation techniques can be used with this technology such as, frequency shift keying (FSK), OFDM, binary phase shift keying (BPSK) and spread-FSK (S-FSK). PLCs systems have been used for different applications such as, home automation, home networking, narrow-band PLC - Radio broadcasting and automotive^{80,81}. The NB-PLC systems have been generating widespread attention from academia and industries owing to its applications in different fields such as; home-control, the smart-grid, smart energy generation and micro-inverters.

The BB-PLC was initially used for home applications only, but recent studies have proved that this technology can fulfill the future requirements of smart-grid applications⁸³. This technology has been also used in vehicles applications for the recent years⁹. Transmission data between the electronic parts of the vehicle such as sensors and actuators can be achieved by using its electrical wires network without any extra weight and cost⁸⁴. Inside trains, the BB-PLC technology can be used for different purposes. In train entertainment can be provided to the commuter of the long-haul trips through the power line networks of the train. This technology can also distribute a high-speed internet to the commuters inside trains if the trains are connected to a proper communication network⁹. Passengers can check the trip information, order meals and make tickets booking using this on-board network. For safety and security reasons, cameras and other safety devices can be connected by the BB-PLC to monitor the train coaches. Furthermore, connecting the on-board electronic equipment with each other to share the important data⁸⁴. Fig. 8 shows PLC and VLC systems within a train coach.

Due to the harsh transmission medium of the PLCs technology, a number of technical issues is associated. These power lines were firstly designed for current transmission only. First of all, the varying channel model, this is a huge variation in response between frequency, phase and amplitude of the signal. Furthermore, the transmission over such channel can be attenuated by the signal reflection due to the mismatching of the impedance of the electrical network because of its topology and physical properties. Therefore, one of the major issues is studying the transfer function of the PLCs and to find appropriate channel model which can perfectly represent it in computer simulations⁸⁵. However, there are number of the channel models that can accurately model the transmission channel are proposed in the literature such as multi-path and two-port network models, the latter also know as ABCD matrix channel mode^{86,87}.

Transmission over PLCs is also affected by noise which is considered one of the most destructive issues in this technology. Noise over PLCs is categorized into two main categories namely, colored-background noise and impulsive noise. While the former varies slowly with time and remains stationary over some minutes and some time up to hours, the latter occurs randomly with short duration and high power spectral density (PSD)⁸⁸. Although the impulsive noise has a short duration, it can severely disturb and affect the transmission over the PLCs channels⁸⁶. However, a number of mitigation techniques are proposed in the



Fig. 8 PLC and VLC systems inside train.

literature for the purpose of mitigating this channel impairments. These include multi-carrier modulation (MCM), blanking non-linearity, clipping non-linearity, hybrid blanking/clipping non-linearity, coding, multiple input multiple output (MIMO) and time and frequency domain (TFD) techniques^{88,89,90,91}.

The power cables radiate electrical signals to the surroundings when the information signals travel along the PLCs between the transmitter and the receiver⁹². This radiated signals can cause a malfunction to the nearby electronic equipment. This phenomena known as electromagnetic interference (EMI). Therefore, a number of standard bodies has set electromagnetic compatibility (EMC) standards to control both modes of the EMI, namely inductive and conductive, at acceptable level ensuring the reliability and the safety of the PLCs systems^{92,93,94}. On top of the above issues, PLCs systems can not provide services to the end users at mobility. Therefore, combining PLCs systems with other communications systems such as, RF and VLCs can provide better mobility and performance to the end users^{78,65}. However, the implementation of such hybrid systems can also tackle the networks coverage problems and increase the overall capacity of the systems.^{78,65}

4.4 | Hybrid Communication Systems

Reliable communication systems which can provide better network coverage, throughput and mobility to the train commuters can be one of the most critical issues in onboard communication system designing. This is due to the increase of the multi-media users in trains which means that single network on board might not be able to provide reliable services to the passengers. However, implementing hybrid communication systems, such as, PLC/VLC, PLC/RF and VLC/RF in indoor environments can improve the system performance and the user's QoS and provide better mobility to the end users^{78,72,65}. Since each network does not affect the coverage of the other networks as there is no interference between them, the total capacity of the hybrid system is better than that in the single system⁷². Relays such as amplify-and-forward (AF) and decode-and-forward (DF) are often used with the hybrid systems to increase the transmission distances and offer greater system throughput^{65,78}.

Integrating networks is one of the most significant current discussions in indoor applications and has attracted both academia and industry^{78,65,72}. The study in⁷² discusses the implementation of the hybrid Li-Fi/Wi-Fi network in indoor environments. The authors believe that the 300 THz license-free used by the Li-Fi technology can be considered as a solution to the problem of limited availability of the radio frequency (RF) spectrum. The electromagnetic spectrum used by each one of these two technologies is totally different so they do not interfere with each other which enables the implementation of such a cooperative network⁷². The study proposed a dynamic load balancing (LB) to tackle the issue of the frequent handover between the LoSs of the LEDs during the movement of the end users. The Wi-Fi system provides services to the moving users and the static ones are served by the Li-Fi network. The authors concluded that the Li-Fi link provides higher data rate to the static users than that provided to the moving users by the Wi-Fi one⁷².

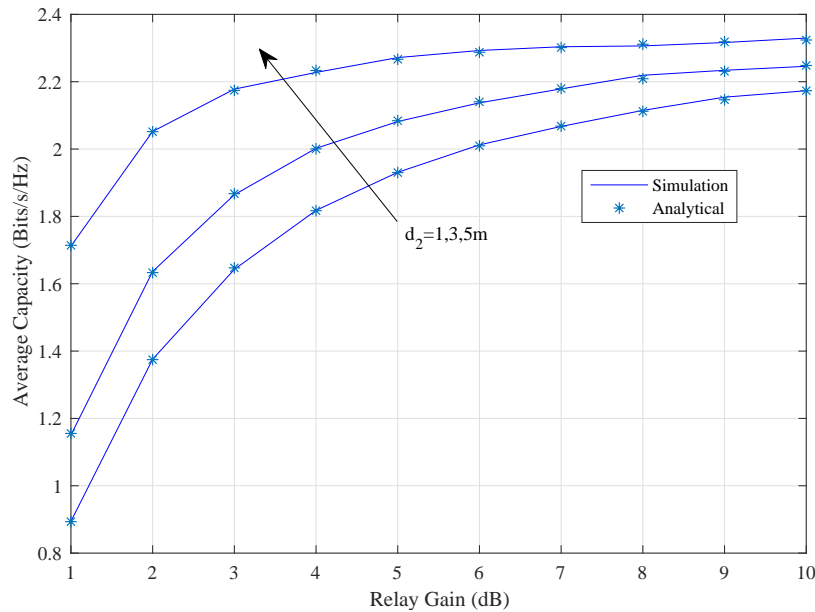


Fig. 9 Average capacity versus the relay gain for different values of relay-destination distance.

Using the Li-Fi technology as a complementary network to the RF one was investigated in⁹⁵. The authors considered a cooperative VLC/RF down-link where the full coverage is provided by the RF network supported by the LoS of the LEDs. The authors indicated that the proposed cooperative system is capable of providing higher data rate than the single systems. It was also indicated that this system is able to overcome some issues of the RF and Li-Fi networks such as limited availability of RF spectrum, the frequent handover of the Li-Fi due to its small-coverage area and the Li-Fi network incapability of providing convenient Up-Link coverage⁹⁵. From the context of that, the hybrid Li-Fi/Wi-Fi system can enhance the robustness and increase throughput, the authors of⁹⁶ studied the cooperation between these two networks. The results of this study showed that the hybrid system performs much better than the WiFi one, especially in the crowded areas. It was also found that the VLC system can provide better performance than that provided by Wi-Fi system when the transmission distance is relatively small.

The advantage of utilizing the existing electrical network in indoor environments offers the opportunity to use PLCs system as back-hull for both RF and VLCs. The discussion regarding implementing hybrid PLC/RF started in the last decade where each network was considered working at a different time from the other. The proposed hybrid system was considered for vehicular and home applications as well as for automated meter infrastructure^{97,98,99}. The implementation of such a cascade links for the same application was discussed in^{100,101}, which considered that both networks are working simultaneously. The cooperative PLC/RF system was also discussed in different aspects and different system setups by^{102,103,104}. Their conclusions can be summarized by that the hybrid PLC/RF can increase the throughput and enhance the performance of the system by offering better data rate to end users. This was also confirmed by our work in⁷⁸ where we compared the performance of the hybrid PLC/RF with its counterpart in PLC only.

Several studies investigated the use of relays with the PLC, RF, and hybrid PLC/RF systems^{99,78,105,106,107}. The studies involved different relaying protocols such as AF, DF, include incremental DF (IDF) and selective DF (SDF). The authors in^{108,109} indicated that optimizing the relay position on the network can offer better performance and improve the power consumption of the system. They also concluded that the use of relays can be more beneficial to the RF network than to the PLC one. We discussed the implementation of AF relay in hybrid PLC/RF network in⁷⁸. The proposed system was investigated in terms of average capacity. The effect of some of the system parameter on its performance was studied. The results showed that the considered system can offer better performance and mobility to the end users. As it can be seen from Fig. 9 that the performance of the system can be improved by increasing the relay gain which justifies the use of the relay in the system.

Recently, PLC technology has been associated with the new technology VLCs. The advantage of using the pre-installed infrastructures of the power line networks for the PLCs and the LEDs for the VLCs makes the hybrid PLC/VLC system an attractive and cost-effective system. In the cooperative PLC/VLC system, the PLC is utilized as a backbone for the VLC which in turns transforms the electrical signal into an optical signal then deliver it to the users¹¹⁰. This hybrid system was first presented

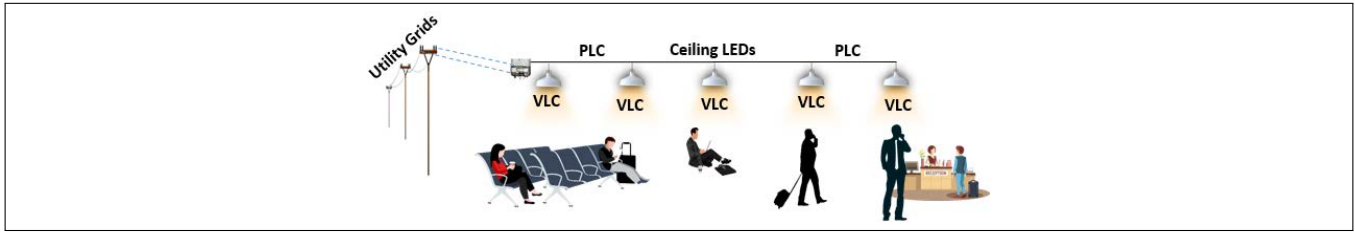


Fig. 10 A cooperative PLC/VLC system inside a train station.

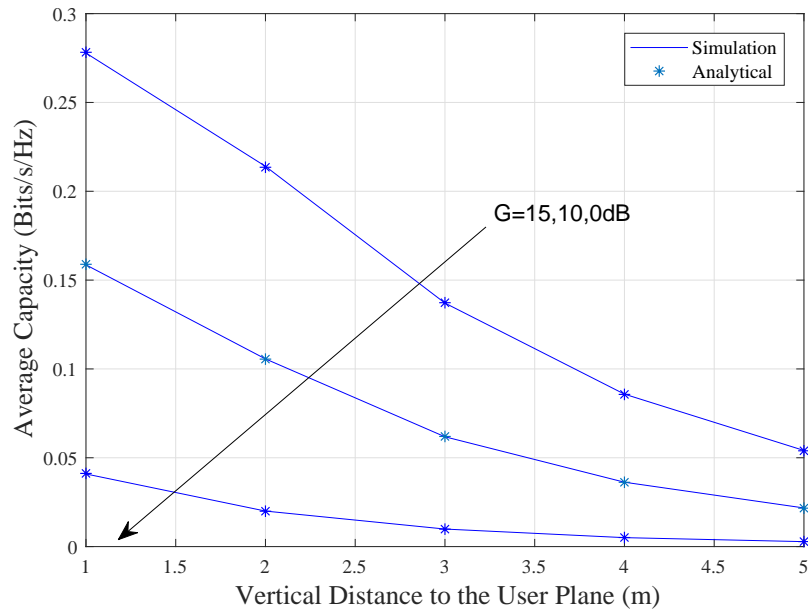


Fig. 11 Average capacity with respect to the vertical distance to the user plane for different values of the relay gain.

and discussed in¹¹¹. The authors used the ubiquitous electricity power-lines as backbones the VLC technology which employs the ceiling white LEDs for indoor optical wireless. They concluded that such integration will play a crucial role in both indoor and outdoor applications. The main reason for this is that no new installations are required for the implementation of such a cascaded system. Furthermore, there is no need for demodulating the transmitted signal through the PLC which makes its deployment a very simple task¹¹¹. Fig. 10 shows a cooperative PLC/VLC system inside train station.

Since then, this hybrid system has been investigated by many researchers in several aspects^{111,112,113,114,65}. Motivated by adopting the concepts of the RF communications for the hybrid PLC/VLC system, the authors in¹¹² has investigated the implementation of MIMO and relaying techniques for this system. A novel and cost-effective scheme for the cooperative PLC/VLC was proposed in¹¹³. The results showed that the required modification to the current infrastructure is less than the other schemes and simplifies the complexity of the network protocol of VLC. Frequency-domain and time-domain schemes were proposed in¹¹⁴ for the positioning purpose. The authors also considered a direct re-transmission concept in order to reduce the modifications to the origin network. In our study⁶⁵ we discussed the implementation of AF relay with the PLC/VLC. The results of this study indicated that the performance of the system is negatively affected by the overall distance and it can be improved by increased the relay gain as shown in Fig. 11. It was also revealed that the proposed system performs better by increasing the input power as appears in Fig. 12.

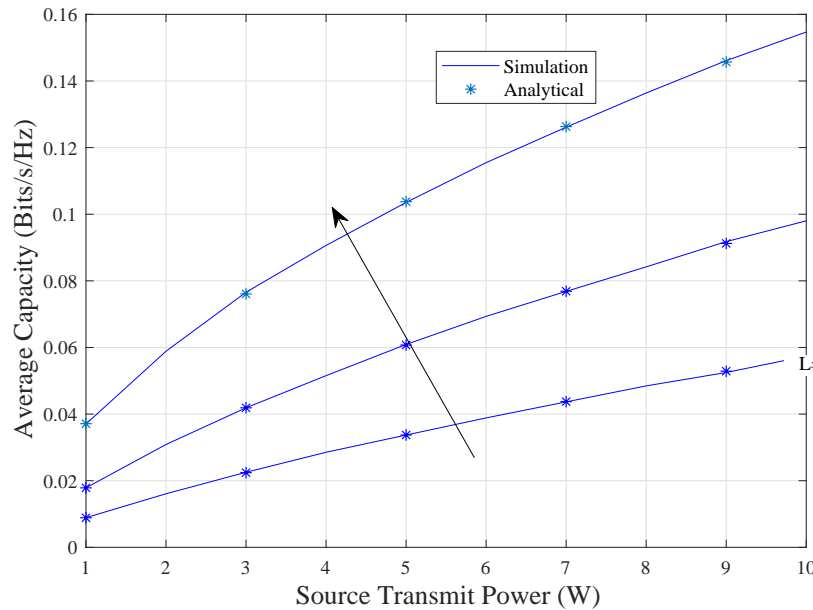


Fig. 12 Average capacity as a function of input power for different values of the vertical distance to the user plane.

5 | FUTURE OF RAILWAY COMMUNICATIONS

With the increase of video contents on the internet, most people prefer to remain glued to their smart gadgets while traveling. Most of the time, the speed of the internet plays the spoilsports. Due to this, consumers demand higher data rate and more reliable communication systems from service providers. This demand and for the commuters satisfaction will push the entire industry towards finding a proper candidate for communication systems that are mentioned above in this paper. The sixth-generation technology (6G) with its expected data rate of 1 Tbps might be one of the candidates for the railway communication networks. The speeds of the mentioned systems are by far slower than the expected speed of this future technology. Thanks to its 100 GHz-to-1 THz high-frequency that 6G technology is predicted to play an essential role in different applications. This includes the Internet of Everything (IoE), robotics, autonomous drone delivery and transport systems¹¹⁵.

The outdoor wireless communication (OWC), which is known by free-space optical (FSO) communication, is used for high-data-rate communications between two antennas over a long distance. The available optical bandwidth of the FSO links is very high compared to its counterpart of the RF. Thanks to the very narrow laser beams used by the FSO that increases the overall system security and reduces the electromagnetic interference^{116,117}. FSO systems utilize unlicensed frequencies above 300 GHz. As a result, no license fee is required for the FSO system¹¹⁸. This technology is appealing for several applications such as backhaul for wireless links, medical data transmission, videos monitoring, etc.¹¹⁶. FSO systems can be installed as a complementary network to the current railway systems to cover their coverage holes, particularly in tunnels.

In our study¹¹⁹, we investigated using the overhead line equipment (OLE) as access network connecting trains to the backbone communication networks. These lines are used to deliver electricity from feeder substations to the trains so they could move. OLE falls under the medium-voltage transmission lines as it carries power electricity at 25 kV. The authors believe that medium-voltage power line communication (MV-PLC) can provide reliable transmission and is a key technology for the last-mile communication. The authors developed a two-port network model to represent the channel transfer function of the OLE using the transmission lines theory. Different channel scenarios were involved to investigate the OLE channel and to study the effect of different channel parameters (e.g., the channel length and the transmission frequency) on the performance of the transmission.

One of the scenarios which were studied in this study is the impact of the train moving away from the railway substation at different speeds. The train starts with steady-state then accelerates from speed zero up-to 80 Km/h in 5 minutes time. Then it continuous its 80 Km/h speed for 10 minutes before it starts to decelerate for 5 minutes from its current speed until it totally stops at the next train stop. Movement equations are used to calculate the train acceleration and to update the train position which represents the length of the channel. The results showed that both the length of OLE and the frequency have a negative

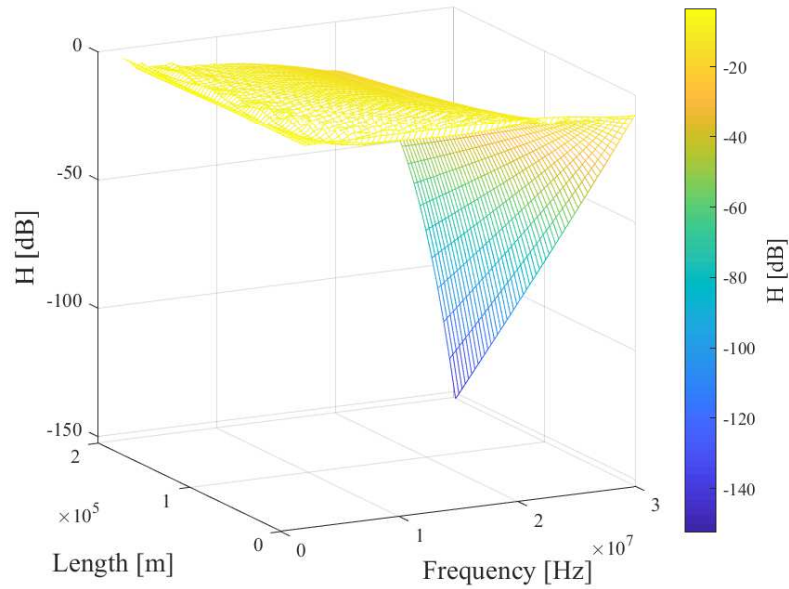


Fig. 13 A 3D surface plot for the channel response as a function of frequency and line length.

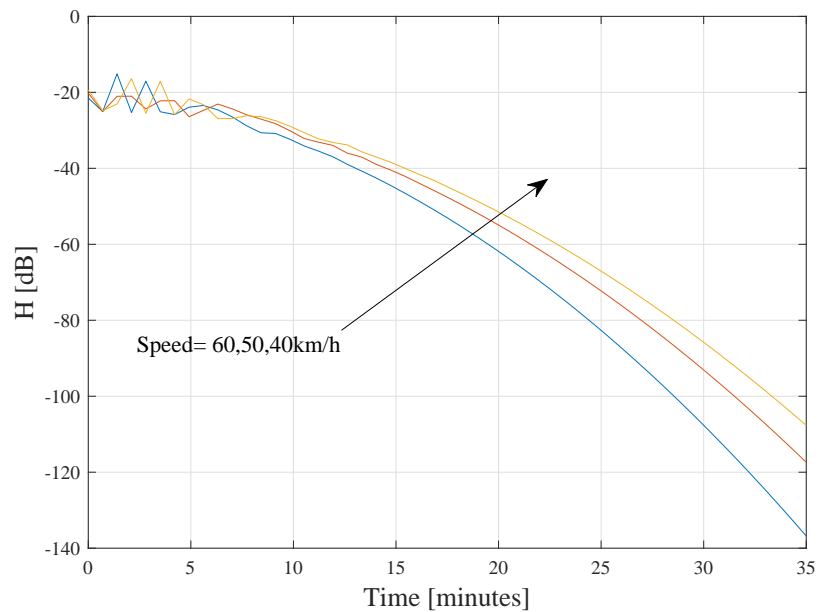


Fig. 14 Channel transfer function with respect to time traveling for different train speeds.

impact on the transmission as it was clear that the transmission is less attenuated at lower frequencies and shorter distances. We also found that the transmission is negatively affected the speed of the train see Figs. 13 and 14.

6 | CONCLUSION

The HSR has been positioned as a solution to current intercity transportation, offering new perspective and using novel technologies to address current and future problems facing the mobility sector. This is expected to attract more commuters and

consequently increase profitability. However, the growth of railway demand and its development require a reliable communication system to meet users satisfaction. This paper provided a survey of potential HSR-communication systems and the challenges of the current communication system. We showed that the LTE-R, which is a special configuration of the public network LTE, has the ability to fulfil the current HSR requirements. Having said that, we noted that, the need for a system that is more reliable than LTE-R is inevitable. We presented an overview of inside train communication, the advantages and disadvantages of onboard distribution systems, and posited that hybrid systems provide more reliable services to the train commuters compared to the services provided by the single ones.

7 | ACKNOWLEDGEMENT

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Data Availability Statement

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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Conflict of interest

The authors declare no conflict of interest.

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Waled Gheth. was born in Alkhomos, Libya in 1980. Received the B.Sc. in electrical and electronic engineering from Almergeb University, Alkhomos, Libya, in 2003. Received the M.Sc. Degree from Manchester Metropolitan University in Industrial Communication and Automation, in 2017. After the successful completion of his M.Sc., he has been awarded Manchester Metropolitan University studentship to pursue his Ph.D. in communication engineering. His research interests include signal processing and analysis of power-line, visible-light and wireless communication networks for indoor applications.



Khaled M. Rabie. received the Ph.D. degree in electrical and electronic engineering from the University of Manchester, UK, in 2015, and is currently an assistant professor with the department of Engineering at the Manchester Metropolitan University (MMU), U.K. He has worked as a part of several large-scale industrial projects and has published 100+ journal and conference papers (mostly IEEE). His primary research focuses on various aspects of the next-generation wireless communication systems. He serves regularly on the Technical Program Committee (TPC) of several major IEEE conferences, such as GLOBECOM, ICC, and VTC. Khaled has received numerous awards over the past few years in recognition of his research contributions including the Best Student Paper Award at the IEEE ISPLC (TX, USA, 2015), the MMU Outstanding Knowledge Exchange Project award of 2016, as well as the IEEE ACCESS Editor of the month award for August 2019. He serves as an Editor for IEEE COMMUNICATIONS LETTERS, an Associate Editor for IEEE ACCESS, an Area Editor for PHYSICAL COMMUNICATIONS, and an Executive Editor for the TRANSACTIONS on EMERGING TELECOMMUNICATIONS TECHNOLOGIES. Khaled is also a Fellow of the U.K. Higher Education Academy (FHEA).



Bamidele Adebisi. (SM'15) is a full professor of intelligent infrastructure systems at the Metropolitan University, Manchester, UK. He received masters degree in advanced mobile communication engineering and Ph.D. in communication systems from Lancaster University, UK, in 2003 and 2009, respectively. He has worked on several commercial and government projects focusing on various aspects of smart infrastructure systems. He is particularly interested in collaborative research and development of technologies for electrical energy monitoring/management, transport, water, home automation, IoTs, Cyber Physical Systems and critical infrastructures protection. He is a Chartered Engineer, member of IET and a senior member of IEEE.



Muhammad Ijaz. has received his M.Sc. in Optoelectronic and Communication Engineering degree with commendation from Northumbria University at Newcastle upon Tyne, UK in 2009. After the successful completion of his M.Sc., he has been awarded Northumbria University studentship to pursue his Ph.D. He was awarded his PhD degree in 2013 at the same Northumbria University, UK for his research work in Free-Space Optical (FSO) Communications. He also worked as Research Fellow in Visible Light Communication at University of Edinburgh, UK between 2013-15. He worked in modelling and designing a large scale multiple-input multiple-output (MIMO) based visible light communication (VLC) system using spatial modulation and for novel methods of energy harvesting ideas in the field of wireless communications. Muhammad Ijaz is currently working as a lecturer at Manchester Metropolitan University, UK from 2015. His specialized areas of research and interests are optical wireless/fibre communications, advanced modulation schemes including OFDM, Visible light communication, applications of LiFi, powerline communications, IoTs and photonics and optical sensors design. He is a member of IET and a member of IEEE.



Georgina Harris. Dr Georgina Diane Harris MEng (Hons), MBA, EngD, CEng, FIMechE, MIET, MInstP, FRAS, FHEA. Georgina is Chair of the Recruitment and Admissions Committee of the Engineering Professors' Council. Georgina is the Greater Manchester Area Chair and Fellow of the Institution of Mechanical Engineers, a member of the Institution of Engineering and Technology, a member of the Institute of Physics, a Fellow of the Royal Astronomical Society and a Fellow of the Higher Education Academy. Georgina was a founder member and is a current governor of the Crewe Engineering and Design University Technical College and an academic at the Open University. Georgina has previously held the post of Head of School at Manchester Metropolitan University, Site Engineer and Power Specialist for the Square Kilometre Array Program Development Office (SPDO) and the SKA Support Engineer at the new Square Kilometre Array (SKA) Organisation. Georgina held the roles of PrepSKA UK Project Manager (October 2009 to December 2010) and SKADS System Design and Team Leader (October 2006 to September 2009) responsible for the production of the UK SKA demonstrator, 2-PAD (2 Polarisation All Digital) at Jodrell Bank Observatory in Cheshire. She is a Chartered Mechanical Engineer with an Engineering Doctorate, a

Masters Degree in Mechanical Engineering and a Masters Degree in Business Administration. Georgina has worked in a number of academic-industrial collaboration projects. Her successes to date include the development of a combined particulate and NOx reduction technology for treatment of diesel exhaust gases and the redesign of the crank axle for fatigue prevention on the working replica of Robert Stephenson's 'Planet' locomotive at the Museum of Science and Industry in Manchester.

