6G Survey on Challenges, Requirements, Applications, Key Enabling Technologies, Use Cases, AI integration issues and Security aspects

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Abstract—The fifth-generation (5G) network is likely to bring in high data rates, more reliability, and low delays for mobile, personal and local area networks. Alongside the rapid growth of smart wireless sensing and communication technologies, data traffic has significantly risen, and existing 5G networks are not fully capable of supporting future massive data traffic in terms of services, storage, and processing. To meet the forthcoming challenges, the research community is investigating the Terahertzbased sixth-generation (6G) wireless network which is supposed to be offered for industrial usage in around 10 years. This is right time to explore and learn about various 6G aspects that will play a key role in successful execution and implementation of 6G networks in future. This survey provides a review on specification, requirements, applications, enabling technologies including disruptive and innovative, integration of 6G with advanced architectures and networks like software defined networks (SDN), network functions virtualization (NFV), cloud/fog computing etc, artificial intelligence (AI) oriented technologies, privacy and security issues and solutions, and potential futuristic use cases: virtual reality, smart healthcare and Industry 5.0. Furthermore, based on the conducted review, challenges and future research directions are highlighted to aid the deployment of 6G networks.

Index Terms—5G, 6G, artificial intelligence, automation,machine learning, security, massive connectivity, virtual reality, terahertz.

I. INTRODUCTION

6th generation (6G) networks are considered as a successor to 5G networks and will be capable of using higher frequencies than frequencies used by 5G networks, and also delivering significantly higher capacity and very low latency [30, 123]. One of the milestones of 6G is to provide one-microsecond transmission latency which will be 1,000 times faster than one millisecond available in 5G networks [77]. 6G networks

will improve the performance of different technological areas including location awareness, imaging, and telepresence, etc. 6G networks will also incorporate the machine learning and artificial intelligence (AI) technologies, and these technologies will make the 6G-autonomous systems. 6G is expected to provide high transmission rates of up to 1 terabyte per second (Tbps) using the Terahertz spectrum.

Such a level of network capacity with very low latency is exceptional and it will also increase the performance efficiency of some existing applications. Furthermore, the high frequencies in 6G networks will lead to a higher sampling rate which will increase the transmission quality of wireless devices. Figure 1 shows the THz spectrum with the range 100 GHz to 3 THz which is going to be used as 6G's spectrum.

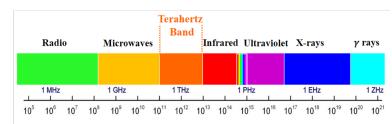


Fig. 1. TeraHertz Spectrum [121]

It is expected that 6G will be commercially available in 2030. The research and industrial efforts have already been started. The research activities for 6G networks are initiated under the International Mobile Telecommunications 2030 project [29]. China already initiated the project Broadband Communications and New Networks [61] for 2030. The European Commission Horizon 2020 program has funded various projects for 6G networks like TERRANOVA (Tb/s wireless

connectivity using THz band with the optical network) [18]. The Semiconductor Research Corporation in the United States funded a research project on future communication over THz band in cellular architecture [123]. The Federal Communications Commission (FCC) has begun investigating 6G networks using the THz band. Similarly, the International Telecommunication Union (ITU) has established a research group focusing on network requirements for the year 2030. Finland funded 6Genesis [28] and arranged the in 2019. Each of these research activities shows how important it is to explore beyond 5G to fulfill future quality of service (QoS) requirements [94].

Similar to the 5G which, is facing various deployment challenges, there will be many new challenges for 6G deployment as well. One of the prominent challenges is the development of commercial transceivers that operates on THz frequencies. The electronics and networking component providers need to play their role by introducing new innovative transceiver designs. It is expected that in the near future, trillions of sensors will be implanted into cities, homes, and industries, and these sensorbased systems will create a plethora of new applications, therefore, smart transceivers' design could play an important role to manage these huge sensor-based implementations.

This survey provides a comprehensive review of the various aspects of the 6G technology and the challenges in its adoption. We have explored major databases like ACM Digital Library, Science Direct, IEEE Xplore, and Scopus and have selected papers from well-known publishers such as IEEE Communications Surveys Tutorials, IEEE Access, IEEE Vehicular Technology Magazine, IEEE Transactions on Wireless Communications, and IEEE Sensors. We have searched for works related to 6G using the search term such requirements, use cases, advanced architectures, integration, SDN, IoT, big data, ML and security issues, etc. We have focused on recent articles which are published during the last decade and selected around 50 papers for our review.

We address four key areas for 6G: potential use cases, enabling technologies, AI technologies, and applications. Figure 2 presents the taxonomy of this survey. Potential use cases are further discussed in three aspects including virtual reality, smart healthcare, and Industry 5.0. Enabling technologies are sub-divided and discussed into three main categories: innovative architectures, disruptive, and intelligence integration. AI technologies are discussed in terms of big data, optimization of existing algorithms, and cases of intelligent communication. Various 6G-based applications with respect to challenges, security and privacy, and distributed ML are also discussed

at the end of this work. We review state-of-the-art works to address all these aspects of 6G networks and provide the user with a comprehensive overview of all the opportunities, challenges, and requirements of the 6G network. To ease the reading, a list of acronyms used throughout this paper is given in Table I.

The key contributions of this work are as follows:

- This work links the various technologies and architectures (such as Blockchain, Industry 5.0, augmented reality (AR), mixed reality (MR), virtual reality (VR), mmwave, Unmanned Aerial Vehicle (UAV), software-defined networks (SDN) and many more) with 6G networks by addressing their integration issues.
- Most of the previous surveys used only Yes or No for comparing different factors which hardly provides any details. Unlike the previous surveys, this work provides a fine-grained comparison like Low (L), Medium (M), High (H), and No (N) for different factors.
- This survey provides a detailed categorization of various 6G-related aspects. For instance, use cases are categorised into VR, health, and Industry 5.0, enabling technologies (disruptive and innovative), and AI (machine learning (ML) and big data, etc.).
- Suggestions for the integration of various technologies with 6G are provided in this survey.
- New 6G performance metrics are proposed which were previously ignored in the literature. These include Industry 5.0, big data, integration (6G and disruptive technologies), and security and privacy.

The remainder of this paper is structured as follows. Section II discusses the related work and Section III provides the background for communication technologies. Section IV describes the 6G key enabling technologies while Section V provides discussion on AI-enabled technologies for future 6G. Section VI presents the potential use cases of 6G technology. Section VII presents AI-based 6G applications. Section VIII discusses the challenges in 6G network and the future research directions. Section IX concludes this work.

II. RELATED WORK

There are several surveys in the literature which have reviewed the research work conducted in the area of 6G. These surveys have focused on different aspects of 6G technologies. This section provides an overview of some of the most recent surveys and also provides a comparison with our work.

The survey [95] discusses the 6G-based features and challenges for Cellular IoT which can connect enormous physical

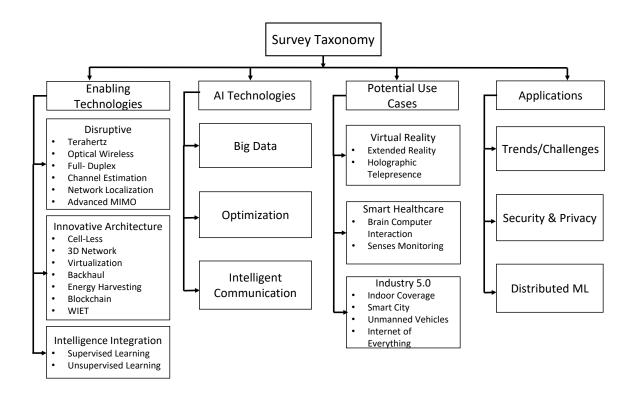


Fig. 2. Survey Taxonomy

and virtual objects to the Internet using cellular networks. These issues include delay and throughput provision for bandwidth-hungry applications like holographic communication etc. The survey also discusses various aspects of 6G networks like needs, requirements, applications, key performance indicators, and the potential key enabling technologies. However, it doesn't provide the details about security, ML/AI, and various potential use cases like industry 5.0.

The article [43] provides a comprehensive survey on 6G-enabled massive IoT. A detailed discussion is provided regarding the driving forces and requirements of the emerging IoT-enabled applications, alongside the constraints of 5G/6G. The authors also discussed the 6G core areas that can be linked with IoTs, these areas include technical requirements, use cases, and trends. The authors proposed an architecture of IoTs that is supposed to use 6G technologies, this architecture is called space—air-ground—underwater/sea networks and it's incorporated the ML mechanisms. The article lacks the 6G-related discussion about security, and also various use cases are ignored in the survey including VR, industry 5.0, big data, and health applications.

The article [110] discusses a vision of the recent paradigm shift of 6G wireless communication networks and provides performance evaluation metrics for such a network. The focus of the survey is to provide a comprehensive analysis of channel characteristics on various 5G and 6G frequency channels including mm-wave, terahertz, and optical wireless communication. These channel characteristics are discussed in application scenarios of satellite, UAV, maritime, and underwater. The future challenges of 6G channel measurements and models were pointed out; however, the article lacks details on 6G-based disruptive technologies. The article also ignored the security challenges on these channels which is a critical aspect of 6G networks.

The articles [81, 40] review the generations of mobile wireless technologies including requirements, advantages, and disadvantages. The authors focused on the channel modeling, especially the channel modeling options of the 6G networks. The cost-benefit analysis is also provided. However, the articles lack the discussion of the integration of the channel models with 6G networks.

Free space optical (FSO) [37] is an emerging technology for 6G networks and has the potential to resolve the bandwidth bottleneck. The authors discussed the issues caused by the fog's attenuation to FSO and they proposed an empirical prediction model to calculate its impact.

TABLE I
LIST OF ACRONYMS AND THE CORRESPONDING DEFINITIONS

Acronyms	Definition	Acronyms	Definition
1/2/3	First/Second/Third	Tbps	Terabyte per second
/4/5/6 G	/Fourth/Fifth/Sixth		
	Generation		
AI	Artificial Intelligence	THz	Tera Hertz
3GPP	3rd Generation Part-	GHz	Giga Hertz
	nership Project		
mmWave	millimeterWave	FCC	Federal Communica-
			tions Commission
QoS	Quality of Service	NMR	Nordic Mobile Radio
			System
GSM	Global System	SMS	Short Messaging Ser-
	for Mobile		vice
	Communication		
EDGE	Enhanced Data Rates	GPRS	General Packet Radio
	for GSM Evolution		Service
UMTS	Universal Mobile	CDMA	Code Division Multi-
	Telecommunication		ple Access
	System		
D2D	Device to Device	LTE	Long-Term Evolution
ML	Machine Learning	VR	Virtual Reality
MR	Mixed Reality	AR	Augmented Reality
UAV	Unmanned Aerial Ve-	eMBB	Enhanced Mobile
	hicle		Broadband
SDN	Software Defined	URLLC	Ultra-Reliable
	Network		low Latency
			Communications
FSO	Free Space Optical	IoT	Internet of Things
BCI	Brain Computer Inter-	IoE	Internet of Every
	action		Thing
HCI	Human Computer In-	M2M	Machine to Machine
	teraction		
DAS	Distributed Antenna	UGV	Unmanned Ground
	Systems		Vehicle
MIMO	Multiple-Input-	UUV	Unmanned Underwa-
	Multiple-Output		ter Vehicle
VLC	Visible Light Com-	RF	Radio Frequency
	munication		
NFV	Network Functions	WIET	Wireless Information
	Virtualization		and Energy Transfer

The goal of the survey [109] is to provide the state of UAVs and understand the telecommunications-related issues that need to be resolved. A schematic architecture is described along with the implementation proposed for UAVs. The author provides an analysis of aviation-specific Automatic dependent surveillance-broadcast (ADS-B) to 5G/6G cellular networks. The authors only discussed the fundamental requirements of 6G networks for UAVs; the detailed use cases and security aspects must be provided.

In this survey [12], the authors presented a framework for developing flexible radio access technologies (RATs) for 6G networks and their related requirements. The framework provides flexibility for the selection of RATs. This framework also highlights the inefficiency of the fixed waveform parameterization of 5G/6G numerologies. However, the article lacks a discussion about the security issues of RATs.

The survey [87] provides the evolution of wireless networks in terms of the 5G/6G heterogonous networks architecture along with its requirements and challenges. Further, the authors also discussed the integration of emerging 6G technologies including Software-Defined Networking (SDN) and Machine to Machine Communications (M2M) in the context of 5G/6G networks. However, the survey lacks a detailed discussion about the integration of these domains with 6G networks.

The authors in [89] gives a detailed survey on the Smart grid based on IoT frameworks. Various performance metrics are identified to evaluate such a framework, these metrics include delay, high throughput, power management, security, etc. The authors concluded that a lack of effort was being done to secure IoT-based frameworks and suggested that cyber security should be incorporated as a compulsory aspect of these systems in the future. The survey lacks the discussion about 6G applications, requirements, integration of IoTs with advanced network architectures, etc.

The survey [119] presents a detailed discussion on architectures and requirements of 6G networks. The authors evaluated the recommended architectures based on performance parameters including latency and throughput to check their suitability for 6G networks. The evaluation is done with various applications including senses like 3D video and sensitivity (touch, smell, texture, etc.). The authors concluded that 6G networks with mentioned applications required Super Ultra-Low Latency, High-Precision Latency, and ultra-delays.

The survey [70] discusses a comprehensive review of a cellular system in the context of software-defined 5G/6G networks. A detailed discussion is provided regarding application scenarios, challenges, and key technologies for 6G-based SDN. The authors also discussed the requirements of advanced sensors and monitoring technologies that will be used with upcoming 6G networks. Various important aspects of 6G networks are ignored like cyber security, industry 5.0, big data and ML, etc.

The survey [86] provides a detailed discussion of security and privacy aspects of the 6G networks by visualizing various use cases; however, the authors did not provide enough discussion for the ML, AI, key technologies, and industry 5.0.

The article [104] presents a survey on several ML techniques linked to networking, transmission, and security aspects

of the vehicular networks. The authors also visualize the ways of enabling AI toward a future 6G vehicular network, these visualized areas include intelligent radio (IR), network intelligence, self-learning with proactive exploration, etc. AI mechanisms will enable ultralow delay, better reliability, security, and high bandwidth.

This article [118] discusses the future trends in the evolution of ubiquitous connectivity in rural areas and linked the requirements to the 6G networks. The authors also discussed the application and requirement aspects of the 6G network; however, the article lacks a discussion about ML and security aspects.

Table II provides the comparison of the 6G's surveys. This comparison is conducted based on important and futuristic performances metrics, some of which (virtual reality (VR), health, machine learning (ML), architectures, trends, and disruptive technologies) are extracted from literature and some are proposed metrics from our side like integration, security and privacy, Industry 5.0, and Big data. It can be seen from Table II that most of the surveys lack in the areas like security, integration, Big data, and industry 5.0. Almost all of them discuss the ML, architectures, and challenges in detail. Our survey provides a detailed discussion of all these comparative metrics.

III. BACKGROUND, SPECIFICATION AND REQUIREMENTS

Before jumping to the 6G requirements, it is important to analyze the available generations. In the following section, we provide a brief revision of all the generations with their strengths and limitations. We also discuss the specifications and requirements for 6G networks.

A. Background of Communication Generations

Since the beginning of the first analog communication system in the early eighties, a new mobile communication generation has been launched after every ten years. In the following sections, we go through these generations and present their strengths and limitations.

1) First Generation: First Generation (1G) provided the service of voice calling with a large network coverage. A partial fax service was also introduced in 1G networks. 1G networks faced the issues like incompatibility of different market standards. For instance, at that time USA was using an advanced mobile phone system; whereas several European countries adopted the nordic mobile radio system (NMR). Both standards were incompatible with each other. Digital speech codecs were not introduced in the 1G era [102].

- 2) Second Generation: The global system for mobile communications (GSM) is considered the key standard of second-generation (2G). It began in Europe with a French name Groupe Speciale Mobile, and within years, GSM had around 90 percent of the market share. In GSM, newer voice codecs improved the voice quality. One of the key features of the GSM was the short messaging service (SMS). In addition, GSM also launched digital data services [99]. Initially, a data rate of 9.6 kb/s was achieved; later, the data rate was further improved to 200 kb/s with the launch of general packet radio service (GPRS) and enhanced data rates for GSM evolution (EDGE). 2G had various challenges that include low data rate, high cost, delay, etc.
- 3) Third Generation: Several European regulators agreed to establish a new approach to granting licenses by the mid and end of the 1990s. It was expensive to buy a spectrum from auctions in open markets. Even after the license was granted, no standard came out. However, after several years of license granting, the universal mobile telecommunication system (UMTS)-based cell phones came into the market. UMTS used code division multiple access (CDMA). Initially, UMTS provided the data rates up to 364 kb/s which was far less than the expected rate; however, in the later modifications, higher data rates were achieved. UMTS could not provide the expected performance due to bandwidth issues. Therefore, operators decided to move towards 4G long-term evolution (LTE) [88].
- 4) Fourth Generation: While working with UMTS, operators learned lessons and they were not fully confident to invest in the fourth generation (4G). Also, various technologies were introduced regarding spectrum efficiency which provided the flexibility for operators to select the appropriate option according to their requirements. Most of the LTE standards kept upgrading 3G UMTS to develop 4G communications. The LTE aimed at simplifying the existing UMTS architecture from circuit and packet switching to IP-based architecture. LTE provides up to 300 Mb/s and uploads data rates of up to 75 Mb/s. LTE offers low latency (up to 5 ms) with mobility support. It uses orthogonal frequency division multiple access (FDMA). Although, 4G provides solutions to several problems faced by 3G like low data rates and higher latency values; 4G faced other issues such as performance management for the rapid growth of the number of devices that required ubiquitous connectivity and higher data rates [54].
- 5) Fifth Generation: The fifth-generation (5G) is the new generation of cellular networks. According to the 3GPP project, if a device is using 5G new radio (5G NR) software,

TABLE II
SUMMARY OF EXISTING 6G SURVEYS

Comment	Year	Requirements	Use Cases	Enablers	<u>AI</u>	Technological	Security
Survey	Tear	Challenges	(VR, Health, Industry5.0)	(Disruptive, Innovative)	(ML, Architectures, Big data, Trends)	Integration	Privacy
[40]	2015	M	(N, H, N)	(L, L)	(L, M, M, H)	L	L
[81]	2015	M	(L, M, N)	(L, M)	(N, L, M, M)	L	L
[109]	2016	Н	(N,M,N)	(L, M)	(H, H, L, M)	M	L
[37]	2016	M	(N, M, N)	(L, L)	(M, L, N, L)	L	L
[87]	2017	M	(L, M, L)	(M, L)	(L, H, L, L)	N	L
[12]	2017	M	(L, M, L)	(L, L)	(H, M, L, M)	L	L
[119]	2018	L	(L, M, L)	(M, L)	(L, H, L, L)	N	L
[89]	2018	M	(L, M, L)	(L, L)	(H, M, L, M)	L	L
[70]	2019	L	(L, M, L)	(M, L)	(L, H, L, L)	N	L
[104]	2019	M	(L, M, L)	(L, L)	(H, M, L, M)	L	L
[118]	2020	L	(N,M,N)	(L, M)	(H, H, L, M)	M	L
[110]	2020	M	(N, M, N)	(L, M)	(M, L, N, L)	L	L
[95]	2021	Н	(L, H, N)	(L, M)	(H, M, M, H)	L	L
[43]	2021	L	(H. M, N)	(L, M)	(H, L, M, M)	L	L
Our survey	2022	Н	(H, H, H)	(H, H)	(H, H, H, H)	Н	Н

it is called a 5G device. 5G network is supposed to provide data rates of up to 20 Gb/s. The 5G technology promises to offer a latency between 1 to 5 ms. The speed of 5G in the sub-6GHz band will be greater than the 4G with a similar number of antennas and spectrum. Overall, 5G uses a high-frequency band (above 30 GHz). In recent years, mmWave appeared as one of the potential candidates for 5G by providing data rates in gigabits/sec. It uses a spectrum between 30 and 300 GHz and corresponds to wavelengths between 10mm to 1mm. The characteristics of mmW includes high bandwidth, shortwavelength/high frequency, and high attenuation [31]. Highpower levels are required to overcome the huge path loss, which is expected in mmW communications. The coverage is up to 20 meters at 60 GHz. IEEE 802.15.3c and IEEE 802.11ad standards provide the support of mmW. Moreover, 5G will deliver the services like device-to-device (D2D) connectivity and massive machine-to-machine communications, etc. 5G bands have several challenges including poor foliage penetration, atmospheric and free space path loss, and high deployment cost.

Table III shows a performance comparison for different generations of the communication systems.

B. Specifications and Requirements

There are several performance trade-offs in reliability, delay, throughput, and power consumption for 5G networks and these trade-offs give an impression that 5G could not fulfill the market challenges beyond 2030. The characteristics and features of 6G networks have the potential to overcome these challenges. The main features of 6G networks include high data rates, energy efficiency, reliability, and intelligent

TABLE III
PERFORMANCE COMPARISON AMONG 4G, 5G AND 6G

Characteristics	4G	5G	6G	
Device peak data	1Gbps	10-20 Gbps	1Tbps	
rate				
Latency	100 ms	5-10 ms	10-100 micro sec	
Maximum spec-	15 bps/Hz	30 bps/Hz	100 bps/Hz	
tral efficiency				
Mobility	350 Km/hr	500 km/h	up to 1000 km/h	
Network energy	1x	10-100 x of	10-100 x of 5G	
efficiency		4G		

decision-making per device as well as a whole network at the global scale. The 6G networks are supposed to provide services including enhanced mobile broadband (eMBB), ultra-reliable low latency communications (URLLC), massive machine-type communication (mMTC), and AI and machine learning integration. URLLC, promises to provide a delay of less than 1 ms [105]. Furthermore, the 6G system makes use of energy harvesting techniques so that ultra-lifetime could be provided to the devices.

For the satellite integrated network, 6G is expected to provide improved QoS for satellite communication. 6G aims to make a single wireless operating network by integrating the terrestrial and satellite networks. 6G will provide massive connectivity to wireless devices in the form of IoE; however, such huge connectivity creates challenges like quick processing and transmission delays. To cater to this, 6G will make use of extensive AI techniques at each phase of the communication including signaling, forwarding, and decision making [68].

Ubiquitous connectivity is considered one of the key re-

quirements for 6G networks. In a broader aspect, drones and the satellites in orbits will help to create super-3D connectivity for 6G to provide ubiquitous communication [68]. 5G successfully uses the small cell communication networks to improve QoS including throughput, energy, signal quality, and spectral efficiency; however, it lacks the integration of disciplines like AI, ML, and automation [23, 97, 75].

6G networks will incorporate the approach of small cell networks in a larger aspect. Due to massive device connectivity, the future 6G networks will be ultra-dense with heterogeneous connectivity characteristics.

In recent years, millimeter wave (mmW) appeared as one of the potential candidates for 5G by providing data rates up to gigabits/sec and it could be also useful for the initial implementation of 6G networks. It uses a spectrum between 30 and 300 GHz and corresponds to wavelengths between 10 mm to 1mm. The characteristics of mmW include high bandwidth, short-wavelength/high frequency, and high attenuation [69, 83]. Huge path loss is expected in mmW communications, to recover from these path losses, high power levels are required. Due to high attenuation from solid material (bricks and buildings), mmW requires line of sight (LoS) for efficient and reliable communication. The interference levels in mmW communication are much lower than the 2.4 GHz and 5 GHz. Multiple-antennas solutions in mmW allow the transmission to use narrow beams which help to reduce the attenuation and the interference [113, 58, 45]. There have been several standardization activities for mmW MAC in the 60 GHz band. Most of these standardization efforts are for personal and local area networks under IEEE 802.15.3c and IEEE 802.11ad. IEEE 802.15.3c standard also known as piconet specifies the mmW by supporting a high data rate over 2 Gbps in the 60 GHz band. Among a cluster of IEEE 802.15.3c-based devices, one will be selected as the piconet coordinator (PNC) which manages the synchronization among devices by broadcasting beacon messages. The devices content for the time slots using carrier sense multiple access/collision avoidance (CSMA/CA) and sending data using time division multiple access (TDMA) [108, 116]. The IEEE 802.11ad introduced several modifications at MAC and the physical layer of the existing IEEE 802.11 standard to enable mmW support. It claims to provide a 6.75 Gbps data rate. The coordinator uses a superframe structure to manage the channel access of the connected stations which is composed of beacons, contention access period (CAP) and contention-free period (CFP) [1, 4, 7, 3, 5].

It is important to understand the performance computation process for various technologies under the 6G network could be different and dependent on a specific technology. As an example, a discussion is provided regarding the performance evaluation of a 5th generation's medium access control (MAC) mechanism of the IEEE 802.15.3C standard in terms of end-to-end delay (ED) and maximum throughput (MT). The purpose is to understand how much time it takes for a CTA request in the worst-case scenario. The ED can be calculated as given in Equation (1) [6, 7, 2]:

$$ED = T_{frame} + T_{ACK} + T_{CH} \tag{1}$$

Where T_{frame} represents frame transmission time for a CTA request frame. Further, T_{frame} can be computed as given in Equation (2):

$$T_{frame} = T_{Preamble(PHY)} + T_{Header(MAC+PHY)} + T_{Payload} (2)$$

Where $T_{\rm Preamble}$ is the duration of PLCP preamble, $T_{\rm Header}$ is the duration of PLCP header and $T_{\rm Payload}$ is the duration of the payload. These durations are given in the IEEE 802.15.3C standard.

 T_{ACK} represents the time duration of the ACK, in this case, ACK duration computed as given in Equation (3):

$$T_{ACK} = T_{ImmACK} + 2SIFS \tag{3}$$

Where $T_{\rm ImmACK}$ is time duration of the immediate ACK and can be computed as given in Equation (4):

$$T_{ImmACK} = T_{Preamble} + T_{Header} \tag{4}$$

The ACK of the ImmACK has only MAC header and not a payload as each packet is expected to be acknowledged immediately. $T_{\rm CH}$ represents the time to access the channel, which is computed as given in Equation (5):

$$T_{CH} = (RC * BIFS) + (BC * pBackoffSlot)$$
 (5)

Where RC is the retry counter in the backoff process and its value will be 3 in the worst case as default, BIFS is the backoff IFS and it is calculated by Equation (6):

$$BIFS = pSifsTime + pCcaDetectTime$$
 (6)

The values of pSifsTime and pCcaDetectTime are given in the Table I mentioned by the in the IEEE 802.15.3C standard. BC is the backoff counter calculated as given in Equation (7):

$$BC = Rand(0, BW) \tag{7}$$

BC is computed using a random function that finds a random integer value between zero and BW (backoff window). The value of BW is given in Table IV.

TABLE IV
TIMING AND SPACE PARAMETERS MENTIONED BY IEEE 802.15.3C
STANDARD [107]

PHY Parameter	Duration HSI (μs)	
pSIFSTime	2.5	
pCcaDetectTime	2.5	
pBackoffSlot	5	
T_Preamble	1.31	
T_Header	0.44	
Backoff Windows	[7, 15, 31, 63]	
Retry Count	0 to 3 0 to 65,535	
CAP duration (µs)		
Superframe duration (µs)	0 to 65,535	
MAC header (bytes)	10	
PHY header (bytes)	48	
Acknowledgement (bytes)	10	
Beacon packet (bytes)	100	
Data frame (bytes)	512 to 8,388,608	
Channel data rate (Gbps)	1.5, 3, 5	

The maximum throughput (MT) is defined as a ratio of transmitted information in bits to the transmission duration. Throughput is defined as the ratio of payload size (x) to the total time required to transmit the payload, in the case when there is no priority set the maximum network throughput can be computed as given in Equation (8):

$$MT = X/ED \tag{8}$$

In this regard, multi-tier network architecture will help to manage these ultra-dense networks in 6G. To manage the huge traffic in 6G networks, high-capacity backhaul networks are required [8]. This can be possible by using free-space optical (FSO) systems and a fast optical fiber network. Overall, 6G wireless networks will be able to:

- Provide super-high-definition (SHD) and extremely highdefinition (EHD) video transmission which requires ultrahigh throughput.
- Support extremely low latency up to 10 micro-second.
- Manage the Internet of Nano-Things and Internet of Bodies using smart implantable and wearable devices under very low power consumption.
- Enable efficient underwater and space transmissions to drastically increase the limits of human activity, for example, deep-sea exploration and space traveling.
- Support various advanced service practices like hyperhigh-speed railway (HSR).

- Improve 5G applications, like the huge Internet of Things (IoT) and entirely autonomous vehicles.
- Support enhanced mobile broadband communications, ultra-huge machine-type communications, enhanced ultra-reliable and low-latency communications, and long-distance and high mobility communications.

IV. 6G ENABLING TECHNOLOGIES

This section describes the technological enablers that are supposed to provide the 6G revolution. These key enablers will justify the migration from 5G to 6G networks. We discuss various technologies including Terahertz (THz), optical wireless technology, full-duplex communication, channel estimation techniques, network localization, MIMO, 3D network architecture, network virtualization, FSO, energy harvesting techniques, blockchain, WIET, and supervised and unsupervised learning [57, 64, 41, 11, 93, 112, 8, 106, 100, 42, 33, 10]. Based on technological characteristics, we categorize enabling technologies into three main categories: *disruptive, innovative, and intelligence integration*. We discuss these technologies in the following sections.

A. Disruptive Communication Technologies

Communication technologies like multiple-input-multiple-output (MIMO) and mmWave are considered key enablers of 5G networks and provide required QoS. To meet the requirements of 6G networks, 6G will exploit the unused terahertz band and visible light communications (VLC).

1) Terahertz Communications: The radio frequency (RF) band is nearly exhausted and not enough to fulfill the 6G requirements. Spectral efficiency can be enhanced by expanding the bandwidth, which can be achieved by applying THz bands and massive MIMO technologies. The THz band will play an important role in 6G communication [106]. The THz band is intended to be the next frontier of high-datarate communications. THz communications use the frequency bands between 100 GHz and 10 THz with wavelengths in the 0.03 mm - 3 mm range. ITU-R recommends 275 GHz - 3 THz bands for the communication of cellular networks [100]. In comparison with mmWave, THz faces challenges due to ultrahigh frequencies. The main challenges that are hurdles for terahertz's commercial adoption are the propagation loss, the molecular absorption at a higher frequency, the high penetration loss for solid objects, and, the antenna design complexity. In mmWave, the propagation loss can be controlled using the directional antenna arrays mechanism. However, some of the frequencies in the terahertz spectrum are more sensitive to atmospheric molecular absorption. This issue can be avoided by only using selected frequencies band in Terahertz spectrum [57].

- 2) Optical Wireless Technology: Optical wireless technology (OWC) is considered a key enabler for 6G communications; however, it is already being used partially in 4G/5G networks. Main OWC technologies include light fidelity, optical camera communication, VLC, and FSO communication [22, 21, 49, 50]. Networks with OWC technologies have the potential to provide ultra-throughput and very low latency. VLC is proposed to support RF communications using the light-emitting diode (LED) luminaries. These devices can switch among various light intensities to modulate the signal. The research activities on VLC are more progressive than the terahertz communications. Although, the IEEE 802.15.7 standard is proposed for VLC, yet not been adopted by 3GPP. VLC has a short-range, requires an illumination source for communication, and is also sensitive to the noise created by any light source including the sun [64]. Due to these reasons, it is mostly recommended for indoor environments.
- 3) Full-Duplex Communication: Recently, cellular networks are adopting full-duplex solutions which will make the base station's transceiver capable of transmitting a signal while receiving within a limited range, such design is achievable using innovative design of self-interference suppression circuits [41]. The main innovation is being achieved by improving the design of the antenna and circuit which reduces the cross-talk between receiver and transmitter for a wireless device [44].

In future, technological advancement will be capable of simultaneous transmission and reception. Such advancements enhance the multiplexing capabilities of the existing cellular systems in terms of throughput. 6G network could be very useful for such a full-duplex network in terms of performance requirements.

- 4) Novel Channel Estimation Techniques: For cellular networks, channel estimation for beam tracking is considered an important element for ultra-high frequencies. Therefore, advanced channel estimation techniques will be highly beneficial in cellular networks. If we talk about mmWave, design challenges exist for channel estimation techniques due to complex antenna architectures. A recent research effort is made to provide channel estimation for mmWave, known as out-of-band estimation, which provides an improvement in the reactiveness of beam management schemes [11].
- 5) Sensing and Network-Based Localization: Techniques based on RF signals have been broadly used to empower concurrent operation of localization and mapping techniques

- [120]. However, it is still not adopted for the case of cellular networks. In this regard, 6G will provide an integrated interface to support localization and mapping mechanisms which will offer multiple advantages including enhancement in control operations, less interference and novel services for applications like eHealth.
- 6) Advanced Multiple-Input-Multiple-Output: Multiple antenna technologies have achieved considerable response from both academia and industry as they are capable of providing high geographical coverage and spatial multiplexing which helps to boost spectral efficiency [39, 15] and could be very useful to achieve the performance goals of 6G networks. Therefore MIMO is a potential area that can integrate itself with 6G networks which will increase the capability of 6G network devices in terms of transmission.

B. Innovative Network Architectures

6G network offers various innovations to the existing communication architecture e.g., virtualization. In this section, we will discuss some of the promising architectural domains.

- 1) Cell-Less Architecture and Tight Integration of Multiple Frequencies: The 6G network will create a strong relationship between cells and the user equipment (UEs) and will create cell-less architecture. This can be accomplished using dual-band techniques with multiple radios. Such architectures provide high mobility support with fewer overheads. It will increase the user capacity by seamlessly transitioning to multiple heterogeneous links (e.g., to identify the best channel) without any prior configurations.
- 2) 3D Network Architecture: 6G networks will support three-dimensional (3D) visualisation by using heterogeneous architecture. Communication technologies like drones and satellites will use these architectures to improve related QoS. Furthermore, these heterogeneous communication architectures could be easily deployed in rural and disaster areas [117].
- 3) Virtualization of Networking Equipment: In 6G networks, network virtualization will be one of the key concepts. The virtualization will be implemented at different layers i.e., network layer, MAC layer, and physical layer. It will reduce the management burden from hardware devices in a cost-effective way. It will create a centralized virtual controller which will be responsible for the policy and data forwarding [9].
- 4) Advanced Access-Backhaul Network (FSO) Integration: In 6G networks, technologies are supposed to provide ultrahigh data rates which also require sufficient expansion of backhaul capacity. Furthermore, future VLC and terahertz

implementations will use a massive number of devices, which need backhaul connectivity with the core network and neighbouring nodes [93].

In some cases, such as, at remote geographical locations (e.g., sea, space and underwater), it is not feasible to deploy optical fibre as a backhaul network. For such scenarios, the FSO backhaul network is a potential communication system for 6G networks [42, 33, 16]. FSO performs like an optical fibre network and provides similar communication services. FSO can provide a large communication range, even greater than 10,000 km. Figure 3 shows an example of an integrated backhaul link.

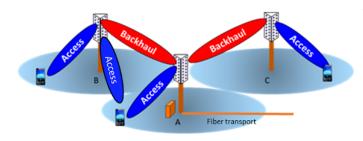


Fig. 3. Integrated backhaul link [32]

5) Energy Harvesting Strategies for Low-Power Consumption Network: Energy/power harvesting is defined as the process by which energy is extracted from external resources including solar, thermal, wind, and kinetic energy, etc., and then preserved for wireless autonomous devices, like wearable biomedical monitoring sensors. The energy harvesting process is capable of producing a small amount of energy which is an ongoing challenge for the industry. One of the oldest applications of energy derived from ambient electromagnetic radiation (EMR) is known as crystal radio [85].

5G networks do consider energy harvesting techniques; however, not much work is done on that due to a lack of interest from manufacturers. As 6G networks deal with a massive number of interconnected smart devices (e.g., IoT devices) that require energy resources to keep the device alive. There is a need to identify the suitable energy-efficient mechanisms for such devices [112].

6) Blockchain: Blockchain manages huge datasets in an efficient way [46, 14, 80]. Blockchain works using the approach of distributed ledger technology. A distributed ledger's database operates in a distributed manner by using various nodes. Every node replicates a copy of the ledger. The nodes can work independently without involving the centralized node. In the blockchain, the data is managed in the form

of blocks that are connected securely. The blockchain can manage huge data involved in IoTs-based systems [26]. Hence, 6G capabilities will support blockchain-based applications in terms of their performance goal.

7) Integration of Wireless Information and Energy Transfer (WIET): Recently, producing energy from the open environment is one of the potential areas which can help to increase the lifetime of battery-operated wireless sensor devices. WIET is recognized as one of the innovative technologies for 6G networks. WIET also utilizes the wireless spectrum for communication. WEIT can be very useful for battery-less devices which are supposed to operate in 6G networks. The base stations in 6G will be used for transferring power as Wireless Information and Energy Transfer (WIET) uses the same fields and waves used in communication systems. WIET is an innovative technology that will allow the development of battery-less smart devices, charging wireless networks, and saving the battery life-time of other devices [35, 111].

C. Integrating Intelligence in the Network

The 6G network complexity in terms of architecture and data demands AI and machine learning techniques to play their role in the successful execution of 6G services. Although 6G does not specify specific techniques, more likely AI based on a data-driven model could be used for the successful deployment of 6G networks [112]. Currently, 5G networks only integrate partial AI and ML techniques while it is expected that in 6G networks AI and ML will be fully integrated with 6G networks like the concept of Industry 5.0.

1) Unsupervised and Reinforcement Learning: Unsupervised and reinforcement learning techniques could be used as a potential learning technique in 6G networks. In 6G networks, a massive amount of data will generate and it will not be an easy task to assign labels as required in supervised learning; whereas, unsupervised learning does not require such labeling and is capable of representing a learning model for such data. Furthermore, unsupervised learning in a combination with reinforcement learning could produce efficient autonomous systems [68].

D. Summary

Table V provides a comparison of 4G, 5G, and 6G technologies in terms of the usage scenarios, applications, network characteristics, and technologies. In 4G networks, a simple implementation of MBB was available which evolved into eMBB and provides better mobile broadband. 5G networks also support eMBB, mMTC, and URLLC and it is expected

TABLE V
NETWORK FEATURES OF 4G, 5G AND 6G

	4G	5G	6G
Usage Scenarios	• MBB	• eMBB	• umMTC
		• URLLC	• ERLLC
		• mMTC	• ELPCs
			• LDHMC
			• FeMBB
Applications	High-Definition Videos	VR/AR/360° Videos	• umMTC
	Voice	UHD Videos	Holographic Verticals and Society,
	Mobile TV	• V2X	Tactile/Haptic Internet
	Mobile Internet	• IoT	Full-Sensory Digital Sensing and Re-
	Mobile Pay	Smart City	ality, Fully Automated Driving
		Telemedicine	Industrial Internet, Space Travel
		Wearable Devices	Deep-Sea Sightseeing
			Internet of Bio-Nano-Things
Network Characteristics	Flat and All-IP based	Intelligence integration	Cloudization
		Clouds architecture	Softwarization
		Software virtualization	Virtualization
		Slicing	Slicing
Technologies	• OFDM	mm-wave Communications	THz Communications
	• MIMO	Massive MIMO	• SM-MIMO
	Turbo Code	LDPC and Polar Codes	LIS and HBF
	Carrier Aggregation	Flexible Frame Structure	OAM Multiplexing
	Hetnet	Ultradense Networks	Laser and VLC
	• ICIC	NOMA	Blockchain-Based Spectrum Sharing
	D2D Communications	Cloud Computing	Quantum Communications and Com-
	Unlicensed Spectrum	Fog/Edge Computing	puting
		SDN/NFV	AI/Machine Learning

that these technologies with further enhanced like umMTC and ERLLC will support enhanced low latency and massive machine to machine communication. The use of ERLLC, umMTC, and FeMBB 6G will support innovative applications like Holographic verticals, Internet of bio-Nano-Things and deep-sea sightseeing, etc. A huge shift in technologies can also be seen among 4G, 5G, and 6G networks. 4G mainly used OFDM and MIMO; 5G uses mm-wave and massive MIMO, and 6G will use THz band and SM-MIMO, etc. to achieve its goal in terms of delay and throughput.

V. AI-ENABLED TECHNOLOGIES FOR 6G WIRELESS NETWORKS

The rapid advancement of wireless networks will make 6G significantly distinct from the earlier generations, as it will be exemplified by a high level of heterogeneity in several aspects including network infrastructures, network access mechanisms, dual-band devices, processing resources, etc. Furthermore, the size of the massive data generated in wireless networks is rising substantially. In this section, we promote AI as an essential tool to expedite intelligent decision-making and learning for 6G wireless networks [59]. We discuss and review

different works which addressed these issues [16, 39, 15, 46, 73, 79, 59, 22, 21, 49, 50, 42, 34, 17].

A. Big Data Analytics for 6G

For 6G wireless networks, there are four main categories of data analytics that can be potentially applied. These categories include descriptive, diagnostic, predictive, and prescriptive analytics. Descriptive analytics uses historical data sets to obtain perceptions performance indicators including traffic profiles, channel states, user viewpoints, etc. Descriptive analysis helps to extend the familiarity of the network operators [71, 76, 92]. Diagnostic analytics is used for the identification of network failures with the potential reason of failure or fault so that future systems can be improved. Predictive analytics closely observes the data pattern in historical data and predicts future behavior and predictions. Predictive analytics are tied with machine learning techniques to get optimal results. Prescriptive analytics helps to improve various domains in learning including resource allocation, network virtualization, cache management, edge, fog computing, etc [79].

B. AI-Enabled Closed-Loop Optimization

Existing optimization mechanisms for wireless networks are considered to be inappropriate for 6G wireless networks due to various characteristics of 6G including dynamicity, complexity, the massive density of devices, and heterogeneity. Furthermore, existing mathematical optimization techniques have shortcomings for such massive 6G networks. For example, the objective functions in the algebraic form help optimizers and make a simple solution; however, 6G wireless networks have different scenarios, and these solutions are not suitable. One of the potential AI mechanisms is an automated and closed loop that can be used for 6G wireless networks. In this regard, current AI mechanisms, like reinforcement and deep reinforcement learning (DRL) can be used, which can establish a feedback loop between the decision process and the wireless network system. By using this approach, the decisionmaking process will make the best decision based on current situation [73].

C. Self-healing in Wireless Networks

Advanced AI technologies could be useful to optimize the physical layer's performance of wireless networks. The existing wireless systems have various physical layer issues including noise, channel and hardware impairments, quadrature imbalance, interference, and fading. AI technologies can provide an optimal way to communicate among different hardware. In the future, AI is supposed to provide self-healing and self-optimizing mechanisms for sensor-based 6G networks [90].

D. Summary

It is expected that in 6G networks, a fully ML and AI-enabled network will be in operation. That's why it is very important to provide a detailed analysis of upcoming network architectures with their requirement in terms of AI. Table VI shows the link between various existing and future network architectures and related AI algorithms. SDN, NFV, and Cloud/fog/edge computing are considered potential network architectures that will use a fully AI-based environment to support 6G networks. Currently, these architectures partially support AI and ML aspects.

VI. 6G POTENTIAL USE CASES

6G network acts as a successor to the 5G cellular network. 6G networks will operate on higher frequencies than the 5G networks to provide higher bandwidth (in terabytes) and ultra-low latency (in microseconds). It is expected that 6G technology will bring a huge performance improvement for various existing communication technologies. For example, it is estimated that cellular data will expand 3-fold from 2016 to 2021 and there will be more than 125 billion connected cellular users globally by 2030 [30].

This section discusses the characteristics and requirements of some potential use cases of 6G networks. There are many research works that discuss the potential use cases for 6G technology [117, 121, 84, 67, 114, 120, 72, 20, 53, 31, 101, 98, 56, 13, 55, 91, 27, 118, 110, 10]. Based on the technology used, we categorize the potential use cases into three broader categories: VR, health, and Industry 5.0 as shown in Figure 2. These categories have various sub-categories which are discussed in this section.

A. Virtual Reality (VR)

VR can be further divided into the following two categories: 1) Extended Reality (XR): XR is a broader term that includes technologies to enhance our senses [24]. It mainly includes augmented reality (AR), mixed reality (MR), and virtual reality (VR). AR, MR, and VR over wireless links have been emerging as the potential future applications targeting various areas such as education, training, entertainment, tourism, sport, and gaming.

AR takes a real-world environment and adds a computer-based input to the environment. Hence, AR is a collaborative activity where real-world environment experience is obtained. The environment is built of enhanced objects and these objects are available in a real-world environment. AR technology makes use of the various sensors to experience the modalities like visual, haptic, olfactory, motion, and somatosensory. AR consists of three basic features: 3D visualization of objects, real-time collaboration, and a mixture of virtual and real-world environments [25].

Figure 4 shows the AR-based user interface for the mobile applications of IKEA, where customers can try various options according to their real-world environment. For example, in a dulux-based AR application, a customer can apply different colors in his real home environment, and in an IKEA application, a customer can try various furniture in a real home environment. Furthermore, these applications also handle the measurement and size issues where you need to deploy the furniture.

VR provides a purely virtual environment without considering user surroundings. VR-based devices such as HTC Vive and Google Cardboard provide users with a completely imaginary environment such as a squawking penguin colony

TABLE VI NETWORK ARCHITECTURES AND AI ALGORITHMS

Network Functions	Descriptions	AI Algorithms
Software Defined Networks (SDN)	In SDN, the control and data-forward func-	• DNN
	tion are decoupled to achieve programmable	Enhanced Q-Learning
	network management and configuration	Support Vector Machines
		Self-Organizing Maps
		Biological Danger Theory
		Gradient-Boosted Regression
		Deep Reinforcement Learning
Network functions virtualization	In NFV, hardware is decoupled from Soft-	Self-Organizing Maps
(NFV)	ware and reduce the dependency of network	Biological Danger Theory
	functions over hardware	Gradient-Boosted Regression
		Deep Reinforcement Learning
Cloud/Fog/Edge Computing	Cloud computing represents a large pool of	Enhanced Q-Learning
	servers and systems which Provides data	Support Vector Machines
	access and use networks of shared IT archi-	Self-Organizing Maps
	tecture. Fog computing extends the edge of	Biological Danger Theory
	the network and enhances the operation of	Gradient-Boosted Regression
	computing, resources, and services between	Deep Reinforcement Learning
	end devices and data centers over cloud ar-	
	chitectures. Edge computing brings process-	
	ing near to the data centers which improve	
	the performance of data transmission.	



Fig. 4. IKEA AR-based applications for customers [17]

with dragons. MR combines the characteristics of VR and AR. MR technology has started to take off with Microsoft's HoloLens, one of the most famous mixed reality apparatuses [115].

These applications process exceptional QoS challenges including quality of experience, latency, and capacity/user. To achieve this, technologies like fog and cloud computing will help to act as computing and intelligence layer for AR/VR applications. 4G has been proven as a key enabling technology for data-hungry applications like video-over-wireless. Later, the high use of these multimedia applications was managed by 5G using the mmW spectrum. The mmW spectrum attracted more data-intensive applications like AR, VR, and MR. It is expected that in the coming years, the 5G spectrum will

be depleted due to the increasing use of these data-intensive applications as they demand system capacity up to 1 Tbps [47]. One of the reasons for high system capacity is that the data used in AR/VR/MR-based applications cannot be compressed as it is presenting real-time interaction. Furthermore, managing real-time user interaction with AR/VR/MR-based data-intensive applications requires a delay in micro-second.

2) Holographic Telepresence: Holographic telepresence is a growing technology for fully interactive 3D video conferencing. Holographic telepresence systems are capable to present real-time, full-motion-based 3D images of people and objects in a room. It also accommodates real-time audio and associates it with a particular 3D image of a person. Images of people and surrounding objects at a remote location are initially captured, then compressed and transmitted over a broadband network. At the destination, the data is decompressed and similarly projected through laser beams as a conventional hologram is produced. Holographic telepresence is capable of revolutionizing various types of communications. For example, telepresence in teleoperation can allow medical specialists to engage in real-time complex operations from thousands of miles away. Furthermore, this technology can also reduce the travel requirement for personal and business meetings. Distance learning using telepresence can shape the future of universities and colleges. Other prominent examples include

programmed movies, entertaining games, 3D navigation applications, etc. The applications mentioned above like a 3D holographic display require a set of high-level QoS requirements. According to a study, [17], a raw uncompressed hologram having colors, and parallax, with 30 fps requires a data rate of up to 4.32 Tbps with a strictly bounded delay of a few milliseconds. 3D holographic requires such a high data rate due to the requirement of thousands of synchronized angles. 6G network is capable of providing such high throughput and less delay required by these applications. Furthermore, an acceptable visual quality at the remote site is a challenging task.

B. Smart Healthcare

The key healthcare challenges for the world's population include the increasing rate of the elderly population, the increase in healthcare cost, and the high death rate because of chronic diseases [2, 19]. In counties like the United States, Germany, United Kingdom, France, Switzerland, Japan, and Australia, the life expectancy has inclined to 79.3 years, 81 years, 81.2 years, 82.4 years, 83.4 years, 83.7 years, and, 82.8 years respectively. It is expected that a high growth rate will overload the performance of existing healthcare systems and the healthcare cost will also increase. Furthermore, a large number of the population dies from fatal and chronic diseases like blood pressure, cardiovascular, diabetes, and asthma. Research efforts revealed that the effect of these diseases can be controlled if they could be identified in the initial stage. To achieve this, future healthcare systems should be revolutionized using digital and communication technologies so that proactive wellness could be provided through early detection and monitoring services. It is estimated that the need for remote healthcare monitoring services will reach 761 million in 2025 [66, 122].

These services will extend from monitoring to telemedicine solutions like remote real-time surgery etc. The existing 5G spectrum has started its role in remote healthcare; however, the use cases like remote surgeries, intensive health monitoring in an elderly care center where each person is equipped with enormous biomedical sensors, and remote healthcare for thousands of soldiers in battle-fields require ubiquitous health monitoring with high data rates in Gbps and Tbps, and ultralow throughput to accommodate real-time solutions. In this context, 6G networks are capable to revolutionize remote healthcare by reducing time and space obstructions [121]. 6G's technological enhancements will showcase the eHealth

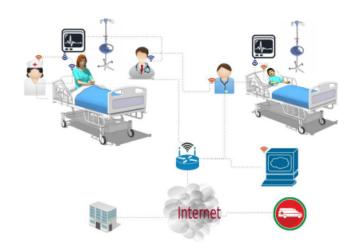


Fig. 5. Remote patient monitoring in a hospital

applications using technological revolutions like mobile edge computing, AI, fog, and cloud computing.

Figure 5 shows a typical remote patient monitoring system for hospitals where patients, nurses, and medical devices are equipped with various healthcare sensors, and the monitoring data is sent to the Internet and cloud computing architectures for further processing. The doctors can see the different results online and can monitor and diagnose the patients in real-time from any remote location.

1) Brain-Computer Interaction: A brain-computer interface (BCI) is a communication pathway between a sensor-equipped and an external device. The main objectives of BCIs include repairing human cognitive or sensory-motor functions [107, 53]. The sensors collect the brain signals and send them to a digital device for analysis.

Research on BCIs started at the University of California, Los Angeles (UCLA) in the early 1970s, under research funding from the National Science Foundation. Recent studies in the area of Human-Computer Interaction (HCI) show that machine learning algorithms can play a key role in successfully extracting features from the frontal lobe and then classifying mental states (Normal, Neutral, focused) and emotional states (Good/bad mood) using EEG generated brain-data [107, 53]. Such communication requires ultra-reliable communication with very low delay, values in microseconds. The characteristics of 6G architecture will support the deployment of BCI systems.

2) Human Senses-Based Applications: Humans have five basic senses: hearing, vision, taste, smell, and touch. In the future, applications will be available that will be capable of transferring human senses data to a remote location for processing. Such applications use sensor-based technologies which make use of neurological methods. It requires ultra-low delay and high throughput. The 6G networks can provide such services [30, 95].

C. Industry 5.0

Industry 5.0 or the Fourth Industrial Revolution, is the recent revolution of traditional manufacturing using smart technology. Technically, it mainly emphasizes the usage of large-scale machine-to-machine communication (M2M) with the help of Internet of Things (IoT) architectures and deployments to obtain automation [98]. Industry 5.0 will make the machine's components capable to perform self-diagnostic and predicting any possible future issues using AI algorithms so that any future failure could be avoided. Such decisions constitute the first steps of the Industry 5.0 era, where machines will make autonomous decisions and these decisions will have significant effects on people's lives. High achievements obtained in many areas with AI algorithms are the basis of these developments in the industry.

Furthermore, machine components should be capable of communicating with the other components and other machines. Predictive maintenance, IoTs, smart sensors, and 3D printers are the main key enablers for Industry 5.0. 6G technology will further promote the Industry 5.0 concept which was initiated with 5G. Industry 5.0 introduced the idea of the digital transformation of manufacturing through cyber-physical systems (CPS), which opens the gates between physical factories and virtual computation. Such a combination will promote new emerging technologies like M2M communications in a cost-effective way [98]. Efficient automation systems in terms of asynchronous communication are considered key enablers of Industry 5.0, in this regard, 6G is proposing the use of terahertz domains to provide the required QoS for smart integrated systems. Figure 6 shows the evolution of Industry 5.0.

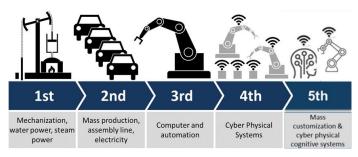


Fig. 6. Automation under Industry 5.0 [51]

- 1) Indoor Coverage: The 5G infrastructure usually operates under the milimeterWave spectrum (60 GHz) for indoor scenarios; however, it faces issues like penetration in solid materials. 5G also proposed the use of distributed antenna systems (DASs) for indoor environments which poses issues like scalability and deployment. 6G focuses on cost-efficient solutions for indoor communication scenarios using ultra-high capacity wireless relays with the visible light spectrum [84].
- 2) Smart City: A smart city can be defined as an urban area equipped with various types of sensors that collect data and then perform analysis of the collected data to manage and improve the infrastructure, services, and quality of life. The collected data may belong to various resources including citizens, installed devices, and buildings. The embedded data analytical capabilities help to manage traffic systems, power plants, schools, libraries, hospitals, water supply networks, waste handling, crime detection, etc [62].

5G technologies act as a key enabler for a smart city; however, 5G only made the city partially smart which means that inside a city, only the fragments (traffic management, water management, electricity, etc.) are individually smart but not holistically as a smart city. 6G technologies have the potential to speed up the adoption of smart cities by offering required QoS using innovative and disruptive communication technologies [120].

6G will provide support for user-centric M2M transmissions to further improve the deployment of smart cities. Furthermore, to provide a long battery life for the devices in smart cities, energy harvesting approaches will be used, though, 5G initially promised to adopt energy harvesting solutions but still, it is not being adopted.

3) Unmanned Vehicular Mobility: Unmanned vehicular mobility refers to vehicular mobility without a driver/pilot on board. These vehicles can be controlled remotely and they are capable of operating and navigating autonomously by sensing their environment. There are different types of unmanned vehicles including Unmanned ground vehicles (UGV) like cars and combat vehicles, Unmanned aerial vehicles (UAV) such as drones and autonomous spaceport drone ships, and unmanned underwater vehicles (UUV) and driver-less trains.

The locomotive industry is precipitously advancing towards fully autonomous transport systems which will ease the management burden on the organization [72]. Connected and autonomous vehicles (CAVs) are one of the potential use cases for future unmanned mobility. However, its deployment is still challenging in terms of time-bounded services and high mobility (up to 1000 Km/h). Further, it is estimated that vehicles

will be fitted out with a high number of sensors (greater than 200 per vehicle by 2020) which can be only served with terahertz spectrum [20]. Figure 7 shows a self-driving car example in Australia with all embedded features and requirements. Moreover, flying vehicles like drones indicate a massive potential for several use cases: industrial construction, agriculture sector, and entertainment. 6G can provide services for such massive data-hungry use cases.



Fig. 7. An unmanned car with numerous sensors [60]

4) Internet of Everything: The term IoE evolved a few years ago, and there is a clear difference between the definition of IoE and IoT. IoE is defined as intelligent connectivity among things, data, processes, and people. The data is converted into useful information and delivered to the right person/object at right time. Billions of objects update their status by using various sensors. The IoT can be defined as the network of physical objects that are accessed on the Internet. IoE incorporates a massive network of things where each thing-network is an autonomous system and capable of coordination with other networks [31]. IoT and IoE have the same purpose in terms of connectivity; however, IoE's terminology is used for a broader aspect with massive data. IoE also introduces the intelligence layer for decision-making. The IoE is expected to provide massive connectivity in various domains including healthcare, agriculture, logistics, manufacturing, and education. The 6G networks will support such massive data connectivity using its flexible heterogeneous architecture [101].

D. Summary

Section II provides a categorization of potential use cases for 6G networks, the categorization includes VR, health, and Industry 5.0. VR is further sub-divided into two categories including XR and teleportation. Both XR and teleportation are discussed in detail with examples. The second important category belongs to healthcare and a couple of potential use cases are discussed under this category including BCI and human sense-based applications. The discussion about the implementation of BCI for the 6G network is provided. Industry 5.0 is discussed as the last category of the potential use cases which maps the AI and ML with industrial applications. Industry 5.0 is being considered a revolution for the automated industry and it is vital to link it with upcoming 6G networks.

VII. 6G APPLICATION REQUIREMENTS AND CHALLENGES

Recently, a variety of AI-based mobile applications emerged that require stringent QoS communication services. Many works have tried to address these requirements [114, 105, 23, 97, 75, 14, 80, 26, 111, 82, 36]. This section discusses how 6G will manage mobile AI applications.

A. Trends and Challenges

AI has performed well in many domains including computer vision and natural language processing. AI processes are computationally rigorous and implemented at data centers with custom-designed servers. With the advancement of mobile communication and Internet of Things devices, numerous applications will be operating in the future and are expected to implement at the edge of wireless networks. The design of the 6G wireless network needs to consider the hardware, QoS, and software requirements for IoT-based applications. Wireless networks in the 6G-AI context face various challenges including privacy, data storage, resource limitations on edge devices, managing heterogeneous devices, and performance QoS [79]. The AI techniques like federated learning, deep learning, and neural learning have the potential to cater to the challenges of 6G wireless networks [73].

B. Security and Privacy

Security and privacy are the key issues in 6G, and it is very important to understand security and privacy concerning various enabling technologies which we already discussed in the previous sections. The security and privacy issues include access control, malicious activity detection, authentication, encryption, etc. In the 6G network, IoT will be one of the dominating areas with its applications in healthcare (sensing devices) and industrial automation, etc., therefore, it is important to address the recent privacy and security issues otherwise 6G will not be able to get its performance boom. In Table VII, we map these issues with enabling technologies. These issues are discussed according to the technologies including

Terahertz, AI, and blockchain. For Terahertz communications, electromagnetic signatures are proposed to address the issue of authentication. In [74], the authors proposed a mechanism to identify the malicious activity in Terahertz. In [71, 76, 92, 48, 82], the authors proposed an access control mechanism, malicious activity detection, authentication, and encryption. The authors in [63, 65, 38] provided security solutions for blockchain in terms of authentication, access control, and communication. All these proposed mechanisms apply to 6G networks.

C. Communication for Distributed Machine Learning

Along with AI techniques, high-level distributed machine learning techniques are required to make a successful execution of wireless networks in a 6G environment. The machine learning techniques elevate the complexities of the cloud wireless architecture, decision making at the network edge, and end devices.

- 1) Communication-Efficient Distributed Training: The expanding processing and storage capacity of advanced communication make devices capable of on-device training, learning, and processing of received data. Yet, transmitting over the unpredictable wireless channel turns into a substantial performance bottleneck for the mobile distributed networks. To handle the security and privacy issues, federated learning [59] keeps the training data at each device. Federated learning is an emerging distributed ML/AI approach with privacy preservation, is specifically useful for various wireless applications, and is used as one of the key solutions to obtain ubiquitous AI in 6G.
- 2) Communication-Efficient Distributed Inference: In 6G networks, it is expected that AI services will be implemented at data centers and end IoT devices, e.g., unmanned vehicles and drones. A lot of research efforts have been made to design inference processes with very low latency and cost. To handle the issues like massive computation, processing, power, and privacy in 6G networks, mobile edge computing is considered as a potential candidate [73]. For instance, in the case of a deep neural network, at end devices, the features can be extracted for decision making, and later this information can be communicated to the edge/cloud computed devices. However, the heterogeneous nature of devices in 6G networks makes computing and inter-processing mechanisms more challenging for neural networks [79].

D. Summary

Table VIII shows the relation between various network layers and potential AI algorithms for those layers. AI algo-

rithms can play a critical role to improve the performance of operational activities of the network model layers. AI algorithms will somehow automate the functionality of these layers. For the physical layer, K-Means, DNNs, CNNs, and CCNSs algorithms are suggested. These algorithms can easily be mapped with physical layer modulating techniques like OFDM and MIMO. To optimize the frame performance in terms of scheduling and error detection, at the data link layer, Q-Learning, supervised learning, and reinforcement learning is suggested. At the network layer, to increase the performance for routing and mobility, reinforcement learning, supervised and unsupervised learning, K-Mean and Q-Leaning are advised.

VIII. FUTURE RESEARCH DIRECTIONS

Numerous technical issues need to be resolved for the successful deployment of 6G networks. Some of the important concerns are discussed below.

A. High-Level Propagation and Atmospheric Absorption of THz

The THz frequency bands offer very high data rates. Yet, the THz bands require to resolve an important issue regarding data transmission over quite long distances which is high propagation loss due to atmospheric absorption characteristics, therefore, absorptive effects are witnessed [77]. The atmospheric situation is often variable and as a result very unpredictable. To solve this issue, a new transceiver architecture with efficient antennas for the THz frequency bands is required. Furthermore, health and safety issues related to the THz band need to be resolved.

B. Complexity in Resource Management for 3D Networking

3D networking is a capability where someone can create a stunning 3D network diagram for a better understanding of the network. 3D networking is considered one of the powerful future networking aspects that will merge with the 6G network. The 3D-based networks expanded in the vertical direction and it requires innovative methods for resource management, routing protocol, mobility support, and channel access. Huge attention is required from industry and academia to implement the concept. It will merge with 6G networks and provide better networking operations and management [52].

C. Heterogeneous Hardware Constraints

6G network is envisioned as a massive collection of heterogeneous devices, frequency bands, architectures, typologies, and operating systems. Furthermore, hardware operational

TABLE VII
SECURITY AND PRIVACY ISSUES IN 6G-ENABLING TECHNOLOGIES

Enabling	Paper	Security Issues	Proposed Solution
Technology			
Terahertz	[8]	Authentication	Electromagnetic signatures are proposed
Terahertz	[74]	Malicious activity	The authors highlighted that signal is transmitted via a narrow beam, it can still be intercepted by an eavesdropper
Artificial Intelligence	[71]	Access control	Authors proposed fine grained control processes
Artificial Intelligence	[76]	Malicious activity	Proposed anomaly detection system
Artificial Intelligence	[92]	Authentication	Unsupervised learning process is used as solution
Artificial Intelligence	[48]	Communication	Antenna based communication is mapped with AI algorithm as a secure solution
Artificial Intelligence	[82]	Encryption	ML and quantum based encryption schemes
Blockchain	[63]	Authentication	A novel architecture is proposed for authentication
Blockchain	[65]	Access control	Proposed a method that improves access control
Blockchain	[38]	communication	Proposed to use hashing mechanism to validate transactions

settings for the mobile terminals and the signaling devices will be substantially different. The MIMO technique will be more advanced in 6G with a further complex architecture than the 5G. Moreover, 6G will need to adjust to the complex communication protocols having complicated algorithms. The addition of advanced AI and machine learning techniques like unsupervised and reinforcement learning could make hardware operations more complex. Subsequently, it will be very challenging to incorporate all the heterogeneous aspects into a single platform [103].

D. Autonomous Wireless Systems

Designing autonomous wireless systems with simultaneous responses in real-time is not an easy task and cannot be achieved by incremental changes to existing control and optimization methodologies. It needs a fundamental shift in the system by merging machine intelligence in wireless architecture and infrastructure. Autonomous wireless systems in 6G networks will be a combination of several heterogeneous technological components like computing, machine learning, autonomous cloud computing systems, and heterogeneous wireless systems [34]. All the mentioned components require a specified quality of service parameters to make a fully autonomous system, these parameters include ML capabilities, quick data processing, huge storage capability, hi Internet availability, and security services. With the advanced infras-

tructure and features of the 6G networks, it is expected that it will provide fully autonomous systems for various machines including cars, UAVs, drones, etc. UAVs, are emerging as one of the potential 6G applications as they can provide ultrahigh data rates and ubiquitous wireless connectivity. UAVs' special features such as ease of deployment, high LoS link probability, and a large degree of freedom are given through their controlled mobility. UAVs can be deployed to extend wireless connectivity in case of disasters such as natural disasters etc. Allowing UAVs to adaptively reposition according to environmental changes and users' demands is one of the most valuable UAV features. The objective of connecting the independent components to be joined by the 6G will be made possible by aerial BSs due to simple deployment.

E. Device Capability

The start-up of the THz spectrum will deliver new sensing capabilities to the 6G devices, these capabilities include high-definition imaging and frequency spectroscopy, etc. In sequence with high precision, these augmented sensing capabilities are subservient in understanding the context and could help to build a trusted and secure environment. The 6G system requires more capabilities from devices to efficiently operate. For example, advanced smartphones equipped with AI, XR, and integrated sensing, should be resourceful to enable 6G's new features like a throughput of 1 Tb/s. The existing 5G

TABLE VIII

COMMUNICATION LAYERS AND AI ALGORITHMS

Network Functions	Descriptions	AI Algorithms
Physical Layer	Physical layer transmits the data on the wireless	K-Means
	medium using different modulating schemes includ-	• DNN
	ing channel coding, advanced modulation schemes	• CNNs
	like OFDM and MIMO etc.	• CCNNs
		Auto-encoder
Data Link Layer	Data link layer is mainly responsible for the frame	• DNNs
	Performance issues i.e., scheduling, error identifica-	Q-Learning
	tion and correction mechanisms, flow control mech-	Reinforcement
	anisms, synchronization, queuing etc.,	Learning
		Supervised Learning
		Transfer Learning
Network Layer	Network layer is responsible for connection man-	• DNNs
	agement, mobility management, load and routing	Reinforcement
	protocols management	Learning
		Supervised Learning
		Unupervised Learning
		K-Means
		Q-Learning

devices may have shortcomings to support some of the 6G features. A massive number of devices connected in 5G should be compatible with 6G.

F. High Capacity Backhaul Network Connectivity

One significant element in the connectivity solution is an efficient backhaul connection. An appropriate backhaul design could be very challenging for remote areas. High-level density access networks for 6G networks are very distinct and pervasive. These access networks will be capable of providing ultrahigh data rates. In the future, the backhaul network will have a critical role in providing massive connectivity between core and access networks. Evolving satellite constellations such as Starlink by SpaceX and the systems by OneWeb and Telesat have a lot of potential to support such scenarios; however, these are expensive solutions. The optical fiber and FSO networks are the more appropriate options and in 6G networks they have the potential to further improve the performance of back-haul networks, hence advancement is required for the back-haul networks [96].

G. Spectrum and Interference Management

The shortage of the spectrum at higher frequencies and their interference problems require efficient and innovative spectrum sharing schemes. Effective spectrum management schemes are vital to achieving optimal resource utilization with QoS maximization. For efficient deployment of 6G, researchers need to tackle concerns like spectrum management

for the heterogeneous networks and devices under the same frequency band [78].

H. Beam Management in THz Communications

Beamforming via advanced MIMO systems is a potential technology to support high data rates. Though, beam management for high-frequency bands like the THz band is a challenging task due to the propagation characteristics. Therefore, the design of an effective beam management scheme to handle the propagation characteristics for advanced MIMO will be a challenging task. However, for seamless handover, it is also important to choose the optimal beam efficiently in high-speed vehicular systems [77].

IX. CONCLUSION

In this survey, we initially evaluated the key successes and challenges of 1G to 5G, and then focused on the potential applications, enabling technologies, specifications, and requirements, and AI-based wireless applications and technologies of 6G. The 5G communication system is expected to be fully deployed globally in 2022. However, the current 5G technologies are not capable of catering to the increasing demand for the future wireless communication which is envisioned for 2030.

Research activities on 6G technologies and systems are yet in their early stages. This survey envisions the options and methods to accomplish the objectives of 6G wireless communication. In this paper, we also presented the potential applications for 6G with key enabling technologies so that stringent QoS requirements of future applications can be

fulfilled. These requirements are ultra-high throughput (1Tb/s to 20 Tb/s), extreme -low latency (tens of microseconds), high reliability, ubiquitous network connectivity, and very low power consumption. To support such QoS, advanced network architectures and technologies like fog computing, cloud computing, software-defined networks, optical wireless networks, network virtualization, and THz spectrum communications are required. Moreover, future applications will generate massive data, to handle such big data, advanced AI techniques and algorithms are required. We summarized some of the potential AI methods for specific network architectures. Along with explaining the vision and goal of 6G communications, we have identified the numerous technologies that could be used for 6G communication. We also discussed the probable challenges and research directions to achieve the goals for 6G.

REFERENCES

- [1] A. Agrawal, V. K. Mishra, A. Gupta, and B. Bansal. "Performance analysis of beamforming aided uncorrelated mm-Wave MIMO system for IEEE 802.15. 3c standard". In: *Physical Communication* 41 (2020), p. 101114.
- [2] M. S. Akbar. "Modelling, analysis and design of MAC and routing protocols for wireless body area sensor networks." PhD thesis. Bournemouth University, 2018.
- [3] M. S. Akbar, H. Yu, and S. Cang. "A holistic simulation model for remote patient monitoring systems using Wireless Body Area Sensor Networks (WBASNs)". In: 9th International Conference on Software, Knowledge, Information Management and Applications (SKIMA). IEEE. 2015, pp. 1–5.
- [4] M. S. Akbar, H. Yu, and S. Cang. "Delay, reliability, and throughput based QoS profile: A MAC layer performance optimization mechanism for biomedical applications in wireless body area sensor networks". In: *Journal of Sensors* 2016 (2016).
- [5] M. S. Akbar, H. Yu, and S. Cang. "Implanted medical devices as future of wireless healthcare monitoring: Investigation and performance evaluation using novel numerical modeling". In: 22nd International Conference on Automation and Computing (ICAC). IEEE. 2016, pp. 522–528.
- [6] M. S. Akbar, H. Yu, and S. Cang. "TMP: Telemedicine protocol for slotted 802.15. 4 with duty-cycle optimization in wireless body area sensor networks". In: *IEEE Sensors Journal* 17.6 (2016), pp. 1925–1936.

- [7] M. S. Akbar, H. Yu, and S. Cang. "IEEE 802.15. 4 frame aggregation enhancement to provide high performance in life-critical patient monitoring systems". In: *Sensors* 17.2 (2017), p. 241.
- [8] I. F. Akyildiz, J. M. Jornet, and C. Han. "Terahertz band: Next frontier for wireless communications". In: *Physical Communication* 12 (2014), pp. 16–32.
- [9] I. Alam, K. Sharif, F. Li, Z. Latif, M. M. Karim, S. Biswas, B. Nour, and Y. Wang. "A survey of network virtualization techniques for Internet of Things using SDN and NFV". In: ACM Computing Surveys (CSUR) 53.2 (2020), pp. 1–40.
- [10] R. Alghamdi, R. Alhadrami, D. Alhothali, H. Almorad, A. Faisal, S. Helal, R. Shalabi, R. Asfour, N. Hammad, A. Shams, et al. "Intelligent surfaces for 6G wireless networks: A survey of optimization and performance analysis techniques". In: *IEEE Access* 8 (2020).
- [11] A. Ali, N. González-Prelcic, and R. W. Heath. "Millimeter wave beam-selection using out-of-band spatial information". In: *IEEE Transactions on Wireless Communications* 17.2 (2017), pp. 1038–1052.
- [12] Z. E. Ankarali, B. Peköz, and H. Arslan. "Flexible radio access beyond 5G: A future projection on waveform, numerology, and frame design principles". In: *IEEE Access* 5 (2017), pp. 18295–18309.
- [13] A. Al-Ansi, A. M. Al-Ansi, A. Muthanna, I. A. Elgendy, and A. Koucheryavy. "Survey on Intelligence Edge Computing in 6G: Characteristics, Challenges, Potential Use Cases, and Market Drivers". In: Future Internet 13.5 (2021), p. 118.
- [14] T. Aste, P. Tasca, and T. Di Matteo. "Blockchain technologies: The foreseeable impact on society and industry". In: *Computer* 50.9 (2017), pp. 18–28.
- [15] M. Attarifar, A. Abbasfar, and A. Lozano. "Modified conjugate beamforming for cell-free massive MIMO". In: *IEEE Wireless Communications Letters* 8.2 (2019), pp. 616–619.
- [16] B. Bag, A. Das, I. S. Ansari, A. Prokeš, C. Bose, and A. Chandra. "Performance analysis of hybrid FSO systems using FSO/RF-FSO link adaptation". In: *IEEE Photonics Journal* 10.3 (2018), pp. 1–17.
- [17] J. Carmigniani and B. Furht. "Augmented reality: an overview". In: *Handbook of augmented reality* (2011), pp. 3–46.
- [18] C. Castro, R. Elschner, T. Merkle, F. Rodrigues, J. Machado, A. Teixeira, and C. Schubert. "THz Commu-

- nications: Paving the Way Towards Wireless Tbps". In: *THz Communications*. Springer, 2022, pp. 417–421.
- [19] L. Catarinucci, D. De Donno, L. Mainetti, L. Palano, L. Patrono, M. L. Stefanizzi, and L. Tarricone. "An IoT-aware architecture for smart healthcare systems". In: *IEEE Internet of Things* 2.6 (2015), pp. 515–526.
- [20] J. Choi, V. Va, N. Gonzalez-Prelcic, R. Daniels, C. R. Bhat, and R. W. Heath. "Millimeter-wave vehicular communication to support massive automotive sensing". In: *IEEE Communications Magazine* 54.12 (2016), pp. 160–167.
- [21] M. Z. Chowdhury, M. T. Hossan, M. K. Hasan, and Y. M. Jang. "Integrated RF/optical wireless networks for improving QoS in indoor and transportation applications". In: *Wireless Personal Communications* 107.3 (2019), pp. 1401–1430.
- [22] M. Z. Chowdhury, M. T. Hossan, A. Islam, and Y. M. Jang. "A comparative survey of optical wireless technologies: Architectures and applications". In: *IEEE Access* 6 (2018), pp. 9819–9840.
- [23] M. Z. Chowdhury, M. T. Hossan, and Y. M. Jang. "Interference management based on RT/nRT traffic classification for FFR-aided small cell/macrocell heterogeneous networks". In: *IEEE Access* 6 (2018), pp. 31340–31358.
- [24] S. H.-W. Chuah. "Why and who will adopt extended reality technology? Literature review, synthesis, and future research agenda". In: Literature Review, Synthesis, and Future Research Agenda (2018).
- [25] A. Çöltekin, I. Lochhead, M. Madden, S. Christophe, A. Devaux, C. Pettit, O. Lock, S. Shukla, L. Herman, Z. Stachoň, et al. "Extended reality in spatial sciences: A review of research challenges and future directions". In: *ISPRS International Journal of Geo-Information* 9.7 (2020), p. 439.
- [26] H.-N. Dai, Z. Zheng, and Y. Zhang. "Blockchain for Internet of Things: A survey". In: *IEEE Internet of Things* 6.5 (2019), pp. 8076–8094.
- [27] N.-N. Dao, Q.-V. Pham, N. H. Tu, T. T. Thanh, V. N. Q. Bao, D. S. Lakew, and S. Cho. "Survey on aerial radio access networks: toward a comprehensive 6g access infrastructure". In: *IEEE Communications Surveys & Tutorials* 23.2 (2021), pp. 1193–1225.
- [28] D. Dardari, F. Guidi, A. Guerra, and E. Leoni. "Initial Access Techniques for 5G Systems". In: *Masters' Thesis* (2018).

- [29] K. David and H. Berndt. "6G vision and requirements: Is there any need for beyond 5G?" In: *IEEE Vehicular Technology Magazine* 13.3 (2018), pp. 72–80.
- [30] C. De Alwis, A. Kalla, Q.-V. Pham, P. Kumar, K. Dev, W.-J. Hwang, and M. Liyanage. "Survey on 6G frontiers: Trends, applications, requirements, technologies and future research". In: *IEEE Open Journal of the Communications Society* 2 (2021), pp. 836–886.
- [31] L. DeNardis. *The Internet in Everything*. Yale University Press, 2020.
- [32] M. Deva Priya, A. Christy Jeba Malar, S. Sam Peter, G. Sandhya, L. Vishnu Varthan, and R. Vignesh. "Dynamic Resource Aware Scheduling Schemes for IEEE 802.16 Broadband Wireless Networks". In: *Progress in Advanced Computing and Intelligent Engineering*. Springer, 2021, pp. 218–230.
- [33] A. Douik, H. Dahrouj, T. Y. Al-Naffouri, and M.-S. Alouini. "Hybrid radio/free-space optical design for next generation backhaul systems". In: *IEEE Transactions on Communications* 64.6 (2016), pp. 2563–2577.
- [34] D. Elliott, W. Keen, and L. Miao. "Recent advances in connected and automated vehicles". In: *Journal* of Traffic and Transportation Engineering (English Edition) 6.2 (2019), pp. 109–131.
- [35] S. Elmeadawy and R. M. Shubair. "Enabling technologies for 6G future wireless communications: Opportunities and challenges". In: arXiv preprint arXiv:2002.06068 (2020).
- [36] M. Elsayed and M. Erol-Kantarci. "AI-enabled future wireless networks: Challenges, opportunities, and open issues". In: *IEEE Vehicular Technology Magazine* 14.3 (2019), pp. 70–77.
- [37] M. A. Esmail, H. Fathallah, and M.-S. Alouini. "Outdoor FSO communications under fog: attenuation modeling and performance evaluation". In: *IEEE Photonics Journal* 8.4 (2016), pp. 1–22.
- [38] P. Ferraro, C. King, and R. Shorten. "Distributed ledger technology for smart cities, the sharing economy, and social compliance". In: *IEEE Access* 6 (2018), pp. 62728–62746.
- [39] H. Gao, Y. Su, S. Zhang, and M. Diao. "Antenna selection and power allocation design for 5G massive MIMO uplink networks". In: *China Communications* 16.4 (2019), pp. 1–15.
- [40] A. U. Gawas. "An overview on evolution of mobile wireless communication networks: 1G-6G". In: *Inter-*

- national Journal on Recent and Innovation Trends in Computing and Communication 3.5 (2015), pp. 3130–3133.
- [41] S. Goyal, P. Liu, S. S. Panwar, R. A. Difazio, R. Yang, and E. Bala. "Full duplex cellular systems: will doubling interference prevent doubling capacity?" In: *IEEE Communications Magazine* 53.5 (2015), pp. 121–127.
- [42] Z. Gu, J. Zhang, Y. Ji, L. Bai, and X. Sun. "Network topology reconfiguration for FSO-based fronthaul/backhaul in 5G+ wireless networks". In: *IEEE Access* 6 (2018), pp. 69426–69437.
- [43] F. Guo, F. R. Yu, H. Zhang, X. Li, H. Ji, and V. C. Leung. "Enabling massive IoT toward 6G: A comprehensive survey". In: *IEEE Internet of Things Journal* 8.15 (2021), pp. 11891–11915.
- [44] K. Hausmair, P. N. Landin, U. Gustavsson, C. Fager, and T. Eriksson. "Digital predistortion for multi-antenna transmitters affected by antenna crosstalk". In: *IEEE Transactions on Microwave Theory and Techniques* 66.3 (2017), pp. 1524–1535.
- [45] S. He, Y. Zhang, J. Wang, J. Zhang, J. Ren, Y. Zhang, W. Zhuang, and X. Shen. "A survey of millimeterwave communication: Physical-layer technology specifications and enabling transmission technologies". In: *Proceedings of the IEEE* 109.10 (2021), pp. 1666– 1705.
- [46] R. Henry, A. Herzberg, and A. Kate. "Blockchain access privacy: Challenges and directions". In: *IEEE* Security & Privacy 16.4 (2018), pp. 38–45.
- [47] M. N. Hindia, F. Qamar, H. Ojukwu, K. Dimyati, A. M. Al-Samman, and I. S. Amiri. "On platform to enable the cognitive radio over 5G networks". In: Wireless Personal Communications 113.2 (2020), pp. 1241–1262.
- [48] T. Hong, C. Liu, and M. Kadoch. "Machine learning based antenna design for physical layer security in ambient backscatter communications". In: Wireless Communications and Mobile Computing 2019 (2019).
- [49] M. Hossan, M. Z. Chowdhury, M. Hasan, M. Shahjalal, T. Nguyen, N. T. Le, Y. M. Jang, et al. "A new vehicle localization scheme based on combined optical camera communication and photogrammetry". In: *Mobile Information Systems* 2018 (2018).
- [50] M. T. Hossan, M. Z. Chowdhury, M. Shahjalal, and Y. M. Jang. "Human bond communication with head-

- mounted displays: Scope, challenges, solutions, and applications". In: *IEEE Communications Magazine* 57.2 (2019), pp. 26–32.
- [51] https://commons.wikimedia.org/wiki/File:Industry_4.0. png. 2020.
- [52] K. M. S. Huq, J. Rodriguez, and I. E. Otung. "3D network modeling for THz-enabled ultra-fast dense networks: a 6G perspective". In: *IEEE Communications Standards Magazine* 5.2 (2021), pp. 84–90.
- [53] S. R. A. Jafri, T. Hamid, R. Mahmood, M. A. Alam, T. Rafi, M. Z. U. Haque, and M. W. Munir. "Wireless brain computer interface for smart home and medical system". In: *Wireless Personal Communications* 106.4 (2019), pp. 2163–2177.
- [54] M. Jaloun, Z. Guennoun, et al. "Wireless mobile evolution to 4G network". In: *Wireless Sensor Network* 2.04 (2010), p. 309.
- [55] B. Ji, Y. Wang, K. Song, C. Li, H. Wen, V. G. Menon, and S. Mumtaz. "A survey of computational intelligence for 6G: Key technologies, applications and trends". In: *IEEE Transactions on Industrial Informatics* 17.10 (2021), pp. 7145–7154.
- [56] W. Jiang, B. Han, M. A. Habibi, and H. D. Schotten. "The road towards 6G: A comprehensive survey". In: *IEEE Open Journal of the Communications Society* 2 (2021), pp. 334–366.
- [57] J. M. Jornet and I. F. Akyildiz. "Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the terahertz band". In: *IEEE Transactions* on Wireless Communications 10.10 (2011), pp. 3211– 3221.
- [58] S. Ju, Y. Xing, O. Kanhere, and T. S. Rappaport. "Millimeter wave and sub-terahertz spatial statistical channel model for an indoor office building". In: *IEEE Journal on Selected Areas in Communications* 39.6 (2021), pp. 1561–1575.
- [59] N. Kato, Z. M. Fadlullah, F. Tang, B. Mao, S. Tani, A. Okamura, and J. Liu. "Optimizing space-air-ground integrated networks by artificial intelligence". In: *IEEE Wireless Communications* 26.4 (2019), pp. 140–147.
- [60] S. K. Khan, U. Naseem, H. Siraj, I. Razzak, and M. Imran. "The role of unmanned aerial vehicles and mmWave in 5G: Recent advances and challenges". In: *Transactions on Emerging Telecommunications Technologies* 32.7 (2021), e4241.

- [61] N. Khiadani. "Vision, Requirements and Challenges of Sixth Generation (6G) Networks". In: 6th Iranian Conference on Signal Processing and Intelligent Systems (ICSPIS). IEEE. 2020, pp. 1–4.
- [62] T.-h. Kim, C. Ramos, and S. Mohammed. *Smart city and IoT*. 2017.
- [63] S. Kiyomoto, A. Basu, M. S. Rahman, and S. Ruj. "On blockchain-based authorization architecture for beyond-5G mobile services". In: 12th International Conference for Internet Technology and Secured Transactions (ICITST). IEEE. 2017, pp. 136–141.
- [64] T. Komine and M. Nakagawa. "Fundamental analysis for visible-light communication system using LED lights". In: *IEEE Transactions on Consumer Electron*ics 50.1 (2004), pp. 100–107.
- [65] K. Kotobi and S. G. Bilen. "Secure blockchains for dynamic spectrum access: A decentralized database in moving cognitive radio networks enhances security and user access". In: *IEEE Vehicular Technology Mag*azine 13.1 (2018), pp. 32–39.
- [66] A. Kumar, R. Krishnamurthi, A. Nayyar, K. Sharma, V. Grover, and E. Hossain. "A novel smart healthcare design, simulation, and implementation using healthcare 4.0 processes". In: *IEEE Access* 8 (2020), pp. 118433–118471.
- [67] J. Lee, B. Bagheri, and H.-A. Kao. "A cyber-physical systems architecture for industry 4.0-based manufacturing systems". In: *Manufacturing Letters* 3 (2015), pp. 18–23.
- [68] K. B. Letaief, W. Chen, Y. Shi, J. Zhang, and Y.-J. A. Zhang. "The roadmap to 6G: AI empowered wireless networks". In: *IEEE Communications Magazine* 57.8 (2019), pp. 84–90.
- [69] Y.-N. R. Li, B. Gao, X. Zhang, and K. Huang. "Beam management in millimeter-wave communications for 5G and beyond". In: *IEEE Access* 8 (2020), pp. 13282– 13293.
- [70] Q. Long, Y. Chen, H. Zhang, and X. Lei. "Software defined 5G and 6G networks: a survey". In: *Mobile Networks and Applications* (2019), pp. 1–21.
- [71] L. Lovén, T. Leppänen, E. Peltonen, J. Partala, E. Harjula, P. Porambage, M. Ylianttila, and J. Riekki. "EdgeAI: A vision for distributed, edge-native artificial intelligence in future 6G networks". In: *The 1st 6G Wireless Summit* (2019), pp. 1–2.

- [72] N. Lu, N. Cheng, N. Zhang, X. Shen, and J. W. Mark. "Connected vehicles: Solutions and challenges". In: *IEEE Internet of Things* 1.4 (2014), pp. 289–299.
- [73] N. C. Luong, D. T. Hoang, S. Gong, D. Niyato, P. Wang, Y.-C. Liang, and D. I. Kim. "Applications of deep reinforcement learning in communications and networking: A survey". In: *IEEE Communications Surveys & Tutorials* 21.4 (2019), pp. 3133–3174.
- [74] J. Ma, R. Shrestha, J. Adelberg, C.-Y. Yeh, Z. Hossain, E. Knightly, J. M. Jornet, and D. M. Mittleman. "Security and eavesdropping in terahertz wireless links". In: *Nature* 563.7729 (2018), pp. 89–93.
- [75] A. J. Mahbas, H. Zhu, and J. Wang. "Impact of small cells overlapping on mobility management". In: *IEEE Transactions on Wireless Communications* 18.2 (2019), pp. 1054–1068.
- [76] M. N. Mahdi, A. R. Ahmad, Q. S. Qassim, H. Natiq, M. A. Subhi, and M. Mahmoud. "From 5G to 6G Technology: Meets Energy, Internet-of-Things and Machine Learning: A Survey". In: *Applied Sciences* 11.17 (2021), p. 8117.
- [77] I. Markit. "The Internet of Things: a movement, not a market". In: *Critical IoT Insights* (2017), pp. 1–9.
- [78] M. Matinmikko-Blue, S. Yrjölä, and P. Ahokangas. "Spectrum management in the 6G era: The role of regulation and spectrum sharing". In: 2nd 6G Wireless Summit (6G SUMMIT). IEEE. 2020, pp. 1–5.
- [79] B. McMahan, E. Moore, D. Ramage, S. Hampson, and B. A. y Arcas. "Communication-efficient learning of deep networks from decentralized data". In: Artificial Intelligence and Statistics. PMLR. 2017, pp. 1273– 1282.
- [80] D. Miller. "Blockchain and the internet of things in the industrial sector". In: *IT Professional* 20.3 (2018), pp. 15–18.
- [81] S. Mondal, A. Sinha, and J. Routh. "A survey on evolution of wireless generations 0G to 7G". In: *International Journal of Advance Research in Science and Engineering (IJARSE)* 1.2 (2015), pp. 5–10.
- [82] S. J. Nawaz, S. K. Sharma, S. Wyne, M. N. Patwary, and M. Asaduzzaman. "Quantum machine learning for 6G communication networks: State-of-the-art and vision for the future". In: *IEEE Access* 7 (2019), pp. 46317–46350.
- [83] S.-i. Ohkoshi, M. Yoshikiyo, K. Imoto, K. Nakagawa, A. Namai, H. Tokoro, Y. Yahagi, K. Takeuchi, F.

- Jia, S. Miyashita, et al. "Magnetic-Pole Flip by Millimeter Wave". In: *Advanced Materials* 32.48 (2020), p. 2004897.
- [84] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra. "Visible light communication, networking, and sensing: A survey, potential and challenges". In: *IEEE Communications Surveys & Tutorials* 17.4 (2015), pp. 2047–2077.
- [85] J. Pei, F. Guo, J. Zhang, B. Zhou, Y. Bi, and R. Li. "Review and analysis of energy harvesting technologies in roadway transportation". In: *Journal of Cleaner Production* 288 (2021), p. 125338.
- [86] P. Porambage, G. Gür, D. P. M. Osorio, M. Liyanage, A. Gurtov, and M. Ylianttila. "The roadmap to 6G security and privacy". In: *IEEE Open Journal of the Communications Society* 2 (2021), pp. 1094–1122.
- [87] I. S. Al-Qasrawi. "Proposed technologies for solving future 5G heterogeneous networks challenges". In: *International Journal of Computer Applications* 975 (2017), p. 8887.
- [88] R. Ramachandran. "Evolution to 3G mobile communication". In: *Resonance* 8.11 (2003), pp. 37–51.
- [89] S. S. Reka and T. Dragicevic. "Future effectual role of energy delivery: A comprehensive review of Internet of Things and smart grid". In: *Renewable and Sustainable Energy Reviews* 91 (2018), pp. 90–108.
- [90] T. Reshmi and M. Azath. "Improved self-healing technique for 5G networks using predictive analysis".
 In: Peer-to-Peer Networking and Applications 14.1 (2021), pp. 375–391.
- [91] A. Salh, L. Audah, N. S. M. Shah, A. Alhammadi, Q. Abdullah, Y. H. Kim, S. A. Al-Gailani, S. A. Hamzah, B. A. F. Esmail, and A. A. Almohammedi. "A Survey on Deep Learning for Ultra-Reliable and Low-Latency Communications Challenges on 6G Wireless Systems". In: *IEEE Access* 9 (2021), pp. 55098–55131.
- [92] R. Sattiraju, A. Weinand, and H. D. Schotten. "AI-assisted PHY technologies for 6G and beyond wireless networks". In: *arXiv preprint arXiv:1908.09523* (2019).
- [93] J. Schloemann, H. S. Dhillon, and R. M. Buehrer. "Toward a tractable analysis of localization fundamentals in cellular networks". In: *IEEE Transactions on Wireless Communications* 15.3 (2015), pp. 1768–1782.

- [94] M. Series. "IMT Vision–Framework and overall objectives of the future development of IMT for 2020 and beyond". In: *Recommendation ITU* 2083 (2015), p. 0.
- [95] A. Shahraki, M. Abbasi, M. Piran, M. Chen, S. Cui, et al. "A comprehensive survey on 6g networks: Applications, core services, enabling technologies, and future challenges". In: *arXiv preprint arXiv:2101.12475* (2021).
- [96] T. Sharma, A. Chehri, and P. Fortier. "Review of optical and wireless backhaul networks and emerging trends of next generation 5G and 6G technologies". In: *Transactions on Emerging Telecommunications Tech*nologies 32.3 (2021), e4155.
- [97] A. Z. Shifat, M. Z. Chowdhury, and Y. M. Jang. "Game-based approach for QoS provisioning and interference management in heterogeneous networks". In: *IEEE Access* 6 (2017), pp. 10208–10220.
- [98] P. L. Show, K. W. Chew, and T. C. Ling. *The Prospect of Industry 5.0 in Biomanufacturing*. CRC Press, 2021.
- [99] S. Shukla, V. Khare, S. Garg, and P. Sharma. "Comparative Study of 1G, 2G, 3G and 4G". In: *Journal of Engineering, Computers, and Applied Sciences* (*JEC&AS*) 2.4 (2013), pp. 55–63.
- [100] I. Siaud and A.-M. Ulmer-Moll. "THz Communications: An Overview and Challenges". In: *Future Networks* (2019).
- [101] T. Snyder and G. Byrd. "The internet of everything".In: *IEEE Computer Architecture Letters* 50.06 (2017), pp. 8–9.
- [102] V. Sytnikov, V. Vysotsky, I. Radchenko, and N. Polyakova. "1G versus 2G-comparison from the practical standpoint for HTS power cables use". In: *Journal of Physics: Conference Series*. Vol. 97. 1. IOP Publishing. 2008, p. 012058.
- [103] J. Tan and L. Dai. "THz precoding for 6G: Applications, challenges, solutions, and opportunities". In: *arXiv preprint arXiv:2005.10752* (2020).
- [104] F. Tang, Y. Kawamoto, N. Kato, and J. Liu. "Future intelligent and secure vehicular network toward 6G: Machine-learning approaches". In: *Proceedings of the IEEE* 108.2 (2019), pp. 292–307.
- [105] F. Tariq, M. R. Khandaker, K.-K. Wong, M. A. Imran, M. Bennis, and M. Debbah. "A speculative study on 6G". In: *IEEE Wireless Communications* 27.4 (2020), pp. 118–125.

- [106] K. Tekbiyik, A. R. Ekti, G. K. Kurt, and A. Görçin. "Terahertz band communication systems: Challenges, novelties and standardization efforts". In: *Physical Communication* 35 (2019), p. 100700.
- [107] A. K. Tripathy, S. Chinara, and M. Sarkar. "An application of wireless brain–computer interface for drowsiness detection". In: *Biocybernetics and Biomedical Engineering* 36.1 (2016), pp. 276–284.
- [108] A. N. Uwaechia and N. M. Mahyuddin. "A comprehensive survey on millimeter wave communications for fifth-generation wireless networks: Feasibility and challenges". In: *IEEE Access* 8 (2020), pp. 62367–62414.
- [109] E. Vinogradov. "Key Wireless Technologies for Civil UAV Traffic Management: A Survey". In: *Networks* 18.2 (2016), pp. 1123–1152.
- [110] C.-X. Wang, J. Huang, H. Wang, X. Gao, X. You, and Y. Hao. "6G wireless channel measurements and models: Trends and challenges". In: *IEEE Vehicular Technology Magazine* 15.4 (2020), pp. 22–32.
- [111] H. Wang, W. Wang, X. Chen, and Z. Zhang. "Wireless information and energy transfer in interference aware massive MIMO systems". In: 2014 IEEE Global Communications Conference. IEEE. 2014, pp. 2556–2561.
- [112] M. Wang, Y. Cui, X. Wang, S. Xiao, and J. Jiang. "Machine learning for networking: Workflow, advances and opportunities". In: *IEEE Network* 32.2 (2017), pp. 92–99.
- [113] P. Wang, J. Fang, H. Duan, and H. Li. "Compressed channel estimation for intelligent reflecting surfaceassisted millimeter wave systems". In: *IEEE Signal Processing Letters* 27 (2020), pp. 905–909.
- [114] M. Wollschlaeger, T. Sauter, and J. Jasperneite. "The future of industrial communication: Automation networks in the era of the internet of things and industry 4.0". In: *IEEE Industrial Electronics Magazine* 11.1 (2017), pp. 17–27.
- [115] S. Wu, L. Hou, and G. K. Zhang. "Integrated application of BIM and eXtended reality technology: a review, classification and outlook". In: *International Conference on Computing in Civil and Building Engineering*. Springer. 2020, pp. 1227–1236.
- [116] S. Xin, W. Ben-yuan, G. Li, and A. M. Liton. "Low Delay and Low Overhead Terahertz Wireless Personal Area Networks Directional MAC Protocols". In: 6th International Conference on Intelligent Computing

- and Signal Processing (ICSP). IEEE. 2021, pp. 687–691.
- [117] X. Xu, Y. Pan, P. P. M. Y. Lwin, and X. Liang. "3D holographic display and its data transmission requirement". In: *International Conference on Information Photonics and Optical Communications*. IEEE. 2011, pp. 1–4.
- [118] E. Yaacoub and M.-S. Alouini. "A key 6G challenge and opportunity—connecting the base of the pyramid: A survey on rural connectivity". In: *Proceedings of the IEEE* 108.4 (2020), pp. 533–582.
- [119] A. Yastrebova, R. Kirichek, Y. Koucheryavy, A. Borodin, and A. Koucheryavy. "Future networks 2030: Architecture & requirements". In: 10th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT). IEEE. 2018, pp. 1–8.
- [120] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi. "Internet of things for smart cities". In: *IEEE Internet of Things* 1.1 (2014), pp. 22–32.
- [121] Q. Zhang, J. Liu, and G. Zhao. "Towards 5G enabled tactile robotic telesurgery". In: *arXiv preprint arXiv:1803.03586* (2018).
- [122] H. Zhu, C. K. Wu, C. H. Koo, Y. T. Tsang, Y. Liu, H. R. Chi, and K.-F. Tsang. "Smart healthcare in the era of internet-of-things". In: *IEEE Consumer Electronics Magazine* 8.5 (2019), pp. 26–30.
- [123] B. Zong, C. Fan, X. Wang, X. Duan, B. Wang, and J. Wang. "6G Technologies: Key drivers, core requirements, system architectures, and enabling technologies". In: *IEEE Vehicular Technology Magazine* 14.3 (2019), pp. 18–27.