A Survey of 6G Wireless Communications: Emerging Technologies

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Abstract—Sixth-generation (6G) communication has attracted much attention from the industry entities and the academia recently. Fifth-generation (5G) networks are inadequate to support the increasing number of applications. Researchers have envisioned the architecture, promising technologies, and services in 6G. In this paper, we present a survey of potential technologies in 6G. Specially, we will introduce artificial intelligence, intelligent surfaces, terahertz communications, and visible light communications techniques in detail, while giving a brief introduction to other potential technologies.

Index Terms—6G, Wireless Communications, IRS.

I. INTRODUCTION

Fifth-generation (5G) networks are under construction commercially in some countries. It is expected that 5G may reach the bottleneck by 2030 [1]. However, upcoming technologies as shown in Fig. 1 including artificial intelligence (AI), virtual reality, and the Internet of Everything (IoE) require high reliability, low latency and ultra-high data rates for the uplink and downlink, which cannot be satisfied by existing 5G’s ubiquitous mobile ultra-broadband (uMUB), ultrahigh-speed-with-low-latency communications (uHSLCC), and ultrahigh data density (uHDD) [2]–[4]. Performance limitations of 5G and the emerging revolutionary technologies drive the development of sixth-generation (6G) networks [5].

Past generations of wireless networks utilized micro-wave communications over the sub-6 GHz band, whose resources are almost used up [6]. Hence, the Terahertz (THz) bands will be major candidate technologies for the 6G wireless communications [13]–[9]. Due to the propagation loss, the THz will be used for high bit-rate short-range communications [10]. Besides, the 90-200GHz spectrum is regarded as useless in the past generations of wireless networks. The sub-THz radio spectrum above 90GHz has not exploited for radio wireless communications yet; thus, it is envisioned to support the increase wireless network capacity [11]. 6G will undergo the transition from radio to subterahertz (sub-THz) and optical spectra (visible light communication) to support explosive 6G applications [12].

Furthermore, the 6G system is envisioned to support new services, such as smart wearable, implants, autonomous vehicles, computing reality devices, sensing, and 3D mapping [2]. Hence, 6G’s architecture is expected to be a paradigm-shift and carries higher data rates with low latency [5]. Ho et al. [4] and Piran et al. [13] present their predictions for 6G’s requirements and features, which are summarized in Table I

In this paper, we will explain promising technologies that enable the paradigm shift in the 6G wireless networks such as artificial intelligence, active/passive intelligent surfaces, terahertz communications, and visible light communications in detail. Besides, we will present other promising technologies in short.

Organization. The rest of the paper is organized as follows. Section II introduces emerging technologies that enable the paradigm shift in 6G wireless networks. Section III concludes the paper.

II. 6G ARCHITECTURE: A PARADIGM SHIFT

6G is destined to be a revolutionary generation of wireless communications because the growing role of intelligence, autonomy, context-awareness, ubiquitous, Internet of Everything, and collaboration in the operation of edge applications, which relies on user’s devices and edge infrastructure components [13]–[14]. Thus, the future networks will be too complicated to be handled in traditional way. AI is expected to enable a significant paradigm shift in 6G wireless networks, including machine learning, deep learning, etc [14]. Besides, Large Intelligent Surfaces may contribute to paradigms of intelligent and active wireless communications, whereas Intelligent Reflecting Surfaces may be helpful in forming the software-defined networking paradigm.

### Table I

| Requirement/Feature | 6G |
|--------------------|----|
| Service types | MBRLLC/mURLLC/HCMS/MPS |
| Jitter | 1 usec |
| Individual data rate | 100 Gbps |
| Peak DL data rate | ≥ 1 Tbps |
| Latency | 0.1 usec |
| Mobility | up to 1000 km/h |
| Reliability | up to 99.99999% |
| Frequency bands | - sub-THz band |
| - Non-RF, e.g., optical, VLC, laser |
| Power consumption | Ultra low |
| Processing delay | ≤ 10ns |
| Network architecture | - Cell-free smart surfaces |
| - Drone-based hotspots and tethered balloons |
| - Satellite networks |
| - Tiny THz cells |
| Security and privacy | Very high |
| Network orientation | Service-centric |
| Wireless power transfer | - Wireless charging Support (BS to devices power transfer) |
| Smart city components | Integrated |
| Autonomous V2X | Fully |
| Localization Precision | 1 cm on 3D |
A. Artificial Intelligence

Artificial Intelligence (AI) can provide intelligence for wireless networks by learning as illustrated in Fig. 1. AI techniques are envisioned as widely used in the 6G. Researchers foresee a booming number of techniques and applications leveraging AI technologies in wireless networks. Artificial intelligence which resides in new local “clouds” and “fog” environments will help to create a plethora of new applications using the sensors that will embed into every corner of our life. In the following, we will present potential AI techniques and applications.

1) An overview of AI and related techniques: Deep learning, considered as the vital ingredient of AI technology, has been widely used in the wireless networks in the last decade. In the 6G, it will play an essential role in semantic communications, holistic management of communication, computation, caching, and control resources areas, etc., which pushes the paradigm-shift of the 6G.

2) Key AI Techniques in 6G: In this section, we summarize some potential AI techniques in 6G.

Supervised Learning and Unsupervised Learning. Supervised Learning trains the model using labeled training data. Some well developed algorithms that can be used in the 6G network, such as independent component analysis, locally linear embedding, principle component analysis, isometric mapping, K-means clustering, and hierarchical clustering. However, unsupervised learning is used to discover undefined patterns in the dataset without pre-determining labels. Commonly used unsupervised learning techniques include k-nearest neighbors, neural networks, decision tree, random forest, Bayesian learning, linear / logic regression, and support vector machine, etc.

Model-Driven Deep Learning. The model-driven approach is to train an artificial neural network (ANN) with prior information based on expert knowledge. A pure data-driven (model-free, train-based) deep learning approach requires tremendous computing resources and considerable time to train, which is not suitable for most communication devices. Zappone et al. propose a two-step method to train the ANN: firstly, we can use theoretical models derived from wireless communication problems as prior expert information for training ANN. Secondly, we can subsequently tune ANN with small sets of live data even though initial theoretical models are inaccurate.

Deep Reinforcement Learning. Deep Reinforcement Learning (DRL) uses Markov decision models to choose the next “action” based on the state transition models. DRL technique is considered as one of the promising solutions to maximize some notion of cumulative reward by sequential decision-making. It is an approach to solve resource allocation problems in 6G. As 6G wireless networks serve a wider variety of users in the future, the radio-resource will become extremely scarce. Hence, efficient radio-resource allocation is urgent and challenging. Q-learning, neural network, and deep Q-learning are three popular approaches for DRL.

Federated Learning. Federated Learning (FL) is to train a centralized model with training data to remain distributed at clients, while the network connections are slow. As 6G heads towards a distributed architecture, FL technologies may contribute to enable the shift of AI moves from a centralized cloud-based model to the decentralized devices based. In addition, as the edge computing gets well developed in the 6G wireless network, edge devices become smarter. AI computing tasks are starting to distribute from central nodes to edge nodes. Federated learning is one of the essential machine learning methods to enable the deployment of accurate generalized models across multiple devices.

Explainable Artificial Intelligence. Since there will emerge a large scale of mission-critical service applications, including autonomous driving and remote surgery in the 6G era, it is necessary to make artificial intelligence explainable for building trust between humans and machines. AI decisions should be explainable and understood by human experts to become trustworthy. Summarized by Guo, most AI approaches in PYH, and MAC layers in 5G wireless networks are inexplicable. However, applications such as autonomous driving and remote surgery are considered as widely used in the next generation of the wireless network, which requires explainability to enable trust. Existing methods to improve deep learning explainability, including visualization with case studies, hypothesis testing, and didactic statements.

3) AI Applications in 6G: In this section, we present some potential use cases of AI in 6G.

AI in network management. AI can help improve the flexibility and efficiency in the network management. Machine learning as one of AI technologies can enable networks learn to address problems by itself without human intervention. Physical layer. Existing AI techniques have involved in physical layer designs and resource allocation in wireless communications. Due to the network is gaining...
complexity, we may utilize deep learning instead of human operators [13]. For example, unsupervised learning can be used for channel-aware feature-extraction, optimal modulation, interference cancellation, channel estimation, etc [13]. Deep reinforcement learning can be employed for link preservation, channel tracking, on-demand beamforming, energy harvesting, etc [13,27].

Network layer. In addition to the physical layer, AI technologies can help the network layer, too. Supervised learning techniques can solve problems, such as resource allocation, fault prediction, anomaly detection, etc [13]. Besides, unsupervised learning algorithms can help in routing, traffic control, parameter prediction, resource allocations, etc [13]. Reinforcement learning can be used for multi-objective routing, packet scheduling, security, traffic prediction, and classification, etc [13,27].

AI in Autonomy. 6G wireless systems are considered as autonomous, which rely on AI technology to inject intelligence into future wireless networks [14,31,32,27]. Agents with intelligence can detect and resolve network issues actively and autonomously. Ho et al. [4] envision that AI will also play an essential role in the optimization of the 6G systems designed, such as fully autonomous aerial vehicles and autonomous robots. AI-enabled network management can monitor real-time network status and maintain network health. Lovén et al. [14] believe that future 6G network will equip with unprecedented security and personality through cooperation between AI and edge computing.

AI in Edge Computing. 6G provides high bandwidth and low latency services network environment to the future Internet of Things. The edge computing serves as the key component of future 6G technologies, as it may contribute to distributing cloud applications and providing more bandwidth and reducing latencies [14].

Security of Edge Computing. AI techniques provide intelligence at the edges, which enables edges to learn to solve security problems autonomously. Porambahage et al. [30] consider that security and edge AI are related in two ways, including “AI for edge computing” and “security for edge AI”. They mean that AI is incorporated in securing the edge devices, or there are security related issues and challenges towards the realization of edge AI.

B. Large Intelligent Surfaces and Intelligent Reflecting Surfaces

Currently, two types of intelligent surfaces shown in Fig. 8 attract researchers’ attention – the Large Intelligent Surfaces (LISs) and the Intelligent Reflecting Surfaces (IRSs). LISs are helpful for constructing an intelligent and active environment with integrated electronics and wireless communication [31,32,27]. However, Renzo et al. [33] predict future wireless networks will serve as an intelligent platform to connect the physical world and the digital world seamlessly. They foresee that the wireless network will be smart radio environments which have the potential to realize uninterrupted wireless connectivity, and use existing radio waves to transmit data without generating new signals.

Large Intelligent Surfaces (LISs). The LIS is considered as a promising candidate to improve the signal quality at the receiver by modifying the phase of incident waves [32,34–39]. The concept of deploying antenna arrays as LIS in massive MIMO systems was originally proposed by Hu et al. [37]. LISs are electromagnetically active in the physical environment, where each part of a LIS can transmit and receive electromagnetic fields. Buildings, roads, and walls are expected to be electronically active after decorating with LISs [31]. LISs have following main favorable features [31]: (I) They are more likely to yield perfect LoS indoor and outdoor propagation environments. (II) They impose little restrictions on how antenna elements can be spread. Hence, mutual coupling effects and antenna correlations can easily be avoided, such that sub-arrays are large and the channel is well-conditioned for propagation. Thus, LISs can be realized via Terahertz Ultra-Massive MIMO (UM-MIMO). LISs support simple channel estimation techniques and simple feedback mechanisms, which are important for low-latency applications.

Intelligent Reflecting Surfaces (IRSs). IRSs are surfaces of electromagnetic (EM) material that are electronically controlled with integrated low-cost passive reflecting elements, which may contribute to forming the smart radio environment [40]. The highly probabilistic wireless channel is turned
into a deterministic space by using the software-controlled propagation of the EM waves in the smart radio environment realized by IRSs. IRSs help to enhance the communication between a source and a destination by reflecting the incident wave [40]–[42]. By adjusting the reflection of the incident electromagnetic waves, IRSs enable the reflected signals being coherently added at the receiver without adding additional noise [42]. Besides, IRSs can modify the signal phase and increase signal power [31]. In particular, graphene-based plasmonic reconfigurable metasurfaces can achieve beam steering, beam focusing, and wave vorticity control utilizing local tuning [43]. Unlike LISs, IRSs use passive array architecture for reflecting purpose [44].

Distinguishable features of IRSs summarized by Basar et al. [40] and Wu et al. [44] include:

- They comprise low-cost passive elements which are controlled by software programming.
- They do not need any dedicated energy source for transmission; they do not need any backhaul connections to exchange traffics.
- The IRS is viewed as a contiguous surface and any point can shape the wave impinging upon it.
- They are fabricated with low profile, lightweight, and conformal geometry, such that they are easily deployed.
- They operate in the full-duplex mode without any self-interference; they do not increase the noise level.

The IRS-aided network includes both active components (BS, AP, user terminal) and passive component (IRS). IRS is different from existing technologies, including active relay, backscatter communication, and active surface based massive MIMO. We highlight some differences between IRS and well-known technologies as follows:

I. **Massive MIMO:** IRSs and massive MIMO consist of different array architectures (passive versus active) and operating mechanisms (reflecting versus transmitting) [44]. Benefit from the passive arrangement of the elements, IRSs achieves much more gains compared to massive MIMO while consuming low energy [45].

II. **Amplify-and-forward relay:** Relay uses active transmit elements to assist the source-destination communication, but the IRS serves as a passive surface only reflects the received signal [44] [45]. Relays reduce the available link rate if they operate in half-duplex mode, or are subject to severe self-interference if they operate in full-duplex mode. IRSs overcome AF’s outstanding shortcomings. Active relay usually works in the half-duplex mode, which wastes spectrum compare to IRS, which works under full-duplex mode. If AF implements full-duplex mode, it needs costly self-interference cancellation techniques to implement.

III. **Backscatter:** The reader needs to implement self-interference cancellation at its receiver to decode the radio frequency identification (RFID) tag’s message because RFID communicates with the reader by modulating its reflected signal sent from the reader [44]. However, IRS only reflects received signal without modifying information; thus, the receiver can add both the direct-path and reflect-path signals to improve the signal strength for decoding.

C. **Terahertz Communications**

Current wireless communication systems are unable to catch up with the ever-increasing applications and requirements in 6G. Terahertz frequency band, which ranges from 0.1 to 10 THz, is the last unexplored span of radio spectrum [45][46]. Terahertz communications provide ultra-high bandwidth and ultra-low latency communication paradigms [46]. It is envisioned to provide up to Tbps data speed to satisfy 6G applications’ requirements of high throughput and low latency [45]. A novel approach to generate the terahertz frequency is discovered by Chevalier et al. [47]. They build a compact device that can use the nitrous oxide or laughing gas to produce a terahertz laser whose frequency can be tuned over a wide range at room temperature. Traditionally, the terahertz gap limits the widespread use of THz. Terahertz transceiver design is regarded as the most critical factor in facilitating terahertz communications [45].
Recent technology advancements in terahertz transceivers, such as electronics-based devices and photonics-based devices, overcome the terahertz gap, and enable some potential use cases in 6G [46]. The electronic technologies such as standard silicon CMOS, silicon-germanium BiCMOS, and III-V semiconductor related technologies (where the roman numerals III and V refer to the old numbering of the periodic system groups), have been vastly advanced, such that amplifiers and mixers are able to operate at a frequency close to 1THz [45, 48]. The photonic technologies, including optical down-conversion systems based on photomixers or photoconductive antennas, uni-traveling carrier photodiodes (UTC), and quantum cascade lasers (QCLs), have been demonstrated as potential enablers of practical THz communication systems [45, 48]. In addition, the combination of electronic-based transmitter and photonics-based receiver is possible, too. Besides, recent nanomaterials may help to develop novel plasmonic devices for THz communications [48].

D. Visible Light Communications

Visible light communication (VLC) is considered as one of potential techniques in the 6G. It is a form of wireless communication for short-range, and it uses data-modulated white light-emitting diodes (LEDs) or laser diodes (LDs) as transmitters and photodetectors (PDs) as receivers. Besides, it uses low-cost hardware and low interference and a free, unlicensed spectrum [7]. VLC is considered to be a complementary technology of RF communications [7]. Currently, the best data rate of VLC in each link has proven the Gbps experience.

The Laser diode (LD)-phosphor conversion lighting technology is expected to be the most promising next-generation technology because it can provide higher brightness, higher efficiency and farther illumination range than traditional lighting technology [45]. The LD-based VLC system can potentially reach 100Gbps, and it is more suitable to ultra-high data density (uHDD) services in 6G. In addition, the upcoming new light sources based on microLED will overcome the limitation of low speed in short range communication [19]. As massive parallelization of microLED arrays, spatial multiplexing techniques, CMOS driver arrays, and terahertz communications develop, VLC’s data rate is expected to reach Tbps in the short range indoor scenario by the year of 2027 [19, 46].

VLC can be used in indoor scenarios because it has limited coverage range, and it needs an illumination source and suffers from shot noise from other light sources (e.g., the sun) [7]. However, VLC can integrate space/air networks and underwater networks with terrestrial networks to provide superior coverage [10]. Traditional electromagnetic-wave signals cannot achieve high-speed data transmission using laser beams in the free space and underwater, but VLC has ultra-high bandwidth and achieve high-speed data transmission [49]. Therefore, VLC can also be useful in scenarios in which traditional RF communication is less active such as in-cabin internet service in airplanes, underwater communication, healthcare zones, etc [11]. Furthermore, VLC is envisioned to be widely used in the vehicle-to-vehicle communications which depend on car’s head and tail lights for communications [145, 49].

E. Other Potential Technologies

Dynamic Spectrum Sharing with Blockchain. Blockchain provides a secure and distributed database for transaction records by enabling all participants to record blocks, each of which includes the previous block’s cryptographic hash, a time stamp, and transaction data [21]. Blockchain can provide a secure architecture for next-generation wireless networks [50]. Besides, blockchain-like mechanisms are expected to provide distributed authentication [19]. Combining with federated learning, blockchain-based AI architectures are shifting AI processing to the edge [30]. Thus, blockchain can help to form a secure and decentralized environment in 6G [50].

Advanced duplex. Existing spectrum sharing is imbalanced. One promising technique to solve the imbalanced utilization of spectrum is the full degree of freedom duplex (i.e., free-duplex) [45]. Free Duplex can achieve more efficient utilization of spectrum resources by sharing all-degree-of-freedom (time, frequency, and space) spectrum resources between transceiver and receiver links, to improve throughput and reduce the transmission delay.

Holographic radio. Traditional wireless networks treat unwanted signals as a harmful phenomenon, but 6G intends to consider interference as a useful resource to develop holographic communication systems [5]. Computational holographic radio is one of the most promising interference-exploiting technologies [45].

III. Conclusion

In this paper, we summarize promising technologies in 6G networks. We present a detailed explanation of artificial intelligence, intelligent surfaces, and visible light communications. Besides, we briefly introduce potential technologies, including blockchain, full-duplex, holographic radio, and terahertz communication. In the next decade, we envision that the industry and the academia will pay more attention to the research of these technologies in 6G.

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