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What should 6G be?

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The standardization of fifth generation (5G) communications has been completed, and the 5G network should be commercially launched in 2020. As a result, the visioning and planning of 6G communications has begun, with an aim to provide communication services for the future demands of the 2030s. Here, we provide a vision for 6G that could serve as a research guide in the post-5G era. We suggest that human-centric mobile communications will still be the most important application of 6G and the 6G network should be human centric. Thus, high security, secrecy and privacy should be key features of 6G and should be given particular attention by the wireless research community. To support this vision, we provide a systematic framework in which potential application scenarios of 6G are anticipated and subdivided. We subsequently define key potential features of 6G and discuss the required communication technologies. We also explore the issues beyond communication technologies that could hamper research and deployment of 6G.

Since the initial development of the Advanced Mobile Phone System (AMPS) by Bell Labs, which was later called the first generation (1G) network, there have been three large-scale and radical updates to wireless communication networks over the past four decades, resulting in the 2G, 3G and 4G networks[1]. The launch of the 5G network is ongoing and is expected to be commercialized by 2020. As the standardization of 5G has gradually been solidified, researchers have begun to consider the future 6G communication network[2–7].

In this Perspective, we consider what 6G should be. We believe that conventional mobile communications will still be the most important application of 6G in the 2030s, though other application scenarios will become ubiquitous and increasingly significant. Consequently, the 6G network should be human centric, rather than machine centric, application centric or data centric. Following this rationale, high security, secrecy and privacy should be the key features of 6G. Furthermore, user experience would be adopted as a pivotal metric in 6G communication networks. To support this vision for 6G communications, we provide a comprehensive and systematic framework. Specifically, we first anticipate and subdivide the potential application scenarios of 6G. We then define key features of 6G and discuss the required enabling communication technologies. We also explore issues beyond the communication technologies that could significantly affect the research and deployment of 6G in the 2030s.

Background

To justify our 6G vision, we first provide some background that covers network evolution from 1G to 4G, the 5G status quo and the current research progress towards 6G (Fig. 1).

Network evolution from 1G to 4G. Wireless communication stems from Marconi's pioneering demonstration of wireless telegraphy in the nineteenth century and was theoretically constructed based on information theory formed by Shannon in 1948. In the 1980s, the 1G analogue wireless cellular network was in use to allow mobile communications of voice, which was then replaced by the 2G digital cellular network in the early 1990s. Because of digitalization, 2G was capable of providing encrypted services and data services in addition to the traditional voice services, such as short messaging service (SMS). In the early twenty-first century, 3G, represented by wideband code-division multiple access (WCDMA), CDMA2000, time-division synchronous CDMA (TD-SCDMA) and Worldwide Interoperability for Microwave Access (WiMAX), enabled various data services, including internet access, video calls and mobile television[8]. In 4G/Long-Term Evolution (LTE) networks initialized in 2009, multiple-input and multiple-output (MIMO) antenna architecture, orthogonal frequency-division multiplexing (OFDM) and all-internet protocol (IP) technology were jointly applied to achieve high-speed mobile data transmission[9]. 4G has been a significant success both technologically and commercially. With the proliferation of smartphones and tablets, mobile communications have become mainstream, providing a considerable amount of data throughput in 4G networks[2], and the information and communications technologies accompanying 4G have helped reshape society[10–14].

What 5G has been. In 2014, a paper was published that discussed what 5G will be and pointed out that the key technologies to achieve 5G were network densification, millimetre-wave transmission and massive MIMO architecture[15]. Since then, the concept of 5G has been gradually solidified, and the main technological companies and operators have now launched their construction plans for 5G networks in order to deliver large-scale commercial deployment by 2020.

In the first deployment stage of 5G networks, most operators and device manufacturers adopt the 3rd Generation Partnership Project 5G New Radio standard for dense urban areas[16]. The corresponding 5G network operates on the 2–6 GHz spectrum. Both millimetre-wave and massive MIMO technologies are widely used in 5G networks, though network densification construction has been delayed. Network slicing is involved in some 5G mission-critical solutions. Internet Protocol television and high-definition video streaming, data services over high mobility, basic virtual reality and augmented reality services can be well supported. Indoor services and data services in dense metropolitan areas will continue to be the main focus in the 5G era. For different application scenarios, a complete 5G communication network provides three service options: enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC) and massive machine-type communications (mMTC)[17].

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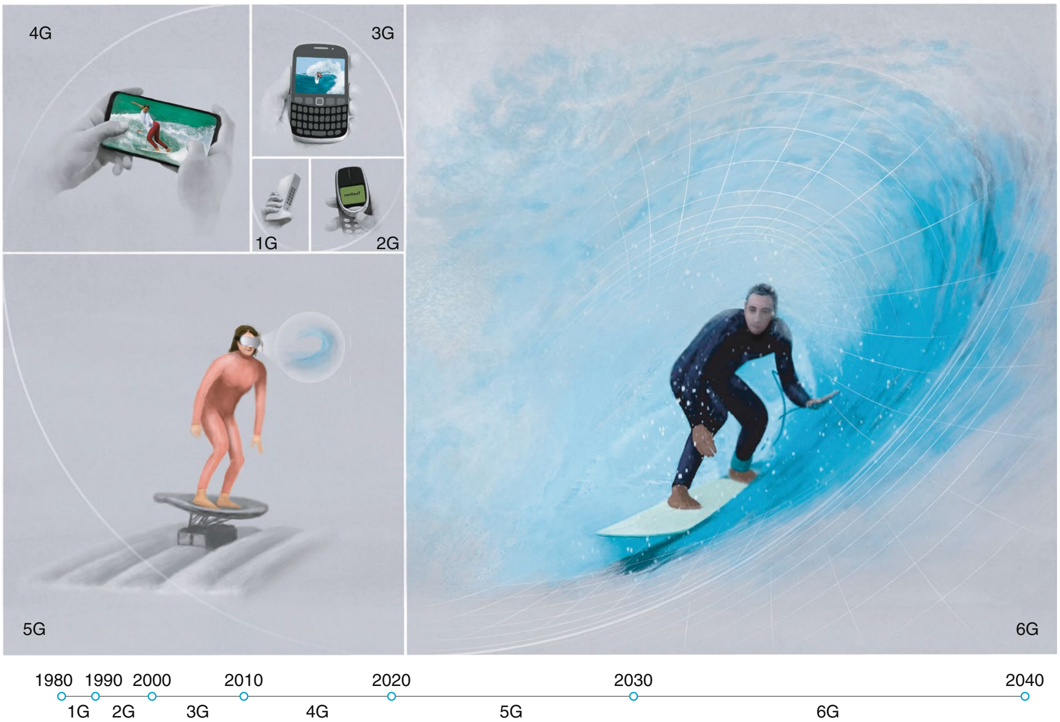

Fig. 1 | A user's perception of the different communications networks, from 1G to the hypothetical 6G. In 1G and 2G, voice and text are available. In 3G and 4G, picture and video become commonplace. In 5G, live ultra-high-definition three-dimensional data can be employed. In 6G, it is expected that we could have a ubiquitous virtual existence. Note that the gaps between years at the bottom of the figure have been expanded to reflect the increasing capabilities of the different communications networks. Credit: Ivan Gromicho, KAUST

On the other hand, there are also a variety of state-of-the-art communication and networking technologies that have not been incorporated in 5G standards yet. The main reasons are related to both supply and demand. From the supply side, some technologies still require experimental verification and in-depth tests in practical environments. Meanwhile, high cost and unsatisfactory backward compatibility also prevent them from being used. From the demand side, the services and devices supported by some advanced communication and networking technologies are not widely in demand.

Although 5G has adopted a gradual evolution strategy that is able to provide much more and better services than 4G, there is no ground-breaking technology in 5G. Instead, it inherits the fundamental performance enhancement mechanisms since 4G, and performance gains are achieved through an investment in more spectral and hardware resources[18].

Current research progress towards 6G. A number of researchers have already provided visions for 6G and a series of advanced research planning activities have begun[2–7]. In the 6G vision and requirements suggested in ref. [2], special attention is paid to the battery lifetime of mobile device and service classes in 6G, rather than data rate and latency. In ref. [3], it is pointed out that the communication system research in the post-5G era must account for circuit and device manufacturing capabilities so as to form a closed feedback loop of research activities. A number of new communication scenarios in future networks in the 2030s are predicted in ref. [4], which encompass holographic calls, flying networks, teleoperated driving and the tactile internet. Further, it is foreseen that the same level of reliability as wired communications will be offered to future wireless communications.

The future driving applications and trends as well as enabling technologies in 6G networks are summarized in refs. [5,6]. In particular, network decentralization based on blockchain technology is believed to be a key to simplify network management and provide satisfactory performance in 6G. The concept of human-centric service is also proposed and viewed as the emphasis in 6G. The key performance indicators of 6G are defined, and a speculative comparison between 5G and 6G is provided in ref. [7].

Recent publications have discussed practical implementations, including multiple access[19], air interfaces[20] and data centres for 6G communications[21]. Networking patterns of 6G networks are outlined in refs. [22–24], in which cell-less architecture, decentralized resource allocation and three-dimensional super-connectivity are highly expected to exist in 6G networks. Machine-type communications (MTCs) and vertical-specific wireless network solutions for 6G are studied in ref. [25], and suggests that 6G could facilitate the first wall-breaking standard to completely replace existing industry-specific communication standards and provide a unified solution enabling seamless connectivity for all needs in vertical industries.

Among all technological works pertaining to 6G, terahertz communications, artificial intelligence (AI) and reconfigurable intelligent surfaces are the most eye-catching ideas. They are viewed as revolutionary technologies in wireless communications. A comprehensive study of terahertz communications for 6G is reported in ref. [26], which includes a detailed technological overview, transmitter–receiver designs and various practical demonstrations. AI-empowered 6G is believed to be able to provide a series of new features, for example, self-aggregation, context awareness, self-configuration and opportunistic set-up[27]. Additionally, AI-empowered 6G would unlock the full potential of radio signals and enable the transformation from cognitive radio to intelligent radio[28]. Machine learning is, in particular, crucial for realizing AI-empowered 6G from the algorithmic perspective, which has been detailed in ref. [29]. Besides the algorithms, reconfigurable intelligent surfaces are supposed to be used to construct the hardware foundation of AI in wireless communications[30]. Reconfigurable intelligent surfaces are also envisaged as the massive MIMO 2.0 in 6G and analysed in refs. [31–33]. These attractive materials can also incorporate index modulation to yield an increase in spectral efficiency in 6G networks[34].

Apart from the works discussed above, a number of 6G projects have already been started around the world, which aim to first initiate and define 6G and then to reshape the framework as well as the business model of wireless communications. The first of these is the 6Genesis Flagship Program, a recently formed Finnish consortium. This was followed by the Terabit Bidirectional Multi-user Optical Wireless System for 6G LiFi, which started at the beginning of 2019. In March 2019, the first 6G Wireless Summit was held in Levi, Finland and formally triggered the start of the 6G research race in academia. A number of small-scale workshops and seminars were also held worldwide to discuss the possibility of 6G, for example, the Huawei 6G Workshop, the Wi-UAV Workshop of Globecom 2018 and the Carleton 6G Workshop.

Beyond academia, 6G and future networks also attract standardizing bodies, industrial organizations and governments. IEEE launched IEEE Future Network with the tagline 'Enabling 5G and beyond' in August 2018. ITU-T Study Group 13 also established the ITU-T Focus Group Technologies for Network 2030 intending to understand the service requirements for future networks round 2030. Project Loon was triggered by Google and is now running independently, which plans to provide reliable internet connection to the unconnected five billion population. A research group based on the EU's Terranova project is now working toward the reliable 6G connection with 400 Gbit s^{-1} transmission capability in the terahertz spectrum. LG Electronics also announced the foundation of a 6G research centre at the Korea Advanced Institute of Science and Technology, Daejeon, South Korea. Samsung kicked off its 6G research in June 2019. SK Telecom announced collaboration with Nokia and Ericsson in 6G research in 2019. In late 2018, China's Ministry of Industry and Information Technology declared the ambition of leading the wireless communication market in the 2030s by expanding research investment in 6G. The Federal Communications Commission of the United States opened the 95 GHz to 3 THz spectrum for the use of 6G research, which marks the participation of the United States, the world's biggest economic entity, in the 6G research race. In addition, an EU–Japan project under Horizon 2020 ICT-09-2017 funding, called 'Networking Research beyond 5G', also investigates the possibility of using the terahertz spectrum from 100 GHz to 450 GHz. Country-wise research initiatives to achieve 6G are summarized in Table 1.

Table 1 | Country-wise research initiatives to achieve 6G

Country	Research initiative	Year
Finland	Finnish 6G research activity is coordinated by the University of Oulu, where a 6G initiative was launched.	2018
United States	The Federal Communications Commission opened the spectrum between 95 GHz and 3 THz to create a new category of experimental licenses.	2019
South Korea	LG Electronics established a 6G research centre in collaboration with the Korea Advanced Institute of Science and Technology. The Electronics and Telecommunications Research Institute has signed a memorandum of understanding with the University of Oulu in Finland to develop 6G network technology. Samsung Electronics and SK Telecom work together to develop technologies and business models related to 6G. SK Telecom signed agreements with Finnish firm Nokia and Sweden's Ericsson to step up collaboration on 6G network research and development.	2019
China	The Ministry of Science and Technology planned to set up two working groups to carry out the 6G research activities; the first is from government departments to promote 6G research and development, the second is made up of 37 universities, research institutes and companies, focusing on the technical side of 6G.	2019
Japan	Japan readies US$2 billion to support industry research on 6G technology. NTT and Intel have decided to form a partnership to work on 6G mobile network technology.	To be decided

Potential application scenarios and challenges

6G communications are expected to provide improved services in terms of coverage and data rate, and allow users to connect to each other everywhere. 6G is expected to adopt unconventional communication networks to access several types of data and transmit them through conventional improved radio-frequency networks, allowing new communication experience with virtual existence and involvement anywhere. To explicitly define the probable features of 6G communications, we foresee the potential application scenarios and challenges for 6G communications in this section. In this speculative study of 6G, we cover a large range of topics discussed in recently published works and conference releases, but with our own thoughts and comments to appraise these 6G candidate technologies.

Enhanced conventional mobile communications. 6G communications should be human centric, which implies that conventional mobile communications will still hold the position of protagonist in 6G, in which the classic cellular phone is the major tool of mobile communications. The challenges regarding conventional mobile communications come from five aspects: how to enhance security and protect privacy; how to expand network coverage in a rapid and cost-efficient way, especially in distant and isolated areas; how to reduce the cost of mobile communications; how to extend the battery life of the mobile device; and how to provide a higher data rate with a lower end-to-end latency.

Accurate indoor positioning. With the help of GPS, outdoor positioning has become full-fledged and can be regarded as accurate in most application scenarios now. However, indoor positioning is still far from maturity, because of the complex indoor electromagnetic propagation environment[35]. Accurate and reliable indoor positioning services will radically change the living habits of mobile users and open up new niches for economic prosperity. On the other hand, there is a growing consensus that accurate indoor positioning might not be viable via radio-frequency communications alone[36]. Such a crucial and impactful application is highly expected to be realized in the era of 6G with more advanced non-radio-frequency communication technologies.

New communications terminals. In addition to the classic mobile phone and tablet, it is foreseen that there will be an increasing number of new communication devices in the 2030s. These new communication devices could be wearable devices, integrated headsets or implantable sensors[37]. Different from the portable phone and tablet, these emerging devices impose diverse environmental and system requirements on communication networks. For example, there must be strict constraints on the transmitted power and frequency band used in these devices for health reasons. The device weight restrictions will become more sensitive when designing wearable devices and integrated headsets. Reliable power supply and security for implantable sensors are of high importance. In addition, there should be major dissimilarity in mathematical modelling between these emerging communication devices and classic mobile phones and tablets.

High-quality communication services on board aircraft. Despite the effort and endeavour of researchers in the 4G and 5G eras, communication services on board aircraft are still, in general, unsatisfactory. The communication services provided on board aircraft are challenged by the high mobility, Doppler shift, frequent hand-over and lack of coverage demanded by this application, among other factors[38]. Satellite communications enable communication services on board with acceptable service quality, but are too costly, especially in aircraft cabins[39]. To provide high-quality communication services on board aircraft, not only must new communication technologies be employed in 6G communications, but also novel networking architectures must be in use.

Worldwide connectivity and integrated networking. In the past decade, researchers drew attention to the communication services in dense metropolitan areas, especially for indoor communication scenarios. However, it should be noted that there is a large population around the world that has no access to basic data services, especially in sparse, developing and rural areas[40]. The advent of the 6G era should not only benefit the majority in dense areas, but be extended to less dense areas. Making wireless networks vertical and horizontal would benefit a much larger population. In this regard, worldwide connectivity is expected to be realized in 6G communications by a low-cost implementation scheme in order to guarantee communication fairness in sparse areas. Providing this service is greatly dependent on novel networking technologies.

To achieve the goal of worldwide connectivity, three-dimensional integrated networking would be used, which encompasses terrestrial, airborne and satellite communications[41]. Apart from satellite communications, most existing communication and networking architectures only consider two-dimensional scenarios, in which the heights of communication nodes are negligible[42]. This modelling assumption is appropriate and efficient for 5G application scenarios. However, it is envisioned that communications of flying nodes for achieving worldwide connectivity will become ubiquitous in the 2030s and should be taken into consideration when planning 6G networks. Such a three-dimensional integrated network could bring considerable performance gains and unprecedented services to users[5].

Besides communications on ground and over sky, extending the communication network to underwater environments is a crucial and even necessary element of worldwide connectivity, especially considering that most of the Earth's surface is covered by water, and several marine applications require live monitoring[43]. Underwater optical wireless communication can play a vital role in establishing reliable high-data-rate links with the help of acoustic communications[44]. Underwater communication nodes such as autonomous vehicles, sensors and divers can be connected via underwater base stations using underwater optical wireless communication. Moreover, underwater communication networks can be connected to terrestrial networks via water-surface networks and aerial networks. Securing a sustainable energy source by wind, Sun and water flow is an essential requirement for both underwater and water-surface networks.

Communications supporting vertical industries. To serve the physical world, 6G communications are also expected to continuously support applications in vertical industries, including building and factory automation, manufacturing, e-health, transportation, agriculture, surveillance and smart grid. These applications are essential to 'industry 4.0'[45]. They pose special service requirements in addition to conventional mobile telephony and broadband data communications. In particular, these vertical industries normally necessitate high standards with respect to connection reliability, transmission latency and security[46]. To integrate these vertical industries in 6G communications, mMTC in 5G needs to be upgraded. More MTC application scenarios and types of machine nodes are required to be considered.

In general, these vertically industrial applications can be classified into robotic communications and vehicular communications. Robotic communications are related to the communications of kinesthetic robotics and manufacturing robotics. Because any error, delay and malicious action in robotic communication applications could result in severe instability, robotic communications are reliability critical, delay critical and security critical. Moreover, a huge number of heterogeneous data streams are generated in robotic communication networks, which yield a challenge for the current centralized networking architecture[47].

For vehicular communications, two emerging technological trends in the vehicular industry are reshaping the physical world: self-driving and remote-driving technologies[48]. Owing to the development of both technologies in recent years, it is believed that they will be technically mature and widely applied before 2030. To enable both driving technologies in practice, massive vehicle-to-everything communications must be studied and incorporated in 6G, providing the basis for high reliability and low latency as well as secure exchange of massive driving and ambient data.

Holographic communications. 6G is expected to be a conversion point from the traditional video conferencing to a virtual in-person meeting. To this end, a realistic projection of real-time movement needs to be transferred in negligible time[49]. In fact, transmitting three-dimensional images along with voice is not sufficient to convey the in-person presence. There is a need to have a three-dimensional video with stereo audio that can be reconfigured easily to capture several physical presences in the same area. In other words, one can interact with the received holographic data and modify the received video as needed. All this information needs to be captured and transmitted over reliable communication networks that should have an extremely large bandwidth.

Tactile communications. After using holographic communication to transfer a virtual vision of close-to-real sights of people, events, environments and so on, it is beneficial to remotely exchange the physical interaction through the tactile internet in real time[50]. Specifically, the expected services include teleoperation, cooperative automated driving and interpersonal communication, where it should be possible to apply haptic control through communication networks. Efficient cross-layer communication-system design has to be conducted to meet the stringent requirements of these applications. For example, new physical layer (PHY) schemes need to be developed, such as to improve the design of signalling systems, waveform multiplexing and so on. As for the delay, all delay sources should be treated carefully, including buffering, queuing, scheduling, handover and the delays induced from protocols. Existing wireless communication systems cannot fulfil these requirements, and there is a necessity for over-the-air fibre communication systems[51].

Human-bond communications. 6G is expected to widely support the human-centric communication concept, where the human can access and/or share physical features. The human-bond communication concept is proposed to allow access to the five human senses[52]. Recently, the concept has been expanded with the help

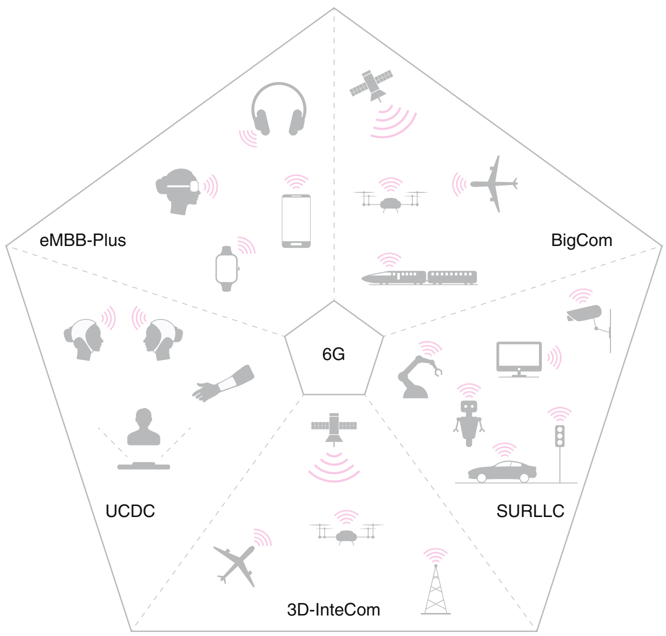

Fig. 2 | Five application scenarios supported by 6G communications. eMBB-Plus supports high-quality conventional mobile communications. BigCom supports basic communications for remote areas. SURLLC in 6G is a joint upgrade of the URLLC and mMTC in 5G with higher requirements of reliability. 3D-InteCom raises the network optimization and planning dimension to three. UCDC provides the possibility to incorporate novel communication prototypes and paradigms. Credit: Ivan Gromicho, KAUST

of a 'communication through breath' scheme to allow reading the human bioprofile using exhaled breath, and even interaction with the human body by inhalation using volatile organic compounds[53]. As a result, it is possible to diagnose diseases, detect emotions, collect biological features and interact with the human body remotely. Developing communication systems that can replicate the human senses and human biological features requires interdisciplinary research. Such systems are expected to have hybrid communication technologies that are able to sense different physical quantities and then share them with the intended receiver in a secure manner.

Summary. We anticipate five application scenarios supported by 6G communications: Enhanced Mobile Broadband Plus (eMBB-Plus), Big Communications (BigCom), Secure Ultra-Reliable Low-Latency Communications (SURLLC), Three-Dimensional Integrated Communications (3D-InteCom) and Unconventional Data Communications (UCDC). These five application scenarios are pictorially illustrated in Fig. 2.

eMBB-Plus in 6G is the successor of eMBB in 5G, serving conventional mobile communications with much higher requirements and standards. It should also be more capable of optimizing cellular networks in terms of interference and hand-over, as well as big data transmission and processing. Additional functionality will also be provided with an affordable expense to subscribers, for example, accurate indoor positioning and globally compatible connection among diverse mobile operating networks. Most importantly, special attention to security, secrecy and privacy shall be paid by eMBB-Plus communication services.

Different from 5G, which emphasizes extremely good communication services in dense areas but to some extent neglects the service in remote areas, BigCom in 6G cares about service fairness between dense and remote areas. To be feasible, BigCom does not intend to provide equally good services in both areas, but keep a better resource balance. At least, BigCom guarantees that the network coverage has to be large enough so as to provide acceptable data service wherever the communication subscribers are living or moving to. The Gini index and the Lorenz curve could be involved to evaluate the service fairness provided by BigCom and should be treated as crucial indicators of user experience in 6G (ref. [54]).

SURLLC in 6G is a joint upgrade of the URLLC and the mMTC in 5G, but with higher requirements of reliability (higher than 99.9999999%, that is, 'seven sigma' from the viewpoints of quality control and process improvement) and latency (less than 0.1 ms)[25], as well as an additional demand on security. SURLLC mainly serves industrial and military communications, for example, a variety of robots, high-precision machine tools and conveyor systems in the 6G era. In addition, vehicular communications in 6G could also greatly benefit from SURLLC.

3D-InteCom in 6G stresses that the network analysis, planning and optimization shall be raised from two dimensions to three dimensions, where the heights of communications nodes must be taken into consideration. Satellite, unmanned aerial vehicle (UAV) and underwater communications are examples of this three-dimensional scenario and benefit from three-dimensional analysis, planning and optimization. Accordingly, the analytical framework constructed for two-dimensional wireless communications that stemmed from stochastic geometry and graph theory needs to be updated in the era of 6G (ref. [55]). Considering the node height also enables the implementation of elevation beamforming with full-dimensional MIMO architectures, which provides another direction for network optimization[56].

UCDC is probably the most open-ended application scenario in 6G communications. We intend this application scenario to cover those novel communication prototypes and paradigms that cannot be classified into the other four application scenarios. Currently, the definition and embodiment of UCDC is still awaiting further exploration, but it should at least cover holographic, tactile and human-bond communications.

Key features and enabling communication technologies of 6G

Based on the application scenarios and challenges as well as the five supported application scenarios in 6G discussed in the last section, we are now able to define the key features of 6G. To enable the key features of 6G, multiple state-of-the-art communication technologies must be jointly applied.

To begin, a qualitative comparison between 5G and 6G communications is summarized in Fig. 3. In it, we first suppose that the spectral efficiency in 5G has already been close to the boundary by the advances in massive MIMO, network densification and millimetre-wave transmission as well as by a set of legacy multiplexing techniques inherited from 4G. As bounded by the Shannon limit, the spectral efficiency in 6G would hardly be improved on a large scale. In contrast, security, secrecy and privacy in 6G communications should be significantly enhanced by new technologies. In 5G networks, traditional encryption algorithms based on the Rivest–Shamir–Adleman (RSA) public-key cryptosystems are still in use to provide transmission security and secrecy. RSA cryptosystems have become insecure under the pressure of Big Data and AI technologies, but novel privacy protection mechanisms are still far from full-fledged in the 5G era. Incremental improvements would happen for energy efficiency, intelligence, affordability and customization. The energy efficiency gain would be accomplished by the maturity of energy harvesting technology and green communications. Intelligence in 6G can be classified into operational, environmental and service levels, which will benefit from the thrust in AI developments. The improvements on affordability and customization rely on novel networking architectures, promotion and operational

Fig. 3 | Qualitative comparison between 5G and 6G communications. The comparison, which is speculative, is made in terms of: security, secrecy and privacy; spectral efficiency; intelligence; energy efficiency; and affordability and customization. Credit: Ivan Gromicho, KAUST

strategies on the market. Detailed comparisons of 1G to 6G communications are given in Table 2.

High security, secrecy and privacy. Researchers placed great emphasis on network throughput, reliability, latency and the number of served users in 4G and 5G communications. It has also been widely recognized that the two most efficient ways to improve these metrics are to densify the network and use a higher frequency to transmit signals[18]. However, the security, secrecy and privacy issues of wireless communications have been, to some extent, overlooked in the past decades. To protect data security, classic encryption based on RSA algorithms is being challenged by increasingly powerful computers[57]. PHY security technologies and quantum key distribution via visible-light communications (VLC) would be the solutions to the data security challenge in 6G (refs. [58–60]). More advanced quantum computing and quantum communication technologies might also be deployed to provide intensive protection against various cyber attacks[61]. Meanwhile, communication/data service providers have legally collected an enormous amount of user information, and private data leakage incidents happened occasionally. This becomes an unstable factor in the human-centric 6G network and could lead to a disastrous consequence without proper countermeasures. To solve this problem, it is envisioned that complete anonymization, decentralization and untraceability can be realized in 6G networks by blockchain technology[62].

High affordability and full customization. Again, from a human-centric perspective, technological success should not directly or indirectly increase the financial burden or deprive users' options. Therefore, high affordability and full customization should be two important technological indicators of 6G communications. The former is ignored in most existing works. The proposed schemes in these works might have a much higher transmission rate and/or reliability, but the cost rendered by such improvements will completely restrict their implementations in real life. The academic research activities for 6G should always try to get rid of such speciousness and endeavour to provide high affordability.

Full customization allows users to choose the service modes and adjust individual preferences. For example, some users might like to have a low-rate but reliable data service; others might tolerate an unreliable data service in order to get a lower communication expense in return; others still might only care about the energy consumption of their devices; and some might even want to get rid of the smart functionality due to concerns about data security and privacy. All users will be granted the right to choose what they like in 6G, and such rights should not be diminished by intelligent technologies or unnecessary system configurations. Accordingly, the performance analysis of 6G communication systems should also integrate multiple performance metrics into a whole, instead of treating them independently. User experience would be explicitly defined and adopted as a pivotal metric for performance evaluation in the 6G era. That is, unlike 1G–5G, for which we added more elements in the quality-of-service vector, we should map all required performance metrics as a whole to a unique user-experience performance metric for each individual user in 6G.

Low energy consumption and long battery life. The daily charging requirements of smartphones and tablets in 4G/LTE networks will continue in the foreseeable 5G era. To overcome the daily charging constraint for most communication devices and facilitate communication services, low energy consumption and long battery life are two research emphases in 6G communications. To lower energy consumption, the computing tasks of a user device can be off-loaded to smart base stations with reliable power supply or pervasive smart radio space[63]. Cooperative relay communications and network densification would also help to reduce the transmit power of mobile devices by reducing the per-hop signal propagation distance[64,65]. To achieve a long battery life, various energy harvesting methodologies would be applied in 6G, which not only harvest energy from ambient radio-frequency signals, but also from micro-vibrations and sunlight[66]. Long-distance wireless power charging would also be a promising approach to extend battery life, but in-depth investigations are indispensable to avoid health-related issues[67].

High intelligence. The high intelligence in 6G will benefit network operations, wireless propagation environments and communication services, which refer to operational intelligence, environmental intelligence and service intelligence, respectively.

Operational intelligence. Conventional network operation involves a great number of multi-objective performance optimization problems subject to a series of complex constraints. Resources, including communication devices, frequency bands, transmission power and so on, are required to be arranged in a proper way so as to achieve a satisfactory level of network operation. Moreover, these multi-objective performance optimization problems are usually NP-hard, and optimal solutions are difficult to obtain on a real-time basis. With the development of machine-learning techniques, especially deep learning, a base station equipped with graphics processing units or the control centre of the core network could carry out relevant learning algorithms to allocate resources efficiently to achieve performance close to the optimum[68].

Environmental intelligence. Meanwhile, through advances on smart radio space and smart materials, distributed and pervasive intelligence of the holistic communication environment, including wireless channels, would become possible[69]. This could provide self-organizing and self-healing properties for the 6G network and enable reliable device-to-device communications in a fully intelligent way. Latest works have defined and justified the conception of reconfigurable intelligent surfaces, which are designed to sense the wireless environment and apply customized transformations to the

Table 2 | Detailed comparisons of 1G to 6G communications

Features	1G	2G	3G	4G	5G	6G (supposed)
Period	1980–1990	1990–2000	2000–2010	2010–2020	2020–2030	2030–2040
Maximum rate	2.4 kb s^{-1}	144 kb s^{-1}	2 Mb s^{-1}	1 Gb s^{-1}	35.46 Gb s^{-1}	100 Gb s^{-1}
Maximum frequency	894 MHz	1,900 MHz	2,100 MHz	6 GHz	90 GHz	10 THz
Service level	Voice	Text	Picture	Video	3D VR/AR	Tactile
Standards	MTS, AMPS, IMTS, PTT	GSM, IS-95, CDMA, EDGE	UMTS, WCDMA, IMT2000, CDMA2000, TD-SCDMA	WiMAX, LTE, LTE-A	5G NR, WWWW	–
Multiplexing	FDMA	FDMA, TDMA	CDMA	OFDMA	OFDMA	Smart OFDMA plus IM
Architecture	SISO	SISO	SISO	MIMO	Massive MIMO	Intelligent surface
Core network	PSTN	PSTN	Packet N/W	Internet	Internet, Internet of Things	Internet of Everything
Highlight	Mobility	Digitization	Internet	Real-time streaming	Extremely high rate	Security, secrecy, privacy

VR, virtual reality; AR, augmented reality; MTS, Mobile Telephone Service; IMTS, Improved Mobile Telephone Service; PTT, push to talk; GSM, Global System for Mobile Communications; IS-95, Interim Standard 95; CDMA, code-division multiple access; EDGE, Enhanced Data rates for GSM Evolution; UMTS, Universal Mobile Telecommunications Service; IMT2000, International Mobile Telecommunications-2000; LTE-A, Long-Term Evolution Advanced; 5G NR, Fifth-Generation New Radio; WWWW, World Wide Wireless Web; FDMA, frequency-division multiple access; TDMA, time-division multiple access; OFDMA, orthogonal frequency-division multiple access; IM, index modulation; SISO, single-input single-output; PSTN, public switched telephone network; Packet N/W, packet-switched network.

radio waves in an adaptive manner[30,70]. This conception solidifies the hardware foundation of environmental intelligence.

Service intelligence. Furthermore, as a human-centric network, the high intelligence of the 6G network is directly reflected in a plethora of communication services, for example, indoor/outdoor positioning, multi-device management, information search, e-health, surveillance and cyber security[36,71]. Service intelligence enables these services to be provided in a satisfactory and personalized way. For example, the accuracy of indoor positioning can be greatly improved by deep-learning techniques[72], and personalized healthcare is realized by an intelligent Internet of Things and multi-modal data-collection infrastructure[73]. Service intelligence mainly benefits from high-performance core networks implemented in 6G (refs. [74,75]).

Extremely large bandwidth compared with 5G. The terahertz band defined from 0.1 THz to 10 THz was known as a gap band between the microwave and optical spectra[76], but terahertz electronic, photonic and hybrid electronic–photonic methods have now been developed[77]. Thus, hybrid terahertz/free-space-optical systems are expected to be realized in 6G using hybrid electronic–photonic transceivers, where an optical laser can be used to generate a terahertz signal or send an optical signal. The hybrid link offers plenty of bandwidth for signal transmission and has immunity to adverse weather conditions[78]. Terahertz transmission can play a vital role in the uplink, because a line-of-sight link is not required. Thus, a terahertz uplink solution offers a reliable communication link for VLC networks compared with the infrared solution that needs a tracking and positioning system. A hybrid VLC/terahertz system introduces robust communication solutions against ambient light that reduces the signal-to-noise ratio of the VLC system.

Trade-offs between key features and potential solutions. It should be noted that as an engineering system, it is not possible to satisfy all wished-for features without investing more resources, because there exists a number of trade-offs between these features. For 6G communications, we must figure out a way to invest adequate resources to guarantee some critical features, while raising all features in a balanced way. To this end, we highlight a set of crucial trade-offs in 6G communications and their potential solutions.

Privacy versus intelligence. As a human-centric network, the trade-off between privacy and intelligence would be the most important one in 6G communications. On the one hand, AI algorithms need to get access to personal data and process them, so as to optimize network operations, adapt network coefficients and provide high-quality services. On the other hand, privacy would be sacrificed for the sake of high intelligence. A potential solution is to introduce an intermediate agent between the end-user data and AI algorithms. Such an intermediate agent should be third-party and unmanned if possible, and operate on a decentralized basis. All private and sensitive data will be anonymized by this third-party agent and become untraceable in any way.

Affordability versus intelligence. High intelligence introduces a high degree of system complexity, which could raise up the costs to network operators and device manufacturers. All these raised costs will translate into less affordable products for end users. To resolve this trade-off, technological breakthroughs in intelligent systems are necessary, but more importantly, a new commercial strategy would be helpful. Once security, secrecy and privacy are guaranteed, end users have the right to exchange the accessibility of their anonymized data for a lower data price. A similar feature of the smart grid, by which electricity users can sell self-generated electricity back to electricity companies, would be borrowed by 6G communication networks.

Customization versus intelligence. High intelligence provided by AI algorithms and smart devices weakens the free will of human beings. In other words, the user preference might not be always aligned with the optimized option produced by AI algorithms. The contradictory situation becomes more severe when multiple users are taken into account. This conflict can be formulated as the trade-off between customization and intelligence in 6G communications. In our opinion, the priority shall always be given to customization, and prohibitive clauses are required for AI algorithms and smart devices. These prohibitive clauses should be stipulated in the most fundamental and underlying protocols of 6G communications. In this way, intelligent services can only be provided within the permissible boundary.

Security versus spectral efficiency. Conventionally, to ensure a secure transmission, more spectral resources shall be in use for preventive measures, and the net load for transmitting information is lowered accordingly, given a limited radio spectrum. We have to recognize that this trade-off between security and spectral efficiency is difficult to resolve, but we can mitigate it in three possible ways. First, researchers might try to design a more efficient encryption algorithm. However, this direction would be rather difficult due to the maturity of data encryption. Second, researchers might resort to PHY security technologies for providing security protection without a great loss of spectral efficiency. Third, AI algorithms can also help to detect network anomalies and would be utilized in 6G networks to provide an early warning mechanism for security enhancement.

Spectral efficiency versus energy efficiency. The trade-off between spectral efficiency and energy efficiency is a frequent topic in the field of wireless communications. The discussion pertaining to this well-known trade-off ran through all wireless generations and will, of course, be one of the focuses in 6G communications. However, different from 1G–5G, a new path-breaking technology would be introduced to greatly alleviate this trade-off, which is energy harvesting. By energy harvesting, user devices are capable of harvesting radio, vibratory and solar energy from the ambient environment and the constraint on energy consumption can thereby be released. The environmental intelligence realized by ubiquitous intelligent surfaces would also help to mitigate the spectrum–energy trade-off by adapting radio propagation environments.

Beyond the communication technologies

Communication technologies are crucial, but not all. To promote a new technological paradigm and make it socioeconomically profitable, we must always keep the issues beyond technology in mind. In this section, we briefly discuss several crucial issues relating to 6G beyond the communication technologies themselves.

Dependency on basic sciences. The advancement of wireless communications is highly restricted by basic sciences, especially mathematics and physics. As detailed in ref. [18], we are squeezing the last juice of Shannon's treatise published in 1948 and have almost reached the hard wall set by information theory. What is worse, current mathematical tools prevent us from exploring the exact performance of communication systems. As a result, a large number of impractical assumptions are made in order to make analysis mathematically tractable, which cannot provide much insight or guidelines for 6G communications. A breakthrough in mathematics has often resulted in a new research boom in wireless communications, one example being stochastic geometry and graph theory applied to wireless network modelling[55]. In short, researchers need to pay sufficient attention to basic sciences and interdisciplinary fields in order to realize 6G networks.

Dependency on upstream industries. In the wireless communication research community, it is widely agreed that the most efficient ways to enhance wireless communication systems are to expand the usage to the high-frequency spectrum and to reduce the coverage of a single cell[18]. The former approach can be seen in the evolution from the cellular radio-frequency spectrum to the millimetre-wave spectrum, terahertz spectrum and visible-light spectrum. The latter approach refers to the network densification. On the other hand, both approaches must match the developments in the upstream industries, for example, electronics manufacturing. First of all, in theoretical research, one can assume an arbitrarily high frequency for use, but in reality, the communication devices comprising realistic electronic components must be able to meet these requirements. In some cases, the resultant data rate has even exceeded the constraint on the electronic circuit made by the current manufacturing level, or the signal on higher-frequency bands cannot be processed by current commercial chips at all. Thus, we cannot neglect the dependency on upstream industries.

Demand-oriented research roadmap. There exists a noticeable mismatch of PHY research activities in industry and academia[11]. As suggested in refs. [3,18], a closer connection between industrial and academic researches should be constructed so as to form a positively closed feedback loop for adjusting the research roadmap. More directly, such a positively closed feedback loop can be extended to the market and the end beneficiaries of 6G. In this way, a demand-oriented research roadmap can be well designed and adapted in a much more effective and efficient manner. To achieve this goal, it is required to introduce the ideas of value engineering to plan academic research activities. In this way, the 6G research roadmap should not be defined by the technological embodiments, but by the function and cost as a whole from a value-engineering view. In other words, research activities in 6G should not simply aim at adding more functions without considering the cost and demand from the end beneficiaries' perspective, but target the value of the implemented service. Specifically, end beneficiaries shall be granted the right to have their voices to reshape the research roadmap in the 6G era. To satisfy the demands of multiple stakeholders, and to bridge the gap between academic and real-world problems, the barrier among various disciplines should be removed. More economic and sociological methodologies, for example, empirical analysis and political, economic, social, technological, environmental and legal factor analysis, could be introduced for appraising and tailoring the 6G research roadmap.

Business model and commercialization of 6G. Previous research activities primarily focused on the technology itself, but rarely on the business model and commercialization. Omitting the marketing aspects would lead to failure (3G could be, to some extent, an example of such failure[2]). Network densification is a promising solution to satisfy the data transmission burst, but who should pay for it? Building new base stations is costly after all, because of land-use-rights granting and construction operations. Moreover, as 6G communications would bring ground-breaking communication technologies relying on novel network architectures, how to ensure the backward compatibility of 6G with 4G/LTE, Wi-Fi and 5G is still questionable and worth investigating. The overall cost for updating the existing infrastructures for 6G communications needs to be evaluated first, and then the business model and commercialization of 6G should be studied for its commercial success. One should always remember that for most ordinary users and government policymakers, paying several times more to get a dispensable performance gain in terms of transmission rate or latency will not be accepted, let alone appreciated.

Potential health and psychological issues for users. The 'base station myth' is a frequent topic in public media and could trigger severe protests[79], which reflects the health concerns of users about radiation safety. With a densified network with a smaller coverage per base station and the use of a higher-frequency band, there are reasons to believe that such concerns will be aggravated in the era of 6G. As 6G communications are expected to be human centric, special attention must be paid to the potential health issues brought to users. In this context, electromotive-force-aware transmission would be a novel concept to be introduced in 6G to mitigate the health concerns[80]. Bandwidth expansion from the millimetre-wave regime to the terahertz regime also causes uncertain biological impacts on humans and animals. Careful studies are required to examine the safety of terahertz radiation[26].

Apart from health issues, the psychological barrier would also be a factor hindering the large-scale implementation of 6G from a human-centric perspective. As envisioned in some proposals even for 5G networks, massive sensors are deployed everywhere in daily life, and they are able to detect, understand, communicate and respond (fortunately, such a sci-fi scene has been greatly exaggerated). Then, the questions will be: Will people really enjoy and be comfortable living in such a 'smart' space? Will people be happy to be recorded and watched by such a technocratic 'big brother'? Without a careful study on these psychological issues before implementing the technology, 6G could have catastrophic consequences and could deconstruct existing trust in information and communication technologies[81]. 6G is expected to be not only technologically trustworthy[82], but also societally trustworthy.

Social factors hindering the worldwide connectivity. As pointed out in the background paper of the World Economic Forum at Davos Annual Meeting 2017[40], apart from technological and economic factors, social factors could also prevent worldwide connectivity in 6G. That is, the people living in developing areas are not motivated to be connected, because of the lack of content relevance, language barrier and computer illiteracy. This is mainly a demand-side issue and should be given full consideration when deploying 6G networks for worldwide connectivity. Incentive schemes and campaigns sponsored by local governments and private companies would be beneficial to persuade the unconnected in distant areas to be connected and promote the concept of worldwide connectivity in the 6G era. The promotions of e-payments and e-taxis in China are good examples that connect most people who never used smart phones before.

Conclusions

We have presented a vision for 6G communications from a human-centric perspective that could serve as a research guide in the post-5G era. We suggest that high security, secrecy and privacy should be the key features of 6G, and should be given particular attention by the wireless research community. We provided and explained potential application scenarios that should be supported in 6G. We also introduced key features and enabling technologies for 6G communications. Finally, we discussed other crucial issues beyond communication technologies that should be considered in the development of 6G.

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Author contributions

M.-S.A. and B.S. conceived the work and suggested the outline of the paper. S.D. and O.A. carried out investigations and wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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