6G WIRELESS NETWORKS

Vision, Requirements, Architecture, and Key Technologies

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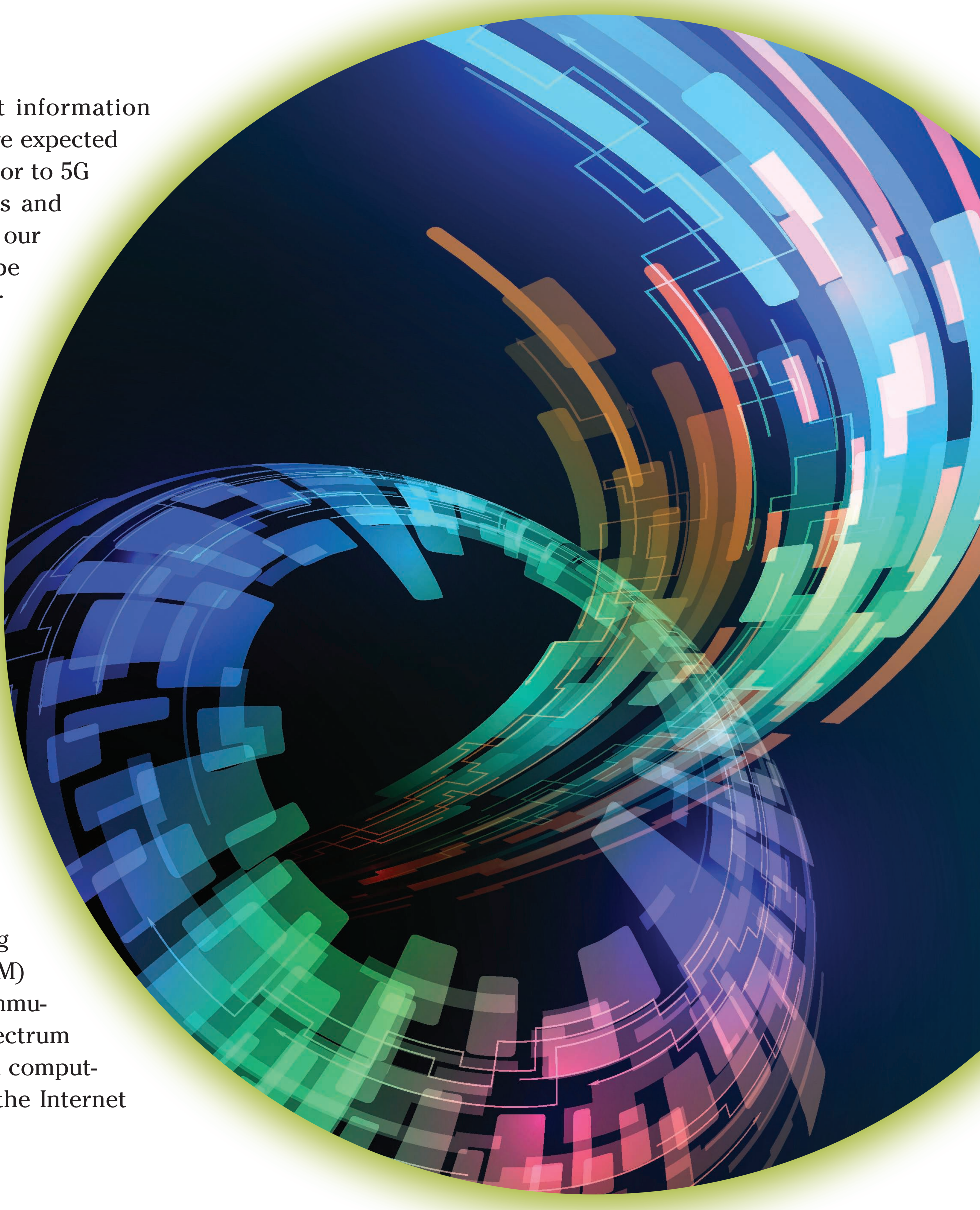
A key enabler for the intelligent information society of 2030, 6G networks are expected to provide performance superior to 5G and satisfy emerging services and applications. In this article, we present our vision of what 6G will be and describe usage scenarios and requirements for multi-terabyte per second (Tb/s) and intelligent 6G networks. We present a large-dimensional and autonomous network architecture that integrates space, air, ground, and underwater networks to provide ubiquitous and unlimited wireless connectivity. We also discuss artificial intelligence (AI) and machine learning [1], [2] for autonomous networks and innovative air–interface design. Finally, we identify several promising technologies for the 6G ecosystem, including terahertz (THz) communications, very-large-scale antenna arrays [i.e., supermassive (SM) multiple-input, multiple-output (MIMO)], large intelligent surfaces (LISs) and holographic beamforming (HBF), orbital angular momentum (OAM) multiplexing, laser and visible-light communications (VLC), blockchain-based spectrum sharing, quantum communications and computing, molecular communications, and the Internet of Nano-Things.



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Background

5G wireless networks are the key enabler for the information society of 2020. The 3rd Generation Partnership Project is making comprehensive

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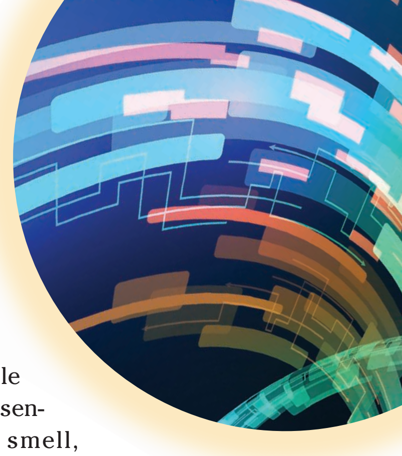
efforts to promote 5G development. Meanwhile, the IEEE 802.11ax standard [16] for next-generation wireless local area networks is being developed. With millimeter-wave (mm-wave) communications and large-scale antenna arrays (i.e., massive MIMO), 5G can achieve a maximum of 20 Gb/s peak data transmission for end users.

Research on 6G wireless networks (i.e., International Mobile Telecommunications 2030 [3] and Network 2030 [4]) has also been added to the agenda to satisfy the requirements for the intelligent information society of 2030. China launched the project "Broadband Communications and New Networks" for 2030 and beyond. The European Commission's Horizon 2020 program sponsored several beyond-5G (B5G) projects, such as TERRANOVA [Tb/s wireless connectivity via innovative THz technologies to deliver optical network quality of experience (QoE) in B5G systems]. In the United States, the Semiconductor Research Corporation sponsored research on the convergence of THz communications and sensing technologies for future cellular infrastructure. The U.S. Federal Communications Commission (FCC) has started researching 6G networks and already opened the THz band. The International Telecommunication Union (ITU) Telecommunication Standardization Sector (ITU-T) Study Group 13 established the ITU-T Focus Group Technologies for Network 2030. Finland sponsored the first 6G project, 6Genesis [5], and organized the world's first 6G wireless summit. All of these demonstrate that it is time to think about what 6G will be and exploit fundamental technologies for future 6G.

6G Vision, Usage Scenarios, and Requirements

Vision

The 2030 intelligent information society will be highly digitized, intelligence inspired, and globally data driven, enabled by near-instant and unlimited full wireless connectivity [5]. 6G will be the key enabler for achieving this blueprint; it will connect everything, provide full-dimensional wireless coverage, and integrate all functions, including sensing, communication, computing, caching, control, positioning, radar, navigation, and imaging, to support full-vertical applications. 6G will be an autonomous ecosystem with human-like intelligence and consciousness. It will evolve from human-centric to both human- and machine-centric, and it will provide multiple ways, such as through fingers, voice, eyes, and brainwaves (or neural signals), to communicate and interact with smart terminals.



Usage Scenarios

The mobile Internet and Internet of Everything (IoE) are two drivers for 6G that will support holographic and high-precision communications for tactile and haptic applications (e.g., the tactile Internet) [4] to provide a full sensory (i.e., vision, hearing, smell, taste, and touch) experience; this requires processing a very high volume of data in near real time, extremely high throughput (approximately Tb/s), and low latency. Furthermore, 6G wireless networks will

- support super-high-definition (SHD) and extremely high-definition (EHD) videos, with super-high throughput demands
- provide extremely low-latency communications (approximately 10 μs) for the industrial Internet [4]
- support the Internet of Nano-Things and Internet of Bodies through smart wearable devices and intrabody communications achieved by implantable nanodevices and nanosensors with extremely low power consumption (on the order of picowatts, nanowatts, and microwatts)
- support underwater and space communications to significantly expand the boundaries of human activity, such as deep-sea sightseeing and space travel
- provide consistent service experiences in emerging scenarios, such as hyper-high-speed railway (HSR)
- enhance 5G vertical applications, such as the Massive Internet of Things (IoT) and fully autonomous vehicles [6].

Therefore, the typical scenarios shown in Figure 1(a) should be supported by 6G, including further enhanced mobile broadband, ultra-massive machine-type communications, extremely reliable and low-latency communications (also known as *enhanced ultrareliable and low-latency communications*), long-distance and high-mobility communications, and extremely (or ultra-) low-power communications.

Requirements

The key performance indicators for evaluating 6G wireless networks include spectrum and energy efficiency, peak data rate, user-experienced data rate, area traffic capacity (or space traffic capacity), connectivity density, latency, and mobility [6]. The detailed technical objectives are presented in Figure 1(b) and include the following:

- *A peak data rate of at least 1 Tb/s [9], which is 100 times that of 5G.* For some special scenarios, such as THz wireless backhaul and fronthaul (x-haul) [9], the peak data rate is expected to reach up to 10 Tb/s.

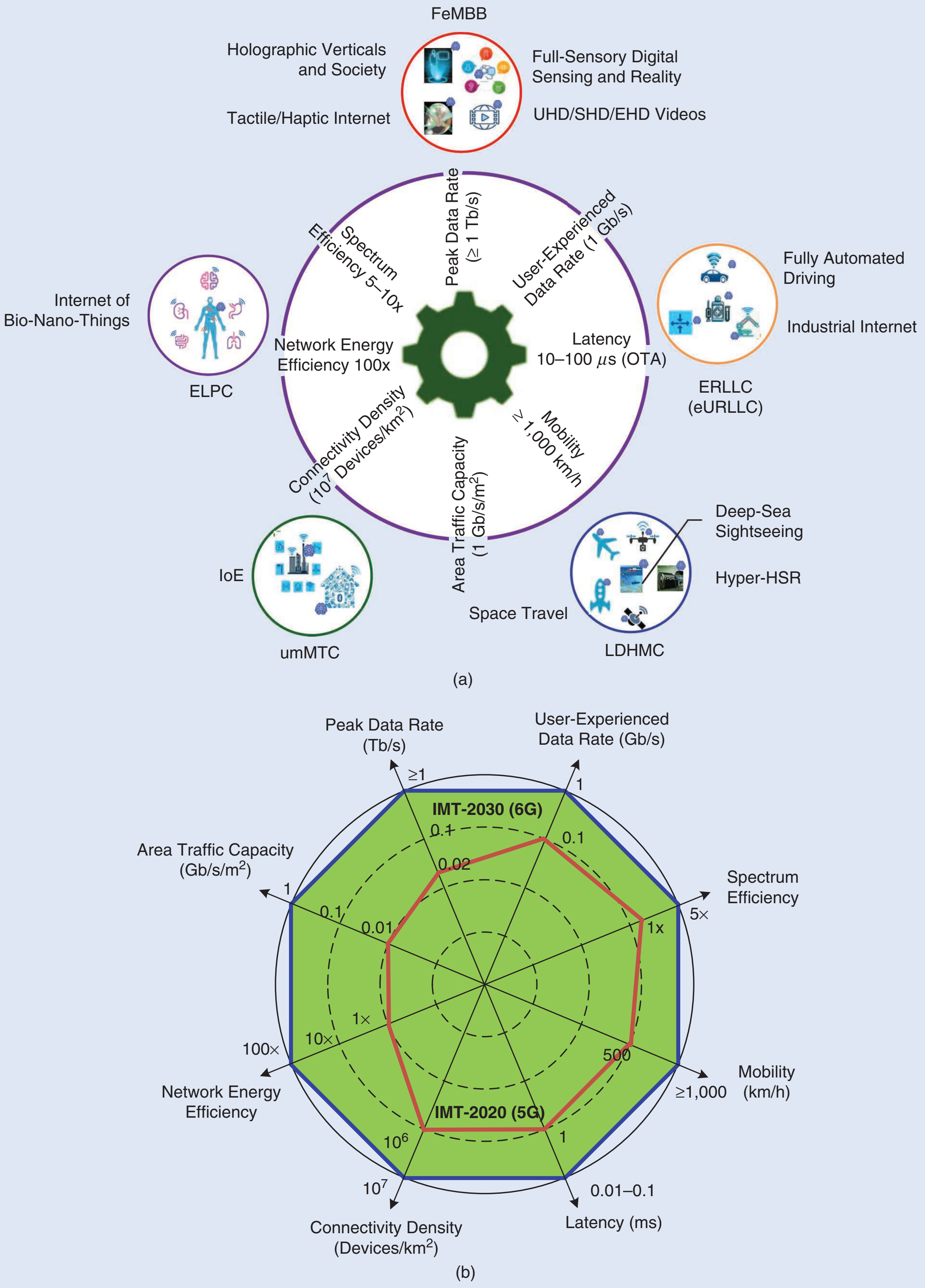


FIGURE 1 The (a) typical scenarios and (b) key capabilities of 6G networks [6]. IMT-2030: International Mobile Telecommunications 2030; eURLCC: extremely ultrareliable and low-latency communications.

- *A user-experienced data rate of 1 Gb/s, which is 10 times that of 5G.* It is also expected to provide a user-experienced data rate of up to 10 Gb/s for some scenarios, such as indoor hotspots.
- *An over-the-air latency of 10–100 μs and high mobility* $(\geq 1{,}000\ km/h)$. This will provide acceptable QoE for such scenarios as hyper-HSR and airline systems.
- *Ten times the connectivity density of 5G.* This will reach up to 10^7 devices/km^2 and area traffic capacity of up to 1 Gb/s/m^2 for scenarios such as hotspots.
- *An energy efficiency of 10–100 times and a spectrum efficiency of 5–10 times those of 5G.*

To satisfy typical scenarios and applications for the 2030 intelligent information society, 6G will provide superior network capabilities. Figure 2 summarizes the network features of human-oriented 4G, IoE-oriented 5G, and future interaction of everything-oriented 6G. Next, we discuss design considerations for 6G, as shown in Figure 3.

Large-Dimensional and Autonomous 6G Networks

In the 6G era, human activity will dramatically expand from the ground to air, space, and deep sea. Meanwhile, people will pay more attention to human microcosms and spaces that enhance health and capabilities and

		4G	5G	6G
Usage Scenarios		• MBB	• eMBB • URLLC • mMTC	• FeMBB • ERLLC • umMTC • LDHMC • ELPC
Applications		• High-Definition Videos • Voice • Mobile TV • Mobile Internet • Mobile Pay	• VR/AR/360° Videos • UHD Videos • V2X • IoT • Smart City/Factory/Home • Telemedicine • Wearable Devices	• Holographic Verticals and Society • Tactile/Haptic Internet • Full-Sensory Digital Sensing and Reality • Fully Automated Driving • Industrial Internet • Space Travel • Deep-Sea Sightseeing • Internet of Bio-Nano-Things
Network Characteristics		Flat and All-IP	• Cloudization • Softwarization • Virtualization • Slicing	• Intelligentization • Cloudization • Softwarization • Virtualization • Slicing
Service Objects		People	Connection (People and Things)	Interaction (People and World)
KPI	Peak Data Rate	100 Mb/s	20 Gb/s	≥1 Tb/s
	Experienced Data Rate	10 Mb/s	0.1 Gb/s	1 Gb/s
	Spectrum Efficiency	1×	3× that of 4G	5–10× that of 5G
	Network Energy Efficiency	1×	10–100× that of 4G	10–100× that of 5G
	Area Traffic Capacity	0.1 Mb/s/m^2	10 Mb/s/m^2	1 Gb/s/m^2
	Connectivity Density	10^5 Devices/km^2	10^6 Devices/km^2	10^7 Devices/km^2
	Latency	10 ms	1 ms	10–100 μs
	Mobility	350 km/h	500 km/h	≥1,000 km/h
Technologies		• OFDM • MIMO • Turbo Code • Carrier Aggregation • Hetnet • ICIC • D2D Communications • Unlicensed Spectrum	• mm-Wave Communications • Massive MIMO • LDPC and Polar Codes • Flexible Frame Structure • Ultradense Networks • NOMA • Cloud/Fog/Edge Computing • SDN/NFV/Network Slicing	• THz Communications • SM-MIMO • LIS and HBF • OAM Multiplexing • Laser and VLC • Blockchain-Based Spectrum Sharing • Quantum Communications and Computing • AI/Machine Learning

FIGURE 2 The network features of 4G, 5G, and the future 6G. AR: augmented reality; ELPC: extremely low-power communications; eMBB: enhanced mobile broadband; ERLLC: extremely reliable and low-latency communications; FeMBB: further-enhanced mobile broadband; LDHMC: long-distance and high-mobility communications; mMTC: massive machine-type communications; NFV: network function virtualization; SDN: software-defined networking; UHD: ultrahigh definition; umMTC: ultra-massive machine-type communications; URLLC: ultrareliable and low-latency communications; VR: virtual reality; V2X: vehicle to everything; KPI: key performance indicator; LDPC: low-density parity check codes.

prolong life. To enable this, 6G networks must provide full wireless coverage. Based on the 5G space–air–ground networks, 6G will further integrate underwater (or sea) networks to form a large-dimensional space–air–ground–underwater network. Furthermore, 6G networks will be zero-touch and intent-based to significantly improve the efficiency of network operation and maintenance and reduce operational expenditures. Intelligence is the key to achieving such autonomous networks; thus, AI will be the major innovative technique for 6G. Therefore, two important features of 6G will be large-dimensional and autonomous networks. Figure 4(a) illustrates the architecture for these networks, which will be AI-enabled space–air–ground–underwater networks to provide near-instant and unlimited superconnectivity.

Space–Air–Ground–Underwater Networks

Four-Tier Network Descriptions

Current terrestrial network capabilities are far from enough to satisfy 6G requirements for extremely broad coverage and ubiquitous connectivity. Therefore, a large-dimensional network integrating nonterrestrial and terrestrial networks is needed to support various applications, such as flight in the sky, voyage at sea, or vehicles on land. Structurally, 6G will be a cell-free and four-tier large-dimensional network that can be divided into space, air, terrestrial, and underwater (or sea) network tiers.

- *Space-network tier*: This will support orbit or space Internet services in such applications as space travel and provide wireless coverage by densely deploying low-Earth-orbit, medium-Earth-orbit, and geostationary-Earth-orbit satellites [7] for unserved and underserved areas not covered by terrestrial networks. For high-capacity satellite–ground transmission, satellites with mm-wave communications will be deployed. Laser communications can be used to achieve long-distance intersatellite transmission in free space.
- *Air-network tier*: This works in the low-frequency, microwave, and mm-wave bands to provide more flexible and reliable connectivity for urgent events or in remote mountain areas by densely employing flying base stations (BSs), such as unmanned aerial vehicles (UAVs) [7], and floating BSs, such as high-altitude platforms. The location features of floating BSs can help connect space networks and reachable UAV BSs via the 6G-defined optical interface.
- *Terrestrial-network tier*: This will still be the main solution for providing wireless coverage for most human activities. To satisfy the requirements for services with a Tb/s data rate, such as hologram and full-sense digital reality, the THz band will be exploited; thus, terrestrial networks will support low-frequency, microwave, mm-wave, and THz bands (i.e., full band). Because mm-wave and THz communications suffer from very high path loss, more small BSs will be deployed; thus, 6G terrestrial networks will be an ultradense heterogeneous network, which requires deployment of ultra-high-capacity x-haul. Optical fiber will still be important

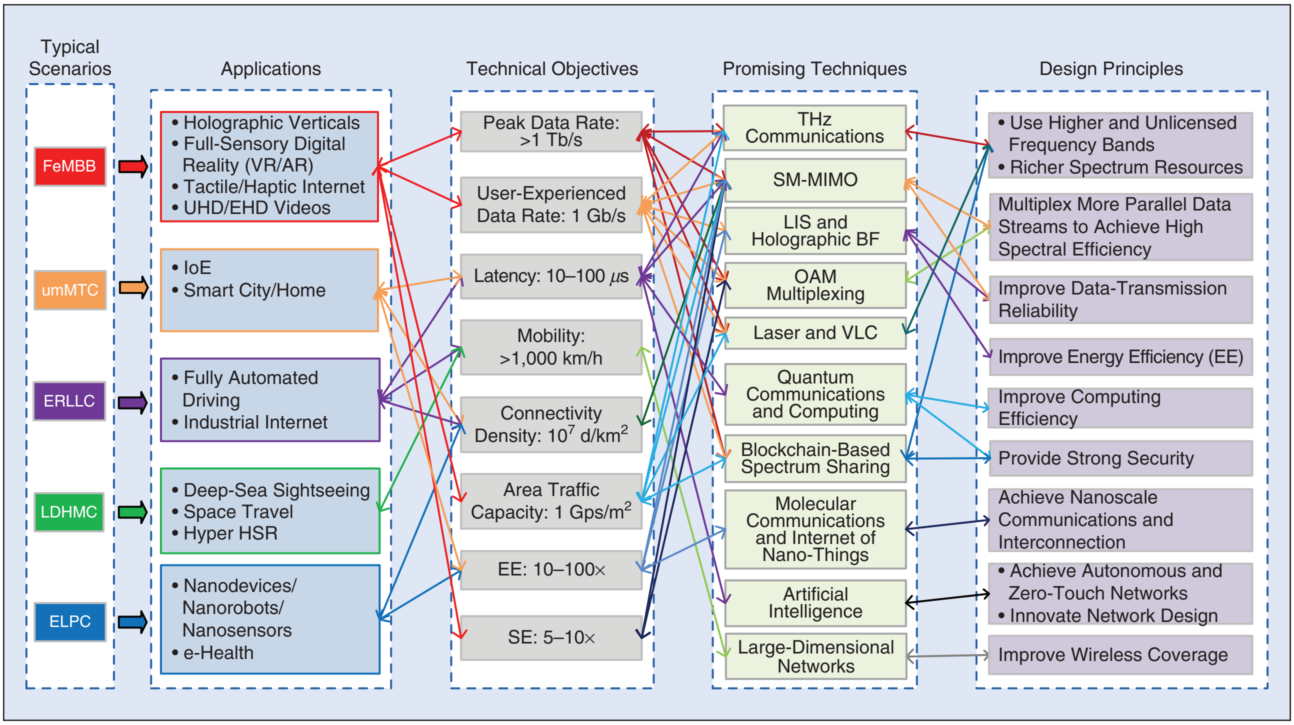


FIGURE 3 Design considerations for 6G networks. SE: spectrum efficiency.

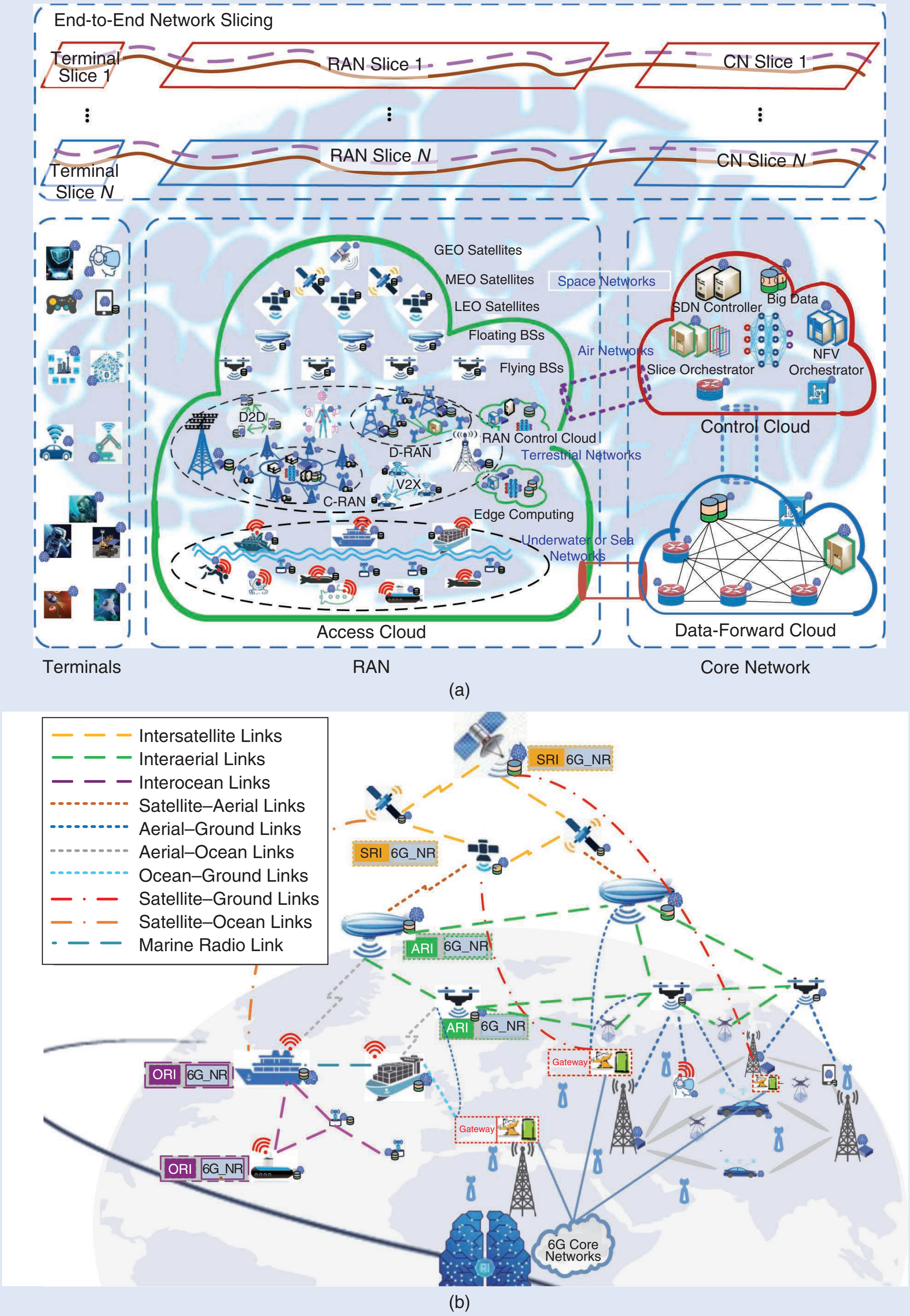


FIGURE 4 The (a) network architecture and (b) interface design and operation of large-dimensional and autonomous networks. GEO: geostationary Earth orbit; LEO: low-Earth orbit; MEO: medium-Earth orbit; CN: core networks; D2D: device to device; C-RAN: cloud radio access networks; D-RAN: distributed radio access networks; ORI: ocean radio interface; SRI: satellite radio interface.

IN LARGE-DIMENSIONAL NETWORKS, THE SAME AREAS CAN BE COVERED BY MULTIPLE ACCESS NETWORK TIERS, WHICH WILL RESULT IN SEVERE INTERFERENCE AMONG TIERS.

for 6G, while THz wireless x-haul will be an attractive solution.

- *Underwater-network tier*: This will provide coverage and Internet services for broad-sea and deep-sea activities with military or commercial applications. Because water exhibits different propagation characteristics from land, acoustic and laser communications can be used to achieve high-speed data transmission for bi-directional underwater communications, and more underwater hubs can be deployed.

Interface and Operation of Large-Dimensional Networks

Figure 4(b) illustrates the operations and interfaces of large-dimensional 6G networks. Two design principles are available for large-dimensional 6G networks to integrate terrestrial networks and nonterrestrial networks (NTNs): 1) transparent NTNs, where the NTN plays only an analog radio-frequency repeater, and 2) regenerative NTNs, where the NTN regenerates the signals received from terrestrial networks.

For regenerative NTNs, space, airborne, surface, and underwater platforms will deploy 6G BS functions. Space/air access networks connect 6G core networks through gateways and then provide services for fixed very-small-aperture terminals (VSATs) and handheld/mobile/IoT devices. Sea surface access networks connect 6G core networks by gateways or space/air networks; underwater networks connect surface networks to provide services for devices in underwater stations. Therefore, for VSATs, the communication links are VSAT ↔ satellite ↔ gateway ↔ 6G core networks. For handheld/mobile terminals, the communication links are terminal ↔ satellite ↔ gateway ↔ 6G core networks; terminal ↔ airborne station ↔ gateway ↔ 6G core networks; or terminal ↔ airborne station ↔ satellite ↔ gateway ↔ 6G core networks. The communication links of underwater terminals are terminal ↔ underwater station ↔ surface station ↔ satellite ↔ gateway ↔ 6G core networks.

Connectivity Management in Large-Dimensional Networks

In large-dimensional networks, multiconnectivity technique can enable terminals to establish multiple connectivities with different access network tiers and achieve coverage enhancements. To manage connectivity efficiently, the operation of dynamic connectivity addition and deletion is needed. However, for large-dimensional networks, the radio link between the space/aerial tier and the terrestrial tier is nonideal and will suffer from large latency. This will greatly affect the assisted information transfer used to optimize connectivity management. Furthermore, moving BSs with ultrahigh mobility results in the difficulty of obtaining channel state information (CSI), which poses another challenge for connectivity management.

Radio-Resource Management in Large-Dimensional Networks

In large-dimensional networks, the same areas can be covered by multiple access network tiers, which will result in severe interference among tiers. This interference can be suppressed by collaborative scheduling, which shares information (such as CSI) to optimize user scheduling. However, unlike links between terrestrial BSs, the intersatellite, interaerial, intersatellite–aerial, intersatellite–terrestrial, and interaerial–terrestrial links are nonideal, so they will suffer from large latency, which is a challenge for collaborative scheduling in large-dimensional networks. Furthermore, long-distance and high-mobility moving BSs will generate severe channel estimation errors, another challenge for designing robust and high-performance scheduling algorithms.

AI-Enabled Autonomous Networks

Softwarization, cloudization, virtualization, and slicing are still important characteristics of autonomous networks; thus, software-defined networking (SDN), network function virtualization (NFV), and network slicing (NS) [8], first introduced to design the 5G network architecture, are still an important technique set for designing 6G. However, intelligence is the key characteristic of 6G autonomous networks. AI techniques can provide intelligence for wireless networks through learning and big data training; therefore, AI will be the most innovative technique for designing 6G autonomous networks.

The combination of AI and SDN/NFV/NS can achieve dynamic and zero-touch network orchestration, optimization, and management, which promotes the evolution from 5G to autonomous 6G networks. AI-enabled network orchestration can dynamically orchestrate network architecture and slices and self-aggregate different radio-access technologies to achieve liquidized networks and satisfy the demands of constantly changing services and applications. AI-enabled network optimization can monitor real-time network key performance indicators (KPIs) and quickly adjust network parameters to continuously provide extreme QoE. AI-enabled network management can monitor real-time network status and maintain network health. To promote the development of AI for wireless networks, the ITU-T established a focus group on machine learning for future networks, including 5G.

Multilevel AI deployment will be used to provide intelligence for 6G networks. Giant cloud/centralized AI will be deployed at the core network side with the control cloud, while AI accelerators can be embedded into data-forward function equipment, such as routers. Content providers will deploy cloud/centralized AI at a remote data center. Furthermore, cloud/centralized AI and fog/distributed AI will coexist and be deployed at the edge of radio access networks (RANs), where cloud/centralized AI will process multi-BS–related tasks, such as mobility and interference management (e.g., deployed with cloud-RAN), whereas fog/distributed AI will handle single-BS–related tasks, such as physical-layer (PHY) transmission, and can be deployed with distributed BSs. Finally, edge AI will be deployed at massive terminal devices to provide light-level AI processing. With the development of the massive IoT, AI will gradually shift from the data center to the network edge.

Convergence of Intelligent Wireless Sensing, Communication, Computing, Caching, and Control

6G will significantly extend wireless network depth from single information transmission to information transmission, storage, and processing, which will maximize network utility and provide extreme QoE for various services and applications, such as fully self-driving vehicles and intelligent industry. Therefore, the convergence of intelligent wireless sensing, communication, computing, caching, and control is needed. With this convergence, according to the control objects and targets as well as the communications, caching, and computing (3 C) resource states, the networks can make optimal decisions about what things should be sensed, what computing tasks should be processed by which computing units and what data should be cached by which cache units.

However, achieving the convergence is very hard, as it faces the following challenges:

1) massive sensing objects, such as humans, things, and environments, for various vertical applications
2) complicated communications resources, including multidimensional radio and x-haul resources
3) multilevel computing resources, including cloud, fog, and edge computing (i.e., x-computing)
4) multilevel cache resources.

AI will be an efficient solution for achieving the convergence, as it can choose optimal sensing objects and efficiently manage 3 C resources by big data training, learning, and predicting.

AI-Enabled Innovative Wireless Network Design

Conventionally, wireless networks are designed using mathematical and statistical models, which requires expert knowledge. The signal processing flows from transmission to reception into several independent expert modules, such as coding, modulation, and detection. These modules are designed independently to match specific channel models and overcome performance degradation over wireless channels. This design requires the transfer of system characteristic information, such as instantaneous CSI, between the transmitter and receiver to achieve reliable and efficient data transmission. Each module uses this information to choose a set of system parameters and perform processing. In practical networks, the signal will suffer from distortions due to nonideal hardware components, and perfect system characteristic information cannot always be captured.

AI PROVIDES A NEW WAY TO DESIGN WIRELESS NETWORKS AND WILL BE AN INNOVATE TECHNOLOGY FOR 6G, LEADING TO SUPERIOR PERFORMANCE.

For example, perfect CSI cannot be obtained in a scenario of high mobility due to rapid time variation, delay, and other factors. Therefore, this design cannot always work well in practical networks. Furthermore, it is not always optimal, and it makes decisions and obtains output according to only the current input because it lacks the input predicted by big data training and cannot perform joint decisions according to current input and predicted input.

AI can learn, predict, and make decisions with big data training, which gives it the potential to transform and replace the fields in wireless networks that require expert knowledge and models or to enhance the performance of wireless networks with imperfect system characteristic information. Therefore, AI provides a new way to design wireless networks and will be an innovate technology for 6G, leading to superior performance.

Typical AI Design Patterns

Three typical AI design patterns for wireless communication systems can be available: 1) layer-free AI, 2) layered AI, and 3) cross-layer AI. Layer-free AI treats all function blocks of the air interface as a black box in an x-learning module, whereas layered AI performs only one or more intralayer function blocks in an x-learning module. Cross-layer AI allows one or more intralayer function blocks to be performed by an x-learning module and also supports one or more interlayer function blocks to perform joint AI design. As a comparison of these design patterns, layer-free AI simplifies processing but suffers from complicated data-model training, whereas layered AI cannot achieve optimum performance because it does not support AI operation for interlayer function blocks. Therefore, the cross-layer AI pattern is more attractive.

WITH AI, BSS CAN OPTIMIZE SYSTEM PARAMETERS, SUCH AS MOBILITY PARAMETERS, TO ACHIEVE LOAD BALANCING AND ENHANCE NETWORK ROBUSTNESS.

AI for Designing the 6G Air Interface

Figure 5 summarizes the impact of AI on 6G network functions. In particular, AI will significantly renovate the design for the 6G air interface.

PHY

The PHY is the key to achieving reliable and high-speed data transmission over wireless channels. At the transmitter, the bit streams are processed by such modules as coding, modulation, MIMO precoding, and orthogonal frequency-division multiplexing (OFDM) modulation; the inverse procedure is performed at the receiver to recover the desired bits. The most ambitious hope is to build an AI-based end-to-end PHY architecture, which would potentially transform and replace those aspects that require expert knowledge and modules. Autoencoders from deep learning can be used to build the end-to-end PHY as three modules, including one transmitter, channel, and receiver. However, because of the complexity, the application of AI to independently design and enhance one or more PHY functions rather than the end-to-end PHY is more readily possible. Deep learning is an important technique for designing and enhancing the PHY, where convolutional neural networks (CNNs) can be used for signal classification and channel decoding, deep neural networks (DNNs) can be used for channel estimation and signal detection, and complex CNNs (CCNNs) can be used to build OFDM receivers.

Data-Link Layer

The data-link layer includes sublayers for the service data adaptation protocol, packet data-convergence protocol, radio-link control, and medium-access control, each of which can be enhanced by AI. AI-enabled resource allocation, with or without traffic prediction [2], can choose the most suitable scheduling for users. AI can achieve security enhancements, which reduces the security overhead of data transmission by choosing appropriate security algorithms, especially for IoT scenarios with short packets. Furthermore, AI can optimize the retransmission redundancy version of automatic repeat request (ARQ) and hybrid ARQ to enhance the reliability of data transmission and reduce retransmission overheads.

Network Layer

The network layer mainly provides user-specific functions, such as user radio resource control (RRC) connectivity and mobility management, together with BS-specific functions, such as load balancing. With AI, users can choose optimal serving cells, dynamically manage multiple connectivities, and choose optimal handover target cells to guarantee service continuity. Furthermore, with AI, BSs can optimize system parameters, such as mobility parameters, to achieve load balancing and enhance network robustness.

An Example of an AI-Based MIMO-OFDM Receiver

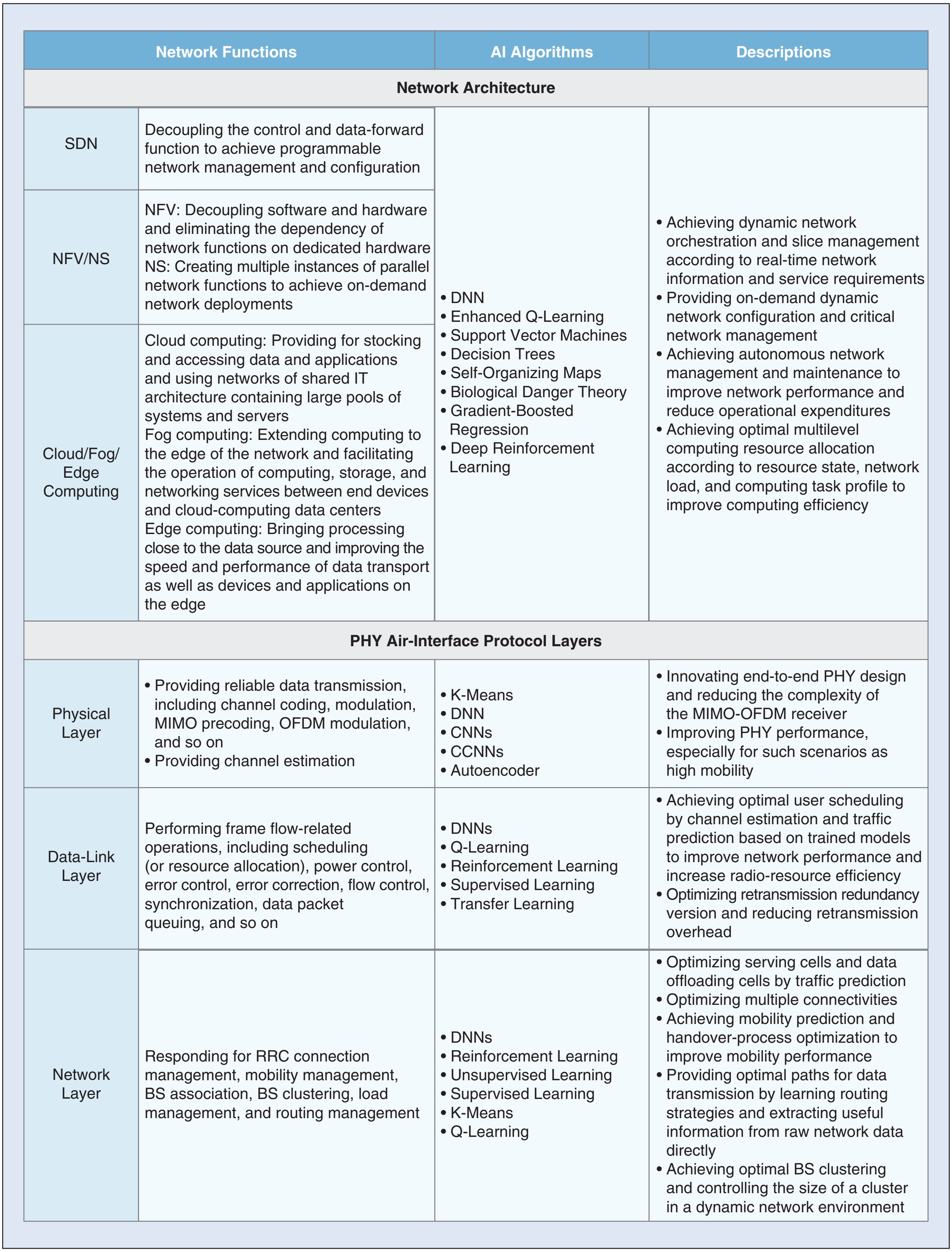
Figure 6 illustrates an example of an AI-based N-stage MIMO-OFDM receiver. Each AI module achieves the function of the corresponding conventional expert module and can choose different AI algorithms (e.g., CNN, DNN, or CCNN). If $N = 1$, the MIMO-OFDM receiver is considered one AI module. An AI-based N-stage MIMO-OFDM receiver consists of two stages: offline training and online deployment. In the offline training phase, with the MIMO-OFDM reception and wireless channel considered to be black boxes, the AI-based N-stage MIMO-OFDM receiver is trained by massive training data under various channel models. After training, an effective AI-based N-stage MIMO-OFDM receiver can be deployed online. During the online training phase, the AI-based N-stage MIMO-OFDM receiver recovers the desired data from the received signals without explicit expert modules.

Promising Technologies for 6G Networks

Shannon information theory will still be an important design basis for 6G and reveals two main ways of increasing system capacity: increasing system bandwidth and improving spectrum efficiency. Following that, we see several promising techniques for multi-Tb/s data transmission: THz communications [9], very-large-scale antenna arrays (i.e., SM-MIMO) [10], OAM multiplexing [11], laser communications and VLC [12], and blockchain-based spectrum sharing [13]. THz communications, laser communications and VLC, and spectrum sharing are important techniques to increase 6G's spectrum resources, while blockchain-based spectrum sharing can significantly improve the efficiency and security of conventional spectrum sharing. SM-MIMO and OAM multiplexing can improve spectrum efficiency significantly by multiplexing many parallel data streams on the same frequency channel. Quantum communications and computing [14] can improve the efficiency of computing and provide strong security for 6G.

THz Communications

THz communications [9] in the 0.1–10-THz band have far richer spectrum resources than those in the mm-wave band and can take advantage of both electromagnetic and light waves. THz communications are expected to provide multi-Tb/s data transmission for scenarios including hotspot, x-haul, and last-meter indoor wireless access. IEEE 802.15.3d [17] has also specified two types



Network Functions		AI Algorithms	Descriptions
Network Architecture			
SDN	Decoupling the control and data-forward function to achieve programmable network management and configuration	• DNN • Enhanced Q-Learning • Support Vector Machines • Decision Trees • Self-Organizing Maps • Biological Danger Theory • Gradient-Boosted Regression • Deep Reinforcement Learning	• Achieving dynamic network orchestration and slice management according to real-time network information and service requirements • Providing on-demand dynamic network configuration and critical network management • Achieving autonomous network management and maintenance to improve network performance and reduce operational expenditures • Achieving optimal multilevel computing resource allocation according to resource state, network load, and computing task profile to improve computing efficiency
NFV/NS	NFV: Decoupling software and hardware and eliminating the dependency of network functions on dedicated hardware NS: Creating multiple instances of parallel network functions to achieve on-demand network deployments		
Cloud/Fog/ Edge Computing	Cloud computing: Providing for stocking and accessing data and applications and using networks of shared IT architecture containing large pools of systems and servers Fog computing: Extending computing to the edge of the network and facilitating the operation of computing, storage, and networking services between end devices and cloud-computing data centers Edge computing: Bringing processing close to the data source and improving the speed and performance of data transport as well as devices and applications on the edge		
PHY Air-Interface Protocol Layers			
Physical Layer	• Providing reliable data transmission, including channel coding, modulation, MIMO precoding, OFDM modulation, and so on • Providing channel estimation	• K-Means • DNN • CNNs • CCNNs • Autoencoder	• Innovating end-to-end PHY design and reducing the complexity of the MIMO-OFDM receiver • Improving PHY performance, especially for such scenarios as high mobility
Data-Link Layer	Performing frame flow-related operations, including scheduling (or resource allocation), power control, error control, error correction, flow control, synchronization, data packet queuing, and so on	• DNNs • Q-Learning • Reinforcement Learning • Supervised Learning • Transfer Learning	• Achieving optimal user scheduling by channel estimation and traffic prediction based on trained models to improve network performance and increase radio-resource efficiency • Optimizing retransmission redundancy version and reducing retransmission overhead
Network Layer	Responding for RRC connection management, mobility management, BS association, BS clustering, load management, and routing management	• DNNs • Reinforcement Learning • Unsupervised Learning • Supervised Learning • K-Means • Q-Learning	• Optimizing serving cells and data offloading cells by traffic prediction • Optimizing multiple connectivities • Achieving mobility prediction and handover-process optimization to improve mobility performance • Providing optimal paths for data transmission by learning routing strategies and extracting useful information from raw network data directly • Achieving optimal BS clustering and controlling the size of a cluster in a dynamic network environment

FIGURE 5 AI for the renovation of wireless network design, and AI impacts on 6G network functions. RRC: radio resource control; CP: cyclic prefix.

of THz PHYs (i.e., single-carrier and on–off keying PHYs) in the lower frequency band of 0.252–0.325 THz to achieve 100-Gb/s data transmission. THz communications have the following advantages:

- Massive spectrum resources of up to hundreds of gigahertz, far richer than the 5G mm-wave band from 24.25 to 52.6 GHz, can satisfy 6G's massive bandwidth demands and achieve multi-Tb/s data transmission.
- The THz frequency band can be beneficial for integrating more antennas to provide hundreds of beams because its wavelength is far shorter than that of the mm-wave band. It is expected that more than 10,000 antenna elements can be integrated into THz BSs, which can form super-narrow beams to overcome propagation loss and generate narrower beams to achieve higher data transmission and serve more users simultaneously.

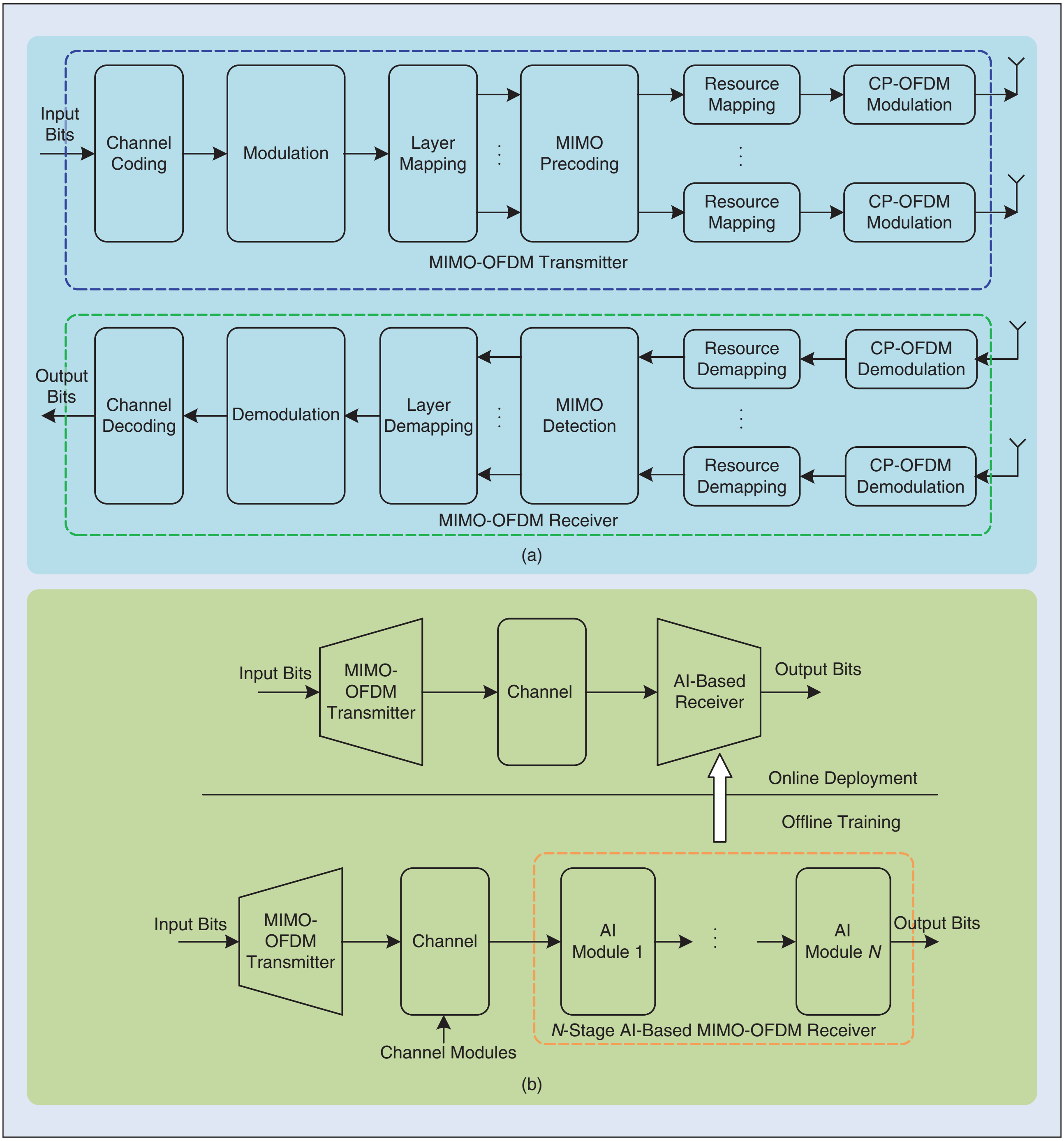


FIGURE 6 AI for the renovation of wireless network design. Examples of (a) conventional MIMO-OFDM systems and (b) an AI-enabled MIMO-OFDM receiver.

- THz communications exhibit highly directional transmission, which can significantly mitigate intercell interference, dramatically reduce the probability that communications can be listened to, and provide better security.

SM-MIMO, Large Intelligent Surfaces, and Holographic Beamforming

From eight-antenna 4G MIMO to 256–1,024-antenna 5G massive MIMO, the multiantenna technique [10] has played a key role in wireless communications and can significantly boost system capacity by spatial multiplexing, achieve reliable transmission by diversity, and overcome propagation loss by beamforming. For 6G, SM-MIMO with more than 10,000 antenna elements is expected to be deployed, providing the following benefits.

- Super-high spectrum efficiency can be achieved through spatial multiplexing, which transmits hundreds of parallel data streams on the same frequency channel. SM-MIMO can also significantly improve energy efficiency and reduce latency.
- Hundreds of beams can be provided, serving more users simultaneously, in the form of massive-user MIMO rather than multiuser MIMO [10], to significantly increase network throughput. Furthermore, the combination of SM-MIMO and nonorthogonal multiple-access techniques will be an enabler for massive access communications to support SM connectivities.
- Forming super-narrow beams will help overcome the severe propagation loss for the mm-wave and THz bands and reduce the aggregated co-channel intercell interference.

With the development of advanced antenna technology such as metasurface (i.e., passive reflectarrays), LIS systems [10] consisting of passive reflectarrays and control elements are attracting increasing attention. Compared with active BSs and access points with conventional antenna arrays, LIS can overcome the half-wavelength limit and has the advantages of low cost and low power consumption. Additionally, LIS leads to line-of-sight propagation and near-field communications, as it can be easily deployed on building facades, walls, or ceilings that are inaccessible to users. LIS integrates massive passive reflecting elements with controllable phase or amplitude on a surface and has the property of a spatially continuous transmitting/receiving aperture, which stimulates novel HBF [10]. HBF generates the desired beams through holographic recording and reconstruction and so can achieve higher spatial resolution than conventional beamforming with discrete phased antenna arrays.

OAM Multiplexing

The OAM multiplexing technique [11] can achieve superior spectral efficiency by using a set of orthogonal electromagnetic waves to multiplex multiple data streams on the same frequency channel by exploiting angular momentum of the electromagnetic wave as a new degree of freedom. This is different from spatial multiplexing, which employs multiple separated transmit and receive antennas. The OAM of the electromagnetic wave can be characterized as $e^{js\phi}$ [11], where the OAM state, s, is an unbounded integer and ϕ is the azimuthal angle. This means that there are infinite OAM states and that any two OAM states are orthogonal. Theoretically, any number of data streams can be multiplexed on the same frequency channel.

VLC EMPLOYS ULTRAHIGH BANDWIDTH TO ACHIEVE HIGH-SPEED DATA TRANSMISSION AND IS WIDELY AVAILABLE, MAKING IT SUITABLE FOR SUCH SCENARIOS AS AN INDOOR HOTSPOT.

Laser Communications and VLC

6G will integrate space/air networks and underwater networks with terrestrial networks to provide superior coverage. However, the space/air- and underwater-propagation environments are different from the terrestrial environment; therefore, conventional wireless communications based on electromagnetic-wave signals cannot provide high-speed data transmission for these scenarios. Laser communications have ultrahigh bandwidth and can achieve high-speed data transmission using laser beams, which are suitable for environments such as free space and under water. On the other hand, VLC [12], working in the frequency range of 400–800 THz, is another promising technique for 6G and uses visible light generated by illuminant-like LEDs to transmit data. VLC employs ultrahigh bandwidth to achieve high-speed data transmission and is widely available, making it suitable for such scenarios as an indoor hotspot.

Blockchain-Based Spectrum Sharing

The unlicensed spectrum, which allows different users to share the same spectrum, is a promising strategy for overcoming the low spectrum utilization and spectrum monopoly of conventional spectrum auctions and satisfying the huge spectrum requirements for massive information consumption. However, centralized spectrum-access systems, such as the FCC's three-layer spectrum system for 3.5-GHz unlicensed spectrum, are still far behind this goal due to administrative expense, efficiency problems, and transaction costs. Recently, blockchain [13] has gained attention because it can provide a secure and distributed database for all transaction records (i.e., blocks) by enabling all participants to record blocks, each of which includes the previous block's cryptographic

THE COMBINATION OF QUANTUM THEORY AND AI (I.E., QUANTUM AI) CAN DEVELOP MORE POWERFUL AND EFFICIENT AI ALGORITHMS TO SATISFY THE REQUIREMENTS OF 6G.

hash, a time stamp, and transaction data. This model is suitable for the characteristics of spectrum sharing. Therefore, blockchain-based spectrum sharing [13] is a promising technology for 6G to provide secure, smarter, low-cost, and highly efficient decentralized spectrum sharing.

Quantum Communications and Computing

6G will satisfy higher security requirements with the support of full applications/scenarios. Quantum communications [14] can provide strong security by applying a quantum key based on the quantum no-cloning theorem and uncertainty principle. When eavesdroppers want to carry out observations or measurements or copy actions in quantum communications, the quantum state will be disturbed, and the eavesdropping behavior can be easily detected. Theoretically, quantum communications can achieve absolute security. However, Tb/s data transmission and full applications/scenarios pose challenges for wireless computing in 6G. Compared to conventional computing with 0–1-b operations, quantum computing based on quantum superposition and entanglement can largely boost computing capability using unitary transformations in the form of qubits [14]. Therefore, quantum computing can significantly accelerate and enhance AI algorithms that require big data and massive training. Furthermore, the combination of quantum theory and AI (i.e., quantum AI) can develop more powerful and efficient AI algorithms to satisfy the requirements of 6G.

Molecular Communications and the Internet of Nano-Things

Advanced nanotechnology can enable the manufacture of nanodevices, such as nano-robots, implantable chips, and biosensors, and this has important applications in such scenarios as nanoscale sensing and biomedicine [15]. In particular, the application of nanotechnology to biomedicine has attracted attention because it can be used to perform such tasks as intelligent drug delivery in blood vessels and monitoring of body organs to significantly improve human health care. Connecting nanodevices to the Internet or forming networks (i.e., the Internet of Nano-Things) can achieve effective communication and information transmission; in biomedicine, the Internet of Bio-Nano-Things (IoBNT) [15] can enable nanodevices and biological entities to be connected. Molecular communication [15] is an enabling technique for the IoBNT, which uses biochemical molecules to communicate and transfer information among nanodevices. Furthermore, the combination of the IoBNT and body area networks, which are short-distance wireless networks consisting of wearable monitoring devices/sensors and sensing devices inside or on the body, can provide comprehensive solutions for health-care enhancements.

Conclusions

In this article, we focused on researching multi-Tb/s and intelligent 6G wireless networks for 2030 and beyond. We presented a 6G vision and discussed usage scenarios and key capabilities of 6G. We illustrated a large-dimensional and autonomous network architecture that integrates space–air–ground–underwater networks to provide full coverage and unlimited wireless connectivity. Furthermore, we introduced AI as a key enabler of 6G and discussed the impacts of AI on achieving autonomous networks and designing innovative wireless networks. Finally, we identified several promising techniques, including THz communications, SM-MIMO, LIS and HBF, OAM multiplexing, laser communications and VLC, quantum communications and computing, blockchain-based spectrum sharing, and molecular communications and the Internet of Nano-Things, followed with a discussion of their potential for 6G.

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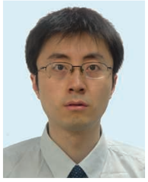

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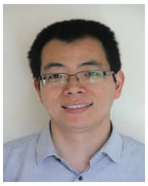

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References

[1] *Unified Architecture for Machine Learning in 5G and Future Networks*, International Telecommunication Union–Telecommunication Standardization Sector, Technical Specification ITU-T FG-ML5G-ARC5G, Jan. 2019.

[2] Q. Mao, F. Hu, and Q. Hao, “Deep learning for intelligent wireless networks: A comprehensive survey,” *IEEE Commun. Surveys Tut.*, vol. 20, no. 4, pp. 2595–2621, 2018. doi: 10.1109/COMST.2018.2846401.

[3] 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, Sept. 2018. doi: 10.1109/MVT.2018.2848498.

[4] R. Li, “Network 2030: Market drivers and prospects,” in *Proc. 1st International Telecommunication Union Workshop on Network 2030*, New York, Oct. 2018. [Online]. Available:https://www.itu.int/en/ITU-T/Workshops-and-Seminars/201810/Documents/Richard_Li_Presentation.pdf

[5] M. Latva-aho, “Radio access networking challenges towards 2030,” in *Proc. 1st International Telecommunication Union Workshop on Network 2030*, New York, Oct. 2018. [Online]. Available: https://www.itu.int/en/ITU-T/Workshops-and-Seminars/201810/Documents/Matt_Latva-aho_Presentation.pdf

[6] *IMT Vision—Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond*, International Telecommunication Union–Radiocommunications Sector, Recommendation ITU-R M.2083-0, Sept. 2015.

[7] J. Liu, Y. Shi, Z. M. Fadlullah, and N. Kato, “Space-air-ground integrated network: A survey,” *IEEE Commun. Surveys Tut.*, vol. 20, no. 4, pp. 2714–2741, 2018. doi: 10.1109/COMST.2018.2841996.

[8] I. Afolabi, T. Taleb, K. Samdanis, A. Ksentini, and H. Flinck, “Network slicing and softwarization: A survey on principles, enabling technologies, and solutions,” *IEEE Commun. Surveys Tut.*, vol. 20, no. 3, pp. 2429–2453, 2018. doi: 10.1109/COMST.2018.2815638.

[9] A.-A. A. Boulogeorgos et al. “Terahertz technologies to deliver optical network quality of experience in wireless systems beyond 5G,” *IEEE Commun. Mag.*, vol. 56, no. 6, pp. 144–151, June 2018. doi: 10.1109/MCOM.2018.1700890.

[10] E. Björnson, L. Sanguinetti, H. Wymeersch, J. Hoydis, T. L. Marzetta, Massive MIMO is a reality—What is next? Five promising research directions for antenna arrays. 2019. [Online]. Available: https://arxiv.org/abs/1902.07678

[11] Y. Ren et al. “Line-of-sight millimeter-wave communications using orbital angular momentum multiplexing combined with conventional spatial multiplexing,” *IEEE Trans. Wireless Commun.*, vol. 16, no. 5, pp. 3151–3161, May 2017. doi: 10.1109/TWC.2017.2675885.

[12] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, “Visible light communication, networking, and sensing: A survey, potential and challenges,” *IEEE Commun. Surveys Tut.*, vol. 17, no. 4, pp. 2047–2077, Sept. 2015. doi: 10.1109/COMST.2015.2476474.

[13] K. Kotobi and S. G. Bilen, “Secure blockchains for dynamic spectrum access: A decentralized database in moving cognitive radio networks enhances security and user access,” *IEEE Veh. Technol. Mag.*, vol. 13, no. 1, pp. 32–39, Mar. 2018. doi: 10.1109/MVT.2017.2740458.

[14] P. Botsinis et al., “Quantum search algorithms for wireless communications,” *IEEE Commun. Surveys Tut.*, vol. 21, no. 2, pp. 1209–1242, 2019. doi: 10.1109/COMST.2018.2882385.

[15] 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. doi: 10.1109/JPROC.2016.2537306.

[16] E. Khorov, A. Kiryanov, A. Lyakhov, and G. Bianchi, “A tutorial on IEEE 802.11ax high efficiency WLANs,” *IEEE Commun. Surv. Tut.*, vol. 21, no. 1, pp. 197–216, 1st Quarter 2019.

[17] *IEEE Standard for High Data Rate Wireless Multi-Media Networks–Amendment 2: 100 Gb/s Wireless Switched Point-to-Point Physical Layer*, IEEE Standard 802.15.3d, 2017.

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