Towards 6G Communication: Key Technologies, Challenges, And Applications

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Abstract. With the continuous development of the information age, communication technology, as one of the fundamental infrastructures for information transmission, is also evolving and innovating continuously. Currently, 5G communication technology has gradually been commercialized, bringing about significant changes to people's lives and work. However, with the rapid development of emerging technologies such as the Internet of Things, artificial intelligence, and big data, the demand for communication technology is also increasing continuously. The future society will develop from informatization to intelligence. In order to meet the future society's demands for larger capacity, higher speed, lower latency, more safer transmissions, and more intelligent connections, researchers have begun to explore the next generation of communication technology, namely 6G communication technology. This paper will provide an overview of the development direction, key technologies, potential challenges, and application prospects of future 6G communication technology, in hopes of providing reference for the development of future communication technology.

Keywords: 6G, terahertz, multiple-input multiple-output, intelligent reflecting surface, artificial intelligence.

1. Introduction

Nowadays, 5G has been gradually commercialized. The high data transfer capacity and low latency characteristics of 5G will greatly change people's lives. Virtual reality, mixed reality, and augmented reality are some applications of 5G [1]. The properties of 5G can also be used to develop the Internet of Things, helping to construct a world where everything is connected and usher humanity into the era of smart industry (Industry 4.0) [2]. However, there are still some limitations of 5G. To achieve the goal of intelligent connectivity for everything, the next generation of communication technology needs to possess the following characteristics: extremely high data transfer rates, extremely low transmission latency, extensive coverage, lower energy consumption, and the capability for artificial intelligence and machine learning [3]. 6G will be a revolutionary technology that is expected to bring about changes and innovations in multiple fields. This paper aims to present a broad prospective vision for 6G communication. In this paper, the author attempted to explore emerging technologies for achieving 6G communication, address the challenges faced in the development of 6G communication, and outline future research directions. Finally, this paper enumerated application scenarios for 6G and concluded.

2. Technologies for achieving 6G

2.1. Terahertz communication

The terahertz band (0.1THz-10GHz) is considered to be a potential driving factor for achieving ultra-high data rates in the 6G networks [4]. Terahertz features high frequency and large bandwidth. Therefore, it can support high-volume data transmission, and its susceptibility to diffraction is minimal, effectively enhancing communication security [5]. Additionally, due to its wavelength being much shorter than that of millimeter-wave frequencies, terahertz is conducive to integrating more antennas [6]. It is expected to integrate over 10,000 antenna elements into base stations, forming ultra-narrow beams to overcome propagation losses, achieve higher data transfer rates, and simultaneously provide services to a greater number of users [6].

2.2. MIMO technology

Multiple-input multiple-output (MIMO) is a pioneering technology that uses multiple antennas on the transmitter and the receiver to send and receive multiple data streams on the same channel simultaneously. Recently, a new technology called massive MIMO brought possibilities to increase the efficiency of communication further [7]. Massive MIMO involves using a large number of antennas to provide services to a smaller number of user devices, significantly reducing signal interference and minimizing energy consumption. Massive MIMO is divided into two types: centralized and distributed [7]. Centralized access concentrates antennas at main base stations, resulting in lower costs [7]. On the other hand, distributed access disperses antennas throughout various regions, effectively combating signal attenuation and ensuring optimal service for each device [7]. The differences between the two of them are shown in Figure 1.

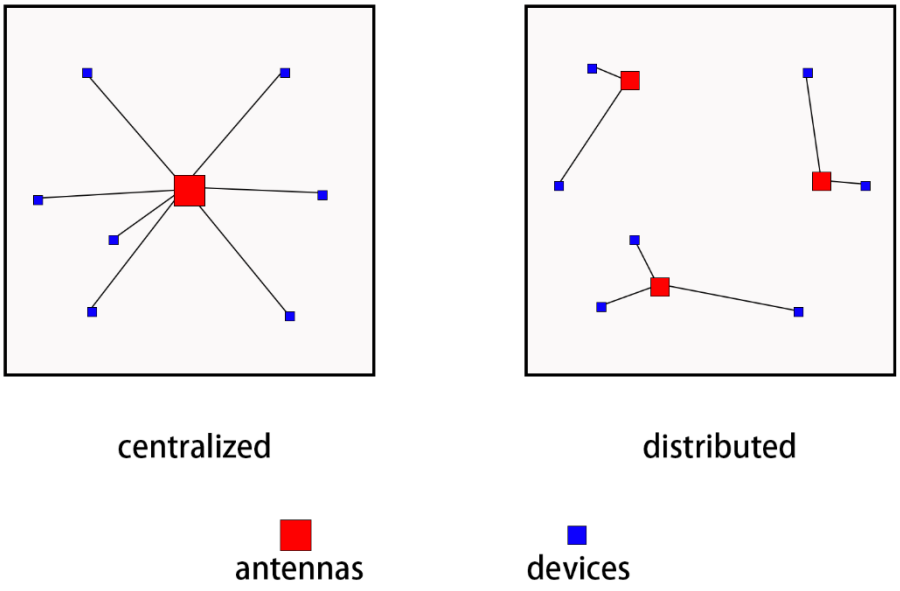


Fig. 1 Two types of massive MIMO.

2.3. Intelligent reflecting surface

An intelligent reflecting surface (IRS) consists of a planar surface and numerous reflective elements, with a smart controller controlling each element to adjust phase, frequency, and other parameters for incoming signals independently [8,9]. Intelligent reflecting surface technology offers advantages such as low energy consumption, high transmission rates, and broad coverage. Reflective elements only reflect incoming signals and do not actively emit signals [9]. Additionally, intelligent reflecting surfaces are lightweight, compact, and easily deployable on a large scale [9]. Intelligent reflecting surface technology can be combined with MIMO technology. IRS-assisted MIMO systems enable base stations to deploy fewer antennas while ensuring the quality of service for users [8]. This is achieved by leveraging the large aperture of IRS to create fine-grained reflected beams through intelligent passive reflection [8]. In Figure 2, the author compared pure MIMO and IRS-assisted MIMO. This technology holds significant potential for future implementation and is poised to be a beneficial catalyst for realizing 6G communication.

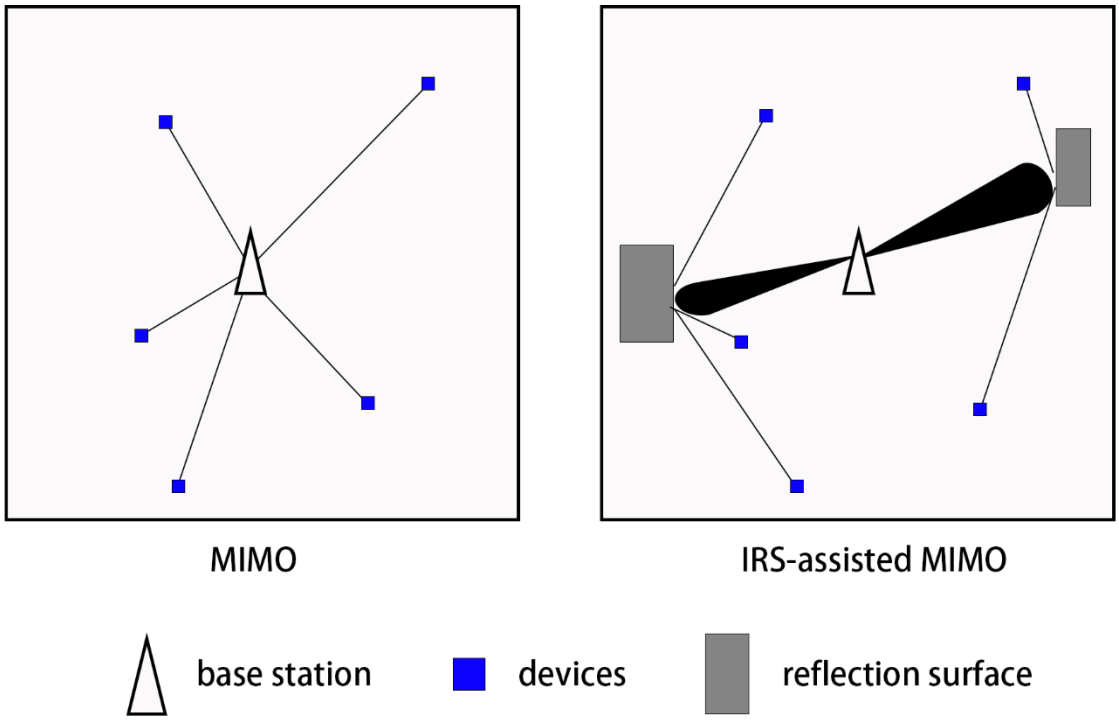


Fig. 2 MIMO system compared with IRS-assisted MIMO system.

2.4. Artificial intelligence

The channel algorithm design for wireless communication typically relies on establishing mathematical models. However, in 6G communication systems, the scale and density of networks will become vast and complex, making modeling such systems exceptionally challenging [3]. With the rapid advancement of AI technologies recently, emerging techniques like deep learning or reinforcement learning can learn complex relationships between variables [3,10]. This assists designers in designing wireless communication systems without precise knowledge of mathematical models [10]. Furthermore, AI can be used for designing resource allocation and interference management strategies [5]. AI algorithms can predict network traffic and adjust resource allocation based on the results to achieve optimal utilization, reduce network latency, and minimize energy consumption [5]. With the help of machine learning, the invaders' behavior can be detected promptly. Neural networks will process device communication information collected, and then the illegal behaviors and communications will be identified and listed, providing enhanced protection for network security [11].

3. Difficulties and challenges

3.1. The design of the algorithm and the collection of data

Despite the rapid development of artificial intelligence, there are still some challenges that need to be overcome. Using AI to analyze and learn the algorithm requires a huge amount of data. Therefore, collecting data from wireless communication is essential. However, there is currently no unified training dataset available for model generation, so a significant investment is required to build a large-scale wireless signal dataset that can be shared [11]. Additionally, researchers have not yet reached a consensus on the optimal algorithms for addressing issues such as resource allocation and channel design in wireless networks [12]. The process of data collection and data transmission in networks may lead to the leakage of user privacy, posing an urgent challenge to privacy security in the era of big data [5].

3.2. Dynamic networks

In the future, the locations of devices and base stations will tend to be dynamic. Therefore, 6G technology needs to acquire channel state information and calculate channel capacity at any location in space [5]. Therefore, it is necessary to integrate electromagnetic theory and information theory. Electromagnetic theory is used to capture the distribution of the electromagnetic field in continuous space, while information theory is employed to calculate the channel capacity in discrete space [5]. The combination of these two theories is achieved through antenna theory and wireless propagation modeling theory [5]. As antennas emit electromagnetic waves, information is conveyed through wireless propagation channels. With a significant increase in the number of antennas in MIMO technology, the relationship between antennas and wireless propagation channels becomes more closely intertwined [5]. Therefore, it is essential to consider both when designing antennas and calculating channels. Unifying these four theories will be a key breakthrough in achieving 6G technology.

3.3. Terehertz technology

In theory, due to the high bandwidth characteristics of terahertz communication technology, the data transfer rate can increase linearly with the signal bandwidth. However, there are still some obstacles in translating the theoretical data transfer rate into reality due to certain hardware limitations. The circuit power consumption significantly increases with the expansion in signal bandwidth, with analog-to-digital converter (ADC) and digital-to-analog converter (DAC) being the major power-consuming components [13]. As the number of signal bits transmitted per second increases, energy consumption will exhibit exponential growth [14]. Additionally, high data density poses challenges in waveform design. The frequency synchronization requirements between multi-carrier waveforms and ADC are very strict and demand high-speed samplers that are currently lacking [13]. Due to the lack of diffraction in the terahertz frequency band, path loss in channel propagation is high, necessitating the combination of multiple antenna techniques in MIMO to provide beamforming compensation for the loss. However, large-scale antenna arrays require a complex signal distribution network when allocating signals in the millimeter-wave band, resulting in significant signal loss [13]. Therefore, new antenna and transceiver architecture designs will be necessary.

3.4. Global cover

In the future, wireless communication is bound to achieve global coverage. Therefore, satellite communication, underwater communication, and underground communication need to be integrated with 6G technology to form seamless coverage across land, sea, and air. When establishing communication in underground and underwater areas, signals must overcome harsh environments, making traditional radio waves potentially obsolete [15,16]. Magnetic Induction (MI) technology is a potential solution [15]. However, communication based on MI technology has shorter transmission distances, and higher interference, and requires the use of relay coils to address these issues [15]. The installation, charging, and lifespan extension of underground relay coils are still worth researching [15]. In satellite communication, network protocols and resource allocation urgently need innovation to reduce costs and ensure the widespread use of satellite communication by mobile users [17]. Phased array technology is an emerging, low-power, small-sized, and cost-effective satellite communication terminal [17]. Many small antennas receive signals through software algorithms, as shown in Figure 3. However, the high communication bandwidth of future 6G technology poses a challenge for fewer electronic devices to process signals. How to achieve mutual conversion between digital and analog signals on smaller mobile platforms remains an open research problem.

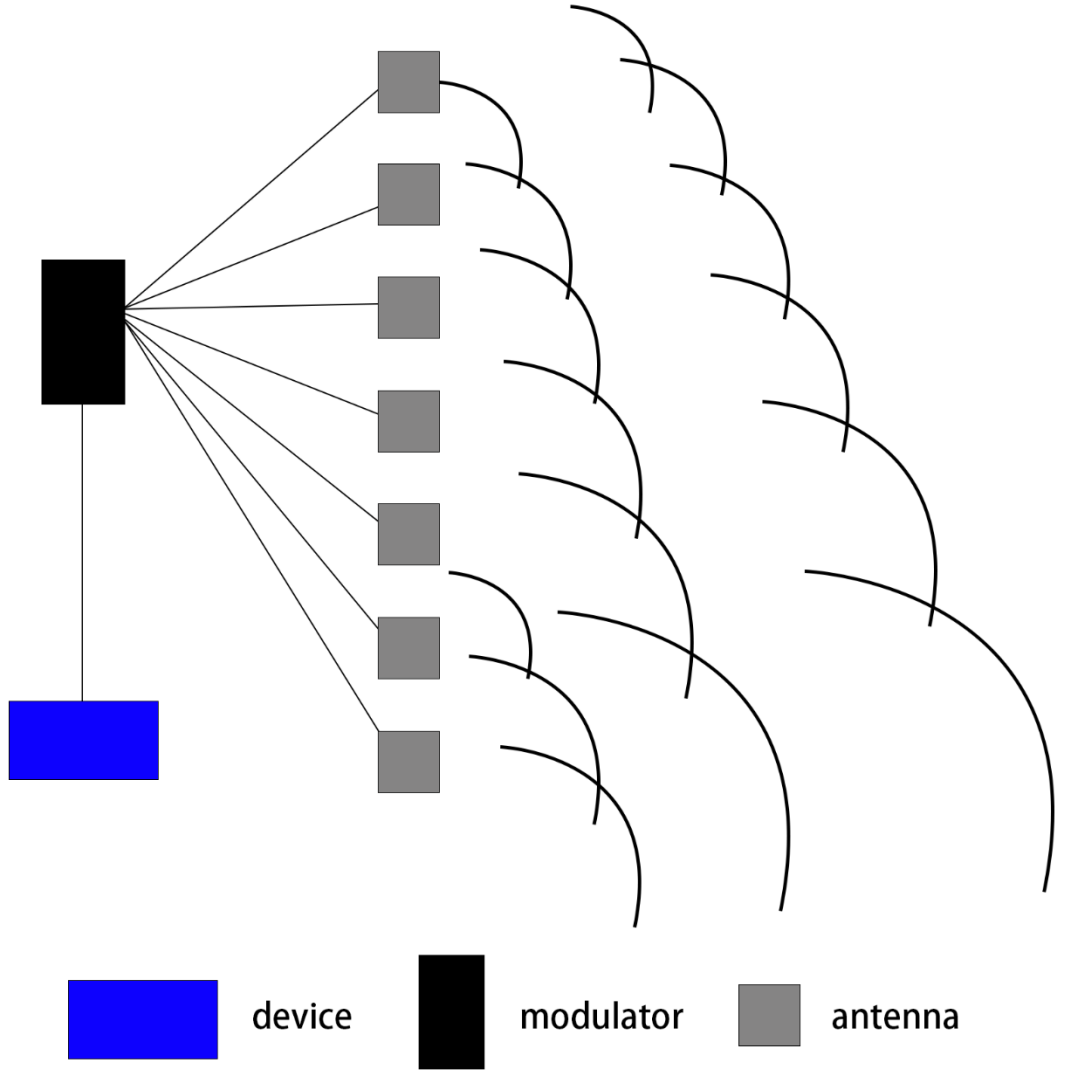


Fig. 3 Phased array technology.

Each antenna is independently responsible for receiving signals in different frequency bands, which are then integrated and transmitted to the device after digital-to-analog conversion by the modulator. In the diagram, thick black curved lines represent electromagnetic waves at different frequencies, while thin black straight lines depict signal transmission.

4. Applications

4.1. Holographic communication

Holographic communication is considered to be the successor to virtual reality and augmented reality [12]. It can transmit multisensory data, including visual, auditory, olfactory, gustatory, and tactile sensations, providing users with an immersive experience [12]. It gives the impression of face-to-face communication, which has large application potential in educational, medical, and commercial fields. The characteristics of high bandwidth, low latency, and high transmission rates associated with 6G can support the realization of this technology depicted in science fiction.

4.2. Intelligent industry

The extremely low latency and high data throughput of 6G will provide the foundation for interconnecting various sectors in industrial production. Collaboration through information exchange between devices can significantly enhance work efficiency, reduce resource wastage, and achieve

intelligent production management. Additionally, interconnected factories can serve as significant sources of big data, offering essential information for decision-makers [12].

4.3. Autonomous physical systems

Autonomous driving cars are a prime example of autonomous physical systems. The car's sensors continuously collect vast amounts of surrounding terrain data in real-time and connect to servers for tasks such as route optimization and reporting safety information [12,18]. Unmanned aerial vehicles (UAVs) represent another type of autonomous physical system with significant applications in military, agriculture, disaster management, and other fields [18]. Both of these systems involve high-speed movements, necessitating the use of 6G's dynamic network connectivity technology for reliable high-speed data transmission [12].

4.4. Wireless brain-machine interface

Brain-computer interface is a rapidly developing technology in recent years that involves the mutual conversion of human brain biological signals and electronic digital signals. When combined with wireless communication, this technology enables remote interaction between individuals and electronic devices [5]. It provides a means of information transfer for patients with neurological impairments, allowing them to control household appliances or prosthetics. Furthermore, doctors can utilize this technology for remote medical monitoring, enabling real-time monitoring of patients' physiological information and even facilitating remote surgeries [18]. Biomedicine is expected to become a crucial application scenario for 6G communication technology.

4.5. Digital twins

Digital twinning has become a hot topic in the academic community in recent years [19]. The digital twinning technology effectively handles the interaction between the real world and the virtual world [5]. As urbanization continues to expand, city management becomes increasingly challenging. Therefore, building smart cities is considered to be the optimal direction for future urban development [19]. With the aid of artificial intelligence, data from various infrastructure elements can be collected and used to create models predicting future developments, such as traffic networks, ecological environments, and power systems [5,19]. The implementation of digital twinning in cities allows decision-makers to respond quickly to emergency events and assess development plans [5,19]. Among these, an intelligent data transmission system is essential for constructing the future smart city.

5. Conclusion

This paper investigates the development of 6G communication. The author highlights several promising key technologies, including terahertz, MIMO, IRS, and artificial intelligence. Additionally, the author explores the challenges that may be encountered in the development of 6G. Finally, several potential applications of 6G are proposed. In conclusion, the development of 6G technology still faces numerous open challenges, and it is hoped that this summary of the current state of 6G communication technology will provide insights for future research.

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