6G: Envisioning the Key Technologies, Applications and Challenges

Syed Agha Hassnain Mohsan[1], Alireza Mazinani[2], Warda Malik[3], Imran Younas[4]
Nawaf Qasem Hamood Othman[5], Hussain Amjad[6], Arfan Mahmood[7]
Department of Electrical Engineering, COMSATS University Islamabad (CUI), Islamabad, Pakistan[1]
School of Electronic and Information Engineering, Beihang University, Beijing, China[2]
Department of Electrical Engineering, COMSATS University Islamabad (CUI), Wah, Pakistan[3]
Department of Electronics Engineering, Xi'an Jiaotong University (XJTU), Xi'an, China[4]
Department of Information and Communication Engineering, Xi'an Jiaotong University (XJTU), Xi'an, China[5]
Department of Marine Science and Information Technology, Ocean College, Zhejiang University, Zhoushan, China[6]
Complex Networks and Control Lab, Shanghai Jiao Tong University, Shanghai, China[7]

***Abstract*—In 2030, 6G is going to bring remarkable revolution in communication technologies as it will enable Internet of Everything. Still many countries are working over 5G and B5G has yet to be developed, while some research groups have already initiated projects on 6G. 6G will provide high and sophisticated QoS e.g. virtual reality and holographic communication. At this stage, it is impossible to speculate every detail of 6G and which key technologies will mark 6G. The wide applications of ICT, such as IoT, AI, blockchain technology, XR (Extended Reality) and VR (Virtual Reality), has created the emergence of 6G technology. On the basis of 5G technique, 6G will put profound impact over ubiquitous connectivity, holographic connectivity, deep connectivity and intelligent connectivity. Notably, research fraternity should focus on challenges and issues of 6G. They need to explore various alternatives to meet desired parameters of 6G. Thus, there are many potential challenges to be envisioned. This review study outlines some future challenges and issues which can hamper deployment of 6G. We subsequently define key potential features of 6G to provide the state of the art of 6G technology for future research. We have provided a review of extant research on 6G. In this review, technology prospects, challenges, key areas and related issues are briefly discussed. In addition, we have provided technologies breakdown and framework of 6G. We have shed light over future directions, applications and practical considerations of 6G to help researchers for possible breakthroughs. Our aim is to aggregate the efforts and eliminate the technical uncertainties towards breakthrough innovations for 6G.**

Keywords—IoT; AI; communication technologies; holographic communication; blockchain

I. Introduction

Although the era of 5G is not fully developed, the limitations of 5G have created the demand for 6G networks. In 2019, communication synergy around the globe drafted first 6G white paper in world's first 6G summit in Finland. After that, many government organizations and research group from prestigious institutes started introducing their 6G projects. UK government has decided to invest in 6G technology [1], while Academy of Finland has launched "6 Genesis" project.

What is 6G technology? Some people expect more than just a faster version of 5G. For example, there should be no limitation of coverage to ground level. Instead, it must provide undersea and space coverage. It must enable higher Artificial Intelligence (AI) characteristics. In fact, some researchers consider it as an "AI-empowered" network [2]. It should not merely involve AI but it must integrate AI networking functions and tool. In addition, secrecy, privacy and risk mitigation must be a core component of its architecture [3]. In this review, we have investigated privacy and security challenges along with potential applications of 6G network. An overview of different dimensions of 6G networks is shown in Fig. 1.

After commercialization of 5G network, academia and industrial experts have started thinking about next 6G network, services and requirements behind it. If we look at standardization methods of 5G technology, three aspects were investigated as, ultra-reliable and low latency communications (URLLC), massive machine type communications (mMTC) and enhanced mobile broadband (eMBB). Although such scenarios are not fully investigated for 6G networks, however some pioneering works [4-5] forecast the idea to link everything via unlimited, reliable and instantaneous wireless resources. We have shown an overview of 6G coverage in Fig. 2.

To bring this revolution to connect everything worldwide, 6G will require extreme communication techniques such as smart living based wireless brain-computer interactions [6], smart working based on seamless holographic projection [7] and smart design considering real-time digital twins [8]. The evolution from 5G to 6G is summarized in Table I.

We have provided some performance metrics for 6G networks below and compared with conventional 5G requirements.

- *Mobility:* The highest speed to be achieved will be increased from 500 km/h to 1000 km/h.
- *Reliability:* 99.99% reliability will be achieved to support unmanned vehicles including AUVs and collaborative robotics.

- *Latency:* The communication latency will be decreased by 10 times for end-to-end point of view.
- *Throughput:* A maximum throughput of 1 Tb/s will be needed for 6G which is 1000 times speedy than 5G. 100 times advancement is expected.
- *Energy and Spectrum Efficiency:* 100 times energy efficiency and 10 times spectrum efficiency will be achieved.

The above described metrics involve disruptive features in 6G networks to use more flexible frame structure, more frequency bands and more spatial dimensions. Many industrial experts and technologies have discussed to meet these requirements. Such as, Space-Air-Ground integrated network [9] have suggested to enhance the spatial degrees of freedom by incorporating airborne, terrestrial and satellite networks, which extend 2D into 3D space for reliable and efficient connectivity [10]. Under-utilized high frequency bands can be explored through Terahertz (THz). Visible light communication (VLC) is a promising candidate for tens of GHz bandwidth [11] and 1 Tb/s throughput. Meanwhile, AI driven communication [12] with intelligent control will be possible.

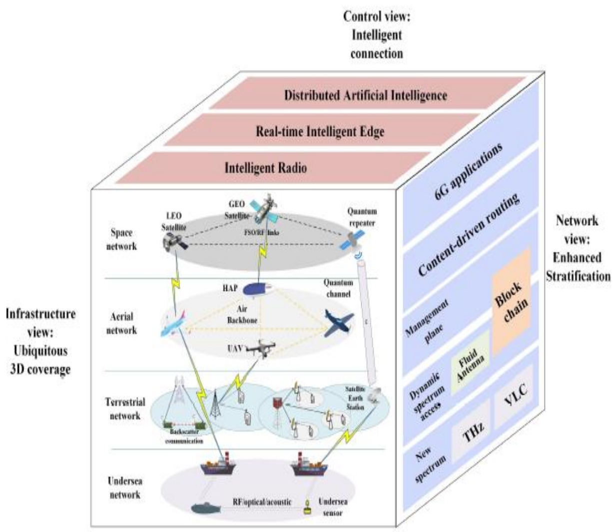

Fig. 1. Different Dimensions of 6G Architecture [17].

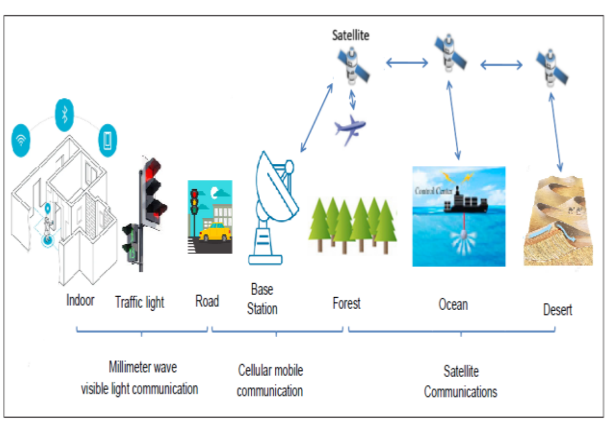

Fig. 2. An Overview 6G Network Coverage.

TABLE I. EVOLUTION FROM 5G TO 6G

Key parameter	**5G**	**6G**
Mobility (km/h)	350-500	1000
Peak spectral efficiency (b/s/Hz)	30	60
End-to-end latency (ms)	1	0.1
Reliability	10-5	10-9
Connection Density (device/km2)	106	107
Area traffic capacity (Mbps/m2)	10	1000
Channel bandwidth (GHz)	1	100
Spectral efficiency (b/s/Hz)	0.3	3
Energy Efficiency (Tb/J)	NA	1
User Data rate (Gbps)	1Gb/s	>10Gb/s
Peak data rate	10-20Gb/s	>100Gb/s
Receiver sensitivity	-120dBm	<-130dBm
Position precision	m	cm
Coverage	70%	>99%
Delay	ms	<ms

II. HISTORICAL OVERVIEW

A. 1G and 2G - 10 Times Reduction

1G and 2G networks provide the basic service of voice calling. Significant contribution has been made from 1G to 2G realization, such as China Mobile's annual report revealed 10 times price depletion from 0.1 to 0.01 US dollar/minute [13]. In addition, world's population using these services also increased from 10% (1G) to above 50% (2G) within 20 years [14].

B. 3G and 4G - 1000 Times Reduction

3G and 4G networks provide the key service of data transmission. Technical development from 3G to 4G include orthogonal frequency division multiplexing (OFDM) and multiple-input multiple-output (MIMO) and user-sensitive goal of1000 times price reduction. Initial 3G users are limited to business community to access company resources and emails, while further enhancement occurs only after the deployment of 4G networks.

C. 5G and 6G - 1000 Times Reduction

An explosive growth of 5g and beyond is found to facilitate human-to-machine and machine-to-machine communications. Although the existing 5G is still based on eMBB with the similar price strategy of 4G networks. However, it will be more reasonable to charge on the basis of connection rather than data traffic. According to FTTH systems, China is charging 100-200 US dollars for each terminal [15]. However, 100 trillion sensors are expected to be manufactured and connect to internet by the end of 2030 to revolutionize 6G. Hence, 1000 times price reduction will be required to develop a sustainable smart society. Table II summarizes different features of 5G and 6G.

A details comparison of 1G to 6G [16] technologies is summarized in Table III.

TABLE II. COMPARISON BETWEEN 5G AND 6G

Feature	5G	6G
VLC	No	Yes
Reliability	Good	Extreme
AI	No	Yes
Centre	User	Service
Capacity	1D /2D	3D
WPT	No	Yes
Core	IoT	IoE
Privacy	Good	Extreme
Real Time	No	Yes

TABLE III. COMPARISON OF 1G TO 6G TECHNOLOGIES

Feature	1G	2G	3G	4G	5G	6G
Time span	1980-1990	1990-2000	2000-2010	2010-2020	2020-2030	2030-2040
Highlight	Mobility	Digitization	Internet connectivity	Real-time applications	Extreme data rates	Privacy, secrecy, security
Core network	PSTN	PSTN	Packet N/W	Internet	IoT	IoE
Services	Voice	Text	Picture	Video	3D VR/AR	Tactile
Architecture	SISO	SISO	SISO	MIMO	Massive MIMO	Intelligent Surface
Multiplexing	FDMA	FDMA, TDMA	CDMA	OFDMA	OFDMA	Smart OFDMA plus IM
Maximum Frequency	894 MHz	1900 MHz	2100 MHz	6 GHz	90 GHz	10 THz
Maximum Data rate	2.4 kb/s	144 kb/s	2 Mb/s	1 Gb/s	35.46 Gb/s	100 Gb/s

III. CURRENT RESEARCH PROGRESSES TOWARDS 6G

Many research groups have shown the vision of 6G and research fraternity has started advance research activities and projects [18-20]. There is a growing inclination in research publications in this domain. Recently, Yang Lu et al. [21] filtered extant articles about 6G as various institutes have been conducting research on several approaches towards 6G. Publishing trend between 2016 and 2020 is depicted in Fig. 3. X-axis shows the number of publications while Y-axis shows specific year. It can be seen that maximum papers were published in IEEE conferences and journals.

E. Basar et al. [22] have discussed MIMO paradigm for 6G. They focused on research activities related to device manufacturing capabilities. S.M. Bohloul et al. [23] have made a good discussion about trends, opportunities and developments in 6G. They have outlined communication technologies e.g. tactile internet, flying networks and holographic calls for future networks in 2030. In [24] and [25], future trends and applications enabling 6G technology have been summarized. Blockchain technology, human centric services and key performance indicators of 6g are investigated in these studies. 6G prospect, challenges and key performance indicators are defined. Authors have illustrated the role of OWC [26] in 6G technology. Some recent articles have provided detailed discussions about green 6G network architecture [27], 6G spectrum management [28], security challenges [29], potential solutions [33], machine learning technologies for 6G [30-31] and performance evolution of terahertz [32] communications. Some publications have discussed data center connectivity [34] and practical implementation of multiple access [35] for 6G networks. Network patterns for 6G are highlighted in some studies [36-37]. 6G based AI applications [38-39] which will unlock the full potential of radio signals are outlined in some studies. Hardware foundation of AI [40] is proposed in an article. Zhao et al. [41] have provided a survey on intelligent reflective surfaces for 6G networks. These promising materials can enhance the spectral efficiency [42] in 6G networks. In addition, several countries have started research projects to initiate, develop, define and reshape framework of 6G networks. Table IV summarizes country wise research initiatives in 6G networks.

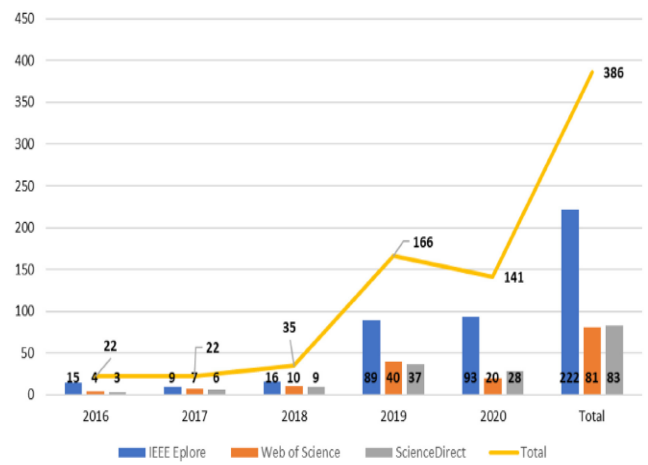

Fig. 3. A Trend of Publications on 6G [21].

TABLE IV. 6G PROJECTS IN DIFFERENT COUNTRIES

Country	Year	Research Initiative
2018	Finland	6G initiative was launched in University of Oulu.
2019	China	37 research institutes have started focusing on 6G research.
2019	USA	Spectrum between 95 GHz and 3 THz has been opened.
2019	South Korea	KAIST and LE Electronics have established a 6G research center with collaboration.
2020	Japan	Sony, Intel and NTT have collaborated to work on 6G technology. Japan has planned to spend $US 2 billion on 6G industrial research.
2020	Saudi Arabia	Researchers from KAUST have started working on 6G technology.
2021-2026	South Korea	Government of Korea will invest $169 million to secure 6G and planning to launch 6G pilot project in 2026.

IV. TECHNOLOGY BREAKDOWN

We have discussed each generation in the aspects of frequency, spatial and time domains as given below. Technology breakdown from 1G to 6G is also displayed in Fig. 4.

A. Spatial - 10 Times

The purview of the Space-Air-Ground integrated network enfolds an extensive range of terminals, satellite communications, flying drones, which proffers two times cost reduction with low number of base stations. Ultra-scale MIMO can improve 50% throughput without extra costs; thereby 1.5 times cost reduction can be achieved. Intelligent adaptation of beam eventually brings three to four times reduction, while 10 times reduction is possible through different network architectures.

B. Frequency - 10 Times

In frequency domain, the cost reduction is dependent on utilization of low cost spectrum. Although mmWave, VLC and THz are capable to offer significant bandwidth for wireless transfer, the befitting scenario is indoor users with pedestrian mobility, which is 70% of the overall traffics. Thus, higher frequency bands can facilitate with 3 times reduction. Moreover, another 3-4 times reduction is possible by flexible usage of multiple frequency bands.

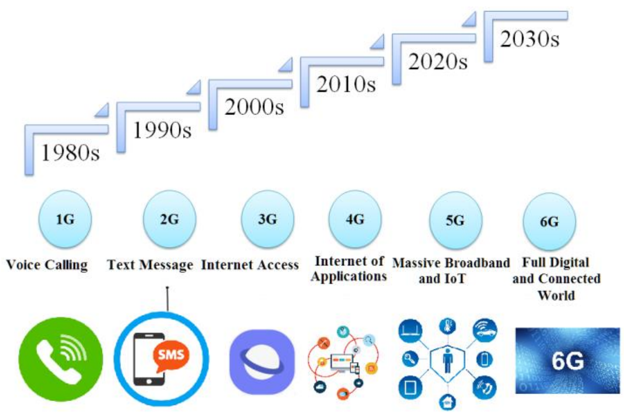

Fig. 4. An Overview of 1G-6G Devices nd the Corresponding Technology Breakdown.

C. Time - 10 Times

Another prominent alternative is to profoundly impact the resolution of time-frequency resource to feature flexible frame structure and integrate modulation scheme like index modulation. A fast mode adaptation can enhance the performance with a massive combination of duplex schemes, modulation techniques and frame structures. By incorporating several techniques, we expect 1000 times reduction can be achieved. The core element is AI-assisted intelligent communication which can reduce cost up to 20-50 times.

V. 6G REQUIRES A NEW PARADIGM

Next generation 6G network requires wide bandwidth for high resolution and high carrier frequencies for small antennas. A potential issue is to analyze and process radio systems over wide bandwidth without prior information of signal, modulation and carrier frequency. An idea option is photonics defined system as it can provide high spectrum capacity with extreme bandwidth. It is an extended version of microwave photonics through coherent optics, optical computing and photonics DSP. A paradigm shift and hyper-S curve [43] presenting a revolution of mobile of communication technologies is shown in Fig. 5.

Open loop control, reduced feedbacks, software defined systems and interference cancellation have developed this system. A radical innovation is expected in case of 6G which will result into a new S curve. The logical start of 6G is shown in Fig. 6.

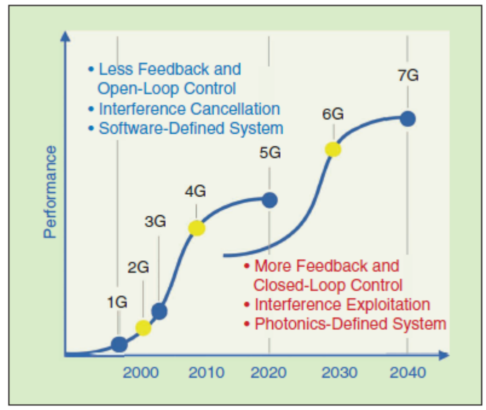

Fig. 5. Hyper-S Curve and Paradigm Shift [43].

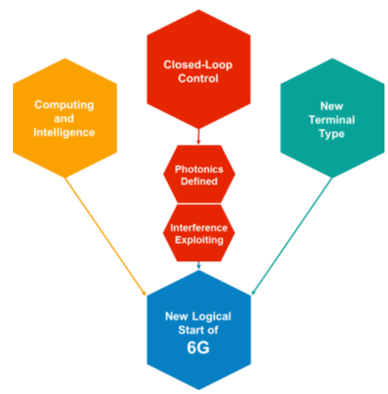

Fig. 6. New Logical Start of 6G.

VI. KEY AREAS IN 6G NETWORKS

We will discuss key areas in 6G networks and we have also investigated privacy and security issues in these areas.

A. Real-Time Intelligent Edge

It is not fully possible to implement Unmanned Aerial Vehicle (UAV) networks with existing technologies as it needs real time intelligence and extremely low latency to control the network. Although 5G technology has supported autonomous driving, however prediction, self-adaption and self-awareness for network entities is not supported [44]. Thus, a new technology is required to overcome these issues. It will be possible through 6G technology to enable AI-powered services. As AI will be incorporated in vehicle networks, it will support several security mechanisms. However, it will cause new privacy and security issues. Tang et al. [45]

investigated that both network and physical environments should be considered for a vehicle network as it can reduce malicious activities.

B. Distributed AI

6G networks will support Internet of Everything (IoE). It will make 6G network advance enough to take intelligent decisions [27]. In addition, IoT needs to support various requirements. 1) The edge device must compute and store data. 2) It should have the capability to clean and abstract data [46]. This approach can improve the privacy and security of the network. Machine learning algorithms can be integrated with 6G to ensure security [47] and data integrity.

C. 3D Intercoms

In 6G network, network optimization and designing will move from 2D to 3D [48]. 6G technologies will be capable of supporting 3D communication to enable undersea, UAVs and satellite communication. A 3D intercom can facilitate this feature with accurate time and location. In addition, resource management, routing and mobility characteristics also require network optimization in 3D intercom. Currently, THz bands are being experienced. With this band, some new technologies e.g. quantum and molecular communications can be applied for remote communication [49]. Wei et al. [50] highlighted some security risks for authentication process. In addition, performance of 6G networks in undersea environment is still unpredicted. Once 6G network operations in undersea environment are possible, more opportunities and challenges will emerge in near future. Fig. 7 illustrates some application scenarios supported by 6G technologies.

D. Intelligent Radio

The transceiver devices can be separated in 6G while they were designed together in earlier generations. Hence, it has the capability to update itself. Some operating systems are developed on the basis of hardware information and AI technology. Researchers have investigated signal jamming and suspicious activities in data transmission. Thus, 6G will enable intelligent and secure data transmission.

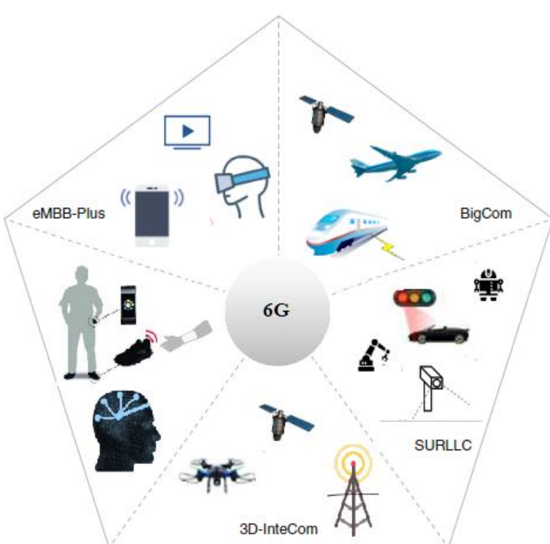

Fig. 7. Applications Supported by 6G.

VII. 6G Technologies

In this section, we have discussed 6G technologies and associated privacy and security concerns. Table V presents an overview of 6G technologies and security issues. While Fig. 8 illustrates potential key technologies of 6G networks.

TABLE V. EVOLUTION FROM 5G TO 6G

Technology	Reference	Privacy and security issue
AI	[48]	Malicious attack
AI	[51]	Communication
AI and quantum communication	[52]	Encryption
Blockchain	[53]	Communication
Blockchain	[54]	Access control
Blockchain	[55]	Authentication
VLC	[56]	Malicious attack
VLC	[57]	Communication
THz	[58]	Malicious attack
THz	[59]	Authentication
Quantum communication	[60]	Encryption

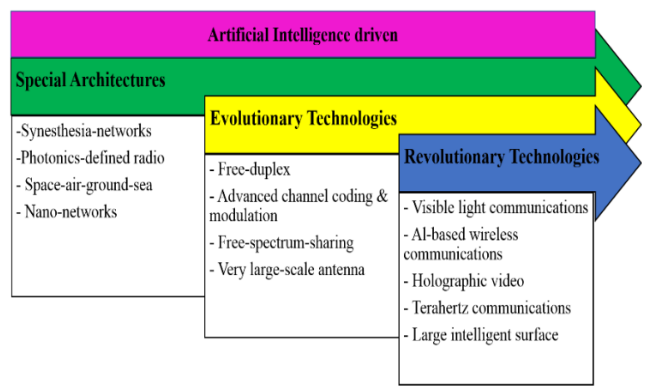

Fig. 8. Key Technologies of 6G Network.

A. AI

AI plays the most important role in future network infrastructures as compared to other technologies. AI has gained a lot of attention from various research groups. With this growing research, various privacy and security problems are also emerging. Although AI is also integrated in 5G technology, however it is considered as the key component of future 6G. AI technologies are subdivided into physical layer consisting of network infrastructure, architecture layer, computing layer which contains software defined networks, edge/cloud computing and network function virtualization.

B. Quantum Communication

Another promising technology in 6G network is quantum communication. It can significantly increase reliability and security of data transmission. Quantum state is affected with any adverse eavesdrop. Quantum communication offers security with essential breakthroughs. It can provide solutions and elevate communication which is not possible to achieve through traditional communication techniques [61]. However, it is not the only panacea for all security threats. Although research has been carried out to develop quantum cryptography, but fiber attenuation is a serve issue in long distance quantum communication. Zhang et al. [62] and Nawaz et al. [52] have presented quantum mechanism for secure communication through quantum key distribution models.

C. Blockchain

Another prominent technology is 6G network is blockchain. It has several used such as spectrum sharing, distributed ledger technology and network decentralization. S. Dang et al. [48] used network decentralization to enhance network performance. Strinati et al. [63] also increased authentication security through distributed ledger technology. Blockchain technology can also overcome spectrum monopoly and low spectrum utilization [64]. Blockchain privacy concerns are related to communication, authentication and access control. X. Ling et al. [65] have illustrated authentication and secure network access features through blockchain technology.

D. Visible Light Communication (VLC)

VLC is a promising technology to meet the rapidly growing needs of wireless connectivity [66]. VLC has been deployed in vehicular Ad Hoc networks and indoor positioning systems. J. Luo et al. [67] have presented an indoor positioning system based on VLC. It is noticed that VLC limits EM interference. Some research studies have demonstrated high speed data transmission by using LEDs. Some deficiencies exist which affect the performance of VLC communication. In particular, VLC technology mainly supports indoor scenario as it is severely affected by natural light. The security issues of VLC technology include communication problem and malicious activities. A SecVLC protocol [57] is developed for secure data transmission in a vehicular network. Fig. 9 presents an overview of OWC in 6G technologies. We have provided a detailed discussion of OWC and 6G our recent systematic study [68]. 6G is expected revolution in UWPT [69] and UWOC.

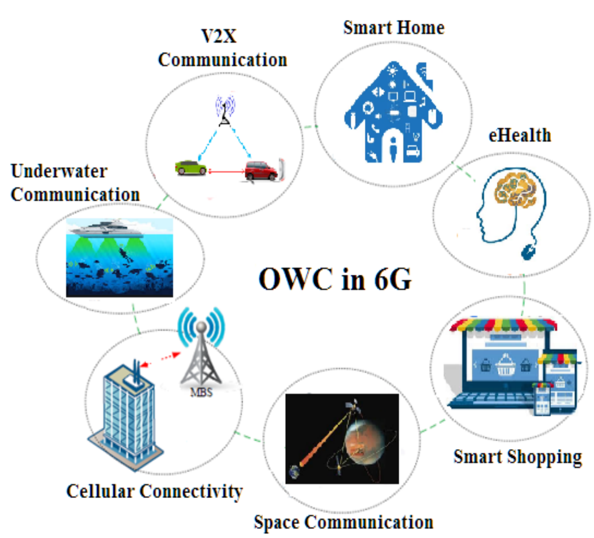

Fig. 9. OWC and 6G.

E. Terahertz Technology (THz)

Existing RF band cannot be utilized for future 6G technologies [70]. It has spurred the demand for THz technology. THz communication technology used 0.1-10 THz band. Moreover, it exploits optical signals and EM waves. Huang et al. [27] have highlighted several benefits of THz band including 100 Gbps data rate, high security and limited eavesdropping. THz can significantly minimize intercell impact [64]. Strianti et al. [63] have investigated energy consumption problem in THz communication. THz faces security risks of authentication and malicious attack. We have summarized a comparison between VLC and THz communication in Table VI.

TABLE VI. COMPARISON BETWEEN VLC AND THZ

Feature	VLC	THz
Cost	Cheap	Expensive
Data rate	10 Gbps	100 Gbps
EM radiation	no	yes
Transmission	LOS	NLOS
Transmission power	Low	High
Spectrum regulation	Unlicensed	Liscensed
Inter cell interference	No	Yes
Bandwidth	10-100 GHz	100 THz

VIII. POTENTIAL CHALLENGES

There are several critical challenges which can affect future 6G technology. In this section, we have discussed big data, power, latency and hardware design challenges.

A. Wireless Big Data

AI technology has proven its great stature in computer vision tasks. It has potential application in ImageNet big data sets. Such supervised learning method can solve complex optimization challenges in wireless communication. However, there exist many serious concerns for developing public wireless data sets for research purpose. As big data is processed and stored through cloud computing. The DIoE will cause new challenges to manage this data.

B. Portable and Low-Latency Algorithm

The current AI technologies are developed to meet certain requirements; however, it has limited migration capability. However, an important performance metric is to design portable and low latency algorithms. In addition, latency trade-off and accuracy is highly required as compared to than traditional computer vision tasks.

C. Hardware Co-Design

High density parallel computing methods are required in AI-assisted technologies. Wireless network architecture requires certain parameters to support AI-assisted communication. Moreover, computer performance can face degradation in case of advance materials e.g. graphene transistors and high temperature superconductors.

D. Power Supply

6G technology can make an efficient connection between mobile devices. Energy-efficient algorithms and strategies must be adopted in such cases. 6G will introduce new power control mechanism such as advance wireless power transfer (WPT) for smart devices. It will enable energy harvesting and optimization technique for efficient performance in harsh environment such as undersea environment.

E. Network Security Issue

Researchers need to focus on privacy concerns in future 6G technology. They must investigate new security approaches for secure data transmission. A significant extension in 5G security methods can also enable 6G security. Researchers can find new techniques to efficiently integrate THz with mmWaves. It can put profound impact on 6G privacy and security mechanism.

IX. 6G Potential Applications

Every new epoch of network technology introduces new services. In this section, we have outlined some potential applications for future 6G technology.

A. Multi-Sensory XR Applications

The low latency and high bandwidth of 5G technology has extended the VR/AR experience for 5G users. Nonetheless, some existing challenges should be removed in 6G network. The VR/AR experience will be enhanced in 6G network. Multiple sensors can be allocated to gather sensory data. Hence, the XR in 6G network will be formulated from URLLC and eMBB. The security concerns of eMBB and URLLC include internal communication, access control and malicious attack. Chen et al. [71] have investigated security problems in URLLC applications. J.M. Hamamreh et al. [72] have suggested a technique to improve security again URLLC attacks. Similarly, Yamakami et al. [73] have proposed a 3D model for secrecy risks in XR applications.

B. Connected Robotics and Autonomous Systems

Another promising application of 6G technology is the connected robotics and autonomous systems. A comprehensive autonomous system is required in 6G network as compared to 5G. This system should be based on a multi-dimensional network. In addition, the system must be capable to embed AI across the network. This feature will support automatic controlling of internal components. Strianti et al. [63] have envisioned resource control, caching and automatic handling in network. They developed an automated factory which contains cloud services, database and UAV networks to make it a complete autonomous system. 6G will be helpful for underwater robotic tasks such as security, imaging and rescue. 6G will enable efficient surveillance, navigation and robotic communication. It will develop a reliable, secure and smooth communication channel for real-time applications. Low latency and high speed data transmission of 6G will be helpful to obtain video data.

C. Wireless Brain-Computer Interactions

The concept of wireless BCI is to develop a link between device and human brain. This device can be placed inside or outside the body. The key application of wireless BCI is to control auxiliary equipment for disabled people. It is expected that BCI will have more applications with involving 6G technology. In 2015, Chen et al. [74] developed a brain-computer interface to speed up spelling. The security risks of wireless BCI contain encryption and malicious behavior. Several research studies [75-76] have discussed security issues, protection techniques and hacking applications to mitigate security issues.

D. Accurate Indoor Positioning

With evolving GPS, outdoor positioning systems have been developed accurately. However, indoor position systems need research attention to cope up with complicated indoor EM propagation. New aspects of full-fledge applications are expected with reliable and accurate indoor positioning services. However, alone RF communication cannot achieve accurate indoor positioning. Such crucial application can only be realized with 6G technology.

E. Holographic Communications

6G will make it possible to realize virtual in-person meeting than traditional video conferencing. It can be achieved through a realistic projection of real time mobility in short time. It is not sufficient to transmit 3D image with voice to realize in-person presence. However, it requires a stereo audio incorporated in 3D video. We can state that user interacts with holographic data and can carry out possible modifications as needed. This scenario can be captured by reliable communication networks with extremely large bandwidth.

F. Tactile Communications

After realizing holographic communication for virtual in-person meeting, it is advantageous to carry out tactile communication to transfer the physical interaction remotely. Specifically, it includes interpersonal communication, cooperative automated driving and teleoperation. Stringent demands or these applications can be met through reliable cross-layer communication-system. Moreover, delay can be mitigated by carefully handling handover, scheduling, queuing and buffering.

G. Internet of Nano-Things

Nanotechnology is providing remarkable opportunities to design advance materials. It has developed nanodevices like nanosensors. It has the capability to perform simple task and enable internet connectivity. IoNT [77] is developed by integrating nanotechnology with IoT. It has the ability to sense and transmit information. IoNT can be deployed with allied technologies such as big data, cloud computing, WSN, UWSN [78-79] and IoT. However, IoNT faces limited memory space issue for real-time implementation as data storage depends on the size of nano memory. Another potential issue is high biological noise and congestion control in nanodevices. An overview of 6G applications is summarized in figure 10.

H. Intelligent Internet of Medical Things (IIoMT)

IIoMT will remove space and time hurdles to perform surgical operations. 6G will provide high speed communication for efficient performance of telesurgery beyond boundaries. IIoMT will make use of holographic communication, tactile communication and AR/VR to assist remote doctors. Thus, 6G technology will ensure intelligent healthcare. It is expected to bring mobile hospital technology which can remove ambulance services. In future, it can offer medical devices to perform special medical tasks which can greatly reduce the possibility of medical staff in contacting with viruses. An overview of 6G applications is summarized in Fig. 10.

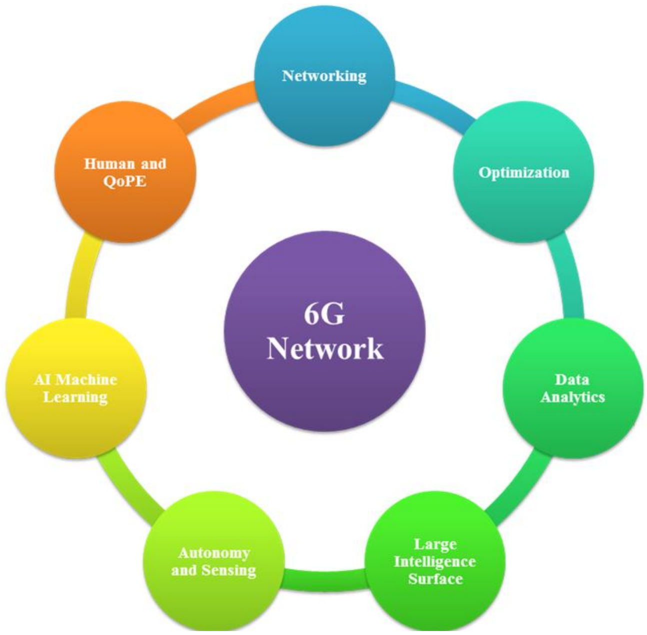

Fig. 10. Potential Applications of 6G.

X. Conclusions

During the worldwide deployment of 5G, academia and industrial experts have started conceptualizing 6G. Unlike 5G networks, the next generation 6G will focus on communication among users, industries and multiple objects. Network transmission performance is no longer only important parameter; blockchain technology, IoT and AI have become important components. 6G network will keep penetrating into virtual society, human-perceived actions and ubiquitous spaces. It will provide a secure, reliable, intelligent, deep, seamless and holographic network infrastructure. 6G network will fulfil the growing demands of industries with continuous innovations of AI. We outlined research activities in different countries which aim to create a vision of 6G. 6G will enable many new technologies such as VLC, tactile and holographic communication. In conclusion, we expect that this review article will pave the way to identify 6G roadmap. This paper reviews the key technologies and areas of 6G networks and highlights a prospective on future research. We have presented a vision of 6G network as a research guide for readers. We have also addressed key features, security challenges and explained potential applications which will be supported in 6G. We have presented an overview of 1G to 6G. We then examine the key areas of 6G network. This review article started by highlighting the historical overview of communication technologies and their pivotal elements aiming at fostering future 6G in various dimensions. Then, we discussed technology breakdown, potential challenges associated with future 6G technology and possible solutions to foster 6G. In addition, we have profoundly examined research activities in different countries including industries and research institutes. Finally, this study concludes with potential applications of future 6G. The key contribution of our study is that it clarifies the promising solution for potential issues and challenges in 6G technology. Thus, this review will open new horizons for future research directions.

References

[1] P. Yang, Y. Xiao, M. Xiao, S. Li, 6g wireless communications: vision and potential techniques, IEEE Network 33 (4) (2019) 70–75.

[2] K.B. Letaief, W. Chen, Y. Shi, J. Zhang, Y.-J.A. Zhang, The roadmap to 6g: Ai empowered wireless networks, IEEE Commun. Mag. 57 (8) (2019) 84–90.

[3] T. Zhu, P. Xiong, G. Li, W. Zhou, S. Y. Philip, Differentially private model publishing in cyber physical systems, Future Generat. Comput. Syst..

[4] K. David and H. Berndt, “6G vision and requirements: Is there any need for beyond 5G?” IEEE Veh. Technol. Mag., vol. 13, no. 3, pp. 72–80, Sep. 2018.

[5] T. Chen, S. Barbarossa, X. Wang, G. B. Giannakis, and Z.-L. Zhang, “Learning and management for internet of things: Accounting for adaptivity and scalability,” Proc. IEEE, vol. 107, no. 4, pp. 778–796, Apr. 2019.

[6] W. Saad, M. Bennis, and M. Chen, “A vision of 6G wireless systems: Applications, trends, technologies, and open research problems,” IEEE Netw., to be published, doi: 10.1109/MNET.001.1900287.

[7] K. Wakunami et al., “Projection-type see-through holographic threedimensional display,” Nature Commun., vol. 7, no. 1, pp. 1–7, Oct. 2016.

[8] E. Ahmed, I. Yaqoob, A. Gani, M. Imran, and M. Guizani, “Internet-ofthings- based smart environments: State of the art, taxonomy, and open research challenges,” IEEE Wireless Commun., vol. 23, no. 5, pp. 10– 16, Oct. 2016.

[9] N. Zhang, S. Zhang, P. Yang, O. Alhussein, W. Zhuang, and X. Shen, “Software defined space-air-ground integrated vehicular networks: Challenges and solutions,” IEEE Commun. Mag., vol. 55, no. 7, pp. 101–109, Jul. 2017.

[10] S. Zhang, S. Xu, G. Y. Li, and E. Ayanoglu, “First 20 years of green radios,” IEEE Trans. Green Commun. Netw., vol. 4, no. 1, pp. 1–15, Mar. 2020.

[11] P. Yang, Y. Xiao, M. Xiao, and S. Li, “6G wireless communications: Vision and potential techniques,” IEEE Netw., vol. 33, no. 4, pp. 70–75, Jul. 2019.

[12] K. B. Letaief, W. Chen, Y. Shi, J. Zhang, and Y.-J. A. Zhang, “The roadmap to 6G: AI empowered wireless networks,” IEEE Commun. Mag., vol. 57, no. 8, pp. 84–90, Aug. 2019.

[13] China Mobile Limited, “China mobile limited (2015) annual report 2015,” China Mobile Limited, Tech. Rep., 2016. [Online]. Available: http://www.chinamobileltd.com/en/ir/reports/ar2015.pdf

[14] X. Gong and C. Cortese, “A socialist market economy with Chinese characteristics: The accounting annual report of China Mobile,” Accounting Forum, vol. 41, no. 3, pp. 206–220, 2017.

[15] TTH Council Asia-Pacific, “APAC FTTH market panorama report 2019,” FTTH Council Asia-Pacific, Tech. Rep., 2019. [Online]. Available: http://www.ftthcouncilap.org/wp-content/uploads/2019/04/FTTH-APAC-Panorama-Report-2019_Low.pdf

[16] Dang, Shuping, et al. "What should 6G be?." Nature Electronics 3.1 (2020): 20-29.

[17] Huang, Tongyi, et al. "A survey on green 6G network: Architecture and technologies." IEEE Access 7 (2019): 175758-175768.

[18] Raghavan, V. & Li, J. Evolution of physical-layer communications research in the post-5G era. IEEE Access 7, 10392‑10401 (2019).

[19] Calvanese Strinati, E. et al. 6G: the next frontier: from holographic messaging to artificial intelligence using subterahertz and visible light communication. IEEE Veh. Technol. Mag. 14, 42‑50 (2019).

[20] Saad, W., Bennis, M. & Chen, M. A vision of 6G wireless systems: applications, trends, technologies, and open research problems. IEEE Netw. https://doi.org/10.1109/MNET.001.1900287 (2019).

[21] Lu, Yang, and Xianrong Zheng. "6G: A survey on technologies, scenarios, challenges, and the related issues." Journal of Industrial Information Integration (2020): 100158.

[22] E. Basar, Reconfigurable intelligent surface-based index modulation: a new beyond MIMO paradigm for 6G, IEEE Trans. Commun. 68 (5) (2020) 3187-3196.

[23] S.M. Bohloul, Smart cities: a survey on new developments, trends, and opportunities, J. Ind. Integr. Manag. (2020) Early Access.

[24] E. Carter, P. Adam, D. Tsakis, S. Shaw, R. Watson, P. Ryan, Enhancing pedestrian mobility in Smart Cities using Big Data, J. Manag. Anal. (2020) 1-16.

[25] S. Chen, S. Sun, G. Xu, X. Su, Y. Cai, Beam-space multiplexing: practice, theory, and trends, from 4G TD-LTE, 5G, to 6G and Beyond, IEEE Wirel. Commun. 27 (2) (2020) 162-172.

[26] M.Z. Chowdhury, M. Shahjalal, M. Hasan, Y.M. Jang, The role of optical wireless communication technologies in 5G/6G and IoT solutions: prospects, directions, and challenges, Appl. Sci. 9 (20) (2019) 4367.

[27] T. Huang, W. Yang, J. Wu, J. Ma, X. Zhang, D. Zhang, A survey on green 6G network: architecture and technologies, IEEE Access 7 (2019) 175758-175768.

[28] M. Matinmikko-Blue, S. Yrjölä, P. Ahokangas, Spectrum management in the 6G Era: the role of regulation and spectrum sharing, 2020 2nd Wireless Summit (6G SUMMIT), IEEE, 2020, March, pp. 1-5.

[29] G. Gui, M. Liu, F. Tang, N. Kato, F. Adachi, 6G: opening new horizons for integration of comfort, security and intelligence, IEEE Wireless Commun (2020).

[30] N. Kato, B. Mao, F. Tang, Y. Kawamoto, J. Liu, Ten challenges in advancing machine learning technologies toward 6G, IEEE Wireless Commun. (2020).

[31] S.J. Nawaz, et al., Quantum machine learning for 6G communication networks: state-of-the-art and vision for the future, IEEE Access 7 (2019) 46317-46350.

[32] L. Yan, C. Han, J. Yuan, Hybrid precoding for 6G terahertz communications: performance evaluation and open problems, 2020 2nd 6G Wireless Summit (6G SUMMIT), IEEE, 2020, pp. 1-5.

[33] Alsharif, Mohammed H., et al. "Sixth Generation (6G) Wireless Networks: Vision, Research Activities, Challenges and Potential Solutions." Symmetry 12.4 (2020): 676.

[34] Rommel, S., Raddo, T. R. & Monroy, I. T. Data center connectivity by 6G wireless systems. In Proc. IEEE PSC https://doi.org/10.1109/PS.2018.8751363 (IEEE, 2018).

[35] Clazzer, F. et al. From 5G to 6G: has the time for modern random access come? Preprint at https://arxiv.org/abs/1903.03063 (2019).

[36] Yaacoub, E. & Alouini, M.-S. A key 6G challenge and opportunity—connecting the remaining 4 billions: a survey on rural connectivity. Preprint at https://arxiv.org/abs/1906.11541 (2019).

[37] Giordani, M., Polese, M., Mezzavilla, M., Rangan, S. & Zorzi, M. Towards 6G networks: use cases and technologies. Preprint at https://arxiv.org/abs/1903.12216 (2019).

[38] Stoica, R.-A. & de Abreu, G. T. F. 6G: the wireless communications network for collaborative and AI applications. Preprint at https://arxiv.org/abs/1904.03413 (2019).

[39] Letaief, K. B., Chen, W., Shi, Y., Zhang, J. & Zhang, Y. A. The roadmap to 6G: AI empowered wireless networks. IEEE Commun. Mag. 57, 84-90 (2019).

[40] Renzo, D. et al. Smart radio environments empowered by reconfigurable AI meta-surfaces: an idea whose time has come. EURASIP J. Wireless Commun. Netw. 2019, 129 (2019).

[41] Zhao, J. A Survey of intelligent reflecting surfaces (IRSs): towards 6G wireless communication networks. Preprint at https://arxiv.org/abs/1907.04789v3 (2019).

[42] Basar, E. Reconfigurable intelligent surface-based index modulation: a new beyond MIMO paradigm for 6G. Preprint at https://arxiv.org/abs/1904.06704v2 (2019).

[43] Zong, Baiqing, et al. "6G technologies: Key drivers, core requirements, system architectures, and enabling technologies." IEEE Vehicular Technology Magazine 14.3 (2019): 18-27.

[44] M.G. Kibria, K. Nguyen, G.P. Villardi, O. Zhao, K. Ishizu, F. Kojima, Big data analytics, machine learning, and artificial intelligence in next-generation wireless networks, IEEE Access 6 (2018) 32328–32338.

[45] F. Tang, Y. Kawamoto, N. Kato, J. Liu, Future intelligent and secure vehicular network toward 6g: machine-learning approaches, Proc. IEEE.

[46] I. Tomkos, D. Klonidis, E. Pikasis, S. Theodoridis, Toward the 6g network era: opportunities and challenges, IT Prof. 22 (1) (2020) 34–38.

[47] L. Loven, T. Lepp_anen, E. Peltonen, J. Partala, E. Harjula, P. Porambage, M. Ylianttila, J. Riekki, Edge Ai: A Vision for Distributed, Edge-Native Artificial Intelligence in Future 6g Networks, The 1st 6G Wireless Summit, 2019, pp. 1–2.

[48] S. Dang, O. Amin, B. Shihada, M.-S. Alouini, What should 6g be? Nat. Electron. 3 (1) (2020) 20–29.

[49] M. Katz, P. Pirinen, H. Posti, Towards 6g: getting ready for the next decade, in: 2019 16th International Symposium on Wireless Communication Systems (ISWCS), IEEE, 2019, pp. 714–718.

[50] Y. Wei, H. Liu, J. Ma, Y. Zhao, H. Lu, G. He, Global voice chat over short message service of beidou navigation system, in: 2019 14th IEEE Conference on Industrial Electronics and Applications (ICIEA), IEEE, 2019, pp. 1994–1997.

[51] T. Hong, C. Liu, M. Kadoch, Machine learning based antenna design for physical layer security in ambient backscatter communications, Wireless Commun. Mobile Comput. (2019).

[52] S.J. Nawaz, S.K. Sharma, S. Wyne, M.N. Patwary, M. Asaduzzaman, Quantum machine learning for 6g communication networks: state-of-the-art and vision for the fu-ture, IEEE Access 7 (2019) 46317–46350.

[53] P. Ferraro, C. King, R. Shorten, Distributed ledger technology for smart cities, the sharing economy, and social compliance, IEEE Access 6 (2018) 62728–62746.

[54] K. Kotobi, S.G. Bilen, Secure blockchains for dynamic spectrum access: a decentralized database in moving cognitive radio networks enhances security and user access, IEEE Veh. Technol. Mag. 13 (1) (2018) 32–39.

[55] S. Kiyomoto, A. Basu, M.S. Rahman, S. Ruj, On blockchain-based authorization architecture for beyond-5g mobile services, in: 2017 12th International Conference for Internet Technology and Secured Transactions (ICITST), IEEE, 2017, pp. 136–141.

[56] S. Cho, G. Chen, J.P. Coon, Enhancement of physical layer security with simultaneous beamforming and jamming for visible light communication systems, IEEE Trans. Inf. Forensics Secur. 14 (10) (2019) 2633–2648.

[57] S. Ucar, S. Coleri Ergen, O. Ozkasap, D. Tsonev, H. Burchardt, Secvlc: secure visible light communication for military vehicular networks, in: Proceedings of the 14th ACM International Symposium on Mobility Management and Wireless Access, 2016, pp. 123–129.

[58] J. Ma, R. Shrestha, J. Adelberg, C.-Y. Yeh, Z. Hossain, E. Knightly, J.M. Jornet, D.M. Mittleman, Security and eavesdropping in terahertz wireless links, Nature 563 (7729) (2018) 89–93.

[59] I.F. Akyildiz, J.M. Jornet, C. Han, Terahertz band: next frontier for wireless communications, Phys. Commun. 12 (2014) 16–32.

[60] J.-Y. Hu, B. Yu, M.-Y. Jing, L.-T. Xiao, S.-T. Jia, G.-Q. Qin, G.-L. Long, Experimental quantum secure direct communication with single photons, Light Sci. Appl. 5 (9) (2016), e16144.

[61] L. Gyongyosi, S. Imre, H.V. Nguyen, A survey on quantum channel capacities, IEEE Commun. Surv. Tutorials 20 (2) (2018) 1149–1205.

[62] W. Zhang, D.-S. Ding, Y.-B. Sheng, L. Zhou, B.-S. Shi, G.-C. Guo, Quantum secure direct communication with quantum memory, Phys. Rev. Lett. 118 (22) (2017), 220501.

[63] E. C. Strinati, S. Barbarossa, J. L. Gonzalez-Jimenez, D. Ktenas, N. Cassiau, C. Dehos, 6g: the Next Frontier, arXiv_Preprint arXiv:1901.03239.

[64] Z. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. Ding, X. Lei, G.K. Karagiannidis, P. Fan, 6g wireless networks: vision, requirements, architecture, and key technologies, IEEE Veh. Technol. Mag. 14 (3) (2019) 28–41.

[65] X. Ling, J. Wang, T. Bouchoucha, B.C. Levy, Z. Ding, Blockchain radio access network (b-ran): towards decentralized secure radio access paradigm, IEEE Access 7 (2019) 9714–9723.

[66] M.S. Islim, R.X. Ferreira, X. He, E. Xie, S. Videv, S. Viola, S. Watson, N. Bamiedakis, R.V. Penty, I.H. White, et al., Towards 10 gb/s orthogonal frequency division multiplexingbased visible light communication using a gan violet microled, Photon. Res. 5 (2) (2017) A35–A43.

[67] J. Luo, L. Fan, H. Li, Indoor positioning systems based on visible light communication: state of the art, IEEE Commun. Surv. Tutorials 19 (4) (2017) 2871–2893.

[68] Mehedi, Syed Agha Hassnain Mohsan Md, et al. "A Systematic Review on Practical Considerations, Recent Advances and Research Challenges in Underwater Optical Wireless Communication." (2020): 11-7.

[69] Mohsan, Syed Agha Hassnain, et al. "A Review on Research Challenges, Limitations and Practical Solutions for Underwater Wireless Power Transfer." environment 11.8 (2020).

[70] S. Elmeadawy, R.M. Shubair, 6g wireless communications: future technologies and research challenges, in: 2019 International Conference on Electrical and Computing Technologies and Applications (ICECTA), IEEE, 2019, pp. 1–5.

[71] R. Chen, C. Li, S. Yan, R. Malaney, J. Yuan, Physical layer security for ultra-reliable and low-latency communications, IEEE Wireless Commun. 26 (5) (2019) 6–11.

[72] J.M. Hamamreh, E. Basar, H. Arslan, Ofdm-subcarrier index selection for enhancing security and reliability of 5g urllc services, IEEE Access 5 (2017) 25863–25875.

[73] Yamakami, A privacy threat model in xr applications, in: International Conference on Emerging Internetworking, Data & Web Technologies, Springer, 2020, pp. 384–394.

[74] X. Chen, Y. Wang, M. Nakanishi, X. Gao, T.-P. Jung, S. Gao, High-speed spelling with a noninvasive brain–computer interface, Proc. Natl. Acad. Sci. Unit. States Am. 112 (44) (2015) E6058–E6067.

[75] P. McCullagh, G. Lightbody, J. Zygierewicz, W.G. Kernohan, Ethical challenges associated with the development and deployment of brain computer interface technology, Neuroethics 7 (2) (2014) 109–122.

[76] R.A. Ramadan, A.V. Vasilakos, Brain computer interface: control signals review, Neurocomputing 223 (2017) 26–44.

[77] Pramanik, Pijush Kanti Dutta, et al. "Advancing Modern Healthcare With Nanotechnology, Nanobiosensors, and Internet of Nano Things: Taxonomies, Applications, Architecture, and Challenges." IEEE Access 8 (2020): 65230-65266.

[78] Mohsan, Syed Agha Hassnain, et al. "Investigating Transmission Power Control Strategy for Underwater Wireless Sensor Networks."

[79] Mohsan, Syed Agha Hassnain, et al. "Impact of Circular Field in Underwater Wireless Sensor Networks."