IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 8, 2021, accepted October 25, 2021, date of publication November 2, 2021, date of current version November 8, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3124812

6G Wireless Communications Networks: A Comprehensive Survey

MUNTADHER ALSABAH[1], MARWAH ABDULRAZZAQ NASER[2], BASHEERA M. MAHMMOD[3], SADIQ H. ABDULHUSSAIN[3], MOHAMMAD R. EISSA[1], AHMED AL-BAIDHANI[4], NOR K. NOORDIN[5,6], (Member, IEEE), SADIQ M. SAIT[7], KHALED A. AL-UTAIBI[8], (Member, IEEE), AND FAZIRUL HASHIM[5], (Member, IEEE)

[1]Department of Electronic and Electrical Engineering, The University of Sheffield, Sheffield S1 4ET, U.K.
[2]Department of Architectural Engineering, University of Baghdad, Al-Jadriya, Baghdad 10071, Iraq
[3]Department of Computer Engineering, University of Baghdad, Al-Jadriya, Baghdad 10071, Iraq
[4]Ministry of Communications, Basrah 60002, Iraq
[5]Department of Computer and Communication Systems Engineering, Faculty of Engineering, Universiti Putra Malaysia (UPM), Serdang 43400, Malaysia
[6]Wireless and Photonic Networks Research Centre of Excellence (WiPNet), Faculty of Engineering, Universiti Putra Malaysia (UPM), Serdang 43400, Malaysia
[7]Department of Computer Engineering, Center for Communications and IT Research, Research Institute, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia
[8]Department of Computer Engineering, University of Ha'il, Ha'il 55476, Saudi Arabia

Corresponding author: Khaled A. Al-Utaibi (alutaibi@uoh.edu.sa)

ABSTRACT The commercial fifth-generation (5G) wireless communications networks have already been deployed with the aim of providing high data rates. However, the rapid growth in the number of smart devices and the emergence of the Internet of Everything (IoE) applications, which require an ultra-reliable and low-latency communication, will result in a substantial burden on the 5G wireless networks. As such, the data rate that could be supplied by 5G networks will unlikely sustain the enormous ongoing data traffic explosion. This has motivated research into continuing to advance the existing wireless networks toward the future generation of cellular systems, known as sixth generation (6G). Therefore, it is essential to provide a prospective vision of the 6G and the key enabling technologies for realizing future networks. To this end, this paper presents a comprehensive review/survey of the future evolution of 6G networks. Specifically, the objective of the paper is to provide a comprehensive review/survey about the key enabling technologies for 6G networks, which include a discussion about the main operation principles of each technology, envisioned potential applications, current state-of-the-art research, and the related technical challenges. Overall, this paper provides useful information for industries and academic researchers and discusses the potentials for opening up new research directions.

INDEX TERMS 6G, intelligent reflecting surfaces, orthogonal multiple access, NOMA, rate-splitting multiple access, spatial modulation, cell-free massive MIMO, mmWave, terahertz (THz), holographic radio, full duplex, energy harvesting, backscatter, edge computing, optical wireless communications, blockchain, artificial intelligence, machine learning.

I. INTRODUCTION

The global mobile data traffic has increased considerably during the last few years. Assessment of recent statistics collected by International Telecommunication Union (ITU) indicate that global mobile data traffic is expected to grow to 607 Exabytes (EBs) per month by 2025 and 5016 EB by 2030 [1]. The amount of data traffic per subscriber is expected to be around 39 EBs by 2025 and about 257 EBs by 2030. Furthermore, almost 70% of the population is expected to subscribe to mobile services by 2025. Besides this, 60% out of this 70% are estimated to use mobile Internet. The huge data traffic demands have been accompanied by increasing requirements for heterogeneous services, full coverage, ultra high-speed wireless communications with ultra high reliability and ultra low-latency. The main drivers of the dramatic growth in data traffic are personal computers (PCs), laptops, tablets, smartphones, sensors and Internet

The associate editor coordinating the review of this manuscript and approving it for publication was Wei Feng.

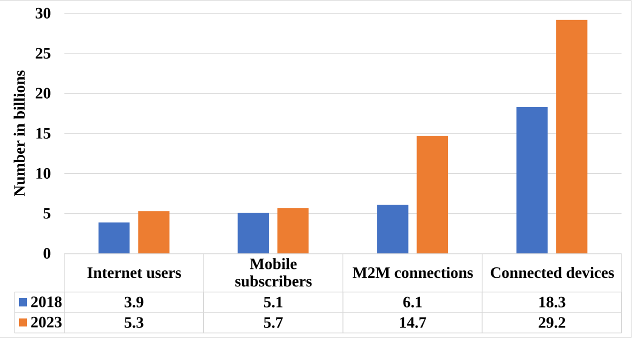


FIGURE 1. Total number of Internet users, mobile subscribers, M2M connections and connected devices.

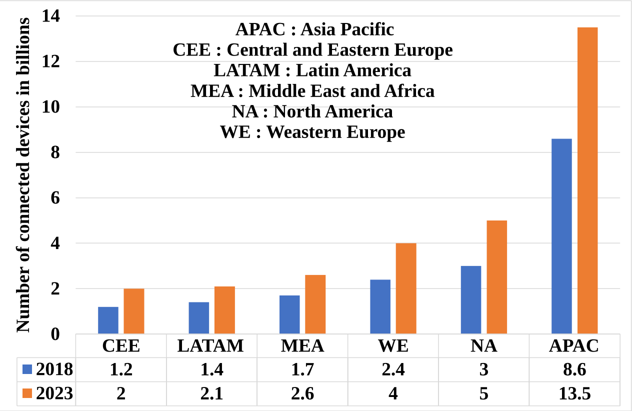


FIGURE 2. Number of connected devices in billions over six different regions.

of Everything (IoE) devices/applications. These devices are typically consuming data capacity (mainly video) rather than voice traffic. In addition to this, the number of Internet users, mobile subscribers, machine-to-machine (M2M) connections and connected devices worldwide are also expected to considerably increase in the next few years. Fig. 1 illustrates the number of Internet connectivity in billions, which compares the total number for four different trends namely:, Internet users, mobile subscribers, M2M connections, and connected devices between 2018 and 2023 [2]. As shown in Fig. 1, the number of Internet users is expected to be 5.3 billion by 2023. Besides this, the growth in the number of M2M and the number of connected devices is expected to be almost doubled by 2023. Fig. 2 compares the total number of connected devices in billions, which are given in total in Fig. 1, for six different regions between 2018 and 2023 [2]. Notably, the growth in the number of connected devices in Asia Pacific countries (APAC) is expected to reach 13.5 billion devices. Besides these statistics that show tremendous growth in Internet connections, wireless broadband connectivity becomes crucial for transportation services, healthcare, infrastructure, and, home and military applications. Therefore, the current generation of wireless communication is unlikely to sustain this ongoing traffic explosion and the emerging applications. In order to support such massive Internet connections with a diverse set of requirements in terms of data rates, reliability, latency, intelligence, security and energy efficiency, the next generation of wireless communication systems, i.e. sixth-generation (6G) networks, is being introduced. However, 6G wireless communications networks will require advanced physical layer solutions, new advanced modulation schemes, advanced multi access techniques, energy harvesting, edge computing, new spectral bands, integration of terrestrial and non-terrestrial communications, cell-free massive MIMO, blockchain and quantum technologies and adoption of artificial intelligence and machine learning techniques.

A. EVOLUTION OF CELLULAR NETWORKS FROM 1G TO 6G

In order to provide a clear vision of what 6G networks could offer, it is essential to give a brief background of the evolution of mobile communications networks from the first generation (1G) to the fifth-generation (5G). To date, there are five different generations of mobile communications systems, which belong to different standards and have different techniques and capabilities (see Table 1). The period of each mobile generation in Table 1 is predicted based on references [3], [4]. Notably, each generation of mobile communications networks has been developed roughly every ten years. The evolution from 1G to 6G mobile wireless communications networks is shown in Fig. 3.

1G was introduced in the 1980s to provide voice services. 1G networks provided a data rate of 2.4 kbps. However, 1G was developed based on analog transmission, and was faced challenges such as low capacity, inconsistent delivery and lack of security [5]. To address the issues of 1G, second-generation (2G) mobile communications networks based on digital modulation technologies were developed in the 1990s. 2G has been used to provide encrypted data services such as short message services (SMS) in addition to traditional voice communications [6]. The second-generation network was based on the global systems for mobile communications (GSM) and provided a data rate of 64 kbps. The 1G and 2G mobile communications systems are based on public switched telephone network (PSTN), which is considered as a combination of several telephone networks, including telephone lines, switching centers, fiber optic networks, cellular networks and satellites networks.

Around the year 2000, the third generation (3G) of mobile communications networks was introduced to support the increasing demands for different multi-data services such as video calls and internet surfing. Therefore, various technologies such as wideband code-division multiple access (WCDMA), CDMA2000, unpaired spectrum based on time-division synchronous CDMA (TD-SCDMA) with time division duplex (TDD) and worldwide interoperability for microwave access (WiMAX) have been used in 3G networks [7]. 3G networks provided a data rate up to 2 Mb/s [8], which is achieved using high-speed packet access (HSPA) technology. In 2009, the fourth

TABLE 1. Key evolution indication of 1G to 5G mobile wireless communications.

Key indication	1G	2G	3G	4G	5G
Period	1980-1990	1990-2000	2000-2010	2010-2020	2020-2030
Technology	Analog voice	GSM	CDMA-2000	WiFi, WiMax, LTE	5G NR, IPv6, LAN, WAN, PAN
Multiplexing	FDMA	TDMA, CDMA	CDMA	CDMA, OFDM	OFDM, BDMA
Data Rate	2.4 - 14.4 kb/s	14.4 - 64 kb/s	3.1 - 14.7 Mb/s	100 Mb/s - 1 Gb/s	1 Gb/s and above
Bandwidth	150 kHz	5 - 20 MHz	25 MHz	100 MHz	1 - 2 GHz
Architecture	SISO	SISO	SISO	MIMO	Massive-MIMO
Main Network	PSTN	PSTN	Packet	Internet	Internet
Features	Voice	Voice, SMS	Voice, data	Video	VoIP, ultra HD
Band-type	Narrow	Narrow	Broad	Ultra-broad	Ultra-wide
Highlight	Mobility	Digitization	Internet	Real-time streaming	Extra-high-rate
Switching	Circuit	Circuit, packet	Packet	All packet	All packet
Handoff	Horizontal	Horizontal	Horizontal	Horizontal, vertical	Horizontal, vertical

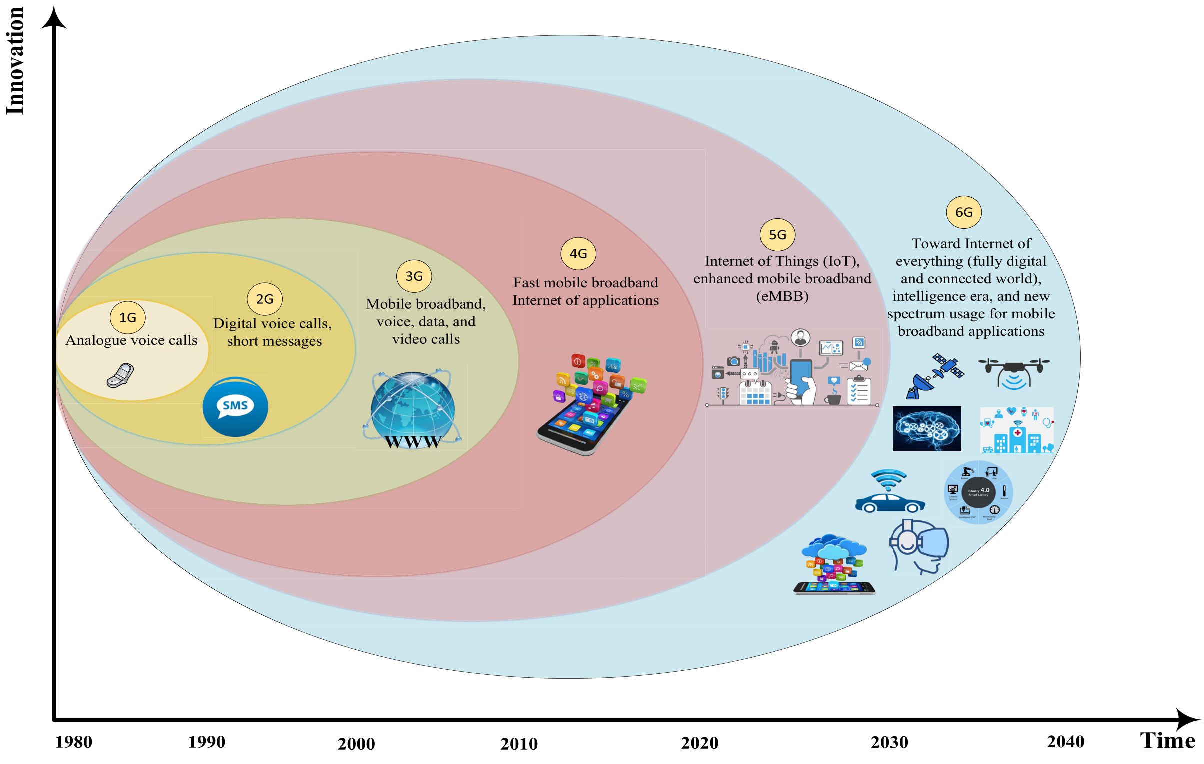


FIGURE 3. The evolution of mobile generation from 1G to 6G.

generation (4G) of mobile communication, which represents the long-term evolution (LTE) network, was launched. LTE networks support both paired and unpaired spectra, i.e., operate in both the time division duplex (TDD) and frequency division duplex (FDD) modes. Different technologies such as orthogonal frequency division multiplexing (OFDM), coordinated multiple transmission/reception (CoMP), and multiple-input and multiple-output (MIMO) techniques have been used in LTE networks. These technologies have been developed to enable a wider transmission bandwidth, to achieve a high data rate, and to allow wider mobile broadband connections. LTE mobile communication system was extended to LTE-Advanced network in 2011, which allows the operation in unlicensed spectrum. 4G LTE network with a 2 × 2 MIMO provides a maximum data rate up to 150 Mb/s while LTE-Advanced networks are able to achieve a maximum data rate of up to 1 Gb/s using a 4 × 4 MIMO system over a 100 MHz aggregated bandwidth [9].

Currently, 5G network is becoming a commercial reality. 5G network can support wide area network (WAN) bands in addition to radios for wireless local area network (LAN) and personal area network (PAN). 5G network has the potential to aggregate spectral, support high-definition (HD) video streaming and several data-hungry applications. Also, 5G network has the ability to achieve faster throughput than the LTE-A system with a maximum data rate of about 20 Gb/s. Furthermore, an advanced multiple access technology termed as beam division multiple access (BDMA) can be exploited in 5G network to increase the system capacity. In this multiplexing technique, an orthogonal beam can be allocated to the users according to their locations [10].

Recent advancements in smart devices and applications have promoted the proliferation of IoE networks. IoE networks involve autonomous and flying vehicles, healthcare applications, intelligent services, and other delay-sensitive applications. Such IoE networks would require ubiquitous sensing and computing capabilities that may exceed the capability of 5G networks. Furthermore, the data rate that can be supported by 5G networks is unlikely to sustain the enormous ongoing data traffic explosion. This has motivated research into continuing to advance the existing wireless systems in order to meet the emerging IoE applications and services. Therefore, the research now shifted to 6G wireless communications networks. Unlike previous networks, future 6G wireless communications systems are expected to support IoE applications and services. 6G supports the integration between different networks, e.g., terrestrial and non-terrestrial networks. For example, 6G supports satellite communication to increase connectivity and provide full coverage. To enable efficient integration between different networks, 6G will make use of network slicing and multi-access edge computing with software defined networks. In comparison with previous networks, 6G is expected to fully utilize artificial intelligence (AI) and machine learning (ML). 6G networks are expected to utilize ultra-high frequencies such as the use of millimeter wave (mmWave) and THz frequencies. The autonomous vehicle is expected to be fully supported by 6G. An extreme densification of the network infrastructure is expected to be deployed by the 6G networks. While the main focus on 5G was given to the massive MIMO technology, the reconfigurable intelligent reflecting surfaces will be the main core transmission technique for 6G networks. Unlike previous networks, 6G aims to fully support the Tactile Internet communication, which needs less than 1 ms delay for being able to perform light surgeries. To sum up, the future vision of 6G wireless communications networks lies in: (a) achieving high data rate/spectral efficiency particularly by moving to higher frequency bands; (b) providing an energy efficiency of 10x higher than 5G networks for green communication; (c) increasing the connectivity and providing full coverage; (d) maintaining security, secrecy and privacy; (e) achieving an ultra-high-reliable and low-latency communication; (f) supporting an externally high mobility of up to 1000 km per hour; and finally (g) realizing intelligence. Further details about the 6G vision are provided in the following subsection.

B. 6G VISION

6G networks are visioned to further enhance the conventional wireless communications systems, improve the quality of services, and support the huge data traffic demands. 6G networks aim to maximize the data rates, reduce energy consumption, enhance broadband connectivity and coverage, improve communication security and trustworthiness, increase link reliability, reduce latency, and achieve intelligent communication. An extremely high data rate of above 100 Gbps with an end to end delay of less than 1ms may be supported by 6G. 6G is also expected to meet the extremely high levels of communication reliability. Furthermore, we expect to move to an ultra era with future 6G networks. 6G networks are expected to support wireless communications with ultra-low latency and ultra-high reliability. Future 6G networks also aim to support ultra-fast mobility. In order to support an ultra-high-speed wireless data transmission, ultra large scale MIMO systems and ultra-high frequencies are expected to be used by 6G networks. Besides this, 6G networks aim to provide an ultra-high broadband connectivity and support an ultra high definition video streaming. Fig. 4 shows a schematic diagram of moving toward an ultra era in the future 6G networks.

The 6G requirements can be achieved through the use of new advance and intelligent communications techniques. For example, the use of reconfigurable intelligent surfaces, extra-large MIMO, new spectrum, holographic radio communications, full-duplex wireless communications, multiple access and modulation, are all essential techniques required for maximizing the data rates. In addition, energy harvesting and backscatter communication techniques are both useful and required to improve energy efficiency. Cell-free massive MIMO systems and the integration between terrestrial and non-terrestrial communications are effective techniques to increase connectivity and provide full coverage. Quantum communication and blockchain are effective techniques to increase communication security, secrecy and privacy. Holographic teleportation (telepresence) and edge computing are useful techniques for achieving an ultra-reliable and low-latency communication. Finally, artificial intelligence and machine learning are essential techniques for realizing intelligence. 6G aims to provide seamless integration of different wireless networks. This includes the integration of terrestrial and other non-terrestrial wireless networks that are airborne, underwater, and that employ satellite communications systems. Having such seamless networks integration allows a useful communication platform and provides high broadband connectivity with full coverage. Unlike previous networks, 6G wireless communications networks are expected to support many delay-sensitive applications such as Tactile Internet, holographic teleportation (telepresence), Internet of Smart Things (IoST) and multi-sensory extended reality (XR), which involves augmented reality (AR), mixed reality (MR), and virtual reality (VR). IoST applications can

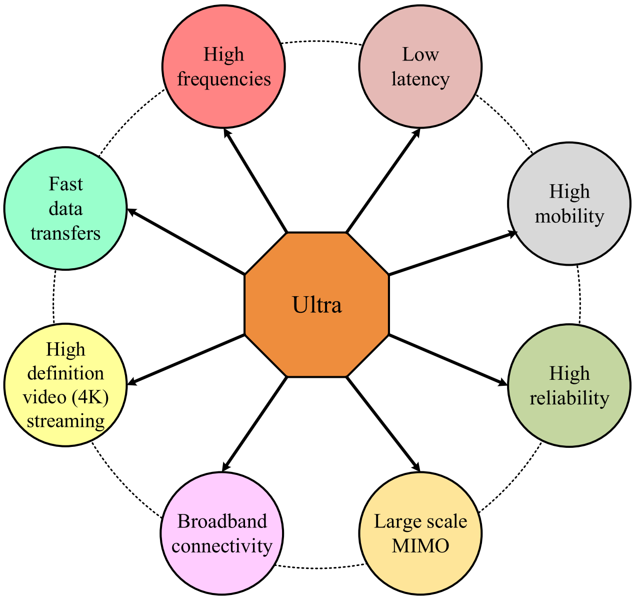


FIGURE 4. **A diagram shows the ultra era in 6G networks.**

be divided into smart city, smart radio environments, smart healthcare, smart grid, smart transportation, smart factories, smart farming and, smart home. All these smart applications are expected to be fully supported by 6G wireless communications networks.

C. RELATED WORKS AND PAPER CONTRIBUTION

Several different studies have investigated the vision of 6G networks, see [4], [11]–[40]. For example, the work in [11] focuses on the role of multiple access technologies. The work in [12] focuses on quantum communication and machine learning in future 6G networks. Likewise, the works in [13]–[15] focus on presenting the role of artificial intelligence in supporting future 6G networks. The work in [16], [17] discusses the integration of satellite and terrestrial communications. The work in [18] discusses the use of random access techniques for Internet of Things (IoT) applications. The work in [19] focuses on presenting the intelligent healthcare systems in 6G, while the works in [20], [21] focus on discussing the role of Blockchain technology. The works in [22], [23] focus on presenting the role of reconfigurable intelligent surfaces in future 6G networks, while the work in [41] focuses on discussing energy harvesting, security, and artificial intelligence. The work in [42] presents the feasibility of using mmWave frequency in satellite communications in the future 6G networks. The work in [24] discusses the use of artificial intelligence in an air interface design, human-machine interface, new spectrum bands, advanced security and privacy techniques and new network architecture for optimizing their performances. The work in [4] focuses on the security, secrecy and privacy issues and their importance in the future 6G networks. The work in [25] focuses on discussing the use of sub-THz and visible light communication, while the work in [26] focuses on the role of THz communication. The works in [27], [28] focus on the role of edge computing. The work in [29] highlights the role of machine learning techniques in supporting vehicular communication the works in [30], [31] focus on the role of deep learning. The works in [32], [33] present the role of unmanned aerial vehicles (UAVs) communications, the work in [34] discusses the key enabling techniques for machine-type communication, while the work in [35] discusses the use of device-to-device communication. The works in [36]–[40] focus on discussing the use cases that can be supported.

The aforementioned survey papers mainly focused on limited (specific) technologies and aspects of 6G wireless communications networks. Therefore, in the previous survey papers there was a lack of identifying what technologies are essential for achieving specific future 6G goals. This paper reviews and covers all the essentials technologies, which are expected to be utilized in the future 6G networks. To this end, this survey paper focuses on discussing the key fundamental performance indicators, which are considered as key drivers for future 6G networks. Unlike previous survey papers, this paper investigates all relevant technologies, which are essentially required to achieve the key fundamental performance indicators. After identifying the relevant technologies, this survey paper discusses the main operation principle of each technology, highlights the key fundamental benefits of each technology, identifies their envisioned potential applications, presents the current state-of-the-art research, and sheds light on the research challenges related to them. Furthermore, this survey paper discusses the application of holographic teleportation (telepresence), multi-sensory extended reality, and the Internet of Smart Things (IoST), which are envisioned to be fully supported by 6G networks. This survey paper can be considered as a useful guide for both industries and academic researchers. Importantly, this survey paper alludes to possible new research directions. Table 2 shows a summary of current related studies on 6G wireless communications systems.

D. THE KEY FUNDAMENTAL PERFORMANCE INDICATORS FOR 6G NETWORKS AND THE ENVISIONED KEY ENABLING TECHNOLOGIES

The main objective of the present paper is to identify the key performance metric indicators/requirements for future 6G networks and provide the envisioned key enabling technologies to achieve those performance indicators/requirements. For each technology, we present the basic operating principle, envisioned potential applications, current state-of-the-art research and technical challenges related to its use. The fundamental performance indications and the envisioned key enabling technologies for future 6G networks are presented in Fig. 5.

E. ORGANIZATION OF THE MANUSCRIPT

The rest of this paper is organized as follows. Section II discusses the technologies required to maximize the data rate of the future 6G wireless communications networks.

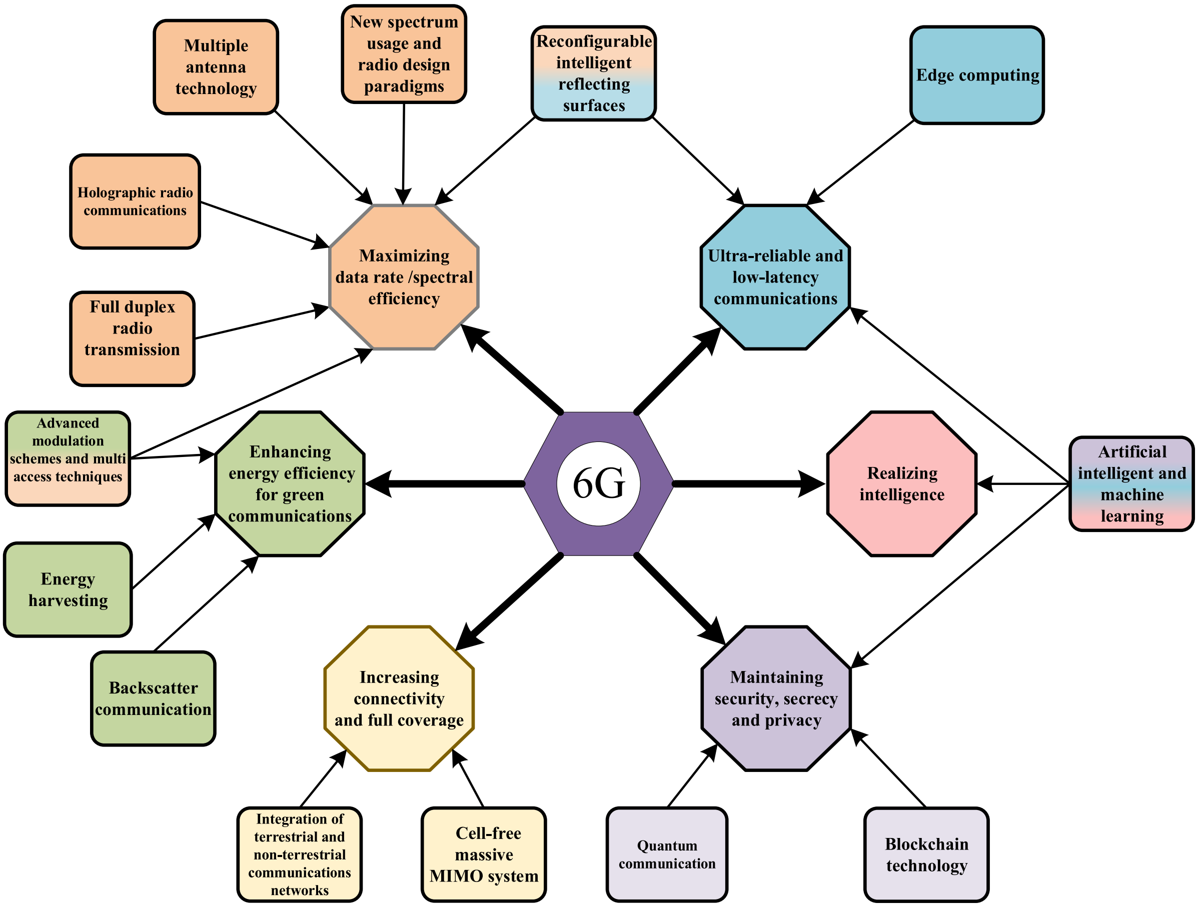


FIGURE 5. The evolution toward 6G with different key performance indicators and key enabler technologies.

Section III provides a review of some of the visionary technologies that are required to enhance their energy efficiency. Section IV presents the technologies required to increase the network connectivity, which is also needed to achieve full coverage. Section V gives a detailed description of the technologies required to maintain security, secrecy and privacy. Section VI highlights the technologies and the applications related to ultra-reliable and low-latency communications (URLLC). Artificial intelligence and machine learning techniques, which are envisioned to ultimately promote the 6G revolution and realizing intelligence, are discussed in detail in Section VII. Finally, this paper is concluded in Section VIII. Fig. 6 provides the paper contains of each section and each subsection.

II. MAXIMIZING THE DATA RATE/SPECTRAL EFFICIENCY

Maximizing the data rate is considered the most important performance indicator for any cellular technology. The following subsections discuss the key fundamental technologies to improve the data rate for future 6G networks.

A. MULTIPLE ANTENNA TECHNOLOGY

Multiple antenna technology which benefits from beamforming, diversity, and spatial multiplexing gains, has attracted significant research interest due to its powerful capability to increase the data rate and communication reliability [43]. The research studies on multiple antenna technologies initially focused on point-to-point (single-user) MIMO communications where the transceiver has multiple antennas to communicate with each other. Later, the focus shifted to multiuser MIMO systems, which quickly made their way in many communications standards such as IEEE 802.11 (WiFi), IEEE 802.16 (WiMAX), LTE and, LTE-A [44]. Unlike point-to-point MIMO, in multiuser MIMO systems, the spatial multiplexing of different data streams intended for different users can be achieved in the spatial domain through a transmission technique known as spatial division multiple access (SDMA) [45]. Recently a scaled-up version of the SDMA systems, i.e., large-scale multiuser MIMO, was proposed in [46], wherein each transmit base station (BS) is equipped with a relatively large number of transmit antenna elements N, which serve a much smaller number of K single-antenna non-cooperative users. Table 3 summarizes the key differences between the point-to-point MIMO and massive MIMO communications systems.

1) KEY POINTS OF USING LARGE NUMBER OF ANTENNA ELEMENTS

When a large number of antenna elements are deployed by the transmit BS, the array gain and the degrees of freedom that

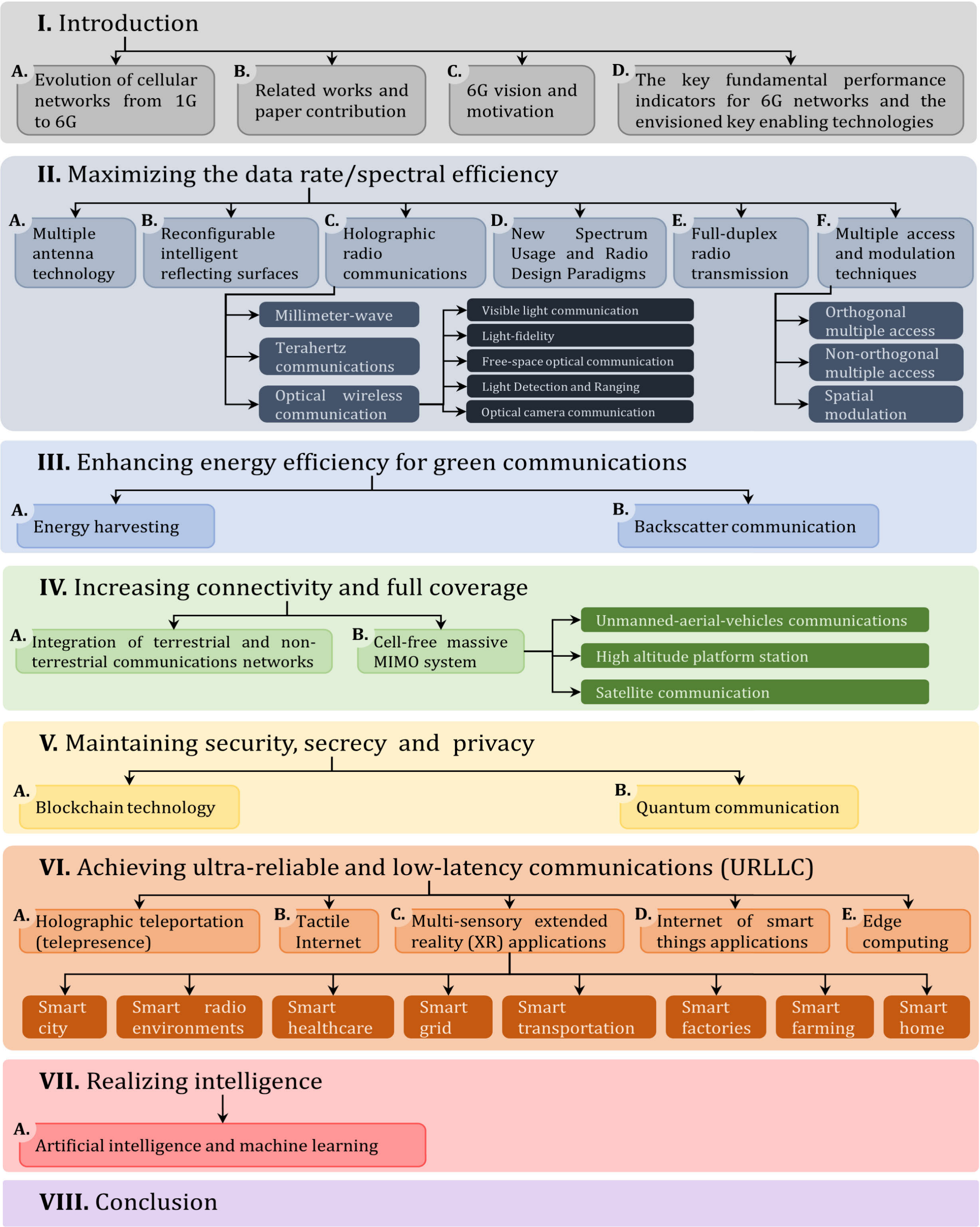


FIGURE 6. Structure of the survey paper and the sections classifications.

the propagation channel offers can be significantly increased. The favorable propagation condition can also be achieved in massive MIMO systems with rich scattering environment, wherein the channel vectors for users become asymptotically orthogonal as the number of BS antennas N grows large while the number of users remains limited. The consequence is that the effect of uncorrelated noise, fast fading, and jamming signals can be asymptotically mitigated [46]. In addition,

TABLE 2. Summary of current related studies on 6G networks.

Ref.	Year	Contribution and main focus
[11]	2019	The role of multiple access technologies
[12]	2019	Quantum communication and machine learning
[13]	2019	The role of artificial intelligence
[14], [15], [24]	2020	Discussing the importance of utilizing artificial intelligence and machine learning techniques
[16]	2019	Discussing the integration of terrestrial and non-terrestrial communications
[17]	2020	The integration of satellite and terrestrial communications
[18]	2019	The use of random access techniques for Internet of Things (IoT) applications
[19]	2021	Presenting the intelligent healthcare systems
[20], [21]	2020	The role of Blockchain technology
[22], [23]	2019	The role of reconfigurable intelligent surfaces
[41]	2020	Energy harvesting, security, and artificial intelligence
[42]	2020	The role of mmWave in satellite communications
[4]	2020	Discussing the security, secrecy and privacy issues
[25]	2019	The use of sub-THz band and visible light communication
[26]	2019	The importance of utilizing THz communication
[27], [28]	2020	The role of edge computing with software defined networks
[29]	2019	The role of machine learning in supporting vehicular communication
[30], [31]	2020	Discussing the role of deep learning technique
[32], [33]	2019	Discussing the importance of using UAVs communication
[34]	2019	The key enabling techniques for machine-type communication
[35]	2020	The use of device-to-device communication
[36]	2019	Discussing the expected use cases in future 6G networks
[37]–[40]	2020	The potential use cases and future applications

massive MIMO allows the use of low-complexity signal processing techniques in uplink (UL) and downlink (DL) transmissions [47]. For example, in the DL, linear precoding schemes can be used to focus the transmitted signal onto the desired users, whereas in the UL, linear combining techniques can be exploited to combine the signals transmitted from different users. In massive MIMO systems, the energy transmitted from the BS can be focused into spatial directions where the users are located. Hence, the radiated power from each element can be reduced, thereby making the massive MIMO systems more energy-efficient [48]. These key advantages promote massive MIMO to be the core technology for the future generation of wireless communications systems [49], [50]. Furthermore, a massive MIMO system is not only the core technology in mobile broadband services but also can be efficiently exploited in other communication and non-communication applications. For example, massive MIMO can be used in radio detection, ranging (radar), sensors and massive machine-type communications systems, which require low-energy consumption [50]. Among these essential applications, the joint use of radar and MIMO communication has received significant research attention during recent years [50], [51]. Joint radar and MIMO communication has several advantages such as (a) enhancing spectrum sharing; (b) allowing the use of low-cost hardware components; (c) improving the number of targets that can be uniquely detected; (d) achieving high spatial signal resolution; (e) reducing the power consumption; and (f) improving interference rejection capabilities to allow superior performance [50], [52]–[56]. Several research contributions in massive MIMO have been made during the past few years. These include providing achievable sum rate analysis [48], [57], [58], addressing pilot contamination issue [59]–[64], investigating the role of correlation in the massive MIMO systems [65], investigating the energy efficiency and power optimization [66]–[68], enabling FDD operation in massive MIMO systems with two-stage precoding [69], [70], and in signal-stage precoding [71]–[74].

An extra large scale massive MIMO system (XL-massive MIMO), also known as ultra-massive MIMO, was recently proposed in [75], [76] to extend the benefit of massive MIMO to high-frequency bands and in order to make wireless connectivity with ultra-high data rates available anytime and anywhere. The XL-massive MIMO aims to considerably increase the signal strength by steering and focusing the transmitted beams in space and frequency domains, where an array size of 1024×1024 is expected to be implemented with plasmonic nano-antennas [77]. XL-massive MIMO can be deployed in a distributed areas in order to serve a large number of users and to increase communication coverage. These areas include the walls of buildings, airports, the structure of stadiums, and shopping malls [78], [79].

2) RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

From the point of view of information theory, which is considered as the abstract mathematical theory that guides the design and implementation of communication systems, the performance of multiple antennas systems depends strongly

TABLE 3. Comparison between conventional MIMO and massive MIMO systems.

The key parameters	Conventional MIMO systems	Massive MIMO systems
Communication type	Point to point	Point to multiple points
Number of Antenna	$N \leq 8$	$N \geq 16$
The relation between N and K	$N = K$	$N \gg K$
Bandwidth	Use more bandwidth	An enhanced usage of the available bandwidth
Degrees of freedom	Not scalable so that provide less degrees of freedom	Provide more degrees of freedom
Degrees of correlation	Typically the channels are less correlated	The channels are highly correlated
Coverage area and cell-edge performance	Provide less coverage	Provide more coverage where the cell-edge SNR increases proportionally to N
Fading effect and reliability	More sensitive to the channel fading, which effects the communication reliability	Provide immunity against fading and thus improves link reliability and diversity gain
CSI estimation	Less sensitive to the CSI with manageable overhead	Sufficiently accurate CSI estimation are required and downlink CSI estimation overhead is problematic
Antennas at users	Multiple antenna at user	Users are equipped with single antenna and are served simultaneously over same time and frequency
Antenna coupling effect	Low coupling effect	High coupling effect
Array gain	Less array gain	Provide high array gain
Radiation pattern	Fixed radiation pattern	The ability to change the radiation patterns over time and frequency
Link quality after precoding/combining	Varies over time and frequency, due to frequency-selective and small-scale fading	Almost no variations over time and frequency due to the advantages of channel hardening
Resource allocation	The resource allocation must change rapidly to account for channel variations	The resource allocation can be planned in advance since the channel varies slowly

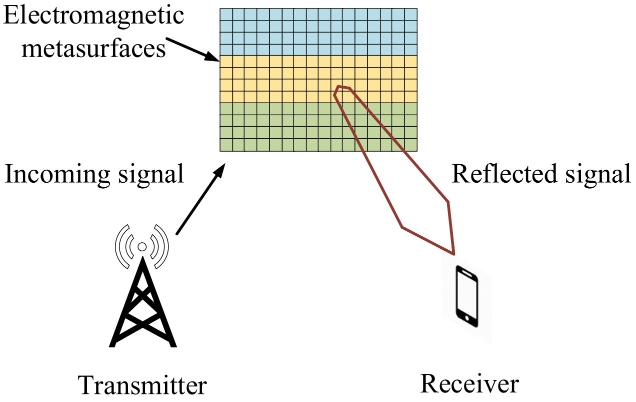


FIGURE 7. Reconfigurable intelligent reflecting surfaces aided mobile communication.

on the accuracy of channel state information (CSI) estimation. While CSI estimation may not be problematic in TDD mode, which relies on UL/DL channel reciprocity, it is of critical importance to most of current mobile networks providers that operate in the FDD mode. In addition to this, 6G networks are expected to operate in high mobility environments and high carrier frequencies, and thus, the channel would exhibit a shorter coherence time. Therefore, finding a feasible design that copes with the high-speeds and high frequencies environments is crucial. Furthermore, an opportunistic and low-complexity scheduling procedure with multiple antennas systems is required to alleviate the need for computationally expensive exhaustive users search whose complexity grows exponentially with the user group size [43]. Furthermore, research investigation to address the technical challenges related to the optimum beam selection and reducing the CSI feedback overhead is also required. To achieve this purpose, different CSI feedback compression schemes can be exploited to reduce the CSI overhead, examples of which are discussed in references [80]–[85]. Another challenge related to the use of large antenna arrays is the non-wide sense stationary properties that may appear along with the array. This implies that different parts of the arrays may have different propagation environments, or they exhibit the same channel paths with different power levels [86]. As such, new channel models that capture these propagation effects are required. In addition to this, using large antenna arrays might practically increase the computational complexity, cost of hardware design and power consumption [87], [88]. Hence, finding a feasible solution that considers the aforementioned issue remains a challenge. The application of large scale MIMO with a radar system could also bring new technical challenges. Besides this, advanced signal processing algorithms for detection and estimation are needed. In such a large scale MIMO system, the overhead would be scaled linearly with the number of BS antennas. Therefore, finding a feasible and robust design that takes into account the antenna array configurations and system overhead with limited coherence time is required [50]. Finally, in 6G networks, we expect to see many different applications that drive the demands for utilizing more compact antennas, more frequency bands and more bandwidth. For example, in addition to the information theory, circuit, wave and electromagnetic theories will also be involved in the design of future communications systems.

B. RECONFIGURABLE INTELLIGENT REFLECTING SURFACES

Moving to higher frequency bands in 6G comes with new challenges such as reducing the coverage area due to the shorter range communications, lessening the number of degrees of freedom offered by the physical channel due to reducing the number of scattering objects, and increasing the signal attenuation that effects the communication reliability between transmitter and receiver. In addition, due to the massive connectivity of IoT devices and sensors, wireless networks are moving to software implementations, an example of which is software defined networks (SDNs). Hence, wireless networks can be controlled remotely through the use of programmable software. Furthermore, there is an essential requirement to find flexible, feasible and cost-effective solutions for increasing the coverage area, improving the communication reliability and maximizing spectral and energy efficiencies of future 6G networks. To this end, a smart reconfigurable transmission mechanism known as reconfigurable intelligent surfaces (RISs) [89], also termed as intelligent reflecting surfaces (IRSs) [90], [91] or large intelligent surfaces (LISs) [92], has appeared as one of the most promising technologies to achieve the aforementioned goals. Such intelligent surfaces are designed based on software-controlled metasurfaces [93], [94]. The reflective metasurface is a low thickness two-dimensional planar surface, which has the potential to control the characteristic of electromagnetic propagation waves in order to shape waveforms, create a passive beam towards the desired terminal and achieve an enhanced received signal [89], [90], [94]–[97]. The configurable electromagnetic material contains integrated electronic circuits on a planar surface and programmable software, which controls the propagation environment. Each surface contains a massive number of low-cost scattering passive elements that have the potential to independently reflect the incident signals toward the desired users by digitally controlling their adjustable amplitude and phase shifts [89], [95], [98]. It should be pointed out that the amplitude and phase shifts can be optimized to maximize the spectral efficiency or minimize power consumption [99].

1) KEY POINTS OF THE IRSs

IRSs can be more energy efficient in comparison to conventional wireless transmission technologies. This is because IRSs do not require power amplifiers, radio-frequency (RF) chains, sophisticated signal processing, and interference management schemes. IRSs can be practically fabricated with low-cost [100]. IRSs can be densely deployed indoors, on walls/ceilings, in exhibition halls, and outdoors on arbitrarily shaped surfaces, buildings, roads, walls, shopping malls, airports, etc. [89], [101]. This wide area deployment increases the network's coverage especially in places where multipath propagation is insufficient [97]. IRSs can be useful to communications systems with high frequencies bands such as mmWaves and THz. This is because high frequencies bands are considered to be highly sensitive to different propagation conditions. IRSs have the ability to provide further improvement in the degrees of freedom of the wireless communications channels, especially when the line-of-sight (LoS) path is not available. IRSs can also be efficiently powered by renewable energy sources, which are energy efficient, and can also be used with wireless power transfer and mobile edge computing to support dense IoT devices, multicell networks, and in cognitive radio communications [94], [97].

Several studies have investigated the performance of IRSs aided smart radio communications. For example, the works in [102], [103] consider the use of IRSs to enhance the propagating signal attenuation in the simultaneous wireless information and power transfer (SWIPT) based systems, thereby allowing the receivers to harvest enough energy. The work in [104] suggests the application of IRSs in mobile edge computing to improve communication reliability and increase the offloading time. It is worth noting that mobile edge computing is considered a newly emerged edge computing paradigm to support computationally intensive IoT applications on mobile devices [105]. Subsection VI-E provides further discussion about the mobile edge computing technique. The work in [106] discusses the application of IRSs in cell-edge of multicell networks to enhance the desired signal transmitted from the serving BS and mitigate the interference signals coming from other BSs. Besides the aforementioned research studies, another line of research study has focused on using IRSs with cognitive radio networks. For example, the work in [107] investigates the application of IRSs to improve the propagation channel condition, and thus, enhance the signal power between transmitter and receiver of the secondary users, which reuse the spectrum of the primary users. The work in [108] presents a scenario where the IRSs are used in the physical layer security to enhance the system security. IRSs have been explored to mitigate the information leakage to the eavesdroppers while enhancing the received signal power at the legitimate users. Several studies have considered the application of IRSs with non-orthogonal multiple access (NOMA) technology to address the challenges of random fluctuation in propagation environments and blocking, see e.g., [109]–[112] and references therein. The works in [113]–[115] investigate the application of IRSs in UAVs networks to enhance the communication coverage and improve the quality of service.

2) RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

The performance of IRSs depends on the availability of accurate CSI, which is required to enable efficient precoding design. Also, the availability of accurate CSI would allow the IRSs to increase their beam focusing capabilities and to adapt transmissions to current channel conditions, and thus, the received SINR can be maximized. However, CSI estimation in RISs is considered to be challenging in comparison to conventional wireless communication systems. This is attributed to the large channel dimension and the large number of reflecting elements. Therefore, there is an essential need to develop suitable channel estimation algorithms to support efficient IRSs transmission. In addition, obtaining the CSI with FDD is more challenging than TDD systems since the former is subject to high feedback overhead. Hence, finding a feasible solution for CSI estimation and feedback with FDD protocol is needed [116]. Besides this, a smart remote controlling mechanism to manipulate the amplitude and phase of the signals in the IRSs might be challenging. As such, in order to achieve the full potential gain of the IRSs, an efficient controlling scheme is required. Since the interest has been growing in exploiting high-frequency bands, particularly mmWave and THz bands, the application of IRSs in such frequency bands is worthy of investigation. Studying the role of IRSs in mitigating the electromagnetic interference waves in sensitive propagation applications such as medical imaging and radar technology is also of interest [94]. Furthermore, since IRSs can be useful to support cellular networks, it is of particular interest to investigate the performance of IRSs in high mobility environments.

C. HOLOGRAPHIC RADIO COMMUNICATIONS

Holographic radio communication, also known as holographic MIMO surfaces or holographic beamforming, is a special form of IRSs communication, discussed in the previous subsection, which can be used to shape/steer electromagnetic waves dynamically according to the desired directions [117]. This dynamic beamforming can be achieved using low-cost software-defined electromagnetic wave modulators and with circuit power consumption [100]. IRSs can be seen as passive surfaces, which can only reflect impinging radio-frequency signals generated from ambient transmitters, while holographic MIMO can be exploited for large active surfaces [92], [118]. It is worth noting that the holographic MIMO is different from standard holographic teleportation, which will be discussed later in subsection VI-A. Holographic MIMO combines both communication theory and electromagnetic theory [117]. Holographic MIMO represents an array with a massive (uncountable) number of antennas that compact into a limited space/surface to allow an approximately spatially-continuous electromagnetic transceiver aperture [50]. The surface either actively conveys beamformed radio-frequency signals or manages its reflections of radio-frequency signals generated at other locations [50].

1) KEY POINTS OF HOLOGRAPHIC COMMUNICATIONS

Holographic MIMO has the capability to control the entire physical space [36]. Owing to the approximately continuous electromagnetic aperture, holographic MIMO can achieve ultra-high density and ultra-high spatial resolution in wireless communications systems [50]. It would also allow electromagnetic waves with arbitrary spatial frequency components to be produced and detected without side-lobes [50]. Owing to the extreme spatial resolution, holographic MIMO aims at achieving a remarkable reduction in power consumption and a significant improvement in spatial multiplexing [92], [117]. Holographic MIMO can form super-narrow beams, which can be used to overcome the severe propagation loss for the mmWave and THz bands and reduce interference [119]. Holographic MIMO combines imaging and wireless communication system and has the potential to improve spectrum efficiency and network capacity.

2) RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

To achieve the full potential of the holographic MIMO system, further research is needed. For example, developing accurate channel modeling and channel estimation techniques that explore the spatial correlation structure are required. Further, finding feasible pilot designs with short coherence time using fully digital or hybrid analog and digital beamforming architectures for holographic MIMO systems are essential [117]. Besides, new signal processing algorithms and networking techniques for realizing holographic MIMO system are crucial. Developing feasible protocols and algorithms for fast reconfiguration of the reflection electromagnetic signals are also needed [50]. Finally, optimal resource allocation mechanisms and low-complexly users scheduling schemes for holographic MIMO system are worth investigating in the future.

D. NEW SPECTRUM USAGE AND RADIO DESIGN PARADIGMS

The number of connected devices to the Internet has rapidly increased during the past few years, which results in significant growth in data traffic. In addition, there is an ever-increasing demand for higher data rates to support bandwidth-hungry applications driven by the IoT. Thus, there could be a significant network capacity shortfall in the near future. This has motivated the researchers to efficiently exploit the currently available spectrum, i.e., below 10 GHz, and move to higher operational frequency bands, i.e., mmWave and THz. Furthermore, to support a diverse set of IoT requirements, the coexistence of different frequency bands within the same system would be inevitably required. This will not only achieve spectrum relief to the currently crowded radio-frequency network but will also make wireless communication more energy efficient and less sensitive to interference. Also, utilizing higher frequency bands is extremely useful for future 6G networks and presents an opportunity to achieve high-speed peak data rates, communication reliability, and ultra-low latency. Besides, 6G networks are expected to achieve a joint wireless communication interface by making use of the existing sub-10 GHz bands technologies with higher bands and guarantee seamless handover between these different frequency bands [97]. However, moving from sub-10 GHz band to higher bands with fully digital precoding will introduce several challenges in terms of hardware design and implementation, and hence might require significant changes in the physical layer design [120].

1) MILLIMETER-WAVE (mmWave)

Millimeter-wave (mmWave) communications are useful for future 6G networks to meet the ever-growing demands for extremely high-speed data rate wireless access [121]. This is due to the huge available bandwidth in mmWave bands that can potentially be exploited in mobile broadband applications to achieve peak data rates of multiple gigabit-per-second (Gbit/s) for indoor and fixed outdoor wireless systems [121]–[125]. A large spectrum is included in mmWave frequencies. This spectrum ranges from 30 to 300 GHz, which corresponds to wavelength from 10 mm to 1 mm [126]. Hence, multiple gigahertz frequencies can be fully supported to offer an order of magnitude capacity improvement for future 6G networks. In addition, owing to larger bandwidth, mmWave communications can be useful for delay-sensitive applications [123]. MmWave communications have already been considered in IEEE standard (IEEE 802.11ad [127]) for short-range stationary scenarios and deployed for indoor applications such as small-cell backhaul [128].

a: KEY POINTS OF mmWave COMMUNICATIONS

MmWave communications are essential for cellular heterogeneous networks [129], [130] to increase the data rate. Besides, mmWave can be efficiently used to support automated vehicular communication, which would allow the vehicles with

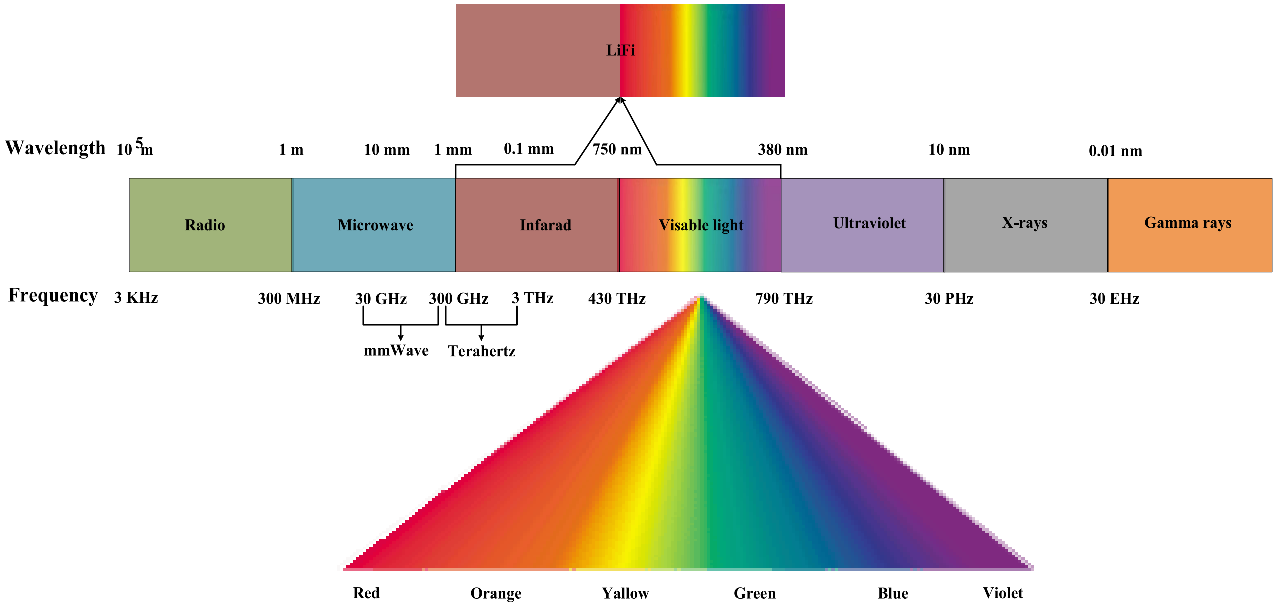


FIGURE 8. An illustration of electromagnetic spectrum.

high speed to exchange information seamlessly [131], [132]. MmWave communication also has the potential to support self wireless backhaul in cellular networks [133]. Experimental results in [134] demonstrate that mmWave has the potential to support both outdoor and indoor communications. The results show that a data rate of about 500 Mb/s can be achieved in non-line-of-sight (NLoS) environments and with a mobility of 8 km/h. MmWave can be used with the existing microwave frequencies in cellular communications. In this context, the work in [135] proposes a way of using microwave frequencies to send control information and mmWave frequencies to convey payload data transmission. mmWave communication has the potential to support high-speed data rate for different wireless devices such as smartphones, smartwatches and augmented & virtual realities [136], [137]. However, communication at mmWave frequencies suffers from specific propagation behaviors such as high signal attenuation and absorption as well as high penetration loss. MmWave signals are subject to orders-of-magnitude increase in path loss in comparison to the microwave signals, which are currently used in most cellular systems [138]. However, the short-wavelength range in mmWave communications allows the deployment of small-sized arrays with a large number of antenna elements that can be contained in a small physical dimension. Therefore, using a large number of antenna arrays can achieve a sufficient beamforming gain that is required to overcome the path loss and allow spatial multiplexing of several data streams to further improve the spectral efficiency [138]. Besides that, large beamforming gain provided by mmWave communications has the potential to improve the link quality, extend coverage and reduce interference [139]. The work in [134] demonstrates that using large antenna arrays with mmWave is useful to overcome the high path loss in cellular systems. However, there are fundamental differences between using large antenna arrays in the conventional microwave frequency and mmWave frequency in terms of the propagation channels, hardware design and signal processing algorithms [140]. For example, the existing hardware architecture supports full digital base band beamforming at microwave frequency, which directly controls the phase and amplitude of signals and allows flexible transmission [140]. However, the joint use of analog and digital beamforming is preferable at mmWave frequency to overcome the radio-frequency hardware limitations [138], [141]. It is worth noting that analog-to-digital converters (ADCs) in mmWave systems could be expensive and energy inefficient in comparison to microwave systems [129]. Typically, large base station antenna elements can be easily implemented using fully digital arrays, but the implementation complexity may grow larger with mmWave frequency [140]. Besides, a separate radio-frequency chain for each antenna may be required with mmWave system [129]. In addition, jointly using both analog and digital beamforming in mmWave communication would reduce the multiplexing capability of serving multiple users simultaneously over the same time and frequency, and hence, reduce the spectral efficiency in comparison to full digital beamforming [140]. Therefore, whether mmWave with large antenna arrays will be implemented with full digital or hybrid beamforming remains an open research question [140]. NOMA technique can be combined with mmWave frequencies to improve the data rates, achieve simultaneous multi-user communications and reduce interference [121], [142]–[146]. Furthermore, UAVs communication can benefit significantly from mmWave frequency to provide high data rates for 6G networks [147], [148]. MmWave can be used for radar applications to perform joint radar communications, which make use of high signal range resolution achieved by large bandwidths and radar functionalities [56].

b: RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite the promising results of mmWave communication system when it comes to providing multiple Gbps rates and allowing significant spectrum relief, several technical challenges still exist, which need to be addressed in order to make mmWave communication feasible for future networks [121]. Besides, finding viable approaches for applying mmWave in high mobility environments, improving the communication coverage and mitigating hardware impairments are valid research challenges worth investigating. Further research to overcome the sensitivity of mmWave communication to blockages and atmospheric loss is also needed. From a signal processing point of view, the performance of mmWave communication system depends strongly on radio frequency hardware [126]. Therefore, to achieve the full potential gain of mmWave communication, several research challenges relating to signal processing need to be addressed. Besides, further investigation is required to find robust designs for higher layers, i.e., transport, routing and medium access control (MAC) [149]. In addition, due to the specific propagation behaviors of mmWave system and hardware characteristics, new design aspects related to network coordination, resource allocation, user scheduling and network planning are required. Furthermore, there are some technical challenges related to the implementation of mmWave in vehicular communication systems. For example, finding feasible channel models and viable approaches for beam training, tracking and alignment for mmWave vehicular communication systems are needed [131], [149]–[152]. Further investigation regarding the coexistence between mmWave and the state-of-the-art microwave technologies in heterogeneous cellular networks is also of interest. The application of artificial intelligence and machine learning approaches in mmWave systems is an interesting research topic that should be investigated. The application of IRS technology using mmWave frequency could be a promising solution to the blockage issue and to improve the coverage of mmWave signals [153]. Further investigation in this context is also required. To overcome the limitation of short communication distance in mmWave systems, cellular networks operating at mmWave frequencies will likely require to be considerably denser than the currently deployed microwave networks. Hence, mmWave cellular networks will likely experience undesired interference due to the dense deployment of a large number of access points. Therefore, finding feasible interference management approaches in the mmWave communication systems are needed [154].

2) TERAHERTZ (THz) COMMUNICATIONS

THz communication is envisioned as a key enabler for 6G networks due to its capability to achieve ultra-high-speed data rates (up to 1 Terabit-per-second (Tbps)) and support bandwidth-intensive applications [155]–[159]. THz communication has the potential to alleviate the spectrum scarcity of current wireless communications systems [160], [161]. THz communication explores the frequency spectrum bands between (0.1-10 THz) and the corresponding wavelengths range between (0.03 mm-3 mm) [162]–[164]. THz frequency band is located between mmWave and infrared (IR) bands [165].

a: KEY POINTS OF THz COMMUNICATIONS

THz communication has the potential to offer more bandwidth than the mmWave frequency and provide an enhanced propagation condition in comparison to the IR band. Operating at higher frequency ranges, which are provided by the THz communications, can be efficiently exploited to support various remote sensing applications for 6G network [166]. In addition, THz communications can effectively support traditional macro-scale and future emerging micro-scale applications, which include the Internet of NanoThings (IoNT) and the Internet of BioNanoThings (IoBT) [155]. Recently, Federal Communications Commission (FCC) has considered the spectrum frequencies between 95 GHz to 3 THz to be used for future 6G research [4]. THz frequency has been considered in IEEE standards (IEEE 802.15 IG- THz and IEEE 802.15.3d-2017) for short-range communications. THz can be used to enable holographic teleportation, which requires data rates of approximately 5 Tbps and microsecond-range latency of less than 1ms [155], [167]. Communication at THz frequencies would necessitate the use of tiny cells where the radius of such cells could be a few tens of meters [36]. In addition, due to the higher carrier frequency and shorter wavelength, THz communication might make use of ultra massive antenna arrays to allow efficient beamforming [168], [169]. Therefore, hundreds of narrow beams can be generated by ultra massive antenna arrays, which are efficient in increasing the signal strength, improving the data rates and reducing the interference [155]. Although fully digital beamforming is still perdurable and optimum choice, hybrid or analog beamforming could be used with THz and ultra massive antenna arrays communication in 6G networks [97], [170]. THz can also be integrated with other wireless communications systems to form flexible hybrid networks [163]. For example, a hybrid between THz and a free-space-optical system and a hybrid between THz and VLC system can be used in future 6G networks to achieve robust communication solutions. Furthermore, THz can be used with IRSs to provide NLOS propagation and improve communication coverage [116], [171], [172]. THz frequencies can also be explored in healthcare applications such as terahertz pulse imaging in dermatology, pharmaceutical industry [173] and other new cognition and sensing IoT communications, which could be exploited by automated machinery and autonomous vehicles [158]. The spatial modulation technique can be used with THz communication to achieve sufficient spatial degrees of freedom for spatial multiplexing [169]. THz communications can be used in D2D, drone, and vehicular communications and also as an alternative to wired-backbone-connectivity in data centers [174].

b: RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Although THz communication provides abundant bandwidth and presents a special opportunity for supporting multi-gigabit-per-second towards Terabit-per-second links, it suffers from unique challenges. These challenges are related to strong atmospheric attenuation, propagation path loss, blockage effects and molecular absorption [116], [162], [175]. Therefore, these technical challenges need to be addressed to release efficient THz wireless communications in practice. Further, Increasing the communication range of THz and finding feasible beams steering and tracking algorithms are necessary to establish successive THz communications systems [156], [162], [176]. Since the cell sizes of THz communications are expected to be tiny, new architectural designs for such denser deployment cells and efficient backhaul connectivity are required. Also, further research related to channel modeling, channel coding, modulation techniques, channel estimation, signal processing algorithms, transceiver designs, propagation measurements, networking, resource allocation for THz band communications are required. Investigating the coexistence of the THz band with other frequency bands such as mmWave and microwave is an interesting research topic that should be investigated in the future. Some related research work in this context can be found in [163]. The Doppler effect is another technical challenge that may face THz broadband communications. Hence, new mobility management approaches for THz band communications are needed. Furthermore, there are also some technical challenges with THz frequencies deployment. These challenges are related to hardware constraints and the speed of data converters. Besides, developing new transceiver designs that are adequate to THz frequencies operation are required [36], [157]. Finally, finding power-efficient solutions and reducing the computational complexity of THz communication are still open research directions that should be investigated in the future [158].

3) OPTICAL WIRELESS COMMUNICATION

Beyond the THz communication, optical wireless communication (OWC) systems, which include infrared (IR), visible and ultraviolet frequency bands [177], are considered as an efficient way to explore the available electromagnetic spectrum to provide more broadband connectivity and coverage for 6G networks [178]. Due to the availability of extremely wide ranges of the unlicensed and safe spectrum, OWC has the potential to overcome the spectrum shortage challenges in RF-based wireless communications [179]. The exploration of such huge bandwidth in OWC would support a wide range of IoT connectivity and applications. These applications include hospitals, large shopping malls, stadiums, homes and offices, public transportation stations, e.g., railway stations and airports, industries, underwater communications and space communications [178]. Using OWC in telecommunication can be useful since it provides high-speed data rates, cost efferent infrastructure, secure communications and supper low latency, hence, acting as a complementary efficient technique for existing RF-based wireless communications to fulfill the potential requirements of 6G networks [180]. The performance of OWC systems can be affected by ambient light noise [181]–[184], atmospheric turbulence & path loss in outdoor scenarios [185]–[189] and pointing errors [190]–[193]. Several technologies are involved in OWC systems include visible light communication (VLC), light fidelity (LiFi), free-space optical (FSO) communication, LiDAR and optical camera communication (OCC). Each one of these communication technologies has its unique operation principle (such as transmission, receiving, modulation), advantages and challenges. Fig. 9 provides OWC types. In what follows, we provide a description of OWC communication technologies.

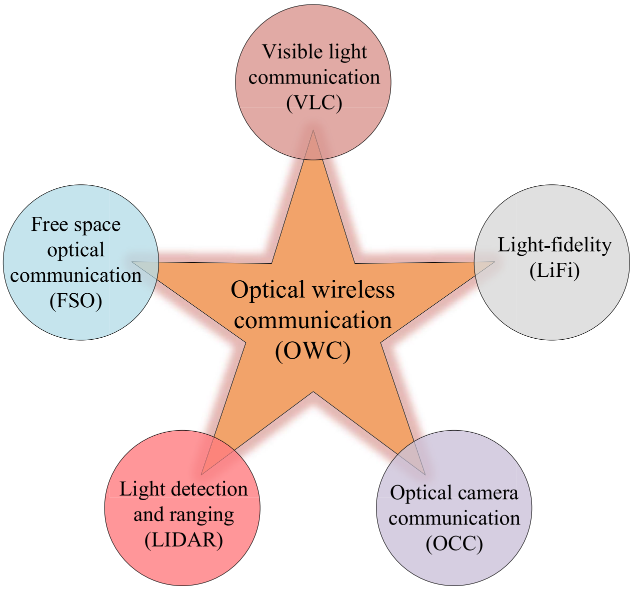


FIGURE 9. **Optical wireless communication types.**

a: VISIBLE LIGHT COMMUNICATION

Visible light communication (VLC) is a special form of OWC that uses the visible part of the spectrum for wireless transmission of information [97], [194]. VLC has been introduced as a key promising technology for 6G networks due to its capability to combine lighting and high-speed wireless communication in a single source, i.e., power-efficient light-emitting diodes (LEDs), and to complement the existing RF networks [194], [195]. In VLC systems, LEDs are used at the transmitter to transfer high-speed data rates, where the data is wirelessly transmitted using intensity modulation (IM) technique [119], [195], [196]. VLC uses photodiode (PD) or laser diodes (LDs) and direct detection (DD) technique, which has the potential to convert the received light intensity to a useful signal at the receiver [195], [196]. Spatial modulation [197] and wavelength division multiplexing (WDM) [198]–[200] techniques can be useful to enhance the preference of VLC communication. VLC is included in IEEE 802.15.7 standard [201].

- Key points of VLC

VLC has the potential to provide a fast data rate while maintaining energy consumption. Since VLC uses LED lights, it is considered to be a low-complexity and cost-efficient communication technique in comparison to radio-frequency communication. In addition, VLC is able to achieve a higher speed data rate with lower latency in comparison with the conventional radio-frequency networks. Owing to the directional property of visible light, VLC communication has the potential to provide relative positioning with sub-meter accuracy. Due to the short-range communication, the VLC technique is considered to be more secure in comparison to conventional radio-frequency communication. VLC provides high immunity against unauthorized eavesdropping or attack signals that are transmitted or received from out of coverage sight. Besides, VLC is considered a promising technology to complement classical encryption techniques [4], which could be applied to address the key security challenges in 6G networks. VLC offers high degrees of immunity against electromagnetic radiation interference [194], [202], [203]. VLC technology has the potential to support diverse IoT applications for the future 6G networks, which include smart buildings, smart homes, smart grids, smart cities, smart factories and smart transportation. Integrating VLC and IoT would release a new concept called the Internet of Light Things (IoLT) [204]. In IoLT, VLC can be considered as one of the key sources to supply and convey wireless communication and also to enable energy harvesting. VLC technology can be applied in the smart indoor network including home/office environments. Hence, VLC would bring both lighting and wireless communication for home and office environments, which would provide relief to the RF spectrum bands. VLC can also be used to transmit useful data in large shopping malls and supermarkets. VLC can be applied with an RF system to form a hybrid RF/VLC wireless communication, which would allow highly energy-efficient communication and enhance the user experience. Specifically, VLC can be flexibly integrated with the current RF networks to support high connectivity and coverage. For example, VLC could extend the RF signals coverage in order to cover blind spots, such as in tunnels and subways [24], [25], [205]. A possible application of VLC outdoors could be in vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, which could be used in traffic offloading, providing useful information about road works and accidents. VLC has the potential to allow underwater communication at a longer distance in comparison to the RF electromagnetic waves, which are considered to be highly absorbed in the water.

- Related challenges and future research directions

Further investigation about VLC is still needed. For example, developing an accurate channel modeling for VLC is an interesting research topic that can be investigated in the future. In addition, developing fast switching mechanisms between optical and radio-frequency systems is required. Since VLC relies on intensity modulation and direct detection, which satisfies positive-valued amplitude signals, new theoretical bounds for channel capacity are needed. Besides, conventional algorithms that have been used in radio-frequency communications might not directly apply to VLC. Thus, further investigation to find suitable algorithms for the VLC system is needed. Physical layer security and coding in VLC are open research directions that worth investigating. In VLC, the light intensity is rapidly decreased with distance, which is considered as a major technical issue that needs to be addressed in the future. Artificial noise and natural light are also considered as sources of interference that affect VLC performance considerably [203]. Therefore, finding a viable solution to mitigate such undesired interference is required. In addition, VLC faces a challenge in separating multiple optical signals from different sources. As such, developing an advance technique for efficient signals separation is needed. Besides, using an advanced modulation scheme such as spatial modulation may improve the performance of VLC systems. Also, using a large scale MIMO system and NOMA communications systems with VLC can also be useful to enhance the VLC network performance. Therefore, further investigations regarding the use of spatial modulation, large scale MIMO and NOMA with VLC are needed. Furthermore, the application of VLC in a high mobility scenario is needed. Overcoming the technical challenges related to VLC may allow such a communication technique to be practically applicable and efficiently integrated with conventional wireless standards.

b: LIGHT-FIDELITY (LiFi)

Light-Fidelity (LiFi) was introduced as a key promising technology to complement the currently deployed wireless fidelity (WiFi) network [179], [206]–[209]. LiFi is considered an effective extension of VLC technology with an aim to provide a more secure, bi-directional, higher data rate and realize fully connected wireless networks [207], [209]. LiFi is a part of optical wireless communication that explores the infrared and visible light spectrum. This allows the available unlicensed spectrum to be fully exploited and provides wireless data communication together with illumination. This is because full utilization of the combination of infrared and visible light communication can offer around 2600 times larger resources spectrum than the size of the current RF spectrum. LiFi technology makes use of the light-emitting diodes (LEDs) to transmit data symbols in the downlink while photodetectors (PDs) are used at the receiver to receive these data symbols. The experiment results in [210] show that LiFi is able to provide up to 3Gb/s data rate from a single spot LED micro-light through the use of direct current optical orthogonal frequency division multiplexing (DCO-OFDM) modulation.

- Key points of LiFi technology

LiFi technology has the potential to support bi-directional multiuser communication, which includes the transmission from point to multipoint and also multipoint to single point [207]. LiFi can also be efficiently integrated with the currently deployed RF wireless networks to achieve heterogeneous wireless networks from both optical and RF domains [207]. LiFi has the ability to support user mobility and handover [207]. Using LiFi technology in a wireless network is known as an optical attocell network [211], [212], which can be a promising topology to overcome the looming spectrum crisis in the current RF wireless networks. Recently, experimental results, which are carried out in [213], showed that the LiFi concept can be effectively used with a WiFi network. The results demonstrated that using software-defined networking with LiFi technology allows the performance of the WiFi network to be considerably enhanced, which is used for traffic offloading and load balancing. The results also showed that over three orders of magnitude improvement in data density can be achieved by using LiFi technology. From the economic perspective, LiFi can be considered as a cost-effective solution since it can be easily integrated with the current RF network and makes use of the same existing lighting infrastructure [213], [214]. In LiFi based network, it is possible to combine an optical diffuser with LDs source to achieve broad illumination and wireless communication transmission simultaneously [215]. Since LiFi technology depends on LEDs lighting, it is considered to be a more secure source of communication, which can be safely unitized in aircraft cabins, nuclear & chemical plants, petrol stations, hospitals and also in the outdoor environment, i.e. street lamps, vehicle headlamps and traffic signals [216]. These key features and advantages promote LiFi technology to be one of the core technologies for the future 6G networks [25], [213]. LiFi has also been included in IEEE 802.15.7 standard [201] and it is expected to be integrated with currently existing wireless standards. The first design of transceivers application-specific integrated circuits components (ASICs) is presented in [207]. This transceivers architecture can be effectively used with current smart mobile and wearable devices to support fully connected IoT in 6G networks.

- Related challenges and future research directions

There are some practical technical challenges related to the deployment of LiFi that need to be addressed to achieve its full potential. These challenges include short-range communication, interference caused by different artificial and natural light sources, LiFi signal modulation, and detection. Besides, developing an accurate channel model for LiFi communication systems is essential. Furthermore, finding feasible interference mitigation techniques, which are required to achieve fairness and high system capacity [207], is an interesting research topic that should be investigated. In addition, investigation of the effectiveness of using LiFi technology in load balancing is also worth investigating. Also, further research studies are needed to investigate the application of LiFi technology in outdoor scenarios.

c: FREE-SPACE OPTICAL COMMUNICATION

Free space optical (FSO) communication is a special form of OWC system that takes place in the near-infrared frequency range [178], [217]. FSO is considered as a promising technology for providing wireless backhaul broadband connectivity to enable long-range communications [177], i.e, several kilometers, to meet the huge traffic demands in 6G networks [173], [218]. FSO communication explores laser technology to produce a focused light or narrow beam towards the desired user [219]. The optical light beam in FSO system is used to convey a high-speed data rate for long-distances wirelessly. Typically, FSO system uses laser diodes at the transmitter side and a photodiode (PD) at the receiver side, which involves optical filters with lens, to detect the desired laser beam [177]. It is worth noting that at the receiver, the light signal is converted to a voltage. Using FSO, it is possible to transmit up to 10 Gbps data rate for long-distance as discussed in [220].

- Key points related to the FSO transmission technique

FSO system has the capability of providing up to 40-Gbps data rate over a relatively short distance, e.g., 20m [221]. Providing such a huge data rate allows the FSC system to be a comparable technology to the fiber optics communication networks. FSO system has several advantages such as (a) allowing the use of high-frequency reuse factor; (b) achieving a secure communication; (c) providing immunity against electromagnetic interference; and (d) reducing the power consumption [222], [223]. Several research works have investigated the application of FSO with radio-frequency systems in order to perform a hybrid radio-frequency with FSO transmission, see, e.g., [224]–[228]. The combination of radio-frequency and FSO communications can be used to enhance the capacity and coverage of conventional radio-frequency communication. Therefore, this combination could be useful for future 6G networks. FSO communication can be used in civilian (commercial) and military applications. FSO communication can be utilized with various networks both in space optical and terrestrial communications [220]. For example, FSO can be exploited in ground-to-satellite, satellite-to-ground, satellite-to-airplane, airplane-to-airplane, satellite-to-satellite, satellite-to-UAVs, satellite-to-balloons and satellite-to-ship communications [229]–[231]. FSO systems can also be used in remote sensing applications, remote healthcare systems to transmit efficient and secure medical images and videos, cellular networks to provide backhaul connectivity and underwater communications.

- Related challenges and future research directions

Despite the several advantages of the FSO communication system, it is considered to be highly sensitive to blockage and atmospheric turbulence, which induces fading and sensitivity to weather conditions [219], [223]. Besides, FSO could face several unpredictable attenuation and propagation factors such as rain attenuation, fog, clouds, snow, haze, which could affect the performance of FSO communication systems [220]. Therefore, further research works are required to investigate the application of FSO with other technologies, which are currently used with conventional radio-frequency communication systems. For example, advanced physical layer techniques such as MIMO system [232], [233], adaptive modulation and channel coding schemes [234] and cooperative diversity [235] can be used to improve the performance of FSO communication. FSO communication could be more suitable for fixed wireless systems. Besides, the application of FSC communication systems with high mobility scenarios is essential, which can be more challenging than fixed wireless communication. Therefore, the application of FSC in high mobility scenarios requires further investigations in future. The combination between radio-frequency and FSO may be subject to several restrictions such as mismatch between radio-frequency and optical domains, circuitry design, and atmospheric attenuation. Therefore, further research investigations are required to overcome these limitations.

d: LIGHT DETECTION AND RANGING (LiDAR)

LiDAR technology is considered as a part of OWC operating in infrared frequency band rang. LiDAR denotes an image light wireless communication technology that can be used to provide a dynamic digital representation of different objects surroundings [165]. The narrow beam produced by LiDAR can be efficiently used to map different physical objects with relatively high resolution. This could significantly enhance the safety and efficiency of automated driving [131]. LiDAR uses different components such as optical light, position & navigation systems, photodetector and scanner [178]. Combining LiDAR sensing with radio-frequency communication or radar systems can be useful for future 6G networks especially for autonomous driving systems [236]. LiDAR sensing can be used with robotics to gather sufficient information about the dynamic digital representation of the surrounding objects with a high degree of accuracy [178].

- Key points related to the LiDAR

LiDAR is a key sensing technology that can be used in advanced driver assistance systems (ADAS) and autonomous driving systems [237]. LiDAR sensing can be efficiently exploited with UAVs to provide high resolution, accurate data transmission and sensing information [238], [239]. Due to its high reliability and accuracy, LiDAR is considered as the most appropriate remote sensing technique to measure range, identify different objects, shapes, headings and positions [165], [240]. Hence, LiDAR could be a promising technology for future 6G networks.

- Related challenges and future research directions

The LiDAR system is sensitive to weather conditions (e.g., rain, snow, and fog) and ambient light. In addition, implementing such technology in cars could be cost-inefficient [240]. Besides, the LiDAR system needs to meet the automotive ultra-Reliable Low-Latency communications [241] in order to grantee a safely automatic deriving. As such, further experimental platforms are required to investigate the performance of the LiDAR system and its application in practice. Furthermore, applying artificial intelligence and machine learning algorithms in LiDAR is possible for enhancing the system performance. This could be a possible research direction that is worth investigating in the future.

e: OPTICAL CAMERA COMMUNICATION (OCC)

Optical camera communication (OCC), which uses image sensors or cameras for communication, positioning, and navigation, is introduced as a promising technology for wireless communication in the future networks [159], [242]. OCC is considered as a part of OWC that explores the available spectrum regions related to the infrared and ultraviolet frequency bands to provide wireless data communication [243], [244]. Hence, much wider spectrum regions can be occupied by OCC in comparison with the spectrum regions of VLC, hence alleviating some of the currently congested communication traffic [242]. However, since the bit decoding method used for the camera is different from the photodiode method used in VLC, some adjustments are still required with OCC transmission systems. This is attributed to the fact that the output of cameras in OCC are images and not voltages as in most of the VLC systems [242]. OCC has been included in IEEE 802.15.7r1 standard [201], [243]. OCC uses commercial LED lighting sources at the transmitter and image sensors or cameras to decode LED modulated data at the receiver. The transmitted signal in the OCC system is modulated using on−off keying (OOK) [242], [245]. When OCC uses visible light spectrum only as a communication medium, it acts as a VLC system [178].

- Key points related to the OCC transmission technique

OCC can be straightforwardly integrated on or implemented with current smart infrastructure, e.g., smartphone and laptop cameras, to achieve ubiquitous coverage in both indoors and outdoors scenarios. This straightforward implementation of OCC enables the portable devices to provide various services [246]–[248]. OCC has the potential to mitigate the interference denoted by the light coming from different sources and directions. This is because advanced lenses are used in mobile cameras to project lights from different sources and to separate different signals and sample them using different pixels [178]. Thus, the undesired signals can be straightforwardly discarded. OCC can be used indoor for localization in shopping malls and large supermarkets. In addition, OCC can also possibly be applied outdoor in V2V and V2I communications. Further, OCC can be applied with virtual reality and augmented reality [178], and it might be useful to implement with UAV communication systems.

- Related challenges and future research directions

Due to the limited camera's frame LED pulse rates, the OCC telecommunication system faces a challenge related to synchronization, which happens due to the camera frame. LED flickering, which is known as an undesired light illumination, is considered to be one of the challenges in the

OCC system. LED flickering is happened due to the limited camera frame rate. Therefore, further research investigation is required in order to find a feasible way to address the synchronization and light flickering problems in OCC systems. In this context, advanced modulation sachems might be essential to overcome these issues [242]. Furthermore, due to the LoS nature in OCC systems, i.e., no multipath diversity is available, the signals could be subject to block by objects, which prevents light penetration, and thus, could result in losing the connection [242]. Therefore, further investigation is needed to address this technical issue in the OCC system.

E. FULL-DUPLEX RADIO TRANSMISSION

While the current wireless communications systems make use of either TDD or FDD duplex operation modes, in-band full-duplex (IBFD) is introduced as a promising operation mode to improve the data rate for future 6G wireless networks. IBFD could allow efficient usage of radio resources, reducing the delay between UL and DL [249], and increasing the spectral efficiency in comparison to the conventional duplex operation modes [250]. In IBFD, the transmission and reception are carried out simultaneously at the same time over the same frequency band [251]. Thus, the number of information bits that are reliably transmitted per second per Hz can be doubly increased [252]. IBFD radio transmission can also be beneficial for the access layer, where a node is capable to reliably transmit the outgoing frame while simultaneously receiving the ongoing one [253].

1) KEY POINTS OF FULL-DUPLEX RADIO COMMUNICATION

IBFD technique can support a diverse set of IoT applications. These applications include cognitive radio, small-scale heterogeneous networks, bidirectional communication, cooperative transmission, and relaying networks [97]. Among these applications, IBFD relaying is considered to be the most promising one to achieve the full potential gain of IBFD, which is predicted to double the spectral efficiency [254]. This is attributed to the traffic symmetric pattern of relaying systems, wherein a relatively same amount of data can be transmitted and received over the same frequency band in the full-duplex mode [255]. Therefore, the frequency reuse with relaying systems can be efficiently maximized. In addition, the transmission power of relay systems is relatively small, which makes it more feasible for a full-duplex communication system to mitigate the self-interference [256]. Note that relay networks play an essential role in extending the radio coverage, especially in a strongly shadowed urban environment [257], [258]. Besides, the self-interference can be stronger than the desired signal, thus making it impossible for the receiver to decode the signal of interest. This can severely deteriorate the performance of IBFD systems. Typically, self-interference cannot be perfectly mitigated in practice. As such, effective self-interference mitigation techniques are the key to create a pathway for realizing IBFD in practice. Specifically, advanced signal processing techniques could play an essential role in reducing self-interference. Self-interference cancellation is to date considered as an open research problem in IBFD systems, albeit several cancellation techniques have been proposed (see e.g. [253] and the references therein). These proposed techniques include the use of orthogonal polarizations, digital and analog cancellation based approaches, passive suppression, and antenna placement [258]–[260].

2) RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Although the use of large-scale antenna arrays at the relay could help in mitigating the interference, it might come at the cost of the energy efficiency of the relay system, whose transmit power is relatively low. In particular, the energy consumed by analog to digital converters (ADCs) at a fully digital relay receiver is scaled linearly with the number of antenna arrays [261], [262]. Thus, using large-scale antenna arrays systems with the IBFD technique is still an open research topic [97]. As such, further investigation in this regards is needed. It is worth noting that the intelligent reflecting surface can be used to improve the performance of full-duplex systems [263]. Therefore, further investigation about the application of Intelligent reflecting surfaces with full-duplex systems is required. Although the effect of imperfect CSI estimation on half-duplex communication systems has been extensively investigated and becomes a rather mature subject, the full-duplex counterpart has yet received limited attention. Therefore, CSI estimation based on feasible training sequence design in full-duplex systems should be investigated.

F. MULTIPLE ACCESS AND MODULATION TECHNIQUES

Efficient multiple access and modulation techniques could play an essential role in improving the data rate and reducing energy consumption of future 6G networks.

1) ORTHOGONAL MULTIPLE ACCESS

Several orthogonal multiple access (OMA) technologies have been used in many practical systems, including frequency division multiple access (FDMA), which has been used in 1G, time division multiple access (TDMA), which has been adopted in 2G, code division multiple access (CDMA), which has been utilized in 3G, and orthogonal frequency division multiple access (OFDM), which is currently used in the DL of 4G and 5G NR networks [264], [265]. Among the above techniques, OFDM has been the dominant modulation technique for multicarrier communications and received significant research attention. This is due to its capability to provide immunity against frequency selective fading, co-channel interference, and impulse noise [264]. OFDM modulation transmission has several advantages such as (a) allowing the use of adaptive modulation schemes to increase the data rate; (b) enhancing spectrum efficiency, i.e., efficient utilization of the available bandwidth, i.e., dividing the available spectrum between users efficiently; (c) providing immunity against intersymbol interference (ISI); and (d) supporting multipath delay spread [266]. These key advantages allow OFDM to be utilized in several wire-line and wireless communications standards and also to be used in 5G NR networks, though several developments and standardization works are yet in progress. It is worth noting that the 5G NR networks support multicarrier OFDM in the DL and single-carrier DFT-spread-OFDM in UL transmission.

a: THE CHALLENGES RELATED TO THE OFDM TRANSMISSION TECHNIQUE

Despite the attractiveness of OFDM transmission technique in increasing the data rate, it is to date suffers from a high peak-to-average power ratio (PAPR) [264], [267]. This results in an unwanted in-band distortion and unwanted out-of-band (OOB) radiation due to the non-linearity of the power amplifier (PA). Hence, in order to guarantee linear amplification of the input signal, the PA needs to operate at the back off from its saturation point, and thus, it becomes less efficient as the back-off increases. This may have a direct impact on mobiles battery life and energy-sensitive applications. Therefore, advanced multiple access techniques are required.

Several alternative multicarrier transmission techniques, which address some of the shortcomings of OFDM, have been proposed as new candidates for the next generation of mobile communications. For example, filter bank multicarrier (FBMC) with an offset quadrature amplitude modulation (OQAM) has been proposed in [268] to provide a higher data rate and reduce the unwanted OOB radiation that faces the OFDM technique. In FBMC transmission, the nonadjacent subcarriers are well separated through the use of a bank of well-designed filters. The FBMC can be well designed to reduce the narrow-band interference and unwanted sidelobes. However, the length of the filter impulse response in FBMC needs to be increased by at least four times the transmit symbols. This design constrain may make the FBMC technique infeasible to be applied to the delay sensitize applications, wherein high spectral efficiency requires to be achieved with short burst transmissions. Therefore, the focus has shifted to the universal filtered multicarrier (UFMC) [269], wherein a group of several subcarriers is filtered together instead of per subcarrier filtering with a larger length using in FBMC. Therefore, by applying the filtering operation to a group of consecutive subcarriers in the UFMC technique, the length of the filter impulse response could be reduced while reducing the unwanted out-of-band radiation. However, the UFMC technique comprises the need for cyclic prefix (CP) insertion, which is typically required in most of the multicarrier waveforms, thus making the UFMC technique more vulnerable to time misalignment in comparison to most CP-based techniques. Also, UFMC is subject to ISI with moderately large delay spreads. Filtered-OFDM (f-OFDM) has been also introduced as a new waveform for future wireless systems [270] to overcome the limitation of the UFMC technique. In contrast to the UFMC, the filtered-OFDM technique allows the filter length to be varied and even exceed the CP length in conventional CP-based techniques to obtain better balancing between the time and frequency localization. However, increasing the CP length is not necessarily a feasible solution for low-latency applications in the future communications networks. A more flexible modulation technique, termed generalized frequency division multiplexing (GFDM) has been proposed in [271], [272] as a candidate waveform for future wireless communications. GFDM technique takes the advantages of both OFDM and single carrier frequency. In GFDM technique, the subcarriers are filtered and combined into blocks and each block is modulated independently. However, such filtering and combining approach could result in non-orthogonal subcarriers, which might lead to increase the inter-carrier interference and ISI. Therefore, efficient receiving techniques are required with GFDM based techniques in order to mitigate the ISI and ICI. Although using such interference cancellation techniques could be useful to obtain a reasonable performance, this comes at the expense of increasing the computational complexity. It is worth noting that FBMC and GFDM are considered as pulse shaping modulation techniques while UFMC and f-OFDM are considered to be subband filtering schemes [273]. Recently, a two-dimensional modulation scheme, which is a generalization of both CDMA and OFDM, termed as orthogonal time-frequency space (OTFS) has been proposed in [274] to support high-speeds, high frequencies, and large antenna arrays transmissions. OTFS modulation has the ability to covert the time-varying multipath wireless channel into a time-independent channel, which allows each transmitted symbol to be experienced a near-constant channel gain. The results show that OTFS modulation can provide higher diversity gains over time and frequency in comparison to the conventional OFDM modulation scheme. Such constant channel gain overall symbols would allow the system overhead and complexity to be reduced. Analog types of modulations may also be possible for future 6G networks. It is worth noting that the typical key performance indicators that have been used in the performance evaluation of the aforementioned transmission techniques are PARP, design complexity, filter length, power-spectral density (PSD), bit-error-rate (BER), spectral efficiency (SE), and latency.

b: RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Although the aforementioned techniques have been proposed to efficiently partition system bandwidth and increase the data rate, which might be useful for 6G networks, their performance should be further investigated and compared to meet the use case requirements and applications of 6G networks. Also, it would be worth investigating the key potential problems of the currently existing techniques and see their feasibility with the requirements of the 6G networks. For example, the compatibility of the aforementioned waveforms with high frequencies needs to be investigated. Besides, single-carrier DFT-spread-OFDM, which reduces the PAPR in comparison to the OFDM transmission technique, can be used with high carrier frequencies in 6G networks. The work in [120] showed that single-carrier frequency division multiple access provides more immunity and robustness against the phase noise and can achieve a larger power amplifier efficiency in comparison to cyclic-prefix OFDM in sub-THz bands. In addition, using high-order modulations with high carrier frequencies might increase the peak data rate considerably but it might also come at the cost of increasing the BER and implementation complexity. Hence, the tradeoff between the reliability, measured in BER, the data rates, and the computational complexity should be investigated. Intelligence OFDM transmission techniques as well as subcarrier index modulation (IM) schemes [23], [275], [276] may be considered for spatial multiplexing in future 6G networks. The compatibility of OMA techniques with large-scale MIMO systems should be investigated. In addition, many IoT delays and battery life sensitize devices and applications are expected to be considered in 6G networks. Therefore, efficient carrier techniques are required. Specifically, it is expected to extend the OMA techniques capabilities to support an extremely high data rate and low latency. The tradeoff amongst the range of potentially conflicting 6G requirements, such as the complexity, cost, energy-efficient, delay, while maintaining the system performance, is one of the key concerns that worth investigating.

2) NON-ORTHOGONAL MULTIPLE ACCESS (NOMA)

With OMA techniques, the available resource blocks within each cell are divided orthogonally and allocated either in the time, frequency, or code domains, thus reducing the interference among adjacent blocks and allowing simple signal detection. However, OMA techniques serve a single user in each orthogonal radio resource block. Therefore, the number of served users is limited by the number of available radio resource blocks, and thus, the available spectrum might not be efficiently exploited. In addition, the orthogonality transmission could be broken down due to the channel impairments and the random nature of the wireless propagation channels, which will affect the communication reliability and spectral efficiency. Furthermore, motivated by the diverse requirements of massive access IoT networks, advanced multiple access techniques to efficiently exploit the available spectrum are required for future 6G networks [277], [278]. NOMA is introduced as a key enabling technique for supporting multiple non-orthogonal radio resource blokes among the users either by sharing the same time-frequency recourse block in the power domain [279]–[282] or by spreading code in the code domain [273], [283].

a: KEY POINTS RELATED TO THE NOMA TRANSMISSION TECHNIQUE

NOMA has the potential capability to efficiently exploit the available radio resources and serve multiple users simultaneously in the same resource bloke with different QoS requirements, i.e., achieving more fairness between multiple users [284], [285]. In the power-domain NOMA, the transmit signals at the BS are superposed and transmitted to multiple users using different power levels. Thus, the users with relatively high received SNR levels would decode interfering signals before decoding their own signal by using successive interference cancellation (SIC), while the users with lower SNR levels would consider the interference as noise. In contrast, in code-domain NOMA, which uses spreading codes, the users are provided with relatively high SNR levels but at the cost of increasing the interference. Although the spectral efficiency and fairness can be improved with NOMA transmission technique, this comes at the cost of increasing the receiver complexity in comparison to the traditional OMA techniques [121]. Besides, the NOMA technique can be used to provide massive connectivity and satisfactory wireless communications for IoT applications [286], [287].

It is worth noting that SDMA, mentioned in subsection II-A, can be considered as a non-orthogonal spatial multiplexing technique because it spatially multiplexes the transmitted data in the spatial domain, i.e., power domain. SDMA uses linear precoding to spatially separate users in the power domain [288]. Massive MIMO system is considered as an extended version of SDMA, as discussed in subsection II-A. Massive MIMO system can be utilized to mitigate the interference. However, the interference management using massive MIMO technology might be insufficient due to the extremely limited spatial resolution of the large antenna arrays, which could occur when the transmit array is far away from the users [97]. Therefore, NOMA could be seen as an efficient candidate to mitigate the residual multi-user interference at the protocol layer. NOMA has been considered by 3GPP LTE Release-12 [289] for interference cancellation and later by 3GPP LTE-A Release-13 [290], which is termed as multiuser superposition transmission (MUST). Some other popular forms of NOMA and multiple access techniques have also been proposed recently. These techniques include sparse code multiple access (SCMA) [291], [292] and low density spreading (LDS) [293]–[295], successive interference cancellation amenable multiple access (SAMA) [296], and multi-user shared access (MUSA) [297], which are considered as a code-domain NOMA [285], and other multiple access techniques in multiple domains such as pattern division multiple access (PDMA) [296], [298], [299], lattice partition multiple access (LPMA) [300] and bit division multiplexing (BDM) [301]. Delta orthogonal multiple access (D-OMA) has been recently proposed in [11] as a candidate multiple access technique for future 6G networks. D-OMA transmission relies on the coordinated multipoint (CoMP) concept and makes use of partially overlapping NOMA subbands spectrum. However, several system parameters are required to be optimized in D-OMA transmission including, the size of the NOMA cluster, the amount of spectrum overlap between NOMA clusters, the number of collaborating CoMP, and power-allocation. This could be challenging in the ultra-dense networks due to the nonlinearity of the objective function introduced by the dynamic propagation environments. In addition, an efficient SIC algorithm is still essential to mitigate the interference.

b: KEY POINTS RELATED TO THE RATE SPLITTING MULTIPLE ACCESS TRANSMISSION TECHNIQUE

Rate splitting multiple access (RSMA), which is non-orthogonal multiple access, has been recently proposed in [288] as another promising technology for future 6G networks. RSMA is considered a bridging technology between the SDMA and NOMA transmission techniques. However, RSMA differs from the SDMA and NOMA approaches in the mechanism of decoding the signals and canceling the interference. Similar to the SDMA technique, RSMA treats part of the residual interference as noise, while it decodes part of the interference in a way similar to the NOMA based technique [288]. RSMA uses precoding at the transmitter and SIC at the receivers. This partial interference management allows RSMA to be a more flexible transmission technique in comparison to SDMA and NOMA techniques.

c: RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite the advantages of the above multiple-access techniques, there are several technical challenges related to their use in practice. These challenges need to be addressed. For example, robust interference management to enable successful signal decoding is required. However, this might come at the expense of implementation complexity and increasing power consumption at the receivers. Therefore, tradeoffs between performance, complexity, and energy efficiency need to be considered. In addition, all the above multiple-access techniques are sensitive to the imperfect CSI estimation, which could be one of the key obstacles that prevent such techniques from achieving their full potential gain in practice. Therefore, finding feasible pilot design schemes and advanced channel estimation algorithms is required to achieve accurate CSI estimation. Using adaptive modulation/coding techniques for efficient resource allocation may also be a challenging issue, which needs to be considered in future.

3) SPATIAL MODULATION

Using extremely large-scale antenna arrays, which are highly required by the 6G networks to increase the data rate, could pose some technical challenges related to the implantation complexity, the use of high-cost multiple radio-frequency chains, and increase power consumption [302]. With large-scale antenna arrays, each antenna element requires a complete radio-frequency chain to produce digital modulation. This implies that a large number of full-active antennas could have large form factors that require high-cost components to guarantee efficient transmission. In addition, it is likely that much of the power consumption will come from RF power amplifiers and the associated baseband signal processing [303], [304], and thus, this might reduce the energy efficiency of 6G networks. Hence, a low-complexity coded modulation mechanism, known as spatial modulation, is proposed as an efficient modulation transmission to meet the energy efficiency requirements of next-generation wireless communications. Spatial modulation design paradigm aims to erode the cost and complexity of the large-scale antenna transmissions while maintaining a feasible data rate and end-to-end system performance. The basic principle of spatial modulation is to map a block of information bits at the transmitter into two units: 1) an information symbol, which is selected from a constellation diagram, and 2) information over the channel, which is chosen from a set of indices related to unique transmit antennas [197], [305], [306]. This would allow the spatial position of each signal antenna at the transmitter in the antenna array to be exploited as an extra dimension for sending information [305].

a: THE KEY POINTS RELATED TO THE SPATIAL MODULATION

Spatial modulation transmission presents an opportunity to use a low-cost single-carrier RF structure with a low-complexity single-stream detection. This would also allow the transmit signals to be more robust against RF hardware impairments, such as phase-noise and inter-Channel Interference (ICI), which may occur due to sending superimposing of independent information [302], [305]. In addition, spatial modulation benefits from the single carrier RF implementation to mitigate the power dissipation of power amplifiers. Furthermore, spatial modulation has the potential to reduce the RF power consumption owing to the inherent multiplexing gain that can be achieved by the spatial constellation diagram.

b: THE CHALLENGES RELATED TO THE SPATIAL MODULATION

However, spatial modulation, though achieving low-cost and complexity implementation, is constrained by spastic coded modulation sets, which could limit the data rate required for scalable IoT networks. Therefore, advanced index/coded modulation schemes [276], which make use of larger code sets to increase the data rate, are required. The high-order modulation with spatial modulation design could be considered in the future to improve the data rate. Using the index/coded modulation with IRC, which controls the electromagnetic waves in order to increase the signal quality, coverage, and/or data rate [307], could be investigated in the future. In addition, the optimum number of radio-frequency chains with spatial modulation that achieves the best tradeoff between the achievable data rate and energy efficiency while maintaining hardware simplicity needs to be investigated. A summary of the techniques discussed in this subsection is provided in Fig. 10.

III. ENHANCING ENERGY EFFICIENCY FOR GREEN COMMUNICATIONS

The continuous growth in wireless data traffic, which comes from connecting billions of devices to the Internet, has led to an increase in energy consumption. In addition, network operators have recognized that the traditional approaches of

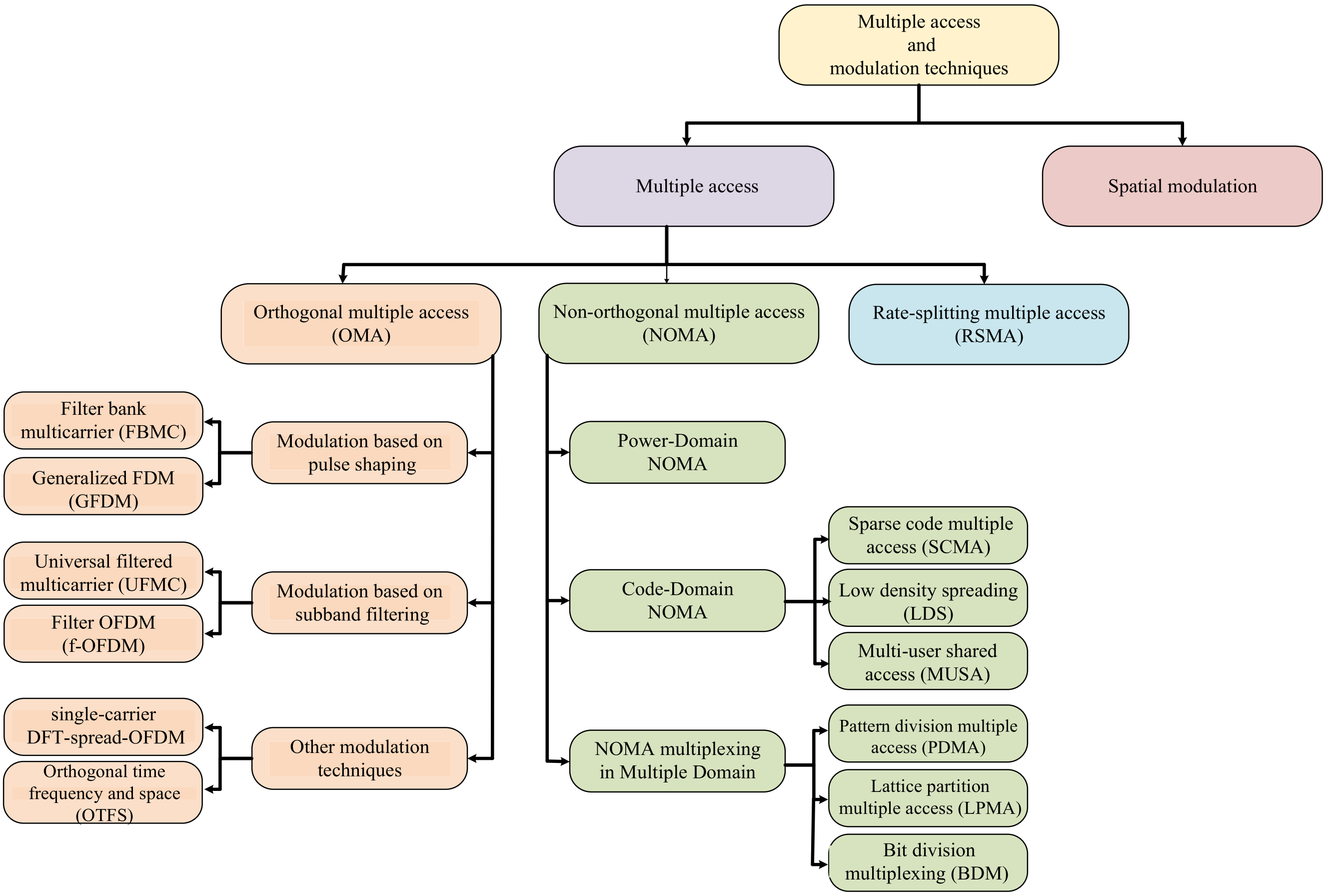


FIGURE 10. Schematic diagram illustrates multiple access and modulation techniques.

deploying more small cells might not be sufficient to meet the ongoing huge data traffic demands. Besides, one of the significant challenges that face the small cell networks deployment is the considerable amount of intercell interference (ICI) from other cells [308]. Thus, finding feasible energy-efficient designs and operations for future 6G networks with an aim to reduce the undesirable carbon dioxide (CO2) emission per mobile subscriber becomes essential [309]. In addition, finding suitable designs for realizing economically sustainable future wireless communications systems that achieve both spectral and energy efficiencies with low hardware cost are crucial [88], [310]. Therefore, green radio access network concept has been introduced to optimize the spectrum resources and minimize energy consumption. The radio resources in the wireless communications systems can be efficiently allocated to maximize energy efficiency [311]. The metric for calculating the energy efficiency of a communication link is obtained by dividing the number of information bits (over the total consumed energy) by the entire network measured in [bit/Joule] [312]. Energy management is essential for the sustainability of future 6G wireless communications networks [313]. Recently, cloud radio access network (C-RAN) concept [314] is introduced as a promising network infrastructure to overcome the increasing mobile traffic demands in cellular systems [315], [316]. In C-RAN, most of the intensive computational tasks, such as precoding matrix calculation, baseband signal processing, and channel estimation are moved to the cloud [316]. In this regard, C-RAN has the potential to reduce energy consumption in order to achieve green wireless communications systems [317]. However, finding feasible front-haul solutions to centralization the C-RAN network is essential [317]. In addition, the C-RAN network requires a virtualization implementation to realize resource cloudification [317]. Furthermore, energy consumption can be reduced using an efficient network planning scheme [318]. Also, suitable switch-on/switch-off algorithms may be required to control the traffic conditions and reduce the energy consumption [319], [320]. Besides, finding feasible hardware designs that account for energy consumption is essential for energy-efficient wireless communications systems [321]. This includes the design of an efficient radio-frequency chain and the use of simplified transmitter/receiver structures, e.g., one-bit signal quantization and the utilization of hybrid analog/digital beamforming [318]. Mobile cloud computing such as fog and edge computing is another impressive technique for achieving energy efficiency in wireless communications systems [316], [322], [323]. Mobile cloud computing allows users with huge computing demands to offload their intensive tasks to the edge cloud in order to save energy. Further discussion about edge computing is provided in subsection VI-E. Combining mobile cloud computing and C-RAN might lead to a significant energy saving for future communications networks [324], [325]. Recently, several studies have investigated the energy efficiency maximizing with large number antennas arrays, see e.g., [67], [326]–[329]. These investigations have focused on exploiting an optimum power allocation, scheduling algorithms, and network topology to reduce energy consumption. It is worth noting that using an externally large number of base station antenna arrays might not achieve the energy efficiency requirements of future 6G networks. This is because energy consumption can be increased with the number of radio-frequency chains.

A. ENERGY HARVESTING

Energy harvesting is considered one of the most promising techniques to increase energy efficiency in 6G networks. Energy harvesting enables wireless devices to harvest energy from radio-frequency signals using rectenna circuits, which can be used to charge the devices' batteries wirelessly to support their operations [330]. For example, wireless sensor networks (WSNs) are widely used for healthcare monitoring. As such, the total power consumption in such networks, which require long-term connectivity and long battery life, is considered a major issue. Therefore, energy harvesting can be efficiently exploited to support WSNs [331].

1) KEY POINTS OF ENERGY HARVESTING

The energy harvesting technique has the potential to reduce the carbon footprint [332]. The energy harvesting technique allows an efficient battery-powered operation for wireless networks. This makes wireless networks to be deployed in remote rural areas and in the human body [332]. Energy harvesting can be used in many medical and safety applications and in remote monitoring with extended battery life and longer communications ranges [332]. Furthermore, the energy harvesting technique allows wireless communications networks to be powered by clean sources of energy [318]. Typically, energy harvesting technique includes wireless power transfer (WPT), wireless powered communication network (WPCN) and simultaneous wireless information and power transfer (SWIPT) [330], [333], [334]. Therefore, a special design at the receiver side is required to retrieve the information and energy. In the WPT approach, the power transmitter transfers the energy to user devices without information. The transferred energy is then utilized to charge the devices' batteries. The WPT-based approach has the potential to be used with implant devices for medical purposes, electric cars and wireless grids [335]. In WPCN based approach, the energy is firstly harvested in the user devices and then used to transmit data. Hence, the communication efficiency of wireless devices can be significantly improved [336]. In SWIPT based approach, the power transmitter can simultaneously transfer energy and information to the user devices. Then, the users would either harvest energy or decode the information sent by the power transmitter. As such, an efficient energy-information transmission can be achieved [337]. SWIPT technique has the potential to achieve the best use of the radio-frequency spectrum/radiation [338]. SWIPT technique allows a massive number of IoT devices to be powered and connected anywhere and anytime [338]. Several studies have investigated the energy harvesting technique for green communications. For example, the trade-off between the energy harvesting and the information rate in additive white Gaussian noise (AWGN) channels has been investigated in [339]. This study assumed a realistic receiver, which harvests the energy and decodes the information from the same signal. A more practical scenario with power-splitting (PS) and time-switching (TS) based approaches has been considered in [340]. In PS based technique, the receiver can split the received signal into two diffident parts, one to decode the useful information and one to harvest the energy. In TS, however, the receiver can instantaneously switch between the decoding information and the energy harvesting. The antenna switching (AS) technique, which uses switches to switch between antenna elements to achieve decoding or rectifying, can also be used for SWIPT [340]. A new approach that exploits spatial switching (SS) of the information and energy was proposed in [341]. In SS based approach, the MIMO channel can be efficiently decomposed into parallel channels using singular value decomposition (SVD). In this case, the MIMO wireless channels can carry either information or energy, thereby neither TS nor PS is necessary. A new approach that exploits the generalized triangular decomposition (GTD) structure was proposed in [342]. The proposed GTD approach allows the MIMO channel to be decomposed and jointly used for energy harvesting and information exchange. The energy harvesting and information can be effectively separated at the receiver.

2) RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Finding accurate models for energy harvesting systems is considered as one of the major challenges [338]. Another challenge that faces energy harvesting systems is the randomness nature of the energy available at any given time [318]. In addition, new advancements in network design and signal processing are required. Resource allocation and scheduling are also considered as major issues in energy harvesting systems [343], [344]. More practical experiments are required in order to investigate the efficiency of energy transfer and harvesting. Furthermore, in order to enable efficient energy harvesting design the complexity and cost of the devices' circuits might be increased. This is also considered as one of the technical challenges that need to be addressed to achieve the full potential gain of energy harvesting systems. Also, an ambient backscatter communication system might be used to address this issue.

B. BACKSCATTER COMMUNICATION

As stated earlier, reducing energy consumption is the most essential part of 6G networks. Besides, there are a massive number of IoT devices in 6G networks, which are powered by batteries that have limited capabilities [345]. Therefore, a symbiotic radio is introduced as a promising technology to reduce energy consumption towards achieving green communication. The symbiotic radio technology has the ability to integrate passive backscatter devices with active transmission systems [346]. Ambient backscatter communication [333], [347] is considered as an example of symbiotic radio technology. In this case, the network devices make use of ambient radio frequency signals such as TV, cellular base stations, and WiFi as signal sources to transmit data without the need for an active radio frequency transmission [348], [349]. Thus, a significant battery power saving can be achieved. The user data can be encoded in the reflected and re-emitted signal by modulating the antenna impedance [349].

1) KEY POINTS RELATED TO THE BACKSCATTER COMMUNICATION

Backscatter communication system consumes an order of 10 μW less energy in comparison to the conventional transmission systems [350]. This makes a backscatter communication systems more feasible for future IoT applications [333], sensors and can also be facilitating in-body wireless implantation [345]. Backscatter communication can be applied in radio frequency identification (RFID) for a passive RFID tag, which harvests energy from an incident single-tone wave [345]. Furthermore, ambient backscatter communication system does not need a dedicated frequency spectrum [333]. Backscatter communication enables the IoT devices to transmit information by reflecting and modulating an incident radio frequency wave without the requirement for significant energy consumption [351]. Recently, full-duplex radio transmission is introduced as an enabling technique with backscatter communication in order to support simultaneous wireless communication between multiple ambient backscatter nodes [346]. Programmable metasurface [93], [352] can also be used with backscatter communication to allow more control over the ambient waves [349].

2) RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Backscatter systems may face several technical challenges such as low data rate, uni-directional data transmission, and short communication ranges. The security and jamming signals attacks are other issues that may face the backscatter communication system. This is due to the simplicity of the modulation and coding techniques that are used in backscatter communication systems. The implementation of conventional security solutions might not be possible due to the limited resources in the backscatter communication system [353]. Therefore, developing highly efficient security solutions for backscatter systems is required. Quantum communication may also be used to improve the performance and security of the backscatter system [354]. In addition, self-interference may significantly affect the performance of the backscatter communication system. Hence, developing feasible self-interference cancellation techniques is crucial.

IV. INCREASING CONNECTIVITY AND FULL COVERAGE

6G networks are intended to address the practical challenges that face conventional networks. 6G communications systems aim to support the emerging data-hungry applications by increasing connectivity and extending network capabilities. This can be achieved by improving network coverage, i.e., providing universal coverage in distant and isolated areas [4]. These connectivity demands and full-coverage requirements should be achieved using feasible and cost-efficient solutions. To achieve these aims, 6G networks are intended to be decentralized and designed based on integrating different networks such as terrestrial communications, airborne (aerial) communications, marine, and underwater communications, and satellite systems. This allows the establishment of useful communication access platforms and provides high-precision and high-reliability networks that cover the entire world [36], [97], [165], [166], [355]. Such integration of heterogeneous networks is essential in increasing network capacity and coverage [36]. This integration is also expected to become an essential component of future 6G wireless communications networks. This combination is intended to provide high-speed Internet access in the rural, urban, desert, and sea areas as shown in Fig 11. Such integration could play an essential role in enabling the emerging Internet of underwater things (IoUT) communications systems [356]. IoUT communication is essential for low-cost transportation, positioning and navigation, monitoring and security, and disaster prediction and prevention. Therefore, in order to achieve seamless communications networks, new networking architectures, infrastructures and cell-less architecture with high-quality communication services are required [4].

A. INTEGRATION OF TERRESTRIAL AND NON-TERRESTRIAL COMMUNICATIONS NETWORKS

As discussed above, 6G future networks are expected to integrate terrestrial platforms, which contain conventional base stations, with non-terrestrial (airborne) platforms such as UAVs, high altitude platform stations (HAPSs), and satellites communications. This integration can be exploited to provide cost-efficient, high-speed data-rate, ubiquitous broadband connectivity and full coverage [17], [39], [97], [119]. In particular, the integration between the terrestrial and non-terrestrial networks in future 6G communications systems can be used to increase the wireless coverage to reach unserved areas or poorly-served areas. For example, non-terrestrial can be used in blind spots such as deserts, mountains, and seas. In addition, the integration can also be used to enhance the service availability, continuity and reliability. For instance, a secondary backup route can be provided by non-terrestrial platforms to sustain the communication

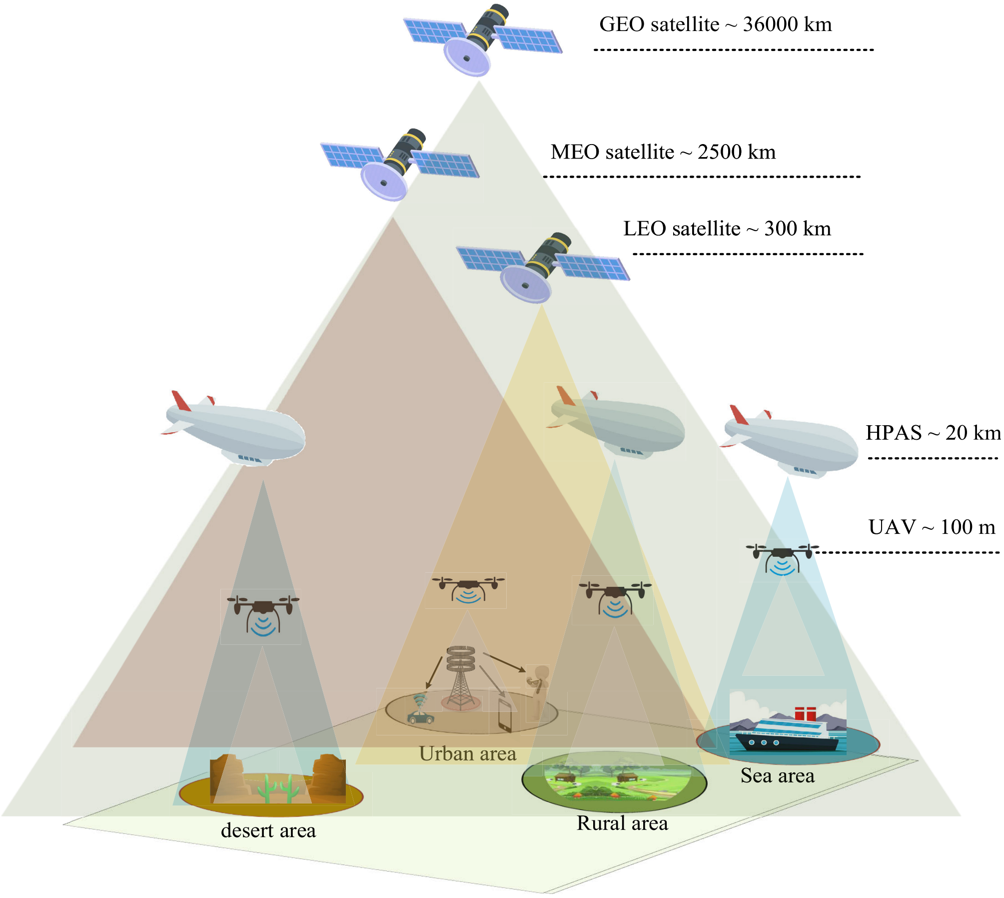


FIGURE 11. **The integration of terrestrial and non-terrestrial networks to achieve full coverage.**

networks when the primary route is inaccessible. Such backup route may happen in remote areas or oceans, or when terrestrial towers are out of operation, for example, after natural disasters. Furthermore, the integration between the terrestrial and non-terrestrial can support the network flexibility, scalability and adaptability. In this regards, non-terrestrial can be used to offload the network in heavy-load situations. Furthermore, the non-terrestrial networks could support high-speed wireless backhaul and allow seamless service continuity and reliability [357]. The recent studies show the possibility to use the non-terrestrial networks to relay the transmitted signals between terrestrial elements such as base station; see e.g., [358]–[360].

The aforementioned benefits of the integration between the terrestrial and non-terrestrial will jointly contribute to a better user experience in future 6G networks. In addition, seamless integration between terrestrial and non-terrestrial networks will ensure a high-quality broadband connectivity. In this context, 6G networks may further expand the unification of the terrestrial and non-terrestrial components into a multidimensional and multilayered architecture in order to achieve an enhanced capacity, flexibility, and resilience. Recent advances in software defined networks, artificial intelligence, and network slicing technologies provide enabling tools for seamless integration between the terrestrial and non-terrestrial networks. The software defined networks can play an essential role in efficiently and dynamically network controlling and inter-segment operation. Further, artificial intelligence can be exploited in the integration between terrestrial and non-terrestrial networks for automation in networks operation and control and for achieving resilience, flexibility and scalability in system management. Artificial intelligence can also be exploited to make fast, effective and accurate real-time decisions, which will help the successfulness of the integration between the terrestrial and non-terrestrial networks. Furthermore, network slicing based resource management can be potentially exploited to improve the performance of the integrated service provisioning to different users with different applications. Besides, mmWave communication can be used to enhance the performance of non-terrestrial communication networks. In this regards, an efficient beam management and network self-healing mechanisms for non-terrestrial communication networks can be used to achieve this goal [361]. Fig. 12 shows the non-terrestrial wireless communication networks. In what follows, the non-terrestrial wireless communication networks are discussed.

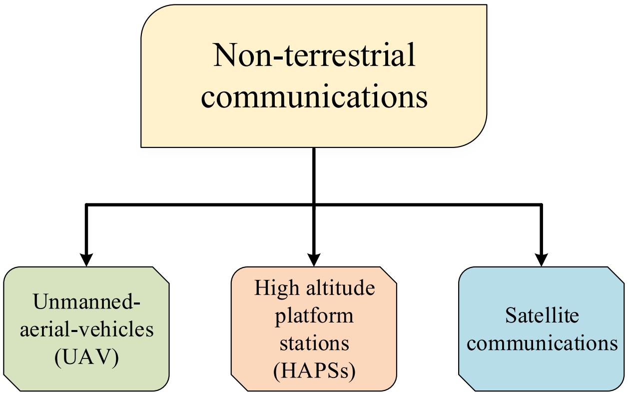


FIGURE 12. The classification of non-terrestrial networks.

1) UNMANNED-AERIAL-VEHICLES (UAVs) COMMUNICATIONS

6G networks are expected to fully support the connection of autonomous vehicles and drone-based communications systems. The vehicle and drone-based communications systems field of research are known as UAV communications systems. UAVs communications are expected to be exploited in 6G networks to enable cell-free communications [362]. UAVs are considered as a part of low altitude platforms (LAPs), which are ranged between 0 to 4 km [363]. In particular, in [357], it has been stated that UAVs have the ability to fly at low altitudes (e.g., a few hundred meters). To this end, Fig. 1 (left) in [357] shows that UAVs can be approximately flying with a range of 100 m above the ground. This short altitude of UAVs is justified due to the time flight restriction and movement constraint. As such, UAVs would need the shortest paths to perform their given missions. Recently, there has been a significant interest in integrating UAVs into wireless networks in order to improve network connectivity in heavy-load situations [364]. For example, UAVs can be considered as flying base stations, access points, or relays with cost and energy efficiency to provide radio coverage for users in various geographical areas [40].

a: KEY POINTS RELATED TO THE UAV COMMUNICATION

UAV-based networks can play a fundamental role in supporting high-speed backhaul connectivity for wireless networks [365]. UAVs can be efficiently integrated with cell-free massive MIMO systems to obtain cell-free networks with relatively small latency [38]. UAV with an aid of MIMO communications systems can be efficiently explored for data collection in an IoT scenario [366]. UAVs can fly at a few hundred meters and can be flexibly contorted [357]. In addition, UAVs can be efficiently combined with HAPSs and satellites to enable more accurate data processing and support continuous information broadcasting in comparison to standalone deployments [357]. Artificial intelligence and machine learning can be exploited to aid the UAVs' communications systems [38]. For example, artificial intelligence and machine learning can be used to dynamically optimize the UAVs' paths and in a reconfiguration of network topology. UAVs can assist communications networks and have the capability to facilitate on-demand services, avoid coverage holes and allow line-of-sight links with high communication reliability. UAVs technology can be designed to benefit from wireless power transfer techniques and make use of renewable energy (e.g., solar power). The utilization of such techniques allows the UAVs to be fully charged for a long time. UAVs can be used to support underwater communications systems and also to discover oil spills. Besides, UAVs can be efficiently used to accomplish several essential purposes such as emergency services, forecast & early warning systems, security monitoring & surveillance, fire detection, natural disaster management, package delivery, and pollution monitoring [367]. UAVs can be used to assist mobile edge computing networks to increase computing efficiency and reduce latency [279], [368]–[370]. These key essential services promote UAVs to be one of the most important technologies for future 6G wireless communications networks.

b: RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite the promising advantages of UAVs technology, there are several technical challenges that need to be addressed. For example, the small sizes of UAVs and the variability of positions and speeds make the detection and tracking of UAVs challenging. Therefore, developing a robust mechanism for the identification and tracking of UAVs is essential. Large-scale MIMO systems can be jointly used with radars to increase the probability of UAVs detection [50]. In addition, UAVs are typically consumed high energy to support their movement flexibility and maintain long-distance travel [357]. Therefore, an advanced power management mechanism is required. UAVs are typically collecting huge amounts of data. Such huge data collection can cause storage constraint problems to UAVs [371]. Hence, new data compression techniques to come up with storage issues are required. In this context, edge computing can be exploited as a viable low-cost and energy-efficient solution to increase the computation capability of UAVs [372], [373]. UAVs are able to efficiently offload their computational-intensive activities to edge computing. Also, advanced signal and image processing techniques are required for UAVs. Thus, efficient and low-complex signal and image compression schemes can be used, see e.g., [374]–[377]. Furthermore, developing efficient and robust protection mechanisms to deal with cyber and physical attacks in UAV systems is crucial. Moreover, developing an accurate channel modeling and fast channel estimation mechanism for UAVs system is needed. Besides, new communication and routing protocols for UAV systems are required. Interference is another crucial issue that affects UAVs' communication reliability. Such interference becomes more serious in the dominated line of sight scenarios where the UAVs are hovering at high altitudes [378]. Hence, developing an interference avoidance mechanism for UAVs is an interesting research topic that needs to be considered in the future.

2) HIGH ALTITUDE PLATFORM STATION (HAPS)

HAPs such as airships and balloons are considered as quasi-stationary networked aerial platforms located in the stratosphere region of the atmosphere [379], [380]. In general, HAPs have lower altitudes than satellites. The altitude communication distances of HAPs are ranged between 15 to 25 km above Earth's surface [381], [382]. Technically, HAPSs are considered as repeaters flying to provide broadcast/multicast wireless broadband services and extend wireless connectivity and coverage [383], [384].

a: KEY POINTS OF HAPSs COMMUNICATIONS

HAPSs communications have several advantages such as: (a) operational simplicity; (b) implementation simplicity (i.e., require simple infrastructure); (c) low-cost deployment and launch; (d) efficiently utilize the available spectrum; and (e) supporting long geographical coverage [383]. In terms of flight time and coverage, HAPs achieve better performance in comparison to the UAVs systems [385]. HAPs can be considered as a valuable low-cost solution, which is effectively used to complement satellite communication networks [386]. HAPs have significantly lower propagation delay in comparison to Geostationary Earth Orbit (GEO) and low Earth orbit (LEO) satellites. HAPs can fly on-demand to provide fast wireless consecutively for different regions. This feature can be useful to support delay-sensitive IoT applications in 6G networks. HAPs can be used as an intermediate communication layer between the satellite and the terrestrial receiver to provide communications services at a local regional [363], [386]. The HAPs communication layer can be exploited to accomplish several signal processing tasks locally, supplement existing terrestrial and satellite communications systems, supporting multimedia broadcast and multicast services, and improving link budget [363], [387]. HAPs can also be exploited to support a large number of terrestrial cells in heavy-load situations and to achieve high throughput backhaul links. HAPs can be exploited to serve multiple tasks such as surveillance, navigation & position, remote sensing, intelligent transportation systems, and emergency communications [387]. HAPSs platforms can host mobile edge computing to provide additional computing and storage functionalities, and hence, assist terrestrial terminals. HAPSs can exploit renewable energy, e.g., solar panels, which are more energy-efficient sources of power in comparison to the traditional power sources.

b: RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Although HAPs have the potential to support several essential applications, they still face some technical challenges that need to be addressed in order to be globally adopted [363], [388]. For example, the limited autonomy of HAPs is considered one of the key challenges that need to be addressed. In addition, HAPS are more sensitive to weather conditions (e.g., high-speed wind, rain attenuation, snow attenuation, temperatures, and fog). As such, a robust design that makes HAPS stabilize in the air and operate in the desired weather conditions is needed. The interference is another issue that faces the HAPs communications and limits the link-level performance in such wireless networks. Therefore, an interference mitigation scheme for HAPs is required. Besides, HAPs need to be seamlessly integrated with the existing networks to provide high-speed backhaul/fronthaul links. Therefore, further investigation in this regard is needed. Developing accurate channel models for HAPs that aim to predict the received signal power at a given distance from the transmitter is of interest [386]. Developing efficient signal processing, resource allocation, scheduling, modulation, coding, protocols, and handover mechanisms for HAPs systems are also required [384]. Finally, using a large-scale MIMO system and mmWave frequencies with HAPs is an interesting research topic that needs to be investigated in the future.

3) SATELLITE COMMUNICATION

Satellite communication is introduced to be one of the essential technologies for future 6G networks in order to achieve broadband connectivity, high-capacity airborne platforms, accurate global coverage, and high-speed data rate backbone links. The main aim of the 6G networks is to integrate satellite platforms with the terrestrial networks. The airborne communication systems and terrestrial base stations may require satellite connectivity to provide backhaul support and additional wide area coverage [36].

a: KEY POINTS OF SATELLITE COMMUNICATIONS

Satellite communications can be efficiently used in navigation, emergency rescue, positioning, tracking, and detection. Satellite communications can be exploited to complement terrestrial networks by supporting several essential IoT services and other wireless communications services such as AR, VR, and multimedia broadcast with 4K, 8K video transmission. Owing to its capability, the satellite communication system has received much attention from both industry and academia. Typically, satellite stations are divided into three platforms based on their orbit characteristics. These categories include Geostationary Earth Orbit (GEO) satellites with a height of about 35,800 km, medium Earth orbit (MEO) satellites with a height between 2,000 and 35,000 km, and low Earth orbit (LEO) satellites with a height between 200 and 2,000 km [357]. The altitudes provided in Fig. 12 are predicted based on references [357], [363].

While the GEO satellite can cover extremely large geographical areas and is constantly seen from terrestrial stations, it suffers from extensive signal transmission delay and attenuation due to the long communication links. In contrast, LEO and MEO satellites offer an enhanced received signal-to-noise ratio with lower transmission delay due to their shorter distance to the earth. For broadband applications, the LEO satellite system received considerable attention in recent years. This is due to the fact that LEO platforms are located close to the ground in comparison to the MEO and GEO satellites. Hence, LEO has the ability to reduce transmission latency, mitigate path loss and achieve a high signal-to-noise ratio, and hence, provide a high data rate [17], [97]. LEO satellite communication is essential for the rural and remote areas, which can provide greater coverage and capacity and can be used in combination with HAPS and UAVs-based communications systems. Besides, the Intelligent between the satellite and UAVs networks can be very effective for future 6G networks to enable wide coverage, see, e.g., [389]–[392]. Using a large-scale MIMO system with an LEO satellite can achieve high array gains, hence improving the communication performance significantly.

b: RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Satellite communications may face some technical challenges such as doppler variation and doppler shift, higher bit error rate, sensitivity to path loss, and transmission delay due to the large communication distances [17], [393]. These challenges need to be addressed since they may affect communication like synchronization, reliability, signal processing & detection, and random access. The integration of terrestrial and non-terrestrial networks face challenges related to the physical layer transmission and media access control (MAC) protocols, e.g., random access and hybrid automatic repeat request (HARQ). In order to cover the earth, several satellite stations need to be deployed. This may create synchronization challenges as satellites are constantly in motion [17], [97]. Accurate air-to-ground channel modeling, trajectory optimization, and efficient resource allocation mechanisms for satellite communications are required [39]. Machine learning method can be useful for satellite communications systems. For example, machine learning method can be explored in satellite operations, weather monitoring, earth observation applications, and sensor fusion for navigation [363]. In addition, machine learning can be used to address the complexity issue in satellite networks and to improve the efficiency of traditional model-based algorithms for signal processing and resource allocation. Therefore, further research regarding the application of machine learning in satellite communications is required. Intelligent mobility management techniques, which take into account handover satellite and earth stations are required [17]. Interference between the terrestrial and satellite platforms is another issue that could limit the link-level performance in satellite networks. Another challenge is related to the effective utilizing of the resources and the efficient use of the available spectrum with satellite networks. Furthermore, developing new communication protocols is also required in order to achieve seamless transmissions between terrestrial and satellite networks [17]. Overall, despite the attractive advantages of realizing ubiquitous coverage in 6G networks by integrating terrestrial and non-terrestrial networks, which may overcome the conventional coverage limitations, several challenges still need to be addressed before such global coverage can be effectively exploited in the future 6G networks.

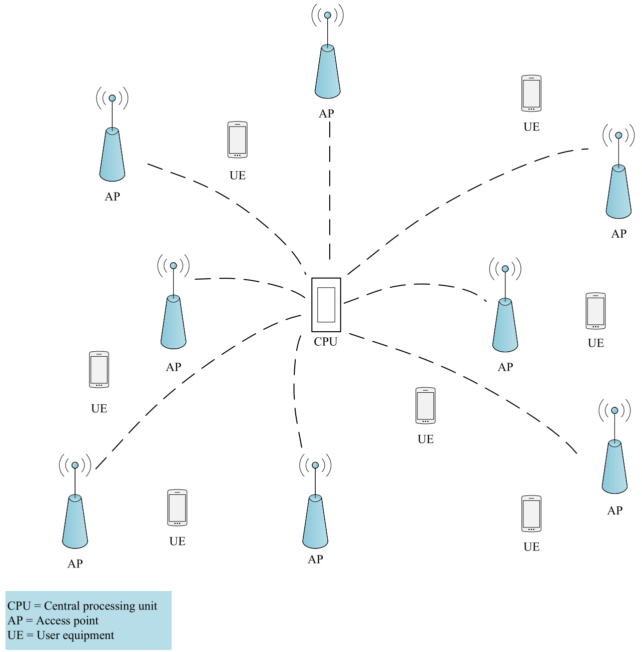


FIGURE 13. **Cell-free massive MIMO with a large number of distributed access points (APs). All APs cooperate phase-coherently through the use of a backhaul network and serve all mobile users simultaneously over the same time-frequency [394].**

B. CELL-FREE MASSIVE MIMO SYSTEM

Cell-free is considered as a key fundamental technique to increase the connectivity and provide full-coverage in future 6G networks [394], [395]. In 6G networks, there will be an integration of different frequencies and heterogeneous communication technologies. To this end, the uses in the networks have to be moved seamlessly from one network to another without the requirement for making any manual configurations. In the currently deployed networks, the users mobility are subject to many handovers in the networks. As a results, there will be many handover delays, handover failures, and information losses. Therefore, 6G networks need to break the limitation of the cells concept in conventional wireless communications systems to achieve better quality of service. The cell-free on-demand coverage is established to overcome the cost-ineffectiveness of conventional cellular architecture. Recent results in [389] have found that cell-free achieves a promising solution to efficiently support massive access for IoE devices in the future 6G networks. It is worth noting that, the infrastructures of 6G networks are expected to be densified, which will cooperate to form a cell-free network with seamless quality of service. In particular, the network densification can be achieved by employing multiple access points that are connected to a central processing unit (CPU) [396]. The access points are arbitrarily distributed in a geographical area. Each access point is equipped with multiple antennas, which can cooperate to form a scalable cell-free network MIMO that serves multiple mobile devices over a large geographical area. The basic principle of cell-free massive MIMO comes from the conventional distributed MIMO communications [397], [398] or what is known as coordinated multipoint (CoMP) communications [50], [399], [400].

1) KEY POINTS OF THE CELL-FREE COMMUNICATION

Cell-free massive MIMO communication system has the potential to achieve spatial diversity by allowing a mobile user to be jointly served on the same time-frequency resource by more than one base station in a coordinated manner. The main difference between cell-free communication and conventional MIMO systems is that instead of allocating each mobile user to a particular cell with a specific base station, which is equipped with a relatively large number of antenna elements, it relaxes the constraint of cell boundaries. Thus, the inter-cell interference caused by mobile users located at cell boundaries can effectively be mitigated or even eliminated. In addition, the disadvantage of poor channel quality that may happen when only one base station is serving can be effectively addressed. Furthermore, the main objective of a cell-free massive MIMO communication system is to achieve coherent processing over large geographically distributed base station antennas. This would allow an enhanced quality of service, nearly uniform achievable rates across the coverage area, and seamless handover across all mobile users regardless of their position in the networks. In cell-free massive MIMO systems, all mobile users have relatively equal distances to the allocated access points. Owing to its capability of exploring the spatial diversity against the fading, cell-free massive MIMO communication can potentially provide a much higher probability of coverage in comparison to the conventional collocated MIMO systems. Using a large number of arbitrarily distributed access points in a cell-free massive MIMO system would offer high multiplexing gain, more degrees of freedom, and high array gain. Cell-free massive MIMO works with any frequency bands, including sub-6 GHz, mmWave bands, and THz frequencies [401]. In addition, cell-free massive MIMO communication is particularly beneficial for cell-edge mobile users that experience severe large-scale fading. Cell-free networks are operated in TDD mode, which relies on UL/DL channel reciprocity to obtain the CSI for DL precoding. Cell-free massive MIMO can also be integrated with aerial systems to efficiently improve energy efficiency and enhance system coverage [402]. Cell-free massive MIMO system allows low-complexity digital signal processing schemes to be implemented in both UL and DL transmissions. Hence, most baseband signal processing can be accomplished locally at the access points and under computational assistance from the CPU [394]. This UPU can be considered as a cloud-edge processor where its design is reminiscent of the framework of C-RAN [118], [403], discussed in III. The results in [394], [395], [404] show that cell-free massive MIMO system outperforms conventional small-cell and cellular massive MIMO systems. The results in [394] demonstrate that cell-free massive MIMO can achieve up to five times improvement in terms of 95%-likely per-user data rate in comparison to the conventional small-cell system, and, more importantly, is more robust to undesired fading and interference. Even an enhanced 95%-likely per-user data rate performance can be achieved by cell-free massive MIMO when the access points and users are equipped with multiple antennas [405]. Several works have investigated the performance of cell-free massive MIMO see, e.g., [395], [404], [406]–[412]. The works in [395], [404], [406]–[412] deal with cell-free massive MIMO system under different scenarios; namely, the work in [395] investigates precoding and power optimization, [404] investigates the MMSE processing, [410], [411] and [412]–[414] consider the spatially correlated Rayleigh and Rician fading channels, respectively, the works in [406], [408], [415] deal with the performance analysis and power control of cell-free massive MIMO system with hardware impairments, [407] investigates channel hardening effect and favourable propagation, while [409] considers a user-centric virtual cell approach with a reduced backhaul overhead. A common conclusion arises from [395], [404], [406]–[412] is that cell-free massive MIMO system has the potential to achieve a significant improvement in wireless communications systems under different deployment scenarios.

2) RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Similar to the conventional MIMO systems, the performance of cell-free massive MIMO relies on the accuracy of the CSI estimation, which is obtained using training sequence transmission between the access points and users. However, since the channels are varied in time and frequency, the pilot resources need to be reused between users. Hence, this pilot reused may cause pilot contamination that reduces the cell-free massive MIMO performance. In addition, CSI estimation may be problematic in FDD operation mode where the channel reciprocity between UL and DL does not hold. The backhaul is another practical constraint that faces the cell-free massive MIMO system, which needs to be investigated. Besides, the system-level performance of cell-free massive MIMO should be thoroughly investigated. For example, developing low-complexity scheduling techniques that achieve fairness across the users are required, especially when a large number of users need to be served simultaneously over the same time and frequency resource block. Finding feasible resource allocation algorithms in cell-free massive MIMO networks is also needed. In addition, optimizing the access point locations and how to efficiently broadcast system information and signals synchronization is also essential. Finding a feasible user-centric approach is still challenging. As such, further investigation in this regard is required. The application of machine learning and deep learning in cell-free massive MIMO systems is also an interesting research topic that needs to be investigated in the future. Furthermore, developing a feasible mechanism for random access and power control algorithms, which balance delay, fairness, and data rate, in cell-free massive MIMO networks is required [396]. NOMA-enabled two-step random access channel (RACH) [416] can be used with cell-free massive MIMO networks to enhance resource utilization efficiency and reduce delay [401]. This combination of NOMA and cell-free massive MIMO systems should be further investigated in the future.

V. MAINTAINING SECURITY, SECRECY AND PRIVACY

Security, secrecy, and privacy are expected to be essential parts in future 6G communications systems [4]. However, the technical challenges related to security, secrecy, and privacy should be addressed in the 6G communications systems. For example, cyber-attacks and physical layer security need to be addressed in future 6G communications systems. Hence, finding feasible techniques for addressing such challenges is crucial. Besides, privacy in healthcare systems is essential for patients. Therefore, 6G should provide the highest level of privacy and security protection, especially in the healthcare systems. On the other hand, the security of implantable devices is another important issue that needs to be considered in healthcare systems. Conventional solutions may not be sufficient to meet the future 6G security requirements. Therefore, new advanced technologies become necessary to fulfill the security, secrecy, and privacy requirements. Furthermore, future 6G networks are expected to achieve a paradigm shift toward autonomous, dynamic, and intelligence. To this end, blockchain, quantum communications, artificial intelligence and machine learning are introduced as powerful technologies for addressing the security, secrecy, and privacy challenges of the future 6G networks.

A. BLOCKCHAIN TECHNOLOGY

Blockchain technology is expected to play an essential role in the security and authenticating of future 6G communications systems. For example, blockchain is expected to overcome the security issue of information communication [173], [417]–[419]. Also, blockchain allows simultaneous resource allocation and authentication.

1) KEY POINTS RELATED TO THE BLOCKCHAIN

Blockchain has the potential to enhance network collaboration efficiency. Blockchain has several advantages such as (a) allowing reliable communication to be achieved; (b) achieving interoperability through devices; and (c) providing decentralization and transparency communications [21], [173]. Blockchain has the ability to exchange data between different sources reliably without going through a transportation center. Blockchain can be useful for mobile edge computing. Blockchain can also be beneficial to industrial environments since it allows straightforward remote access. It also controls a massive number of industrial equipment connections. Furthermore, blockchain can enhance the performance of healthcare systems.

2) RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Applying blockchain technology may introduce some delays in processing, which might affect the wireless communication performance especially in latency-sensitive applications. The scalability coming from the use of massively connected devices is to date considered as a potential issue for blockchain. In addition, blockchain requires to be customized to make it feasible for IoT devices with limited computation and storage resources. Therefore, intensive research works are required in order to find a feasible solution to improve the performance of blockchain and make it feasible for future 6G networks.

B. QUANTUM COMMUNICATION

Quantum communication is a new promising technology for future 6G networks. Quantum communication allows strong communication systems security for 6G wireless networks. This is achieved by applying a quantum key technique, which is accomplished based on the principle of uncertainty and the quantum no-cloning theorem. Quantum communication has the potential to improve the efficiency of detecting unwanted eavesdropping behavior [420]. In addition, quantum communication has the potential to provide an extremely high data rate and strong protection against different cyber attacks [12]. Quantum communication is also feasible for long-distance wireless communication [38], [421].

1) KEY POINTS RELATED TO THE QUANTUM COMMUNICATION

Quantum communication has the potential to solve complex optimization problems with multiple objectives functions [155], [422]. Quantum-based techniques have the ability to execute the algorithms much faster and beyond the capability of the classical systems. Quantum communication can be combined with an artificial intelligence technique to further enhance the security of 6G wireless networks [119]. Quantum communication can considerably enhance the efficiency and speed of artificial intelligence algorithms that require big data and massive training. Quantum communication can be useful for the future 6G communication networks. For example, it can enhance the channel capacity, has the ability to transmit an unknown quantum state, i.e, quantum teleportation, and to achieve a secure information, i.e., quantum cryptography by exploiting a number of advanced communication protocols [12]. Such advanced communication protocols are not possible with the classical techniques.

2) RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Quantum error correction is considered as a major technical challenge that needs to addressed. As such, developing quantum error correction coding scheme is of significant importance. In addition, the construction of network entities with quantum Internet is consider as another technical challenge that may face the quantum communication, which requires quantum switches/routers and repeaters. Another challenge is related to the capacity measures of quantum communication channels. This is attributed to the fact that the quantum channels can have different possibilities in terms of delivering information including quantum information, entanglement assisted classical information [12]. Therefore, intensive research works are required to make quantum communication practically feasible in future 6G communications systems.

VI. ACHIEVING ULTRA-RELIABLE AND LOW-LATENCY COMMUNICATIONS (URLLC)

While 5G networks support machine-type communication (MTC) and URLLC scenarios, 6G is expected to support massive MTC (mMTC) and massive URLLC (mURLLC) applications. This allows 6G networks to deliver any required performance within the rate-reliability-latency space. The URLLC in 5G networks was specified to limited reliability and latency applications. However, 6G networks with mMTC and mURLLC departs form the limited reliability and latency requirements toward archiving the scalability requirements. Also, 6G aims to achieve the best trade-off between these requirements. These massive services classes of 6G networks will lead to ubiquitous mobile ultrabroadband (uMUB), ultrahigh- speed-with-low-latency communications (uHSLLC), and ultrahigh data density (uHDD) [236]. Emerging uMUB, uHSLLC, and uHDD services will require a new codesign of communication, control, sensing, and computing features that are mostly absent in the 5G networks. As such, 6G aims to fully support these future requirements. 6G networks are expected to evolve toward allowing massive ubiquitous connectivity, integration of different technologies and applications, enabling intelligence, and achieve massive decentralized computation operations [117]. 6G networks also aim to enable machine-to-machine and human-to-machine with real-time interactive applications such as holographic teleportation communications and tactile Internet and haptic, multi-sensory extended reality (XR), which includes augmented reality (AR) mixed reality (MR), and virtual reality (VR), as well as support Internet of smart things (IoST) applications [423]. The aforementioned Internet of Everything (IoE) applications create an ultra-high data density (uHDD) and some of them create core requirements for ultra-high-speed connectivity with ultra-reliable and low-latency communications (URLLC) services. Hence, future 6G networks need to support these applications with extremely high data rates and diverse quality-of-service (QoS) requirements. The ultra-low transmission latency requirements could be ranging from one to a few milliseconds end-to-end latency while the ultra-reliability communication could be higher than 99.9999%. Age of Information (AoI) is a new concept related to URLLC, which is introduced recently in order to characterize the status update quality of channel information and measure latency as observed by the control layer. AoI can be considered as an efficient indication tool for measuring the delay in real-time applications. However, to meet all these demands and a diverse set of requirements, 6G wireless networks will need to exploit an edge computing technique. This would allow some of the service-specific processing and data storage to be moved from the central cloud to edge network nodes. These edge network nodes will be located closer to the data providers and end-users. In addition, artificial intelligence and machine learning (e.g. deep neural networks) techniques are expected to be the key enabling factor for future 6G networks to achieve a URLLC and meet the diverse set of requirements and services.

A. HOLOGRAPHIC TELEPORTATION (TELEPRESENCE)

6G networks are expected to support a new form of human remote interaction, which makes use of all human senses including hearing, vision, taste, smelling, and touch in order to provide real-time remote physical communication [6], [25], [393]. Holographic teleportation is considered as virtual teleportation in real-time, which can be conducted based on a three-dimensional video with mixed-reality technology.

1) KEY POINTS FOR HOLOGRAPHIC TELEPORTATION

Holographic teleportation exploits many multiple-view cameras and multiple sensors to enable real-time remote interaction and create a reconstruction of in-person hologram [25]. This can be seen as a paradigm shift from traditional video conferencing to a virtual real-time in-person meeting, thus improving the communicating experience, allowing virtual concerts, enabling virtual sports, and more indicative remote/distance education. Holographic teleportation is considered one of the applications that require massive URLLC service. However, such connectivity and powered interaction and communications will require a huge amount of information in terms of image and video, In addition, it requires a data rate with an order of terabits per second (Tb/s) [25], [167]. To this end, the work in [424] demonstrates that to display three-dimensional holographic teleportation with a raw hologram, 4.32 Tb/s data rate is required.

2) RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Holographic teleportation requires an end-to-end latency in an order of sub-millisecond [39]. Therefore, to enable holographic teleportation, new semantic inference algorithms are required [25]. Such algorithms would allow the incorporation of knowledge representation in communications [25]. In addition, ultra-reliable communication with extremely large bandwidth is required for conveying holographic information. Furthermore, artificial intelligence and machine learning techniques maybe the key enabler for future holographic communications. Hence, further investigation of applying artificial intelligence and machine learning techniques for holographic communications is required.

B. TACTILE INTERNET

The Tactile Internet is described by the International Telecommunication Union (ITU) as an Internet network that incorporates ultra-low latency with extremely high reliability. Thus, Tactile Internet requires a URLLC communication service [249]. Tactile Internet allows real-time interaction between human-to-machine and machine-to-machine over a wireless network [425]. The Tactile Internet has been defined by the IEEE P1918.1 standard in [426] as a real-time virtual object network or a mechanism for remote controlling access perception. There are various applications for Tactile Internet such as education, business, healthcare (telesurgery), industrial (telemaintenance), smart grid and societal [427]. The Tactile Internet service is the next evolution that will allow the IoE applications to be controlled in real-time.

1) KEY POINTS OF TACTILE INTERNET

Tactile Internet has the ability to enhance the interaction of all human senses with machines. Tactile Internet is the key to enable haptic interaction, which is mainly related to sense/perception of touch in humans and is known as kinesthetic perception communication [428], [429]. Tactile Internet has the potential to provide an ultra-reliable/ultra-responsive communication network to the haptic [430]. Tactile Internet can be used in intelligent transportation to avoid collision owing to its low end-to-end latency and high reliability [431]. Tactile Internet has the potential to revolutionize the current online/distance learning and online works. Tactile Internet can be supported by the edge and fog computing technologies, which enable fast response communication, high reliability and availability [432].

2) RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

To enable efficient Tactile Internet service, a new artificial intelligence algorithm for edge and fog cloud architectures is necessary. In addition, efficient cross-layer architecture is required to meet the stringent requirements of Tactile Internet service. Also, new advanced physical layer techniques are needed. For example, new designs for channel coding, advanced waveform multiplexing, and multiple-access techniques for Tactile Internet service are required [249]. Furthermore, 6G networks will require seamless integration of various technologies, ultra-high-speed connectivity, high-speed backhaul, new air interface, new mechanisms for protocols, a new queuing scheme, new scheduling mechanism, and efficient coding techniques.

C. MULTI-SENSORY EXTENDED REALITY (XR) APPLICATIONS

Augmented reality (AR), mixed reality (MR), and virtual reality (VR) are considered as use cases of URLLC services [249] and part of IoE applications [35]. Existing AR/MR/VR applications, which are recently included under a new umbrella term as XR [362], greatly benefit from the Tactile Internet technology [249], discussed in subsection VI-B. Exceptionally high data rate and extremely low latency are required to achieve a fully AR/MR/VR immersive communication experience [39]. Tactile Internet can be anticipated to enable an extremely low-latency requirement and allow shared virtual environments with real-time interaction. Tactile Internet allows the static contents in XR to be transferred to a dynamic [433].

1) KEY POINTS RELATED TO THE XR COMMUNICATION

XR has the potential to combine real and virtual environments. Such applications would use a computer-simulated platform with reality experience and create a virtual world that looks exactly like the real world. In addition, the audios, videos, global positioning system (GPS) would be exploited to create an interactive environment for XR technologies. XR is considered as one of the key applications of future 6G networks [434]. XR enables users to virtually interacting and engaging with playing games, painting, educating, experiencing sports, and attending concerts [36], [435]. XR can also allow interactive extension of the field of view of a user so that it is possible to prevent harmful incidents [433]. VR and AR applications have already been considered by the IEEE working group (IEEE P2048), where 12 IEEE standards have been developed in this version [436]. VR and AR applications can play an essential role in telemedicine. For example, such applications can be used in renal intervention to allow precise planning and achieve three-dimensional orientation [437].

2) RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

The application of XR technology in 6G networks would increase the amount of data traffic. Therefore, advanced techniques to offload such huge data traffic in future heterogeneous networks are required. In addition, efficient utilization of spectrum resources is needed in order to meet the low transmission latency requirements of XR technology. Furthermore, developing new data compression schemes, data streaming management, and synchronization for efficient XR applications are of interest. Besides, developing an accurate estimation of the distance of the object in a virtual environment, e.g., depth perception, is crucial.

D. INTERNET OF SMART THINGS APPLICATIONS

Internet of things (IoT) is defined as interconnected machines and objects that contain various computing capabilities [438]. In IoT networks, several different sensors and chips are embedded in physical devices or objects, which make them wirelessly connected [418]. These physical sensors and objects have the ability to exchange a huge amount of data between each other and with other digital components without any human intervention. The IoT connections and applications are expected to be significantly increased in the future 6G communications systems. 6G networks are expected to support massive Internet of smart things connections, which include smart cities, smart radio environments, smart

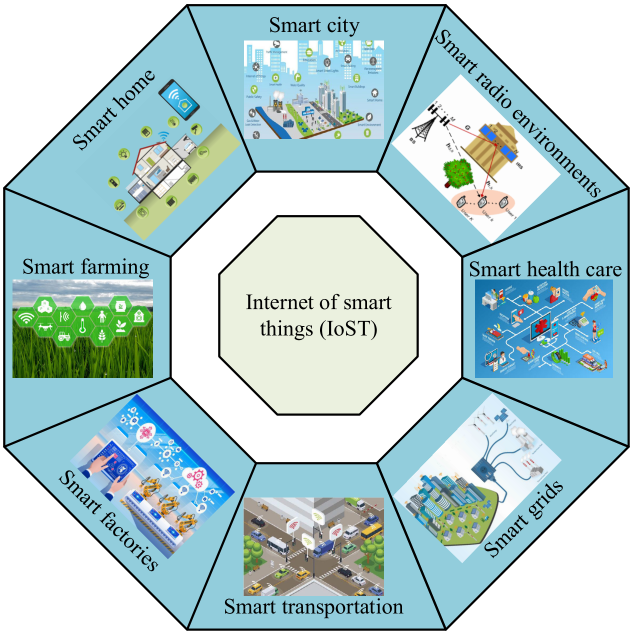


FIGURE 14. The key essential applications on the Internet of Smart Things (IoST).

healthcare systems, smart grids, smart transportation, smart factories, smart farming, and smart home. Fig. 14 summarizes the key smart applications, which will be discussed in the next subsections. Generally speaking, the vast majority of these smart applications are delay-sensitive, energy-demanding, small in size, and required computational demanding signal processing capabilities [439]–[442].

1) SMART CITY

A smart city aims to exploit a massive amount of sensors, which can be deployed in buildings, vehicles, roads, factories, and houses to support an extremely large variety of services for the city's administration, companies and individuals [443]. One of the smart city goals is to improve the quality of service offered by citizens, make better use of public resources, and reduce the operational costs [443].

a: KEY POINTS FOR SMART CITY

The implementation of a smart city would bring a significant advantage in terms of controlling the traditional services. This includes public transportation networks, surveillance for security, garbage collection/waste management, and maintaining public areas. Smart cities would improve the awareness of citizens about the city status. Several essential things, sensors, and services can be enabled by the smart city. For example, enabling smart buildings, deployment sensors to monitor air quality, which may help in reducing greenhouse gas emissions, monitor the traffic congestion and traffic management, allowing an automatic water system for gardens, monitor energy consumption, enabling smart utilities of electricity and water, and enabling the use of smart parking and smart lighting. Hence, a unified network architecture might be deployed in 6G networks. A smart city ecosystem is expected to be further explored in 6G networks. Hence, edge computing, software-defined networks, and artificial intelligence algorithms are expected to be used in smart cities to achieve a secure transmission, automatic maintenance, intelligent real-time monitoring system, and seamless networking.

b: RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Further investigation about the application of artificial intelligence in a smart city is required. Besides, maintaining connectivity in smart cities may raise several challenges. For example, providing a reliable connectivity to massively deployed devices with high mobility is required [444]. In addition, an advance technique to allow a connectivity transition from device to network level and vice versa is essential. Also, big data analytics is to date considered as a one of the major research challenges in the IoT-based smart cities applications [445]. Finding a feasible solutions for low power consumption to maintain battery life at very low cost in smart city applications are required. Further research investigations to address the aforementioned challenges are needed.

2) SMART RADIO ENVIRONMENTS

6G networks are envisioned to realize distributed intelligent wireless communications. 6G networks also aim to make the wireless environment, denoted by the radio waves, controllable and more energy-efficient [101]. This motivates the development of smart radio environment, where the physical objects are coated with large reconfigurable material, which is termed as large reconfigurable intelligent surfaces [101]. Further discussion about reconfigurable intelligent surfaces is provided in subsection II-B. Smart radio environments have the capability to provide future 6G networks with more wireless connectivity and coverage [101]. In addition, smart radio environments have the potential to transmit information without generating new radio signals [101]. The propagation of radio waves will be shaped and customized using large reconfigurable meta-material surfaces. Thus, smart radio environments will reduce energy consumption, improve connectivity and increase communication reliabilit [446]–[448]. Smart radio environments extend the network softwarization concept from the logical domain into the physical domain. Therefore, radio environments can be remotely controlled, configured, programmed, and optimized.

a: RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

There are still many practical issues related to the radio environments that need to be investigated and addressed in the future. For example, experimental validation, measurements, hardware implementation, and accurate channel modeling that reflects the realistic characteristics of using smart radio environment require thorough investigation [89], [449].

3) SMART HEALTHCARE

According to the world health organization, almost 524 million people were aged more than 65 years and it is expected to grow to 1.5 billion by 2050 [450]. Such aging of the population worldwide makes traditional healthcare systems unsustainable in the future. Hence, developing smart remote healthcare systems or making telemedicine systems to be smarter through IoT becomes crucial [451]. At the same time, recent years have witnessed significant advancements in sensing and communication technologies. This has opened up new possibilities for efficient and real-time remote patients' health monitoring and intelligent medical systems. Besides, recent years have witnessed a huge growth in the number of IoT wearable/implantable devices and sensors that can perform different functionalities. The devices and sensors can be placed close to (off-body), attached on (on-body), or implanted inside the human body (in-body) [452]. Connected these devices and sensors wirelessly lead to what known as a wireless body area network (WBAN) [453], which has the potential to monitor humans and provide real-time information about their health. In addition, patients' symptoms can be extracted from the data provided by these IoT devices and sensors. Therefore, patients can be remotely treated, which will result in more efficient and smarter remote healthcare systems.

a: KEY POINTS RELATED TO THE SMART HEALTHCARE

Smart healthcare systems allow doctors to remotely monitor the patients. Further, the progression of patients' disease can also be monitored [451]. Smart healthcare systems help in disease detection, diagnosis, recognition, prediction, prevention, and treatments. The heterogeneous data collection from different devices and sensors can be stored and analyzed so that the doctors can easily access the patients' records. However, such large amounts of real-time data may lead to what known as a big data challenge [451]. Therefore, new feasible solutions and algorithms are required to deal with such a vast amount of heterogeneous real-time data. In addition, artificial intelligence and machine learning techniques can be exploited to analyze data, increase reliability and accuracy, allow real-time fast processing and make smart decisions [454]. The work in [455] proposes a smart e-health gateway based on IoT, which can be used to address some of the communication challenges related to healthcare systems such as interoperability, reliability, security, and scalability. Therefore, future 6G networks aim to exploit a smart healthcare system to allow easy remote diagnostics where the patients can be diagnosed and treated even though they are physically located far away from hospitals and clinics, i.e., at their homes. Another potential of 6G networks is to allow remote surgery. Future 6G networks are expected to adopt advanced technologies to assist medical care and in-home remote monitoring. Future 6G networks are visioned to advance the current healthcare systems to allow further decentralization, and improve security and privacy performances. Future 6G networks aim to achieve more harmonious human-machine interaction and a more efficient medical process. However, healthcare applications are delay-sensitive and require extremely ultra-reliable communications. Recently, the Internet of Medical Things (IoMT) has been introduced as a new concept related to IoT devices and sensors that deal with medical applications. IoMT deals with medical data collection (obtained from different patients), and medical software applications. IoMT has the potential to make fast decisions, predict risks and take suitable actions automatically. Security and privacy issues are essential for IoMT, which is needed to protect the patient's data. However, the use of the IoMT system for diagnosis may raise several challenges related to the accuracy of clinical guidelines, as well as medico-legal and ethical concerns [454]. Fog/edge computing networks are promising techniques that can be used to address some of the challenges in healthcare systems [456]. The Internet of Nano things (IoNT) concept has been introduced in [457], which has the potential to drive innovation in smart healthcare applications [456]. This is attributed to the limited size of devices and sensors, i.e., microscales and nanoscales, which can be easily distributed, implanted, attached on or close to a human body [438]. These IoNT devices and sensors can be cooperated and connected together through a unified network and performed different signal processing tasks. Motivated by the advancement in the field of nanotechnology and synthetic biology, the Internet of Bio-Nano thing (IoBNT) concept has been recently introduced as a viable solution for smart healthcare systems [438]. Therefore, molecular communication has been proposed as a key enabling technique for IoBNT, whereby biochemical molecules can be exploited to encode, transfer and receive information among nanodevices [458], [459].

b: RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

The security and privacy issues are considered as major challenges that face the healthcare system. Typically, the patient's health information should be carefully stored and considered sensitive. Failing to do so may lead to humiliation and wrong treatments. Hence, reliable and advanced commutation and networking techniques are essential. Besides, further research studies in investigating the use of molecular communication in smart healthcare systems are required in the future. In addition, further investigation related to the practical implementation of molecular communication with IoBNT is needed.

4) SMART GRID

6G networks aim to improve electricity production and transit the traditional centralized energy grid towards a distributed generation system, which can heavily depend on renewable energy as an essential source of power and smartly control the energy usage. Hence, such energy grid system should be smartly connected and controlled using advanced communication technologies. Therefore, efficient smart grid systems can be exploited. Smarts grid is defined as an intelligent electricity network that is integrated with communication technologies to achieve economic and social benefits [460].

a: KEY POINTS RELATED TO THE SMART GRID

Smart grid is a promising power infrastructure that can intelligently control electricity usage and achieve bidirectional communication between electricity suppliers and consumers. In smart grid, several advanced smart meters, smart devices, renewable energy resources, sensing and control technologies can be used. The data collected from these sources can also be monitored and analyzed in real-time to provide predictive information and useful recommendations to all stakeholders, e.g., electricity suppliers, grid operators and consumers [460]. Deploying smart grid system would have the advantages of improving substantially and managing electricity usage [461]. Hence, all stakeholders (e.g., electricity suppliers grid operators and consumers) can benefit from this smart implementation.

b: RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Maintaining the system security in the smart grid distributed network is considered as a major challenge [460]–[462]. Therefore, further research to address the security challenges in smart grid networks is required. Besides, increasing interconnection and integration of smart grid networks may introduce several challenges. As such, further research works to overcome these technical challenges are needed.

5) SMART TRANSPORTATION

Smart transportation (also known as intelligent transportation) is a promising technology for future 6G networks, which allows autonomous vehicles to communicate with each other, exchange information with other end devices and public networks [463]. Smart transportation is considered as a special case of smart cities [444].

a: KEY POINTS RELATED TO THE SMART TRANSPORTATION

Smart transportation helps in reducing the number of vehicle accidents significantly [464]. Smart transportation-based vehicular communication networks can facilitate several mobile data services, allow self-driving assistance and enable traffic management [465], [466]. Typically, the vehicles can be equipped with several sensors to make them more smarter and automated [466]. Vehicle-to-everything (V2X) is one of the autonomous vehicular networks application that has already been considered by IEEE standard (IEEE 802.11) [464]. To date, various information exchange methods and protocols among vehicles and infrastructure have been introduced [464]. Recently, the Internet of Vehicles (IoV) concept is introduced as an extension to the conventional V2X communication in order to allow ubiquitous automotive networks with an extremely large number of applications and functions [464]. Vehicle's communications systems require URLLC and high level of security. To achieve this requirement, edge computing has recently been introduced by the European Telecommunications Standards Institute (ETSI) [467] as a promising solution to satisfy the URLLC transmission requirements of autonomous vehicles communications [468]. Further details regarding edge computing systems are provided in the next subsection. Artificial intelligence techniques may also play an essential role in enabling and supporting efficient vehicle communications systems for future 6G networks. However, combining various conventional and emerging wireless technologies are required in order to fully deploy connected vehicle networks. Furthermore, future vehicular communications systems require special design network architecture to support high-speed vehicles and massive connectivity [468]. Network slicing can be considered as a feasible solution to support vehicular communication, whereby the physical networks can be sliced into multiple virtual networks.

b: RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Enabling network slicing in future 6G networks is still an open research topic that worth investigating. In addition, advanced networking techniques to support high-speed vehicles and massive connectivity in vehicular communications systems are required.

6) SMART FACTORIES

The last decade has witnessed a huge growth in industrialization and informatization methods. This has motivated the progress in developing the next generation of smart manufacturing and factories technologies [469]. The fourth industrial revolution, i.e., Industry 4.0 [470], is the latest trend in the manufacturing sector, which is characterized by a high degree of automation, productivity, operational efficiency and industrial integration [471]–[473]. Automatic control systems and communication technologies can be integrated and effectively used in Industry 4.0 in order to reduce the requirement for human intervention in the industrial process. Such a combination between automatic control systems and communication technologies leads to the implementation of industrial control network (ICN) [474], [475]. ICN has been introduced recently by 5G NR standard as a specific URLLC application [475]. Wireless isochronous real-time (WIRT) system has been introduced in [475] to further improve the performance of ICN in Industry 4.0. 6G networks aim to revolutionize the manufacturing industry by achieving fully digitize manufacturing, making use of robotics and automation systems, remote maintenance, customization of products, and achieve higher flexibility in product development, and guarantee full connection with the entire production cycle.

a: KEY POINTS RELATED TO THE SMART FACTORY

Smart factory tends to keep a reasonable balance between supply and demand, make advanced product planning and developing, achieve best practice selling and shipping products and automatic monitoring. This can be achieved through the use of unified networks. In addition, future 6G networks tend to manage the resources in terms of power, water, and the flow of environmental waste. Besides, future 6G networks aim to move toward the circular economy with reuse, remote repair, re-manufacture, recycle, and refurbish [401]. Furthermore, there is a need for a fluent ecosystem collaboration. Thus, more seamless and collaboration between humans, robots, and machines are crucial for 6G networks [476]. For example, devices, machines, and humans will be connected together and exchange information inside factories [401]. These functionalities will indeed require real-time data processing as well as low latency and high-reliability communications. Also, these functionalities need the convergence of multiple technologies. Edge computing and artificial intelligence can be used to support the smart factory requirements [477], [478]. MmWave (particularly 60 GHz band) is identified as a possible solution towards achieving the URLLC in smart factory [475].

b: RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Smart factory requires massive connectivity of industrial manufacturing equipment. Therefore, decentralized network architectures become necessary. Besides, independent and intelligent decision-making methods are needed to achieve full autonomous factories. Further research investigations regarding the role of edge computing, artificial intelligence, and mmWave frequency in enabling smart factories are required. The latency and scalability issues are to date considered as major challenges in smart factories. Further investigations to address the latency and scalability challenges in a smart factory are required.

7) SMART FARMING

Smart farming is a concept that makes use of communication technology in farming [479]. The application of wireless communication technologies in smart farming allows a large variety of services to be achieved. For example, it enables the farmers to save time and effort, achieve better productivity and profit [480].

a: KEY POINTS RELATED TO THE SMART FARMING

Smart farming enables an intelligent water system and achieves the best irrigation, automation and precision, plant monitoring, crop and livestock, weather forecasting and monitoring and plant diseases detection [481]–[485]. Smart farming can also be exploited to ensure proper plant lighting and moisture for optimum growth, improving greenhouse plant production and disease prediction [486], [487]. This would allow an increase in food production and food security, which is considered as a major concern for most countries [488]. New enabling technologies such as cloud computing and artificial intelligence are expected to be used in this development. Machine learning algorithms can be used for disease recognition from the plant/leaves images. Besides, advanced data analytics schemes can be utilized to enhance the operational efficiency and productivity in the smart farming sector [488]. UAV technology can also play an essential role in a smart farming system. For example, UAVs can be feasibly used by farmers to monitor the farm condition at the beginning of any crop year [489]. In addition, UAVs can also be exploited in soil monitoring, field analysis, irrigation, and in managing the nitrogen level to achieve better crop growth [489], [490]. Hence, smart farming can get special benefit from the integration between airborne, terrestrial, and satellite communications networks.

b: RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

However, the scalability issue in smart farming, which may result from using billions of IoT devices and sensors as well as UAVs, is considered a major technical challenge that needs to be addressed in smart farming. Hence, further research to overcome the scalability issue in smart farming is required.

8) SMART HOME

Smart home is one of IoT applications, which is defined as a network of pervasive physical devices that provide context-aware services [491].

a: KEY POINTS RELATED TO THE SMART HOME

Smart home has the ability to monitor home environment, facilitate remote residents' interactions and provide remote meter reading of different utilities such as electricity, gas and water [492], [493]. Smart home can also be used for different purposes, including healthcare monitoring, managing energy consumption and home automation. Smart home system has the potential to improve the safety in home, which can be achieved by using multiple sensors for intelligent monitoring and deploying smart video surveillance. Smart home system can assure more economic and comfortable home operation. It can also provide a high degree of intelligent functionality and flexibility [491]. Furthermore, smart home has the potential to provide useful information and assistive services anytime and anywhere [494].

b: RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

The security and scalability are two major challenges in smart home system. Therefore, data encryption and cryptography algorithms and data compression methods are required to address these challenges [495], [496]. Further investigation to address these challenges in smart home is needed.

E. EDGE COMPUTING

Driven by the IoST requirements, discussed in the previous section, recent years have witnessed a new paradigm shift towards enabling softwarization and virtualization of networks, i.e., achieve programmable decentralized networks by allowing the use of edge computing [497]. This can be achieved by dividing the network into different communication layers or Tiers from end-user devices to edge computing platform to core and cloud (data center) platform. These layers can be used to overcome the long propagation distance from the end-user to the cloud center, and thus, can address the delay sensitivity of the IoT applications [497].

1) KEY POINTS RELATED TO THE EDGE COMPUTING

Mobile edge computing (MEC) is considered as an important type of edge computing platform that located on the edge of a cellular network and can rapidly process large amounts of data upon receipt [498], [499]. The key concept of MEC is to move part of the service-specific processing, computing, and data storage from the centralized cloud core network to edge network nodes, which can be located near data providers and end-users [476], [500]. Several intensive computation services can be offloaded to MEC, which consists from network of servers [497]. Thus, MEC is considered as a key enabling technology to achieve URLLC, traffic optimization, enhancing the performance of 6G networks [476]. Using MEC in 6G yields a significant improvement in network capacity completes critical delay-sensitive tasks and accomplishes network-intensive computations. MEC can be used as an effective solution to extend the battery life in mobile devices and reduce the network energy consumption since huge mobile applications with highly demanding signal processing can be offloaded to MEC [105]. MEC is responsible for enhancing the network capabilities and management, improving services, achieving energy and resource management, and reducing the load on the backhaul [499]. Cisco has recently introduced the idea of fog computing, which is similar to MEC. In a fog computing network, the definition of edge devices becomes wider [500], [501]. All these essential tasked with MEC can be accomplished based on a virtualized software-based platform that makes use of network functions virtualization (NFV) [502] and software-defined networks (SDN) [503]. NFV allows a single edge computing server to provide several mobile devices with computing services. This is achieved by creating multiple virtual machines that able to conduct several tasks simultaneously or operate various network functions [504]. In addition, NFV has the potential to manage computing services and enhance the reliability, scalability, and flexibility of the network services [502]. On the other hand, SDN allows the MEC network to dynamically managing different services. It also has the potential to decouple control and data plane [503], [505]–[507]. SDN can provide a logically centralized control platform to the edge computing network [508]. Using such centralized control platform would allow easier management of data traffic within the network, achieve optimal resource allocation, address the scalability issue in the network, reduce overhead, improve the reliability of the network, and most importantly reduced the latency.

Several different IoT applications can benefit from edge computing including a smart home for monitoring and metering, healthcare for monitoring and data generated, video surveillance for security, a smart grid for energy management, smart cities for controlling cities light, smart transportation, and monitoring environment. Edge computing enables real-time interactive applications such as holographic teleportation, Tactile Internet and XR [401], [432], [499]. Combining edge computing with artificial intelligence techniques leads to a new communication paradigm shift known as *edge intelligence*, which can play an essential role in 6G networks [476], [509]. 6G networks will adopt distributed artificial intelligence, which moves the intelligence from the central cloud to edge computing. Edge intelligence capability will support the development of new Internet of intelligent things (IoIT) services and functions of 6G networks. Edge intelligence has the potential to perform data analysis and develop solutions near data providers and end-users. In addition, edge intelligence can improve data security and preserve privacy, reduce cost, allow adaptive traffic control, reduce latency and reduce network traffic congestion. Edge intelligence can also be exploited to achieve more reliable and safer autonomous driving in-vehicle networks [510]. Recently, the work in [511] proposes a dynamic resource allocation scheme for edge intelligence, which is located at the edge server. Besides, deep reinforcement learning can be explored to reduce the latency, facilitate the automated execution of IoT applications and improve the network capacity. From a communication perspective, IRS technique has been recently proposed as a solution to enhance the performance of the MEC system [104]. The results showed that IRS is able to improve the performance of the MEC system. NOMA technique has also been recently combined with MEC system to improve offloading performance, maximize the system capacity and achieve an energy saving [287], [512].

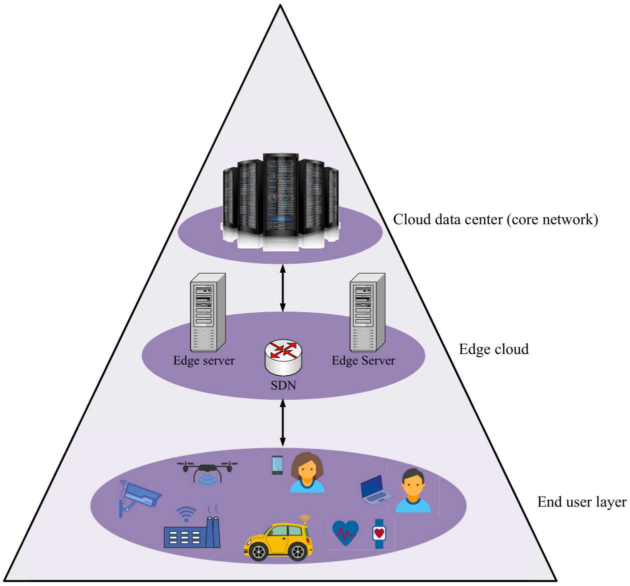


FIGURE 15. Network platforms with MEC.

2) RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Resource management, mobility management, and network security are the main challenges that face edge computing deployment. Data offloading with vehicle communication is to date considered as a challenging issue due to the high-speed movement of vehicles. Besides, there is an essential requirement to cope with traffic congestion in high mobility environments and make an intelligent decision for data offloading. Furthermore, developing efficient learning algorithms for realizing edge intelligence and network optimization is required. Also, new network architectures for supporting distributed edge learning are needed. Developing efficient algorithms for analyzing big data that gathering from different IoT devices is essential. Besides, developing an efficient data compression scheme that copes with such big data is necessary. In addition, there is an essential requirement to design a dynamic and flexible network configuration for mobile edge computing with heterogeneous environments. Therefore, developing new communication protocols for edge computing with a heterogeneous environment is of interest.

VII. REALIZING INTELLIGENCE

There is no doubt that future 6G wireless communications networks will encounter many technical challenges. A large amount of data will be periodically collected in real-time from various smart, sensing, and wearable devices. This huge data collection results in what known as a big data challenge. To cope with these requirements and challenges, future 6G networks need to be super intelligent and automated both at the edge and the core of networks. Also, future 6G networks require performing self-learning, carry out self-configuration, allocate resources dynamically, and make a suitable decision. Future 6G networks are expected to realize intelligence and make use of several control functions and predictive data analytics [513]. Such intelligence in networking the future 6G systems will reduce the complexity of traditional model-based algorithms and make them efficiently managed and optimized. Besides, artificial intelligence and machine learning are considered as key enablers to make 6G networks more intelligent and achieve a high level of dynamic network management and optimization. Artificial intelligence and machine learning techniques have the potential to help network operators to carry out intelligent operations and enrich decision making in wireless communications systems [514]. Artificial intelligence and machine learning techniques are essential for ultra-reliable and low-latency communications in 6G networks [30], [515]. Furthermore, artificial intelligence and machine learning techniques are expected to play an essential role in the security of future 6G networks. Compared to the other related survey papers on artificial intelligence, we provide an in-depth discussion of the role of artificial intelligence, machine learning, and deep learning techniques in future 6G networks. In particular, this paper explains in details the effectiveness of exploiting the artificial intelligence and machine learning techniques in enabling the key future technologies of 6G networks. The main focuses in this paper is on wireless communications systems. Furthermore, this paper identifies the challenges related to the application of artificial intelligence and machine learning in future 6G networks. This paper also opens up new opportunity for future research directions. Further details about artificial intelligence and machine learning are discussed in the following section.

A. ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

Artificial intelligence and machine learning is expected to play an essential role in the future 6G networks. In general, artificial intelligence makes the machines behave like humans. It also allows the machines to make suitable decisions and achieve specific goals. Machine learning, in particular, is considered as a part of artificial intelligence, which allows the computer agents to precept, gain knowledge, thinking, and make intelligent decisions based on the data collected. Typically, machine learning learns the essential information either from data-sets or by interactions with existing environments [516].

1) KEY POINTS OF USING ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING TECHNIQUES IN THE WIRELESS SYSTEMS

Artificial intelligence and machine learning techniques are expected to be integrated into the optimization, planning, and design of the future 6G wireless communications networks. This includes supporting massive essential services such as healthcare, industrial manufacturing, online education, online shopping, online gaming, and customer services [476]. Furthermore, artificial intelligence and machine learning techniques will be the core technique for future 6G wireless communications systems, which have the ability to achieve intelligence resource management, intelligence decision-making, smart estimation and detection, smart routing, automated maintenance, automated network operations, and managements [35], [517]. Artificial intelligence and machine learning can also be used to enhance the communication system performance, process massive amounts of data, reduce energy consumption, and reduce end-to-end network latency. Artificial intelligence and machine learning algorithms have the potential to address the challenges related to the network complexity and maintaining the quality of service [517]. Artificial intelligence and machine learning can be utilized in the design of future autonomous wireless systems [518]. Artificial intelligence and machine learning algorithms can also be useful for satellite communications systems. Also, artificial intelligence and machine learning algorithms are essential for interference mitigation, weather monitoring, managing the spectrum and power resources, sensor fusion for navigation, managing the large constellations, and optimizing the operation of satellite networks [363]. Artificial intelligence and machine learning have the opportunity to address various wireless communications problems such as classification, network optimization, signal detection, protocol designs, analysis, and sparse signal recovery [12], [519]. Deep learning techniques are classified into supervised, unsupervised, and reinforcement

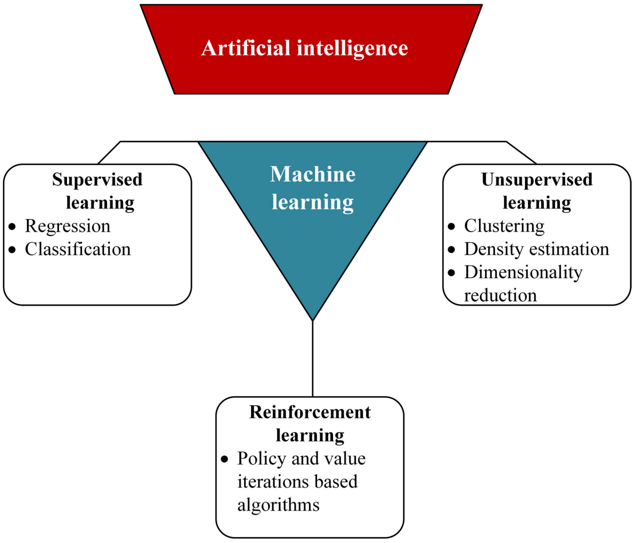


FIGURE 16. **Artificial intelligence and machine learning techniques along with their classifications.**

learning [516], [519]–[522], as shown in Fig. 16. Each one of these techniques has its unique features. For example, in supervised learning, the labeled training data sets, which should be known beforehand, are required. Typically, supervised learning needs a large number of data sets (pairs of input and desired output) to be trained. In contrast, in unsupervised learning, the labeled data sets are not needed, which aims to infer features in the data sets. Finally, data sets that are obtained from implementation rather than historical data sets are needed in reinforcement learning, which allows the learning agents to learn from experience. In reinforcement learning, at every step, the learning agents observe the state of the environment, perform an action or make a satiable decision and then move to the next stage. Reinforcement learning is considered to be more feasible for dynamic wireless communications systems [523], [524]. Machine learning technology can be effectively used in telemedicine systems [525]. In addition, machine learning techniques can be exploited with intelligent programmable metasurfaces to achieve high energy efficiency, reduce the system overhead, and allow high-accuracy object recognition [526]–[528]. Furthermore, machine learning techniques can be effectively utilized in interference management for UAV communications systems [524].

2) KEY POINTS RELATED TO THE DEEP LEARNING TECHNIQUE

Deep learning is considered as a special method of machine learning, which makes use of large multi-layers artificial neural networks (ANNs). Deep learning is a powerful technique that can be useful for speech recognition, wireless optimization and image processing [529]. Deep learning can also be efficiently used in numeral recognition, features extraction, and in many signal processing applications [530]–[532]. Furthermore, deep learning can be utilized in joint radar communications systems. It can effectively be used to allocate the required resources dynamically with a reduced overhead [56]. Deep learning has the potential to address the challenges related to the channel estimation in high frequency and high mobility scenarios. Besides, deep learning can be exploited for data compression, dimensionality reduction regression, clustering, classification, density estimation, and data recovery. For example, deep learning can be used in data compression by extracting the most significant features from a specific data. Hence, such efficient features extraction using deep learning method can be utilized to identify the compressed data with high accuracy. As such, the data size and end-to-end latency can be significantly reduced. In addition. deep learning is considered an essential tool for addressing many technical challenges related to UAVs-based communications systems. Deep learning is also a promising method for addressing many technical challenges related to wireless AR, MR, and VR. Deep learning technique is expected to play an essential role in the design of mobile edge caching and computing approaches. Deep learning has the potential to encode the data automatically by jointly learning transmitter and receiver implementations [533]. These tasks can be accomplished without any prior knowledge. Deep learning can guarantee performance improvements in complex communications scenarios, which are challenging to be described with tractable mathematical models. For example, deep learning has been considered in [534] for blind detection in MIMO communications systems with low-resolution quantization. In [535], a deep learning method has been used for solving resource management problems in wireless communication systems. Recently, deep learning has been investigated for signal compression [536], channel decoding [537], channel coding [538], improve the estimation quality of a massive MIMO system in single carrier modulation [539] and in multicarrier modulation [540] and modulation recognition networks [541]. Furthermore, in [542]–[544], hybrid precoding for mmWave massive MIMO communications systems has been investigated using a deep learning approach. The results showed that the deep learning approach improves the communication system performance and allows less computation time in comparison with conventional techniques. In addition, deep learning technique can be exploited to accomplish different tasks for compressing sensing [545], [546]. Deep learning technique can also be jointly combined with the traditional optimization theory to speed up the computation of the optimal resources in wireless communications networks. Deep learning technology has the potential to support adaptive and real-time massive MIMO beamforming so that to properly track the structural information of the radio channels, efficiently allocate the required power, and capture mobility patterns.

3) RELATED CHALLENGES AND FUTURE RESEARCH DIRECTIONS

The adaptation of artificial intelligence and machine learning algorithms in future 6G networks is essentially required to discover their full potential gain in wireless communications systems. In particular, to guarantee the quality of service requirements, which are standard in the design of the wireless communications systems, a detailed understanding of the fundamental performance limits with artificial intelligence and machine learning applications is needed. Conventional artificial intelligence and machine learning algorithms might not be readily implemented in mobile or wearable devices due to their high complexity and energy consumption. Hence, developing efficient algorithms, which are suitable for implementation in small devices, are required. In addition, the tradeoff between prediction accuracy of artificial intelligence and machine learning algorithms and the training complexity needs to be considered. Besides, there are some technical challenges related to the long convergence times of machine-learning algorithms. Therefore, further investigation to find efficient machine-learning algorithms with fast convergence times is required. Furthermore, wireless networks are subject to highly dynamic mobility and traffic conditions. As such, feasible algorithms that cope with these realistic conditions are crucial. Federated learning is considered a promising technique that can be applied to enhance learning efficiency [509], [547]. However, the application of federated learning in future 6G networks needs to be further investigated. Further research is needed to investigate the use of artificial intelligence and machine learning techniques for channel estimation with high mobility environments and with mmWave channels.

VIII. CONCLUSION

This paper presented a comprehensive review of evolution toward the future 6G wireless communications networks. To this end, the key performance indicators of 6G networks have been identified. In addition, the essential technologies that can achieve the key performance indicators of 6G networks have been described in detail. In particular, the key idea and operation principle of each technology has been presented. Furthermore, the key fundamental benefit and the potential application of each technology has been described. The current state-of-the-art research related to each technology has been highlighted. This paper also elaborated several research challenges that remain open and identified new research directions that worth investigating in the future. This paper also delivered important insights and recommendations related to the practical implementation of the technologies considered. New applications that might be supported by 6G networks have also been presented in this paper. Overall, this paper provided a clear vision of what should 6G wireless communications networks be, which is essential for both industries and academic researchers.

REFERENCES

[1] *IMT Traffic Estimates for the Years 2020 to 2030*, document ITU 0–2370, 2015.

[2] Cisco, "Cisco annual internet report (2018–2023)," White Paper, 2020. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html

[3] T. Huang, W. Yang, J. Wu, J. Ma, X. Zhang, and D. Zhang, "A survey on green 6G network: Architecture and technologies," *IEEE Access*, vol. 7, pp. 175758–175768, 2019.

[4] S. Dang, O. Amin, B. Shihada, and M.-S. Alouini, "What should 6G be?" *Nature Electron.*, vol. 3, no. 1, pp. 20–29, Jan. 2020.

[5] A. Gupta and E. R. K. Jha, "A survey of 5G network: Architecture and emerging technologies," *IEEE Access*, vol. 3, pp. 1206–1232, 2015.

[6] K. David and H. Berndt, "6G vision and requirements: Is there any need for beyond 5G?" *IEEE Veh. Technol. Mag.*, vol. 13, no. 3, pp. 72–80, Sep. 2018.

[7] S. Chen, J. Zhao, and Y. Peng, "The development of TD-SCDMA 3G to TD-LTE-advanced 4G from 1998 to 2013," *IEEE Wireless Commun.*, vol. 21, no. 6, pp. 167–176, Dec. 2014.

[8] P. Sharma, "Evolution of mobile wireless communication networks-1G to 5G as well as future prospective of next generation communication network," *Int. J. Comput. Sci. Mobile Comput.*, vol. 2, no. 8, pp. 47–53, 2013.

[9] I. F. Akyildiz, D. M. Gutierrez-Estevez, R. Balakrishnan, and E. Chavarria-Reyes, "LTE-advanced and the evolution to beyond 4G (B4G) systems," *Phys. Commun.*, vol. 10, pp. 31–60, Mar. 2014.

[10] C.-X. Wang, F. Haider, X. Gao, X.-H. You, Y. Yang, D. Yuan, H. M. Aggoune, H. Haas, S. Fletcher, and E. Hepsaydir, "Cellular architecture and key technologies for 5G wireless communication networks," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 122–130, Feb. 2014.

[11] Y. Al-Eryani and E. Hossain, "The D-OMA method for massive multiple access in 6G: Performance, security, and challenges," *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 92–99, Sep. 2019.

[12] S. J. Nawaz, S. K. Sharma, S. Wyne, M. N. Patwary, and M. Asaduzzaman, "Quantum machine learning for 6G communication networks: State-of-the-art and vision for the future," *IEEE Access*, vol. 7, pp. 46317–46350, 2019.

[13] K. B. Letaief, W. Chen, Y. Shi, J. Zhang, and Y.-J.-A. Zhang, "The roadmap to 6G: AI empowered wireless networks," *IEEE Commun. Mag.*, vol. 57, no. 8, pp. 84–90, Aug. 2019.

[14] S. Zhang, C. Xiang, and S. Xu, "6G: Connecting everything by 1000 times price reduction," *IEEE Open J. Veh. Technol.*, vol. 1, pp. 107–115, 2020.

[15] R. Shafin, L. Liu, V. Chandrasekhar, H. Chen, J. Reed, and J. Zhang, "Artificial intelligence-enabled cellular networks: A critical path to beyond-5G and 6G," *IEEE Wireless Commun.*, vol. 27, no. 2, pp. 212–217, Apr. 2019.

[16] X. Huang, J. A. Zhang, R. P. Liu, Y. J. Guo, and L. Hanzo, "Airplane-aided integrated networking for 6G wireless: Will it work?" *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 84–91, Sep. 2019.

[17] S. Chen, Y. Liang, S. Sun, S. Kang, W. Cheng, and M. Peng, "Vision, requirements, and technology trend of 6G: How to tackle the challenges of system coverage, capacity, user data-rate and movement speed," *IEEE Wireless Commun.*, vol. 27, no. 2, pp. 218–228, Apr. 2020.

[18] F. Clazzer, A. Munari, G. Liva, F. Lazaro, C. Stefanovic, and P. Popovski, "From 5G to 6G: Has the time for modern random access come?" 2019, *arXiv:1903.03063*.

[19] S. Nayak and R. Patgiri, "6G communication technology: A vision on intelligent healthcare," in *Health Informatics: A Computational Perspective in Healthcare*. Singapore: Springer, 2021, pp. 1–18.

[20] G. Manogaran, B. S. Rawal, V. Saravanan, P. M. Kumar, O. S. Martínez, R. G. Crespo, C. E. Montenegro-Marin, and S. Krishnamoorthy, "Blockchain based integrated security measure for reliable service delegation in 6G communication environment," *Comput. Commun.*, vol. 161, pp. 248–256, Sep. 2020.

[21] T. Hewa, G. Gur, A. Kalla, M. Ylianttila, A. Bracken, and M. Liyanage, "The role of blockchain in 6G: Challenges, opportunities and research directions," in *Proc. 2nd 6G Wireless Summit (6G SUMMIT)*, Mar. 2020, pp. 1–5.

[22] J. Zhao, "A survey of intelligent reflecting surfaces (IRSs): Towards 6G wireless communication networks," 2019, *arXiv:1907.04789*.

[23] E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M. Alouini, and R. Zhang, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116753–116773, 2019.

[24] H. Viswanathan and P. E. Mogensen, "Communications in the 6G era," *IEEE Access*, vol. 8, pp. 57063–57074, 2020.

[25] E. C. Strinati, S. Barbarossa, J. L. Gonzalez-Jimenez, D. Ktenas, N. Cassiau, L. Maret, and C. Dehos, ''6G: The next frontier: From holographic messaging to artificial intelligence using subterahertz and visible light communication,'' *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 42–50, Sep. 2019.

[26] Q. Xia and J. M. Jornet, ''Expedited neighbor discovery in directional terahertz communication networks enhanced by antenna side-lobe information,'' *IEEE Trans. Veh. Technol.*, vol. 68, no. 8, pp. 7804–7814, Aug. 2019.

[27] I. Tomkos, D. Klonidis, E. Pikasis, and S. Theodoridis, ''Toward the 6G network era: Opportunities and challenges,'' *IT Prof.*, vol. 22, no. 1, pp. 34–38, Jan. 2020.

[28] Y. Zhang, B. Di, P. Wang, J. Lin, and L. Song, ''HetMEC: Heterogeneous multi-layer mobile edge computing in the 6G era,'' *IEEE Trans. Veh. Technol.*, vol. 69, no. 4, pp. 4388–4400, Apr. 2020.

[29] F. Tang, Y. Kawamoto, N. Kato, and J. Liu, ''Future intelligent and secure vehicular network toward 6G: Machine-learning approaches,'' *Proc. IEEE*, vol. 108, no. 2, pp. 292–307, Feb. 2020.

[30] C. She, R. Dong, Z. Gu, Z. Hou, Y. Li, W. Hardjawana, C. Yang, L. Song, and B. Vucetic, ''Deep learning for ultra-reliable and low-latency communications in 6G networks,'' *IEEE Netw.*, vol. 34, no. 5, pp. 219–225, Sep./Oct. 2020.

[31] M. S. Sim, Y.-G. Lim, S. H. Park, L. Dai, and C.-B. Chae, ''Deep learning-based mmWave beam selection for 5G NR/6G with sub-6 GHz channel information: Algorithms and prototype validation,'' *IEEE Access*, vol. 8, pp. 51634–51646, 2020.

[32] M. Salehi and E. Hossain, ''On the effect of temporal correlation on joint success probability and distribution of number of interferers in mobile UAV networks,'' *IEEE Wireless Commun. Lett.*, vol. 8, no. 6, pp. 1621–1625, Dec. 2019.

[33] Y. Zeng, Q. Wu, and R. Zhang, ''Accessing from the sky: A tutorial on UAV communications for 5G and beyond,'' *Proc. IEEE*, vol. 107, no. 12, pp. 2327–2375, Dec. 2019.

[34] N. Huda Mahmood, H. Alves, O. Alcaraz López, M. Shehab, D. P. Moya Osorio, and M. Latva-aho, ''Six key enablers for machine type communication in 6G,'' 2019, *arXiv:1903.05406*.

[35] S. Zhang, J. Liu, H. Guo, M. Qi, and N. Kato, ''Envisioning device-to-device communications in 6G,'' *IEEE Netw.*, vol. 34, no. 3, pp. 86–91, Jun. 2020.

[36] W. Saad, M. Bennis, and M. Chen, ''A vision of 6G wireless systems: Applications, trends, technologies, and open research problems,'' *IEEE Netw.*, vol. 34, no. 3, pp. 134–142, May/Jun. 2020.

[37] K. Samdanis and T. Taleb, ''The road beyond 5G: A vision and insight of the key technologies,'' *IEEE Netw.*, vol. 34, no. 2, pp. 135–141, Mar./Apr. 2020.

[38] F. Tariq, M. R. A. Khandaker, K.-K. Wong, M. A. Imran, M. Bennis, and M. Debbah, ''A speculative study on 6G,'' *IEEE Wireless Commun.*, vol. 27, no. 4, pp. 118–125, Aug. 2020.

[39] M. Giordani, M. Polese, M. Mezzavilla, S. Rangan, and M. Zorzi, ''Toward 6G networks: Use cases and technologies,'' *IEEE Commun. Mag.*, vol. 58, no. 3, pp. 55–61, Dec. 2020.

[40] G. Gui, M. Liu, F. Tang, N. Kato, and F. Adachi, ''6G: Opening new horizons for integration of comfort, security, and intelligence,'' *IEEE Wireless Commun.*, vol. 27, no. 5, pp. 126–132, Oct. 2020.

[41] B. Mao, Y. Kawamoto, and N. Kato, ''AI-based joint optimization of QoS and security for 6G energy harvesting Internet of Things,'' *IEEE Internet Things J.*, vol. 7, no. 8, pp. 7032–7042, Aug. 2020.

[42] Y. Zhou, L. Liu, L. Wang, N. Hui, X. Cui, J. Wu, Y. Peng, Y. Qi, and C. Xing, ''Service-aware 6G: An intelligent and open network based on the convergence of communication, computing and caching,'' *Digit. Commun. Netw.*, vol. 6, no. 3, pp. 253–260, 2020.

[43] D. Gesbert, M. Kountouris, R. W. Heath, Jr., C.-B. Chae, and T. Sälzer, ''Shifting the MIMO paradigm,'' *IEEE Signal Process. Mag.*, vol. 24, no. 5, pp. 36–46, Sep. 2007.

[44] L. Lu, G. Y. Li, A. L. Swindlehurst, A. Ashikhmin, and R. Zhang, ''An overview of massive MIMO: Benefits and challenges,'' *IEEE J. Sel. Topics Signal Process.*, vol. 8, no. 5, pp. 742–758, Oct. 2014.

[45] R. H. Roy, ''Spatial division multiple access technology and its application to wireless communication systems,'' in *Proc. IEEE 47th Veh. Technol. Conf. Technol. Motion*, vol. 2, May 1997, pp. 730–734.

[46] T. L. Marzetta, ''Noncooperative cellular wireless with unlimited numbers of base station antennas,'' *IEEE Trans. Wireless Commun.*, vol. 9, no. 11, pp. 3590–3600, Nov. 2010.

[47] T. L. Marzetta, E. G. Larsson, H. Yang, and H. Q. Ngo, *Fundamentals of Massive MIMO*. Cambridge, U.K.: Cambridge Univ. Press, Nov. 2016.

[48] H. Q. Ngo, E. G. Larsson, and T. L. Marzetta, ''Energy and spectral efficiency of very large multiuser MIMO systems,'' *IEEE Trans. Commun.*, vol. 61, no. 4, pp. 1436–1449, Apr. 2013.

[49] S. Parkvall, E. Dahlman, A. Furuskar, and M. Frenne, ''NR: The new 5G radio access technology,'' *IEEE Commun. Standards Mag.*, vol. 1, no. 4, pp. 24–30, Dec. 2017.

[50] E. Björnson, L. Sanguinetti, H. Wymeersch, J. Hoydis, and T. L. Marzetta, ''Massive MIMO is a reality—What is next?: Five promising research directions for antenna arrays,'' *Digit. Signal Process.*, vol. 94, pp. 3–20, Nov. 2019.

[51] F. Liu, C. Masouros, A. Li, H. Sun, and L. Hanzo, ''MU-MIMO communications with MIMO radar: From co-existence to joint transmission,'' *IEEE Trans. Wireless Commun.*, vol. 17, no. 4, pp. 2755–2770, Apr. 2018.

[52] D. Bliss and K. Forsythe, ''Multiple-input multiple-output (MIMO) radar and imaging: Degrees of freedom and resolution,'' in *Proc. 37th Asilomar Conf. Signals, Syst. Comput.*, vol. 1, Nov. 2003, pp. 54–59.

[53] P. Stoica, J. Li, and Y. Xie, ''On probing signal design for MIMO radar,'' *IEEE Trans. Signal Process.*, vol. 55, no. 8, pp. 4151–4161, Aug. 2007.

[54] J. Li, P. Stoica, L. Xu, and W. Roberts, ''On parameter identifiability of MIMO radar,'' *IEEE Signal Process. Lett.*, vol. 14, no. 12, pp. 968–971, Dec. 2007.

[55] J. Li and P. Stoica, ''MIMO radar with colocated antennas,'' *IEEE Signal Process. Mag.*, vol. 24, no. 5, pp. 106–114, Sep. 2007.

[56] K. V. Mishra, M. R. B. Shankar, V. Koivunen, B. Ottersten, and S. A. Vorobyov, ''Toward millimeter-wave joint radar communications: A signal processing perspective,'' *IEEE Signal Process. Mag.*, vol. 36, no. 5, pp. 100–114, Sep. 2019.

[57] J. Hoydis, S. ten Brink, and M. Debbah, ''Massive MIMO in the UL/DL of cellular networks: How many antennas do we need?'' *IEEE J. Sel. Areas Commun.*, vol. 31, no. 2, pp. 160–171, Feb. 2013.

[58] H. Yang and T. L. Marzetta, ''Performance of conjugate and zero-forcing beamforming in large-scale antenna systems,'' *IEEE J. Sel. Areas Commun.*, vol. 31, no. 2, pp. 172–179, Feb. 2013.

[59] J. Jose, A. Ashikhmin, T. L. Marzetta, and S. Vishwanath, ''Pilot contamination and precoding in multi-cell TDD systems,'' *IEEE Trans. Wireless Commun.*, vol. 10, no. 8, pp. 2640–2651, Aug. 2011.

[60] R. R. Müller, L. Cottatellucci, and M. Vehkaperä, ''Blind pilot decontamination,'' *IEEE J. Sel. Topics Signal Process.*, vol. 8, no. 5, pp. 773–786, Oct. 2014.

[61] Z. Chen and C. Yang, ''Pilot decontamination in wideband massive MIMO systems by exploiting channel sparsity,'' *IEEE Trans. Wireless Commun.*, vol. 15, no. 7, pp. 5087–5100, Jul. 2016.

[62] H. Yin, L. Cottatellucci, D. Gesbert, R. R. Müller, and G. He, ''Robust pilot decontamination based on joint angle and power domain discrimination,'' *IEEE Trans. Signal Process.*, vol. 64, no. 11, pp. 2990–3003, Jun. 2016.

[63] S. S. Ioushua and Y. C. Eldar, ''Pilot contamination mitigation with reduced RF chains,'' in *Proc. IEEE 18th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Jul. 2017, pp. 1–5.

[64] E. Björnson, J. Hoydis, and L. Sanguinetti, ''Massive MIMO has unlimited capacity,'' *IEEE Trans. Wireless Commun.*, vol. 17, no. 1, pp. 574–590, Jan. 2018.

[65] M. A. Naser, M. I. Salman, and M. Alsabah, ''The role of correlation in the performance of massive MIMO systems,'' *Appl. Syst. Innov.*, vol. 4, no. 3, p. 54, Aug. 2021.

[66] H. Yang and T. L. Marzetta, ''Total energy efficiency of cellular large scale antenna system multiple access mobile networks,'' in *Proc. IEEE Online Conf. Green Commun. (OnlineGreenComm)*, Oct. 2013, pp. 27–32.

[67] S. K. Mohammed, ''Impact of transceiver power consumption on the energy efficiency of zero-forcing detector in massive MIMO systems,'' *IEEE Trans. Commun.*, vol. 62, no. 11, pp. 3874–3890, Nov. 2014.

[68] E. Björnson, L. Sanguinetti, J. Hoydis, and M. Debbah, ''Optimal design of energy-efficient multi-user MIMO systems: Is massive MIMO the answer?'' *IEEE Trans. Wireless Commun.*, vol. 14, no. 6, pp. 3059–3075, Oct. 2015.

[69] A. Adhikary, J. Nam, J.-Y. Ahn, and G. Caire, ''Joint spatial division and multiplexing: The large-scale array regime,'' *IEEE Trans. Inf. Theory*, vol. 59, no. 10, pp. 6441–6463, Oct. 2013.

[70] J. Nam, G. Caire, and J. Ha, ''On the role of transmit correlation diversity in multiuser MIMO systems,'' *IEEE Trans. Inf. Theory*, vol. 63, no. 1, pp. 336–354, Jan. 2017.

[71] M. Q. Alsabah, M. Vehkapera, and T. O'Farrell, "Non-iterative downlink training sequence design based on sum rate maximization in FDD massive MIMO systems," *IEEE Access*, vol. 8, pp. 108731–108747, 2020.

[72] M. Alsabah, "Downlink training sequence design based on achievable sum rate maximisation in FDD massive MIMO systems," Ph.D. dissertation, Dept. Electron. Elect. Eng., Univ. Sheffield, Sheffield, U.K., 2020.

[73] M. A. Naser, M. Alsabah, B. M. Mahmmod, N. K. Noordin, S. H. Abdulhussain, and T. Baker, "Downlink training design for FDD massive MIMO systems in the presence of colored noise," *Electronics*, vol. 9, no. 12, p. 2155, Dec. 2020.

[74] M. A. Naser, M. Q. Alsabah, and M. A. Taher, "A partial CSI estimation approach for downlink FDD massive-MIMO system with different base transceiver station topologies," *Wireless Pers. Commun.*, vol. 119, pp. 3609–3630, Apr. 2021.

[75] C. Han, J. M. Jornet, and I. Akyildiz, "Ultra-massive MIMO channel modeling for graphene-enabled terahertz-band communications," in *Proc. IEEE 87th Veh. Technol. Conf. (VTC Spring)*, Jun. 2018, pp. 1–5.

[76] E. D. Carvalho, A. Ali, A. Amiri, M. Angjelichinoski, and R. W. Heath, "Non-stationarities in extra-large-scale massive MIMO," *IEEE Wireless Commun.*, vol. 27, no. 4, pp. 74–80, Aug. 2020.

[77] J. M. Jornet and I. F. Akyildiz, "Graphene-based plasmonic nanotransceiver for terahertz band communication," in *Proc. 8th Eur. Conf. Antennas Propag. (EuCAP)*, Apr. 2014, pp. 492–496.

[78] J. Medbo, K. Borner, K. Haneda, V. Hovinen, T. Imai, J. Jarvelainen, T. Jamsa, A. Karttunen, K. Kusume, J. Kyrolainen, P. Kyosti, J. Meinila, V. Nurmela, L. Raschkowski, A. Roivainen, and J. Ylitalo, "Channel modelling for the fifth generation mobile communications," in *Proc. 8th Eur. Conf. Antennas Propag. (EuCAP)*, Apr. 2014, pp. 219–223.

[79] A. O. Martinez, E. De Carvalho, and J. O. Nielsen, "Towards very large aperture massive MIMO: A measurement based study," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2014, pp. 281–286.

[80] M. Q. Abdulhasan, M. I. Salman, C. K. Ng, N. K. Noordin, S. J. Hashim, and F. Hashim, "An adaptive threshold feedback compression scheme based on channel quality indicator (CQI) in long term evolution (LTE) system," *Wireless Pers. Commun.*, vol. 82, no. 4, pp. 2323–2349, Jun. 2015.

[81] M. Q. Abdulhasan, M. I. Salman, C. K. Ng, N. K. Noordin, S. J. Hashim, and F. B. Hashim, "Approximate linear minimum mean square error estimation based on channel quality indicator feedback in LTE systems," in *Proc. IEEE 11th Malaysia Int. Conf. Commun. (MICC)*, Nov. 2013, pp. 446–451.

[82] M. Q. Abdulhasan, M. I. Salman, C. K. Ng, N. K. Noordin, S. J. Hashim, and F. B. Hashim, "A channel quality indicator (CQI) prediction scheme using feed forward neural network (FF-NN) technique for MU-MIMO LTE system," in *Proc. IEEE 2nd Int. Symp. Telecommun. Technol. (ISTT)*, Nov. 2014, pp. 17–22.

[83] M. Q. Abdulhasan, M. I. Salman, C. K. Ng, N. K. Noordin, S. J. Hashim, and F. B. Hashim, "A threshold feedback compression scheme of channel quality indicator (CQI) in LTE systems," in *Proc. IEEE Student Conf. Res. Developement*, Dec. 2013, pp. 181–186.

[84] M. Q. Abdulhasan, M. I. Salman, C. K. Ng, N. K. Noordin, S. J. Hashim, and F. Hashim, "Review of channel quality indicator estimation schemes for multi-user MIMO in 3GPP LTE/LTE-a systems," *KSII Trans. Internet Inf. Syst.*, vol. 8, no. 6, pp. 1848–1868, 2014.

[85] M. I. Salman, M. Q. Abdulhasan, C. K. Ng, N. K. Noordin, B. M. Ali, and A. Sali, "A partial feedback reporting scheme for LTE mobile video transmission with QoS provisioning," *Comput. Netw.*, vol. 112, pp. 108–121, Jan. 2017.

[86] X. Gao, F. Tufvesson, and O. Edfors, "Massive MIMO channels—Measurements and models," in *Proc. Asilomar Conf. Signals, Syst. Comput.*, Nov. 2013, pp. 280–284.

[87] S. Zhang, Q. Wu, S. Xu, and G. Y. Li, "Fundamental green tradeoffs: Progresses, challenges, and impacts on 5G networks," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 33–56, 1st Quart., 2017.

[88] Q. Wu, G. Y. Li, W. Chen, D. W. K. Ng, and R. Schober, "An overview of sustainable green 5G networks," *IEEE Wireless Commun.*, vol. 24, no. 4, pp. 72–80, Aug. 2016.

[89] W. Qingqing and Z. Rui, "Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network," *IEEE Commun. Mag.*, vol. 58, no. 1, pp. 106–112, Jan. 2019.

[90] Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network: Joint active and passive beamforming design," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2018, pp. 1–6.

[91] S. Abeywickrama, R. Zhang, Q. Wu, and C. Yuen, "Intelligent reflecting surface: Practical phase shift model and beamforming optimization," 2020, *arXiv:2002.10112*.

[92] S. Hu, F. Rusek, and O. Edfors, "Beyond massive MIMO: The potential of data transmission with large intelligent surfaces," *IEEE Trans. Signal Process.*, vol. 66, no. 10, pp. 2746–2758, May 2018.

[93] T. J. Cui, M. Q. Qi, X. Wan, J. Zhao, and Q. Cheng, "Coding metamaterials, digital metamaterials and programmable metamaterials," *Light: Sci. Appl.*, vol. 3, no. 10, p. e218, Oct. 2014.

[94] C. Liaskos, S. Nie, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, and I. Akyildiz, "A new wireless communication paradigm through software-controlled metasurfaces," *IEEE Commun. Mag.*, vol. 56, no. 9, pp. 162–169, Sep. 2018.

[95] Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," *IEEE Trans. Wireless Commun.*, vol. 18, no. 11, pp. 5394–5409, Nov. 2019.

[96] E. Björnson and L. Sanguinetti, "Power scaling laws and near-field behaviors of massive MIMO and intelligent reflecting surfaces," 2020, *arXiv:2002.04960*.

[97] N. Rajatheva, I. Atzeni, E. Bjornson, A. Bourdoux, S. Buzzi, J.-B. Dore, S. Erkucuk, M. Fuentes, K. Guan, and Y. Hu, "White paper on broadband connectivity in 6G," 2020, *arXiv:2004.14247*.

[98] O. Özdogan, E. Björnson, and E. G. Larsson, "Intelligent reflecting surfaces: Physics, propagation, and pathloss modeling," *IEEE Wireless Commun. Lett.*, vol. 9, no. 5, pp. 581–585, May 2020.

[99] C. Huang, A. Zappone, G. C. Alexandropoulos, M. Debbah, and C. Yuen, "Reconfigurable intelligent surfaces for energy efficiency in wireless communication," *IEEE Trans. Wireless Commun.*, vol. 18, no. 8, pp. 4157–4170, Aug. 2019.

[100] G. C. Alexandropoulos, G. Lerosey, M. Debbah, and M. Fink, "Reconfigurable intelligent surfaces and metamaterials: The potential of wave propagation control for 6G wireless communications," 2020, *arXiv:2006.11136*.

[101] M. Di Renzo, M. Debbah, D.-T. Phan-Huy, A. Zappone, M.-S. Alouini, C. Yuen, V. Sciancalepore, G. C. Alexandropoulos, J. Hoydis, and H. Gacanin, "Smart radio environments empowered by reconfigurable ai meta-surfaces: An idea whose time has come," *EURASIP J. Wireless Commun. Netw.*, vol. 2019, no. 1, pp. 1–20, 2019.

[102] C. Pan, H. Ren, K. Wang, M. Elkashlan, A. Nallanathan, J. Wang, and L. Hanzo, "Intelligent reflecting surface aided MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 8, pp. 1719–1734, Aug. 2020.

[103] Q. Wu and R. Zhang, "Joint active and passive beamforming optimization for intelligent reflecting surface assisted SWIPT under QoS constraints," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 8, pp. 1735–1748, Aug. 2020.

[104] T. Bai, C. Pan, Y. Deng, M. Elkashlan, A. Nallanathan, and L. Hanzo, "Latency minimization for intelligent reflecting surface aided mobile edge computing," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 11, pp. 2666–2682, Nov. 2020.

[105] P. Mach and Z. Becvar, "Mobile edge computing: A survey on architecture and computation offloading," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 3, pp. 1628–1656, 3rd Quart., 2017.

[106] C. Pan, H. Ren, K. Wang, W. Xu, M. Elkashlan, A. Nallanathan, and L. Hanzo, "Multicell MIMO communications relying on intelligent reflecting surfaces," *IEEE Trans. Wireless Commun.*, vol. 19, no. 8, pp. 5218–5233, Aug. 2020.

[107] L. Zhang, Y. Wang, W. Tao, Z. Jia, T. Song, and C. Pan, "Intelligent reflecting surface aided MIMO cognitive radio systems," *IEEE Trans. Veh. Technol.*, vol. 69, no. 10, pp. 11445–11457, Jul. 2020.

[108] S. Hong, C. Pan, H. Ren, K. Wang, and A. Nallanathan, "Artificial-noise-aided secure MIMO wireless communications via intelligent reflecting surface," 2020, *arXiv:2002.07063*.

[109] Z. Ding and H. V. Poor, "A simple design of IRS-NOMA transmission," *IEEE Commun. Lett.*, vol. 24, no. 5, pp. 1119–1123, May 2020.

[110] X. Mu, Y. Liu, L. Guo, J. Lin, and N. Al-Dhahir, "Exploiting intelligent reflecting surfaces in NOMA networks: Joint beamforming optimization," *IEEE Trans. Wireless Commun.*, vol. 19, no. 10, pp. 6884–6898, Oct. 2020.

[111] W. Ni, X. Liu, Y. Liu, H. Tian, and Y. Chen, "Resource allocation for multi-cell IRS-aided NOMA networks," 2020, *arXiv:2006.11811*.

[112] A. S. de Sena, D. Carrillo, F. Fang, P. H. J. Nardelli, D. B. da Costa, U. S. Dias, Z. Ding, C. B. Papadias, and W. Saad, "What role do intelligent reflecting surfaces play in multi-antenna non-orthogonal multiple access?" *IEEE Wireless Commun.*, vol. 27, no. 5, pp. 24–31, 2020, doi: 10.1109/MWC.001.2000061.

[113] S. Li, B. Duo, X. Yuan, Y.-C. Liang, and M. Di Renzo, "Reconfigurable intelligent surface assisted UAV communication: Joint trajectory design and passive beamforming," *IEEE Wireless Commun. Lett.*, vol. 9, no. 5, pp. 716–720, Jan. 2020.

[114] Q. Wang, Z. Chen, H. Li, and S. Li, "Joint power and trajectory design for physical-layer secrecy in the UAV-aided mobile relaying system," *IEEE Access*, vol. 6, pp. 62849–62855, 2018.

[115] L. Yang, F. Meng, J. Zhang, M. O. Hasna, and M. D. Renzo, "On the performance of RIS-assisted dual-hop UAV communication systems," *IEEE Trans. Veh. Technol.*, vol. 69, no. 9, pp. 10385–10390, Sep. 2020.

[116] C. Pan, H. Ren, K. Wang, J. Florentin Kolb, M. Elkashlan, M. Chen, M. Di Renzo, Y. Hao, J. Wang, A. Lee Swindlehurst, X. You, and L. Hanzo, "Reconfigurable intelligent surfaces for 6G systems: Principles, applications, and research directions," 2020, *arXiv:2011.04300*.

[117] C. Huang, S. Hu, G. C. Alexandropoulos, A. Zappone, C. Yuen, R. Zhang, M. Di Renzo, and M. Debbah, "Holographic MIMO surfaces for 6G wireless networks: Opportunities, challenges, and trends," *IEEE Wireless Commun.*, vol. 27, no. 5, pp. 118–125, Oct. 2020.

[118] J. Zhang, E. Björnson, M. Matthaiou, D. W. K. Ng, H. Yang, and D. J. Love, "Prospective multiple antenna technologies for beyond 5G," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 8, pp. 1637–1660, Aug. 2020.

[119] Z. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. Ding, X. Lei, G. K. Karagiannidis, and P. Fan, "6G wireless networks: Vision, requirements, architecture, and key technologies," *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 28–41, Sep. 2019.

[120] O. Tervo, T. Levanen, K. Pajukoski, J. Hulkkonen, P. Wainio, and M. Valkama, "5G new radio evolution towards sub-THz communications," in *Proc. 2nd 6G Wireless Summit (6G SUMMIT)*, Mar. 2020, pp. 1–6.

[121] M. Xiao, S. Mumtaz, Y. Huang, L. Dai, Y. Li, M. Matthaiou, G. K. Karagiannidis, E. Björnson, K. Yang, and I. Chih-Lin, "Millimeter wave communications for future mobile networks," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 9, pp. 1909–1935, Sep. 2017.

[122] Z. Pi and F. Khan, "An introduction to millimeter-wave mobile broadband systems," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 101–107, Jun. 2011.

[123] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5G cellular: It will work!" *IEEE Access*, vol. 1, pp. 335–349, 2013.

[124] S. Rangan, T. S. Rappaport, and E. Erkip, "Millimeter-wave cellular wireless networks: Potentials and challenges," *Proc. IEEE*, vol. 102, no. 3, pp. 366–385, Mar. 2014.

[125] A. Ghosh, T. A. Thomas, M. C. Cudak, R. Ratasuk, P. Moorut, F. W. Vook, T. S. Rappaport, G. R. MacCartney, S. Sun, and S. Nie, "Millimeter-wave enhanced local area systems: A high-data-rate approach for future wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1152–1163, Jun. 2014.

[126] R. W. Heath, N. González-Prelcic, S. Rangan, W. Roh, and A. M. Sayeed, "An overview of signal processing techniques for millimeter wave MIMO systems," *IEEE J. Sel. Topics Signal Process.*, vol. 10, no. 3, pp. 436–453, Apr. 2016.

[127] *Draft Standard for Information Technology-Telecommunications and Information Exchange Between Systems-Local and Metropolitan Area Networks-Specific Requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications-Amendment 4: Enhancements for Very High Throughput in the 60 GHz Band*, IEEE Standard P802.11ad/d9.0, 2012.

[128] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, "Five disruptive technology directions for 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 74–80, Feb. 2014.

[129] T. Bai, A. Alkhateeb, and R. W. Heath, "Coverage and capacity of millimeter-wave cellular networks," *IEEE Commun. Mag.*, vol. 52, no. 9, pp. 70–77, Sep. 2014.

[130] C. Saha and H. Dhillon, "Millimeter wave integrated access and backhaul in 5G: Performance analysis and design insights," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 12, pp. 2669–2684, Dec. 2019.

[131] J. Choi, V. Va, N. G.-Prelcic, R. Daniels, C. R. Bhat, and R. W. Heath, "Millimeter-wave vehicular communication to support massive automotive sensing," *IEEE Commun. Mag.*, vol. 54, no. 12, pp. 160–167, Dec. 2016.

[132] B. Wang, R. Shi, F. Shi, and J. Hu, "MmWave-NOMA-based low-latency and high-reliable communications for enhancement of V2X services," *IEEE Access*, vol. 8, pp. 57049–57062, 2020.

[133] S. Singh, M. N. Kulkarni, A. Ghosh, and J. G. Andrews, "Tractable model for rate in self-backhauled millimeter wave cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 10, pp. 2196–2211, Oct. 2015.

[134] W. Roh, J.-Y. Seol, J. Park, B. Lee, J. Lee, Y. Kim, J. Cho, K. Cheun, and F. Aryanfar, "Millimeter-wave beamforming as an enabling technology for 5G cellular communications: Theoretical feasibility and prototype results," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 106–113, Feb. 2014.

[135] Y. Kishiyama, A. Benjebbour, T. Nakamura, and H. Ishii, "Future steps of LTE-A: Evolution toward integration of local area and wide area systems," *IEEE Wireless Commun.*, vol. 20, no. 1, pp. 12–18, Feb. 2013.

[136] A. Pyattaev, K. Johnsson, S. Andreev, and Y. Koucheryavy, "Communication challenges in high-density deployments of wearable wireless devices," *IEEE Wireless Commun.*, vol. 22, no. 1, pp. 12–18, Feb. 2015.

[137] T. Lv, Y. Ma, J. Zeng, and P. T. Mathiopoulos, "Millimeter-wave noma transmission in cellular M2M communications for Internet of Things," *IEEE Internet Things J.*, vol. 5, no. 3, pp. 1989–2000, Jun. 2018.

[138] O. El Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath, "Spatially sparse precoding in millimeter wave MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, pp. 1499–1513, Mar. 2014.

[139] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1617–1655, 3rd Quart., 2016.

[140] E. Bjornson, L. Van der Perre, S. Buzzi, and E. G. Larsson, "Massive MIMO in sub-6 GHz and mmWave: Physical, practical, and use-case differences," *IEEE Wireless Commun.*, vol. 26, no. 2, pp. 100–108, Apr. 2019.

[141] A. Alkhateeb, O. El Ayach, G. Leus, and R. W. Heath, Jr., "Channel estimation and hybrid precoding for millimeter wave cellular systems," *IEEE J. Sel. Topics Signal Process.*, vol. 8, no. 5, pp. 831–846, Oct. 2014.

[142] S. A. R. Naqvi and S. A. Hassan, "Combining NOMA and mmWave technology for cellular communication," in *Proc. IEEE 84th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2016, pp. 1–5.

[143] B. Wang, L. Dai, Z. Wang, N. Ge, and S. Zhou, "Spectrum and energy-efficient beamspace MIMO-NOMA for millimeter-wave communications using lens antenna array," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2370–2382, Oct. 2017.

[144] A. S. Marcano and H. L. Christiansen, "Performance of non-orthogonal multiple access (NOMA) in mmWave wireless communications for 5G networks," in *Proc. Int. Conf. Comput., Netw. Commun. (ICNC)*, Jan. 2017, pp. 969–974.

[145] D. Zhang, Z. Zhou, C. Xu, Y. Zhang, J. Rodriguez, and T. Sato, "Capacity analysis of NOMA with mmWave massive MIMO systems," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 7, pp. 1606–1618, Jul. 2017.

[146] Z. Ding, P. Fan, and H. V. Poor, "Random beamforming in millimeter-wave NOMA networks," *IEEE Access*, vol. 5, pp. 7667–7681, 2017.

[147] C.-H. Liu, K.-H. Ho, and J.-Y. Wu, "Mmwave UAV networks with multi-cell association: Performance limit and optimization," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 12, pp. 2814–2831, Dec. 2019.

[148] X. Wang and M. C. Gursoy, "Coverage analysis for energy-harvesting UAV-assisted mmWave cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 12, pp. 2832–2850, Dec. 2019.

[149] J. Zhao, D. Xie, X. Wang, and A. Madanayake, "Towards efficient medium access for millimeter-wave networks," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 12, pp. 2786–2798, Dec. 2019.

[150] W. Yi, Y. Liu, Y. Deng, A. Nallanathan, and R. W. Heath, "Modeling and analysis of mmWave V2X networks with vehicular platoon systems," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 12, pp. 2851–2866, 2019.

[151] H. Zhou, D. Guo, and M. L. Honig, "Beam acquisition and training in millimeter wave networks with narrowband pilots," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 12, pp. 2759–2771, Dec. 2019.

[152] I. Aykin, B. Akgun, and M. Krunz, "Multi-beam transmissions for blockage resilience and reliability in millimeter-wave systems," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 12, pp. 2772–2785, Dec. 2019.

[153] P. Wang, J. Fang, X. Yuan, Z. Chen, and H. Li, "Intelligent reflecting surface-assisted millimeter wave communications: Joint active and passive precoding design," *IEEE Trans. Veh. Technol.*, vol. 69, no. 12, pp. 14960–14973, Dec. 2020.

[154] Z. Marzi and U. Madhow, "Interference management and capacity analysis for mm-wave picocells in urban canyons," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 12, pp. 2715–2726, Dec. 2019.

[155] I. F. Akyildiz, A. Kak, and S. Nie, "6G and beyond: The future of wireless communications systems," *IEEE Access*, vol. 8, pp. 133995–134030, 2020.

[156] V. Petrov, A. Pyattaev, D. Moltchanov, and Y. Koucheryavy, "Terahertz band communications: Applications, research challenges, and standardization activities," in *Proc. 8th Int. Congr. Ultra Modern Telecommun. Control Syst. Workshops (ICUMT)*, Oct. 2016, pp. 183–190.

[157] Y. Xing and T. S. Rappaport, "Propagation measurement system and approach at 140 GHz-moving to 6G and above 100 GHz," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2018, pp. 1–6.

[158] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Madanayake, S. Mandal, A. Alkhateeb, and G. C. Trichopoulos, "Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond," *IEEE Access*, vol. 7, pp. 78729–78757, 2019.

[159] L. Bariah, L. Mohjazi, S. Muhaidat, P. C. Sofotasios, G. Karabulut Kurt, H. Yanikomeroglu, and O. A. Dobre, "A prospective look: Key enabling technologies, applications and open research topics in 6G networks," 2020, *arXiv:2004.06049*.

[160] H.-J. Song and T. Nagatsuma, "Present and future of terahertz communications," *IEEE Trans. Terahertz Sci. Technol.*, vol. 1, no. 1, pp. 256–263, Sep. 2011.

[161] I. F. Akyildiz, J. M. Jornet, and C. Han, "Terahertz band: Next frontier for wireless communications," *Phys. Commun.*, vol. 12, pp. 16–32, Sep. 2014.

[162] I. F. Akyildiz, C. Han, and S. Nie, "Combating the distance problem in the millimeter wave and terahertz frequency bands," *IEEE Commun. Mag.*, vol. 56, no. 6, pp. 102–108, Jun. 2018.

[163] A. S. Cacciapuoti, K. Sankhe, M. Caleffi, and K. R. Chowdhury, "Beyond 5G: THz-based medium access protocol for mobile heterogeneous networks," *IEEE Commun. Mag.*, vol. 56, no. 6, pp. 110–115, Jun. 2018.

[164] H. Elayan, O. Amin, B. Shihada, R. M. Shubair, and M.-S. Alouini, "Terahertz band: The last piece of RF spectrum puzzle for communication systems," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 1–32, 2019.

[165] Y. Lu and X. Zheng, "6G: A survey on technologies, scenarios, challenges, and the related issues," *J. Ind. Inf. Integr.*, vol. 19, Sep. 2020, Art. no. 100158.

[166] P. Yang, Y. Xiao, M. Xiao, and S. Li, "6G wireless communications: Vision and potential techniques," *IEEE Netw.*, vol. 33, no. 4, pp. 70–75, Jul./Aug. 2019.

[167] R. Li, "Towards a new internet for the year 2030 and beyond," in *Proc. 3rd Annu. ITU IMT-2020/5G Workshop Demo Day*, 2018, pp. 1–21.

[168] C. Lin and G. Y. Li, "Terahertz communications: An array-of-subarrays solution," *IEEE Commun. Mag.*, vol. 54, no. 12, pp. 124–131, Dec. 2016.

[169] H. Sarieddeen, M.-S. Alouini, and T. Y. Al-Naffouri, "Terahertz-band ultra-massive spatial modulation MIMO," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 9, pp. 2040–2052, Jul. 2019.

[170] I. F. Akyildiz and J. M. Jornet, "Realizing ultra-massive MIMO (1024×1024) communication in the (0.06–10) terahertz band," *Nano Commun. Netw.*, vol. 8, pp. 46–54, Jun. 2016.

[171] S. Nie, J. M. Jornet, and I. F. Akyildiz, "Intelligent environments based on ultra-massive MIMO platforms for wireless communication in millimeter wave and terahertz bands," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP)*, May 2019, pp. 7849–7853.

[172] X. Ma, Z. Chen, W. Chen, Y. Chi, Z. Li, C. Han, and Q. Wen, "Intelligent reflecting surface enhanced indoor terahertz communication systems," *Nano Commun. Netw.*, vol. 24, May 2020, Art. no. 100284.

[173] M. Z. Chowdhury, M. Shahjalal, S. Ahmed, and Y. M. Jang, "6G wireless communication systems: Applications, requirements, technologies, challenges, and research directions," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 957–975, 2020.

[174] A. Celik, B. Shihada, and M.-S. Alouini, "Wireless data center networks: Advances, challenges, and opportunities," 2018, *arXiv:1811.11717*.

[175] K. Tekbiyik, A. R. Ekti, G. K. Kurt, and A. Görçin, "Terahertz band communication systems: Challenges, novelties and standardization efforts," *Phys. Commun.*, vol. 35, Aug. 2019, Art. no. 100700.

[176] S. Mumtaz, J. Miquel Jornet, J. Aulin, W. H. Gerstacker, X. Dong, and B. Ai, "Terahertz communication for vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 7, pp. 5617–5625, Jul. 2017.

[177] H. Elgala, R. Mesleh, and H. Haas, "Indoor optical wireless communication: Potential and state-of-the-art," *IEEE Commun. Mag.*, vol. 49, no. 9, pp. 56–62, Sep. 2011.

[178] M. Z. Chowdhury, M. T. Hossan, A. Islam, and Y. M. Jang, "A comparative survey of optical wireless technologies: Architectures and applications," *IEEE Access*, vol. 6, pp. 9819–9840, 2018.

[179] S. Dimitrov and H. Haas, *Principles of LED Light Communications: Towards Networked Li-Fi*. Cambridge, U.K.: Cambridge Univ. Press, 2015.

[180] M. Uysal, C. Capsoni, Z. Ghassemlooy, A. Boucouvalas, and E. Udvary, Eds., *Optical Wireless Communications: An Emerging Technology*. Cham, Switzerland: Springer, 2016, doi: 10.1007/978-3-319-30201-0.

[181] A. C. Boucouvalas, "Ambient light noise and its effect on receiver design for indoor wireless optical links," in *Proc. Int. Conf. Commun. (ICC/SUPERCOMM)*, vol. 3, Jun. 1996, pp. 1472–1476.

[182] A. C. Boucouvalas, "Indoor ambient light noise and its effect on wireless optical links," *IEE Proc.-Optoelectron.*, vol. 143, no. 6, pp. 334–338, 1996.

[183] C.-L. Lin, P.-S. Chen, C.-H. Chang, J.-S. Yu, C. Chang, and Y.-H. Tseng, "A hydrogenated amorphous silicon thin-film transistor optical pixel sensor for ameliorating influences of ambient light and reflected light," *IEEE J. Electron Devices Soc.*, vol. 5, no. 4, pp. 262–265, Jul. 2017.

[184] S.-H. Lee, "Reducing the effects of ambient noise light in an indoor optical wireless system using polarizers," *Microw. Opt. Technol. Lett.*, vol. 40, no. 3, pp. 228–231, Feb. 2004.

[185] S. Arnon, "Effects of atmospheric turbulence and building sway on optical wireless-communication systems," *Opt. Lett.*, vol. 28, no. 2, pp. 129–131, Jan. 2003.

[186] X. Song and J. Cheng, "Optical communication using subcarrier intensity modulation in strong atmospheric turbulence," *J. Lightw. Technol.*, vol. 30, no. 22, pp. 3484–3493, Nov. 15, 2012.

[187] X. Song and J. Cheng, "Subcarrier intensity modulated MIMO optical communications in atmospheric turbulence," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 5, no. 9, pp. 1001–1009, Sep. 2013.

[188] A. Jaiswal, M. R. Bhatnagar, P. Soni, and V. K. Jain, "Differential optical spatial modulation over atmospheric turbulence," *IEEE J. Sel. Topics Signal Process.*, vol. 13, no. 6, pp. 1417–1432, Oct. 2019.

[189] M. Gebhart, E. Leitgeb, and J. Bregenzer, "Atmospheric effects on optical wireless links," in *Proc. 7th Int. Conf. Telecommun. (ConTEL)*, vol. 2, Jun. 2003, pp. 395–401.

[190] H. G. Sandalidis, T. A. Tsiftsis, and G. K. Karagiannidis, "Optical wireless communications with heterodyne detection over turbulence channels with pointing errors," *J. Lightw. Technol.*, vol. 27, no. 20, pp. 4440–4445, Oct. 15, 2009.

[191] S. E. Trevlakis, A.-A.-A. Boulogeorgos, and G. K. Karagiannidis, "Outage performance of transdermal optical wireless links in the presence of pointing errors," in *Proc. IEEE 19th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Jun. 2018, pp. 1–5.

[192] A. Jaiswal, M. R. Bhatnagar, and V. K. Jain, "Performance of optical space shift keying over gamma–gamma fading with pointing error," *IEEE Photon. J.*, vol. 9, no. 2, pp. 1–16, Apr. 2017.

[193] I. S. Ansari, M.-S. Alouini, and J. Cheng, "Ergodic capacity analysis of free-space optical links with nonzero boresight pointing errors," *IEEE Trans. Wireless Commun.*, vol. 14, no. 8, pp. 4248–4264, Aug. 2015.

[194] M. Ylianttila, R. Kantola, A. Gurtov, L. Mucchi, I. Oppermann, Z. Yan, T. H. Nguyen, F. Liu, T. Hewa, and M. Liyanage, "6G white paper: Research challenges for trust, security and privacy," 2020, *arXiv:2004.11665*.

[195] A. R. Ndjiongue, T. M. N. Ngatched, O. A. Dobre, and A. G. Armada, "VLC-based networking: Feasibility and challenges," *IEEE Netw.*, vol. 34, no. 4, pp. 158–165, Jul. 2020.

[196] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, "Visible light communication, networking, and sensing: A survey, potential and challenges," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2047–2077, 4th Quart., 2015.

[197] M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, "Spatial modulation for generalized MIMO: Challenges, opportunities, and implementation," *Proc. IEEE*, vol. 102, no. 1, pp. 56–103, Jan. 2014.

[198] K. Wang, A. Nirmalathas, C. Lim, and E. Skafidas, "4×12.5 Gb/s WDM optical wireless communication system for indoor applications," *J. Lightw. Technol.*, vol. 29, no. 13, pp. 1988–1996, Jul. 1, 2011.

[199] J. Vučić, C. Kottke, K. Habel, and K.-D. Langer, "803 Mbit/s visible light WDM link based on DMT modulation of a single RGB LED luminary," in *Proc. Opt. Fiber Commun. Conf./Nat. Fiber Optic Eng. Conf.*, Mar. 2011, pp. 1–3.

[200] F.-M. Wu, C.-T. Lin, C.-C. Wei, C.-W. Chen, Z.-Y. Chen, and H.-T. Huang, "3.22-Gb/s WDM visible light communication of a single RGB LED employing carrier-less amplitude and phase modulation," in *Proc. Opt. Fiber Commun. Conf./Nat. Fiber Optic Eng. Conf.*, Mar. 2013, pp. 1–3.

[201] S. Rajagopal, R. D. Roberts, and S.-K. Lim, "IEEE 802.15.7 visible light communication: Modulation schemes and dimming support," *IEEE Commun. Mag.*, vol. 50, no. 3, pp. 72–82, Mar. 2012.

[202] Y.-S. Shiu, S. Y. Chang, H.-C. Wu, S. C.-H. Huang, and H.-H. Chen, "Physical layer security in wireless networks: A tutorial," *IEEE Wireless Commun.*, vol. 18, no. 2, pp. 66–74, Apr. 2011.

[203] M. Obeed, A. M. Salhab, M.-S. Alouini, and S. A. Zummo, "On optimizing VLC networks for downlink multi-user transmission: A survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2947–2976, 3rd Quart., 2019.

[204] M. Katz and D. O'Brien, "Exploiting novel concepts for visible light communications: From light-based IoT to living surfaces," *Optik*, vol. 195, Oct. 2019, Art. no. 163176.

[205] S. U. Rehman, S. Ullah, P. H. J. Chong, S. Yongchareon, and D. Komosny, "Visible light communication: A system perspective—Overview and challenges," *Sensors*, vol. 19, no. 5, p. 1153, 2019.

[206] D. Tsonev, H. Chun, S. Rajbhandari, J. J. McKendry, S. Videv, E. Gu, M. Haji, S. Watson, A. E. Kelly, and G. Faulkner, "A 3-Gb/s single-LED OFDM-based wireless VLC link using a gallium nitride μLED," *IEEE Photon. Technol. Lett.*, vol. 26, no. 7, pp. 637–640, Apr. 1, 2014.

[207] H. Haas, L. Yin, Y. Wang, and C. Chen, "What is LiFi?" *J. Lightw. Technol.*, vol. 34, no. 6, pp. 1533–1544, Mar. 15, 2016.

[208] H.-H. Lu, C.-Y. Li, H.-W. Chen, C.-M. Ho, M.-T. Cheng, Z.-Y. Yang, and C.-K. Lu, "A 56 Gb/s PAM4 VCSEL-based LiFi transmission with two-stage injection-locked technique," *IEEE Photon. J.*, vol. 9, no. 1, pp. 1–8, Feb. 2017.

[209] H. Haas, "LiFi is a paradigm-shifting 5G technology," *Rev. Phys.*, vol. 3, pp. 26–31, Nov. 2017.

[210] S. Dimitrov and H. Haas, "Information rate of OFDM-based optical wireless communication systems with nonlinear distortion," *J. Lightw. Technol.*, vol. 31, no. 6, pp. 918–929, Mar. 15, 2013.

[211] H. Haas, "High-speed wireless networking using visible light," *SPIE Newsroom*, vol. 1, no. 1, pp. 1–3, 2013.

[212] C. Chen, D. A. Basnayaka, and H. Haas, "Downlink performance of optical attocell networks," *J. Lightw. Technol.*, vol. 34, no. 1, pp. 137–156, Jan. 1, 2016.

[213] H. Haas, L. Yin, C. Chen, S. Videv, D. Parol, E. Poves, H. Alshaer, and M. S. Islim, "Introduction to indoor networking concepts and challenges in LiFi," *J. Opt. Commun. Netw.*, vol. 12, no. 2, pp A190–A203, 2020.

[214] I. Stefan, H. Burchardt, and H. Haas, "Area spectral efficiency performance comparison between VLC and RF femtocell networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2013, pp. 3825–3829.

[215] F. Zafar, M. Bakaul, and R. Parthiban, "Laser-diode-based visible light communication: Toward gigabit class communication," *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 144–151, Feb. 2017.

[216] H. Haas. (Aug. 2015). *Wireless Data Fromevery Light Bulb*. [Online]. Available: http://bit.ly/tedvlc

[217] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical Wireless Communications: System and Channel Modelling With MATLAB*. Boca Raton, FL, USA: CRC Press, 2019.

[218] M. Z. Chowdhury, M. K. Hasan, M. Shahjalal, M. T. Hossan, and Y. M. Jang, "Optical wireless hybrid networks: Trends, opportunities, challenges, and research directions," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 2, pp. 930–966, 2nd Quart., 2020.

[219] F. Demers, H. Yanikomeroglu, and M. St-Hilaire, "A survey of opportunities for free space optics in next generation cellular networks," in *Proc. 9th Annu. Commun. Netw. Services Res. Conf.*, May 2011, pp. 210–216.

[220] H. Kaushal and G. Kaddoum, "Optical communication in space: Challenges and mitigation techniques," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 57–96, 1st Quart., 2017.

[221] W.-S. Tsai, H.-H. Lu, C.-Y. Li, T.-C. Lu, C.-H. Liao, C.-A. Chu, and P.-C. Peng, "A 20-m/40-Gb/s 1550-nm DFB LD-based FSO link," *IEEE Photon. J.*, vol. 7, no. 6, pp. 1–7, Dec. 2015.

[222] V. W. S. Chan, "Free-space optical communications," *J. Lightw. Technol.*, vol. 24, no. 12, pp. 4750–4762, Dec. 2006.

[223] M. A. Khalighi and M. Uysal, "Survey on free space optical communication: A communication theory perspective," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 2231–2258, 4th Quart., 2014.

[224] H. Wu and M. Kavehrad, "Availability evaluation of ground-to-air hybrid FSO/RF links," *Int. J. Wireless Inf. Netw.*, vol. 14, no. 1, pp. 33–45, Mar. 2007.

[225] H. Wu, B. Hamzeh, and M. Kavehrad, "Availability of airborne hybrid FSO/RF links," *Proc. SPIE*, vol. 5819, pp. 89–100, Jun. 2005.

[226] S. D. Milner and C. C. Davis, "Hybrid free space optical/RF networks for tactical operations," in *Proc. IEEE Mil. Commun. Conf. (MILCOM)*, vol. 1, Oct./Nov. 2004, pp. 409–415.

[227] A. Kashyap and M. Shayman, "Routing and traffic engineering in hybrid RF/FSO networks," in *Proc. IEEE Int. Conf. Commun.*, vol. 5, May 2005, pp. 3427–3433.

[228] S. Chia, M. Gasparroni, and P. Brick, "The next challenge for cellular networks: Backhaul," *IEEE Microw. Mag.*, vol. 10, no. 5, pp. 54–66, Aug. 2009.

[229] S. A. Fares and F. Adachi, *Mobile and Wireless Communications: Network Layer and Circuit Level Design*. Norderstedt, Germany: Books on Demand, 2010.

[230] H. Yura and W. McKinley, "Optical scintillation statistics for IR ground-to-space laser communication systems," *Appl. Opt.*, vol. 22, no. 21, pp. 3353–3358, 1983.

[231] V. Sharma and N. Kumar, "Improved analysis of 2.5 Gbps-inter-satellite link (ISL) in inter-satellite optical-wireless communication (IsOWC) system," *Opt. Commun.*, vol. 286, pp. 99–102, Jan. 2013.

[232] T. A. Tsiftsis, H. G. Sandalidis, G. K. Karagiannidis, and M. Uysal, "Optical wireless links with spatial diversity over strong atmospheric turbulence channels," *IEEE Trans. Wireless Commun.*, vol. 8, no. 2, pp. 951–957, Feb. 2009.

[233] Z. Hajjarian, J. M. Fadlullah, and M. Kavehrad, "MIMO free space optical communications in turbid and turbulent atmosphere," *J. Commun.*, vol. 4, no. 8, pp. 524–532, 2009.

[234] Y. Tang, M. Brandt-Pearce, and S. G. Wilson, "Link adaptation for throughput optimization of parallel channels with application to hybrid FSO/RF systems," *IEEE Trans. Commun.*, vol. 60, no. 9, pp. 2723–2732, Sep. 2012.

[235] C. Abou-Rjeily and A. Slim, "Cooperative diversity for free-space optical communications: Transceiver design and performance analysis," *IEEE Trans. Commun.*, vol. 59, no. 3, pp. 658–663, Mar. 2011.

[236] B. Zong, C. Fan, X. Wang, X. Duan, B. Wang, and J. Wang, "6G technologies: Key drivers, core requirements, system architectures, and enabling technologies," *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 18–27, Sep. 2019.

[237] R. Thakur, "Scanning LIDAR in advanced driver assistance systems and beyond: Building a road map for next-generation LIDAR technology," *IEEE Consum. Electron. Mag.*, vol. 5, no. 3, pp. 48–54, Jul. 2016.

[238] P. Amon, U. Riegl, P. Rieger, and M. Pfennigbauer, "UAV-based laser scanning to meet special challenges in lidar surveying," in *Proc. Geomatics Indaba*, 2015, pp. 138–147.

[239] G. Mandlburger, M. Pfennigbauer, R. Schwarz, S. Flöry, and L. Nussbaumer, "Concept and performance evaluation of a novel UAV-borne topo-bathymetric LiDAR sensor," *Remote Sens.*, vol. 12, no. 6, p. 986, Mar. 2020.

[240] Y. Li and J. Ibanez-Guzman, "Lidar for autonomous driving: The principles, challenges, and trends for automotive lidar and perception systems," 2020, *arXiv:2004.08467*.

[241] N. Jayaweera, D. Marasinghe, N. Rajatheva, and M. Latva-Aho, "Factory automation: Resource allocation of an elevated LiDAR system with URLLC requirements," in *Proc. 2nd 6G Wireless Summit (6G SUMMIT)*, Mar. 2020, pp. 1–5.

[242] N. Saha, M. S. Ifthekhar, N. T. Le, and Y. M. Jang, "Survey on optical camera communications: Challenges and opportunities," *IET Optoelectron.*, vol. 9, no. 5, pp. 172–183, 2015.

[243] S. Hranilovic and F. R. Kschischang, "Short-range wireless optical communication using pixilated transmitters and imaging receivers," in *Proc. IEEE Int. Conf. Commun.*, vol. 2, Jun. 2004, pp. 891–895.

[244] T. Nguyen, A. Islam, M. T. Hossan, and Y. M. Jang, "Current status and performance analysis of optical camera communication technologies for 5G networks," *IEEE Access*, vol. 5, pp. 4574–4594, 2017.

[245] R. D. Roberts, "Undersampled frequency shift ON-OFF keying (UFSOOK) for camera communications (CamCom)," in *Proc. 22nd Wireless Opt. Commun. Conf.*, May 2013, pp. 645–648.

[246] C. Danakis, M. Afgani, G. Povey, I. Underwood, and H. Haas, "Using a CMOS camera sensor for visible light communication," in *Proc. IEEE Globecom Workshops*, Dec. 2012, pp. 1244–1248.

[247] N. Iizuka, *OCC Proposal of Scope of Standardization and Applications*, IEEE Standard 802.15 SG7a standardization documents, 2014.

[248] K. Kuraki, S. Nakagata, R. Tanaka, and T. Anan, "Data transfer technology to enable communication between displays and smart devices," *Fujitsu Sci. Tech. J*, vol. 50, no. 1, pp. 40–45, 2014.

[249] K. S. Kim, D. K. Kim, C.-B. Chae, S. Choi, Y.-C. Ko, J. Kim, Y.-G. Lim, M. Yang, S. Kim, and B. Lim, ''Ultrareliable and low-latency communication techniques for tactile Internet services,'' *Proc. IEEE*, vol. 107, no. 2, pp. 376–393, Feb. 2019.
[250] A. Osseiran, F. Boccardi, V. Braun, K. Kusume, P. Marsch, M. Maternia, O. Queseth, M. Schellmann, H. Schotten, and H. Taoka, ''Scenarios for 5G mobile and wireless communications: The vision of the METIS project,'' *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 26–35, May 2014.
[251] M. Chung, M. S. Sim, J. Kim, D. K. Kim, and C.-B. Chae, ''Prototyping real-time full duplex radios,'' *IEEE Commun. Mag.*, vol. 53, no. 9, pp. 56–63, Sep. 2015.
[252] D. Bharadia, E. Mcmilin, and S. Katti, ''Full duplex radios,'' in *Proc. ACM SIGCOMM Conf. SIGCOMM*, Aug. 2013, pp. 375–386.
[253] A. Sabharwal, P. Schniter, D. Guo, D. W. Bliss, S. Rangarajan, and R. Wichman, ''In-band full-duplex wireless: Challenges and opportunities,'' *IEEE J. Sel. Areas Commun.*, vol. 32, no. 9, pp. 1637–1652, Sep. 2014.
[254] M. Heino, D. Korpi, T. Huusari, E. Antonio-Rodriguez, S. Venkatasubramanian, T. Riihonen, L. Anttila, C. Icheln, K. Haneda, and R. Wichman, ''Recent advances in antenna design and interference cancellation algorithms for in-band full duplex relays,'' *IEEE Commun. Mag.*, vol. 53, no. 5, pp. 91–101, May 2015.
[255] M. Vehkapera, T. Riihonen, R. Wichman, and B. Xu, ''Power allocation for balancing the effects of channel estimation error and pilot overhead in full-duplex decode-and-forward relaying,'' in *Proc. IEEE 17th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Jul. 2016, pp. 1–5.
[256] M. S. Sim, M. Chung, D. Kim, J. Chung, D. K. Kim, and C.-B. Chae, ''Nonlinear self-interference cancellation for full-duplex radios: From link-level and system-level performance perspectives,'' *IEEE Commun. Mag.*, vol. 55, no. 9, pp. 158–167, Jun. 2017.
[257] T. Riihonen, S. Werner, and R. Wichman, ''Hybrid full-duplex/half-duplex relaying with transmit power adaptation,'' *IEEE Trans. Wireless Commun.*, vol. 10, no. 9, pp. 3074–3085, Sep. 2011.
[258] Z. Zhang, X. Chai, K. Long, A. V. Vasilakos, and L. Hanzo, ''Full duplex techniques for 5G networks: Self-interference cancellation, protocol design, and relay selection,'' *IEEE Commun. Mag.*, vol. 53, no. 5, pp. 128–137, May 2015.
[259] S. Hong, J. Brand, J. I. Choi, M. Jain, J. Mehlman, S. Katti, and P. Levis, ''Applications of self-interference cancellation in 5G and beyond,'' *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 114–121, Feb. 2014.
[260] M. Shafi, A. F. Molisch, P. J. Smith, T. Haustein, P. Zhu, P. De Silva, F. Tufvesson, A. Benjebbour, and G. Wunder, ''5G: A tutorial overview of standards, trials, challenges, deployment, and practice,'' *IEEE J. Sel. Areas Commun.*, vol. 35, no. 6, pp. 1201–1221, Jun. 2017.
[261] C. Kong, C. Zhong, S. Jin, S. Yang, H. Lin, and Z. Zhang, ''Full-duplex massive MIMO relaying systems with low-resolution ADCs,'' *IEEE Trans. Wireless Commun.*, vol. 16, no. 8, pp. 5033–5047, Aug. 2017.
[262] M. Sarajlić, L. Liu, and O. Edfors, ''When are low resolution ADCs energy efficient in massive MIMO?'' *IEEE Access*, vol. 5, pp. 14837–14853, 2017.
[263] Z. Peng, Z. Zhang, C. Pan, L. Li, and A. Lee Swindlehurst, ''Multiuser full-duplex two-way communications via intelligent reflecting surface,'' 2020, *arXiv:2006.05147*.
[264] S. H. Han and J. H. Lee, ''An overview of peak-to-average power ratio reduction techniques for multicarrier transmission,'' *IEEE Wireless Commun.*, vol. 12, no. 2, pp. 56–65, Apr. 2005.
[265] E. Dahlman, S. Parkvall, and J. Skold, *4G: LTE/LTE-Advanced for Mobile Broadband*. New York, NY, USA: Academic, 2013.
[266] R. V. Nee and R. Prasad, *OFDM for Wireless Multimedia Communications*. Norwood, MA, USA: Artech House, 2000.
[267] T. Jiang and Y. Wu, ''An overview: Peak-to-average power ratio reduction techniques for OFDM signals,'' *IEEE Trans. Broadcast.*, vol. 54, no. 2, pp. 257–268, Jun. 2008.
[268] B. Farhang-Boroujeny, ''OFDM versus filter bank multicarrier,'' *IEEE Signal Process. Mag.*, vol. 28, no. 3, pp. 92–112, May 2011.
[269] V. Vakilian, T. Wild, F. Schaich, S. ten Brink, and J.-F. Frigon, ''Universal-filtered multi-carrier technique for wireless systems beyond LTE,'' in *Proc. IEEE Globecom Workshops (GC Wkshps)*, 2013, pp. 223–228.
[270] J. Abdoli, M. Jia, and J. Ma, ''Filtered OFDM: A new waveform for future wireless systems,'' in *Proc. IEEE 16th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Jun. 2015, pp. 66–70.
[271] G. Fettweis, M. Krondorf, and S. Bittner, ''GFDM–generalized frequency division multiplexing,'' in *Proc. IEEE 69th Veh. Technol. Conf.*, Apr. 2009, pp. 1–4.
[272] N. Michailow, M. Matthé, I. S. Gaspar, A. N. Caldevilla, L. L. Mendes, A. Festag, and G. Fettweis, ''Generalized frequency division multiplexing for 5th generation cellular networks,'' *IEEE Trans. Commun.*, vol. 62, no. 9, pp. 3045–3061, Sep. 2014.
[273] Y. Cai, Z. Qin, F. Cui, G. Y. Li, and J. A. McCann, ''Modulation and multiple access for 5G networks,'' *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 629–646, 1st Quart., 2018.
[274] R. Hadani, S. Rakib, M. Tsatsanis, A. Monk, A. J. Goldsmith, A. F. Molisch, and R. Calderbank, ''Orthogonal time frequency space modulation,'' in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Mar. 2017, pp. 1–6.
[275] E. Başar, ''Index modulation techniques for 5G wireless networks,'' *IEEE Commun. Mag.*, vol. 54, no. 7, pp. 168–175, Jul. 2016.
[276] E. Basar, M. Wen, R. Mesleh, M. Di Renzo, Y. Xiao, and H. Haas, ''Index modulation techniques for next-generation wireless networks,'' *IEEE Access*, vol. 5, pp. 16693–16746, 2017.
[277] T. Wen and P. Zhu. (2013). *5G: A Technology vision*. Huawei. [Online]. Available: http://www.huaweicom/en/abouthuawei/publications/winwin-magazine/hw-329304.htm
[278] N. Docomo, ''5G radio access: Requirements, concept and technologies,'' white paper, 2014.
[279] Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, and K. Higuchi, ''Non-orthogonal multiple access (NOMA) for cellular future radio access,'' in *Proc. IEEE 77th Veh. Technol. Conf. (VTC Spring)*, Jun. 2013, pp. 1–5.
[280] K. Higuchi and A. Benjebbour, ''Non-orthogonal multiple access (NOMA) with successive interference cancellation for future radio access,'' *IEICE Trans. Commun.*, vol. 98, no. 3, pp. 403–414, 2015.
[281] S. M. R. Islam, N. Avazov, O. A. Dobre, and K.-S. Kwak, ''Power-domain non-orthogonal multiple access (NOMA) in 5G systems: Potentials and challenges,'' *IEEE Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 721–742, 2nd Quart., 2017.
[282] S. Ali, E. Hossain, and D. I. Kim, ''Non-orthogonal multiple access (NOMA) for downlink multiuser MIMO systems: User clustering, beamforming, and power allocation,'' *IEEE Access*, vol. 5, pp. 565–577, 2017.
[283] Z. Ding, X. Lei, G. K. Karagiannidis, R. Schober, J. Yuan, and V. Bhargava, ''A survey on non-orthogonal multiple access for 5G networks: Research challenges and future trends,'' *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2181–2195, Oct. 2017.
[284] Y. Liu, Z. Qin, M. Elkashlan, Z. Ding, A. Nallanathan, and L. Hanzo, ''Non-orthogonal multiple access for 5G and beyond,'' *Proc. IEEE*, vol. 105, no. 12, pp. 2347–2381, Dec. 2017.
[285] L. Dai, B. Wang, Z. Ding, Z. Wang, S. Chen, and L. Hanzo, ''A survey of non-orthogonal multiple access for 5G,'' *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 2294–2323, 3rd Quart., 2018.
[286] L. Dai, B. Wang, Y. Yuan, S. Han, I. Chih-Lin, and Z. Wang, ''Non-orthogonal multiple access for 5G: Solutions, challenges, opportunities, and future research trends,'' *IEEE Commun. Mag.*, vol. 53, no. 9, pp. 74–81, Sep. 2015.
[287] J. Du, W. Liu, G. Lu, J. Jiang, D. Zhai, F. R. Yu, and Z. Ding, ''When mobile-edge computing (MEC) meets nonorthogonal multiple access (NOMA) for the Internet of Things (IoT): System design and optimization,'' *IEEE Internet Things J.*, vol. 8, no. 10, pp. 7849–7862, May 2021.
[288] Y. Mao, B. Clerckx, and V. O. K. Li, ''Rate-splitting multiple access for downlink communication systems: Bridging, generalizing, and outperforming SDMA and NOMA,'' *EURASIP J. Wireless Commun. Netw.*, vol. 2018, no. 1, p. 133, May 2018.
[289] *Study on Network-Assisted Interference Cancellation and Suppression (naics) for LTE V.12.0.1*, 3GPP, Sophia Antipolis, France, document TR 36.866, Mar. 2014.
[290] *New SI Proposal: Study on Downlink Multiuser Superposition Transmission for LTE*, Mediatek, Hsinchu, Taiwan, 3GPP document RP-150496, Mar. 2015.
[291] H. Nikopour and H. Baligh, ''Sparse code multiple access,'' in *Proc. IEEE 24th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2013, pp. 332–336.
[292] M. Taherzadeh, H. Nikopour, A. Bayesteh, and H. Baligh, ''SCMA codebook design,'' in *Proc. IEEE 80th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2014, pp. 1–5.

[293] M. AL-Imari, M. A. Imran, R. Tafazolli, and D. Chen, "Performance evaluation of low density spreading multiple access," in *Proc. 8th Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Aug. 2012, pp. 383–388.

[294] M. AL-Imari, M. A. Imran, and R. Tafazolli, "Low density spreading for next generation multicarrier cellular systems," in *Proc. Int. Conf. Future Commun. Netw.*, Apr. 2012, pp. 52–57.

[295] M. Al-Imari, P. Xiao, M. A. Imran, and R. Tafazolli, "Uplink non-orthogonal multiple access for 5G wireless networks," in *Proc. 11th Int. Symp. Wireless Commun. Syst. (ISWCS)*, Aug. 2014, pp. 781–785.

[296] X. Dai, S. Chen, S. Sun, S. Kang, Y. Wang, Z. Shen, and J. Xu, "Successive interference cancelation amenable multiple access (SAMA) for future wireless communications," in *Proc. IEEE Int. Conf. Commun. Syst.*, Nov. 2014, pp. 222–226.

[297] Z. Yuan, G. Yu, W. Li, Y. Yuan, X. Wang, and J. Xu, "Multi-user shared access for Internet of Things," in *Proc. IEEE 83rd Veh. Technol. Conf. (VTC Spring)*, May 2016, pp. 1–5.

[298] I. Chih-Lin, S. Han, Z. Xu, Q. Sun, and Z. Pan, "5G: Rethink mobile communications for 2020+," *Philos. Trans. Roy. Soc. A, Math., Phys. Eng. Sci.*, vol. 374, no. 2062, Mar. 2016, Art. no. 20140432.

[299] S. Chen, B. Ren, Q. Gao, S. Kang, S. Sun, and K. Niu, "Pattern division multiple access—A novel nonorthogonal multiple access for fifth-generation radio networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 4, pp. 3185–3196, Apr. 2017.

[300] D. Fang, Y.-C. Huang, Z. Ding, G. Geraci, S.-L. Shieh, and H. Claussen, "Lattice partition multiple access: A new method of downlink non-orthogonal multiuser transmissions," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2016, pp. 1–6.

[301] J. Huang, K. Peng, F. Yang, C. Pan, and H. Jin, "Scalable video broadcasting using bit division multiplexing," *IEEE Trans. Broadcast.*, vol. 60, no. 4, pp. 701–706, Dec. 2014.

[302] P. Yang, Y. Xiao, Y. L. Guan, K. Hari, A. Chockalingam, S. Sugiura, H. Haas, M. Di Renzo, C. Masouros, and Z. Liu, "Single-carrier SM-MIMO: A promising design for broadband large-scale antenna systems," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1687–1716, 3rd Quart., 2016.

[303] G. Y. Li, Z. Xu, C. Xiong, C. Yang, S. Zhang, Y. Chen, and S. Xu, "Energy-efficient wireless communications: Tutorial, survey, and open issues," *IEEE Wireless. Commun.*, vol. 18, no. 6, pp. 28–35, Dec. 2011.

[304] D. Feng, C. Jiang, G. Lim, L. J. Cimini, Jr., G. Feng, and G. Y. Li, "A survey of energy-efficient wireless communications," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 1, pp. 167–178, 1st Quart., 2013.

[305] M. Di Renzo, H. Haas, and P. M. Grant, "Spatial modulation for multiple-antenna wireless systems: A survey," *IEEE Commun. Mag.*, vol. 49, no. 12, pp. 182–191, Dec. 2011.

[306] P. Yang, M. Di Renzo, Y. Xiao, S. Li, and L. Hanzo, "Design guidelines for spatial modulation," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 6–26, 1st Quart., 2015.

[307] E. Basar, "Reconfigurable intelligent surface-based index modulation: A new beyond MIMO paradigm for 6G," *IEEE Trans. Commun.*, vol. 68, no. 5, pp. 3187–3196, May 2020.

[308] J. Hoydis, M. Kobayashi, and M. Debbah, "Green small-cell networks," *IEEE Veh. Technol. Mag.*, vol. 6, no. 1, pp. 37–43, Mar. 2011.

[309] M. I. Salman, M. Q. Abdulhasan, C. K. Ng, N. K. Noordin, A. Sali, and B. M. Ali, "Radio resource management for green 3GPP long term evolution cellular networks: Review and trade-offs," *IETE Tech. Rev.*, vol. 30, no. 3, pp. 257–269, 2013.

[310] S. Tombaz, A. Vastberg, and J. Zander, "Energy- and cost-efficient ultra-high-capacity wireless access," *IEEE Wireless Commun.*, vol. 18, no. 5, pp. 18–24, Oct. 2011.

[311] A. Zappone and E. Jorswieck, "Energy efficiency in wireless networks via fractional programming theory," *Found. Trends Commun. Inf. Theory*, vol. 11, nos. 3–4, pp. 185–396, 2015.

[312] L. M. Correia, D. Zeller, O. Blume, D. Ferling, Y. Jading, I. Gódor, G. Auer, and L. V. Der Perre, "Challenges and enabling technologies for energy aware mobile radio networks," *IEEE Commun. Mag.*, vol. 48, no. 11, pp. 66–72, Nov. 2010.

[313] B. Matthiesen, A. Zappone, K.-L. Besser, E. A. Jorswieck, and M. Debbah, "A globally optimal energy-efficient power control framework and its efficient implementation in wireless interference networks," *IEEE Trans. Signal Process.*, vol. 68, pp. 3887–3902, Jun. 2020.

[314] C. Mobile, "C-RAN: The road towards green RAN," White paper, ver 2, 2011, pp. 1–10.

[315] J. Wu, Z. Zhang, Y. Hong, and Y. Wen, "Cloud radio access network (C-RAN): A primer," *IEEE Netw.*, vol. 29, no. 1, pp. 35–41, Jan. 2015.

[316] K. Wang, K. Yang, and C. S. Magurawalage, "Joint energy minimization and resource allocation in C-RAN with mobile cloud," *IEEE Trans. Cloud Comput.*, vol. 6, no. 3, pp. 760–770, Jul. 2018.

[317] C.-L. I, J. Huang, R. Duan, C. Cui, J. Jiang, and L. Li, "Recent progress on C-RAN centralization and cloudification," *IEEE Access*, vol. 2, pp. 1030–1039, 2014.

[318] S. Buzzi, C.-L. I, T. E. Klein, H. V. Poor, C. Yang, and A. Zappone, "A survey of energy-efficient techniques for 5G networks and challenges ahead," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 697–709, Apr. 2016.

[319] Z. Niu, Y. Wu, J. Gong, and Z. Yang, "Cell zooming for cost-efficient green cellular networks," *IEEE Commun. Mag.*, vol. 48, no. 11, pp. 74–79, Nov. 2010.

[320] E. Oh, K. Son, and B. Krishnamachari, "Dynamic base station switching-on/off strategies for green cellular networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 2126–2136, May 2013.

[321] C. Han, T. Harrold, S. Armour, I. Krikidis, S. Videv, P. M. Grant, H. Haas, J. S. Thompson, I. Ku, and C.-X. Wang, "Green radio: Radio techniques to enable energy-efficient wireless networks," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 46–54, Jun. 2011.

[322] K. Kumar and Y.-H. Lu, "Cloud computing for mobile users: Can offloading computation save energy?" *Computer*, vol. 43, no. 4, pp. 51–56, Apr. 2010.

[323] S. Kosta, A. Aucinas, P. Hui, R. Mortier, and X. Zhang, "ThinkAir: Dynamic resource allocation and parallel execution in the cloud for mobile code offloading," in *Proc. IEEE INFOCOM*, Mar. 2012, pp. 945–953.

[324] Y. Cai, F. R. Yu, and S. Bu, "Cloud radio access networks (C-RAN) in mobile cloud computing systems," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Apr. 2014, pp. 369–374.

[325] J. Tang, W. P. Tay, and T. Q. S. Quek, "Cross-layer resource allocation with elastic service scaling in cloud radio access network," *IEEE Trans. Wireless Commun.*, vol. 14, no. 9, pp. 5068–5081, Sep. 2015.

[326] J. Xu and L. Qiu, "Energy efficiency optimization for MIMO broadcast channels," *IEEE Trans. Wireless Commun.*, vol. 12, no. 2, pp. 690–701, Feb. 2013.

[327] D. Nguyen, L.-N. Tran, P. Pirinen, and M. Latva-Aho, "Precoding for full duplex multiuser MIMO systems: Spectral and energy efficiency maximization," *IEEE Trans. Signal Process.*, vol. 61, no. 16, pp. 4038–4050, Aug. 2013.

[328] L. Venturino, A. Zappone, C. Risi, and S. Buzzi, "Energy-efficient scheduling and power allocation in downlink OFDMA networks with base station coordination," *IEEE Trans. Wireless Commun.*, vol. 14, no. 1, pp. 1–14, Jan. 2015.

[329] E. Björnson, L. Sanguinetti, and M. Kountouris, "Deploying dense networks for maximal energy efficiency: Small cells meet massive MIMO," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 832–847, Apr. 2016.

[330] I. Krikidis, S. Timotheou, S. Nikolaou, G. Zheng, D. W. K. Ng, and R. Schober, "Simultaneous wireless information and power transfer in modern communication systems," *IEEE Commun. Mag.*, vol. 52, no. 11, pp. 104–110, Nov. 2014.

[331] Z. Zhang, T. He, M. Zhu, Z. Sun, Q. Shi, J. Zhu, B. Dong, M. R. Yuce, and C. Lee, "Deep learning-enabled triboelectric smart socks for IoT-based gait analysis and VR applications," *npj Flexible Electron.*, vol. 4, no. 1, pp. 1–12, Dec. 2020.

[332] S. Ulukus, A. Yener, E. Erkip, O. Simeone, M. Zorzi, P. Grover, and K. Huang, "Energy harvesting wireless communications: A review of recent advances," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 3, pp. 360–381, Apr. 2015.

[333] N. Van Huynh, D. T. Hoang, X. Lu, D. Niyato, P. Wang, and D. I. Kim, "Ambient backscatter communications: A contemporary survey," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 4, pp. 2889–2922, 4th Quart., 2018.

[334] K. Huang and E. Larsson, "Simultaneous information and power transfer for broadband wireless systems," *IEEE Trans. Signal Process.*, vol. 61, no. 23, pp. 5972–5986, Dec. 2013.

[335] X. Mou and H. Sun, "Wireless power transfer: Survey and roadmap," in *Proc. IEEE 81st Veh. Technol. Conf. (VTC Spring)*, May 2015, pp. 1–5.

[336] D. Niyato, D. I. Kim, M. Maso, and Z. Han, "Wireless powered communication networks: Research directions and technological approaches," *IEEE Wireless Commun.*, vol. 24, no. 6, pp. 88–97, Dec. 2017.

[337] Y. Alsaba, S. K. A. Rahim, and C. Y. Leow, "Beamforming in wireless energy harvesting communications systems: A survey," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 2, pp. 1329–1360, 2nd Quart., 2018.

[338] B. Clerckx, R. Zhang, R. Schober, D. W. K. Ng, D. I. Kim, and H. V. Poor, ''Fundamentals of wireless information and power transfer: From RF energy harvester models to signal and system designs,'' *IEEE J. Sel. Areas Commun.*, vol. 37, no. 1, pp. 4–33, Jan. 2019.
[339] L. R. Varshney, ''Transporting information and energy simultaneously,'' in *Proc. IEEE Int. Symp. Inf. Theory*, Jul. 2008, pp. 1612–1616.
[340] R. Zhang and C. K. Ho, ''MIMO broadcasting for simultaneous wireless information and power transfer,'' *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1989–2001, May 2013.
[341] S. Timotheou and I. Krikidis, ''Joint information and energy transfer in the spatial domain with channel estimation error,'' in *Proc. IEEE Online Conf. Green Commun. (OnlineGreenComm)*, Oct. 2013, pp. 115–120.
[342] A. Al-Baidhani, M. Vehkapera, and M. Benaissa, ''Simultaneous wireless information and power transfer based on generalized triangular decomposition,'' *IEEE Trans. Green Commun. Netw.*, vol. 3, no. 3, pp. 751–764, Sep. 2019.
[343] J. Huang, C.-C. Xing, and C. Wang, ''Simultaneous wireless information and power transfer: Technologies, applications, and research challenges,'' *IEEE Commun. Mag.*, vol. 55, no. 11, pp. 26–32, Nov. 2017.
[344] T. D. P. Perera, D. N. K. Jayakody, S. Chatzinotas, and J. Li, ''Simultaneous wireless information and power transfer (SWIPT): Recent advances and future challenges,'' *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 264–302, 1st Quart., 2018.
[345] W. Liu, K. Huang, X. Zhou, and S. Durrani, ''Next generation backscatter communication: Systems, techniques, and applications,'' *EURASIP J. Wireless Commun. Netw.*, vol. 2019, no. 1, pp. 1–11, Dec. 2019.
[346] R. Long, H. Guo, L. Zhang, and Y.-C. Liang, ''Full-duplex backscatter communications in symbiotic radio systems,'' *IEEE Access*, vol. 7, pp. 21597–21608, 2019.
[347] G. Yang, Q. Zhang, and Y.-C. Liang, ''Cooperative ambient backscatter communications for green Internet-of-Things,'' *IEEE Internet Things J.*, vol. 5, no. 2, pp. 1116–1130, Apr. 2018.
[348] V. Liu, A. Parks, V. Talla, S. Gollakota, D. Wetherall, and J. R. Smith, ''Ambient backscatter: Wireless communication out of thin air,'' *ACM SIGCOMM Comput. Commun. Rev.*, vol. 43, no. 4, pp. 39–50, 2013.
[349] H. Zhao, Y. Shuang, M. Wei, T. J. Cui, P. D. Hougne, and L. Li, ''Metasurface-assisted massive backscatter wireless communication with commodity Wi-Fi signals,'' *Nature Commun.*, vol. 11, no. 1, pp. 1–10, Dec. 2020.
[350] U. Karthaus and M. Fischer, ''Fully integrated passive UHF RFID transponder IC with 16.7-μW minimum RF input power,'' *IEEE J. Solid-State Circuits*, vol. 38, no. 10, pp. 1602–1608, Oct. 2003.
[351] C. Boyer and S. Roy, ''Backscatter communication and RFID: Coding, energy, and MIMO analysis,'' *IEEE Trans. Commun.*, vol. 62, no. 3, pp. 770–785, Mar. 2014.
[352] L. Li and T. J. Cui, ''Information metamaterials–from effective media to real-time information processing systems,'' *Nanophotonics*, vol. 8, no. 5, pp. 703–724, 2019.
[353] S. G. Hong, Y. M. Hwang, S. Y. Lee, Y. Shin, D. I. Kim, and J. Y. Kim, ''Game-theoretic modeling of backscatter wireless sensor networks under smart interference,'' *IEEE Commun. Lett.*, vol. 22, no. 4, pp. 804–807, Apr. 2018.
[354] R. Di Candia, R. Jantti, R. Duan, J. Lietzen, H. Khalifa, and K. Ruttik, ''Quantum backscatter communication: A new paradigm,'' in *Proc. 15th Int. Symp. Wireless Commun. Syst. (ISWCS)*, Aug. 2018, pp. 1–6.
[355] A. Yastrebova, R. Kirichek, Y. Koucheryavy, A. Borodin, and A. Koucheryavy, ''Future networks 2030: Architecture & requirements,'' in *Proc. 10th Int. Congr. Ultra Modern Telecommun. Control Syst. Workshops (ICUMT)*, Nov. 2018, pp. 1–8.
[356] M. C. Domingo, ''An overview of the internet of underwater things,'' *J. Netw. Comput. Appl.*, vol. 35, no. 6, pp. 1879–1890, 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1084804512001646
[357] M. Giordani and M. Zorzi, ''Non-terrestrial networks in the 6G era: Challenges and opportunities,'' *IEEE Netw.*, vol. 35, no. 2, pp. 244–251, Mar. 2021.
[358] B. Evans, N. Wang, Y. Rahulan, and S. Kumar, ''An integrated satellite–terrestrial 5G network and its use to demonstrate 5G use cases,'' *Int. J. Satell. Commun. Netw.*, vol. 39, no. 4, pp. 358–379, 2021.
[359] A. Vanelli-Coralli, A. Guidotti, T. Foggi, G. Colavolpe, and G. Montorsi, ''5G and beyond 5G non-terrestrial networks: Trends and research challenges,'' in *Proc. IEEE 3rd 5G World Forum (5GWF)*, Sep. 2020, pp. 163–169.
[360] J.-H. Lee, J. Park, M. Bennis, and Y.-C. Ko, ''Integrating LEO satellite and UAV relaying via reinforcement learning for non-terrestrial networks,'' in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2020, pp. 1–6.
[361] P. Zhou, X. Fang, Y. Fang, R. He, Y. Long, and G. Huang, ''Beam management and self-healing for mmWave UAV mesh networks,'' *IEEE Trans. Veh. Technol.*, vol. 68, no. 2, pp. 1718–1732, Feb. 2019.
[362] S. Elmeadawy and R. M. Shubair, ''Enabling technologies for 6g future wireless communications: Opportunities and challenges,'' 2020, *arXiv:2002.06068*.
[363] O. Kodheli, E. Lagunas, N. Maturo, S. K. Sharma, B. Shankar, J. F. Mendoza Montoya, J. C. Merlano Duncan, D. Spano, S. Chatzinotas, S. Kisseleff, J. Querol, L. Lei, T. X. Vu, and G. Goussetis, ''Satellite communications in the new space era: A survey and future challenges,'' 2020, *arXiv:2002.08811*.
[364] G. Wikstrom, J. Peisa, P. Rugeland, N. Johansson, S. Parkvall, M. Girnyk, G. Mildh, and I. L. Da Silva, ''Challenges and technologies for 6G,'' in *Proc. 2nd 6G Wireless Summit (6G SUMMIT)*, Mar. 2020, pp. 1–5.
[365] U. Challita and W. Saad, ''Network formation in the sky: Unmanned aerial vehicles for multi-hop wireless backhauling,'' in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2017, pp. 1–6.
[366] W. Feng, J. Wang, Y. Chen, X. Wang, N. Ge, and J. Lu, ''UAV-aided MIMO communications for 5G Internet of Things,'' *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1731–1740, Apr. 2019.
[367] M. Erdelj, M. Król, and E. Natalizio, ''Wireless sensor networks and multi-UAV systems for natural disaster management,'' *Comput. Netw.*, vol. 124, pp. 72–86, Sep. 2017.
[368] Y. Zhou, C. Pan, P. L. Yeoh, K. Wang, M. Elkashlan, B. Vucetic, and Y. Li, ''Secure Communications for UAV-enabled mobile edge computing systems,'' *IEEE Trans. Commun.*, vol. 68, no. 1, pp. 376–388, Jan. 2020.
[369] Z. Yang, C. Pan, K. Wang, and M. Shikh-Bahaei, ''Energy efficient resource allocation in UAV-enabled mobile edge computing networks,'' *IEEE Trans. Wireless Commun.*, vol. 18, no. 9, pp. 4576–4589, Sep. 2019.
[370] F. Zhou, R. Q. Hu, Z. Li, and Y. Wang, ''Mobile edge computing in unmanned aerial vehicle networks,'' *IEEE Wireless Commun.*, vol. 27, no. 1, pp. 140–146, Feb. 2020.
[371] B. Alzahrani, O. S. Oubbati, A. Barnawi, M. Atiquzzaman, and D. Alghazzawi, ''UAV assistance paradigm: State-of-the-art in applications and challenges,'' *J. Netw. Comput. Appl.*, vol. 166, Sep. 2020, Art. no. 102706.
[372] J. Zhang, L. Zhou, Q. Tang, E. C.-H. Ngai, X. Hu, H. Zhao, and J. Wei, ''Stochastic computation offloading and trajectory scheduling for UAV-assisted mobile edge computing,'' *IEEE Internet Things J.*, vol. 6, no. 2, pp. 3688–3699, Apr. 2019.
[373] X. Cao, J. Xu, and R. Zhang, ''Mobile edge computing for cellular-connected UAV: Computation offloading and trajectory optimization,'' in *Proc. IEEE 19th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Jun. 2018, pp. 1–5.
[374] S. H. Abdulhussain, A. R. Ramli, A. J. Hussain, B. M. Mahmmod, and W. A. Jassim, ''Orthogonal polynomial embedded image kernel,'' in *Proc. Int. Conf. Inf. Commun. Technol. (ICICT)*, 2019, pp. 215–221.
[375] Z. N. Idan, S. H. Abdulhussain, B. M. Mahmmod, K. A. Al-Utaibi, S. A. R. Al-Hadad, and S. M. Sait, ''Fast shot boundary detection based on separable moments and support vector machine,'' *IEEE Access*, vol. 9, pp. 106412–106427, 2021. [Online]. Available: https://ieeexplore.ieee.org/document/9496657/
[376] A. M. Abdul-Hadi, S. H. Abdulhussain, and B. M. Mahmmod, ''On the computational aspects of charlier polynomials,'' *Cogent Eng.*, vol. 7, no. 1, Jan. 2020, Art. no. 1763553.
[377] S. H. Abdulhussain and B. M. Mahmmod, ''Fast and efficient recursive algorithm of Meixner polynomials,'' *J. Real-Time Image Process.*, 2021. [Online]. Available: https://link.springer.com/article/10.1007%2Fs11554-021-01093-z, doi: 10.1007/s11554-021-01093-z.
[378] Y. Zeng, J. Lyu, and R. Zhang, ''Cellular-connected UAV: Potential, challenges, and promising technologies,'' *IEEE Wireless Commun.*, vol. 26, no. 1, pp. 120–127, Feb. 2019.
[379] G. M. Djuknic, J. Freidenfelds, and Y. Okunev, ''Establishing wireless communications services via high-altitude aeronautical platforms: A concept whose time has come?'' *IEEE Commun. Mag.*, vol. 35, no. 9, pp. 128–135, Sep. 1997.
[380] D. Grace and M. Mohorcic, *Broadband Communications Via High Altitude Platforms*. Hoboken, NJ, USA: Wiley, 2011.

[381] L. Reynaud and T. Rasheed, "Deployable aerial communication networks: Challenges for futuristic applications," in *Proc. 9th ACM Symp. Perform. Eval. Wireless Ad Hoc, Sensor, Ubiquitous Netw.*, 2012, pp. 9–16.

[382] J. V. Llop, P. C. Roberts, Z. Hao, L. R. Tomas, and V. Beauplet, "Very low earth orbit mission concepts for earth observation: Benefits and challenges," in *Proc. Reinventing Space Conf.*, 2014, pp. 18–21.

[383] A. Mohammed, A. Mehmood, F.-N. Pavlidou, and M. Mohorcic, "The role of high-altitude platforms (HAPs) in the global wireless connectivity," *Proc. IEEE*, vol. 99, no. 11, pp. 1939–1953, Nov. 2011.

[384] X. Cao, P. Yang, M. Alzenad, X. Xi, D. Wu, and H. Yanikomeroglu, "Airborne communication networks: A survey," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 10, pp. 1907–1926, Sep. 2018.

[385] M. Ding and D. López-Pérez, "Performance impact of base station antenna heights in dense cellular networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 12, pp. 8147–8161, Dec. 2017.

[386] S. Karapantazis and F. Pavlidou, "Broadband communications via high-altitude platforms: A survey," *IEEE Commun. Surveys Tuts.*, vol. 7, no. 1, pp. 2–31, 1st Quart., 2005.

[387] G. Araniti, A. Iera, and A. Molinaro, "The role of HAPs in supporting multimedia broadcast and multicast services in terrestrial-satellite integrated systems," *Wireless Pers. Commun.*, vol. 32, nos. 3–4, pp. 195–213, Feb. 2005.

[388] Iskandar, M. A. Wibisono, S. Priatna, T. Juhana, Hendrawan, and N. Rachmana, "On the design and development of flying BTS system using balloon for remote area communication," in *Proc. 11th Int. Conf. Telecommun. Syst. Services Appl. (TSSA)*, Oct. 2017, pp. 1–5.

[389] C. Liu, W. Feng, Y. Chen, C.-X. Wang, and N. Ge, "Cell-free satellite-UAV networks for 6G wide-area Internet of Things," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 4, pp. 1116–1131, Apr. 2021.

[390] X. Li, W. Feng, J. Wang, Y. Chen, N. Ge, and C.-X. Wang, "Enabling 5G on the ocean: A hybrid Satellite-UAV-terrestrial network solution," *IEEE Wireless Commun.*, vol. 27, no. 6, pp. 116–121, Dec. 2020.

[391] T. Wei, W. Feng, Y. Chen, C.-X. Wang, N. Ge, and J. Lu, "Hybrid satellite-terrestrial communication networks for the maritime Internet of Things: Key technologies, opportunities, and challenges," *IEEE Internet Things J.*, vol. 8, no. 11, pp. 8910–8934, Jun. 2021.

[392] Y. Wang, W. Feng, J. Wang, and T. Q. S. Quek, "Hybrid satellite-UAV-terrestrial networks for 6G ubiquitous coverage: A maritime communications perspective," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 11, pp. 3475–3490, Nov. 2021.

[393] S. Nayak and R. Patgiri, "6G communication: Envisioning the key issues and challenges," 2020, *arXiv:2004.04024*.

[394] H. Q. Ngo, A. Ashikhmin, H. Yang, E. G. Larsson, and T. L. Marzetta, "Cell-free massive MIMO versus small cells," *IEEE Trans. Wireless Commun.*, vol. 16, no. 3, pp. 1834–1850, Mar. 2017.

[395] E. Nayebi, A. Ashikhmin, T. L. Marzetta, H. Yang, and B. D. Rao, "Precoding and power optimization in cell-free massive MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 16, no. 7, pp. 4445–4459, Jul. 2017.

[396] G. Interdonato, E. Björnson, H. Q. Ngo, P. Frenger, and E. G. Larsson, "Ubiquitous cell-free massive MIMO communications," *EURASIP J. Wireless Commun. Netw.*, vol. 2019, no. 1, p. 197, Dec. 2019.

[397] S. Shamai and B. M. Zaidel, "Enhancing the cellular downlink capacity via co-processing at the transmitting end," in *Proc. IEEE VTS 53rd Veh. Technol. Conf.*, vol. 3, May 2001, pp. 1745–1749.

[398] S. Zhou, M. Zhao, X. Xu, J. Wang, and Y. Yao, "Distributed wireless communication system: A new architecture for future public wireless access," *IEEE Commun. Mag.*, vol. 41, no. 3, pp. 108–113, Mar. 2003.

[399] D. Gesbert, S. Hanly, H. Huang, S. S. Shitz, O. Simeone, and W. Yu, "Multi-cell MIMO cooperative networks: A new look at interference," *IEEE J. Sel. Areas Commun.*, vol. 28, no. 9, pp. 1380–1408, Dec. 2010.

[400] E. Björnson, R. Zakhour, D. Gesbert, and B. Ottersten, "Cooperative multicell precoding: Rate region characterization and distributed strategies with instantaneous and statistical CSI," *IEEE Trans. Signal Process.*, vol. 58, no. 8, pp. 4298–4310, Aug. 2010.

[401] A. Pouttu, F. Burkhardt, C. Patachia, and L. Mendes, "6G white paper on validation and trials for verticals towards 2030's," Univ. Oulu, Oulu, Finland, Tech. Rep. 4, 2020.

[402] C. D'Andrea, A. Garcia-Rodriguez, G. Geraci, L. G. Giordano, and S. Buzzi, "Cell-free massive MIMO for UAV communications," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, May 2019, pp. 1–6.

[403] M. Peng, Y. Sun, X. Li, Z. Mao, and C. Wang, "Recent advances in cloud radio access networks: System architectures, key techniques, and open issues," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 2282–2308, 3rd Quart., 2016.

[404] E. Björnson and L. Sanguinetti, "Making cell-free massive MIMO competitive with MMSE processing and centralized implementation," *IEEE Trans. Wireless Commun.*, vol. 19, no. 1, pp. 77–90, Jan. 2020.

[405] T. C. Mai, H. Quoc Ngo, and T. Q. Duong, "Cell-free massive MIMO systems with multi-antenna users," in *Proc. IEEE Global Conf. Signal Inf. Process. (GlobalSIP)*, Nov. 2018, pp. 828–832.

[406] E. Nayebi, A. Ashikhmin, T. L. Marzetta, and B. D. Rao, "Performance of cell-free massive MIMO systems with MMSE and LSFD receivers," in *Proc. 50th Asilomar Conf. Signals, Syst. Comput.*, Nov. 2016, pp. 203–207.

[407] Z. Chen and E. Björnson, "Channel hardening and favorable propagation in cell-free massive MIMO with stochastic geometry," *IEEE Trans. Commun.*, vol. 66, no. 11, pp. 5205–5219, Nov. 2018.

[408] J. Zhang, X. Xue, E. Björnson, B. Ai, and S. Jin, "Performance analysis and power control of cell-free massive MIMO systems with hardware impairments," *IEEE Access*, vol. 6, pp. 55302–55314, 2018.

[409] S. Buzzi and C. D'Andrea, "Cell-free massive MIMO: User-centric approach," *IEEE Wireless Commun. Lett.*, vol. 6, no. 6, pp. 706–709, Dec. 2017.

[410] W. Fan, J. Zhang, E. Bjornson, S. Chen, and Z. Zhong, "Performance analysis of cell-free massive MIMO over spatially correlated fading channels," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2019, pp. 1–6.

[411] J. Qiu, K. Xu, Z. Shen, W. Xie, D. Zhang, and X. Li, "Downlink performance analysis of cell-free massive MIMO over spatially correlated Rayleigh channels," in *Proc. IEEE 19th Int. Conf. Commun. Technol. (ICCT)*, Oct. 2019, pp. 122–127.

[412] Z. Wang, J. Zhang, E. Bjornson, and B. Ai, "Uplink performance of cell-free massive MIMO over spatially correlated rician fading channels," *IEEE Commun. Lett.*, vol. 25, no. 4, pp. 1348–1352, Apr. 2021.

[413] H. Q. Ngo, H. Tataria, M. Matthaiou, S. Jin, and E. G. Larsson, "On the performance of cell-free massive MIMO in Ricean fading," in *Proc. 52nd Asilomar Conf. Signals, Syst., Comput.*, Oct. 2018, pp. 980–984.

[414] Ö. Özdogan, E. Björnson, and J. Zhang, "Performance of cell-free massive MIMO with Rician fading and phase shifts," *IEEE Trans. Wireless Commun.*, vol. 18, no. 11, pp. 5299–5315, Nov. 2019.

[415] J. Zheng, J. Zhang, L. Zhang, X. Zhang, and B. Ai, "Efficient receiver design for uplink cell-free massive MIMO with hardware impairments," *IEEE Trans. Veh. Technol.*, vol. 69, no. 4, pp. 4537–4541, Apr. 2020.

[416] *study on Non-Orthogonal Multiple Access (NOMA) for NR, Release 15*, 3GPP document TR 38.812, May 2017.

[417] Y. Lu, "Blockchain and the related issues: A review of current research topics," *J. Manage. Anal.*, vol. 5, no. 4, pp. 231–255, 2018.

[418] D. E. Kouicem, A. Bouabdallah, and H. Lakhlef, "Internet of Things security: A top-down survey," *Comput. Netw.*, vol. 141, pp. 199–221, Aug. 2018.

[419] W. Viriyasitavat, L. D. Xu, Z. Bi, D. Hoonsopon, and N. Charoenruk, "Managing QoS of Internet-of-Things services using blockchain," *IEEE Trans. Comput. Social Syst.*, vol. 6, no. 6, pp. 1357–1368, Dec. 2019.

[420] P. Botsinis, D. Alanis, Z. Babar, H. V. Nguyen, D. Chandra, S. X. Ng, and L. Hanzo, "Quantum search algorithms for wireless communications," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 2, pp. 1209–1242, 2nd Quart., 2019.

[421] S.-T. Cheng, C.-Y. Wang, and M.-H. Tao, "Quantum communication for wireless wide-area networks," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 7, pp. 1424–1432, Jul. 2005.

[422] L. K. Grover, "A fast quantum mechanical algorithm for database search," in *Proc. 28th Annu. ACM Symp. Theory Comput. (STOC)*, 1996, pp. 212–219.

[423] Z. Ma, M. Xiao, Y. Xiao, Z. Pang, H. V. Poor, and B. Vucetic, "High-reliability and low-latency wireless communication for Internet of Things: Challenges, fundamentals, and enabling technologies," *IEEE Internet Things J.*, vol. 6, no. 5, pp. 7946–7970, Oct. 2019.

[424] X. Xu, Y. Pan, P. P. M. Y. Lwin, and X. Liang, "3D holographic display and its data transmission requirement," in *Proc. Int. Conf. Inf. Photon. Opt. Commun.*, Oct. 2011, pp. 1–4.

[425] A. A. Ateya, A. Vybornova, R. Kirichek, and A. Koucheryavy, "Multilevel cloud based tactile internet system," in *Proc. 19th Int. Conf. Adv. Commun. Technol. (ICACT)*, 2017, pp. 105–110.

[426] O. Holland, E. Steinbach, R. V. Prasad, Q. Liu, Z. Dawy, A. Aijaz, N. Pappas, K. Chandra, V. S. Rao, and S. Oteafy, "The IEEE 1918.1 'tactile internet' standards working group and its standards," *Proc. IEEE*, vol. 107, no. 2, pp. 256–279, Feb. 2019.

[427] G. P. Fettweis, "The tactile Internet: Applications and challenges," *IEEE Veh. Technol. Mag.*, vol. 9, no. 1, pp. 64–70, Mar. 2014.

[428] K. Antonakoglou, X. Xu, E. Steinbach, T. Mahmoodi, and M. Dohler, "Toward haptic communications over the 5G tactile internet," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 4, pp. 3034–3059, 4th Quart., 2018.

[429] D. van den Berg, R. Glans, D. De Koning, F. A. Kuipers, J. Lugtenburg, K. Polachan, P. T. Venkata, C. Singh, B. Turkovic, and B. Van Wijk, "Challenges in haptic communications over the Tactile internet," *IEEE Access*, vol. 5, pp. 23502–23518, 2017.

[430] S. Aggarwal and N. Kumar, "Fog computing for 5G-enabled tactile internet: Research issues, challenges, and future research directions," *Mobile Netw. Appl.*, 2019, doi: 10.1007/s11036-019-01430-4.

[431] G. Association. (Oct. 2015). *5G Automotive Vision*. 5GPPP assoc., white paper. [Online]. Available: https://5gppp.eu/

[432] S. Kitanov, E. Monteiro, and T. Janevski, "5G and the fog—Survey of related technologies and research directions," in *Proc. 18th Medit. Electrotech. Conf. (MELECON)*, Apr. 2016, pp. 1–6.

[433] M. Simsek, A. Aijaz, M. Dohler, J. Sachs, and G. Fettweis, "5G-enabled tactile internet," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 3, pp. 460–473, Mar. 2016.

[434] M. Katz, M. Matinmikko-Blue, and M. Latva-Aho, "6Genesis flagship program: Building the bridges towards 6G-enabled wireless smart society and ecosystem," in *Proc. IEEE 10th Latin-Amer. Conf. Commun. (LATINCOM)*, Nov. 2018, pp. 1–9.

[435] S. Elmeadawy and R. M. Shubair, "6G wireless communications: Future technologies and research challenges," in *Proc. Int. Conf. Electr. Comput. Technol. Appl. (ICECTA)*, Nov. 2019, pp. 1–5.

[436] Y. Yuan, "Paving the road for virtual and augmented reality [Standards]," *IEEE Consum. Electron. Mag.*, vol. 7, no. 1, pp. 117–128, Jan. 2018.

[437] F. J. Detmer, J. Hettig, D. Schindele, M. Schostak, and C. Hansen, "Virtual and augmented reality systems for renal interventions: A systematic review," *IEEE Rev. Biomed. Eng.*, vol. 10, pp. 78–94, 2017.

[438] I. F. Akyildiz, M. Pierobon, S. Balasubramaniam, and Y. Koucheryavy, "The internet of bio-nano things," *IEEE Commun. Mag.*, vol. 53, no. 3, pp. 32–40, Mar. 2015.

[439] X. Lyu, H. Tian, P. Zhang, and C. Sengul, "Multiuser joint task offloading and resource optimization in proximate clouds," *IEEE Trans. Veh. Technol.*, vol. 66, no. 4, pp. 3435–3447, Apr. 2016.

[440] C. Wang, C. Liang, F. R. Yu, Q. Chen, and L. Tang, "Computation offloading and resource allocation in wireless cellular networks with mobile edge computing," *IEEE Trans. Wireless Commun.*, vol. 16, no. 8, pp. 4924–4938, Aug. 2017.

[441] Y. Mao, J. Zhang, S. H. Song, and K. B. Letaief, "Stochastic joint radio and computational resource management for multi-user mobile-edge computing systems," *IEEE Trans. Wireless Commun.*, vol. 16, no. 9, pp. 5994–6009, Sep. 2017.

[442] D. Zhai, R. Zhang, L. Cai, B. Li, and Y. Jiang, "Energy-efficient user scheduling and power allocation for NOMA-based wireless networks with massive IoT devices," *IEEE Internet Things J.*, vol. 5, no. 3, pp. 1857–1868, Jun. 2018.

[443] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for smart cities," *IEEE Internet Things J.*, vol. 1, no. 1, pp. 22–32, Feb. 2014.

[444] Y. Mehmood, F. Ahmad, I. Yaqoob, A. Adnane, M. Imran, and S. Guizani, "Internet-of-Things-based smart cities: Recent advances and challenges," *IEEE Commun. Mag.*, vol. 55, no. 9, pp. 16–24, Sep. 2017.

[445] I. Vilajosana, J. Llosa, B. Martinez, M. Domingo-Prieto, A. Angles, and X. Vilajosana, "Bootstrapping smart cities through a self-sustainable model based on big data flows," *IEEE Commun. Mag.*, vol. 51, no. 6, pp. 128–134, Jun. 2013.

[446] C. L. Holloway, E. F. Kuester, J. A. Gordon, J. O'Hara, J. Booth, and D. R. Smith, "An Overview of the theory and applications of metasurfaces: The two-dimensional equivalents of metamaterials," *IEEE Antenn. Propag. Mag.*, vol. 54, no. 4, pp. 10–35, Jul. 2012.

[447] N. Kaina, M. Dupré, G. Lerosey, and M. Fink, "Shaping complex microwave fields in reverberating media with binary tunable metasurfaces," *Sci. Rep.*, vol. 4, no. 1, pp. 1–8, Dec. 2014.

[448] Y.-C. Liang, R. Long, Q. Zhang, J. Chen, H. V. Cheng, and H. Guo, "Large intelligent surface/antennas (LISA): Making reflective radios smart," *J. Commun. Inf. Netw.*, vol. 4, no. 2, pp. 40–50, Jun. 2019.

[449] E. Björnson and L. Sanguinetti, "Rayleigh fading modeling and channel hardening for reconfigurable intelligent surfaces," 2020, *arXiv:2009.04723*.

[450] *National Institute on Aging, National Institutes of Health, US Department of Health and Human Services (2011) Global Health and Aging*, World Health Organization, Geneva, Switzerland, 2017.

[451] T. Shah, A. Yavari, K. Mitra, S. Saguna, P. P. Jayaraman, F. Rabhi, and R. Ranjan, "Remote health care cyber-physical system: Quality of service (QoS) challenges and opportunities," *IET Cyber-Phys. Syst.: Theory Appl.*, vol. 1, no. 1, pp. 40–48, 2016.

[452] S. Hausman and Ł. Januszkiewicz, "Impact of indoor environment on path loss in body area networks," *Sensors*, vol. 14, no. 10, pp. 19551–19560, Oct. 2014.

[453] D. Kurup, W. Joseph, G. Vermeeren, and L. Martens, "In-body path loss model for homogeneous human tissues," *IEEE Trans. Electromagn. Compat.*, vol. 54, no. 3, pp. 556–564, Jun. 2012.

[454] C. Krittanawong, A. J. Rogers, K. W. Johnson, Z. Wang, M. P. Turakhia, J. L. Halperin, and S. M. Narayan, "Integration of novel monitoring devices with machine learning technology for scalable cardiovascular management," *Nature Rev. Cardiol.*, vol. 18, pp. 75–91, Oct. 2020.

[455] A.-M. Rahmani, N. K. Thanigaivelan, T. Nguyen Gia, J. Granados, B. Negash, P. Liljeberg, and H. Tenhunen, "Smart e-health gateway: Bringing intelligence to Internet-of-Things based ubiquitous healthcare systems," in *Proc. 12th Annu. IEEE Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2015, pp. 826–834.

[456] Y. A. Qadri, A. Nauman, Y. B. Zikria, A. V. Vasilakos, and S. W. Kim, "The future of healthcare Internet of Things: A survey of emerging technologies," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 2, pp. 1121–1167, 2nd Quart., 2020.

[457] I. F. Akyildiz and J. M. Jornet, "The internet of nano-things," *IEEE Wireless Commun.*, vol. 17, no. 6, pp. 58–63, Dec. 2010.

[458] O. B. Akan, H. Ramezani, T. Khan, N. A. Abbasi, and M. Kuscu, "Fundamentals of molecular information and communication science," *Proc. IEEE*, vol. 105, no. 2, pp. 306–318, Feb. 2017.

[459] N. Farsad, H. B. Yilmaz, A. Eckford, C.-B. Chae, and W. Guo, "A comprehensive survey of recent advancements in molecular communication," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1887–1919, 3rd Quart., 2016.

[460] J. Liu, Y. Xiao, S. Li, W. Liang, and C. L. P. Chen, "Cyber security and privacy issues in smart grids," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 4, pp. 981–997, 4th Quart., 2012.

[461] F. Dalipi and S. Y. Yayilgan, "Security and privacy considerations for IoT application on smart grids: Survey and research challenges," in *Proc. IEEE 4th Int. Conf. Future Internet Things Cloud Workshops (FiCloudW)*, Aug. 2016, pp. 63–68.

[462] N. Komninos, E. Philippou, and A. Pitsillides, "Survey in smart grid and smart home security: Issues, challenges and countermeasures," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 1933–1954, 4th Quart., 2014.

[463] N. Cheng, F. Lyu, J. Chen, W. Xu, H. Zhou, S. Zhang, and X. Shen, "Big data driven vehicular networks," *IEEE Netw.*, vol. 32, no. 6, pp. 160–167, Nov./Dec. 2018.

[464] H. Zhou, W. Xu, J. Chen, and W. Wang, "Evolutionary V2X technologies toward the internet of vehicles: Challenges and opportunities," *Proc. IEEE*, vol. 108, no. 2, pp. 308–323, Feb. 2020.

[465] S. Al-Sultan, M. M. Al-Doori, A. H. Al-Bayatti, and H. Zedan, "A comprehensive survey on vehicular ad hoc network," *J. Netw. Comput. Appl.*, vol. 37, pp. 380–392, Jan. 2014.

[466] N. Lu, N. Cheng, N. Zhang, X. Shen, and J. W. Mark, "Connected vehicles: Solutions and challenges," *IEEE Internet Things J.*, vol. 1, no. 4, pp. 289–299, Aug. 2014.

[467] M.-A. E. Computing, *Study on MEC Support for V2X Use Cases*, Standard 022 v2.1.1, vol. 22, 2018, p. V2.

[468] H. Yang, K. Zheng, K. Zhang, J. Mei, and Y. Qian, "Ultra-reliable and low-latency communications for connected vehicles: Challenges and solutions," *IEEE Netw.*, vol. 34, no. 3, pp. 92–100, May 2020.

[469] L. D. Xu, E. L. Xu, and L. Li, "Industry 4.0: State of the art and future trends," *Int. J. Prod. Res.*, vol. 56, no. 8, pp. 2941–2962, 2018.

[470] H. Lasi, P. Fettke, H. G. Kemper, T. Feld, and M. Hoffmann, "Industry 4.0," *Bus. Inf. Syst. Eng.*, vol. 6, no. 4, pp. 239–242, 2014.

[471] L. Thames and D. Schaefer, "Software-defined cloud manufacturing for industry 4.0," *Proc. CIRP*, vol. 52, pp. 12–17, Jan. 2016.

[472] K. Schwab, *The Fourth Industrial Revolution*. Cham, Switzerland: World Economic Forum, 2017.

[473] L. D. Xu, "The contribution of systems science to industry 4.0," *Syst. Res. Behav. Sci.*, vol. 37, no. 4, pp. 618–631, Jul. 2020.

[474] B. Galloway and G. P. Hancke, "Introduction to industrial control networks," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 2, pp. 860–880, 2nd Quart., 2013.

[475] G. Berardinelli, N. H. Mahmood, I. Rodriguez, and P. Mogensen, "Beyond 5G wireless IRT for industry 4.0: Design principles and spectrum aspects," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2018, pp. 1–6.

[476] E. Peltonen, M. Bennis, M. Capobianco, M. Debbah, A. Ding, F. Gil-Castiñeira, M. Jurmu, T. Karvonen, M. Kelanti, A. Kliks, T. Leppänen, L. Lovén, T. Mikkonen, A. Rao, S. Samarakoon, K. Seppänen, P. Sroka, S. Tarkoma, and T. Yang, "6G white paper on edge intelligence," 2020, *arXiv:2004.14850*.

[477] N. H. Mahmood, H. Alves, O. A. Lopez, M. Shehab, D. P. M. Osorio, and M. Latva-Aho, "Six key features of machine type communication in 6G," in *Proc. 2nd 6G Wireless Summit (6G SUMMIT)*, Mar. 2020, pp. 1–5.

[478] L. D. Xu, "Industrial information integration—An emerging subject in industrialization and informatization process," *J. Ind. Inf. Integr.*, vol. 17, 2020, Art. no. 100128. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2452414X20300042, doi: 10.1016/j.jii.2020.100128.

[479] S. Wolfert, L. Ge, C. Verdouw, and M. J. Bogaardt, "Big data in smart farming–a review," *Agricult. Syst.*, vol. 153, pp. 69–80, May 2017.

[480] V. Saiz-Rubio and F. Rovira-Más, "From smart farming towards agriculture 5.0: A review on crop data management," *Agronomy*, vol. 10, no. 2, p. 207, Feb. 2020.

[481] R. Zaier, S. Zekri, H. Jayasuriya, A. Teirab, N. Hamza, and H. Al-Busaidi, "Design and implementation of smart irrigation system for groundwater use at farm scale," in *Proc. 7th Int. Conf. Modeling, Identificat. Control (ICMIC)*, Dec. 2015, pp. 1–6.

[482] A. Giri, S. Dutta, and S. Neogy, "Enabling agricultural automation to optimize utilization of water, fertilizer and insecticides by implementing Internet of Things (IoT)," in *Proc. Int. Conf. Inf. Technol. (InCITe)-Next Gener. IT Summit Theme-Internet Things: Connect your Worlds*, Oct. 2016, pp. 125–131.

[483] D. García-Lesta, D. Cabello, E. Ferro, P. López, and V. M. Brea, "Wireless sensor network with perpetual motes for terrestrial snail activity monitoring," *IEEE Sensors J.*, vol. 17, no. 15, pp. 5008–5015, Aug. 2017.

[484] O. Chieochan, A. Saokaew, and E. Boonchieng, "IOT for smart farm: A case study of the Lingzhi mushroom farm at Maejo university," in *Proc. 14th Int. Joint Conf. Comput. Sci. Softw. Eng. (JCSSE)*, Jul. 2017, pp. 1–6.

[485] F. Viani, M. Bertolli, M. Salucci, and A. Polo, "Low-cost wireless monitoring and decision support for water saving in agriculture," *IEEE Sensors J.*, vol. 17, no. 13, pp. 4299–4309, Jul. 2017.

[486] S. Zhang, X. Chen, and S. Wang, "Research on the monitoring system of wheat diseases, pests and weeds based on IOT," in *Proc. 9th Int. Conf. Comput. Sci. Educ.*, Aug. 2014, pp. 981–985.

[487] H. Lee, A. Moon, K. Moon, and Y. Lee, "Disease and pest prediction IoT system in orchard: A preliminary study," in *Proc. 9th Int. Conf. Ubiquitous Future Netw. (ICUFN)*, Jul. 2017, pp. 525–527.

[488] O. Elijah, T. A. Rahman, I. Orikumhi, C. Y. Leow, and M. N. Hindia, "An overview of Internet of Things (IoT) and data analytics in agriculture: Benefits and challenges," *IEEE Internet Things J.*, vol. 5, no. 5, pp. 3758–3773, Oct. 2018.

[489] V. Puri, A. Nayyar, and L. Raja, "Agriculture drones: A modern breakthrough in precision agriculture," *J. Statist. Manage. Syst.*, vol. 20, no. 4, pp. 507–518, 2017.

[490] P. Tripicchio, M. Satler, G. Dabisias, E. Ruffaldi, and C. A. Avizzano, "Towards smart farming and sustainable agriculture with drones," in *Proc. Int. Conf. Intell. Environments*, Jul. 2015, pp. 140–143.

[491] M. R. Alam, M. B. I. Reaz, and M. A. M. Ali, "A review of smart homes—Past, present, and future," *IEEE Trans. Syst., Man, Cybern., C (Appl. Rev.)*, vol. 42, no. 6, pp. 1190–1203, Nov. 2012.

[492] N. Zhu, T. Diethe, M. Camplani, L. Tao, A. Burrows, N. Twomey, D. Kaleshi, M. Mirmehdi, P. Flach, and I. Craddock, "Bridging e-health and the Internet of Things: The SPHERE project," *IEEE Intell. Syst.*, vol. 30, no. 4, pp. 39–46, Jul./Aug. 2015.

[493] E. Ahmed, I. Yaqoob, A. Gani, M. Imran, and M. Guizani, "Internet-of-Things-based smart environments: State of the art, taxonomy, and open research challenges," *IEEE Wireless Commun.*, vol. 23, no. 5, pp. 10–16, Oct. 2016.

[494] S. S. I. Samuel, "A review of connectivity challenges in IoT-smart home," in *Proc. 3rd MEC Int. Conf. Big Data Smart City (ICBDSC)*, Mar. 2016, pp. 1–4.

[495] D. Pishva and K. Takeda, "Product-based security model for smart home appliances," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 23, no. 10, pp. 32–41, Oct. 2008.

[496] D. Pishva and K. Takeda, "A product based security model for smart home appliances," in *Proc. 40th Annu. Int. Carnahan Conf. Secur. Technol.*, Oct. 2006, pp. 221–222.

[497] Y. Mao, C. You, J. Zhang, K. Huang, and K. B. Letaief, "A survey on mobile edge computing: The communication perspective," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2322–2358, 4th Quart., 2017.

[498] X. Huang, R. Yu, J. Kang, Y. He, and Y. Zhang, "Exploring mobile edge computing for 5G-enabled software defined vehicular networks," *IEEE Wireless Commun.*, vol. 24, no. 6, pp. 55–63, Dec. 2017.

[499] N. Hassan, S. Gillani, E. Ahmed, I. Ibrar, and M. Imran, "The role of edge computing in Internet of Things," *IEEE Commun. Mag.*, vol. 56, no. 11, pp. 110–115, Nov. 2018.

[500] M. Chiang and T. Zhang, "Fog and IoT: An overview of research opportunities," *IEEE Internet Things J.*, vol. 3, no. 6, pp. 854–864, Dec. 2016.

[501] S. Yi, C. Li, and Q. Li, "A survey of fog computing: Concepts, applications and issues," in *Proc. Workshop Mobile Big Data*, 2015, pp. 37–42.

[502] R. Mijumbi, J. Serrat, J.-L. Gorricho, N. Bouten, F. De Turck, and R. Boutaba, "Network function virtualization: State-of-the-art and research challenges," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 1, pp. 236–262, 1st Quart., 2016.

[503] D. Kreutz, F. Ramos, P. E. Veríssimo, C. E. Rothenberg, S. Azodolmolky, and S. Uhlig, "Software-defined networking: A comprehensive survey," *Proc. IEEE*, vol. 103, no. 1, pp. 14–76, Jan. 2015.

[504] Y. C. Hu, M. Patel, D. Sabella, N. Sprecher, and V. Young, "Mobile edge computing–A key technology towards 5G," *ETSI White Paper*, vol. 11, pp. 1–16, 2015.

[505] T. Mahmoodi and S. Seetharaman, "On using a sdn-based control plane in 5G mobile networks," in *Proc. 32nd Meeting Wireless World Res. Forum*, 2014, pp. 1–6.

[506] C.-Y. Chang, K. Alexandris, N. Nikaein, K. Katsalis, and T. Spyropoulos, "MEC architectural implications for LTE/LTE–A networks," in *Proc. Workshop Mobility Evolving Internet Archit.*, Oct. 2016, pp. 13–18.

[507] S. D. A. Shah, M. A. Gregory, S. Li, and R. D. R. Fontes, "SDN enhanced multi-access edge computing (MEC) for E2E mobility and QoS management," *IEEE Access*, vol. 8, pp. 77459–77469, 2020.

[508] I. M. Ali and M. I. Salman, "SDN-assisted service placement for the IoT-based systems in multiple edge servers environment," *Iraqi J. Sci.*, pp. 1525–1540, Jun. 2020.

[509] J. Park, S. Samarakoon, M. Bennis, and M. Debbah, "Wireless network intelligence at the edge," *Proc. IEEE*, vol. 107, no. 11, pp. 2204–2239, Nov. 2019.

[510] B. Yang, X. Cao, K. Xiong, C. Yuen, Y. Liang Guan, S. Leng, L. Qian, and Z. Han, "Edge intelligence for autonomous driving in 6G wireless system: Design challenges and solutions," 2020, *arXiv:2012.06992*.

[511] Y. Qian, L. Shi, J. Li, Z. Wang, H. Guan, F. Shu, and H. V. Poor, "A workflow-aided Internet of Things paradigm with intelligent edge computing," *IEEE Netw.*, vol. 34, no. 6, pp. 92–99, Nov. 2020.

[512] F. Fang, Y. Xu, Z. Ding, C. Shen, M. Peng, and G. K. Karagiannidis, "Optimal resource allocation for delay minimization in NOMA-MEC networks," *IEEE Trans. Commun.*, vol. 68, no. 12, pp. 7867–7881, Dec. 2020.

[513] S. Bi, R. Zhang, Z. Ding, and S. Cui, "Wireless communications in the era of big data," *IEEE Commun. Mag.*, vol. 53, no. 10, pp. 190–199, Oct. 2015.

[514] W. Xu, H. Zhou, H. Wu, F. Lyu, N. Cheng, and X. Shen, "Intelligent link adaptation in 802.11 vehicular networks: Challenges and solutions," *IEEE Commun. Standards Mag.*, vol. 3, no. 1, pp. 12–18, Mar. 2019.

[515] M. Chen, U. Challita, W. Saad, C. Yin, and M. Debbah, "Artificial neural networks-based machine learning for wireless networks: A tutorial," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 4, pp. 3039–3071, 4th Quart., 2019.

[516] K. Sharma and X. Wang, "Toward massive machine type communications in ultra-dense cellular IoT networks: Current issues and machine learning-assisted solutions," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 1, pp. 426–471, 1st Quart., 2019.

[517] M. Elsayed and M. Erol-Kantarci, "AI-enabled future wireless networks: Challenges, opportunities, and open issues," *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 70–77, Sep. 2019.

[518] H. Gacanin, "Autonomous wireless systems with artificial intelligence: A knowledge management perspective," *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 51–59, Sep. 2019.

[519] O. Simeone, "A very brief introduction to machine learning with applications to communication systems," *IEEE Trans. Cogn. Commun. Netw.*, vol. 4, no. 4, pp. 648–664, Dec. 2018.

[520] M. A. Alsheikh, S. Lin, D. Niyato, and H. P. Tan, "Machine learning in wireless sensor networks: Algorithms, strategies, and applications," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 1996–2018, 4th Quart., 2014.

[521] N. Kato, Z. M. Fadlullah, B. Mao, F. Tang, O. Akashi, T. Inoue, and K. Mizutani, "The deep learning vision for heterogeneous network traffic control: Proposal, challenges, and future perspective," *IEEE Wireless Commun.*, vol. 24, no. 3, pp. 146–153, Jun. 2017.

[522] T. Park, N. Abuzainab, and W. Saad, "Learning how to communicate in the Internet of Things: Finite resources and heterogeneity," *IEEE Access*, vol. 4, pp. 7063–7073, 2016.

[523] N. C. Luong, D. T. Hoang, S. Gong, D. Niyato, P. Wang, Y.-C. Liang, and D. I. Kim, "Applications of deep reinforcement learning in communications and networking: A survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 4, pp. 3133–3174, 4th Quart., 2019.

[524] U. Challita, W. Saad, and C. Bettstetter, "Interference management for cellular-connected UAVs: A deep reinforcement learning approach," *IEEE Trans. Wireless Commun.*, vol. 18, no. 4, pp. 2125–2140, Apr. 2019.

[525] O. H. Salman, Z. Taha, M. Q. Alsabah, Y. S. Hussein, A. S. Mohammed, and M. Aal-Nouman, "A review on utilizing machine learning technology in the fields of electronic emergency triage and patient priority systems in telemedicine: Coherent taxonomy, motivations, open research challenges and recommendations for intelligent future work," *Comput. Methods Programs Biomed.*, vol. 209, Sep. 2021, Art. no. 106357.

[526] L. Mohjazi, A. Zoha, L. Bariah, S. Muhaidat, P. C. Sofotasios, M. A. Imran, and O. A. Dobre, "An outlook on the interplay of artificial intelligence and software-defined metasurfaces: An overview of opportunities and limitations," *IEEE Veh. Technol. Mag.*, vol. 15, no. 4, pp. 62–73, Dec. 2020.

[527] L. Li, H. Ruan, C. Liu, Y. Li, Y. Shuang, A. Alù, C.-W. Qiu, and T. J. Cui, "Machine-learning reprogrammable metasurface imager," *Nature Commu.*, vol. 10, no. 1, pp. 1–8, 2019.

[528] C. Liaskos, A. Tsioliaridou, S. Nie, A. Pitsillides, S. Ioannidis, and I. Akyildiz, "An interpretable neural network for configuring programmable wireless environments," in *Proc. IEEE 20th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Jul. 2019, pp. 1–5.

[529] A. Zappone, M. Di Renzo, M. Debbah, T. T. Lam, and X. Qian, "Model-aided wireless artificial intelligence: Embedding expert knowledge in deep neural networks for wireless system optimization," *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 60–69, Jul. 2019.

[530] S. H. Abdulhussain, B. M. Mahmmod, M. A. Naser, M. Q. Alsabah, R. Ali, and S. A. R. Al-Haddad, "A robust handwritten numeral recognition using hybrid orthogonal polynomials and moments," *Sensors*, vol. 21, no. 6, p. 1999, Mar. 2021. [Online]. Available: https://www.mdpi.com/1424-8220/21/6/1999

[531] B. M. Mahmmod, S. H. Abdulhussain, M. A. Naser, M. Alsabah, and J. Mustafina, "Speech enhancement algorithm based on a hybrid estimator," in *Proc. IOP Conf., Mater. Sci. Eng.*, 2021, vol. 1090, no. 1, Art. no. 012102.

[532] K. A. AL-Utaibi, S. H. Abdulhussain, B. M. Mahmmod, M. A. Naser, M. Alsabah, and S. M. Sait, "Reliable recurrence algorithm for high-order Krawtchouk polynomials," *Entropy*, vol. 23, no. 9, p. 1162, Sep. 2021. [Online]. Available: https://www.mdpi.com/1099-4300/23/9/1162

[533] T. O'Shea and J. Hoydis, "An introduction to deep learning for the physical layer," *IEEE Trans. Cogn. Commun. Netw.*, vol. 3, no. 4, pp. 563–575, Dec. 2017.

[534] Y.-S. Jeon, S.-N. Hong, and N. Lee, "Blind detection for MIMO systems with low-resolution ADCs using supervised learning," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2017, pp. 1–6.

[535] H. Sun, X. Chen, Q. Shi, M. Hong, X. Fu, and N. D. Sidiropoulos, "Learning to optimize: Training deep neural networks for wireless resource management," in *Proc. IEEE 18th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Jul. 2017, pp. 1–6.

[536] T. J. O'Shea, J. Corgan, and T. C. Clancy, "Unsupervised representation learning of structured radio communication signals," in *Proc. 1st Int. Workshop Sens., Process. Learn. Intell. Mach. (SPLINE)*, Jul. 2016, pp. 1–5.

[537] T. Gruber, S. Cammerer, J. Hoydis, and S. T. Brink, "On deep learning-based channel decoding," in *Proc. 51st Annu. Conf. Inf. Sci. Syst. (CISS)*, Mar. 2017, pp. 1–6.

[538] E. Nachmani, Y. Be'ery, and D. Burshtein, "Learning to decode linear codes using deep learning," in *Proc. 54th Annu. Allerton Conf. Commun., Control, Comput. (Allerton)*, Sep. 2016, pp. 341–346.

[539] Ö. T. Demir and E. Björnson, "Channel estimation in massive MIMO under hardware non-linearities: Bayesian methods versus deep learning," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 109–124, 2020.

[540] H. Ye, G. Y. Li, and B.-H. Juang, "Power of deep learning for channel estimation and signal detection in OFDM systems," *IEEE Wireless Commun. Lett.*, vol. 7, no. 1, pp. 114–117, Feb. 2018.

[541] T. J. O'Shea, J. Corgan, and T. C. Clancy, "Convolutional radio modulation recognition networks," in *Proc. Int. Conf. Eng. Appl. Neural Netw.* London, U.K.: Springer, 2016, pp. 213–226.

[542] A. Alkhateeb, S. Alex, P. Varkey, Y. Li, Q. Qu, and D. Tujkovic, "Deep learning coordinated beamforming for highly-mobile millimeter wave systems," *IEEE Access*, vol. 6, pp. 37328–37348, 2018.

[543] A. M. Elbir, "CNN-based precoder and combiner design in mmWave MIMO systems," *IEEE Commun. Lett.*, vol. 23, no. 7, pp. 1240–1243, Jul. 2019.

[544] H. Huang, Y. Song, J. Yang, G. Gui, and F. Adachi, "Deep-learning-based millimeter-wave massive MIMO for hybrid precoding," *IEEE Trans. Veh. Technol.*, vol. 68, no. 3, pp. 3027–3032, Mar. 2019.

[545] Y. Zhang, Y. Mu, Y. Liu, T. Zhang, and Y. Qian, "Deep learning-based beamspace channel estimation in mmWave massive MIMO systems," *IEEE Wireless Commun. Lett.*, vol. 9, no. 12, pp. 2212–2215, Dec. 2020.

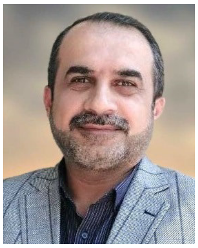
[546] A. Mousavi, G. Dasarathy, and R. G. Baraniuk, "DeepCodec: Adaptive sensing and recovery via deep convolutional neural networks," 2017, *arXiv:1707.03386*.

[547] A. Zappone, M. Di Renzo, and M. Debbah, "Wireless networks design in the era of deep learning: Model-based, AI-based, or both?" *IEEE Trans. Commun.*, vol. 67, no. 10, pp. 7331–7376, Oct. 2019.

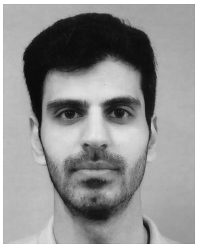
MUNTADHER ALSABAH received the B.S. degree in electrical engineering from the University of Baghdad, Iraq, in 2007, the M.S. degree in wireless communication engineering from Universiti Putra Malaysia (UPM), Malaysia, in 2014, and the Ph.D. degree in wireless communication from The University of Sheffield, Sheffield, U.K., in 2020. His current research interests include wireless communications, multiple-input-multiple-output (MIMO) systems, mmWave frequencies, image processing, signal processing, and in applying the artificial intelligence and machine learning techniques in wireless communications systems.

MARWAH ABDULRAZZAQ NASER received the B.Sc. degree in electronics and communication engineering from the University of Baghdad, Iraq, in 2008, and the M.Sc. degree in wireless communication systems from The University of Sheffield, U.K., in 2016. She is currently working as an Assistant Lecturer with the University of Baghdad. Her current research interests include wireless communication systems, signal processing, image processing, and mobile networks.

BASHEERA M. MAHMMOD received the B.S. degree in electrical engineering and the M.S. degree in electronics and communication engineering from the University of Baghdad, in 1998 and 2012, respectively, and the Ph.D. degree in computer and embedded system engineering from Universiti Putra Malaysia, in 2018. Since 2007, she has been a Staff Member with the Department of Computer Engineering, Faculty of Engineering, University of Baghdad. Her research interests include speech enhancement, signal processing, computer vision, RFID, and communication.



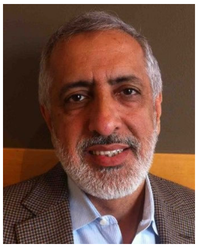
SADIQ H. ABDULHUSSAIN received the B.S. degree in electrical engineering and the M.S. degree in electronics and communication engineering from the University of Baghdad, in 1998 and 2001, respectively, and the Ph.D. degree in computer and embedded system engineering from Universiti Putra Malaysia, in 2018. Since 2005, he has been a Staff Member with the Department of Computer Engineering, Faculty of Engineering, University of Baghdad. His research interests include computer vision, signal processing, speech and image processing, and communication.



MOHAMMAD R. EISSA received the Ph.D. degree from The University of Sheffield, in 2018. After the Ph.D. degree, he was a Researcher with the Department of Electronic and Electrical Engineering, The University of Sheffield. His research interests include artificial intelligence and machine learning, particularly their application in various fields, such as healthcare, communications, and hardware. His current research interests include the use of artificial intelligence and machine learning on time series data and the IoT devices.

AHMED AL-BAIDHANI received the M.S. degree in communications systems engineering from the University of Portsmouth, U.K., in 2008, and the Ph.D. degree from The University of Sheffield, U.K., in 2019. His current research interests include SWIPT, energy-efficient communication, and resource allocations.

NOR K. NOORDIN (Member, IEEE) received the B.Sc. degree in electrical engineering with a major in telecommunication from The University of Alabama, Tuscaloosa, USA, the master's degree from Universiti Teknologi Malaysia, and the Ph.D. degree from Universiti Putra Malaysia (UPM). She has been with UPM, since 1988, and was appointed as an Associate Professor, in 2006, and a Full Professor, in 2012. During her tenure, she has been the Head of the Department, the Deputy Dean of academics, and the Director of Corporate Strategy and Communication of UPM, where she is currently the Dean of the Faculty of Engineering. She has secured more than 30 research and consultancy projects worth USD 10mil in the area of wireless and communication engineering and engineering education. For the past five years, she has started to collaborate with European partners in Erasmus and Erasmus+ and had secured four capacity building projects. During her more than 25 years with the university, she has published more than 300 journals and conference papers.



SADIQ M. SAIT was born in Bengaluru. He received the bachelor's degree in electronics engineering from Bengaluru University, in 1981, and the master's and Ph.D. degrees in electrical engineering from the King Fahd University of Petroleum & Minerals (KFUPM), in 1983 and 1987, respectively. He is currently a Professor of computer engineering and the Director of the Center for Communications and IT Research, Research Institute, KFUPM. He has authored over 300 research papers, contributed chapters to technical books, and lectured in over 25 countries. He is also the principle author of two books. He received the Best Electronic Engineer Award from the Indian Institute of Electrical Engineers, Bengaluru, in 1981.

KHALED A. AL-UTAIBI (Member, IEEE) was born in Riyadh, Saudi Arabia, in 1973. He received the B.S., M.S., and Ph.D. degrees in computer engineering from the King Fahd University of Petroleum and Engineering, Dhahran, Saudi Arabia, in 1997, 2002, and 2019, respectively. He worked as a Lecturer with the Department of Computer Engineering, King Fahd University of Petroleum and Minerals, from 2002 to 2004. In 2004, he joined the Department of Computer Engineering, University of Ha'il, Ha'il, Saudi Arabia, as a Lecturer, where he became an Assistant Professor, in 2020. His current research interests include image cryptography, optimization algorithms, machine learning, and artificial intelligence.

FAZIRUL HASHIM (Member, IEEE) received the B.Eng. degree from Universiti Putra Malaysia, in 2002, the M.Sc. degree from Universiti Sains Malaysia, in 2006, and the Ph.D. degree from The University of Sydney, Australia, in 2010. He is currently an Associate Professor with the Department of Computer and Communication Systems Engineering, Universiti Putra Malaysia. He also leads the Communication Network Laboratory, and is a member of the Wireless and Photonics Networks (WiPNET) Research Group. He has published more than 150 articles in reputable journals and conferences. His research interests include wireless communication networks include mobile networks, network and computer security, wireless sensor networks, software-defined networking, network function virtualization, blockchain, and vehicular communication.