Received November 15, 2019, accepted November 29, 2019, date of publication December 4, 2019, date of current version December 18, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2957648

A Survey on Green 6G Network: Architecture and Technologies

TONGYI HUANG[1], WU YANG[2], JUN WU[1], (Member, IEEE), JIN MA[1], XIAOFEI ZHANG[3], AND DAOYIN ZHANG[3]

[1]School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[2]Information Security Research Center, Harbin Engineering University, Harbin 150001, China
[3]State Grid Electric Power Research Institute, Nanjing 211000, China

Corresponding authors: Wu Yang (yangwu@hrbeu.edu.cn) and Jun Wu (junwuhn@sjtu.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61831007 and Grant 61972255, in part by the State Key Laboratory of Smart Grid Protection and Control under Grant SGNROOOOGZJS1808084, and in part by the Research on Key Technologies of Security Vulnerabilities and Risk Experiment Capabilities of State Grid Headquarters Science and Technology Projects.

ABSTRACT While 5G is being commercialized worldwide, research institutions around the world have started to look beyond 5G and 6G is expected to evolve into green networks, which deliver high Quality of Service and energy efficiency. To meet the demands of future applications, significant improvements need to be made in mobile network architecture. We envision 6G undergoing unprecedented breakthrough and integrating traditional terrestrial mobile networks with emerging space, aerial and underwater networks to provide anytime anywhere network access. This paper presents a detailed survey on wireless evolution towards 6G networks. In this survey, the prime focus is on the new architectural changes associated with 6G networks, characterized by ubiquitous 3D coverage, introduction of pervasive AI and enhanced network protocol stack. Along with this, we discuss related potential technologies that are helpful in forming sustainable and socially seamless networks, encompassing terahertz and visible light communication, new communication paradigm, blockchain and symbiotic radio. Our work aims to provide enlightening guidance for subsequent research of green 6G.

INDEX TERMS 6G, architecture, green networks, VLC, blockchain.

I. INTRODUCTION

With the completion of the first full set of 5G standards, the initial commercial deployment of 5G wireless networks has begun in 2019. 5G wireless network marks the beginning of a true digital society and achieves significant breakthroughs in terms of latency, data rates, mobility and number of connected devices in contrast to previous generations [1]. Looking back at the evolution of mobile communication, it takes about one decade from the initial concept research to the commercial deployment, while its subsequent usage lasts for at least another 10 years. That is, when the previous generation mobile network enters the commercial phase, the next generation begins concept research. As 5G is in the initial stages of commercialization, now is the right time to launch research on 5G's successor.

In the past few years, some countries have issued strategic plans for the development of 6G [2]. In 2018, Finland announced the 6Genesis Flagship program, an eight-year program with the overall volume of $290 million to develop a complete 6G ecosystem [3]. The U.K. and German governments have invested in some potential technologies for 6G such as quantum technology, and the United States began research on terahertz-based 6G mobile networks. The Minister of Industry and Information Technology in China has made the official pronouncement that the country has focused on the development of 6G.

Novel service requirements and scale increases are the driving force behind the evolution of wireless network. The rapid development of emerging applications results in a never-ending growth in mobile data traffic. According to the forecast by International Telecommunication Union (ITU), global mobile data traffic will reach 5 zettabytes by 2030 [4], as shown in Fig. 1. Upcoming applications (e.g. e-health and autonomous driving) have more stringent requirements for latency and throughput, which will eventually exceed the limits of 5G networks. It is expected that 5G will reach its limits in a decade or so and to meet these demands, the main technical objectives for 6G networks will be

- Ultra-high data rate (up to 1Tbps) and ultra-low latency.
- High energy efficiency for resource-constrained devices.

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

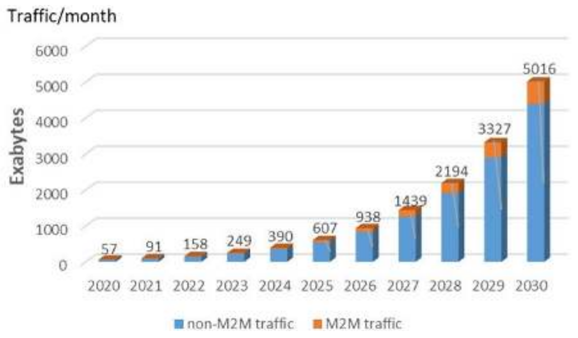


FIGURE 1. Global mobile data traffic in 2020-2030 forecast by ITU.

- Ubiquitous global network coverage.
- Trusted and intelligent connectivity across the whole network.

In this paper, we discuss some emerging ideas about potential architecture and technologies of 6G. The rest of the paper is organized as follows. Section II presents the evolution of mobile communication networks. Section III gives the detailed description of architectural changes of 6G. Section IV provides a brief overview of some visionary technologies that may be key parts of 6G. Finally, this paper is concluded in Section V.

II. EVOLUTION OF MOBILE COMMUNICATION NETWORK

There has been a phenomenal advancement in mobile communication network since the first emergence of analog communications network in the 1980s. This advancement is not a one-step process, but consists of several generations which have different standards, capacities and techniques. New generation have been introduced nearly every ten years [5]. The evolution of mobile network is shown in Fig. 2.

A. FROM 1G TO 3G

The first generation mobile network was introduced in the 1980s, which was designed for voice services, with a data rate up to 2.4 kbps. It used analog signal to transmit information and there was no universal wireless standard, leading to many drawbacks such as problematic hand-off, low transmission efficiency and no security [6]. Compared to first-generation systems, 2G was based on digital modulation technologies such as Time Division Multiple Access(TDMA) and Code Division Multiple Access(CDMA). It has a data rate up to 64kbps, supporting not only better voice services, but also services like Short Message Service (SMS). The all-dominant mobile communication standard in the 2G era was the GSM (Global System for Mobile Communication) [7]. The third generation was proposed in 2000 with the goal of offering high-speed data transmission. 3G network provides a data transfer rate of at least 2 Mbps as well as high speed access to Internet [8]. It enables advanced services not supported by 1G and 2G networks, including Web browsing, TV streaming, navigational maps and video services. In order to achieve global roaming, an organization called 3rd Generation Partnership Project (3GPP) was established to define technical specifications and continue the work by defining mobile standards and systems [9].

B. 4G

4G is an all IP based network introduced in the late 2000s, which is capable of providing high-speed data rates up to 1Gbits/s in the downlink and 500Mbits/s in the uplink. It apparently improves spectral efficiency and reduces latency, accommodating the requirements set by advanced applications like Digital Video Broadcasting (DVB), High Definition TV content and video chat. Moreover, 4G enables terminal mobility to provide wireless services at anytime and anywhere, through automatic roaming

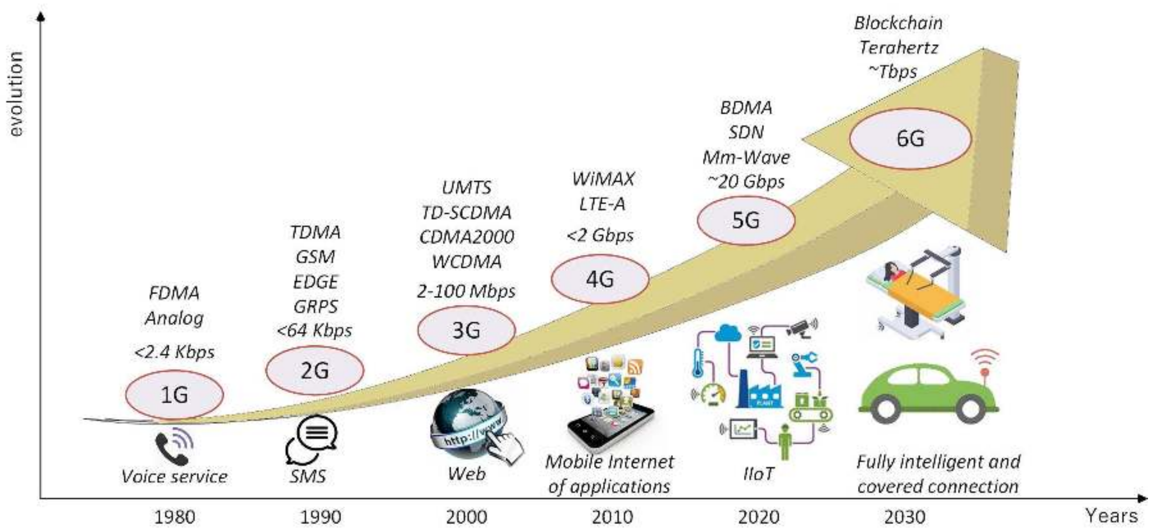


FIGURE 2. Evolution of mobile wireless systems.

across geographic boundaries of wireless networks. Long Term Evolution-Advanced (LTE-A) and Wireless Interoperability for Microwave Access (WiMAX) are considered as 4G standards [10]. LTE integrates existing and new technologies such as coordinated multiple transmission/reception (CoMP), multiple-input multiple-output (MIMO), orthogonal frequency division multiplexing (OFDM).

C. 5G

The fifth generation mobile communication network has almost completed the initial basic tests, hardware facilities construction and standardization process, and will soon be put into commercial use. The goal of 5G is to make revolutionary advances in data rates, latency, network reliability, energy efficiency, and massive connectivity [11]. It not only uses the new spectrum of the microwave band (3.3-4.2 GHz), but also innovatively uses the millimeter-wave band for the first time, greatly increasing data rates (up to 10 Gbps). 5G applies advanced access technologies, including Beam Division Multiple Access (BDMA) and Filter Bank multi carrier (FBMC). Many emerging technologies are integrated into 5G to improve network performance: Massive MIMO for capacity increase, Software Defined Networks (SDN) for flexibility in network, device-to-device (D2D) for spectral efficiency, Information Centric Networking (ICN) for reduction in network traffic and network slicing for quick deployment of various services [12]–[14]. IMT 2020 proposed three major 5G usage scenarios: Enhanced mobile broadband (eMBB), Ultra-reliable and low latency communications (URLLC) and Massive machine type communications (mMTC).

D. VISION OF GREEN 6G

As 5G is entering the commercial deployment phase, research institutions around the world have begun to pay attention to 6G, which is considered to be deployed in about 2030. Green 6G is expected to enhance the performance of information transmission - peak data rates up to 1 Tbps and ultra-low latency in microseconds. It features terahertz frequency communication and spatial multiplexing, providing as much as 1000 times higher capacity than 5G networks. One goal of 6G is to achieve ubiquitous connectivity by integrating satellite communication networks and underwater communications to provide global coverage [19]. Energy harvesting technologies and the use of new materials will greatly improve the system energy efficiency and realize sustainable green networks. Three new 6G service classes were described in [15]: ubiquitous mobile ultrabroadband (uMUB), ultrahigh-speed-with-low-latency communications (uHSLLC) and ultrahigh data density (uHDD).

III. ARCHITECTURES OF GREEN 6G NETWORK

Green 6G networks are expected to achieve energy-efficient and socially seamless wireless connections in a global scope, while the existing network architecture is nuable to guarantee future application delivery constraints — ultra-high throughput, ultra-low latency and reliability. Therefore, forward-looking research on future network frameworks is necessary. FG NET-2030 has established Sub-Group 3 to formulate architecture of Network 2030. However, it is unrealistic to accurately illustrate what the future network architecture will be. Sub-Group 3 has reached a compromise — interpreting the architecture from different dimensions rather than defining a unified framework. In this section, we introduce the architectural changes associated with 6G from three dimensions, as shown in Fig. 3.

A. FROM TERRESTRIAL TO UBIQUITOUS 3D COVERAGE

One target of the next generation network architecture is to expand the breadth and depth of communication coverage. The current network architecture based on legacy terrestrial cellular infrastructure has the following two drawbacks: inability to meet the high-altitude and deep-sea communication scenarios, which is an inevitable requirement for future services; prohibitively expensive provisioning cost for dense cellular networks to provide connectivity in the global scale. In order to cover the above drawbacks, 6G will integrate non-terrestrial networks to provide full wireless coverage [16]. Preliminary envision about Space-Air-Ground-Sea integrated communication has been discussed in [17].

1) SPACE NETWORK: LEO SATELLITE SYSTEM

High throughput satellite (HTS) systems are capable of broadband Internet access service comparable to terrestrial services in terms of pricing and bandwidth. Most communications satellites are in geostationary orbit (GEO) at an altitude of 35,786 km, naturally leading to excessive delay and infeasibility of integration with terrestrial mobile network. Non-geostationary orbit (NGSO) satellite system is proposed to provide low-latency, high-bitrate global Internet connectivity and several satellite constellations are about to begin commercialization:

- Starlink: American company SpaceX plans to launch Starlink, a constellation of 4,425 low Earth orbit LEO) satellites and 7518 VLEO satellites in approximately 340 km orbits. The plan was authorized by the Federal Communications Commission (FCC) [18] and will be fully deployed in 2027.
- OneWeb: On February 27, 2019, OneWeb successfully launched its first six satellite into orbits. The constellation consists of 720 LEO satellite [20] and has got authorization from UK and FCC.
- Hongyan: China Aerospace Science and Technology Corporation (CASC) will launch nine LEO satellites as a pilot demonstration for the Hongyan system, which ultimately will comprise 320 satellites and be completed by 2025.

Although there is still a long time before overall deployment of NGSO satellite systems and convergence of satellite communications and mobile wireless networks, advantages of LEO satellite networks have been confirmed in theory

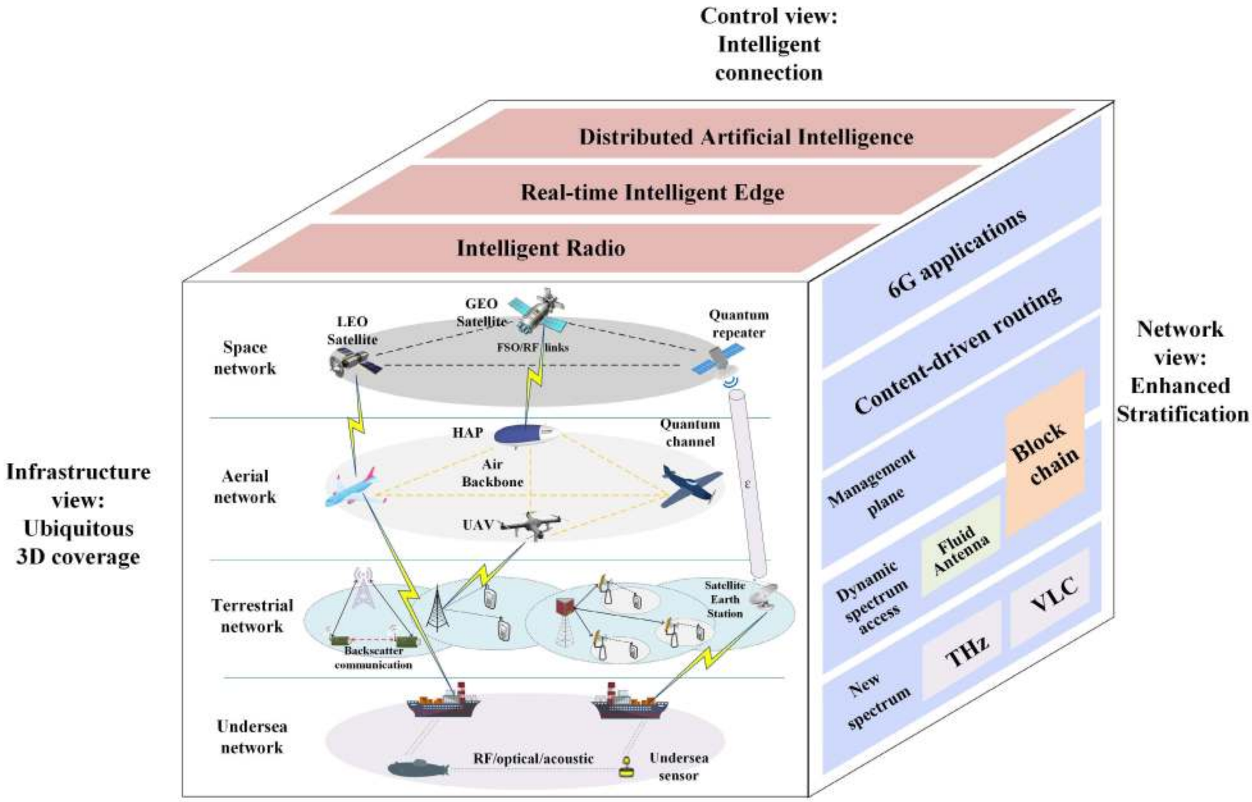


FIGURE 3. Different dimensions of the architecture of green 6G.

and simulation environment. LEO network with laser and radio frequency (RF) co-routing mechanism can provide lower latency communications than terrestrial optical fiber networks when communication distances are greater than about 3000 km [21].

A potential architecture of the space-terrestrial integrated network (STIN) has shown in [22], comprised of the space-based backbone network (SBN) of GEO satellites and the inter-satellite links (ISLs) connecting them, terrestrial networks (TN) and space-based access networks (SAN) of LEO and medium earth orbit (MEO) satellites. SBN is capable of extending coverage and ensuring reliable space-ground connectivity while SAN is essential for integration with terrestrial and HTS networks to support ubiquitous global wireless access. Several emerging technologies are embraced to facilitate the integration of terrestrial and satellite networks. SDN and ICN have been introduced into STIN with the advantages of flexible network control, efficient network configuration and small request delay [23]. The performance of Multipath TCP (MPTCP) was evaluated in [24] and the result indicates that MPTCP strategy improves throughput and provides uninterrupted connections during handover.

2) AERIAL NETWORK: FLEXIBLE RELAY SERVICES

Aerial network can be broadly classified into two categories, high altitude platforms (HAP) which generally operate in the stratosphere and low altitude platforms (LAP) typically at an altitude of no more than several kilometers. Compared to LAP, HAP networks are capable of wider coverage and longer endurance, but the advantages of HAP overlap with LEO satellite network to some extent. On the other hand, LAP networks based on unmanned aerial vehicle (UAV) can be swifter to deploy, more flexibly reconfigured to best suit the communication environment, and present better performance in short-range communication [25]. Besides, flying base stations like UAV can work as relay nodes in long-distance communication to promote the integration of terrestrial and non-terrestrial networks. These features make UAV-based wireless network a potential integral component of next-generation mobile communication system. In [26], a fully integrated, multi-layer vertical architecture for 6G network was presented, including heterogeneous terrestrial networks, UAV-based LAPs, HAPs, LEO and GEO satellite networks.

The most attracting characteristic of UAV wireless network is that it enables mobile communication in situations where there are heavily compromised infrastructures or even no infrastructures, especially in catastrophic and emergency situation. UAV network has been applied to temporary emergency communication services, however, there are issues to be tackled before stable and reliable UAV network can be introduced into common application scenarios [27]. First of all, energy efficiency is critical to long-term network service. Propulsion and directional adjustment consume most of the

TABLE 1. Comparison of diffirent undersea wireless communication technologies.

	RF	Acoustic	Optical
Attenuation	High	Lowest	$\propto$turbidity
Data rates [34]	~Mbps	~Kbps	~Gbps
Latency [34]	Moderate	High	Low
Transmission distance	<10m	<100km	<100m
Power consumption	Moderate	High	Low

energy in UAV communications, therefore new trajectory optimization and route planning schemes are proposed and significantly improve energy efficiency [28], [29]. In [30], a learning-based computing offloading approach was presented to reduce energy consumption and total cost. Secondly, extreme weather condition should be considered in UAV communication. Free space optics (FSO) is introduced into backhaul framework where UAVs transmit information via point-point FSO links, enabling UAV network to offer high data rates in different weather condition [31]. Thirdly, due to frequent topology change caused by high-speed mobility, more advanced mobile ad hoc protocols are demanded. The authors in [32] proposed adaptive hybrid communication protocols which outperform existing protocols.

3) UNDERSEA NETWORK
There is a lot of controversy about whether undersea network is able to become a part of the future 6G network [17]. Undersea wireless communication mainly involves RF, acoustic and optical communication. The comparison between the above three communication technologies is shown in Table 1. Unpredictable and complex underwater environment leads to intricate network deployment, severe signal attenuation and physical damage to equipment [33], leaving plenty of issues to be resolved.

B. TOWARDS INTELLIGENT NETWORK
Artificial intelligence (AI), more specifically machine learning (ML), has attracted a lot of attention from industry and academia in recent years and initial intelligence has been applied to many aspects of 5G cellular networks [35], from physical layer applications such as channel coding and estimation, to MAC layer applications such as multiple access, to network layer applications such as resource allocation and error correction, and etc. In addition, the combination of artificial intelligence and edge computing proves to improve Quality of Experience and reduce costs [36]. Edge learning also provides new possibilities for the implementation of many applications, such as healthcare [37]. However, the application of AI in 5G networks is limited to the optimization of traditional network architecture and it is difficult to fully realize the potential of AI in the 5G era since the 5G network did not take AI into account at the beginning of architecture design. To fulfill the vision of intelligent network, the design of 6G architecture should consider possibilities of AI in network comprehensively and follow an AI-driven approach where intelligence will be an endogenous characteristic of 6G architecture.

Initial intelligence is that a relatively isolated network entity can intelligently adjust the configuration based on multiple predefined options in a different yet deterministic manner [35], which is actually an implementation of perceptual AI without the capability to respond to unintended scenarios. As the network is evolving into an extreme complex and heterogeneous system because of diversified service requirements and explosively growing number of connected devices, a novel AI paradigm of self-aware, self-adaptive, self-interpretive and prescriptive networking is much needed [38]. It requires not only embedding intelligence across whole network, but also embedding the logic of AI into the network structure, in which perception and inference interact in a systematic way, eventually enabling all network components to autonomously connect and control with the ability to recognize unexpected situations and adapt to them. The ultimate expectation of intelligent networks is the autonomous evolution of networks. We highlight three key enablers for intelligent network, as described below.

1) REAL-TIME INTELLIGENT EDGE (RTIE)
Next generation network will require the support of interactive AI-powered services and some services like autonomous vehicles are sensitive to response latency, which needs to interact intelligently with their environments in real time. Centralized cloud AI dealing with static data is incapable of achieving such services and there is an urgent need for the RTIE, where intelligent prediction, inference and decision are made on live data. Major academia and industry have begun to develop technologies and software components that meet the real-time requirements in collaborative research labs such as the Berkeley RISELab [39]. High-performance hardware is another driving factor for RTE and a specialized real-time AI processor has been designed in [40].

2) INTELLIGENT RADIO (IR)
In contrast to deployed physical (PHY) layer with initial intelligence, IR is a broader and deeper conception that separates hardware and transceiver algorithms. It operates as a unified framework where hardware capabilities are estimated and transceiver algorithms can dynamically configure themselves according to the hardware information. From the perspective of PHY layer, IR is able to access the available spectrum, control transmission power and adjust transmission protocols

TABLE 2. Inherent shortcomings of current Internet.

Internet characteristic	Inherent shortcoming
Best-effort delivery	No guarantee of throughput and latency
radio retransmission are not synchronized with TCP flow control	TCP wastefully retransmits packets
Network is not aware of the needs of application layers	Unable to provide deterministic services
Fixed protocol fields	Encapsulation redundancy
Blind and independent congestion control	Unnecessary retransmission and drop
IP address doesn't represent the real communication entities	Hard to satisfy different requests
Tunnels over tunnels and duplicate header fields	High header taxes and low protocol efficiency

with the aid of AI [41]. By decoupling transceiver algorithms from hardware, new design paradigm allows agile adaptation to upgradable and diversified hardware [15].

3) DISTRIBUTED AI

The future network will be a large decentralized system, where intelligent decisions are made at different granular levels. To accelerate the learning and improve the inferential reliability, distributed AI leverages distributed C4 resources (computation, communication, caching and control) [42] in the network through parallel training process that requires splitting the data and model in an appropriate manner. A recently developed distributed AI paradigm is federated learning [43] — models are trained at edge based on local sample patterns and sent to centralized cloud for model averaging, thereby obtaining a shared global model. It also strengthens security and privacy by keeping data at edge.

C. NEW NETWORK PROTOCOL STACK ARCHITECTURE

The existing Internet protocol stack architecture, typically TCP/IP, was originally designed for data delivery and has achieved huge success over the past 40 years. Nonetheless, current Internet has encountered many unprecedented challenges and cannot guarantee futuristic application delivery constraints (e.g., deterministic throughput and latency). In recent years, some protocols built on TCP/IP such as QUIC (Quick UDP Internet Connections) have eased these challenges to some extent. Unfortunately, these patch-like protocols make the Internet more complicated and are not able to completely remedy the inherent Internet shortcomings (shown in Table 2) [44]. This brings the need to rethink the TCP/IP protocols and new developments are expected to provide services beyond end-to-end transportation.

Current network layer packets follow a fixed ''header + payload'' mode, which is isolated from the requirements of upper applications. To support abundant future applications and provide differentiated network services, meta-data and commands defined by the application designer may become important component of new IP protocol. Such protocol fields could include identifiers of real communication entities and information about flow states, applications' requirements, network measurement metrics and security details. Ideally, the network functions could perceive the expected packet format and implement flexible policies based on meta-data and commands. With the aid of additional information from upper layer, the routing and forwarding strategies would be efficient and direct.

Similarly, the transport layer necessitates further enhancement (e.g. differential priorities for data and high-precision synchronization for multipath transmission) to accommodate future communication needs. In [45], a cross-layer transport layer was advocated. It merges traditional network and transport layer and carries out functions of both layers at the same time. The benefit of the combined layer is that it takes into account the requirements of applications and the overall network state, thus reducing congestion more effectively. Furthermore, the cross-layer design breaks the end-to-end principle and provides advanced network function such as flow multiplexing.

IV. PROMISING TECHNOLOGIES OF GREEN 6G

A. SPECTRUM COMMUNICATION TECHNIQUES

Spectrum is the foundation of mobile communications and since the rise of mobile networks in the 1980s, we have witnessed tremendous expansion of spectrum resources in every new generation due to the endless pursuit for data rates. One of the main targets of 6G is to provide Tbps aggregated bit rate and it is inevitable to operate at higher frequencies for available spectrum and bandwidth. Terahertz (THz) and visible light are two attractive candidate spectrums [46].

1) THZ COMMUNICATION

The THz band is the spectral band between microwave and optical bands, with frequency ranging from 0.1 THz to 10 THz. Except for abundant undeveloped spectrum resources, there are many unique characteristics that motivate the use of THz band for future communication networks [47]: (1) THz communication system is promised to support data rates on the order of 100 Gbps or more with tens of GHz available bands in THz spectrum, while there is only 9 GHz bandwidth within mm-Wave band [48]. (2) THz wave could realize secure communication due to narrow beam and short pulse duration that drastically limit the probability of eavesdropping. (3) THz waves are able to penetrate some materials with a small attenuation, which is suitable for some special scenes. With such characteristics, THz wave has broad application prospect in ultra-high speed wireless communication and space communication, thus global regulatory bodies and standard agencies are already trying to expedite the development of new communications technologies in THz spectrum:

- In March 2019, the FCC voted to permit enhanced experimental licensing and unlicensed applications within the

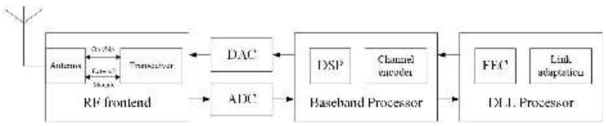


FIGURE 4. THz wireless radio transceiver hardware.

spectrum between 95GHz and 3THz and launched a new license type— Spectrum Horizons License with low barriers and minimal cost in order to accelerate the development of THz technologies [49].

- In Europe, Horizon 2020, the biggest EU Research and Innovation program, has funded several projects in the call ''Networking research beyond 5G'', most of which are aiming at THz technologies.
- IEEE has begun to take the first steps for THz communication standardization by forming the IEEE 802.15 wireless personal area network (WPAN) Task Group 3-D 100 Gb/s Wireless (TG 3d 100 G) [50] and created the first worldwide wireless communication standard in the 250-350 GHz frequency range which channelizes the band into 32 channels of 2.16 GHz.
- The International Telecommunication Union (ITU) has decided to classify 0.12THz and 0.2THz into wireless communication.
- The Ministry of Internal Affairs and Communications of Japan has established an R&D program on Key Technology in Terahertz Frequency Bands and supported a lot of related work, such as CMOS technology in the THz band.

There are tremendous challenges ahead for mature THz wireless communication system, but global research has made some breakthroughs. In [51], the authors designed a 300-GHz band wireless transceiver chipset and a module that connects CMOS chipset to external waveguide antenna to overcome the defect of low antenna gain of on-chip antenna. Recently, a full-featured single-chip transceiver capable of data rates of 80Gb/s was introduced in [52]. Owing to such high frequencies, the reflections, cross-talks, and attenuation on the bonding wires lead to many problems in the design of RF-frontend and baseband such as gain reduction. [53] advocates shifting these problems to data link layer (DLL) and fabricates a DLL processor with low-chip area. Fig. 4 depicts the hardware structure of THz wireless radio transceiver.

In order to support THz communication, the following aspects need further research: (1) Transistor and hardware materials with excellent high frequency characteristics. The most potential material employed for hardware design is graphene which has high thermal and electrical conductivities and plasmonic effects [54]. (2) Robust beam forming and scanning algorithms such as hybrid beamforming approaches. (3) Low-complexity, low-power hardware circuits. (4) Channel and noise modeling. It is hard to establish a common THz channel model and mixture models may be the solution to this problem. (5) Energy efficient modulation schemes and low-density channel codes. (6) Ultra-massive MIMO system. Nano antennas will play an important role in MIMO systems. (7) Powerful synchronization schemes.

2) VISIBLE LIGHT COMMUNICATIONS

Optical Wireless Communications (OWC) are considered as a complementary technology for RF-based mobile communications and the frequency range includes infrared, visible light and ultraviolet spectrum. The visible light spectrum (430-790THz) is the most promising spectrum of OWC due to the technological advances and widespread adoption of LED. One of the most striking aspects of LED different from older illumination technology is that it can switch to different light intensity levels very quickly, which enables data to be encoded in emitted light in a variety of ways [55].

Visible light communication (VLC) takes full advantage of LED to achieve the dual purposes of lightning and high-speed data communication. VLC for short range links (up to few meters) has many attractive advantages over classical radio communication [56]. Firstly, visible light spectrum provides ultra-high bandwidth (THz), and the spectrum is free and unlicensed. Secondly, visible light, VLC's transmission medium, cannot penetrate opaque obstructions. This means that the transmission of network information is confined to one building and receivers outside the building are incapable of receiving the signals, which obviously guarantees the information transmission security and reduces the inter-cell interference that is very serious in high-frequency RF communication. Thirdly, VLC utilizes illumination sources as base stations, which does not need expensive base station construction and maintenance costs that are required in

TABLE 3. Comparison of THz communication and VLC.

	THz	VLC
Available bandwidth	Tens to hundreds of GHz	Hundreds of THz
Transmission distance	non-line-of-sight (NLOS)	LOS
electromagnetic radiation	yes	no
Data rate achieved	100Gbps	10Gbps
Spectrum regulatory	licensed	unlicensed
Penetration ability	Special opaque materials	Transparent materials
Inter-cell interference	serious	none
Cost	expensive	cheap
Transmission power	High	low
diffuse reflection losses	licensed	unlicensed

RF communication. Finally, VLC does not generate electromagnetic radiation and is immune to external electromagnetic interference. Therefore, it is suitable for special situations sensitive to electromagnetic radiation [57] such as aircraft and hospital.

The maximum achievable data rate depends largely on lighting technology [58]. The data rate of VLC based on phosphor coated blue LED is up to 1 Gb/s, while the data rate based on RGB LED can reach multi-Gb/s. The best performing LED technology is micro-LED, which has achieved data rates of more than 10 Gb/s in the lab [59]. With the continuous improvement of the life and luminous efficiency of LED lamps and the advancement of related technologies (e.g. digital modulation technology), VLC is expected to reach the data rate of hundreds of Gb/s, or even Tb/s, in the 6G era.

B. NEW COMMUNICATION PARADIGM

1) MOLECULAR COMMUNICATION

There are many environments (i.e. nanonetwork inside body) where conventional wireless communication based on electromagnetic (EM) waves may not be feasible or efficient. A new communication paradigm inspired by nature is considered a possible solution which uses biochemical signals to transfer information, referred to as molecular communications (MC) [60]. In MC, biochemical signals are typically small particles of a few nanometers to a few micrometers in size such as lipid vesicles and particles, which usually propagate in aqueous or gaseous medium.

Compared with radio communication, MC has certain advantages in both micro and macro scale. On the one hand, at nanoscale dimension, electromagnetic communication is constrained by the ratio of antenna size to EM wavelength, while MC signals are biocompatible, and consume very little energy for generation and propagation [61], which makes MC ideal for intrabody nanonetworks [62]. On the other hand, EM communication is not reliable in some harsh environments such as underground tunnels and gas pipelines due to high propagation path loss. An emerging view is that MC is highly dynamic, leading to the initial research of mobile MC [63]. Mobile carriers are useful for network implementation and increase data transfer rates. Ultimately, MC systems are expected to interface with the Internet and mobile networks and the two major challenges are the interfaces between electrical and chemical domain, and security assurance methods [64].

2) QUANTUM COMMUNICATION

Quantum communication (QC) is another promising communication paradigm with unconditional security. The fundamental difference between quantum communication and classical binary based communication is whether eavesdropping can be detected on-site [65]. The information is encoded in quantum state using photons or quantum particles and cannot be accessed or cloned without tampering it due to quantum principles such as correlation of entangled particles and inalienable law. Furthermore, QC can improve data rates due to the superposition nature of qubits. After decades of exploration, there are many branches of QC: quantum key distribution, quantum teleportation, quantum secret sharing and quantum secure direct communication [66].

A number of works have practically implemented initial quantum network and associated protocols of various branches. The properties and capacities of QC channels were summarized in [67]. Another attractive feature of QC is its huge potential in long-distance communication. Quantum repeaters are critical devices for long-distance global quantum network, which is capable of dividing the distance of QC into shorter intermediate segments and correcting both photon loss and operation errors [68]. A recent work has realized intercontinental QC with a maximal distance of 7600km relying on LEO satellites as relay.

C. FUNDAMENTAL TECHNIQUES

1) BLOCKCHAIN FOR DECENTRALIZED SECURITY

Blockchains are distributed ledger-based databases where transactions can be securely registered and updated without central intermediaries [69]. The inherent features of blockchain such as decentralized tamper-resistance and anonymity make it ideal for various applications [70]. In 2018 Mobile World Congress Americas (MWCA), the FCC commissioner, Jessica Rosenworcel, indicated that blockchain will play an important role in next-generation wireless network [71].

Blockchain is considered as the next revolution for future mobile communication technologies. It guarantees stronger security features throughout the communication since it enables various network entities to securely access the critical data and an untamable distributed ledger containing all data is shared among all relevant entities [72]. Apart from security, blockchain provides several benefits in resource orchestration and network access. Decentralized control mechanism based on blockchain enables direct communication links to be established between network entities, which reduces the administrative costs [73]. Instead of centralized database, the integration of blockchain in spectrum sharing system can increase spectral efficiency. In addition, blockchain facilitates the integration of individual systems developed by different operators by providing a unified authentication and authorization mechanism and billing system [74], and allows roaming across operators and networks.

2) FLEXIBLE AND INTELLIGENT MATERIALS

Despite the tremendous success in wireless communication system over the past decades, the performance of traditional semiconductor materials like silicon seems to reach its limits and materials with better high-frequency and high-temperature characteristics are in urgent need for ultrahigh-speed communication. Novel materials such as Gallium Nitride, Indium Phosphide, Silicon Germanium and Graphene have been used to design next-generation communications devices. Moreover, fluid materials are introduced into the design of frequency-reconfigurable antennas to provide more flexibility [75].

Metamaterial and metasurface can be deployed in a radio-controllable wireless environment [76]. Metamaterials are artificial structures composed by periodic or quasi- periodic meta-atoms with EM properties across any frequency domain. Software-controlled planar metamaterials are possible to reduce the interference by deterministic control over the properties of the environment [77].

3) ENERGY HARVESTING AND MANAGEMENT

The consistent computation demands for AI processing and increasing proliferation of IoT devices are posing significant challenges to the energy efficiency of communication equipment. Therefore, energy-efficient communication technologies will shine in 6G where communication distance is much shorter. There have been numerous efforts spent on energy harvesting and management researches over the past decade. A technology called symbiotic radio (SR) offers a possible solution to the energy problem, which integrates passive backscatter devices with active transmission system [78]. A typical example of SR is ambient backscatter communication, in which network devices utilize ambient RF signals to transmit information without requiring active RF transmission, making battery-free communication possible [79]. Smart energy management is another promising mechanism with the goal of dynamically optimizing the balance between energy demand and supply [80].

V. CONCLUSION

Almost exponential increase in wireless data, especially multimedia data, and rapid proliferation of all kinds of smart devices are setting the stage for next wireless evolution towards 6G. 6G wireless networks are promising a significant increase in QoS and sustainable future. In this paper, we present a detailer survey on wireless evolution towards green 6G networks. We commence with the evolution of mobile wireless network from 1G to 5G, which indicates the development trend of 6G to some extent. Subsequently, the new architectural paradigm shift is explained with three brand new characteristics, including the integration of terrestrial and non-terrestrial networks, truly intelligent connections enabled by pervasive AI and enhanced network protocol stack framework. Finally, we focus our attention on emerging technologies. New spectrum technologies, like THz communication and VLC, and new communication paradigms, such as molecular and quantum communication, have been discussed, which are potential to dramatically improve data rates and become key parts of a seamless society. Innovations in fundamental technologies are also explained, including introduction of blockchain, flexible and intelligent material and ambient backscatter communication. This survey may serve as an enlightening guideline for future research works in green 6G communications.

REFERENCES

[1] D. Soldani and A. Manzalini, "Horizon 2020 and beyond: On the 5G operating system for a true digital society," *IEEE Veh. Technol. Mag.*, vol. 10, no. 1, pp. 32–42, Mar. 2015.

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

[3] 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.

[4] *IMT Traffic Estimates for the Years 2020 to 2030*, document ITU-R SG05, Jul. 2015.

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

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

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

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

[9] A. U. Gawas, "An overview on evolution of mobile wireless communication networks: 1G-6G," *Int. J. Recent Innov. Trends Comput. Commun.*, vol. 3, no. 5, pp. 3130–3133, 2015.

[10] J. Parikh and A. Basu, "LTE advanced: The 4G mobile broadband technology," *Int. J. Comput. Appl.*, vol. 13, no. 5, pp. 17–21, 2011.

[11] M. Shafi, A. F. Molisch, P. J. Smith, T. Haustein, P. Zhu, P. De Silva, F. Tufvesson, A. Benjebbour, and G. Wunder, "5G: A tutorial overview of standards, trials, challenges, deployment, and practice," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 6, pp. 1201–1221, Jun. 2017.

[12] Z. Zhou, M. Dong, K. Ota, G. Wang, and L. T. Yang, "Energy-efficient resource allocation for D2D communications underlaying cloud-RAN-based LTE-A networks," *IEEE Internet Things J.*, vol. 3, no. 3, pp. 428–438, Jun. 2016.

[13] J. Wu, M. Dong, K. Ota, J. Li, W. Yang, and M. Wang, "Fog-computing-enabled cognitive network function virtualization for an information-centric future Internet," *IEEE Commun. Mag.*, vol. 57, no. 7, pp. 48–54, Jul. 2019.

[14] J. Wu, M. Dong, K. Ota, J. Li, and Z. Guan, "Big data analysis-based secure cluster management for optimized control plane in software-defined networks," *IEEE Trans. Netw. Service Manag.*, vol. 15, no. 1, pp. 27–38, Mar. 2018.

[15] 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.

[16] 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.

[17] Y. Zhao, G. Yu, and H. Xu, "6G mobile communication network: Vision, challenges and key technologies," 2019, *arXiv:1905.04983*. [Online]. Available: https://arxiv.org/abs/1905.04983

[18] *Memorandum Opinion, Order and Authorization in the Matter of Application for Approval for Orbital Deployment and Operating Authority for the SPACEX NGSO Satellite System*, document FCC-18-38, Mar. 2018.

[19] A. Yastrebova, R. Kirichek, Y. Koucheryavy, A. Borodin, and A. Koucheryavy, "Future networks 2030: Architecture & requirements," in *Proc. 10th Int. Congr. Ultra Mod. Telecommun. Control Syst. Workshops (ICUMT)*, Nov. 2018, pp. 1–8.

[20] J. Radtke, C. Kebschull, and E. Stoll, "Interactions of the space debris environment with mega constellations—Using the example of the OneWeb constellation," *Acta Astronautica*, vol. 131, pp. 55–68, Feb. 2017.

[21] M. Handley, "Delay is not an option: Low latency routing in space," in *Proc. 17th ACM Workshop Hot Topics Netw.*, 2018, pp. 85–91.

[22] H. Yao, L. Wang, X. Wang, Z. Lu, and Y. Liu, "The space-terrestrial integrated network: An overview," *IEEE Commun. Mag.*, vol. 56, no. 9, pp. 178–185, Sep. 2018.

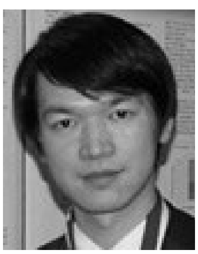
[23] Z. Liu, J. Zhu, C. Pan, and G. Song, "Satellite network architecture design based on SDN and ICN technology," in *Proc. 8th Int. Conf. Electron. Inf. Emergency Commun. (ICEIEC)*, Jun. 2018, pp. 124–131.

[24] P. Du, S. Nazari, J. Mena, R. Fan, M. Gerla, and R. Gupta, ''Multipath TCP in SDN-enabled leo satellite networks,'' in *Proc. IEEE Mil. Commun. Conf. (MILCOM)*, Nov. 2016, pp. 354–359.
[25] Y. Zeng, R. Zhang, and T. J. Lim, ''Wireless communications with unmanned aerial vehicles: Opportunities and challenges,'' *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 36–42, May 2016.
[26] H. Yanikomeroglu, ''Integrated terrestrial/non-terrestrial 6G networks for ubiquitous 3D super-connectivity,'' in *Proc. 21st ACM Int. Conf. Model., Anal. Simulation Wireless Mobile Syst.*, 2018, pp. 3–4.
[27] L. Gupta, R. Jain, and G. Vaszkun, ''Survey of important issues in UAV communication networks,'' *IEEE Commun. Surveys Tuts.*, vol. 18, no. 2, pp. 1123–1152, 2nd Quart., 2016.
[28] Y. Zeng and R. Zhang, ''Energy-efficient UAV communication with trajectory optimization,'' *IEEE Trans. Wireless Commun.*, vol. 16, no. 6, pp. 3747–3760, Jun. 2017.
[29] Z. Zhou, J. Feng, B. Gu, B. Ai, S. Mumtaz, J. Rodriguez, and M. Guizani, ''When mobile crowd sensing meets UAV: Energy-efficient task assignment and route planning,'' *IEEE Trans. Commun.*, vol. 66, no. 11, pp. 5526–5538, Nov. 2018.
[30] N. Cheng, F. Lyu, W. Quan, C. Zhou, H. He, W. Shi, and X. Shen, ''Space/aerial-assisted computing offloading for IoT applications: A learning-based approach,'' *IEEE J. Sel. Areas Commun.*, vol. 37, no. 5, pp. 1117–1129, May 2019.
[31] M. Alzenad, M. Z. Shakir, H. Yanikomeroglu, and M.-S. Alouini, ''FSO-based vertical backhaul/fronthaul framework for 5G+ wireless networks,'' *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 218–224, Jan. 2018.
[32] Z. Zheng, A. K. Sangaiah, and T. Wang, ''Adaptive communication protocols in flying ad hoc network,'' *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 136–142, Jan. 2018.
[33] E. Felemban, F. K. Shaikh, U. M. Qureshi, A. A. Sheikh, and S. B. Qaisar, ''Underwater sensor network applications: A comprehensive survey,'' *Int. J. Distrib. Sensor Netw.*, vol. 2015, no. 11, 2015, Art. no. 896832.
[34] H. Kaushal and G. Kaddoum, ''Underwater optical wireless communication,'' *IEEE Access*, vol. 4, pp. 1518–1547, 2016.
[35] R. Li, Z. Zhao, Z. Xuan, G. Ding, C. Yan, Z. Wang, and H. Zhang, ''Intelligent 5G: When cellular networks meet artificial intelligence,'' *IEEE Wireless Commun.*, vol. 24, no. 5, pp. 175–183, Oct. 2017.
[36] Z. Zhou, H. Liao, G. Gu, K. M. S. Huq, S. Mumtaz, and J. Rodriguez, ''Robust mobile crowd sensing: When deep learning meets edge computing,'' *IEEE Netw.*, vol. 32, no. 4, pp. 54–60, Jul. 2018.
[37] G. Li, G. Xu, A. K. Sangaiah, J. Wu, and J. Li, ''EdgeLaaS: Edge learning as a service for knowledge-centric connected healthcare,'' *IEEE Netw.*, to be published.
[38] M. G. Kibria, K. Nguyen, G. P. Villardi, O. Zhao, K. Ishizu, and F. Kojima, ''Big data analytics, machine learning, and artificial intelligence in next-generation wireless networks,'' *IEEE Access*, vol. 6, pp. 32328–32338, 2018.
[39] RISELAB. *Real-Time Intelligent Secure Explainable Systems*. [Online]. Available: https://rise.cs.berkeley.edu
[40] J. Fowers, K. Ovtcharov, M. Papamichael, T. Massengill, M. Liu, D. Lo, S. Alkalay, M. Haselman, L. Adams, M. Ghandi, S. Heil, P. Patel, A. Sapek, G. Weisz, L. Woods, S. Lanka, S. K. Reinhardt, A. M. Caulfield, E. S. Chung, and D. Burger, ''A configurable cloud-scale DNN processor for real-time AI,'' in *Proc. ACM/IEEE Int. Symp. Comput. Archit.*, Jun. 2018, pp. 1–14.
[41] C. Jiang, H. Zhang, Y. Ren, Z. Han, K.-C. Chen, and L. Hanzo, ''Machine learning paradigms for next-generation wireless networks,'' *IEEE Wireless Commun.*, vol. 24, no. 2, pp. 98–105, Apr. 2017.
[42] A. Ndikumana, N. H. Tran, T. M. Ho, Z. Han, W. Saad, D. Niyato, and C. S. Hong, ''Joint communication, computation, caching, and control in big data multi-access edge computing,'' *IEEE Trans. Mobile Comput.*, to be published.
[43] S. Samarakoon, M. Bennis, W. Saad, and M. Debbah, ''Federated learning for ultra-reliable low-latency V2V communications,'' in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2018, pp. 1–7.
[44] H. Zhang, W. Quan, H.-C. Chao, and C. Qiao, ''Smart identifier network: A collaborative architecture for the future Internet,'' *IEEE Netw.*, vol. 30, no. 3, pp. 46–51, May/Jun. 2016.
[45] M. F. Zhani and H. ElBakoury, ''FlexNGIA: A flexible Internet architecture for the next-generation tactile Internet,'' 2019, *arXiv:1905.07137*. [Online]. Available: https://arxiv.org/abs/1905.07137
[46] E. C. Strinati, S. Barbarossa, J. L. Gonzalez-Jimenez, D. Ktenas, N. Cassiau, L. Maret, and C. Dehos, ''6G: The next frontier: From holographic messaging to artificial intelligence using subterahertz and visible light communication,'' *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 42–50, Sep. 2019.
[47] I. F. Akyildiz, J. M. Jornet, and C. Han, ''Terahertz band: Next frontier for wireless communications,'' *Phys. Commun.*, vol. 12, pp. 16–32, Sep. 2014.
[48] N. Khalid, N. A. Abbasi, and O. B. Akan, ''300 GHz broadband transceiver design for low-THz band wireless communications in indoor Internet of Things,'' in *Proc. IEEE Int. Conf. Internet Things (iThings) IEEE Green Comput. Commun. (GreenCom) IEEE Cyber, Phys. Social Comput. (CPSCom) IEEE Smart Data (SmartData)*, Jun. 2017, pp. 770–775.
[49] *First Report and Order in the Matter of Spectrum Horizons*, document FCC-19-19, Mar. 2019.
[50] *IEEE 802.15 WPAN Study Group 100 Gbit/s Wireless (sg100g)*. Accessed: Aug. 13, 2018. [Online]. Available: http://www.ieee802.org/15/pub/sg100g.html
[51] M. Fujishima, ''300GHz-band CMOS wireless transceiver,'' in *Proc. IEEE Int. Symp. Radio-Freq. Integr. Technol. (RFIT)*, Aug. 2018, pp. 1–3.
[52] S. Lee, R. Dong, T. Yoshida, S. Amakawa, S. Hara, A. Kasamatsu, J. Sato, and M. Fujishima, ''9.5 an 80Gb/s 300GHz-band single-chip CMOS transceiver,'' in *IEEE ISSCC Dig. Tech. Papers*, Feb. 2019, pp. 170–172.
[53] L. Lopacinski, M. Marinkovic, G. Panic, M. H. Eissa, A. Hasani, K. Krishnegowda, and R. Kraemer, ''Data link layer processor for 100 Gbps terahertz wireless communications in 28 nm CMOS technology,'' *IEEE Access*, vol. 7, pp. 44489–44502, 2019.
[54] K. Tekbıyık, A. R. Ekti, G. K. Kurt, and A. Görçin, ''Terahertz band communication systems: Challenges, novelties and standardization efforts,'' *Phys. Commun.*, vol. 35, Aug. 2019, Art. no. 100700.
[55] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, ''Visible light communication, networking, and sensing: A survey, potential and challenges,'' *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2047–2077, 4th Quart., 2015.
[56] S. Cho, G. Chen, and J. P. Coon, ''Enhancement of physical layer security with simultaneous beamforming and jamming for visible light communication systems,'' *IEEE Trans. Inf. Forensics Security*, vol. 14, no. 10, pp. 2633–2648, Oct. 2019.
[57] L. U. Khan, ''Visible light communication: Applications, architecture, standardization and research challenges,'' *Digit. Commun. Netw.*, vol. 3, no. 2, pp. 78–88, May 2016.
[58] H. Haas, ''LiFi is a paradigm-shifting 5G technology,'' *Rev. Phys.*, vol. 3, pp. 26–31, Nov. 2017.
[59] M. S. Islim, R. X. Ferreira, X. He, E. Xie, S. Videv, S. Viola, S. Watson, N. Bamiedakis, R. V. Penty, I. H. White, A. E. Kelly, E. Gu, H. Haas, and M. D. Dawson, ''Towards 10 Gb/s orthogonal frequency division multiplexing-based visible light communication using a GaN violet micro-LED,'' *Photon. Res.*, vol. 5, no. 2, pp. A35–A43, 2017.
[60] U. A. K. Chude-Okonkwo, R. Malekian, B. T. Maharaj, and A. V. Vasilakos, ''Molecular communication and nanonetwork for targeted drug delivery: A survey,'' *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 3046–3096, 4th Quart., 2017.
[61] N. Farsad, H. B. Yilmaz, A. Eckford, C.-B. Chae, and W. Guo, ''A comprehensive survey of recent advancements in molecular communication,'' *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1887–1919, 3rd Quart., 2016.
[62] O. B. Akan, H. Ramezani, T. Khan, N. A. Abbasi, and M. Kuscu, ''Fundamentals of molecular information and communication science,'' *Proc. IEEE*, vol. 105, no. 2, pp. 306–318, Feb. 2017.
[63] T. Nakano, Y. Okaie, S. Kobayashi, T. Hara, Y. Hiraoka, and T. Haraguchi, ''Methods and applications of mobile molecular communication,'' *Proc. IEEE*, vol. 107, no. 7, pp. 1442–1456, Jul. 2019.
[64] I. F. Akyildiz, M. Pierobon, S. Balasubramaniam, and Y. Koucheryavy, ''The Internet of bio-nano things,'' *IEEE Commun. Mag.*, vol. 53, no. 3, pp. 32–40, Mar. 2015.
[65] J.-Y. Hu, B. Yu, M.-Y. Jing, L.-T. Xiao, S.-T. Jia, G.-Q. Qin, and G.-L. Long, ''Experimental quantum secure direct communication with single photons,'' *Light, Sci. Appl.*, vol. 5, no. 9, 2016, Art. no. e16144.
[66] W. Zhang, D.-S. Ding, Y.-B. Sheng, L. Zhou, B.-S. Shi, and G.-C. Guo, ''Quantum secure direct communication with quantum memory,'' *Phys. Rev. Lett.*, vol. 118, no. 22, p. 220501, 2017.
[67] L. Gyongyosi, S. Imre, and H. V. Nguyen, ''A survey on quantum channel capacities,'' *IEEE Commun. Surveys Tuts.*, vol. 20, no. 2, pp. 1149–1205, 2nd Quart., 2018.
[68] S. Muralidharan, L. Li, J. Kim, N. Lütkenhaus, M. D. Lukin, and L. Jiang, ''Optimal architectures for long distance quantum communication,'' *Sci. Rep.*, vol. 6, 2016, Art. no. 20463.
[69] X. Lin, J. Li, J. Wu, H. Liang, and W. Yang, ''Making knowledge tradable in edge-ai enabled IoT: A consortium blockchain-based efficient and incentive approach,'' *IEEE Trans. Ind. Informat.*, to be published.
[70] H. Liang, J. Wu, S. Mumtaz, J. Li, X. Lin, and M. Wen, ''MBID: Micro-blockchain-based geographical dynamic intrusion detection for V2X,'' *IEEE Commun. Mag.*, vol. 57, no. 10, pp. 77–83,

Oct. 2019.
[71] Y. Dai, D. Xu, S. Maharjan, Z. Chen, Q. He, and Y. Zhang, "Blockchain and deep reinforcement learning empowered intelligent 5G beyond," *IEEE Netw.*, vol. 33, no. 3, pp. 10–17, May/Jun. 2019.
[72] I. Ahmad, S. Shahabuddin, T. Kumar, J. Okwuibe, A. Gurtov, and M. Ylianttila, "Security for 5G and beyond," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 4, pp. 3682–3722, 4th Quart., 2019.
[73] X. Ling, J. Wang, T. Bouchoucha, B. C. Levy, and Z. Ding, "Blockchain radio access network (B-RAN): Towards decentralized secure radio access paradigm," *IEEE Access*, vol. 7, pp. 9714–9723, 2019.
[74] S. Kiyomoto, A. Basu, M. S. Rahman, and S. Ruj, "On blockchain-based authorization architecture for beyond-5G mobile services," in *Proc. 12th Int. Conf. Internet Technol. Secured Trans. (ICITST)*, Dec. 2017, pp. 136–141.
[75] C. Borda-Fortuny, K.-F. Tong, A. Al-Armaghany, and K.-K. Wong, "A low-cost fluid switch for frequency-reconfigurable Vivaldi antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 3151–3154, 2017.
[76] H. Yang, X. Cao, F. Yang, J. Gao, S. Xu, M. Li, X. Chen, Y. Zhao, Y. Zheng, and S. Li, "A programmable metasurface with dynamic polarization, scattering and focusing control," *Sci. Rep.*, vol. 6, Oct. 2016, Art. no. 35692.
[77] C. Liaskos, S. Nie, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, and I. Akyildiz, "A new wireless communication paradigm through software-controlled metasurfaces," *IEEE Commun. Mag.*, vol. 56, no. 9, pp. 162–169, Sep. 2018.
[78] R. Long, H. Guo, L. Zhang, and Y.-C. Liang, "Full-duplex backscatter communications in symbiotic radio systems," *IEEE Access*, vol. 7, pp. 21597–21608, 2019.
[79] G. Yang, Q. Zhang, and Y.-C. Liang, "Cooperative ambient backscatter communications for green Internet-of-Things," *IEEE Internet Things J.*, vol. 5, no. 2, pp. 1116–1130, Apr. 2018.
[80] Z. Zhou, J. Gong, Y. He, and Y. Zhang, "Software defined machine-to-machine communication for smart energy management," *IEEE Commun. Mag.*, vol. 55, no. 10, pp. 52–60, Oct. 2017.

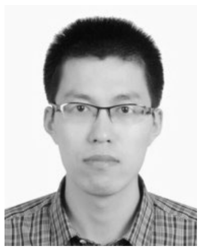
TONGYI HUANG received the B.S. degree in information security from the School of Cyber Security, Shanghai Jiao Tong University, Shanghai, China, in 2019, where he is currently pursuing the M.S. degree with the School of Electronic Information and Electrical Engineering. His research interests include blockchain and the Internet of Things.

WU YANG received the Ph.D. degree in computer system architecture specialty from the Computer Science and Technology School, Harbin Institute of Technology. He is currently a Professor and a Doctoral Supervisor with Harbin Engineering University. His main research interests include wireless sensor networks, peer-to-peer networks, and information security. He is a member of ACM and a Senior Member of CCF.



JUN WU received the Ph.D. degree in information and telecommunication studies from Waseda University, Japan, in 2011. He was a Postdoctoral Researcher with the Research Institute for Secure Systems, National Institute of Advanced Industrial Science and Technology (AIST), Japan, from 2011 to 2012. He was a Researcher with the Global Information and Telecommunication Institute, Waseda University, Japan, from 2011 to 2013. He is currently an Associate Professor with the School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, China. He is also the Vice Dean of the Institute of Cyber Science and Technology and the Vice Director of the National Engineering Laboratory for Information Content Analysis Technology, Shanghai Jiao Tong University. He has hosted and participated in a lot of research projects, including National Natural Science Foundation of China (NFSC), National 863 Plan and 973 Plan of China, and Japan Society of the Promotion of Science Projects (JSPS). His research interests include advanced computing, communications and security techniques of software-defined networks (SDN), information-centric networks (ICN) smart grids, the Internet of Things (IoT), and 5G/6G, where he has published more than 140 refereed articles. He is the Chair of the IEEE P21451-1-5 Standard Working Group. He has been the Track Chair of VTC 2019 and VTC 2020, and a TPC member of more than ten international conferences, including ICC and GLOBECOM. He has been a Guest Editor of the IEEE Sensors Journal, *Sensors*, and *ICT Express*. He is an Associate Editor of IEEE Access and the IEEE Networking Letters.

JIN MA received the Ph.D. degree in information and communication engineering from the School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China, in 2012. She is currently a Faculty Member of the School of Cyber Science and Engineering, Shanghai Jiao Tong University. She is also the Vice Dean of the Institute of Cyber Science and Technology and the Vice Director of the National Engineering Laboratory for Information Content Analysis Technology, Shanghai Jiao Tong University. Her main research interests include information security management/control and AI security.



XIAOFEI ZHANG received the master's degree in system analysis and integration from the Nanjing University of Information Engineering, in 2007. He is currently the Director of the Information Security and Software Laboratory, Experimental Verification Center, State Grid Electric Power Research Institute. He is a national reviewer for qualification certification of inspection and testing institutions, a member of the IEEE P21451-1-5 Standards Committee, a member of the information security standards working group of the energy industry, a member of the software and information system inspection methods professional working group (TC374 / WG62) of the National Technical Committee for standardization of inspection methods for key products of quality supervision, and a professional of information security registered in the national information security assessment. In the intelligent substation network, power system information security and power system software, and hardware testing, there are rich theoretical and practical experiences. He has successively presided over or specialized in more than 20 scientific and technological projects, such as information security test of SG186 project of state grid, demonstration project of grid level protection in-depth defense, major carrier project of Jiangsu Energy Bureau project, and research on key technology of security vulnerability and risk experiment ability improvement of dispatching automation software, and has been responsible for network system and information security test of more than 20 intelligent substations. He has published more than 20 articles and nine standards. Now, he mainly engaged in power system function, performance testing, and information security assessment.

DAOYIN ZHANG received the master's degree in computer application from Nanjing Technology University, China, in 2007. He has worked in the State Grid Electric Power of Institute for more than ten years. His work and research fields are software testing methodology and power system network security. He has published more than ten articles in these fields. His main research interests include smart grid security, network security protection, and security testing technology.