IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

SPECIAL SECTION ON INNOVATIVE TRENDS IN 6G ECOSYSTEMS

Received 21 January 2023, accepted 14 February 2023, date of publication 21 April 2023, date of current version 26 April 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3269297

SURVEY

Innovative Trends in the 6G Era: A Comprehensive Survey of Architecture, Applications, Technologies, and Challenges

VU KHANH QUY[1], ABDELLAH CHEHRI[2], (Senior Member, IEEE), NGUYEN MINH QUY[1], NGUYEN DINH HAN[3], AND NGUYEN TIEN BAN[4]

[1]Hung Yen University of Technology and Education, Hung Yen 160000, Vietnam
[2]Royal Military College of Canada (RMC), Kingston, ON K7K 7B4, Canada
[3]Hanoi University of Science and Technology, Hanoi 100000, Vietnam
[4]Posts and Telecommunications Institute of Technology (PTIT), Hanoi 111000, Vietnam

Corresponding author: Abdellah Chehri (chehri@rmc.ca)

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC) under Grant RGPIN-2022-3256.

ABSTRACT While the fifth-generation mobile network is being commercialized worldwide, researchers have recently started looking towards the next generation, called the 6G network. Unlike 5G and previous generations of wireless technologies designed to improve network performance for greater bandwidth, lower latency, and greater reliability, 6G ecosystems are considered a platform conducive to innovations in computing, artificial intelligence, connectivity and sensors, virtualization, and more. It is designed to meet the requirements of higher global coverage, greater spectral efficiency, and a reduced carbon footprint, emphasizing sustainability, equity, trust, and security through unprecedented architectural evolutions and technology. 6G will be an integrated network system that includes a traditional terrestrial mobile network, space network, and underwater network to provide ubiquitous network access. Even if studies on the vision of the 6G network have already been published, there is still a significant amount of ground to cover. There is no decision made yet regarding anything, and nothing has been ruled out. The focus of this study is to identify a complete picture of changes in architectures, technologies, and challenges that will shape the 6G network. The research results will provide indications for further studies on 6G ecosystems.

INDEX TERMS 6G, architecture, 5G new radio, mobile network, artificial intelligence, technologies, challenges.

I. INTRODUCTION

The fifth generation (5G) deployment has begun in several countries, promising to take telecommunications networks to a new level. The 5G network brings with it a multitude of technological changes but also new uses. The 5G marks the beginning of a truly digital society with high performance that fully supports mobile features, quality of service, a considerable device number, and energy efficiency compared to previous network systems [1].

The associate editor coordinating the review of this manuscript and approving it for publication was Pavlos I. Lazaridis.

Observing the evolutionary history of mobile communications systems, we have found that each mobile network generation takes about a decade to go from the initial research stage to the commercial stage. Then, they had about ten years for commercial deployment. Finally, at the end of this decade, a new network generation is born again [2], [3].

At this time, 5G is beginning to enter the commercialization stage, so 2030 will be the time to deploy the next-generation network of 5G, also known as 6G. Therefore, this is a suitable time to kick off 6G studies.

The research around 6G communications networks is still in its early stages, with experts from both the business and academic sectors examining the vision, trends, and goals

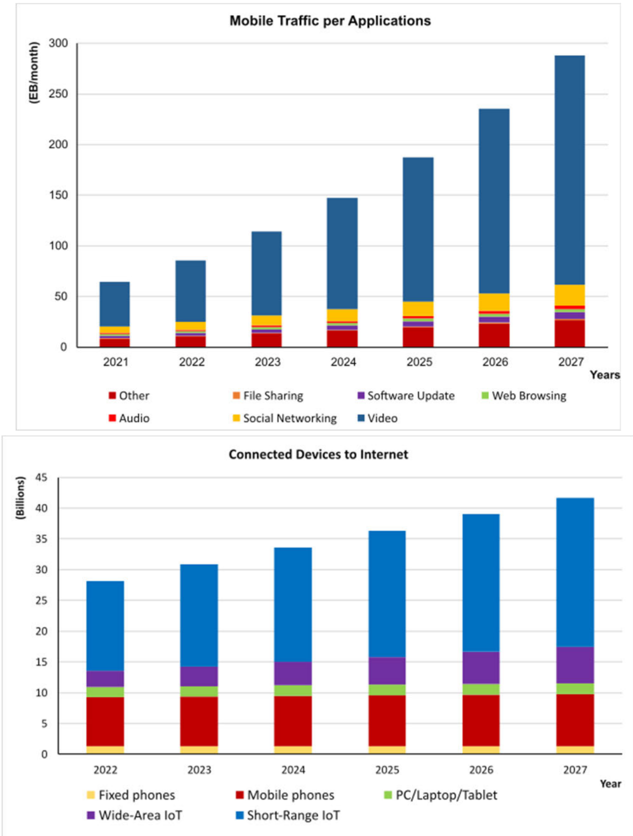

FIGURE 1. **Ericsson forecasts of the data traffic and connected devices to the internet.**

for this future technology. What speeds will be required? Will artificial intelligence be integrated into future networks? What frequencies will be employed? Everything remains on the table. 6G is a technology that has the potential to be ubiquitous to the limits of the imagination. To date, we are only probing the surface of all this. The objective of 6G is to realize its potential from 2030 in green and energy efficiency, digital inclusion, and the adaptability of sectors such as health and safety.

In recent years, several organizations have enacted strategies for developing 6G [4]. In 2018, Finland announced the 8-year six genesis flagship program to develop a complete 6G ecosystem [5]. The United Kingdom (UK) and German governments have researched technologies toward 6G, such as quantum communication. The US has begun exploring 6G mobile networks based on Terahertz communication technology. China also has focused on 6G technology research [6], [7].

Requirements for new services and the rapid increase of mobile devices are the driving forces behind the growth of mobile communication networks. In addition, the rapid development of new applications and services has led to the continued growth of mobile data traffic. According to Ericsson predictions, global mobile data would exceed five zettabytes by 2027 [8], as shown in Fig. 1.

In addition, applications such as healthcare [9], intelligent transport systems [10], smart agriculture [11], smart cities [12], and real-time entertainment applications [13] will require the lowest delay and high throughput, which even exceed the provided capacities of the 5G [14]. Therefore, the main goals for 6G [15] may be summarized as follows:

- High data rates (up to 1Tbps).
- High energy efficiency for limited-resource personal mobile devices.
- Universal coverage network (Space, Aerial, Ground, and Undersea).
- Intelligent and reliable connections across the entire network.

The 6G networks are becoming one of the most topical and exciting research topics in the mobile communication domain, attracting special attention from both academia and industry. Many related studies have been proposed for 6G networks on the roadmap to 6G, vision, architecture, breakout technologies and solutions, and applications. Wherein the roadmap to 6G is emphasized in studies [4], [20], [21], [22], [23], [24], the vision for 6G is in detail described in [14], [21], [23], [26], and [27], highlighting the main requirements of 6G.

The data rate, response time, bandwidth, and energy consumption rely on emerging technologies and solutions. The architecture of 6G is presented in detail in [14] and [29] towards integrating Space- Aeria-Ground Sea communication networks into a high-performance, seamless and reliable system. In order to achieve the requirements of 6G, emerging technologies are mentioned, including endogenous AI, Blockchain, intelligent surfaces, THz and VLC spectrums, etc.

These will become breakthrough technologies to realize 6G networks. Besides, the popularity of applications such as the internet of everything, metaverse, and autonomous vehicles are described in [2], [4], [15], [16], [17], [20], [21], [23], [24], [26], and [29].

Some challenges and technological trends in realizing these applications and main motivations towards 6G are presented in [4], [17], [18], [22], [24], and [29]. However, few studies have mentioned ongoing projects, research activities, architecture standardization, state-of-the-art technologies such as metaverse, digital twins, quantum communication, and its development abilities in the 6G context.

We summarize recent relevant survey studies in various aspects of 6G in **Table 1**. These results have highlighted that the existing works only discussed from several focus perspectives but need to show an overview development context of 6G.

In response, this work presents a complete picture of the evolution of 6G, focusing on many aspects, including development timeline, vision, architecture, state-of-the-art breakout technologies, projects, ongoing research activities, and challenges to realizing the 6G networks in the future.

In this article, we discuss the emerging ideas of technologies and architecture to shape the 6G. The rest of the paper is organized as follows. Section II presents the development history of mobile network generations. Section III presents

TABLE 1. Summary of related surveys on 6G.

Ref.	Research	Year	Roadmap to 6G	Vision/ Requirements	Proposed Architecture	Emerzing Technologies	Applications/Use Cases	Challenges & Future	Contributions
[16]	R. Alghamdi et al. (2020)	2020	L	L	M	M	H	M	Performance optimization based on Intelligent Surfaces
[17]	Y. Sun et al. (2020)	2020	L	M	M	M	H	H	Privacy in 6G based on machine learning
[18]	E. Yaacoub et al. (2020)	2020	L	M	M	H	M	H	6G technologies for providing connectivity to rural
[19]	C. Wang et al. (2020)	2020	L	L	M	H	M	M	6G channel measurements and models
[2]	W. Jiang et al. (2021)	2021	M	M	L	H	H	L	Road Towards 6G
[4]	P. Porambage et al. (2021)	2021	H	M	L	M	H	H	Security and Privacy in 6G
[14]	N. Dao et al. (2021)	2021	L	H	H	M	M	M	Aerial Radio Access Networks
[15]	B. Ji et al. (2021)	2021	L	M	L	H	H	M	Approach 6G to intelligence computing solutions
[20]	M. Alsabah et al. (2021)	2021	H	L	L	H	H	M	Wireless communications networks
[21]	F. Guo et al. (2021)	2021	H	H	M	L	H	M	Amount massive IoT devices enabled in 6G
[22]	V. Linh et al. (2021)	2021	H	M	L	H	M	H	Security and Privacy for 6G
[23]	D. Alwis et al. (2021)	2021	H	H	M	M	H	M	Trends, Applications, Requirements, Technologies
[24]	S. Aggarwal et al. (2021)	2021	H	L	L	M	H	H	Approaching 6G for Blockchain-based UAV communication security problem
[25]	B. Ji et al. (2021)	2021	L	L	L	H	M	M	Key Technologies for 6G
[26]	C. Nguyen et al. (2022)	2022	M	H	L	H	H	M	Internet of Things in 6G
[27]	G. Geraci et al. (2022)	2022	L	H	L	H	M	M	UAV Communication, mmWave, Massive MIMO, and cell-free
[28]	F. Tang et al. (2022)	2022	L	L	M	H	M	M	Combination digital twin and edge computing for 6G
[29]	X. Zhu et al. (2022)	2022	L	L	H	M	H	H	Integrated Satellite-Terrestrial Networks
	Our study	2022	H	H	H	H	H	H	Timeline, Vision, Architecture, Breakout Technologies, Challenges, and Future Research

Low Coverage   Medium Coverage   High Coverage

changes in the 6G architecture. Section IV provides a brief overview of emerging technologies to shape the 6G network. Section V is about challenges and future research, and Section VI is the Conclusion.

The structure of this work is presented in **Fig. 2**. For the convenience of following the article, we have compiled the acronyms in **Table 2**.

II. ROADMAP TO 6G

The development history of mobile communication systems began in the early 1980s. During their development process, mobile communication systems always toward connecting all systems. Terminals are increasingly compact, intelligent, and energy-saving and support all data types, such as voice, video, and real-time applications. As a result, the data rate is improved increasingly with decreased costs [30].

The history of mobile communication systems has also demonstrated that every decade, new generation networks are advent to solve the limitations of previous network generations, as shown in **Fig. 3**.

In the 1980s, the first mobile communication generation, known as 1G, was developed to provide phone services at data rates of up to 2.4 Kbps. However, 1G networks communicate via analogue signals and lack a common wireless foundation, resulting in a number of drawbacks, including limited data speeds and insecurity [31].

2G networks were established in the early 1990s using technology such as TDMA. 2G data rates can reach up to 64 kbps. As a result, 2G offers better voice and introduces new services, such as SMS. The GSM cellular communication protocol is used by 2G networks [32].

In the early 2000s, 3G networks were proposed to boost the data rate of 2G networks. As a result, 3G networks can achieve minimum data speeds of up to 2 Mbps. 3G is the first mobile generation to provide consumers with high-speed Internet access on their mobile devices. Furthermore, 3G networks enable the implementation of a variety of advanced

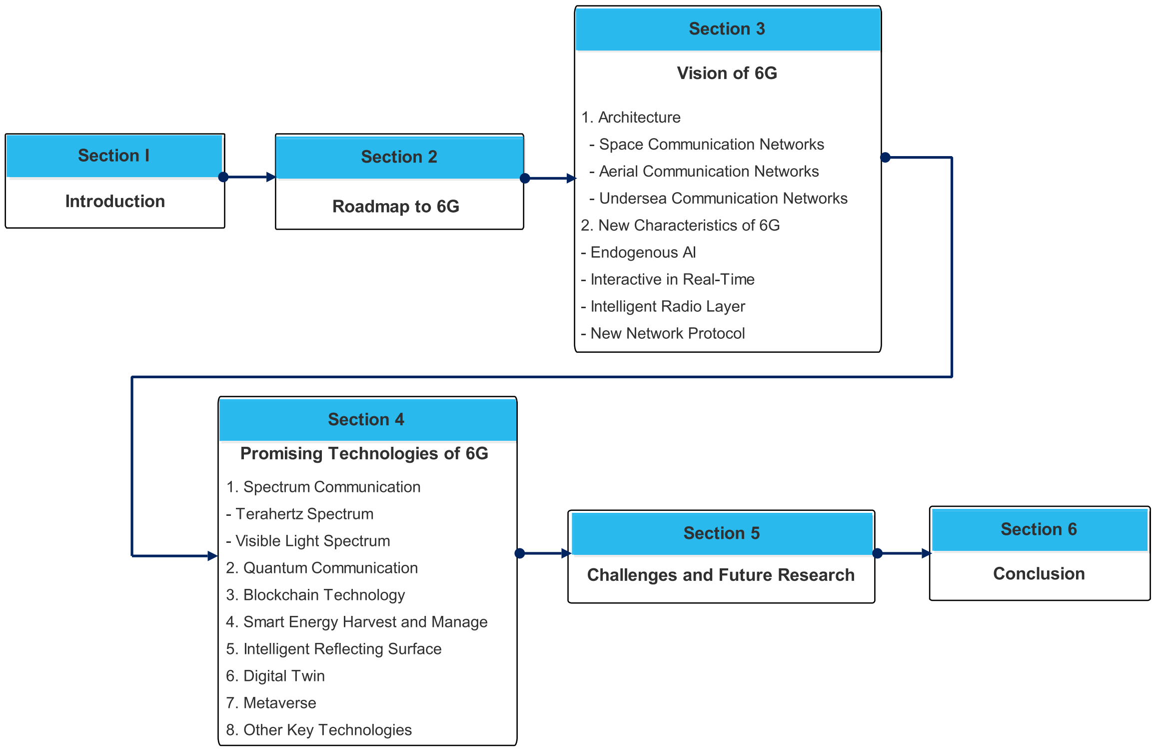

FIGURE 2. Structure of the paper.

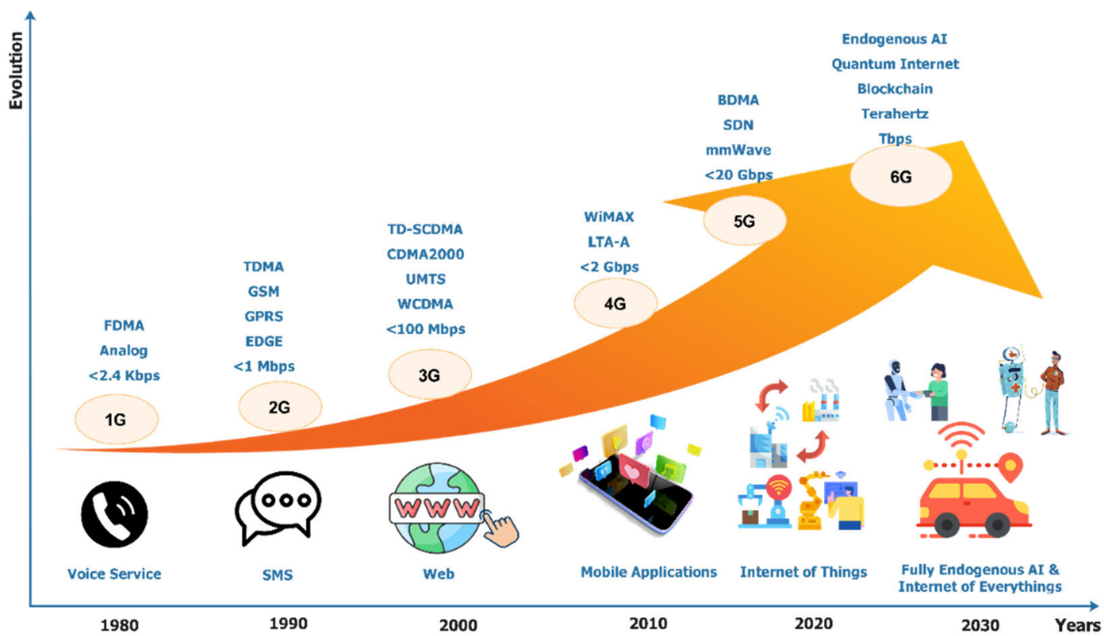

FIGURE 3. Evolution of mobile wireless generations.

services that 1G and 2G networks do not offer, such as video calls, interactive games, and real-time entertainment applications. The international standard organization (3GPP) was founded to define specific standards in order to achieve global roaming [33].

For the first time, a mobile communication generation based solely on the IP protocol, known as 4G, was introduced in the early 2010s. In the downlink, this generation can provide data speeds of up to 1Gpbs. In addition to previous generations' features, 4G has added broadband mobile

TABLE 2. Acronyms used in the survey and definitions.

Acronym	Definition	Acronym	Definition
5G	5th Generation Networks	LTE-A	LTE Advanced
5G NR	5G New Radio	MIMO	Multiple In, Multiple Out
6G	6th Generation Networks	ML	Machine Learning
AI	Artificial Intelligence	NFV	Network Function Virtualization
AR	Augmented Reality	NLOS	Non-Line-Of-Sight
BDMA	Big Data Management - Analytics	NOMA	Non-Orthogonal Multiple Access
CDMA	Code-Division Multiple Access	NGSO	Non-Geostationary Orbital
D2D	Device-to-Device	OWC	Optical Wireless Communication
EC	Edge Computing	QC	Quantum Communication
FC	Fog Computing	RF	Radio Frequency
FCC	Federal Communications Commission	SDN	Software-Defined Networks
GEO	Geostationary Orbit	SMS	Short Message Service
GSM	Global System for Mobile Communications	TDMA	Time Division Multiple Access
HAP	High Altitude Platforms	TD-SCDMA	Time Division-Synchronous Code Division Multiple Access
HTS	High-Throughput Satellite	THz	Terahertz
ICN	Information Center Network	UAVs	Unmanned Aerial Vehicles
IoT	Internet of Things	UMTS	Universal Mobile Telecommunications System
ITU	International Telecommunication Union	VLC	Visible Light Communication
LAP	Low Altitude Platforms	VLEO	Very Low Earth Orbits
LED	Light Emitting Diode	VR	Virtual Reality
LEO	Low Earth Orbit	WCDMA	Wideband Code Division Multiple Access
LIS	Large Intelligent Surface	XR	Extended Reality

internet access, video conferencing, high-definition Internet TV, 3D TV, and cloud computing capabilities. WiMAX and LTE have been chosen as standardization technologies for the 4G generation [34].

In the early 2020s, the fifth mobile communication generation was formed and commercialized. 5G is now standardized and commercially available in some countries [1].

As shown in Table 3, the purpose of 5G is to revolutionize data rates, quality of service, dependability, energy efficiency, and communication with a massive number of devices and to achieve the internet of things concept [3].

In order to reach these aims, novel breakout designs and technologies, including mm-wave [35], device-centric architecture [36], and massive MIMO [37], are introduced for the first time. Furthermore, developing solutions and technologies such as SDN [38], D2D [39], and ICN [40] are incorporated to improve performance by reducing superfluous network traffic, saving energy, and increasing data rates.

III. VISION OF 6G

As 5G networks enter the commercial deployment stage, academics and scientific organizations worldwide have begun to look ahead to 6G, which is scheduled to be deployed around 2030 [2]. The 6G networks are intended to reach extremely high data rates of up to 1 Tbps with ultra-low latency measured in microseconds. Furthermore, 6G combines spatial multiplexing techniques and THz frequency to deliver more than 1000 times the capacity of 5G [4], [5], [6].

Table 4 summarizes the key characteristics of 5G and 6G in terms of various network aspects. 6G networks merge space, underwater, and terrestrial networks to achieve ubiquitous and universal coverage [8]. New energy harvesting techniques and materials will be used in 6G to achieve high energy efficiency and a green 6G [41].

In [42], authors have described services of 6G based on network aspects, including providing global mobile connections, high data rates, low latency, and super high device density.

The 6G network is expected to achieve energy efficiency while providing global wireless connectivity. However, the current network architecture cannot ensure service quality for future applications that require ultra-high throughput, ultra-low latency, and great dependability. As a result, research into the next network architecture is required.

It is impossible to depict the detailed 6G architecture frame accurately. As a result, we approach the construction of 6G networks from many perspectives. As depicted in Fig. 4, this part introduces the modifications to the 6G network from three dimensions, including universal architecture, breakout technologies, and solutions.

TABLE 3. Primary goals of 5G network.

Criteria	Target
Mobile user data rates	1 (Gbps)
Fixed user data rates	1-10 (Gbps)
Lower transmission latency	1 (ms)
Reliability	99.999%
Energy Consumption	90% drop in energy use (per unit of data transmitted) compared to 4G

TABLE 4. The key feature comparison of 5G and 6G.

Features	5G NR	6G
Peak Data Rates	20 Gbps	1 Tbps
Latency	1ms	Less than 1ms
Area Traffic Capacity	10Mbps/m2	1Gbps/m2
Frequency Bands	Sub 6GHz, mmWave (24-52.6 GHz)	Sub 6GHz mmWave band
		THz, VLC
Connection Density	1M devices/Km2	10M devices/Km2
Device Services	Reliable connectivity of devices	Real-Time Physical Interaction Scenarios.
Network Type	SDN, NFV, Slicing	SDN, NFV, Intelligent cloud, AI-based Slicing
		Machine Learning, Deep Learning
Technique Computing	Fog/Edge Computing, Cloud computing	Quantum Computing, Fog/Edge Computing
Mobility	Up to 500 Kmph	Up to 700 Kmph
Technology	D2D communication, Ultra-dense Network, Relaying, Small Cell Access, NOMA	VLC and Quantum Communications, Endogenous AI, Blockchain, Smart Resource Allocation.
Applications	AR, VR, IoT, Smart Cities, Smart Home, Internet of Things	Augmented Reality, Telerobotic, Teledriving, AR/VR/XR, Tele-Education, Internet of Everything

A. ARCHITECTURE

A primary purpose of a 6G network is to provide global coverage. The current network architecture is based on the evolution and inheritance of terrestrial cell networks. This architecture, however, has the following two drawbacks:

(1) an inability to respond to communication scenarios that take place in the air or underwater, which is an unavoidable requirement for future services;

(2) the requirement of an excessively high cost to set up dense cell networks to provide worldwide communications. In order to solve the aforementioned drawbacks, the 6G design will be a completely integrated communication system that will include space, air, ground, and sea [43].

1) SPACE COMMUNICATION NETWORKS

In terms of cost and bandwidth, HTS systems can provide broadband Internet access similar to terrestrial offerings. However, most communication satellites reside in GEO at an altitude of around 35 km, resulting in excessive transmission latency and making integration with mobile terrestrial networks impossible.

To address this issue, NGSO satellite systems are being proposed to provide global Internet access with low transmission delays and high data rates. The following satellite systems are being commercialized:

- *Starlink Plan:* This plan is proposed by SpaceX company, USA, to provide global Internet service. Initially, this plan expected room 12.000 satellites, where 4.425 satellites operating in LEO and 7518 VLEO satellites operating in orbit about 340 km from the ground and will be fully deployed by 2027. This plan was authorized by FCC. Moreover, in May 2019, SpaceX launched firstly 60 Starlink communication satellites in low earth orbit. However, due to the project's feasibility, in October 2019, the United States FCC submitted filings to the ITU to arrange spectrums for 30.000 Starlink

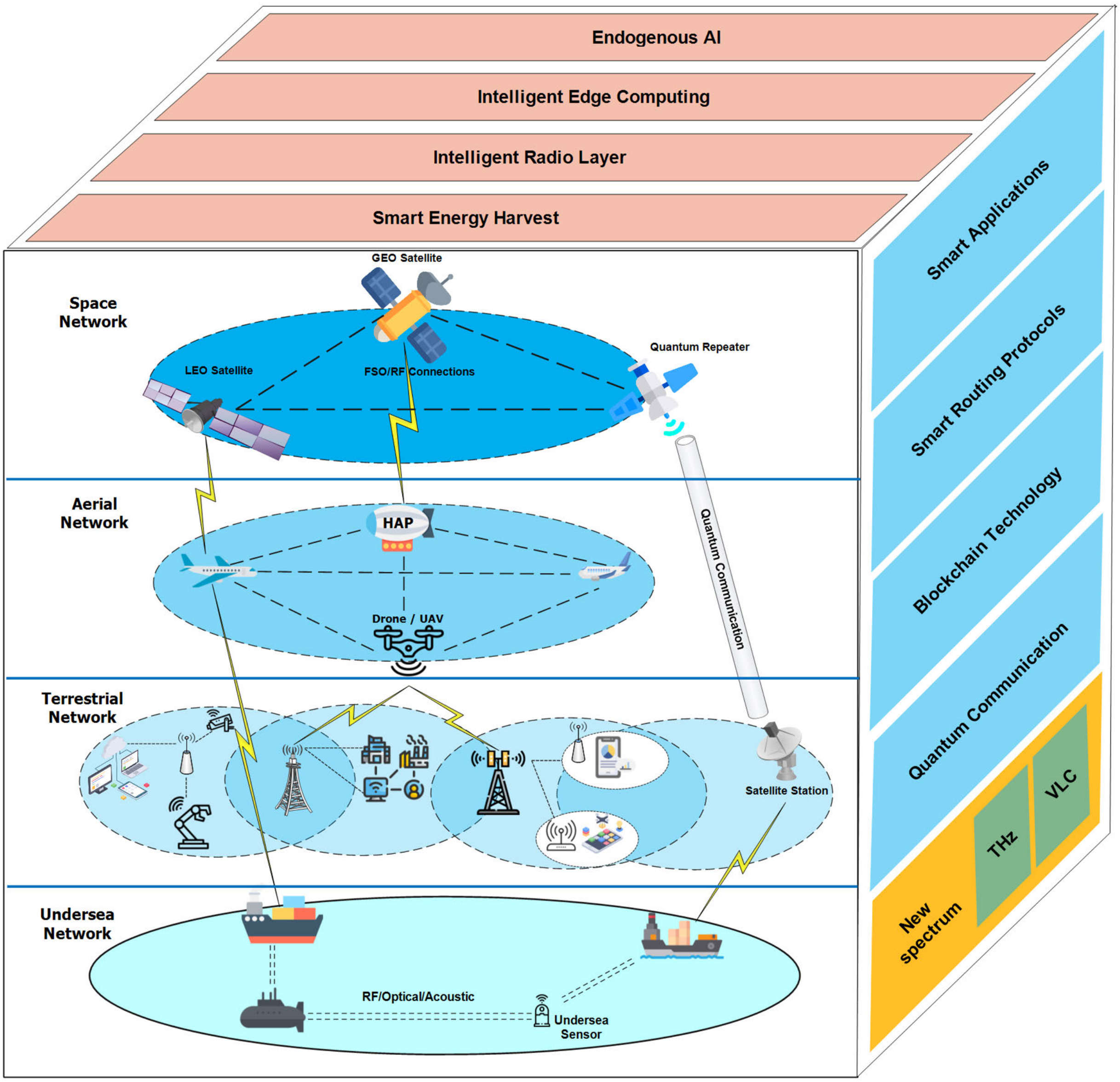

FIGURE 4. The vision on aspects of 6G architecture.

satellites instead of 12.000 Starlink satellites already approved by the FCC [83]. In October 2020, SpaceX started to provide a public beta service in the Northern United States.

- *OneWeb Plan:* This plan is proposed by WorldVu Satellites, UK, to provide internet services to everyone everywhere in the world [44]. OneWeb is expected to launch 650 low-earth orbit satellites. FCC and the United Kingdom authorized this plan. By December 2020, OneWeb had launched a total of 110 satellites successfully [44].
- *Hongyan Plan:* China Aerospace Science and Technology Corporation proposed to launch 320 satellites into low earth orbit to provide worldwide communication services. This plan is also called the Hongyan constellation. It is expected to be deployed fully by 2025 [45].

Although it still takes a long time for satellite systems to be fully deployed, the convergence of space, terrestrial, and LEO satellite networks have proven their outstanding advantages in theory, simulation, and experience.

The communication networks based on LEO satellites using laser and RF, the co-routing mechanism provides lower delay time compared to the terrestrial optical fiber network with a communication distance of over 3000 km [46].

2) AERIAL COMMUNICATION NETWORKS

Aerial communications networks can be classified into two categories based on the altitude operating. HAP satellites operate in the stratosphere, and LAP satellites operate at high altitudes a few kilometers from the ground. Compared to

TABLE 5. Feature comparison of underwater radio communication technologies.

	RF	Acoustic	Optical
Attenuation	High	Lowest	Turbidity
Data Rates	~Mbps	~Kbps	~Gbps
Latency	Moderate	High	Low
Transmission Distance	<10m	<100km	<100m
Energy Consumption	Moderate	High	Low

LAP, HAP communications have broad coverage and more stability. These advantages are similar to LEO systems.

On the other hand, LAP networks based on UAVs can be deployed quickly, configured flexibly, and have good short-range communication performance [47].

In addition, UAVs play a role as mobile base stations and act as relay nodes in multi-hop communication to promote the convergence of terrestrial networks and non-terrestrial networks. These characteristics make UAV-based networks an indispensable component of the future 6G networks.

In [48], a fully integrated multi-layered vertical architecture for 6G networks was discussed and analyzed, including ground networks, LAP-based UAVs, HAPs, LEOs, and satellite GEO networks.

One of the unique features of UAV-based wireless networks is the fast set-up ability of a mobile network without being based on pre-installed infrastructures.

It is suitable for disaster, emergency rescue, and battlefield scenarios [49]. Moreover, UAV networks are possible in the temporary deployment of communication services. Besides advantages, to improve performance and reliability, UAV networks face various challenges, such as saving energy, predicting trajectory, and load balancing [36].

Battery energy-based UAV operation with limited energy levels, so saving energy is critical. In [37], a deep learning-based offloading approach aims to reduce energy consumption and optimize system performance. In addition, the network structure frequently changes due to the high movement speed, leading to low performance, so the optimization and prediction of movement trajectory problems also need to be studied [52].

In [53], the authors designed a real-time video communication system based on UAVs and cellular networks.

3) UNDERSEA COMMUNICATION NETWORKS

Undersea communication may become part of the 6G network in the future, which is attracting significant attention from the scientific community [2], [6], [43]. Undersea radio links are mainly based on three leading communication technologies: optical, RF, and acoustic. A comparison between the wireless technologies underwater is summarized in **Table 5**.

The complex and unpredictable water environment leads to complicated communication deployments, such as serious attenuation signals and physical damage to network devices [54]. These are challenges that need to be addressed.

In [55], the authors propose an advanced dynamic coded cooperation schema to enhance the performance of acoustic-based underwater communication systems. Another challenge of underwater communication systems is the energy supply ability for network devices.

In [56], the authors propose an improved clustering algorithm to optimize energy efficiency for acoustic-based underwater cooperative sensor networks.

In [57], a new stress wave-based communication method is designed to enhance performance for undersea communication environments. Although a series of proposed technologies and solutions, underwater communication still needs to be improved. These issues should continue to be considered.

B. NEW CHARACTERISTICS OF 6G

The 6G design should be approached on multi aspects, such as integrating AI, real-time interactive, intelligent radio layer, and a new network protocol suite. The complex issues are presented as follows.

1) ENDOGENOUS AI

In recent years, AI technology, specifically machine learning (ML), has attracted studies from both academia and industry. However, in reality, AI has been employed in a series of 5G aspects [58], such as channel estimation in the physical layer [59], access control in the MAC layer [60], and resource allocation in the network layer [61].

A detailed survey of integrating AI into IoT and 5G is presented in [62]. Additionally, combining AI and cloud computing has improved the experience and reduced system costs [63]. However, the employment of AI in 5G is an option. The full potential of AI in the 5G era is difficult to realize. In the launch stage, the AI was not integrated into 5G architecture [64], [65].

Previous generation intelligent network systems were relatively isolated network entities. They can intelligently configure or set parameters based on pre-defined options [66], which truly implements perceptual AI [67]. However, these systems are incapable of responding to undesirable situations.

The 6G network will be an extremely complex and heterogeneous system with diversified service requirements and a massive number of connected devices. Therefore, a new AI model of self-awareness and self-adaptive is essential [68], [69].

6G networks require embedding AI on the entire network and AI logic into the network structure, where perception and inference interact systematically, ultimately allowing all system elements to self-config and adapt with the ability to recognize unexpected situations [7], [70].

2) INTERACTIVE IN REAL-TIME

The future network will require services and applications interactive in real-time. For example, intelligent transportation control systems where high-speed autonomous vehicles on the highway should interact with the environment, other cars, and humans in real time. Unfortunately, the existing solutions based on AI and Cloud will only focus on processing static data and un-guarantee real-time requirements.

Recent studies have shown AI solutions at edge networks, where intelligent predictions, inference, and decisions are performed, will be viable to reduce service response time and provide truly real-time services.

In [71], the authors propose a solution to real-time object detection based on edge computing and AI. In [72], the authors propose a real-time semantic segmentation solution based on edge computing and deep convolution neural networks for intelligent transportation applications.

A diversity survey of real-time transportation applications based on AI and edge computing is presented in [73]. Real-time interaction will be one of the urgent requirements of humans in the 6G era.

3) INTELLIGENT RADIO LAYER

In contrast to the physical layer employed with initial intelligence [74], the intelligent radio layer is a concept that aims to separate the hardware and the transceiver algorithms [75], [76]. It operates as a unified framework where predictable hardware abilities and transceiver algorithms are dynamically installed based on hardware configuration, the dynamic spectrum access, control, and monitor the transmission power based on AI [77]. A design model that adapts the diversity system platforms is introduced in [78] by separating the transceiver algorithms from the hardware.

4) NEW NETWORK PROTOCOL

The current Internet uses the TCP/IP protocol suite based on stack architecture for data delivery and communication. Its resounding success is demonstrated over the development history of the Internet. However, the current Internet faces challenges, such as Quality of Service (QoS), saving energy, privacy, and security for future applications. Recently, several protocols have been built to improve the existing TCP/IP suite, such as QUIC (Fast UDP Internet Connection).

A complete survey of the QUIC protocol suite under different network performance aspects is presented in [79].

Recently, several studies have improved the QUIC to enhance performance for 6G based on techniques, such as the multi-pipe technique [80], multi-flow and multi-path [81], and improved scheduling techniques [82]. However, these patches make the protocol suite more complex and cannot wholly overcome the inherent shortcomings of the TCP/IP suite for the current Internet [83], [84].

Also, this direction to meet future differentiated network applications and services, metadata, and defined commands by the application designers will be vital requests of the new IP protocol. A set of TCP/IP protocols with expected breakthroughs will need to be proposed.

To meet future network applications and services, defined metadata and commands by the application designers become a vital component of the new IP protocol. Therefore, a set of TCP/IP protocols with expected breakthroughs will need to be proposed.

In [85], the authors propose a novel MAC layer control protocol based on contention-free for the full-duplex split-plane optical wireless network architecture to provide a guaranteed channel access mechanism. The simulation results have shown that the proposed MAC protocol can serve multi-gigabit applications of 6G.

In [123], the authors propose a novel protocol stack model for 6G. Moreover, they have also improved the physical layer based on blockchain technology to optimize the spectrum allocation schema.

In [86], the authors propose a smart physical layer for 6G to efficiently radio resource allocation and QoS support for M-to-M communications.

Furthermore, the authors in [87] present a full-stack architecture to address the challenges of terabit communications in 6G. In this study, authors have introduced the detailed architectures of the MAC, network, and transport layers when using the terahertz spectrum.

Finally, performance and end-to-end data flows are considered in terahertz-based 6G scenarios.

IV. PROMISING EVOLUTION TECHNOLOGIES OF 6G

A. SPECTRUM COMMUNICATION

The spectrum is one of the key components forming mobile communication systems. Since the advent of cellular systems in the 1980s, we have constantly expanded spectrum resources due to the endless human need for data rates.

One of the main goals of 6G is to provide Tbps data rates. Consequently, 6G inevitably operates at higher frequencies. Some typical candidate spectrum, including Terahertz (THz) and visible light [83], [88], [89], are detailed and presented in the following subsections. **Fig. 5** illustrates the microwave, mmWave, and Terahertz frequency range structures.

1) TERAHERTZ SPECTRUM

The THz spectrum operates in the range (0.1-10) THz. It is a frequency spectrum band with many unique characteristics, has still unexploited. Some of the key features driving the research and exploitation of the THz band for 6G communication networks include [90]:

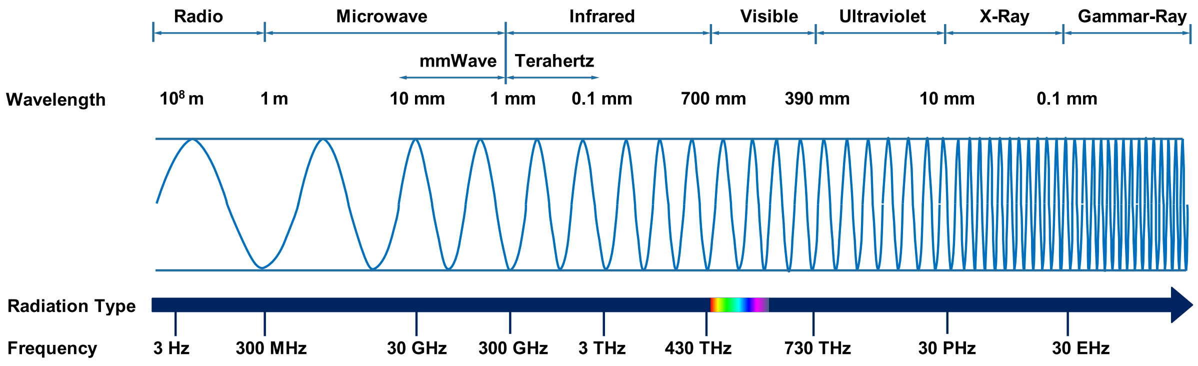

FIGURE 5. Microwave, mmWave, and Terahertz frequency range.

- The THz spectrum promises the provision of data rates up to 100 Gbps with multi-GHz available bandwidth.
- The THz spectrum provides more secure communications since the narrow beam and short pulse duration limit eavesdropping.
- The THz spectrum can pass through numerous low-loss dielectric, nonmetallic, and low-absorption materials such as paper, plastic, ceramic, clothes, and packaging materials. Terahertz radiation also scatters less than near-infrared and optical approaches due to its longer wavelength.

Thanks to these unique characteristics, the THz spectrum is a prime candidate for ultra-high-speed wireless and space communications. Nowadays, organizations are working to standardize this spectrum to promote the development of new communication technologies in the THz spectrum. In 2019, the FCC approved experiments of 95 GHz - 3 THz spectrum ranges and launched a new spectrum license with low barriers and minimal cost to drive the development of the THz spectrum [91]. IEEE has been employing the first steps toward the THz communication standard by forming the IEEE 802.15.x standard [92]. ITU defined spectrum in the range [0.12-0.2] THz for wireless networks [93].

However, one of the biggest challenges of Terahertz communications is the severe attenuation of signals by the environment.

Although there are still many challenges, THz-based communication systems have achieved some breakthroughs in recent years. In [94], the authors propose a new algorithm to control THz Beam for beam alignment in innovative vehicle communications. In [95], the authors have designed a chip-to-chip communication system based on THz for mobile personal devices.

In [96], the authors have proposed a comprehensive solution to optimize data rates for THz-based MIMO communication systems.

In [97], the authors have proposed a multi-dimensional multiplexing technique for THz-based Fiber communication systems. The experiment results have shown achieved data rates up to 1176 Gbps with a transmission distance of 10 m in the 350 GHz band.

In [98], the authors have proposed an improved performance and energy consumption solution to deploy THz-based UAV communication systems to support ground end-users.

In general, spectrum exploitation must synchronize development with hardware technologies. One of the most critical components of transceiver systems is the antenna. In [99], the authors comprehensively surveyed antenna selection and design for THz systems. This study has shown that there are still many challenges to designing antennas for THz communication systems, special in the frequency range (0.1-10) THz.

In our opinion, to promote THz-based communication technologies, the following aspects need to be further studied: (1) the Transistor and materials operating with super-high frequency, (2) the hardware circuits have low complexity and energy consumption, (3) novel channel and interference models, (4) the channel code and energy-saving modulation schemes. (5) Massive MIMO systems, and (6) powerful synchronization algorithms.

2) VISIBLE LIGHT SPECTRUM

Optical wireless communication (OWC) uses visible, infrared (IR), or ultraviolet (UV) light is used to carry a signal. Due to technological advancements and the wide adoption of LEDs, the most promising spectrum range of OWC is (430-790) THz. Moreover, one of the most highlighted aspects of LED lighting is that it can quickly switch to different light levels, allowing encoded data in the light to be transferred in various ways [100].

Visible light communication (VLC) takes full advantage of LEDs to achieve the dual purpose the light and high-speed data communication. VLC-suitable short-range communications (several meters) have many advantages over traditional radio methods [101]:

- The visible light spectrum offers extremely high bandwidth (THz) and unlicensed spectrum.
- Visible light cannot crossover light-blocking objects, so security is enhanced, reducing interference under RF high-frequency communication scenarios.

TABLE 6. Feature comparison of THz and VLC spectrum.

Feature	THz	VLC
Available Bandwidth	0.1 – 10 THz	Hundreds of THz
Transmission Method	NLOS	LOS
Electromagnetic Radiation	Yes	No
Data Rates	100 Gbps	10 Gbps
Spectrum Policy	Licensed	Unlicensed
Penetration Depth	0.1 – 0.3 mm	Transparent Materials
Interference	Serious	Limited
Cost	Expensive	Cheap
Transmission Power	High	Low

- VLC uses lighting sources as base stations without relying on fixed infrastructures.
- VLC does not make electromagnetic radiation and is immune to external electromagnetic interference.

Consequently, it is suitable for particularly sensitive scenarios to electromagnetic radiation, such as in hospitals [102] and on aircraft [103].

VLC's maximum achieved data rate depends on the lighting technology [104], [105]. For example, phosphorus-coated blue LED-based data rates are up to 1 Gbps, while RGB LED-based data rates can reach multi-Gbps.

The best-performance LED technology is micro-LED, which has achieved data rates of over 10 Gbps [106]. Nowadays, LED technologies are constantly improving on aspects of performance and lifetime. As a result, the data rates of VLC are expected to reach hundreds of Gbps, or even Tbps, in the 6G era [107], [108].

The surveyed results have shown that VLC provides very high available bandwidth, low deployment cost, limited interference, and unlicensed spectrum, but short transmission distance and uses line-of-sight transmission.

In contrast, the limitations of VLC are the advantages of THz. Although THz and VLC are being promoted in the 6G network, each spectrum band has unique characteristics.

Table 6 provides a detailed comparison of the THz and VLC communications.

3) QUANTUM COMMUNICATION (QC)

Quantum technology has the potential to provide a completely secure communication mechanism. The primary distinction between quantum communication (QC) and standard binary-based communication is that information is encoded in the quantum state using photons or quantum bits, known as qubits. These bits can hold both zeros and ones at the same time. As a result, it is capable of detecting attacks in real-time.

Quantum communication provides capacities that exceed the limitations of traditional communication solutions on aspects of security, privacy, computing, communication, and measurement capabilities. QC actualization the formation of the future Quantum Internet. A comprehensive survey of potential applications, technologies, and challenges of the Quantum Internet is presented in [109]. In reality, QC has achieved certain results as follows.

Although quantum communication technology is still in the early research stage. In [110], Li et al. designed a novel structure based on the cluster to describe how quantum nodes are interconnected and how the system can improve the performance of qubit transmission and reduce network complexity. Moreover, they also adopt the idea of the OSI model of the current Internet in the design of quantum Internet.

Finally, they build the detailed components of quantum nodes and end-to-end quantum communications experiment deployment. Moreover, quantum communication promises total security, integrity, and data availability, but new vulnerabilities that have yet to appear on the Internet should also be considered.

In [111], Satoh et al. analyzed attacks on quantum repeaters. The results have shown that the traditional networking elements may affect to overall security risks of the whole system.

In [112], Yu et al. argue that the future Internet will integrate traditional and quantum Internet. Therefore, novel protocols should be constructed based on the innovation of the existing protocol set. In this study, the authors propose a novel protocol set for packet quantum internet to handle the packet loss issue in communication.

One of the most interesting characteristics of quantum communication is long-range communication based on quantum repeaters. That allows forward data without physically sending an entangled qubit through the entire distance - by swapping the entanglement generated through shorter links, as illustrated in **Fig. 6**.

A recent study used a LEO satellite relay device to experiment with quantum communications across a distance of 7600 kilometers [113].

Clearly, there are many obstacles ahead for the quantum Internet to reach a robust infrastructure. However, the quantum Internet is an unavoidable Internet development trend to satisfy humanity's expanding needs.

Cacciapuoti et al. offer a comprehensive overview of the Quantum Internet's problems in [114].

4) BLOCKCHAIN TECHNOLOGY

Blockchain technology has recently been used in a variety of domains [115], [116]. Blockchains are distributed ledger databases that allow transactions to be securely registered and

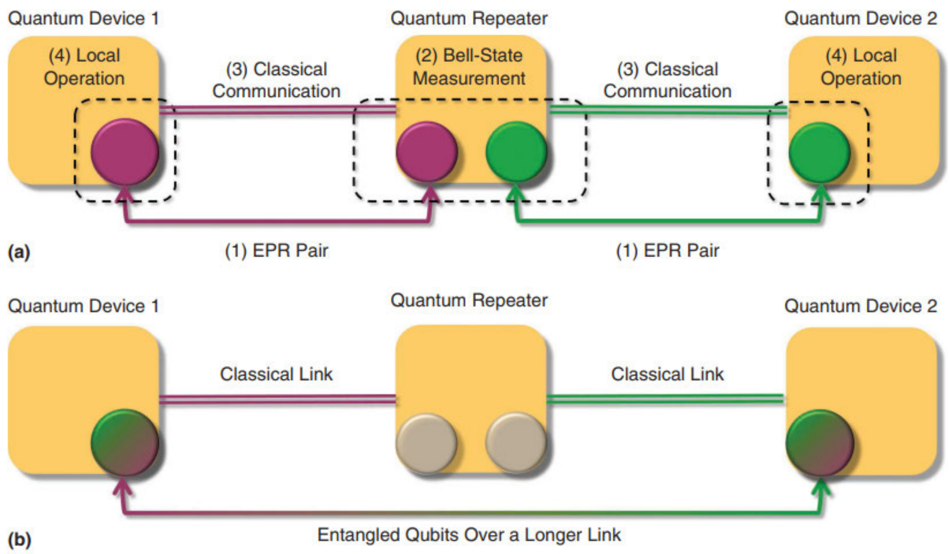

FIGURE 6. An Illustrate of long-range quantum communications based on quantum repeaters.

updated without the need for a central intermediary. Furthermore, blockchain's inherent qualities, such as decentralized tamper resistance and anonymity, make it appropriate for a wide range of applications [117]. As a result, blockchains ushered in a new economy [118], [119]. Figure 7 depicts a thorough representation of a blockchain-based information exchange mechanism.

Blockchain technology, in our opinion, will be the next revolution in future mobile communication technologies [120]. Because it allows diverse network entities to access data securely, blockchain ensures more substantial security characteristics during communication [121].

Aside from security, blockchain provides resource allocation and network access advantages. Blockchains offer a decentralized control system to establish direct links between entities, hence lowering associated expenses [122].

Instead of a centralized spectrum management schema, the authors of [123] suggest the Block6Tel schema, which incorporates blockchain into a spectrum allocation schema to increase spectrum efficiency for 6G.

The authors of [124] proposed a blockchain-based car reputation ranking system for the vehicle social internet. The parameters of a vehicle are obtained with the agreement of the providers. This prevents illegal entities from abusing the rating.

Furthermore, blockchain helps the integration of unique systems established by different operators by offering a common authentication and authorization method as well as a payment system, as well as allowing roaming between operators and networks [125], [126].

5) SMART ENERGY HARVEST AND MANAGE

The growing computing requirements of IoT devices are posing significant challenges to the energy efficiency of communication devices. Therefore, energy-saving communication technologies will shine in 6G as communication distances are shortened [8], [11], [127]. A series of research has been proposed in this domain in the past decade. Some of the achieved results can be summarised as follows.

In [128], energy harvesting technology is applied to optimal energy efficiency for smart grids. In [129], the energy harvesting techniques based on radio frequency are integrated into the modulation scheme for smart cities. In [130], the energy harvesting system from the solar, vibration, and radio-frequency energy sources to convert into dc voltage sources. Smart energy management is another promising mechanism for dynamically optimizing energy demand and supply [131].

6) INTELLIGENT REFLECTING SURFACE

The Intelligent Reflecting Surface (IRS) or Large Intelligent Surface (LIS) is a game-changing 6G technology. IRS was created to improve performance, data throughput, and energy efficiency by changing the transmission signal phase shift using a flat array of reflecting components.

Planar arrays consist of metallic or dielectric patches with minimal power, complexity, and cost. Furthermore, IRS technology enables a programmable space via the IRS controller, which may adjust the wireless propagation environment by using the unique properties of metamaterials-based large antenna arrays, a process known as intelligent control.

The combination of IRS technology and the THz spectrum expected will make breakout the communication abilities of 6G [75].

Recently, the IRS has attracted the interest of researchers and achieved some positive results. For example, in [77], Cao et al. proposed an AI-based MAC access architecture for IRS-assisted multi-user communications systems.

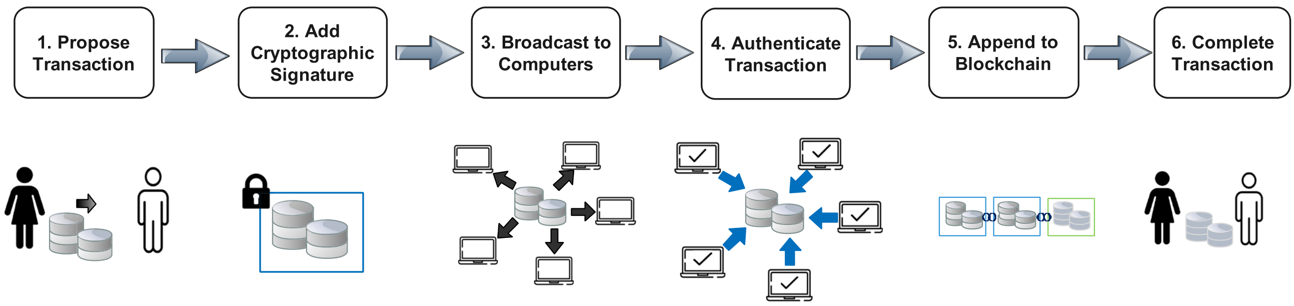

FIGURE 7. An Illustration of six steps of an information transaction process based on blockchain technology.

In [96], Ma et al. proposed a channel estimation schema based on a deep neural network for enhancing communication performance and data rate for THz-based 6G systems.

In [132], Yuan et al. proposed resource allocation algorithms to enhance uplink communication performance for IRS-based communications systems.

In our opinion, IRS will be one of the most critical technologies for THz communication that will be becoming popular in the 6G era, aiming to remove the limited coverage of the THz spectrum. This way, the cost to expand coverage of the THz spectrum will decrease robustly via reducing the number of base station devices in 6G while still achieving the same performance at a lower cost.

7) DIGITAL TWIN

Digital Twin (DT) is a comprehensive solution connecting the physical and digital spaces. It allows the construction of a virtual representation of physical objects. Digital twins are digital representations of a physical entity or product that serves as the indistinguishable digital counterpart of it for practical purposes, such as system simulation, integration, testing, monitoring, and maintenance. Thanks to the advancement of communication and computation technologies, DT consists of three deployment levels, monitoring, simulation, and operation [133], as described in **Table 7**.

- *Monitoring level:* DT is used to mirror or virtually represent a physical object. The physical object does not interact with its virtual model, and vice versa.
- *Simulation level:* DT is a simulator of a physical object. The physical objects can be understood, predicted, and optimized through simulation. The virtual model evolutes with the changes, but the physical object will not be affected by the changes in the virtual model.
- *Operation level:* the interactive of physical objects and their twins is bidirectional. Specifically, the state change of either object will be updated and reflected in both twin and physical objects.

Recently, DT technology has been applied in a series of areas across multiple other levels to monitor, control, and optimize physical objects. For example, in [133], Duong et al. proposed a digital twin-based offloading solution for aerial EC-assisted 6G UAV systems. In this work, they construct the digital twin models on both edge and IoT nodes and perform optimized these models based on related input metrics such as transmit power, offloading parameters, and capacities of edge and IoT nodes.

In [134], Sun et al. proposed a minimal delay offloading solution in 6G-MEC systems. In this work, they establish digital twins of edge nodes. Then, states of edge nodes and the entire MEC system are provided to train digital twins for offloading decisions.

In [135], Dai and Zhang proposed constructing digital twins of both vehicles and roadside units for the optimized management of EC-based vehicular systems. As a result, vehicular systems receive efficient and robust offloading schemas by optimizing digital models based on deep reinforcement learning.

The above studies have shown that, based on the optimization of twin models and reverse interaction with real systems and models, DT is emerging as a possible solution for optimizing systems, enhancing performance, and reducing service response times for latency-sensitive applications. In our opinion, DT is an efficient way to simulate, analyze, predict, and optimize physical systems, and that is expected to have many crucial contributions in the 6G era.

8) METAVERSE

The Metaverse concept was first advanced in 1992 in the science fiction book (Snow Crash) by Neil Stephenson. The term is a combination of the prefix "meta" (transcendent) and the suffix "verse" (universe). In this book, humans from the physical world enter and live in the Metaverse (a parallel virtual world) through a digital avatar based on virtual reality solutions [136].

Recently, the Metaverse is emerging as a potential technology and is recognized as a development model of the future Internet, where users can live like digital natives and experience a virtual world [137]. Thank breakout development of emerging technologies such as AR, AI, and blockchain, the Metaverse is stepping from science fiction to reality. Through many development stages, nowadays, Metaverse is considered a fully immersive, hyper-spatiotemporal, and self-sustaining for people to work, educate, and entertain with six main features, including Immersiveness, Hyper

TABLE 7. The three deployment levels of digital twin.

Deployment Level	Characteristics	Physical-to-Twin	Twin-to-Physical
Monitoring	Twin represents to a physical object	×	×
Simulation	Twin simulation to a physical object	✓	×
Operation	Interactive of physical objects and twins are bidirectional	✓	✓

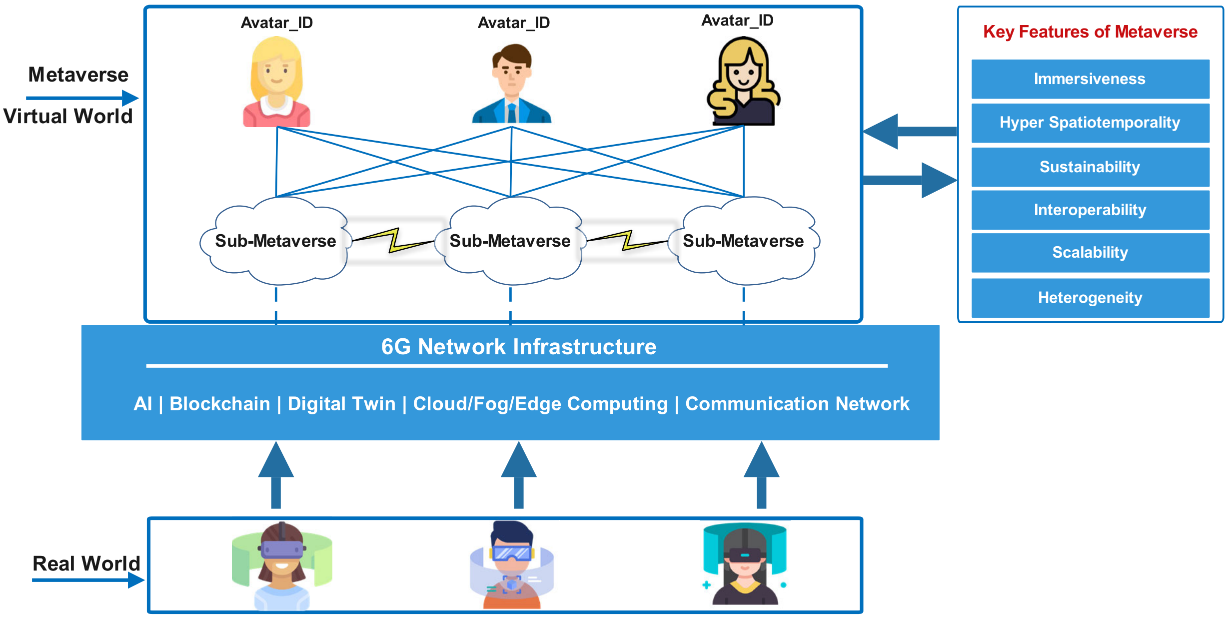

FIGURE 8. An illustration of metaverse architecture and key features.

Spatiotemporally, Sustainability, Interoperability, Scalability, and Heterogeneity, as presented in **Fig. 8**.

A comprehensive survey of applications, technologies, and challenges of the metaverse is presented in [138]. In recent, metaverse has achieved initial results.

In [139], Wang introduced a novel HANOI approach that relies on metaverse and emerging technologies such as digital twins, blockchain, and web 3.0. This allows travelers to perform a journey with the integration of Hanoi's humans, landscape, and nature.

In [140], Lim et al. introduced a virtual city based on the metaverse. Although achieved results, in our opinion, the metaverse is still in its primitive stage. It's a long way from realizing the vision of a seamless, real-time metaverse, given strict QoS requirements. Furthermore, the endogenous characteristics of the metaverse, such as immersiveness, hyper-spatiotemporality, and heterogeneity, make the privacy and security problems more complex and barrier to its widespread implementation.

In our opinion, although it is still at the primitive research stage and faces many challenges, the metaverse will be an inevitable development trend to form an interactive world between virtual and real for humans and is an exciting research topic for both academia and industry in the near future.

9) SYMBIOTIC RADIO NETWORKS (SRN)

SRN are approached based on the principle that "Global order can arise from local interactions" (A. Turing). In reality, SNR is a cognitive backscattering communication system that exploits the benefits and addresses the drawbacks of cognitive radio. Recently, the SRN concept is emerging as a potential technology for 6G. SRN is expected to play a crucial role in wireless networks of 6G to achieve: (1) enhanced spectrum efficiency using mutualism spectrum sharing; and (2) enhanced energy efficiency through highly reliable backscattering communications [141], [142].

10) CELL-FREE MASSIVE MIMO SYSTEMS

In 6G networks, to achieve QoS and data rate, transmitters will be densely distributed, forming massive MIMO systems. Integrating massive connective and high spectral efficiency led to interference management problems. To address this problem, cell-free networks have been proposed.

Cell-free systems can effectively remove inter-cell interference by enabling multiple base stations to cooperate with

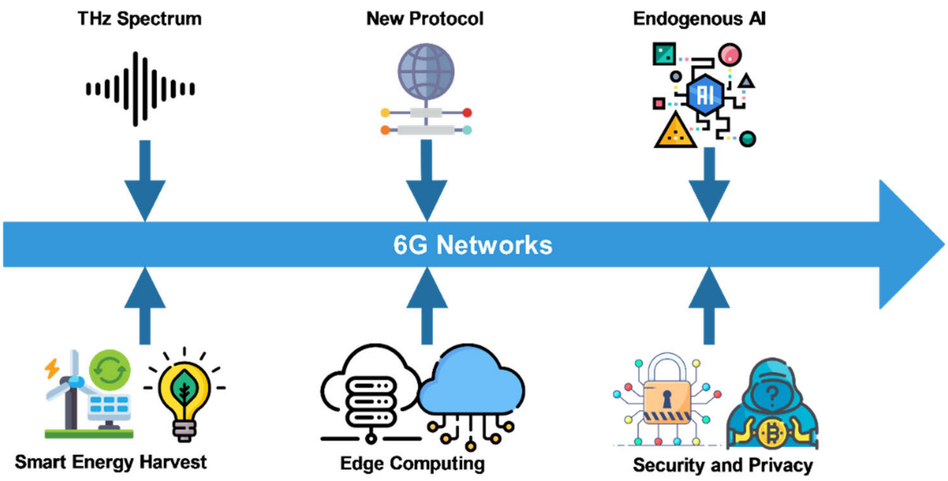

FIGURE 9. Key Challenges of 6G.

users without cell boundaries. However, the traditional cell-free system requires a large-scale deployment of base stations, leading to high energy consumption and hardware cost [143].

Recent results [144], [145] have shown that the combination of metasurfaces, cell-free and massive MIMO, can achieve significant efficiency of resources, performance, energy consumption, and cost and have robust breakout abilities in the 6G era.

11) CONVOLUTIONAL NEURAL NETWORKS AND GRAPH NEURAL NETWORKS

The artificial neural network (so-called Neural Network) is a mathematical model or computational model formed based on the connection of artificial neurons (called nodes). These nodes process information and rely on transmitting data on connections and computing new values at nodes. Thanks to adaptability, neural networks can change their structure based on input and output data. In reality, neural networks have proved robust abilities and have been applied in several domains to serve humans in past decades [146].

In recent, the evolutions of neural networks, namely CNNs (Convolutional Neural Networks) and GNNs (Graph Neural Networks), have been strongly applied in computing and information processing and achieved some breakthrough results in several areas such as recommendation systems [147], collaboration control systems [148], and wireless networks [149].

In the abovementioned applications, CNNs perform preprocessing data to construct further adaptive graphs and then provide it for GCNs. GCNs are information processing architectures that can help efficient handling most graph data types [150].

In our opinion, 3D virtual applications and autonomous vehicles will become popular in the 6G era. These smart IoT and sensor devices will provide a huge amount of information with various data types. However, traditional data processing methods are infeasible. Therefore, new developments in CNNs and GNNs will play an essential role in reducing service response times and data processing rates and enhancing recognition accuracy to support the decision-making of 6G networks.

V. CHALLENGES AND FUTURE RESEARCH

Despite some promising results, studies on 6G are still in their infancy stage. Therefore, many problems and challenges need to be solved in the coming time, in **Fig. 9**. The 6G will be a converged communication system of terrestrial, aerial, and underwater networks with extremely high bandwidth and extremely low latency. Furthermore, 6G will integrate endogenous intelligence and flexible communication solutions. In this section, some issues related to the communication technologies of 6G are discussed, specifically as follows:

- *Heterogenous Networks:* the vision of 6G will be integrating terrestrial, aerial, and underwater networks. Therefore, it is necessary to design more innovative and flexible routing protocols that adapt according to environmental conditions to provide seamless connectivity and interactive ability with different transmission environments [7], [8].
- *The THz spectrum: t*he THz spectrum range is emerging as an attractive technology of 6G to enhance the system's capacity by providing more spectrum bands. However, operating at this high-frequency range faces two key problems: high environmental absorption loss and interference between device components. Consequently, its deployment is only within a short communication range with low transmission power [95], [101], [107]. In our opinion, these problems can be solved by designing smaller circuits and devices with lower operating power.
- *Artificial Intelligence:* The endogenous AI will be integrated into the 6G network. As a result, the system requires extremely high computing power and the ability to handle big data [30], [64], [68]. Therefore, optimizing energy

consumption will be an essential aspect of 6G. Various applications such as holograms, haptic communication, AR, VR, and MR are the most energy consumption applications. LIS-based communication [132] is currently emerging as one of the most potential candidates to solve saving energy. This solution provides low cost, simple installation, and high energy-saving. Therefore, it is also proposed as one of the attractive technologies for 6G.

- *Edge computing:* is considered the revolution of 6G. Edge computing (EC) allows for a significant increase in the computing capacity of the network [59], [72], [73], [151]. Furthermore, the combination of edge computing and AI have shown robust improvement in computing abilities, the utilization efficiency of system resources, and network performance [152]. However, in our opinion, with limited resources and storage capacity, it is challenging to operate very complex AI-based algorithms that require big data processing on edge nodes. Therefore, the design of optimal AI algorithms, efficient scheduling, and offloading techniques for edge nodes to improve the performance of edge-based systems should continue to be considered.
- *Security:* In another aspect, the integration of heterogeneous systems in 6G leads to data security and privacy issues, also challenges to consider. The technologies of 6G require huge data collection and transmission. To ensure security and privacy, several PHY security techniques and encryption algorithms need to be developed [153], [154]. In our opinion, the future economy and society will completely depend on the digital world. Therefore, a trusted architecture with confidentiality and privacy requirements should continue to be studied.

VI. CONCLUSION

The exponential increase of wireless data, especially multimedia data, and the rapid development of intelligent devices are setting the stage for the next wireless generation evolution towards 6G. 6G wireless network promises a revolution of throughput, latency, QoS, energy, security, and a sustainable digital society. This paper presents a detailed survey of the wireless evolution toward 6G networks. First, we analyzed the development of wireless generations from 1G to 5G, which has shown that the development of 6G is an inevitable trend. Then a new architectural model is explained in three aspects: a fully integrated communication system of Space - Aerial - Ground - Underwater, truly intelligent connections based on Endogenous AI, and Interactive in Real-Time. Besides, we have also presented emerging technologies, including new spectrums, such as THz and VLC, and technologies, such as blockchain, energy harvest, and quantum communication. These technologies and solutions have the breakout potential to enhance data rates and are expected will become essential parts of a seamless society in 6G. Although there are still a number of challenges that need to be overcome in the future, we believe that the progression of technology towards 6G is unavoidable. Finally, we hope this survey can serve as an enlightening guide for future research on 6G networks.

REFERENCES

[1] Y. Xu, G. Gui, H. Gacanin, and F. Adachi, "A survey on resource allocation for 5g heterogeneous networks: Current research, future trends, and challenges," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 2, pp. 668–695, 2nd Quart., 2021, doi: 10.1109/COMST.2021.3059896.

[2] W. Jiang, B. Han, M. A. Habibi, and H. D. Schotten, "The road towards 6G: A comprehensive survey," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 334–366, 2021, doi: 10.1109/OJCOMS.2021.3057679.

[3] S. A. Gbadamosi, G. P. Hancke, and A. M. Abu-Mahfouz, "Building upon NB-IoT networks: A roadmap towards 5G new radio networks," *IEEE Access*, vol. 8, pp. 188641–188672, 2020, doi: 10.1109/ACCESS.2020.3030653.

[4] P. Porambage, G. Gur, D. P. M. Osorio, M. Liyanage, A. Gurtov, and M. Ylianttila, "The roadmap to 6G security and privacy," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 1094–1122, 2021, doi: 10.1109/OJCOMS.2021.3078081.

[5] 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, doi: 10.1109/LATINCOM.2018.8613209.

[6] 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, doi: 10.1109/ACCESS.2020.3010896.

[7] G. Liu, Y. Huang, N. Li, J. Dong, J. Jin, Q. Wang, and N. Li, "Vision, requirements and network architecture of 6G mobile network beyond 2030," *China Commun.*, vol. 17, no. 9, pp. 92–104, 2020, doi: 10.23919/JCC.2020.09.008.

[8] G. Wikström, 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, doi: 10.1109/6GSUMMIT49458.2020.9083880.

[9] V. K. Quy, N. V. Hau, D. V. Anh, and L. A. Ngoc, "Smart healthcare IoT applications based on fog computing: Architecture, applications and challenges," *Complex Intell. Syst.*, vol. 8, no. 5, pp. 3805–3815, Oct. 2022, doi: 10.1007/s40747-021-00582-9.

[10] V. K. Quy, V. H. Nam, D. M. Linh, N. T. Ban, and N. D. Han, "Communication solutions for vehicle ad-hoc network in smart cities environment: A comprehensive survey," *Wireless Pers. Commun.*, vol. 122, no. 3, pp. 2791–2815, Feb. 2022, doi: 10.1007/s11277-021-09030-w.

[11] P. K. Tripathy, A. K. Tripathy, A. Agarwal, and S. P. Mohanty, "MyGreen: An IoT-enabled smart greenhouse for sustainable agriculture," *IEEE Consum. Electron. Mag.*, vol. 10, no. 4, pp. 57–62, Jul. 2021, doi: 10.1109/MCE.2021.3055930.

[12] R. O. Andrade, S. G. Yoo, L. Tello-Oquendo, and I. Ortiz-Garcés, "A comprehensive study of the IoT cybersecurity in smart cities," *IEEE Access*, vol. 8, pp. 228922–228941, 2020, doi: 10.1109/ACCESS.2020.3046442.

[13] A. Manzoor, M. Samarin, D. Mason, and M. Ylianttila, "Scavenger hunt: Utilization of blockchain and IoT for a location-based game," *IEEE Access*, vol. 8, pp. 204863–204879, 2020, doi: 10.1109/ACCESS.2020.3037182.

[14] N.-N. Dao, Q.-V. Pham, N. H. Tu, T. T. Thanh, V. N. Q. Bao, D. S. Lakew, and S. Cho, "Survey on aerial radio access networks: Toward a comprehensive 6G access infrastructure," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 2, pp. 1193–1225, 2nd Quart., 2021, doi: 10.1109/COMST.2021.3059644.

[15] B. Ji, Y. Wang, K. Song, C. Li, H. Wen, V. G. Menon, and S. Mumtaz, "A survey of computational intelligence for 6G: Key technologies, applications and trends," *IEEE Trans. Ind. Informat.*, vol. 17, no. 10, pp. 7145–7154, Oct. 2021, doi: 10.1109/TII.2021.3052531.

[16] R. Alghamdi, R. Alhadrami, D. Alhothali, H. Almorad, A. Faisal, S. Helal, R. Shalabi, R. Asfour, N. Hammad, A. Shams, N. Saeed, H. Dahrouj, T. Y. Al-Naffouri, and M.-S. Alouini, "Intelligent surfaces for 6G wireless networks: A survey of optimization and performance analysis techniques," *IEEE Access*, vol. 8, pp. 202795–202818, 2020, doi: 10.1109/ACCESS.2020.3031959.

[17] Y. Sun, J. Liu, J. Wang, Y. Cao, and N. Kato, "When machine learning meets privacy in 6G: A survey," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 4, pp. 2694–2724, 4th Quart., 2020, doi: 10.1109/COMST.2020.3011561.

[18] E. Yaacoub and M.-S. Alouini, "A key 6G challenge and opportunity—Connecting the base of the pyramid: A survey on rural connectivity," *Proc. IEEE*, vol. 108, no. 4, pp. 533–582, Apr. 2020, doi: 10.1109/JPROC.2020.2976703.

[19] C. X. Wang, J. Huang, H. Wang, X. Gao, X. You, and Y. Hao, "6G wireless channel measurements and models: Trends and challenges," *IEEE Veh. Technol. Mag.*, vol. 15, no. 4, pp. 22–32, Dec. 2020, doi: 10.1109/MVT.2020.3018436.

[20] M. Alsabah, M. A. Naser, B. M. Mahmmod, S. H. Abdulhussain, M. R. Eissa, A. Al-Baidhani, N. K. Noordin, S. M. Sait, K. A. Al-Utaibi, and F. Hashim, "6G wireless communications networks: A comprehensive survey," *IEEE Access*, vol. 9, pp. 148191–148243, 2021, doi: 10.1109/ACCESS.2021.3124812.

[21] F. Guo, F. R. Yu, H. Zhang, X. Li, H. Ji, and V. C. M. Leung, "Enabling massive IoT toward 6G: A comprehensive survey," *IEEE Internet Things J.*, vol. 8, no. 15, pp. 11891–11915, Aug. 2021, doi: 10.1109/JIOT.2021.3063686.

[22] V.-L. Nguyen, P.-C. Lin, B.-C. Cheng, R.-H. Hwang, and Y.-D. Lin, "Security and privacy for 6G: A survey on prospective technologies and challenges," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 4, pp. 2384–2428, 4th Quart., 2021, doi: 10.1109/COMST.2021.3108618.

[23] C. D. Alwis, A. Kalla, Q.-V. Pham, P. Kumar, K. Dev, W.-J. Hwang, and M. Liyanage, "Survey on 6G frontiers: Trends, applications, requirements, technologies and future research," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 836–886, 2021, doi: 10.1109/OJCOMS.2021.3071496.

[24] S. Aggarwal, N. Kumar, and S. Tanwar, "Blockchain-envisioned UAV communication using 6G networks: Open issues, use cases, and future directions," *IEEE Internet Things J.*, vol. 8, no. 7, pp. 5416–5441, Apr. 2021, doi: 10.1109/JIOT.2020.3020819.

[25] B. Ji, Y. Han, S. Liu, F. Tao, G. Zhang, Z. Fu, and C. Li, "Several key technologies for 6G: Challenges and opportunities," *IEEE Commun. Standards Mag.*, vol. 5, no. 2, pp. 44–51, Jun. 2021, doi: 10.1109/MCOMSTD.001.2000038.

[26] D. C. Nguyen, M. Ding, P. N. Pathirana, A. Seneviratne, J. Li, D. Niyato, O. Dobre, and H. V. Poor, "6G Internet of Things: A comprehensive survey," *IEEE Internet Things J.*, vol. 9, no. 1, pp. 359–383, Jan. 2022, doi: 10.1109/JIOT.2021.3103320.

[27] G. Geraci, A. Garcia-Rodriguez, M. M. Azari, A. Lozano, M. Mezzavilla, S. Chatzinotas, Y. Chen, S. Rangan, and M. D. Renzo, "What will the future of UAV cellular communications be? A flight from 5G to 6G," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 3, pp. 1304–1335, 3rd Quart. 2022, doi: 10.1109/COMST.2022.3171135.

[28] F. Tang, X. Chen, T. K. Rodrigues, M. Zhao, and N. Kato, "Survey on digital twin edge networks (DITEN) toward 6G," *IEEE Open J. Commun. Soc.*, vol. 3, pp. 1360–1381, 2022, doi: 10.1109/OJCOMS.2022.3197811.

[29] X. Zhu and C. Jiang, "Integrated satellite-terrestrial networks toward 6G: Architectures, applications, and challenges," *IEEE Internet Things J.*, vol. 9, no. 1, pp. 437–461, Jan. 2022, doi: 10.1109/JIOT.2021.3126825.

[30] K. B. Letaief, W. Chen, Y. Shi, J. Zhang, and Y. A. Zhang, "The roadmap to 6G: AI empowered wireless networks," *IEEE Commun. Mag.*, vol. 57, no. 8, pp. 84–90, Aug. 2019, doi: 10.1109/MCOM.2019.1900271.

[31] W. Diego, "Evolution toward the next generation radio access network," in *Proc. IFIP Netw. Conf. (Networking)*, 2020, p. 685.

[32] M. S. Monteiro, F. L. de Caldas Filho, P. D. O. M. E. Souza, V. S. Costa, G. P. C. P. da Luz, L. F. D. O. Carvalho, and R. T. de Sousa, "Solid waste management and monitoring system for smart cities: Development of a low-cost sustainable IoT architecture using GPRS/GSM," in *Proc. Workshop Commun. Netw. Power Syst. (WCNPS)*, Nov. 2021, pp. 1–6, doi: 10.1109/WCNPS53648.2021.9626317.

[33] S. Won and S. W. Choi, "Three decades of 3GPP target cell search through 3G, 4G, and 5G," *IEEE Access*, vol. 8, pp. 116914–116960, 2020, doi: 10.1109/ACCESS.2020.3003012.

[34] A. T. Abed and A. M. Jawad, "Compact size MIMO amer fractal slot antenna for 3G, LTE (4G), WLAN, WiMAX, ISM and 5G communications," *IEEE Access*, vol. 7, pp. 125542–125551, 2019, doi: 10.1109/ACCESS.2019.2938802.

[35] A. Razavieh, Y. Chen, T. Ethirajan, M. Gu, S. Cimino, T. Shimizu, M. K. Hassan, T. Morshed, J. Singh, W. Zheng, V. Mahajan, H. T. Wang, and T. H. Lee, "Extremely-low threshold voltage FinFET for 5G mmWave applications," *IEEE J. Electron Devices Soc.*, vol. 9, pp. 165–169, 2021, doi: 10.1109/JEDS.2020.3046953.

[36] D. Simeonidou and R. Nejabati, "Human-centric networking: From device-centric 5G networks to full cyber-physical convergence in 6G," in *Proc. Eur. Conf. Opt. Commun. (ECOC)*, Sep. 2021, pp. 1–2, doi: 10.1109/ECOC52684.2021.9605913.

[37] L. Bai, Z. Huang, Y. Li, and X. Cheng, "A 3D cluster-based channel model for 5G and beyond vehicle-to-vehicle massive MIMO channels," *IEEE Trans. Veh. Technol.*, vol. 70, no. 9, pp. 8401–8414, Sep. 2021.

[38] A. Abdulghaffar, A. Mahmoud, M. Abu-Amara, and T. Sheltami, "Modeling and evaluation of software defined networking based 5G core network architecture," *IEEE Access*, vol. 9, pp. 10179–10198, 2021, doi: 10.1109/ACCESS.2021.3049945.

[39] N.-S. Vo, T.-M. Phan, M.-P. Bui, X.-K. Dang, N. T. Viet, and C. Yin, "Social-aware spectrum sharing and caching helper selection strategy optimized multicast video streaming in dense D2D 5G networks," *IEEE Syst. J.*, vol. 15, no. 3, pp. 3480–3491, Sep. 2021, doi: 10.1109/JSYST.2020.2995204.

[40] O. Serhane, K. Yahyaoui, B. Nour, and H. Moungla, "A survey of ICN content naming and in-network caching in 5G and beyond networks," *IEEE Internet Things J.*, vol. 8, no. 6, pp. 4081–4104, Mar. 2021, doi: 10.1109/JIOT.2020.3022243.

[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, doi: 10.1109/JIOT.2020.2982417.

[42] M. Adhikari, A. Hazra, V. G. Menon, B. K. Chaurasia, and S. Mumtaz, "A roadmap of next-generation wireless technology for 6G-enabled vehicular networks," *IEEE Internet Things Mag.*, vol. 4, no. 4, pp. 79–85, Dec. 2021, doi: 10.1109/IOTM.001.2100075.

[43] H. Guo, J. Li, J. Liu, N. Tian, and N. Kato, "A survey on space-air-ground-sea integrated network security in 6G," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 1, pp. 53–87, 1st Quart., 2022, doi: 10.1109/COMST.2021.3131332.

[44] O. Markovitz and M. Segal, "Advanced routing algorithms for low orbit satellite constellations," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2021, pp. 1–6, doi: 10.1109/ICC42927.2021.9500740.

[45] J. R. Bhat and S. A. Alqahtani, "6G ecosystem: Current status and future perspective," *IEEE Access*, vol. 9, pp. 43134–43167, 2021, doi: 10.1109/ACCESS.2021.3054833.

[46] E. Sağ and A. Kavas, "Modelling and performance analysis of 2.5 Gbps inter-satellite optical wireless communication (IsOWC) system in LEO constellation," *J. Commun.*, vol. 13, no. 10, pp. 553–558, 2018, doi: 10.12720/jcm.13.10.553-558.

[47] M. U. Akram, U. Saeed, S. A. Hassan, and H. Jung, "UAV-based air-to-ground channel modeling for diverse environments," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, May 2020, pp. 1–6, doi: 10.1109/WCNC45663.2020.9120659.

[48] V. Ziegler, H. Viswanathan, H. Flinck, M. Hoffmann, V. Räisänen, and K. Hätönen, "6G architecture to connect the worlds," *IEEE Access*, vol. 8, pp. 173508–173520, 2020, doi: 10.1109/ACCESS.2020.3025032.

[49] Z. Xiao, L. Zhu, Y. Liu, P. Yi, R. Zhang, X.-G. Xia, and R. Schober, "A survey on millimeter-wave beamforming enabled UAV communications and networking," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 1, pp. 557–610, 1st Quart., 2022, doi: 10.1109/COMST.2021.3124512.

[50] M. Mozaffari, W. Saad, M. Bennis, Y.-H. Nam, and M. Debbah, "A tutorial on UAVs for wireless networks: Applications, challenges, and open problems," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2334–2360, 3rd Quart., 2019, doi: 10.1109/COMST.2019.2902862.

[51] B. Mao, F. Tang, Y. Kawamoto, and N. Kato, "Optimizing computation offloading in satellite-UAV-served 6G IoT: A deep learning approach," *IEEE Netw.*, vol. 35, no. 4, pp. 102–108, Jul. 2021, doi: 10.1109/MNET.011.2100097.

[52] X. Liu, Y. Liu, Y. Chen, and L. Hanzo, "Trajectory design and power control for multi-UAV assisted wireless networks: A machine learning approach," *IEEE Trans. Veh. Technol.*, vol. 68, no. 8, pp. 7957–7969, Aug. 2019, doi: 10.1109/TVT.2019.2920284.

[53] H. Zhou, F. Hu, M. Juras, A. B. Mehta, and Y. Deng, "Real-time video streaming and control of cellular-connected UAV system: Prototype and performance evaluation," *IEEE Wireless Commun. Lett.*, vol. 10, no. 8, pp. 1657–1661, Aug. 2021, doi: 10.1109/LWC.2021.3076415.

[54] M. Jouhari, K. Ibrahimi, H. Tembine, and J. Ben-Othman, "Underwater wireless sensor networks: A survey on enabling technologies, localization protocols, and Internet of Underwater Things," *IEEE Access*, vol. 7, pp. 96879–96899, 2019, doi: 10.1109/ACCESS.2019.2928876.

[55] Y. Chen, X. Jin, L. Wan, X. Zhang, and X. Xu, "Selective dynamic coded cooperative communications for multi-hop underwater acoustic sensor networks," *IEEE Access*, vol. 7, pp. 70552–70563, 2019, doi: 10.1109/ACCESS.2019.2912917.

[56] W. Yu, Y. Chen, L. Wan, X. Zhang, P. Zhu, and X. Xu, "An energy optimization clustering scheme for multi-hop underwater acoustic cooperative sensor networks," *IEEE Access*, vol. 8, pp. 89171–89184, 2020, doi: 10.1109/ACCESS.2020.2993544.

[57] S. He, N. Wang, M. Ho, J. Zhu, and G. Song, "Design of a new stress wave communication method for underwater communication," *IEEE Trans. Ind. Electron.*, vol. 68, no. 8, pp. 7370–7379, Aug. 2021, doi: 10.1109/TIE.2020.3003634.

[58] C. Zhang, P. Patras, and H. Haddadi, "Deep learning in mobile and wireless networking: A survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2224–2287, 3rd Quart., 2019, doi: 10.1109/COMST.2019.2904897.

[59] M. Belgiovine, K. Sankhe, C. Bocanegra, D. Roy, and K. Chowdhury, "Deep learning at the edge for channel estimation in beyond-5G massive MIMO," *IEEE Wireless Commun. Mag.*, vol. 28, no. 2, pp. 19–25, Apr. 2021, doi: 10.1109/MWC.001.2000322.

[60] F. Al-Tam, N. Correia, and J. Rodriguez, "Learn to schedule (LEASCH): A deep reinforcement learning approach for radio resource scheduling in the 5G MAC layer," *IEEE Access*, vol. 8, pp. 108088–108101, 2020, doi: 10.1109/ACCESS.2020.3000893.

[61] P. Yu, F. Zhou, X. Zhang, X. Qiu, M. Kadoch, and M. Cheriet, "Deep learning-based resource allocation for 5G broadband TV service," *IEEE Trans. Broadcast.*, vol. 66, no. 4, pp. 800–813, Dec. 2020, doi: 10.1109/TBC.2020.2968730.

[62] E. Esenogho, K. Djouani, and A. M. Kurien, "Integrating artificial intelligence Internet of Things and 5G for next-generation smartgrid: A survey of trends challenges and prospect," *IEEE Access*, vol. 10, pp. 4794–4831, 2022, doi: 10.1109/ACCESS.2022.3140595.

[63] H. Wu, Z. Zhang, C. Guan, K. Wolter, and M. Xu, "Collaborate edge and cloud computing with distributed deep learning for smart city Internet of Things," *IEEE Internet Things J.*, vol. 7, no. 9, pp. 8099–8110, Sep. 2020, doi: 10.1109/JIOT.2020.2996784.

[64] N. Koursioumpas, S. Barmpounakis, I. Stavrakakis, and N. Alonistioti, "AI-driven, context-aware profiling for 5G and beyond networks," *IEEE Trans. Netw. Service Manage.*, vol. 19, no. 2, pp. 1036–1048, Jun. 2022, doi: 10.1109/TNSM.2021.3126948.

[65] M. Säily, C. B. Estevan, J. J. Gimenez, F. Tesema, W. Guo, D. Gomez-Barquero, and D. Mi, "5G radio access network architecture for terrestrial broadcast services," *IEEE Trans. Broadcast.*, vol. 66, no. 2, pp. 404–415, Jun. 2020, doi: 10.1109/TBC.2020.2985906.

[66] J. Jin and X. Ma, "A multi-objective agent-based control approach with application in intelligent traffic signal system," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 10, pp. 3900–3912, Oct. 2019, doi: 10.1109/TITS.2019.2906260.

[67] S.-B. Ho, M. Edmonds, and S.-C. Zhu, "Actional-perceptual causality: Concepts and inductive learning for AI and robotics," in *Proc. IEEE Symp. Ser. Comput. Intell. (SSCI)*, Dec. 2020, pp. 442–448, doi: 10.1109/SSCI47803.2020.9308168.

[68] B. Mao, F. Tang, Y. Kawamoto, and N. Kato, "AI models for green communications towards 6G," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 1, pp. 210–247, 1st Quart., 2022, doi: 10.1109/COMST.2021.3130901.

[69] Y. Liu, X. Yuan, Z. Xiong, J. Kang, X. Wang, and D. Niyato, "Federated learning for 6G communications: Challenges, methods, and future directions," *China Commun.*, vol. 17, no. 9, pp. 105–118, Sep. 2020, doi: 10.23919/JCC.2020.09.009.

[70] S. Shen, C. Yu, K. Zhang, J. Ni, and S. Ci, "Adaptive and dynamic security in AI-empowered 6G: From an energy efficiency perspective," *IEEE Commun. Standards Mag.*, vol. 5, no. 3, pp. 80–88, Sep. 2021, doi: 10.1109/MCOMSTD.101.2000090.

[71] L. Dong, Z. Yang, X. Cai, Y. Zhao, Q. Ma, and X. Miao, "WAVE: Edge-device cooperated real-time object detection for open-air applications," *IEEE Trans. Mobile Comput.*, early access, Feb. 11, 2022, doi: 10.1109/TMC.2022.3150401.

[72] H.-Y. Han, Y.-C. Chen, P.-Y. Hsiao, and L.-C. Fu, "Using channel-wise attention for deep CNN based real-time semantic segmentation with class-aware edge information," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 2, pp. 1041–1051, Feb. 2021, doi: 10.1109/TITS.2019.2962094.

[73] X. Xu, H. Li, W. Xu, Z. Liu, L. Yao, and F. Dai, "Artificial intelligence for edge service optimization in Internet of Vehicles: A survey," *Tsinghua Sci. Technol.*, vol. 27, no. 2, pp. 270–287, Apr. 2022, doi: 10.26599/TST.2020.9010025.

[74] M. Matthaiou, O. Yurduseven, H. Q. Ngo, D. Morales-Jimenez, S. L. Cotton, and V. F. Fusco, "The road to 6G: Ten physical layer challenges for communications engineers," *IEEE Commun. Mag.*, vol. 59, no. 1, pp. 64–69, Jan. 2021, doi: 10.1109/MCOM.001.2000208.

[75] Z. Peng, Z. Chen, C. Pan, G. Zhou, and H. Ren, "Robust transmission design for RIS-aided communications with both transceiver hardware impairments and imperfect CSI," *IEEE Wireless Commun. Lett.*, vol. 11, no. 3, pp. 528–532, Mar. 2022, doi: 10.1109/LWC.2021.3135413.

[76] Q. Xia, Z. Hossain, M. Medley, and J. M. Jornet, "A link-layer synchronization and medium access control protocol for terahertz-band communication networks," *IEEE Trans. Mobile Comput.*, vol. 20, no. 1, pp. 2–18, Jan. 2021, doi: 10.1109/TMC.2019.2940441.

[77] X. Cao, B. Yang, C. Huang, C. Yuen, M. D. Renzo, Z. Han, D. Niyato, H. V. Poor, and L. Hanzo, "AI-assisted MAC for reconfigurable intelligent-surface-aided wireless networks: Challenges and opportunities," *IEEE Commun. Mag.*, vol. 59, no. 6, pp. 21–27, Jun. 2021, doi: 10.1109/MCOM.001.2001146.

[78] 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, doi: 10.1109/MVT.2019.2921398.

[79] J. Zhang, L. Yang, X. Gao, G. Tang, J. Zhang, and Q. Wang, "Formal analysis of QUIC handshake protocol using symbolic model checking," *IEEE Access*, vol. 9, pp. 14836–14848, 2021, doi: 10.1109/ACCESS.2021.3052578.

[80] G. K. Choudhary, M. R. Kanagarathinam, H. Natarajan, K. Arunachalam, S. R. Jayaseelan, G. Sinha, and D. Das, "Novel MultiPipe QUIC protocols to enhance the wireless network performance," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, May 2020, pp. 1–7, doi: 10.1109/WCNC45663.2020.9120821.

[81] Q. De Coninck and O. Bonaventure, "Multiflow QUIC: A generic multipath transport protocol," *IEEE Commun. Mag.*, vol. 59, no. 5, pp. 108–113, May 2021, doi: 10.1109/MCOM.001.2000892.

[82] F. Chiariotti, A. A. Deshpande, M. Giordani, K. Antonakoglou, T. Mahmoodi, and A. Zanella, "QUIC-EST: A QUIC-enabled scheduling and transmission scheme to maximize VoI with correlated data flows," *IEEE Commun. Mag.*, vol. 59, no. 4, pp. 30–36, Apr. 2021, doi: 10.1109/MCOM.001.2000876.

[83] 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, doi: 10.1109/MVT.2019.2921208.

[84] X. An, J. Wu, W. Tong, P. Zhu, and Y. Chen, "6G network architecture vision," in *Proc. Joint Eur. Conf. Netw. Commun. 6G Summit (EuCNC/6G Summit)*, Jun. 2021, pp. 592–597, doi: 10.1109/EuCNC/6GSummit51104.2021.9482439.

[85] S. Edirisinghe, C. Ranaweera, E. Wong, C. Lim, and A. Nirmalathas, "An adaptable contention-free MAC protocol for full-duplex split-plane optical wireless network," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2021, pp. 1–7, doi: 10.1109/ICC42927.2021.9500719.

[86] Y. Sadi, S. Erkucuk, and E. Panayirci, "Flexible physical layer based resource allocation for machine type communications towards 6G," in *Proc. 2nd 6G Wireless Summit (6G SUMMIT)*, Mar. 2020, pp. 1–5, doi: 10.1109/6GSUMMIT49458.2020.9083921.

[87] M. Polese, J. M. Jornet, T. Melodia, and M. Zorzi, "Toward end-to-end, full-stack 6G terahertz networks," *IEEE Commun. Mag.*, vol. 58, no. 11, pp. 48–54, Nov. 2020, doi: 10.1109/MCOM.001.2000224.

[88] N. Chi, Y. Zhou, Y. Wei, and F. Hu, "Visible light communication in 6G: Advances, challenges, and prospects," *IEEE Veh. Technol. Mag.*, vol. 15, no. 4, pp. 93–102, Dec. 2020, doi: 10.1109/MVT.2020.3017153.

[89] L. Yan, C. Han, and J. Yuan, "Hybrid precoding for 6G terahertz communications: Performance evaluation and open problems," in *Proc. 2nd 6G Wireless Summit (6G SUMMIT)*, 2020, pp. 1–5, doi: 10.1109/6GSUMMIT49458.2020.9083795.

[90] V. Petrov, T. Kurner, and I. Hosako, "IEEE 802.15.3d: First standardization efforts for sub-terahertz band communications toward 6G," *IEEE Commun. Mag.*, vol. 58, no. 11, pp. 28–33, Nov. 2020, doi: 10.1109/MCOM.001.2000273.

[91] 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, doi: 10.1109/6GSUMMIT49458.2020.9083807.

[92] W. Hedhly, O. Amin, B. Shihada, and M.-S. Alouini, "A power saving scheme for IEEE 802.15.3d THz wireless communication links," *IEEE Trans. Mobile Comput.*, vol. 22, no. 4, pp. 1912–1921, Apr. 2023, doi: 10.1109/TMC.2021.3112532.

[93] J. F. O'Hara and D. R. Grischkowsky, "Comment on the veracity of the ITU-R recommendation for atmospheric attenuation at terahertz frequencies," *IEEE Trans. THz Sci. Technol.*, vol. 8, no. 3, pp. 372–375, May 2018, doi: 10.1109/TTHZ.2018.2814343.

[94] B. Chang, X. Yan, L. Zhang, Z. Chen, L. Li, and M. A. Imran, "Joint communication and control for mmWave/THz beam alignment in V2X networks," *IEEE Internet Things J.*, vol. 9, no. 13, pp. 11203–11213, Jul. 2022, doi: 10.1109/JIOT.2021.3126651.

[95] C. Yi, D. Kim, S. Solanki, J.-H. Kwon, M. Kim, S. Jeon, Y.-C. Ko, and I. Lee, "Design and performance analysis of THz wireless communication systems for chip-to-chip and personal area networks applications," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 6, pp. 1785–1796, Jun. 2021, doi: 10.1109/JSAC.2021.3071849.

[96] X. Ma, Z. Chen, W. Chen, Z. Li, Y. Chi, C. Han, and S. Li, "Joint channel estimation and data rate maximization for intelligent reflecting surface assisted terahertz MIMO communication systems," *IEEE Access*, vol. 8, pp. 99565–99581, 2020, doi: 10.1109/ACCESS.2020.2994100.

[97] H. Zhang, L. Zhang, S. Wang, Z. Lu, Z. Yang, S. Liu, M. Qiao, Y. He, X. Pang, X. Zhang, and X. Yu, "Tbit/s multi-dimensional multiplexing THz-over-fiber for 6G wireless communication," *J. Lightw. Technol.*, vol. 39, no. 18, pp. 5783–5790, Sep. 15, 2021, doi: 10.1109/JLT.2021.3093628.

[98] L. Xu, M. Chen, M. Chen, Z. Yang, C. Chaccour, W. Saad, and C. S. Hong, "Joint location, bandwidth and power optimization for THz-enabled UAV communications," *IEEE Commun. Lett.*, vol. 25, no. 6, pp. 1984–1988, Jun. 2021, doi: 10.1109/LCOMM.2021.3064067.

[99] M. A. Jamshed, A. Nauman, M. A. B. Abbasi, and S. W. Kim, "Antenna selection and designing for THz applications: Suitability and performance evaluation: A survey," *IEEE Access*, vol. 8, pp. 113246–113261, 2020, doi: 10.1109/ACCESS.2020.3002989.

[100] L. U. Khan, "Visible light communication: Applications, architecture, standardization and research challenges," *Digit. Commun. Netw.*, vol. 3, no. 2, pp. 78–88, May 2017, doi: 10.1016/j.dcan.2016.07.004.

[101] K. Yan, Z. Li, M. Cheng, and H.-C. Wu, "QoS analysis and signal characteristics for short-range visible-light communications," *IEEE Trans. Veh. Technol.*, vol. 70, no. 7, pp. 6726–6734, Jul. 2021, doi: 10.1109/TVT.2021.3081688.

[102] B. Donmez, R. Mitra, and F. Miramirkhani, "Channel modeling and characterization for VLC-based medical body sensor networks: Trends and challenges," *IEEE Access*, vol. 9, pp. 153401–153419, 2021, doi: 10.1109/ACCESS.2021.3127941.

[103] A. Memedi and F. Dressler, "Vehicular visible light communications: A survey," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 1, pp. 161–181, 1st Quart., 2021, doi: 10.1109/COMST.2020.3034224.

[104] C.-H. Yeh, C.-W. Chow, and L.-Y. Wei, "1250 Mbit/s OOK wireless white-light VLC transmission based on phosphor laser diode," *IEEE Photon. J.*, vol. 11, no. 3, pp. 1–5, Jun. 2019, doi: 10.1109/JPHOT.2019.2911411.

[105] S. Baig, H. Muhammad, S. Mumtaz, M. Shafiq, J.-G. Choi, and T. Umer, "High data rate discrete wavelet transform-based PLC-VLC design for 5G communication systems," *IEEE Access*, vol. 6, pp. 52490–52499, 2018, doi: 10.1109/ACCESS.2018.2870138.

[106] E. Xie, R. Bian, X. He, M. S. Islim, C. Chen, J. J. D. McKendry, E. Gu, H. Haas, and M. D. Dawson, "Over 10 Gbps VLC for long-distance applications using a GaN-based series-biased micro-LED array," *IEEE Photon. Technol. Lett.*, vol. 32, no. 9, pp. 499–502, May 1, 2020, doi: 10.1109/LPT.2020.2981827.

[107] H. Haas, "Opportunities and challenges of future LiFi," in *Proc. IEEE Photon. Conf. (IPC)*, Sep. 2019, pp. 1–2, doi: 10.1109/IPCon.2019.8908391.

[108] C. Ranaweera, J. Kua, I. Dias, E. Wong, C. Lim, and A. Nirmalathas, "4G to 6G: Disruptions and drivers for optical access [invited]," *J. Opt. Commun. Netw.*, vol. 14, no. 2, pp. A143–A153, Feb. 2022, doi: 10.1364/JOCN.440798.

[109] A. Singh, K. Dev, H. Siljak, H. D. Joshi, and M. Magarini, "Quantum internet—Applications, functionalities, enabling technologies, challenges, and research directions," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 4, pp. 2218–2247, 4th Quart., 2021, doi: 10.1109/COMST.2021.3109944.

[110] Z. Li, K. Xue, J. Li, N. Yu, J. Liu, D. S. L. Wei, Q. Sun, and J. Lu, "Building a large-scale and wide-area quantum internet based on an OSI-alike model," *China Commun.*, vol. 18, no. 10, pp. 1–14, Oct. 2021, doi: 10.23919/JCC.2021.10.001.

[111] T. Satoh, S. Nagayama, S. Suzuki, T. Matsuo, M. Hajdušek, and R. V. Meter, "Attacking the quantum internet," *IEEE Trans. Quantum Eng.*, vol. 2, pp. 1–17, 2021, doi: 10.1109/TQE.2021.3094983.

[112] N. Yu, C.-Y. Lai, and L. Zhou, "Protocols for packet quantum network intercommunication," *IEEE Trans. Quantum Eng.*, vol. 2, pp. 1–9, 2021, doi: 10.1109/TQE.2021.3112594.

[113] S.-K. Liao et al., "Satellite-relayed intercontinental quantum network," *Phys. Rev. Lett.*, vol. 120, no. 3, Jan. 2018, Art. no. 030501, doi: 10.1103/PhysRevLett.120.030501.

[114] A. S. Cacciapuoti, M. Caleffi, F. Tafuri, F. S. Cataliotti, S. Gherardini, and G. Bianchi, "Quantum internet: Networking challenges in distributed quantum computing," *IEEE Netw.*, vol. 34, no. 1, pp. 137–143, Jan. 2020, doi: 10.1109/MNET.001.1900092.

[115] D. C. Nguyen, P. N. Pathirana, M. Ding, and A. Seneviratne, "Integration of blockchain and cloud of things: Architecture, applications and challenges," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 4, pp. 2521–2549, 4th Quart., 2020, doi: 10.1109/COMST.2020.3020092.

[116] J. Bao, D. He, M. Luo, and K.-K.-R. Choo, "A survey of blockchain applications in the energy sector," *IEEE Syst. J.*, vol. 15, no. 3, pp. 3370–3381, Sep. 2021, doi: 10.1109/JSYST.2020.2998791.

[117] M. N. M. Bhutta, A. A. Khwaja, A. Nadeem, H. F. Ahmad, M. K. Khan, M. A. Hanif, H. Song, M. Alshamari, and Y. Cao, "A survey on blockchain technology: Evolution, architecture and security," *IEEE Access*, vol. 9, pp. 61048–61073, 2021, doi: 10.1109/ACCESS.2021.3072849.

[118] E. Zaghloul, T. Li, M. W. Mutka, and J. Ren, "Bitcoin and blockchain: Security and privacy," *IEEE Internet Things J.*, vol. 7, no. 10, pp. 10288–10313, Oct. 2020, doi: 10.1109/JIOT.2020.3004273.

[119] Y. K. Tomov, "Bitcoin: Evolution of blockchain technology," in *Proc. IEEE XXVIII Int. Sci. Conf. Electron. (ET)*, Sep. 2019, pp. 1–4, doi: 10.1109/ET.2019.8878322.

[120] L. Mertz, "(Block) chain reaction: A blockchain revolution sweeps into health care, offering the possibility for a much-needed data solution," *IEEE Pulse*, vol. 9, no. 3, pp. 4–7, May/Jun. 2018, doi: 10.1109/MPUL.2018.2814879.

[121] M. Zhaofeng, W. Lingyun, W. Xiaochang, W. Zhen, and Z. Weizhe, "Blockchain-enabled decentralized trust management and secure usage control of IoT big data," *IEEE Internet Things J.*, vol. 7, no. 5, pp. 4000–4015, May 2020, doi: 10.1109/JIOT.2019.2960526.

[122] G. Tian, Y. Hu, J. Wei, Z. Liu, X. Huang, X. Chen, and W. Susilo, "Blockchain-based secure deduplication and shared auditing in decentralized storage," *IEEE Trans. Depend. Sec. Comput.*, vol. 19, no. 6, pp. 3941–3954, Nov. 2022, doi: 10.1109/TDSC.2021.3114160.

[123] F. Patel, P. Bhattacharya, S. Tanwar, R. Gupta, N. Kumar, and M. Guizani, "Block6Tel: Blockchain-based spectrum allocation scheme in 6G-envisioned communications," in *Proc. Int. Wireless Commun. Mobile Comput. (IWCMC)*, Jun. 2021, pp. 1823–1828, doi: 10.1109/IWCMC51323.2021.9498854.

[124] Y. Liu, Z. Xiong, Q. Hu, D. Niyato, J. Zhang, C. Miao, C. Leung, and Z. Tian, "VRepChain: A decentralized and privacy-preserving reputation system for social Internet of Vehicles based on blockchain," *IEEE Trans. Veh. Technol.*, vol. 71, no. 12, pp. 13242–13253, Dec. 2022, doi: 10.1109/TVT.2022.3198004.

[125] Y. Yang, H. Lin, X. Liu, W. Guo, X. Zheng, and Z. Liu, "Blockchain-based verifiable multi-keyword ranked search on encrypted cloud with fair payment," *IEEE Access*, vol. 7, pp. 140818–140832, 2019, doi: 10.1109/ACCESS.2019.2943356.

[126] S. Wang, Y. Wang, and Y. Zhang, "Blockchain-based fair payment protocol for deduplication cloud storage system," *IEEE Access*, vol. 7, pp. 127652–127668, 2019, doi: 10.1109/ACCESS.2019.2939492.

[127] S. Verma, S. Kaur, M. A. Khan, and P. S. Sehdev, "Toward green communication in 6G-enabled massive Internet of Things," *IEEE Internet Things J.*, vol. 8, no. 7, pp. 5408–5415, Apr. 2021, doi: 10.1109/JIOT.2020.3038804.

[128] A. M. Alqasir and A. E. Kamal, "Cooperative small cell HetNets with dynamic sleeping and energy harvesting," *IEEE Trans. Green Commun. Netw.*, vol. 4, no. 3, pp. 774–782, Sep. 2020, doi: 10.1109/TGCN.2020.2985496.

[129] H. K. Sahu, A. K. Padhan, and P. R. Sahu, "Smart devices performance with SSK-BPSK modulation and energy harvesting in smart cities," *IEEE Commun. Lett.*, vol. 25, no. 2, pp. 637–640, Feb. 2021, doi: 10.1109/LCOMM.2020.3026737.

[130] D. Khan, S.-J. Oh, S. Yeo, Y. Ryu, S.-H. In, R. E. Rad, I. Ali, Y.-G. Pu, S.-S. Yoo, M. Lee, K. C. Hwang, Y. Yang, and K.-Y. Lee, "A high-efficient wireless power receiver for hybrid energy-harvesting sources," *IEEE Trans. Power Electron.*, vol. 36, no. 10, pp. 11148–11162, Oct. 2021, doi: 10.1109/TPEL.2021.3071374.

[131] M. U. Saleem, M. R. Usman, and M. Shakir, "Design, implementation, and deployment of an IoT based smart energy management system," *IEEE Access*, vol. 9, pp. 59649–59664, 2021, doi: 10.1109/ACCESS.2021.3070960.

[132] J. Yuan, H. Q. Ngo, and M. Matthaiou, "Towards large intelligent surface (LIS)-based communications," *IEEE Trans. Commun.*, vol. 68, no. 10, pp. 6568–6582, Oct. 2020, doi: 10.1109/TCOMM.2020.3009115.

[133] T. Q. Duong, D. Van Huynh, Y. Li, E. Garcia-Palacios, and K. Sun, "Digital twin-enabled 6G aerial edge computing with ultra-reliable and low-latency communications: (Invited paper)," in *Proc. 1st Int. Conf. 6G Netw. (6GNet)*, Jul. 2022, pp. 1–5, doi: 10.1109/6GNet54646.2022.9830363.

[134] W. Sun, H. Zhang, R. Wang, and Y. Zhang, "Reducing offloading latency for digital twin edge networks in 6G," *IEEE Trans. Veh. Technol.*, vol. 69, no. 10, pp. 12240–12251, Oct. 2020, doi: 10.1109/TVT.2020.3018817.

[135] Y. Dai and Y. Zhang, "Adaptive digital twin for vehicular edge computing and networks," *J. Commun. Inf. Netw.*, vol. 7, no. 1, pp. 48–59, Mar. 2022, doi: 10.23919/JCIN.2022.9745481.

[136] Y. Wang, Z. Su, N. Zhang, R. Xing, D. Liu, T. H. Luan, and X. Shen, "A survey on metaverse: Fundamentals, security, and privacy," *IEEE Commun. Surveys Tuts.*, vol. 25, no. 1, pp. 319–352, 1st Quart., 2023, doi: 10.1109/COMST.2022.3202047.

[137] D. Van Huynh, S. R. Khosravirad, A. Masaracchia, O. A. Dobre, and T. Q. Duong, "Edge intelligence-based ultra-reliable and low-latency communications for digital twin-enabled metaverse," *IEEE Wireless Commun. Lett.*, vol. 11, no. 8, pp. 1733–1737, Aug. 2022, doi: 10.1109/LWC.2022.3179207.

[138] S.-M. Park and Y.-G. Kim, "A metaverse: Taxonomy, components, applications, and open challenges," *IEEE Access*, vol. 10, pp. 4209–4251, 2022, doi: 10.1109/ACCESS.2021.3140175.

[139] F.-Y. Wang, "Parallel intelligence in metaverses: Welcome to Hanoi!" *IEEE Intell. Syst.*, vol. 37, no. 1, pp. 16–20, Jan./Feb. 2022, doi: 10.1109/MIS.2022.3154541.

[140] W. Y. B. Lim, Z. Xiong, D. Niyato, X. Cao, C. Miao, S. Sun, and Q. Yang, "Realizing the metaverse with edge intelligence: A match made in heaven," *IEEE Wireless Commun.*, early access, Jul. 4, 2022, doi: 10.1109/MWC.018.2100716.

[141] Y.-C. Liang, Q. Zhang, E. G. Larsson, and G. Y. Li, "Symbiotic radio: Cognitive backscattering communications for future wireless networks," *IEEE Trans. Cogn. Commun. Netw.*, vol. 6, no. 4, pp. 1242–1255, Dec. 2020, doi: 10.1109/TCCN.2020.3023139.

[142] Q. Zhang, Y.-C. Liang, and H. V. Poor, "Intelligent user association for symbiotic radio networks using deep reinforcement learning," *IEEE Trans. Wireless Commun.*, vol. 19, no. 7, pp. 4535–4548, Jul. 2020, doi: 10.1109/TWC.2020.2984758.

[143] H. A. Ammar, R. Adve, S. Shahbazpanahi, G. Boudreau, and K. V. Srinivas, "User-centric cell-free massive MIMO networks: A survey of opportunities, challenges and solutions," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 1, pp. 611–652, 1st Quart., 2022, doi: 10.1109/COMST.2021.3135119.

[144] Y. Zhang, B. Di, H. Zhang, J. Lin, C. Xu, D. Zhang, Y. Li, and L. Song, "Beyond cell-free MIMO: Energy efficient reconfigurable intelligent surface aided cell-free MIMO communications," *IEEE Trans. Cognit. Commun. Netw.*, vol. 7, no. 2, pp. 412–426, Jun. 2021, doi: 10.1109/TCCN.2021.3058683.

[145] T. V. Chien, H. Q. Ngo, S. Chatzinotas, M. Di Renzo, and B. Ottersten, "Reconfigurable intelligent surface-assisted cell-free massive MIMO systems over spatially-correlated channels," *IEEE Trans. Wireless Commun.*, vol. 21, no. 7, pp. 5106–5128, Jul. 2022, doi: 10.1109/TWC.2021.3136925.

[146] Z. Gao, Z. Lu, J. Wang, S. Ying, and J. Shi, "A convolutional neural network and graph convolutional network based framework for classification of breast histopathological images," *IEEE J. Biomed. Health Informat.*, vol. 26, no. 7, pp. 3163–3173, Jul. 2022, doi: 10.1109/JBHI.2022.3153671.

[147] Z. Huang, X. Xu, H. Zhu, and M. Zhou, "An efficient group recommendation model with multiattention-based neural networks," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 31, no. 11, pp. 4461–4474, Nov. 2020, doi: 10.1109/TNNLS.2019.2955567.

[148] T. Chen, X. Zhang, M. You, G. Zheng, and S. Lambotharan, "A GNN-based supervised learning framework for resource allocation in wireless IoT networks," *IEEE Internet Things J.*, vol. 9, no. 3, pp. 1712–1724, Feb. 2022, doi: 10.1109/JIOT.2021.3091551.

[149] M. Eisen and A. Ribeiro, "Optimal wireless resource allocation with random edge graph neural networks," *IEEE Trans. Signal Process.*, vol. 68, pp. 2977–2991, 2020, doi: 10.1109/TSP.2020.2988255.

[150] L. Ruiz, F. Gama, and A. Ribeiro, "Graph neural networks: Architectures, stability, and transferability," *Proc. IEEE*, vol. 109, no. 5, pp. 660–682, May 2021, doi: 10.1109/JPROC.2021.3055400.

[151] X. Wang, Y. Han, V. C. M. Leung, D. Niyato, X. Yan, and X. Chen, "Convergence of edge computing and deep learning: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 2, pp. 869–904, 2nd Quart., 2020, doi: 10.1109/COMST.2020.2970550.

[152] H. Xiao, C. Xu, Y. Ma, S. Yang, L. Zhong, and G.-M. Muntean, "Edge intelligence: A computational task offloading scheme for dependent IoT application," *IEEE Trans. Wireless Commun.*, vol. 21, no. 9, pp. 7222–7237, Sep. 2022, doi: 10.1109/TWC.2022.3156905.

[153] Y. Hui, N. Cheng, Z. Su, Y. Huang, P. Zhao, T. H. Luan, and C. Li, "Secure and personalized edge computing services in 6G heterogeneous vehicular networks," *IEEE Internet Things J.*, vol. 9, no. 8, pp. 5920–5931, Apr. 2022, doi: 10.1109/JIOT.2021.3065970.

[154] P. Angueira, I. Val, J. Montalban, Ó. Seijo, E. Iradier, P. S. Fontaneda, L. Fanari, and A. Arriola, "A survey of physical layer techniques for secure wireless communications in industry," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 2, pp. 810–838, 2022, doi: 10.1109/COMST.2022.3148857.

VU KHANH QUY was born in Hai Duong, Vietnam, in 1982. He received the M.Sc. and Ph.D. degrees from the Posts and Telecommunications Institute of Technology, in 2012 and 2021, respectively. He is currently a Lecturer with the Hung Yen University of Technology and Education, Vietnam. His research interests include wireless communications, mobile ad-hoc computing, high-performance computing, edge computing, smart agriculture, next-generation networks, the Internet of Things, the IoT ecosystems, and communication networks.

ABDELLAH CHEHRI (Senior Member, IEEE) received the master's degree from University Nice-Sophia Antipolis-Eurecom, France, and the Ph.D. degree from Laval University, Quebec. He is currently an Associate Professor with the Department of Mathematics and Computer Science, Royal Military College of Canada (RMC), Kingston, ON, Canada. He is the coauthor of more than 200 peer-reviewed publications in established journals and conference proceedings sponsored by established publishers, such as IEEE, ACM, Elsevier, and Springer. He is a member of the IEEE Communication Society, the IEEE Vehicular Technology Society (VTS), and the IEEE Photonics Society. He has served for roughly 30 conference and workshop program committees. He served as a guest editor/associate editor for several well-reputed journals.

NGUYEN MINH QUY received the B.S. degree in information technology from the Hanoi University of Science and Technology, the master's degree in software engineering from the VNU University of Engineering and Technology, Vietnam, and the Ph.D. degree in software engineering from the Hanoi University of Science and Technology, in 2015. He is currently the President of the Council of the Hung Yen University of Technology and Education. His research interests include high-performance computing, mobile communication networks, and software engineering.

NGUYEN DINH HAN was born in Hung Yen, Vietnam, in 1977. He received the degree from Vietnam National University, Hanoi, in 2000, the degree from AIT, in 2005, and the Ph.D. degree from the Hanoi University of Science and Technology, Vietnam, in 2013. He was a Postdoctoral Fellow with Korea University, in 2013. He is currently an Associate Professor with the School of Applied Mathematics and Informatics, Hanoi University of Science and Technology. His research interests include the theory of codes and applications, computer and network security, wireless communications, mobile cloud computing, and the Internet of Things.

NGUYEN TIEN BAN was born in Vinh Phuc, Vietnam, in 1967. He received the degree from the Leningrad University of Electrical Engineering (LETI) and the Ph.D. degree from the Saint Petersburg State University of Telecommunications (SUT), Russia, in 2003. He is currently an Associate Professor with the Faculty of Telecommunications, Posts and Telecommunications Institute of Technology (PTIT). His research interests include network performance analysis and design, network design and optimization, and the modeling and simulation of telecommunication systems.