International Journal For Advanced Research In Science & Technology
A peer reviewed international journal
www.ijarst.in
ISSN: 2457-0362

6G wireless networks: Vision, requirements, architecture, and key technologies

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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

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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

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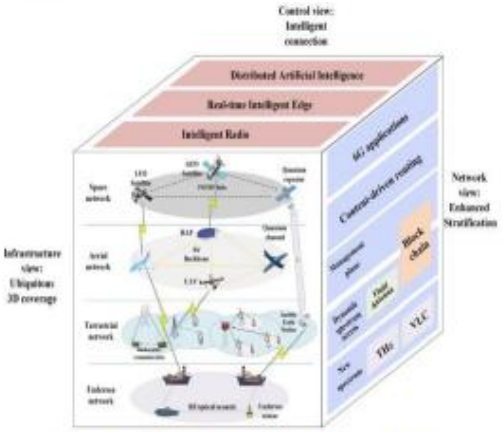

Fig. 1. Different Dimensions of 6G Architecture [17].

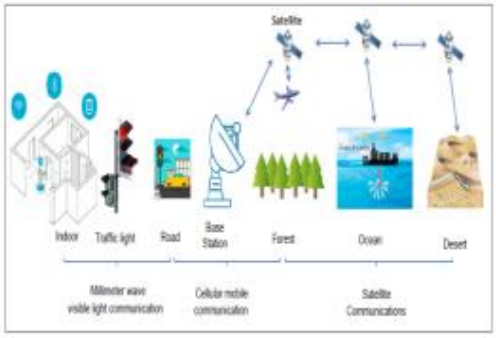

Fig. 2. An Overview 6G Network Coverage.

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

I. 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.

International Journal For Advanced Research In Science & Technology
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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

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started research projects to initiate, develop, define and reshape framework of 6G networks. Table IV summarizes country wise research initiatives in 6G networks.

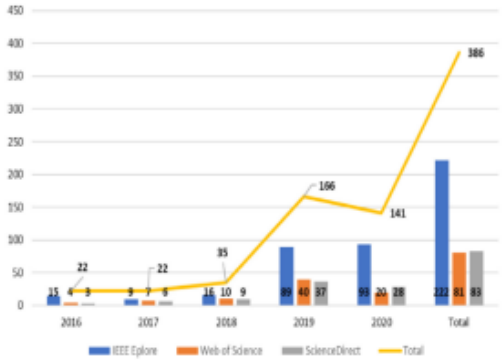

Fig. 3. A Trend of Publications on 6G [21].

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.

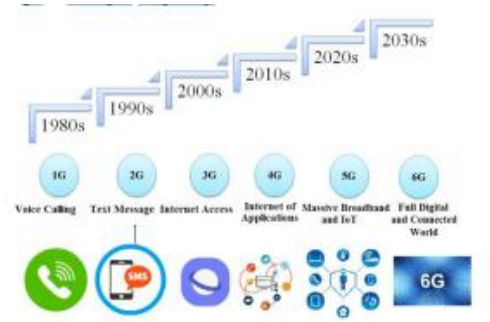

Fig. 4. An Overview of 1G-6G Devices nd the Corresponding Technology Breakdown.

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

International Journal For Advanced Research In Science & Technology
A peer reviewed international journal
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ISSN: 2457-0362

[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.

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.

Fig. 7. Applications Supported by 6G.

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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

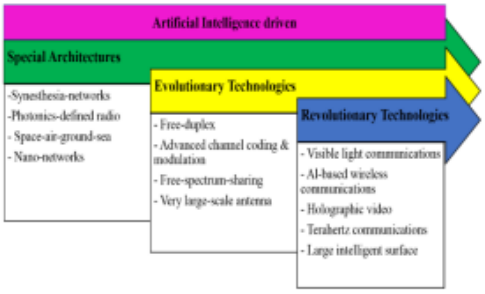

Fig. 8. Key Technologies of 6G Network.

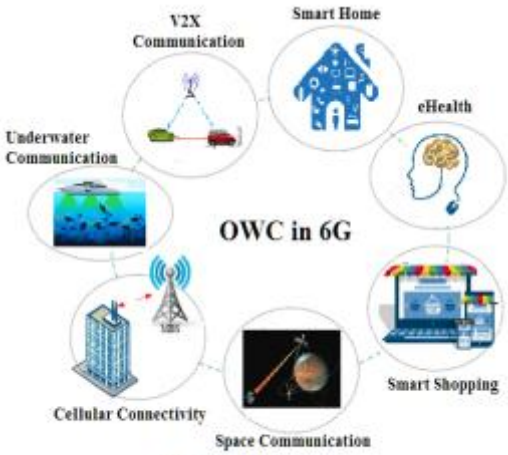

Fig. 9. OWC and 6G.

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 tradeoff 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.

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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.

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