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6G: A survey on technologies, scenarios, challenges, and the related issues

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ABSTRACT

In our present-day world, the global technological and industrial revolution is accelerating. The widespread application of new generation ICT (information and communication technologies), such as AI, VR (Virtual Reality)/AR (Augmented Reality)/XR (Extended Reality), IoT (the Internet of Things), and blockchain technology, has driven the emergence of the 6 G communication system. Building on the basis of 5 G, the development of 6 G will have a profound impact on the intelligence process of communication development, which consists of intelligent connectivity, deep connectivity, holographic connectivity, and ubiquitous connectivity. To identify 6 G and its related issues, we conducted a survey of extant research on 6 G. In this paper, its prospects, core technologies, scenarios, challenges, and the related issues are discussed. Moreover, a potential framework for 6 G is proposed as well. The main contribution of this survey is that it clarifies the state of the art of 6 G for future study.

1. Introduction

ITU (International Telecommunication Union) established the IMT-2030 Standard in May 2019, noting that 6 G aims both to provide a revolutionary user experience and to offer a new set of sensory information and experiences. 6 G will be a combined system composed of multiple different networks: local, mobile cellular, ocean, satellites, and other as yet undefined networks [23].

6 G will explore new communication mechanisms without being restricted by existing network paradigms or technology. It embeds fully compatible new concepts, new architectures, new protocols, and new solutions to support existing and future scenarios. Specifically, the 6 G system is intelligent connectivity, deep connectivity, holographic connectivity, and ubiquitous connectivity. Intelligent connectivity is reflected in all the intelligence of the communication system: the intelligence of the network elements and network architecture, the intelligence of the connected object (the terminal device) and the information carried to support the intelligent service. Deep connectivity means deep sensing, deep learning, and deep mind. The characteristics of holographic connectivity are holographic communication everywhere (and at any time), high-fidelity, and seamless coverage AR/VR/XR. Ubiquitous connectivity is an all-terrain and all-space multiple-dimensional coverage connection [43,46,52,88].

5 G is in the early stages of large-scale commercialization [36,70,74]. Its related technical functions need to be continuously enhanced and improved. The business modes of IoT and industry application scenarios also need to be explored. The next generation mobile communication system (6 G) has the following trends:

(1) Ten-year cycle rules. Each of the last five generations of mobile communication systems (1 G, 2 G, 3 G, 4 G, and 5 G), from concept to commercial application, took about ten years to develop. In other words, when the previous generation entered the business stage, the next generation was already beginning to attract our attention, both theoretically and practically. 5 G began ten years ago, and now it is the time for 6 G.
(2) The “Catfish Effect”. Unlike previous generations of mobile communication systems, 5 G has mainly been aimed at IoT/industry application scenarios. With the large-scale deployment of 5 G networks, especially in the middle and late stages of 5 G, many industries are joining the 5 G ecosystem. Compared with the current situation dominated by traditional operators, the in-depth participation of new-style companies, in the future, will have a huge impact on the traditional communications industry, and will, perhaps, even become a revolution, the so-called “catfish effect”.
(3) The potential for the explosion of IoT business modes. Just as the emergence of smart phones stimulated 3 G applications and triggered the demand for the large-scale deployment of 4 G, some IoT business models will also stimulate the outbreak of the 5 G industry in the 5 G era, thereby stimulating user's demand for both 5 G and

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the future 6 G network [78,86,90].

Basically, 6 G is expanded and upgraded, based on the last generation, 5 G. From the perspective of network access, 6 G will include various access networks, such as mobile cellular, satellite communications, airplane communications, underwater acoustic communications, and visible light communications. From the perspective of network coverage, 6 G will build an integrated network across space, air, oceans, and land to truly achieve global seamless coverage of integrated information [71,21]. From the perspective of network performance, 6 G will greatly improve the transmission rate, the end-to-end latency, reliability, connection density, spectrum efficiency, and network efficiency to meet the different network needs of various industries. From the perspective of network intelligence, the 6 G network and its users will become a unified object. AI will study user needs in more depth, and each user will be able to improve the user experience through AI assistants. From the perspective of network service boundaries, the goal of 6 G services will extend from people, machines, and physical objects in the physical world to the virtual world [8,16,57].

The paper constructs a comprehensive survey and proposes a description of the definitions and features, fundamental and core technologies, applicable scenarios, upcoming challenges, and potential development directions of 6 G by examining extant literature in the databases of IEEE Explorer, Web of Science (WoS), and ScienceDirect. In total, 386 papers related to 6 G were selected and divided into four categories. In addition, this paper proposes a potential framework for 6 G.

The rest of the paper is structured as follows: the background and the current development of 6 G is addressed in Section II. Section III proposes a potential architecture of 6 G. The methodology and screening procedure of literature are described in Section IV, along with some important trends and insights for 6 G research. Section V illustrates the core technologies of 6 G in detail. Potential 6 G scenarios are described in Section VI. Section VII points out upcoming challenges, both technological and non-technical issues. Section VIII summarizes the paper.

2. Background and current development of 6G

Since the 1980s, the next generation of revolutionary technologies has emerged in a ten-year cycle for ICT development (**Fig. 1**.). The continuous development of information and communication technology has played a vital role in the continuous upgrading of the information system and the prosperity of society. Mobile communication before 4 G was mainly concentrated in individual consumer markets that were people oriented. 5 G has achieved revolutionary technological breakthroughs through faster transmission speeds, ultra-low latency, lower power consumption, and a huge number of connections. Consumers range from individual users to users in various industries and fields. The three major scenarios are: eMBB (enhanced Mobile Broadband), mMTC (massive Machine Type Communications), and URLLC (Ultra Reliable Low Latency Communications)[5,26,34]. Especially after the integration and innovation of 5 G and artificial intelligence, the rise of next-generation information technologies, such as big data and edge computing, has further promoted the development of industries such as manufacturing, healthcare, and transportation. In order to adapt to the deep integration between IoT and various industries, the 6 G network will ensure that everything will be connected deeply, intelligently, and seamlessly.

2.1. Sparse theory (Compressed sensing)

Signal sampling is a bridge between analog sources and digital information. The huge demand for information puts huge pressure on the sampling, transmission, and storage of signals. How to alleviate this pressure and how to effectively extract the useful information carried in the signal are two of the key issues to be solved in signal and information processing. Traditional signal processing usually samples and then compresses, and the signal must be sampled and processed at a rate higher than the Shannon-Nyquist frequency. Unlike the Shannon-Nyquist signal sampling mechanism, a novel sampling theory called Compression Sensing/Compression Sampling (CS) successfully implements the sampling and compression of signals, simultaneously. This new model is a very competitive alternative to traditional signal and information processing, and it includes sampling, sensing, compression, estimation, and detection [11,25].

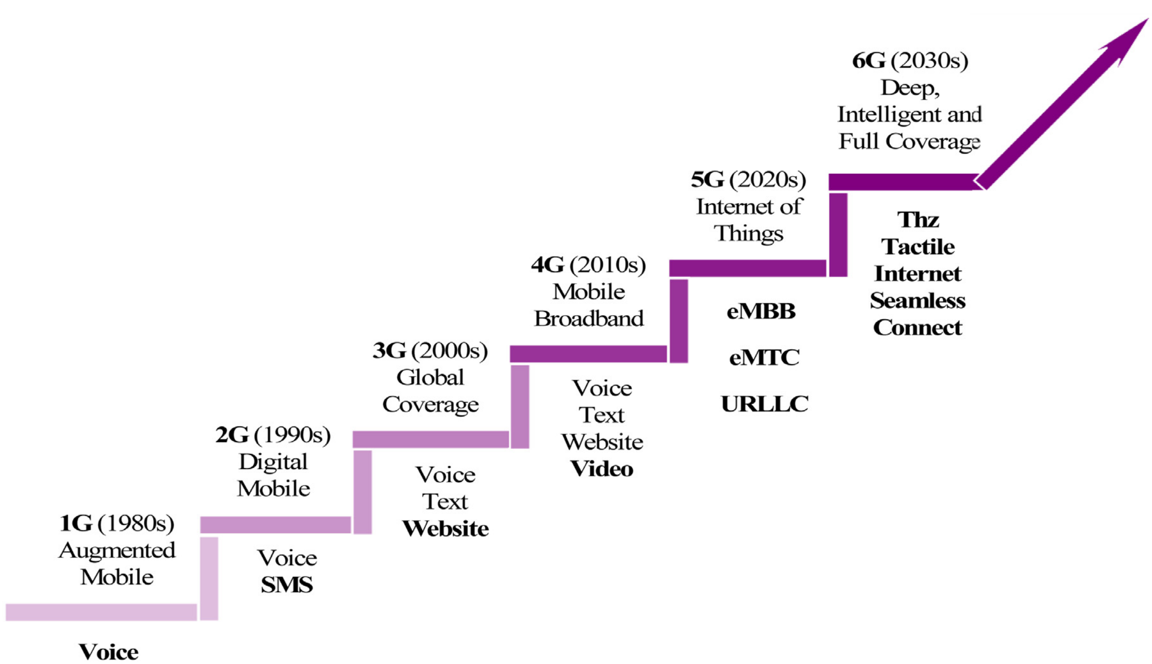

Fig. 1. The development trend of mobile communication.

The core of CS is to recover sparse signals from underdetermined linear systems in a computationally efficient manner. A small number of linear measurements (projections) of the signal contain enough information to be reconstructed. Compression sensing theory points out that when the signal is sparse or compressible in a certain transform domain by using a measurement matrix independent of the transformation matrix, the linear projection of the transformation coefficients can be used as a low-dimensional observation vector. At the same time, the projection maintains the reconstructed signal. By further solving the sparse optimization problem, the required information can be used to accurately reconstruct the original high-dimensional signal based on the low-dimensional observation vector or high probability. Under this theoretical framework, the sampling rate no longer depends on the bandwidth of the signal, but rather, it largely depends on two basic criteria: sparsity and incoherence, or sparsity and equidistance constraints. In compressed sensing theory, the sending terminal replaces signal sampling with information sampling (e.g., data observation or perception), while the receiving terminal replaces traditional decoding with signal reconstruction. Three typical application scenarios for compressed sensing are ultra-wide bandwidth spectrum sensing, wireless sensor network (wireless tactile network), and every large scale antenna [10,58].

2.2. The development of 6G among countries

Due to its importance and its benefits, many leading countries have launched 6 G research and development, among them such as US, China, South Korea, Japan, UK, Finland, etc. The following table (**Table 1**.) provides detail.

3. A potential framework of 6G

Spatial features are one of the main features of future networks and communications (6 G). Network communication can break through the limitations of space, geographical location, the microworld, and thebiological environment. Network interconnection has shifted from the current two-dimensional interconnection on the ground to multi-dimensional entities that cover land, ocean, air, space, the microworld, and outer space. Interstellar interconnection continues to expand to all of the physical dimensions of the Earth. Wireless network coverage in the 6 G era will be extended to the ubiquitous physical space. The 6 G ground mobile communication system, using spatial multiplexing technology, will cooperate with the satellite communication system to form a network, integrating terrestrial wireless communication; high, medium and low latitude satellite Internet; and marine Internet to form the maximal capacity and high-density spectrum ubiquitous coverage (**Fig. 2**.). The 6 G network can cover almost all of the areas of human activity: remote areas with no human living, deep oceans, and even the stratosphere, reflecting the characteristics of ubiquitous interconnected networks [20,29,32,33].

Based on land, sea, space, and air, the 6 G network will use high-throughput satellites to establish orbit satellite communication constellations (space-based). It will integrate various platforms for marine Internet communications (based on the sea) and ground mobile communications (based on the land) to form a high-precision, high-reliability network covering the entire world. The United Nations has identified US GPS, Chinese BeiDou, Russian Glonass, and EU Galileo as the world's four major global navigation satellite systems [17]. As to communications, interconnection technologies, architecture, and standards, 6 G will be able to promote satellites to roam and to switch between any two satellites.

4. Methodology

Bibliographic research has been developing and has covered many different angles by a variety of approaches. In this paper, we follow a fundamental procedure [59],[67] to select and filter the extant literature about 6 G. The detailed process of article screening is shown in the following figure (**Fig. 3**).

Across three databases, IEEE Explore, Web of Science, and ScienceDirect, we used two keywords, “6G” and “6 G communication”, to filter potentially relevant articles. In the initial round, 690 articles (journal papers, conference proceedings, and early access articles) were found. Specifically, there were 375 articles in IEEE Explore, 134 articles in Web of Science, and 181 articles in ScienceDirect. However, some irrelevant or unqualified articles were selected. We implemented two criteria to delete these articles. We reviewed each of the selected article's titles, abstracts, and keywords in detail to double check whether a paper was exactly about 6 G. We deleted all papers that included “6G” but were irrelevant. Another approach we deployed was Google Scholar. Any paper with less than five citations within three years was deleted. Finally, 386 articles met the qualification of IEEE Explore (222), Web of Science (81), and ScienceDirect (83). The figure (**Fig. 4**.) below depicts the publishing trend between 2016 and 2020, based on the selected articles across the three databases.

Among the 386 papers from 2016 to 2020, the number of papers

Table 1
The development of 6G among countries.

Country	Details
US	In September 2018, the Federal Communications Commission (FCC) proposed that 6 G would use terahertz frequency band technology. The New York University Wireless Center is developing channels using terahertz frequencies with transmission speeds up to 100 Gbps. The ComSenTer Research Center of the University of California has studied the fusion of terahertz communication and sensing. As of February 2020, the US space exploratory technology company SpaceX has successfully launched nearly 300 Starlink satellites.
China	On November 3, 2019, China established the National 6 G R&D Promotion Group and Expert Group. Huawei Technologies Co., Ltd. proposed that the frequency spectrum of 6 G should be wider and that the rate should be higher. In the field of terahertz communication technology, some companies have also begun research and development, as among them China Telecom, China Mobile, and China Unicom. China Mobile has established a strategic cooperative relationship with Tsinghua University.
South Korea	In April 2019, the Korea Institute of Communications and Information Science began to develop 6 G and the relevant core technologies. The Korean government and enterprises jointly invested. LG Korea established a 6 G laboratory in January 2019. In June, the mobile operator SK established a strategic partnership with Ericsson and Nokia.
Japan	Japan plans to formulate a comprehensive strategy to achieve 6 G by 2030 through official-civilian cooperation. The plan is hosted by the president of Tokyo University in Japan and is supported by Toshiba and other Japanese technology giants. Hiroshima University has cooperated with the Information Research Organization (NICT) and with the Panasonic Corporation to implement terahertz communications in the 300 GHz band, based on CMOS low-cost technology.
UK	BT (UK) expects 6 G to be commercialized by 2025. Brown University of the United Kingdom has implemented a non-intuitive terahertz data link transmission.
Finland	In March 2019, the University of Oulu, Finland held the first 6 G summit around the world. Nokia, Oulu University, and Finland VTT launched the "6Genesis-Wireless Smart Society and Ecosystem Support 6G" project.

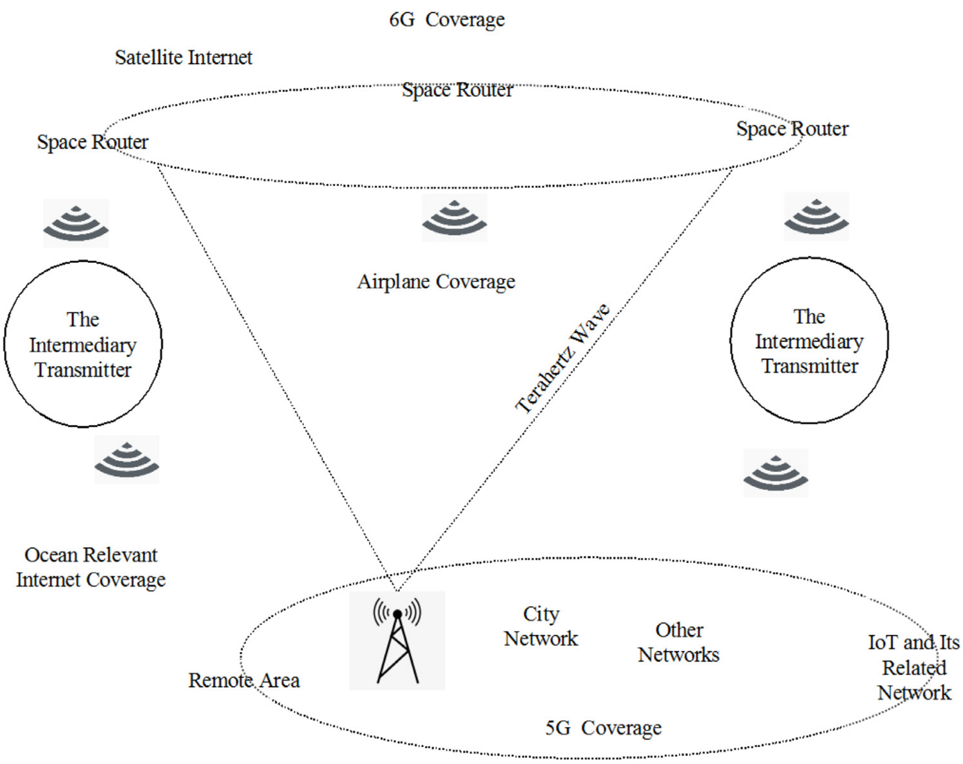

Fig. 2. 6 G full-dimensional network.

published since 2018 is, dramatically, the largest. This is, perhaps, because of the proposal of 6 G proposal in that timeframe. This paper was completed by July 2020; hence, this study could not include any papers published afterwards. Most researchers published their papers in IEEE Explore. This shows that IEEE journals and conferences are the major sources for 6 G research and development. Based on the selected articles, we developed a table (Table 2.) that illustrates the distribution of 6 G research categories. For example, concept and prospect account for 67%, key technologies account for 83%, scenarios account for 38%, and challenges account for 75%. It should be noted that, amid these

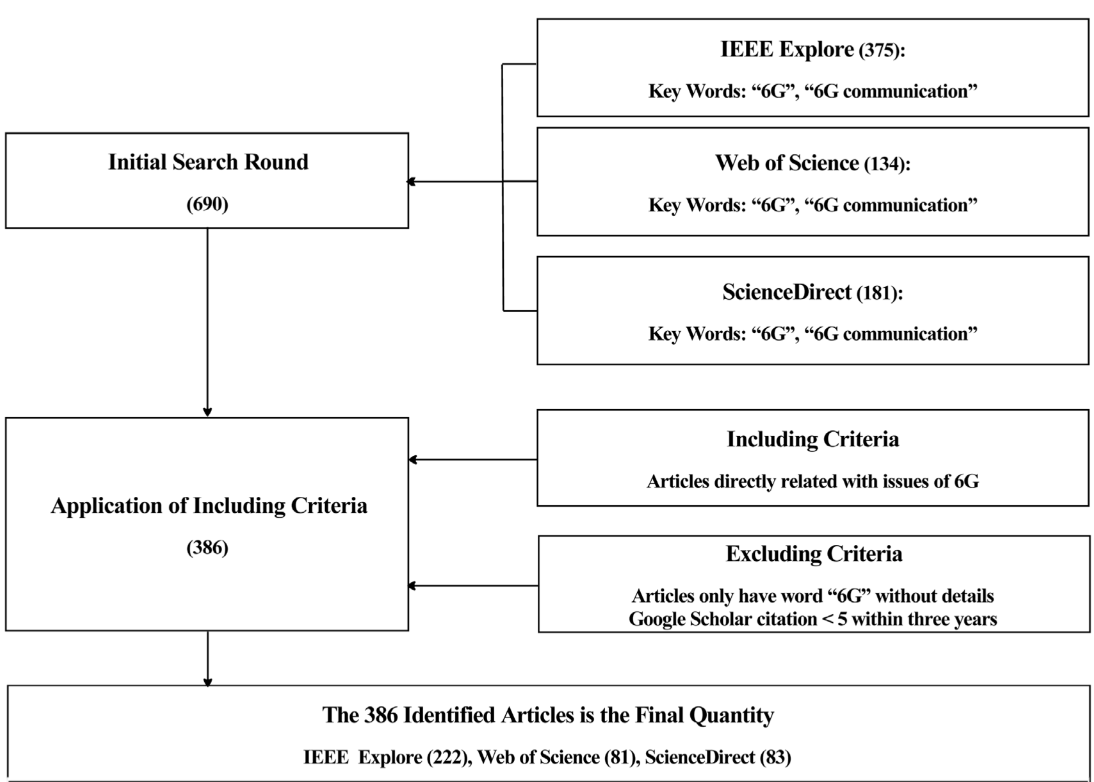

Fig. 3. Literature selecting and identifying procedures.

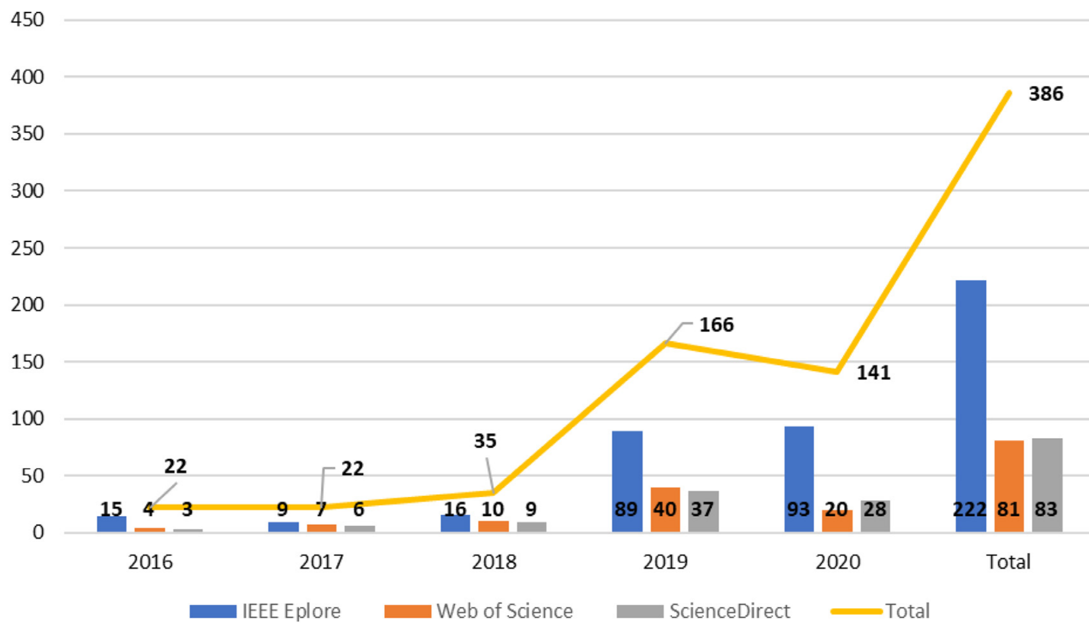

Fig. 4. The trend of publication of 6 G (2016–2020).

Table 2
Research categories of the selected 88 publications.

Research categories	Number of publications	Percentile
Concept and prospect of 6G	258	67%
Key technologies of 6G	322	83%
Scenarios of 6G	146	38%
Challenges of 6G	289	75%

four categories, there are overlaps in the 386 papers selected. All of the potential research categories are worth studying. Because 6 G and the related research has just begun, its technological characteristics and its potential risks attract a good amount of attention from researchers and practitioners. Overall, 6 G has become a popular emerging discipline, as we will see in the next decade.

5. 6G network performance and potential core technologies

This section introduces and illustrates the technological performance and the key enabling technologies of 6 G network. Many 6G-related technologies are being developed, from many different angles. In this paper, we compared and addressed most of the applicable ones, based on our opinions.

5.1. 6G network performance

In the 6G system, more advanced performance will be seen for the first time in ICT development, such as VLC (Visible Light Communication), WTI (Wireless Tactile Internet), and HPC (High Performance Computing) [7,9,5661]. Compared with 5 G, 6 G will have a high peak rate, a high user experience rate, low latency, high traffic density, high connection density, strong mobility, high spectrum efficiency, strong positioning capability, strong spectrum support capability, high reliability, high network energy efficiency, etc. A comparison is depicted in the following table (**Table 3**.).

For several different perspectives of ICT, 6 G can replace 5 G, and it will be the next generation of communication system [3,18,86].

(1) The high peak rate of 6 G is 1 Tbps (5 G at 20 Gbps).
(2) The high user experience rate of 6 G is counted as Gbps, but 5 G can only reach 1 Gbps at most.
(3) The latency of 6 G is as low as 0.1 ms, which is very close to on-time processing, while that of 5 G is 1 ms.
(4) The traffic density of 6 G can vary between 100- 10,000 Tbps/square meter, while the latency of 5 G is only used for 10 Tbps/square meter.
(5) The mobility of 6 G is >1000 km/h, while the mobility of 5 G is 500 km/h.
(6) The spectrum efficiency of 6 G is 200–300 bps/Hz, while the spectrum efficiency of 5 G is 100 bps/Hz.
(7) The reliability (Error Coding Rate) of 6 G is as low as less than 1/1000,000, but that of 5 G is less than 1/100,000.
(8) The positioning capability of 6 G is for Outdoor 1 meter and Indoor 10 cm, while that of 5 G is for Outdoor 10 meter, indoor around 1 meter.
(9) 6 G spectrum support capability is 20 Ghz for conventional carrier bandwidth and 100 Ghz for multi-carrier aggregation; 5 G spectrum support capability is 100 Ghz for Sub conventional carrier bandwidth, 200 Ghz for multi-carrier aggregation.
(10) The network efficiency of 6 G is 200 bits/J, while 5 G network efficiency is 100 bits/J.

5.2. Potential core technologies

In particular, key enabling technologies (Fig. 5) include a wireless communication technology & system (THz communication and visible light communication), next generation antenna and basic synthetic materials, channel coding and modulation techniques (channel coding, non-orthogonal wave, and multiple access system), spectrum sharing (free duplex, full duplex, and dynamic spectrum sharing), and other integrated new technologies (AI, IoT, and the blockchain technology).

5.2.1. Wireless communication technology & system

5.2.1.1. THz communication. Terahertz waves are electromagnetic waves with a frequency spectrum between 0.1 and 10 THz and a wavelength between 30 and 3000 μm. The frequency spectrum is located between the microwave and far infrared light. THz waves exist between macroelectronics and microelectronics. Terahertz communication has the dual advantages of abundant spectrum resources and a high transmission rate. In future mobile communications, this is an advantageous broadband wireless access (Tb/s communication) technology. The United States Federal

Table 3
Comparison of performance between 6G and 5G.

Performance	6G	5G	Effect
Rate	Peak rate: 100Gbps-1Tbps User experience rate: Gbps	Peak rate: 10Gbps-20Gbps User experience rate: < 1Gbps	10–100 times
Latency	0.1 ms, on-time processing	1 ms	10 times
Traffic density	100- 10,000 Tbps/square meter	10 Tbps/square meter	10–100 times
Connection density	Maximum 0.1 billion connections/square meter	1 million connections/square meter	100 times
Mobility	>1000 km/h	500 km/h	2 times
Spectrum efficiency	200–300 bps/Hz	100 bps/Hz	2–3 times
Positioning	Outdoor 1 meter, Indoor 10 cm	Outdoor 10 meter, Indoor around 1 meter	10 times
Spectrum support	Regular carrier bandwidth 20 Ghz, Multi-Carrier Aggregation 100 Ghz	Sub 6 G Regular carrier bandwidth 100 Ghz, Multi-carrier aggregation 200 Ghz,	50–100 times
Reliability	< 1/1000,000	< 1/100,000	10 times
Network efficiency	200 bits/J	100 bits/J	2 times

Communications Commission (FCC) said, at the World Mobile Congress in September 2018, that 6 G can use THz spectrum-based networks and spatial multiplexing technologies [20,50,77].

Terahertz technology has become one of "ten technologies that will change the future world." An important feature of 6 G is the widespread application of terahertz technology [32,54,80],84]. According to 6 G network and business requirements, the terahertz technologies include:

(1) Terahertz space and ground communication and channel transmission theory, such as channel measurement, modeling, and algorithms.
(2) Terahertz signal coding and modulation techniques, such as high-speed and high-accuracy acquisition and tracking mechanisms, waveform and channel coding, terahertz direct modulation, terahertz hybrid modulation, and terahertz broadcast modulation.
(3) Terahertz antenna and radio frequency system technology, such as the research and development of new materials, the research and development of new equipment, the terahertz communication baseband, key antenna technology, the high-speed baseband, signal processing technology, and integrated circuit design methods.
(4) Terahertz communication system experimentation and hardware and equipment development.

Terahertz waves have their unique characteristics and have more advantages than microwave and wireless optical communications. Terahertz waves have broad application prospects in high-speed and short-distance broadband wireless communications, broadband wireless security access, and space communications [19,27,29,47]:

(1) When the terahertz wave propagates in the air, it is easily absorbed by the moisture in the air. It is more suitable for high-speed and short-distance wireless communication.
(2) The beam is narrower, the directionality is better, and the anti-interference ability is stronger.
(3) Terahertz waves have a higher frequency and a wider bandwidth. They can meet the demand of spectrum bandwidth in wireless broadband transmission. The terahertz wave spectrum is between 108 and 1013 GHz, and the available spectrum bandwidth is tens of GHz. It can provide a communication rate exceeding Tb/s.
(4) Regarding space communication: in outer space, terahertz waves

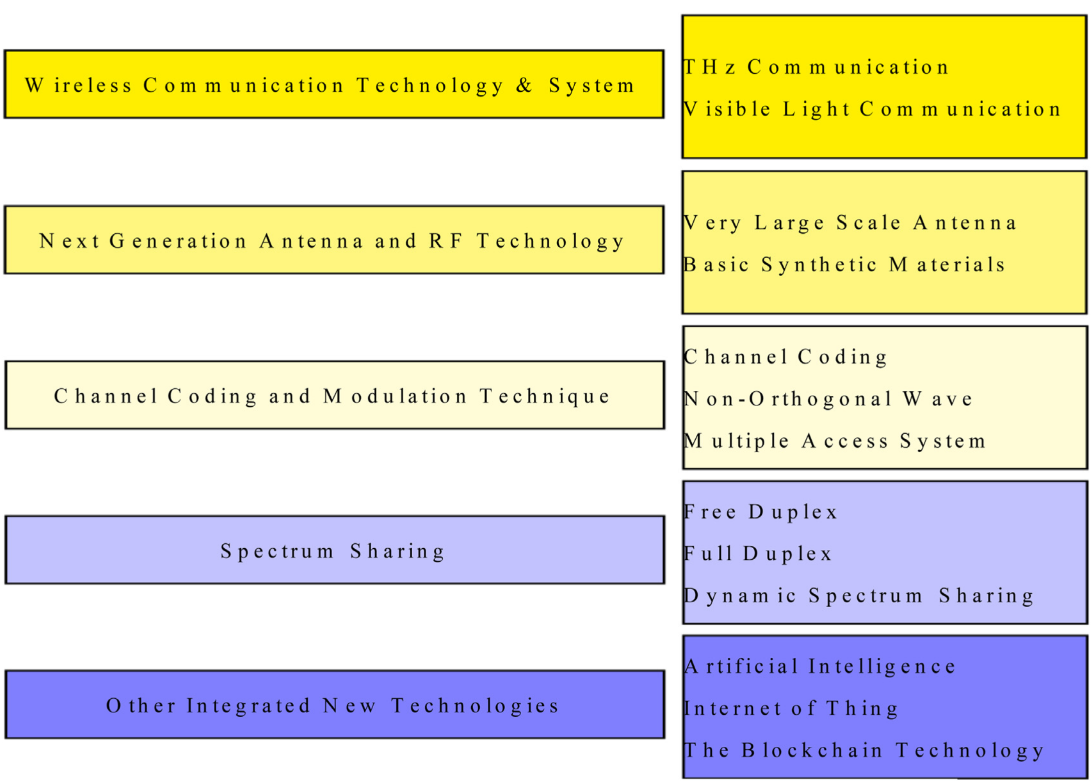

Fig. 5. Core technologies of 6 G network.

have relatively transparent atmospheric windows around the wavelengths of 350 μm, 450 μm, 620 μm, 735 μm, and 870 μm. They can achieve less transmission and low-power long-distance communication.

(5) The short wavelengths in the terahertz band are also suitable for Massive MIMO (multiple-input and multiple-output) with more antenna elements.

(6) Regarding its high energy efficiency: compared with wireless optical communication, the photon energy of terahertz waves is very low, about 10–3 eV. It is only 1/40 of visible light. Using it as an information carrier can achieve extremely high energy efficiency.

(7) Strong penetration. Terahertz waves can penetrate matter with less attenuation. They are suitable for communication needs in some special cases.

5.2.1.2. Visible light communication. One possible supplementary technology of the existing wireless RF communication technology is OWC (Optical Wireless Communications). The frequency band includes infrared, visible, and ultraviolet rays. The visible light frequency is a very important frequency band of OWC [30,31].

The OWC system in the visible band (390–700 nanometers) is commonly referred to as visible light communication (VLC). It makes full use of the advantages of visible light emitting diodes (LEDs) to achieve the dual purpose of lighting and high-speed data communication. Compared with radio communication, VLC has many advantages. First, visible light communication technology can provide many potentially available spectrums (terahertz-level bandwidth). Second, visible light communication does not produce electromagnetic radiation and is not easily affected by external electromagnetic interference; thus, it can be widely used for specialized uses that are sensitive to electromagnetic interference and even to eliminate electromagnetic interference, such as hospitals, airplanes, gas stations, and chemical plants. Third, the network established by visible light communication technology is more secure; the transmission medium used by this technology is visible light and cannot penetrate walls and other obstacles. Transmission is limited to the user's sight. The transmission of network information is limited to buildings. It can effectively prevent malicious outsiders and can maintain information security. Finally, visible light communication technology supports the rapid establishment of wireless networks. It can promote the flexible establishment of temporary networks and communication links, thereby reducing the usage and maintenance costs of the network. Radio frequency signals cover blind spots, such as those in subways and tunnels [51,57,66,86].

5.2.2. Next-generation antenna and basic synthetic materials

5.2.2.3. Very large scale antenna. Multi-antenna technology, especially very large-scale antenna technology, is one of the key technologies that will improve the spectrum efficiency of wireless mobile communication systems. A very large scale antenna is an important means to improve the spectrum efficiency of the communication system. Very large scale antenna technology needs to break through the following problems: to solve the theory and the technical realization problems of the cross-band, high-efficiency, full-space coverage antenna RF field; to study the configurable large array antenna and RF technology, and highly integrated RF circuits; and to understand new large-scale array antenna design theory and technology, highly integrated radio frequency circuit optimization design theory and implementation methods, and the high-performance large-scale analog beamforming network design technology [6,45,49,90].

5.2.2.4. Basic synthetic materials. The RF front-end of wireless communication needs to adapt to higher carrier frequencies, larger communication bandwidths, higher efficiency, and high linearity signal power input and output. The new crystalline compound composite material synthesized from various metal materials can cause communication equipment to have an extremely strong electromagnetic wave absorption capability. Due to its unique electrical and optical properties, it is the first choice for wave-absorbing materials in future RF equipment [1,48].

The word “Metamaterial” is a new vocabulary word that has appeared in the field of physics. In the electromagnetic field, it usually refers to an artificial composite electromagnetic structure formed by arranging wavelengths or sub-wavelength dimension units in a certain arrangement. Because its basic unit and its layout can be arbitrarily designed, it can construct ultra-conventional media parameters that cannot be achieved by traditional materials or technologies. The metasurface is a two-dimensional morphology of metamaterials. The concept of time-coded metamaterials is that the programmable hypersurface designed in the time domain will switch quickly, according to the corresponding time-coded sequence. It can generate harmonic energy distribution in the frequency domain. At the same time, combined with the space-domain coding scheme, space-time joint coding is performed. The surface can simultaneously adjust electromagnetic waves in the space domain and in the frequency domain. It can be used in satellite communications and computational imaging systems in the future [35,86].

5.2.3. Next-generation channel coding and modulation technique

The 6 G network will form a full-region seamless network system at a data rate of 100 Gbps, a THz band higher than the 275 GHz band, and a channel bandwidth of GHz. This poses new challenges for basic channel coding and modulation techniques.

5.2.3.5. Next-generation channel coding. As the foundational technology of wireless network communication, the new generation of channel coding technology should improve the throughput of 6 G networks to Tb/s. In light of the information transmission characteristics of multiuser/multi-complex scenarios in 6 G networks, the existing user channel coding mechanism can be optimized based on the complexity of interference ([46,68,78]; Gui, et al., 2019).

5.2.3.6. Non-Orthogonal wave. No matter how deep and complicated the communication technology is, the essence is to transmit symbols one-to-one. The sign information is usually based on the pulse level of the rectangular square wave corresponding to Sinc function. For each symbol to be effectively transmitted in the atmosphere, the wireless signal can resist signal noise interference and to transmit data at high speed in fading channels and multipath environments. OFDM (Orthogonal Frequency Division Multiplexing) is widely used in cellular mobile communications and in WiFi technology. However, due to the orthogonality of OFDM, mobile communication cannot break many limitations brought by Gabor theory. The square wave used in OFDM has large side lobes and a high sensitivity to carrier frequency drift, and it is difficult to suppress the baseband waveform with a peak-to-average ratio. It is not suitable for synchronization between a discontinuous spectrum and a carrier. This makes OFDM technology difficult to adapt to the next generation of mobile communications [13,53].

Non-orthogonal wireless communication technology is an effective way to obtain the best spectral efficiency as well as good time-frequency domain characteristics in mobile communication. For example, the filter bank-based multi-carrier (FBMC) technology and non-orthogonal multiple access (NOMA) technology that are used in 5 G/6 G combine multiple non-orthogonal transmissions and the data among sub-carriers. The filtering method to distinguish user data can effectively solve many problems caused by the existing orthogonal technology [2,13].

5.2.3.7. Multiple access system. NOMA (non-orthogonal multiple access) will become the representative access technology for 5 G and 6 G mobile communications. It is an important part of the development of 5 G/6 G to implement polarization coding technology to the above system and to optimize the channel polarization decomposition scheme according to the principle of generalized polarization. The 6 G network will further realize the design and the optimization of the polarization multiple access system. The overall architecture and key technologies of NOMA need to be upgraded to establish and optimize the polarization coding communication mechanism, based on the principle of the multiuser. The corresponding algorithms need to be optimized, as well. NOMA provides services for multiple users/frequency/code/space at the same time. At the receiving end, technologies such as continuous interference cancelation (SIC) or multiuser detection (MUD) can eliminate interference, decode user signals, effectively increase network capacity, reduce communication delays, and increase the number of connections. NOMA technology mainly includes power domain NOMA and code domain [2,5383].

5.2.4. Spectrum sharing

Spectrum sharing is mainly used to solve the problem of unbalanced spectrum demand between different networks. On the one hand, it is necessary to expand the available spectrum, both the terahertz spectrum and the visible light spectrum. On the other hand, the spectrum usage rules also need to be changed. Cellular networks mainly use authorized carriers, and spectrum resource owners have exclusive rights to use the spectrum. Even if spectrum resources are temporarily idle, other users have no opportunity to use them. The exclusive authorized spectrum has strict restrictions and requirements on users' technical indicators and usage ranges. It can effectively avoid interference between systems and can be used for a long time. However, despite the high stability and the reliability of this method, there are still problems, such as spectrum idleness and insufficient utilization caused by the dedicated frequency band of authorized users. This exacerbates the contradiction between the supply and demand of the spectrum (Tariq, et al., 2019; [81]).

According to the division of spectrum resource licensing methods, one spectrum sharing is the unlicensed spectrum, in which users are not restricted in using frequency bands. Users have equal rights to usage without protection and/or to technical support. To avoid mutual interference, the spectrum needs to be shared dynamically. On the premise of ensuring that it does not interfere with the primary users, through design permission (such as specified access time, access location, transmission power, interference protection), secondary users can be provided with corresponding spectrum usage rights. Secondary user technologies, such as databases, spectrum sensing, and cognitive radio, can be used to share the spectrum with primary users in different dimensions, e.g., space, time, and frequency (Tariq, et al., 2019; [81]).

5.2.4.8. Free duplex/full duplex spectrum. A full duplex spectrum is mainly used to solve the problem of unbalanced spectrum requirements between different nodes in the same network and between the transceiver links of the same node. One example is that it is used for underseas communication. Due to the Poisson distribution of the data packets of the service, the actual network resource sending and receiving links' (usually referring to the uplink and downlink in the cellular network) resource utilization fluctuates dynamically and can be uneven. The enhancement of the existing duplex technology is to achieve a flexible spectrum allocation between the transmission link and the reception link (this is called flexible spectrum sharing between the transmission link and the reception link). Hence, it can improve the duplex dimension resource rate and the utilization rate [82,86].

The duplex mode uses a dynamic TDD (Time Division Duplex) architecture, while the FDD (Frequency Division Duplex) mode is only a special configuration. The available spectrum of 5 G is mainly distributed in the frequency band above 2 GHz, most of which is in the TDD spectrum. Once these two types of interference are resolved, 5 G will truly be able to support the commercial deployment of Flexible Duplex (Free Duplex) functions, and it will get rid of the resource utilization restrictions of fixed duplex (FDD/TDD). It is expected that the duplex mode in the 6 G era will be expected to achieve a true full-duplex mode (Free Duplex), that is, there will no longer be a difference between FDD and TDD, but this will depend on the business requirements between sending and receiving. The receiving link is in flexible duplex or full-duplex mode and seeks completely flexible and adaptive scheduling. It completely eliminates the limitation of the duplex mechanism on the utilization of spectrum resources between transceiver links. In full-duplex mode, through full idle (time, frequency, space) flexible spectrum resources sharing between transceiver links (or DL and UL), more efficient use of spectrum resources can be achieved to increase throughput and to reduce transmission delay [60,78].

5.2.4.9. Dynamic spectrum sharing technology. The terahertz frequency characteristics of 6 G increase its network density. Dynamic spectrum sharing has become an important means to improve spectrum efficiency and to optimize network deployment. Dynamic spectrum sharing uses an intelligent distributed spectrum sharing access mechanism, which can flexibly expand the available spectrum range and can optimize spectrum usage rules to meet the 6 G system spectrum resource usage requirements. At the same time, promoting the cooperation of blockchain, dynamic spectrum sharing, artificial intelligence, and other technologies to achieve intelligent spectrum sharing and supervision of 6 G networks is another advantage [34,44,55].

5.2.5. Other integrated new technologies

5.2.5.10. Wireless communication technology based on AI. With the advent of the big data era and the growth of various hardware and software computing resources, artificial intelligence (AI), especially deep learning, has become an area with many practical applications and many active research topics. With the help of deep learning, through in-depth induction and analysis of data, new general information and knowledge can be obtained, and this knowledge can be used to build models that will support decision-making, as well as risk analysis or prediction. The emergence of deep learning has promoted the rapid development of many fields such as speech recognition, computer vision, machine translation, and biological information. Academia and industry have been considering how to integrate AI into wireless communication systems to achieve a significant increase in the efficiency of wireless communication systems. The main idea is to introduce AI (especially deep learning) into the field of wireless resource management and allocation [38,41,57,85].

6 G networks inevitably involve high-density networks, antenna arrays, and data volumes. 6 G intelligence should run through each node of the network. AI will effectively realize seamless connection between ground, satellite, and airborne equipment through network data, business data, user data, and other multi-dimensional data-aware learning and real-time high-speed exchange. The network autonomous management and control learning system will continue to be optimized and upgraded. Its key technologies will include intelligent core network and intelligent edge network, self-organizing and deep learning network technology, channel coding and decoding technology based on deep learning, signal estimation and detection technology based on deep learning, and wireless resource allocation technology based on deep learning [24,37],87].

5.2.5.11. Internet of thing in 6 G. Perception Internet is a higher stage of the development of the Internet of Things. It is an intelligent network, and it includes sensors that can communicate data through different networks, such as the tactile Internet and the visual Internet. In the 6 G era, the perception Internet is different from traditional networks. The various intelligent subjects have learning ability. They can feed back and control the information obtained through perception to obtain corresponding experience and to form an expert system. The transmission of pure information content also includes round-trip control information that corresponds to the information content. It is a new generation of information technology that combines a control system and a computer system. It can transform the traditional Internet of Things into AIoT (Artificial Intelligence + Internet of Things) ([7]; Mavromoustakis, 2020).

5.2.5.12. The blockchain technology. To optimize services, 5 G network operators use network slicing and other technologies to control and process traffic and develop differentiated user services. The 6 G network will continue to improve users' personalized services and will use other useful approaches to provide intelligent customized services for each user by traffic management and edge computing. The entire network system will use an automatic distribution structure, and the network will become flatter ([62,63,75];). Due to the uniqueness of blockchain, e.g., decentralization, anonymity, transparency, lack of intervention, and security, the distributed ledger technology of the blockchain can ensure that user information will not be stolen by third parties, can steadily improve the network collaboration efficiency and capability between network service nodes, can enhance the security of information communication, and can improve the security and privacy of the involved entities within the 6 G communication system [40,42,64,65].

6. Prospects of 6G scenarios

Building on 5 G, 6 G will continue to improve the performance and will optimize the experience of ICT through technological innovation; it will expand services from the physical world to the virtual reality. 6 G will explore new application scenarios, new service forms, and new business modes based on the integration and collaboration of people, machines, things, and environments. Potential attractive scenarios (**Fig. 6**.) are the human digital twin, the air Internet, holographic communication, the new smart city, global emergency rescue, smart factory PLUS, cyber robots and autonomous systems, and the wireless tactile Internet, etc.

6.1. Human digital twin

Under the current network capacity, the detection of human body structure by digital technology is mainly used for the detection of common indicators and for the prevention of major diseases. Its real-time availability and accuracy need to be improved. With the upcoming maturity of 6 G technology and with the combination of the interdisciplinary sciences such as bioscience, materials science, and bioelectronic medicine, digital twins of the human body can be created. Aiming to form a complete human virtual world, and realizing the real-time monitoring of personalized health data of the human body, the digital twins of the human body will, through a large number of intelligent sensors (>100 devices per person), accurately (and in real-time) reflect important organs, the mental system, the respiratory system, the urinary system, and musculoskeletal and emotional status. In addition, 6 G will be able to combine MRI (magnetic resonance imaging), CT (cognitive therapy), color doppler ultrasound, blood routines, and urine biochemistry and other professional images and biochemical examination results to provide individuals with an accurate assessment of their health status and then with timely intervention. Also, AI can be integrated for professional medical institution to provide accurate diagnostics and references for implementing a personalized surgical treatment [66,89].

6.2. High speed internet access in the air

It is difficulty, with 5 G, to realize a high-quality air network system. There are two main modes of air network services: ground base stations and satellite transmission. If the ground base station mode is adopted, due to the rapid movement of the aircraft and the large cross-border range, the air network will face challenges, such as high maneuverability, doppler frequency shift, frequent handovers, and narrow base station coverage. If the satellite transmission is used, the quality of the air network can be relatively guaranteed, but the cost will be too high.

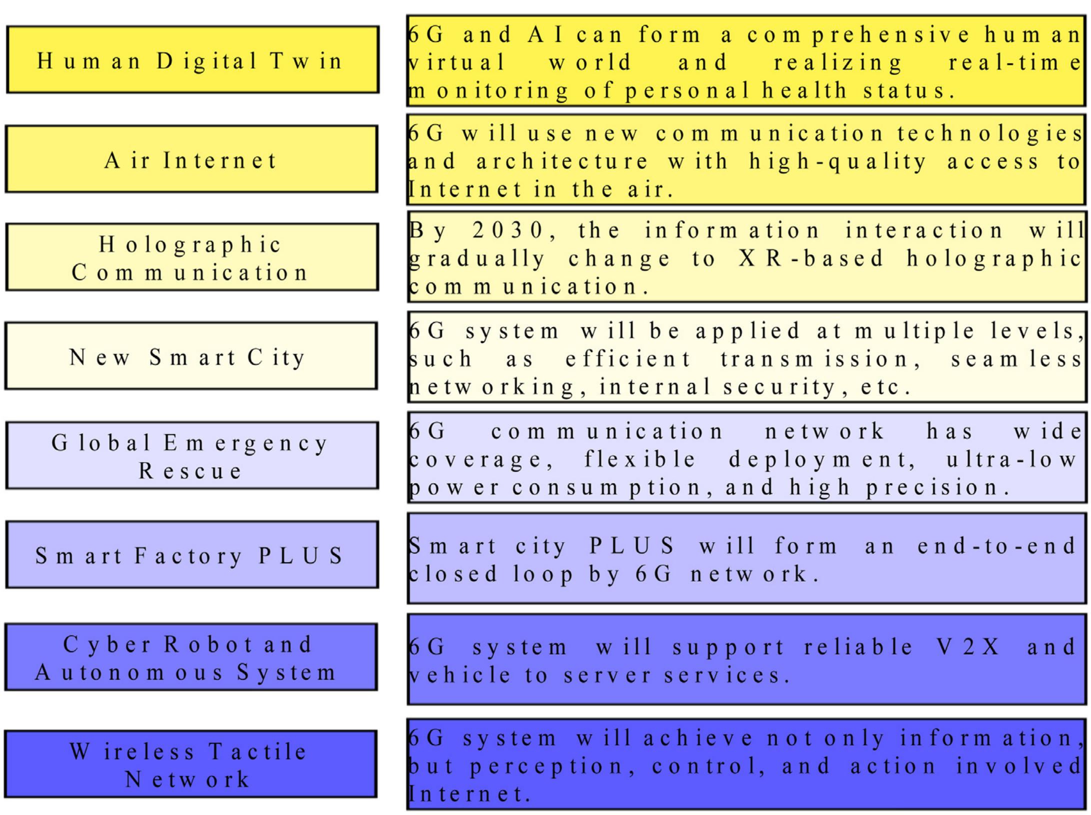

Fig. 6. 6 G Scenarios.

6 G will use new communication technologies and new network architectures other than cellular to provide users with high-quality high-speed Internet access services, while reducing network usage costs (Tariq, et al., 2019; [15]).

6.3. XR (Extended reality) based on holographic communication

AR/VR is one of the most important features of 5 G. The main factors affecting the development of AR/VR technology and its applications are the mobility and freedom of users, that is, users will not be restricted by location. With the rapid development of technology during the years leading to 2030, the form of information interaction will gradually evolve from AR/VR to XR, and even the information interaction of holographic communication system and eventually wireless holographic communication will be accomplished. Users will be able to enjoy the upgrade brought about by holographic communication and holographic display, anytime and anywhere. XR will be able to mobilize sight, hearing, touch, smell, taste, and even emotion. Users will no longer be limited by time and place, but can virtually enjoy and engage education, games, sports, painting, concerts, and other fully immersive holographic experiences ([12,52],).

6.4. New smart city

To achieve a smart city, millions of sensors have been equipped into vehicles, buildings, factories, roads, houses, and other facilities. 6 G will be the reliable wireless high-speed communication approach to support applications that will integrate and collaborate with each other to process data-oriented activities. With the continuous development of the digital age, communication networks have become an essential public infrastructure for smart cities. Since the infrastructure construction and management belong to different administrative departments, the information perception, transmission, analysis, and control of most urban public infrastructure will still be under their own control, so there will be no unified management platform. 6 G will adopt a unified network architecture, introduce new business scenarios, and build a more efficient and comprehensive network. In the future, network virtualization technology, software-defined networks, and network slices will be able to be divided into separate physical and logical networks; AI will be deeply integrated into the 6 G system and can be practically applied at multiple levels, such as efficient transmission, seamless networking, internal security, large-scale deployment, and automatic maintenance. A new smart city ecosystem will be built with the assistance of 6 G ([14,69]; Carter, et al., 2018; [4,22]).

6.5. Global emergency communication rescue

6 G will achieve a seamless network coverage system in all regions. It is expected that, by 2030, ubiquitous connectivity will become one of the main functions of 6 G networks. Existing network blind spots, such as deserts, deep seas, and mountains, will be covered. The 6 G communication network will feature wide coverage, flexible deployment, ultra-low power consumption, and high precision. It will offer a wide range of applications in emergency communications and management, emergency rescue, and the real-time monitoring of unmanned areas. For example, when natural disasters (such as earthquakes) damage terrestrial communication networks, satellite and unmanned aerial networks can be integrated to achieve wide-area seamless coverage. The rescue crew can access the network at any time and can collaborate resources to support emergency management. In addition, the 6 G network can be used for real-time dynamic monitoring of areas prone to natural disasters (such as deserts, oceans and rivers), and can provide early warning services in events such as sandstorms, typhoons and floods to reduce disaster losses [18,79].

6.6. Smart factory plus

The 6 G system uses ultra-high bandwidth, ultra-low latency, and high reliability to collect real-time operational data of workshops, machine tools, and accessory parts. Edge computing and AI technology directly monitor and transmit data in the terminal to execute orders in real time[70,71]. The blockchain technology in 6 G can directly exchange data between all of the terminals in a smart factory without going through a transportation center, thereby achieving decentralized operations and improving production efficiency. 6 G will not only work in the factory, but it also can guarantee full connection with the entire production cycle. Based on the 6 G network, it can flexibly connect any smart devices/terminals that need to be connected within the factory, and it can dynamically adjust and quickly deploy the combination of smart devices according to the needs of the production line, thereby actively adapting to the personalization and customization of C2B. Smart Factory PLUS will form an end-to-end closed loop, from the individual needs of demand-side customers to factory delivery capabilities by using the 6 G network and the relevant technologies (a; b; [72,73,39,76]).

6.7. Cyber robots and autonomous systems

6 G can facilitate the deployment of network robots and autonomous systems, e.g., UAV mail delivery systems. Self-driving cars based on 6 G wireless communication can greatly change daily lives. The 6 G system will promote the large-scale deployment and application of self-driving cars. Self-driving cars use a varietiy of sensors (such as light detection and LiDar, radar, GPS, sonar, odometer, and inertial measurement equipment) to sense and recognize the surrounding environment. The 6 G system will support reliable V2X and vehicle-to-server services. For UAVs, 6 G will support communication between UAVs and ground controllers. UAVs have broad applications in a number of fields such as military, business, science, agriculture, entertainment, governance, logistics, surveillance, aerial photography, emergency rescue, and disaster relief. In addition, when the cellular base station does not exist or does not work, UAV can be used as HAPS to provide broadcast and high-speed Internet services for users in that area [16,28].

6.8. Wireless tactile network

The IoT network involved in the current 5 G network mainly emphasizes perception and connection. In the future, the goal of 6 G network connection will become a common intelligent goal. The connection and communication relationship will not be not only perception, but also real-time control and response, the so-called "tactile Internet." The "tactile Internet" refers to a communication network capable of sending control, touch, and sensing/driving information in real time. The IEEEP1918.1 standard working group defines the tactile Internet as a real-time network or virtual object network or process for remote access, perception, or control perception. The traditional Internet is only used for the interaction of data and information. The tactile Internet will not only responsible for the remote transmission of information, but will also contain remote control and response behavior that will correspond to the transmission of data and information. It will provide a true transition from content delivery to remote skills delivery. The three key elements of the tactile Internet are: physical real-time interaction (access to people and machines, operation and control objects in a sensed real-time manner), ultra-real-time response infrastructure and network for remote control, and control integration and communication [8,18,78].

7. Potential challenges of 6G

The development of the 6 G network faces many challenges (**Table 4**.): the technological issues include terahertz waves, peak

Table 4
Challenges of 6 G achievement.

Category	Challenges
Technological challenges	Terahertz waves Peak throughput Higher energy efficiency Connection flexibility Self-aggregating communications fabric
Non-technical challenges	Industry barriers Spectrum allocation and usage rules Policies and regulations

throughput, higher energy efficiency, connection flexibility, and self-aggregating communications fabric; the non-technical challenges include industry barriers, spectrum allocation and usage rules, and policies and regulations.

7.1. Technological challenges

7.1.1. Terahertz waves

The terahertz frequency band has irreplaceable advantages in the field of mobile communications, but it also faces many challenges [20,27,29,47,77]:

(1) Coverage and directional communication. The propagation characteristics of electromagnetic waves show that the magnitude of free space fading is proportional to the square of the frequency. Therefore, the lower frequency band of terahertz has greater free space attenuation. The terahertz propagation characteristics and the large number of antenna elements mean that terahertz communication is highly directional beam signal propagation. We need to redesign and optimize the relevant mechanism of this highly directional propagation signal function.
(2) Large-scale fading characteristics. The terahertz signal is very sensitive to shadows and has a great influence on coverage. For example, if the signal attenuation of this component is as high as 40–80 dB, the human body will bring about a 20–35 dB signal attenuation. However, the effect of humidity/rainfall fading on THz communication is relatively small, because the humidity/rainfall fading below 100 GHz increases rapidly with increasing frequency, but it is relatively flat above 100 GHz. Several terahertz frequency bands with relatively small rain attenuation can be selected as typical frequency bands for future terahertz communications, such as the frequency bands around 140 GHz, 220 GHz, and 340 GHz.
(3) Fast channel fluctuation and intermittent connection. At a given moving speed, the channel coherence time is linearly related to the carrier frequency. This means that the coherence time in the terahertz band is very small, the toppler spread is large, and its rate of change is faster than the frequency band used in the current Cellular network. In addition, the higher shadow attenuation will cause the attenuation of the terahertz propagation path to fluctuate more violently. At the same time, the terahertz system is mainly composed of small cells covered by a small area, and it is highly spatially directional signal transmission. This means that the path will become weaker and the service beam and cell association will change rapidly. From a system perspective, the connection of the terahertz communication system seems to be highly intermittent, so a fast-adaptive mechanism is needed to overcome this rapidly changing intermittent connection problem.
(4) Processing power consumption. The main challenge of using very large antennas is the power consumption of the analog-to-digital (A/D) conversion of broadband terahertz systems. Power consumption is usually linearly related to the sampling rate, and it is exponentially related to the number of samples per bit. The large bandwidth and huge antennas in the terahertz band require high-resolution quantization; implementing low-power and low-cost devices will be a huge challenge.
(5) In addition, as far as spectrum regulation is concerned, ITU has decided to allocate 0.12 THz and 0.2 THz for wireless communications, but the regulatory rules for the spectrum above 0.3 THz are not yet clear. This will require joint efforts at the ITU level and at WRC meetings to actively promote consensus.

7.1.2. Peak rate

For wireless mobile communication systems, the index that people must first consider is the peak rate. It is one of the key technical indicators that has been pursued since the first generation of wireless mobile communication systems. 6 G will further increase the peak rate, as the Terabit era (Tb/s). There are two applications that will need the increased 6 G peak rate:

(1) Smart (big data) general-purpose applications require large amounts of data transmission requirements. Intelligent applications based on big data may be one of the important driving forces that trigger the development of next-generation mobile communication systems.
(2) AR/VR and holographic communication will become 6G-supported applications, and the required data rate will far exceed other wireless applications [84,86,88].

7.1.3. Higher energy efficiency

Large mobile communication networks have become part of the world's energy consumption. Not only will they generate large amounts of carbon emissions, but they will also incur considerable operating costs. In the future, 6 G networks will have ultra-high throughput, ultra-wide bandwidth, and ultra-large-scale ubiquitous wireless nodes, which will pose a huge challenge to energy consumption. With the increase of both spectrum efficiency and spectrum bandwidth, throughput can be greatly improved, but the energy efficiency problems will be more serious, so it will be necessary to reduce the energy consumption per bit (J/bit). The general understanding of network sensors will bring about energy consumption in two aspects: first, a large number of sensors will bring a high total energy consumption; second, how to conveniently and effectively provide energy for universal deployment will also be a challenge. In addition, the large amount of data processing power consumption and ultra-large-scale antenna processing power consumption in the "intelligent connectivity" scenario will be the power consumption challenges that 6 G networks will face in the future. Facing the huge energy consumption pressure of the future 6 G network, green energy-saving communication is particularly important [7,86].

7.1.4. Connection everywhere and any time

With the advancement of science and technology, human activity space will be further expanded, and the activity area will generally reach high altitude, outer space, the ocean, and the deep sea. Communication nodes, especially those of the Internet of Things, will be distributed in a wider area. Communication networks are already inseparable from human social activities. In the future, it will be necessary to establish a ubiquitous Internet of Things, a universal (with various sensors) recognition system, and universal (based on big data and deep learning) networks, in order to truly achieve the system's connection and interaction needs anytime and everywhere. The communication goal of the future communication network 6 G should be that anyone can interact with any related object for valuable information at any time and anywhere [84].

7.1.5. Self-Aggregating communications fabric

5 G accommodates different types of networks; 6 G will aggregate them dynamically. Almost every generation of 3GPP standards hopes to integrate multiple technical standards, but the result is still a self-

enclosed standard system. In the process of gradually realizing the interconnection of all things, we will have to face the problem of integration with other complex and diverse industry standards and technologies. As it better supports the Internet of Everything and industry applications, 6 G should be able to dynamically integrate multiple technology systems and have the ability to intelligently and dynamically aggregate different types of networks (technology). Although 5 G can adapt to different types of networks (technology) to a certain extent, it can only be combined statically or semi-statically. 6 G will need to implement the aggregation of different types of networks (technologies) in a smarter and more flexible manner to meet complex and diverse scenarios and business needs dynamically and adaptively [12].

7.1.6. Challenges for tactile internet

One of the key technical challenges in realizing the tactile Internet is to integrate communication, control, and computing systems into a shared infrastructure. By using the mobile communication system as a basic wireless network, together with its software and virtualized logical network element entities, it is integrated into a (two-way) real-time control loop to combine the expected real-time control with efficient computing functions. The tactile Internet is still in its infancy. Some open research challenges need to be solved. In addition to physical layer issues, such as waveform selection and robust modulation schemes, intelligent control plane and user plane separation/coordination techniques are also critical in the effort to reduce signaling overhead and air interface delay. In order to reduce end-to-end delay, it is necessary to study highly adaptive network coding technology and scalable routing algorithms. In addition, for tactile Internet applications, security is one of the most critical requirements. An effective guarantee mechanism must be provided to enhance protection against malicious behavior. The main design standard of wireless tactile networks should assist humans through authorization, rather than automatically replace humans to produce new products or provide services [8,18,78].

7.2. Non-technical challenges

The development of 6 G will not only face technological problems, but will also need to overcome many non-technical factors, mainly those that involve industry barriers, spectrum allocation and usage rules, and policies and regulations.

Compared with 5 G, 6 G will penetrate all aspects of social production and life and will be more closely integrated with other industries. This means that mobile communication will no longer be limited to its own field but will need to work closely with other industries/fields. However, the inherent behavior or benefits of some traditional industries will directly or indirectly set up industry barriers to the entry of 6 G [81].

Spectrum allocation and usage rules are another non-technical factor. For example, using the 6 G terahertz frequency will require coordinated allocation from different countries and regions in the world. As much as possible, a unified frequency range needs to be allocated. Consideration must also be given to coordination with users in other areas of the spectrum, such as weather radar [78].

Satellite communications will face more restrictions in terms of policies and regulations. First, the orbit resources and the spectrum resources used by satellite communications need to be resolved through consultations between countries. Second, compared with traditional terrestrial communications, satellite communications will face more challenges in global roaming switching. At present, several major countries and some commercial entities are actively constructing satellite communication systems. How to coordinate the relationship between these satellite communication systems deployed independently of each other will be a complex issue [52,58].

8. Discussion and conclusion

The study presents a systematic overview of 6 G that focuses on prospects and development, core techniques, applicable scenarios, and challenges, and that proposes a framework of the 6 G network, as well. From three popular databases, IEEE Explore, Web of Science, and ScienceDirect, we selected 386 suitable papers as an article data pool. This paper conducts a state-of-the-art survey of the extant and upcoming research on 6 G.

Unlike 5 G networks, which are mainly used for communication between individuals and the Internet of Things, the next generation of communication networks in the 6 G era will be more concerned with communication among individual, industries, and multiple intelligent objects. Network transmission performance is no longer the only performance of the network; data and information, AI, IoT, and the blockchain technology have become important components. 6 G will implement the individualized and on-time needs of the sustainable development of ICT. The network will continue to penetrate ubiquitous spaces, human-perceived actions, and virtual society. It will provide us with an intelligent, deep, holographic, ubiquitous, seamless, and secure network infrastructure. With the continuous innovation and transformation of AI, the 6 G network will fulfill the requirements of individual and industries in practice.

Declaration of Competing Interest

There is no interest that might appear to affect our ability to present data objectively for the paper, “6G: A Survey on Technologies, Scenarios, Challenges, and the Related Issues”.

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