From a Human-Centric Perspective: What Might 6G Be?

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Abstract

As the standardization of fifth generation (5G) communications has been completed and the 5G network will be commercially launched in 2020, the research visioning and planning of sixth generation (6G) communications are being initiated. 6G communications are expected to be the next focus in wireless communication and networking and aim to provide remarkable communication services to meet the future demands in the 2030s. We believe that the human-centric mobile communications will still be the most important application of 6G and 6G network should be human-centric. Following this rationale, high security, secrecy, and privacy are the all-important features of 6G, which shall be paid special attention from the wireless research community. To promote the research and the human-centric design ideology for 6G communications, we imagine in this article a comprehensive and systematic framework of 6G with five slices, key features, and enabling technologies. Furthermore, we briefly discuss the issues of 6G beyond communication technologies.

Since the initial development of 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 of wireless communication networks in the past four decades, resulting in the second, third, and forth generation (2G, 3G, and 4G) networks [1]. The fifth generation (5G) network launching is ongoing and expected to be commercialized by 2020. As the standardization of 5G has gradually been solidified, an increasing number of researchers place their visions on the future sixth generation (6G) communication network and initialize a series of advanced research planning activities [2]–[7].

What might 6G be? Is 6G nothing more than a hype? Will 6G be a technological and commercial success? To answer these questions, we provide our thoughts in this article. Different from the published perceptions, we believe that the conventional mobile communications will still be the most important application of 6G around 2030, although other application scenarios are becoming ubiquitous and increasingly significant. Consequently, 6G network should be human-centric, instead of machine-centric, application-centric, or data-centric. Following this rationale, high security, secrecy, and privacy are the all-important features of 6G. Also, user’s satisfaction of service (SoE) would be adopted as a pivotal metric in 6G communication networks, and a number of new features are required in this new scenario to enhance user’s SoE accordingly.

To promote this research and design ideology for 6G communications, we imagine a comprehensive and systematic framework of 6G in this article. Specifically, we first anticipate the potential application scenarios of 6G and propose five supporting slices in 6G. Following that, we summarize the key features of 6G with enabling communication technologies. Furthermore, we also briefly discuss issues beyond the communication technologies that might significantly affect the research and deployment of 6G in the 2030s.

I. Background

A. Brief Retrospect of the 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, e.g., short messaging service (SMS). Walking into the twenty-first century, 3G, represented by wideband CDMA (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 [6]. In 4G/Long-Term Evolution (LTE) networks initialized in 2009, multiple-input and multiple-output (MIMO) antenna structure, 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 proved to be a game changer and a great success in terms of technology and business. With the proliferation of smartphones and tablets, mobile communications became the mainstream and contributed to a considerable amount of data throughput in 4G networks [2]. The 4G era since 2009 till now is undoubtedly the ‘Golden Decade’ of mobile communications.
B. What Has 5G Been?

In 2014, an enlightening paper was published, which discusses what 5G will be and points out that the key technologies to achieve 5G are network densification, millimetre wave, and massive MIMO architecture [10]. A magnificent scene of the Internet of Everything (IoE) is commonly described and indulged in the literature of 5G. Five years passed since then, the conception of 5G has gradually been solidified in recent days, and main technological companies and operators have launched their construction plans for 5G networks so as to realize the large-scale commercial deployment by 2020. Therefore, it is now an appropriate moment to examine what 5G has been.

In the first deployment stage of 5G networks, most operators and device manufacturers adopt the 3GPP 5G New Radio (NR) standard for dense urban areas [11]. The corresponding 5G network operates on the 2-6 GHz spectra. Both millimetre wave and massive MIMO technologies are widely used in 5G networks, while the network densification construction is delayed for certain reasons. Network slicing is more or less involved in 5G mission-critical solutions. Internet Protocol television (IPTV) and high-definition (HD) video streaming, service over high-speed mobility, basic virtual reality (VR) and augmented reality (AR) 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) [12].

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 can be summarized from two sides. From the supply side, some technologies still require experimental verification and in-depth tests in practical environments. Meanwhile, the 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 have not been widely on demand.

Although 5G has adopted a gradual evolution strategy that is able to provide much more and better services than 4G, it is admitted that there is no ground-breaking technology in 5G that really bring a surprise to us. Inheriting the fundamental performance enhancement mechanisms since 3G [13], more spectral and hardware resources are invested in 5G to harvest performance gains, instead of a technological breakthrough. Furthermore, 5G does not provide a new perceptual dimension compared to 4G. To be vivid, we illustrate the perceptual scenarios for a single user from 1G era to 5G era and 6G era (hypothetical) in Fig. [1] In 1G and 2G, users perceived by voice and text. In 3G and 4G, picture and video help to construct a colourful perception in mind, respectively. In 5G, live ultra-high definition three-dimensional and IoT big data are employed to produce a comprehensive perception. It is highly expected that we will have ubiquitous virtual existence and involvement in the coming 6G era.

C. Current Research Progress Towards 6G

To realize technological breakthroughs in practical communication networks and achieve a new perceptual dimension, the research community of wireless communications has gradually turned attention to and anchor the hope on 6G. The 6G vision and requirements are suggested in [2], in which special attention is paid to the battery lifetime of mobile device and service classes in 6G, rather than data rate and latency. In [3], it is pointed out that the communication system research in the post-5G era must incorporate with 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 around 2030 are predicted in [4], which encompass holographic calls, flying networks, teleoperated driving, and the tactile Internet, etc. Further, it is foreseen that the same level of reliability as wired communications will be offered to future wireless communications. [5] and [6] summarize the future driving applications and trends as well as enabling technologies in 6G networks. 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 (KPIs) of 6G are defined and a speculative comparison between 5G and 6G is provided in [7].

Apart from above-released works, a number of 6G projects have already been started around the world, which aim to attain the initiative, define 6G, and reshape the framework as well as the business model of wireless communications. The first project refers to the 6Genesis Flagship Program (6GFP), a recently formed Finish consortium, which is followed by Terabit Bidirectional Multi-user Optical Wireless System (TOWS) for 6G LiFi started at the beginning of 2019. In March 2019, the first 6G Wireless Summit was held in Levi, Finland and formally triggered the starting gun of 6G research race in academia. Besides the summit, a number of small-scale workshops and seminars were also held worldwide to discuss the possibility of 6G, e.g., Huawei 6G Workshop, Wi-UAV Workshop of Globecom 2018, and Carleton 6G Workshop.

Except for 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 the National Aeronautics and Space Administration (NASA), which plans to globally deploy visualization infrastructure for aerospace networks. LG Electronics also announced the foundation of 6G Research Centre at Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea. In late 2018, China’s Ministry of Industry and Information Technology declared the ambition of leading the wireless communication market around 2030 by expanding the research investment in 6G. Federal Communications Commission of the U.S. opened 95 GHz to 3 terahertz
II. POTENTIAL APPLICATION SCENARIOS AND CHALLENGES

To define the probable features of 6G communications, we first foresee the potential application scenarios and challenges for 6G communications in this section.

A. Enhanced Conventional Mobile Communications

As we declared above, 6G communications should be human-centric, which implies that the conventional mobile communications will still hold the position of protagonist in 6G, in which classic cellular phone is the major tool of mobile communications. The challenges regarding conventional mobile communications comes from five aspects: 1) how to enhance the security and protect privacy; 2) how to expand network coverage in a rapid and cost-efficient way, especially in distant and isolated areas; 3) how to reduce the cost of mobile communications; 4) how to extend the battery life of mobile device; 5) how to provide a higher data rate with a lower end-to-end latency.

B. Accurate Indoor Positioning

With the help of the Global Positioning System (GPS), outdoor positioning becomes 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 [14]. 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 by sole utilizing radio frequency (RF) communications [15]. Such a crucial and impactful application is highly expected to be realized in the era of 6G with more advanced non-RF communication technologies.

C. Communications of Wearable Devices, Integrated Headsets, and Implantable Sensors

In addition to the classic mobile phone and tablet, it is foreseen that there will be an increasing number of new communication tools in the 2030s. These new communication tools can be wearable devices, integrated headsets, and implantable sensors [16]. Different from portable phone and tablet, these emerging devices impose diverse environmental and system requirements on communication networks. For example, there must be strict constraints on transmit power and frequency band used in these devices for health reasons. The device weight will become more sensitive when designing wearable devices and integrated headsets. Reliable power supply and security for implementable sensors are of high importance. In addition, there should be major dissimilarities in mathematical modelling between these emerging communication devices and classic mobile phone and tablet.

D. High-Quality Communication Services on Board

Despite the effort and endeavour of researchers in the 4G and 5G eras, it is undeniable that communication services on board are still unsatisfied in most cases nowadays. The communication services provided on board are challenging by the high mobility, Doppler shift, frequent hand-over, lack of coverage, and so on [17]. Satellite communications enable communication services on board with acceptable service quality, but are too costly, especially in aircraft cabins [18]. To provide high-quality communication services on board, not only new communication technologies must be employed in

(THz) spectra for the use of 6G research, which marks the participation of the U.S., the world’s biggest economic entity, in the 6G research race. In addition, an EU/Japan project under the ICT-09-2017 H2020 called ‘Networking Research beyond 5G’ also investigates the possibility of using THz spectrum from 100 GHz to 450 GHz.

Fig. 1: Perceptual scenarios from 1G to 5G and 6G (hypothetical).
6G communications, but also novel networking modes shall be in use.

E. Worldwide Connectivity and Three-Dimensional Integrated Networking

In the recent decade, researchers drew attention to the communication service provision in dense metropolitan areas, especially for indoor communication scenarios. However, it should not be omitted that there is a large population around the world having no access to basic data services, especially in sparse, developing and rural areas. The advent of the astonishing 6G era should not only benefit the majority in dense areas, but be shadowed to less dense areas. Making wireless networks not only vertical but also 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 the communication fairness of minority in sparse areas. This service provision is greatly dependent on novel networking technologies.

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

Apart from the communications on ground and over sky, extending the communication network to underwater environment is a crucial and even necessary element of worldwide connectivity, especially that more than 70% of the earth’s surface is covered by water and several applications needs live monitoring such as bioscience, oil and gas, geology and weather. Underwater optical wireless communication (UOWC) can play a vital role in establishing reliable high data rate links with the help of acoustic communications. Underwater communication nodes such as autonomous vehicles, sensors and divers can be connected by underwater BSs using UOWC. Moreover, underwater communication networks are connected to terrestrial networks via water surface networks and aerial networks. Both satellites and unmanned aerial vehicles work to establish the aerial networks using electromagnetic and optical carriers. Water surface networks connect the aerial networks and underwater networks via floated nodes, such as ships, buoys, offshore oil and gas platform, and wind turbines, which are equipped by both underwater and aerial communication systems. Securing a sustainable energy source by wind, sun and water flow is an essential requirement for both underwater and water surface networks. Moreover, energy can be transferred by the simultaneous lightwave and information transfer (SLIPT) technology using optical signals.

F. Massive Vehicle-to-Everything Communications

Two emerging technological trends in the vehicular industry are reshaping vehicular communications, which are corresponding to the self-driving and remote-driving technologies. Due to the development of both technologies in recent years, it is believed that both will be technically mature and widely applied before 2030. To enable both driving technologies in practice, massive vehicle-to-everything (V2X) communications must be studied and deployed in 6G, which provide the basics for high-reliability and low-latency as well as secure exchange of massive driving and ambient data.

G. Holographic Communications

6G is expected to be a conversion point from the traditional video conferencing with multiple parties over the world to a virtual in-person meeting with others. To this end, a realistic projection of real-time movement needs to be transferred in negligible time to other parties, which is denoted as holographic communications. In fact, transferring three-dimensional image along the voice is not sufficient to convey the in-person presence. There is a need to have a three-dimensional video with a 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 extremely large bandwidths. The multi-party holographic communication needs an efficient cross-layer communication system that is able to deal with distributed sources necessary to deliver a single holographic message. The communication system reliability can affect significantly the holographic resolution, connection stability and the number of participant users.

H. Tactile Communications

After using holographic communication to transfer a virtual vision of close-to-real sights of people, events, environments, and etc. It is beneficial to remotely exchange the physical interaction between human/machines and machines through the tactile Internet in real time. Specifically, the expected services include teleoperation, cooperative automated driving, and interpersonal communication, where it should be possible to apply haptic control through communication networks. As a result, there is a necessity to realize high-resolution communication systems with ultra-large bandwidth, ultra-reliable links, and ultra-low latency. Efficient cross-layer communication system design has to be conducted to meet these stringent requirements simultaneously. For example, new physical layer schemes need to be developed such as to improve the design of signaling systems, waveform multiplexing, and etc. As for the delay, all delay sources should be treated carefully including buffering, queuing, scheduling, handover and the ones induced from protocols. Existing wireless communication
systems cannot fulfill these requirements, and there is a need to over-the-air fibre communication systems to do this task [27].

I. Human Bond Communications

6G is expected to support widely the human-centric communication concept, where the human can access and/or share remotely several physical features beyond the traditional voice and data. Human bond communication concept is proposed to allow accessing the human five senses in the same way that it is witnessed [28]. Recently, the concept is expanded with the help of ‘communication through breath’ scheme to allow reading the human bio-profile using the exhaled breath and even interact with the human body by inhalation using volatile organic compounds [29]. As a result, it is possible to diagnose diseases, detect emotions, know biological features and interact with the human body through breath and even in a remote way. Developing communication systems that can replicate the human senses and human biological features requires interdisciplinary research. It is expected to have hybrid communication technologies that are able to sense and deal with different physical quantities then share it with the intended receiver while keeping good security and privacy levels. Several key concepts and technology challenges are discussed comprehensively in [28], [29].

J. Summary

Summarized from the above application scenarios, we boldly anticipate five slices 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)
- Unconventional Data Communications (UCDC)

These five slices are pictorially illustrated in Fig. 2.

III. KEY FEATURES AND ENABLING COMMUNICATION TECHNOLOGIES OF 6G

Based on the application scenarios and challenges as well as the five supported slices in 6G discussed in the last section, we are now able to define the key features of 6G in this section. To enable the key features of 6G, multiple state-of-the-art communication technologies must be jointly applied, which are also summarized in this section. To begin with, a qualitative comparison between 5G and 6G communications is summarized in Fig. 3 which indicates that although we can expand the spectrum to a much higher frequency in 6G, the spectral efficiency would hardly be improved. In contrast, security, secrecy, and privacy in 6G communications should be significantly enhanced by new technologies. Incremental improvements would happen for energy efficiency, intelligence, affordability, and customization level.

A. 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 [13]. However, the security, secrecy, and privacy issues of wireless communications have been to some extent overlooked in the past decades. To protect data security, the classic encryption based on Rivest-Shamir-Adleman (RSA) algorithms is being challenged by increasingly powerful computers [30]. Physical layer security technologies and quantum key distribution via visible light communications (VLC) would be the solutions to the data security challenge in 6G [31], [32]. More advanced quantum computing and quantum communication technologies might also be deployed to provide intensive protection against various cyber attacks [33]. Meanwhile, communication/data service providers have legally collected a huge 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 [34].
B. High Affordability and Full Customization

According to 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 always ignored in most existing works. One might find their proposed solutions/schemes having 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 endeavor to provide high affordability.

Full customization allows users to choose the service modes and adjust individual preference. For example, a user would like to have a low-rate but reliable data service; another user tolerates unreliable data service in order to get a lower communication expense in return; some might only care about the energy consumption of their devices; some even intend to get rid of smart functionality due to the concerns of data security and privacy. All users will be granted the right to choose what they like in 6G, which should not be deprived by intelligent technologies and 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. SoE 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 and higher items in the quality of service (QoS) vector, we should map all required performance metrics as a whole to a unique SoE performance metric for each individual user in 6G.

C. Low Energy Consumption and Long Battery Life

The daily charging requirements of smartphones and tablets become annoying in 4G/LTE networks and will continue to the foreseeable 5G era. To release 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 (BSs) with reliable power supply or pervasive smart radio space [35]. Cooperative relay communications and network densification would also help to reduce the transmit power of mobile device by reducing the per-hop signal propagation distance [36], [37]. To achieve a long battery life, various energy harvesting methodologies would be applied in 6G, which not only harvest energy from ambient radios, but also the energy from micro-vibrations and sunlight [38]. 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 [39].

D. High Intelligence

The high intelligence in 6G will benefit both network operations and communication services. 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, transmit 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 hard to be obtained on a real-time basis. With the development of machine learning techniques, especially deep learning, a BS equipped with graphics processing units (GPUs) or the control centre of core network could carry out relevant learning algorithms to allocate resources efficiently to achieve performance close to the optimum [40]. Meanwhile, by the advances on smart radio space and smart materials, distributed and pervasive intelligence of the holistic communication environment, including wireless channels, would become possible [41]. This will provide a self-organizing and self-healing properties for the 6G network, which will enable reliable device-to-device (D2D) communications in a fully intelligent way. Furthermore, as a human-centric network, the high intelligence of 6G network also directly reflects in a plethora of communication services, e.g., indoor/outdoor positioning, multi-device management, information search, e-health, surveillance, cyber security [42].

E. Extremely Larger Bandwidth than 5G

Recent progress in generated technology enables researchers to explore higher frequencies beyond the millimetre-wave band. The THz band defined from 0.1 THz to 10 THz was known as a gap band between the microwave and optical due to the lack of efficient signal generation techniques. Nowadays, electronic, photonic and hybrid electronic-photonic based methods are developed thanks to the THz unique spectrum location [43]. Thus, hybrid THz/free space optical (FSO) systems are highly expected to be realized in 6G using the hybrid electronic-photonic transceivers, where an optical laser can be used to generate THz signal or send an optical signal. The hybrid link offers plenty of bandwidth for signal transmission and has the immunity to operate under different weather conditions, i.e., fog and rain [44]. Another interesting and promising application is complementing the VLC service. VLC is a promising technology that makes use of the lighting infrastructure to send information and even energy. THz transmission can play a vital role in uplink especially that it does not need line-of-sight to establish the link. Thus, THz uplink solution offers a reliable communication link for VLC networks compared with the infrared solution that needs tracking and positioning system. Hybrid VLC/THz system introduces robust communication solutions against sun light or ambient light that reduces the signal-to-noise ratio of the VLC system.

IV. BEYOND THE COMMUNICATION TECHNOLOGIES

Communication technologies are crucial, but not all. To promote a new technological paradigm and make it socio-economically profitable, we must always keep the issues beyond technology in mind. In this section, we briefly discuss
several crucial issues vis-à-vis 6G beyond the communication technologies *per se*.

**A. Dependency on Basic Sciences**

It is admitted that the advancement of wireless communications is highly restricted by basic sciences, especially mathematics and physics. As detailed in [13], we are squeezing the last lemon juice of Shannon’s treatise published in 1948 and almost reach the hard wall set by information theory. What is worse, incapable mathematical tools prevent us from exploring the exact performance of communication systems and make us lost in the *asymptopia*. As a result, a large number of impractical assumptions are made in order to make analysis mathematically tractable, which cannot provide much insight and guideline for 6G communications. The breakthrough in mathematics would often result in a new research boom in wireless communications, and one example is the stochastic geometry and graph theory applied for wireless network modelling [45]. To summarize, researchers shall pay sufficient attention to basic sciences and interdisciplinary fields in order to realize 6G networks. Particularly, ground-breaking research into information theory and new mathematical tools would yield significant impacts on wireless communications.

**B. 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 high-frequency spectrum and to reduce the coverage of a single cell. The former tendency is witnessed by the evolution from cellular radio spectrum to millimetre-wave spectrum, THz spectrum, and visible light spectrum. The later tendency refers to the network densification. On the other hand, both tendencies must match up the developments in upstream industries, e.g., electronics manufacturing. First of all, in theoretical research, one can assume an arbitrarily high frequency for use, but in reality, the communication devices constituted realistic electronic components must be able to meet these requirements. In some cases, the resultant data rate has even exceeded the allowable constraint on the electronic circuit by the current manufacturing level, or the signal on higher frequency bands cannot be proceeded by currently commercial chips at all. Neglecting the dependency on upstream industries will turn the 6G research to be nothing but a theoretical carnival.

**C. Business Model and Commercialization of 6G**

Previous research activities chronically focus 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 BSs is costly after all, because of land use right granting and construction operations. Moreover, as 6G communications would bring ground-breaking communication

... technologies relying on novel network architectures, how to ensure the forward 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 triumph. One should always remember that for most ordinary users and government policy makers, paying several times higher to get a dispensable performance gain in terms of transmission rate or latency will not be accepted, let alone appreciated.

**D. Potential Health and Psychological Issues for Users**

The ‘base station myth’ is a frequent topic in public media and could even trigger severe protests, which reflects the health concerns of users about radiation safety. As reported, electromotive force (EMF) limits have been reached in some cities. With a densified network with a smaller coverage per BS and the use of higher frequency band, there are reasons to believe that such concerns will be aggravated in the era of 6G. As 6G communication is expected to be human-centric, special attention must be paid to the potential health issues brought to users. In this context, EMF-aware transmission would be a novel concept to be introduced in 6G to mitigate the health concerns [46].

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 visioned in some proposals even for 5G networks, massive sensors are deployed all over the space and they are smart to detect, understand, communicate, and respond (fortunately, such a sci-fi scene has been greatly exaggerated). Then, the question will be: will people really enjoy and be comfortable to live in such a smart space? Will people be delighted to be recorded and watched by such a technocratic ‘big brother’? Without a careful study on these psychological issues before implementing in practice, 6G could cause catastrophic consequences and even deconstruct existing trust in information and communications technology.

**E. Social Factors Hindering the Worldwide Connectivity**

As pointed out in the background paper of the World Economic Forum at Davos Annual Meeting 2017 [19], 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 literacy. This is mainly a demand-side issue and shall 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-payment and e-taxi in China are good examples that connect most people who never use smart phone before.
V. CONCLUSION

In this article, we provided our basic thoughts on 6G communications from a human-centric perspective. Overall, 6G is not only an extension of 5G with a much higher rate and lower latency, but also should be human-centric. In this regard, we believe that high security, secrecy, and privacy are the all-important features of 6G, which shall be paid special attention from the wireless research community. We also presented the potential application scenarios of 6G and summarized five slices that should be supported in 6G. Following these slices, key features and enabling technologies for 6G communications were introduced. Beyond the communication technologies, we briefly discussed other crucial issues regarding 6G communications, including the dependency on basic sciences and upstream industries, business model and commercialization, as well as health, psychological, and social impacts. The article aims to provide an envisioned picture of 6G and serve as a research guideline in the post-5G era.

REFERENCES


This is the first publication visioning 6G from the perspective of service.


This paper points out the potential research directions of physical-layer communications in the post-5G era.


This paper details the project of Future Networks 2030.


This editorial summarizes the latest achievements of 5G research deployment.


This paper describes a number of common issues that have lasted for a long time in the research community of wireless communications.


