Thesis Dissertation

EMERGING APPLICATIONS FOR 6G MOBILE COMMUNICATION

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Abstract

The creation of 6G technologies and applications is a quickly developing field of study with enormous potential for wireless communication systems in the future. To support the huge data transfer, ultra-low latency, and high reliability required by the Internet of Things, augmented and virtual reality, autonomous vehicles, and other new technologies, wireless networks must be able to handle these demands.

The main objectives, difficulties, and possibilities associated with the 6G structure and applications are outlined in this thesis. It will examine the different technical aspects of 6G networks, including quantum computing, terahertz frequency bands, new proposed architectures, edge computing, and blockchain technology, and explain how they might be used on 6G to form a strong and adaptable communication infrastructure.

In addition, the thesis will examine the potential applications of 6G in different fields, such as autonomous vehicles, healthcare, entertainment and media, education, training, financial services, and security. Mentioning the variations of opportunities and ethical challenges that may exist together with these. Finally, the thesis will conclude with a discussion of future research directions and open issues in the field and offer some recommendations for future work.

Contents

Chapter 1

Introduction

1.1 Importance of mobile networks

Technology's rapid development has greatly impacted how we live our lives. The rise of smart mobile phones has made them a necessary component of everyday activities. We live in an age where we rely on an online connection to find a location and navigate there, to search for any information on any topic, to communicate with people from work, our family environment, our friends, etc. For this very reason, it's hard for us to imagine our lives without all of these, while at the same time, it doesn't stop us from expecting even more from technology. We want faster speed, better security for our data, immediacy, more convenient mobility with high coverage, and so much more. However, we hardly ever wonder how we managed to have all this today.

As is commonly known, mobile technology is used mostly in mobile communication using cellular networks and other associated elements. It makes use of a platform format so that numerous transmitters can communicate data at once. This platform decreases the probability of frequency interference between two or more sources using separate frequency channels. The uses of mobile technology have evolved and have gradually replaced other comparable sources on the market that are also used for communication, such as landlines and post offices. Our lives are made easier by mobile technology, which has evolved into a multi-tasking gadget with a wide range of features from a basic phone and messaging device. The importance of these networks serves as precisely why I have chosen this subject for my thesis.

1.2 Cellular Networks used today

The most important type of mobile network in use today is the cellular network. Specifically, reference is made by the European Telecommunications Network Operators' Association to the use of fourth and fifth-generation mobile networks through the book “State of Digital Communications | 2022,” where 4G coverage in Europe appears to have reached 99,5% and 5G coverage has reached 62,0% for the years 2020 and 2021. Almost all European countries currently have access to 5G networks, while coverage and capacity might vary greatly. In several nations, 5G is either deployed in a spectrum outside the primary 5G channels or reliant on dynamic spectrum sharing. Some of Europe's most advanced markets are getting close to covering the entire country's population, while others just cover key cities **[1]**.

In terms of technology development periods, the time needed for bringing every generation of cellular technology for communication from the prototype stage to commercialization has greatly decreased since the construction of third-generation mobile networks began. Before its launch in 2000, 3G required 15 years of development, whereas 5G appears to only require eight **[2]**. At the same time, according to Statista, global 5G subscriptions are expected to skyrocket between 2019 and 2027, rising from almost 12 million to more than 4 billion., Nepal, Southeast Asia, Northeast Asia, Bhutan, and India are the regions with the greatest predicted subscription numbers **[3]**.

The organization that developed these networks is known as the 3rd Generation Partnership Project (3GPP), and it brings together a total of seven organizations that work on telecommunication standards (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, and TTC), also referred to as “Organizational Partners,” to create a stable environment for the creation of references and specifications that define 3GPP technologies. Their goal is to develop the mobile broadband standard, with a growing focus on IoT connectivity, including the requirement for sensors and power devices that are inexpensive, energy-efficient, and highly dependable at either end of the spectrum. As this organization reports, the 5G and LTE-Advanced ecosystem will allow the global network to evolve at the right pace for local readiness and market demands. The 3GPP architecture offers the promise of a pervasive end-to-end ecosystem that can serve a growing number of use cases while maximizing its compatibility with existing 3GPP infrastructure and equipment **[4]**.

It should be noted that in contrast to today, we will consume 13 times more data in 2025, the regulator of communications Ofcom predicts for 5G networks. By 2025, there are expected to be 21 billion devices connected to the internet supporting 5G, up from 7 billion today. Many of these new gadgets will power and monitor our transportation, city infrastructure, homes, and other things; this structure is known as the "Internet of Things" (IoT). It has been dubbed "one of the upcoming major technological innovations," and because maintaining connectivity to vital equipment that manages our protection and reliability is vital, fewer delays or faster network response speeds will be needed **[5]**.

Besides what is currently achievable with wireless networks, 5G can fuel other technologies. Because of the rapidity and spectrum, 5G promises to greatly develop 3D holograms, virtual reality (VR), and augmented reality (AR), providing possibilities for joining individuals using techniques that the existing state of mobile networks could not accomplish to increase the reach of mobile broadband. Furthermore, access to 5G technology will benefit crucial services and affect the reliability and protection of current services. Benefits include improved management of traffic, the potential of performing surgeries remotely, smart cities with 5G in public spaces, and numerous further applications that require very rapid responses **[6]**.

Even though the global rollout of 5G networks is still in progress and many regions of the world continue to rely on older and less sophisticated communication networks, experts and business leaders are already anticipating 6G and its potential advantages. We could anticipate 6G trials and deployments as early as 2030 if the development timeframes of earlier cellular technologies are followed. However, we still have a lot of work to do over the next eight years to create pertinent standards that address both the requirements that are currently apparent and those that will emerge in the future. To achieve this, the Institute of Electrical and Electronics Engineers Standards Association (IEEE SA) is leading the charge in defining 6G technology. The overarching goal of 6G is to further connect and integrate the physical and digital worlds into the human world **[7]**. In this thesis, we will make assumptions about the qualities the sixth-generation network will have, including the applications and technologies that will be included and why they are crucial, even though it is too soon to tell what shape 6G will finally take before it is standardized.

Chapter 2

Earlier Generations of Mobile Networks

2.1 First-generation or 1G mobile networks

Speech services in first-generation cellular networks were delivered with an analog signal. In 1979, Nippon Telephone and Telegraph (NTT) in Tokyo, Japan, developed the world's first mobile phone network. Two years later, the cellular age arrived in Europe. In 1982, the Advanced Mobile Phone System (AMPS) was introduced in the United States **[8]**. AMPS was revolutionary for the time it appeared, as it allowed multiple simultaneous uses per tower, as well as automatic handover from tower to tower. However, AMPS was soon essentially replaced by more powerful systems which were Mobile Telephone Service (MTS) and Improved Mobile Telephone Service (IMTS). The two most prevalent analog systems were Nordic Mobile Telephones (NMT) and Total Access Communication Systems (TACS).

The Federal Communications Commission (FCC) granted the network a 40-MHz bandwidth in the 800 to 900 MHz frequency band for AMPS. In reality, it was discovered that a reuse factor of a 7-cell pattern would achieve an 18 dB signal-to-interference ratio (SIR) while using 120-degree directional antennas. The signals from base stations to mobile devices used the onward-direction channel, with frequencies between 869 to 894 MHz. Utilizing these frequencies, the channel in the opposite direction was used for transmissions from mobile devices to base stations. AMPS and TACS used frequency modulation radio transmission technology **[8]**.

2.2 Second-generation or 2G mobile networks

Second-generation wireless mobile technology is abbreviated as 2G. To effectively deploy 2G cellular communication systems, the GSM standard was chosen. A 2G network allows for far greater incursion rates. According to 2G technologies, a lot of cellphone users were able to take advantage of services such as image messages, messages via text, and MMS (multimedia messaging). The 2G system was improved more efficiently than 1G. Both the transmitter and the receiver were protected by the safety features offered through 2G communication. All text messages were encrypted using digital technology. Data may be encrypted and transmitted in order that only the intended receiver can view and interpret it.

Both Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) are protocols used in second-generation protocols. The separation of signals into time slots is possible with TDMA. Meanwhile, CDMA is a type of multiplexing that enables multiple transmissions to share one channel for transmission, thereby maximizing bandwidth utilization. Each user was given a unique code that they can use to communicate via a multiplexed physical channel. In general, IS-136, iDEN, GSM, and PDC, are TDMA systems and they are all different from each other, while IS-95 is a CDMA technology.

The most admired mobile technology standard is GSM (Global System for Mobile Communication) and it was the first technology to contribute to the development of international roaming. The Group Special Mobile in Europe is where GSM first appeared. This protocol made it possible for mobile customers to utilize their connections to use their mobile phones in a variety of nations throughout the world, except for 1G technologies, which required analog signals to convey signals. GSM has enabled users to communicate via short messages (SMS) over any cellular network at any given moment. In contrast to voice calls and conferences, SMS was a quick and affordable way to convey a message to everyone. This technique was advantageous to both network operators and end-users simultaneously at that time.

Between 2G and 3G cellular communication technologies, 2.5G served as a bridge. The expression “second and a half generation” is employed to define 2G networks that use a packet-switched field along with a circuit-switched field. Because High-Speed Circuit Switched Data (HSCSD) also used timeslot bundling, it does not necessarily result in speedier services. General Packet Radio Service (GPRS) was introduced as the first significant step in the transition of GSM networks to 3G. Similar changes were made to CDMA2000 networks with the addition of 1xRTT (Single-Carrier Radio Transmission Technology) which is a functional mode for CDMA2000 wireless transmissions that establishes a single (1x) 1.25 MHz channel. Data speeds up to 115 Kbps could be offered through GPRS. It was being utilized in online communication applications such as email and World Wide Web (WWW) access, as well as services like Wireless Application Protocol (WAP) and Multimedia Messaging Service (MMS). 1xRTT produced both directions (uplink and downlink) at maximum speeds of up to 153.6 kbps on commercial networks, with a median user data throughput of 80-100 kbps.

8PSK encoding enabled the evolution of GPRS networks into EDGE networks with 2.75G. The digital mobile phone system known as Enhanced Data Rates for GSM Evolution, Enhanced GPRS (EGPRS), or IMT Single Carrier (IMT-SC), can change direction and is an addition to traditional GSM that permits improved data transmission rates. Beginning in 2003, Cingular in the US began rolling out EDGE on GSM networks. As a GSM member and a 3GPP standard, EDGE is an upgrade that has the potential of tripling GSM and GPRS network capacity. Moving to more advanced coding techniques like the 8PSK, increased the peak data rates to 236.8 Kbit/s while continuing to employ those GSM time frames as before **[9]**.

Finally, 2G networks were a substantial improvement in mobile telecommunications technology, allowing users to conduct phone calls, send text messages, and transport data at somewhat sluggish speeds. They were a significant improvement over first-generation networks, and they laid the groundwork for future advances in mobile technology. However, as demand grew for faster data speeds and more advanced applications, the limitations of 2G networks became clear. As a result, 3G networks were introduced, which enabled faster data speeds and more complex capabilities, paving the way for further improvements in wireless communications. Despite the introduction of newer technologies, 2G networks are still in use in several regions of the world, offering basic phone and messaging services to millions of users.

2.3 Third-generation or 3G mobile networks

Radio access, or UTRAN (UMTS Terrestrial Radio Access Network), which consists of the components responsible for managing radio resources and connecting to the network, was created by 3GPP as the first version of WCDMA in late 1999. The initial iteration of WCDMA was created in late 1999 and is included in the IMT-2000 specifications. HSDPA (high-speed uplink packet access), which was developed in 2002, increased the rapidity of interaction between the network and the user. Despite the fact that nearly all 3G networks are 3.5G networks, this is considered to be 3G. In theory, mobile TV, internet access, and video conferences are all conceivable at data transfer rates of up to 14 Mbps. At the end of 2004, uplink communications between users and the network displayed speed enhancements known as HSUPA. This has been dubbed as enhanced 3.5G or 3.75G, and it allows for larger capacity, a shorter delay, and further bandwidth to fulfill urban requirements **[10]**.

Numerous new terminologies for network components emerged with the launch of 3G UMTS. UTRA and UTRAN were the two popular ones. The radio access network's components, such as the base station controller and what was formerly known as the base transceiver station, are covered by the UTRA and UTRAN specifications for UMTS radio access. The Radio Network Subsystem (RNS) was another name for the UMTS terrestrial access network, also known as UTRAN. The Radio Network Controller (RNC) and Node Bs were the two primary parts of the UTRAN. The Node Bs connected to it, or the radio resources in its domain, were under the control of the RNC. RNS performed some of the mobility management and radio resource management tasks. Additionally, it was the point at which data encryption and decryption were carried out to shield user data from eavesdropping. Within UMTS, the base station transceiver was mentioned as Node B, which was the name for the base station. The transmitter and receiver for communicating with the UEs inside the cell were in this section of the UTRAN. UTRAN was involved in resource management alongside the RNC **[11]**.

Wideband Code Division Multiple Access is referred to as WCDMA. For the exact purpose of the third-generation or 3G mobile communication networks, it was one of the key systems in use. The phrase UMTS, or Universal Mobile Telecommunications Systems, was frequently used interchangeably. WCDMA was only one type of UMTS technology, technically speaking. The Global System for Mobile Communications (GSM), and CDMA were both the primary mobile phone technologies that were combined in the WCDMA system. Most mobile network operators in the US only employed one of these two technologies. The fact that WCDMA used two channels, each of which covered 5 MHz, was one of the main reasons it had trouble gaining traction in the US. Numerous nations throughout the world used WCDMA. Asia and Europe used it the most **[12]**.

To improve downlink efficiency, High-Speed Downlink Packet Access (HSDPA) technology is first presented, also known as the 3.5G system. A new downlink shared channel called HS-DSCH is what HSDPA was using. The assumption used in considering downlink improvement is that downlink traffic is significantly higher than uplink for the majority of applications, such as browsing, downloading data, etc. High downlink throughput was offered by HSDPA, but uplink data on a 3G system was constrained. Data flowed equally in both directions for some applications, such as video telephony. Therefore, improving Uplink capability was essential to creating a full 3.5G system. HSUPA was still very early in the standardization process. It was incorporated into the 3GPP Release 6 standard by standardization. It was predicted that the HSUPA technology would rely heavily on the current HSDPA (Release 5) technology. Since downlink and uplink functions in CDMA systems were fundamentally dissimilar, HSDPA technology required major advancements before it could be used for HSUPA **[13]**.

Multi-carrier modulation was being used more and more at the air-interface level as part of the Long-Term Evolution (LTE) of 3G mobile systems, also referred to as 3.9G or super 3G. When compared to already deployed cellular systems, this was primarily driven by the requirement for significantly higher data rates, improved spectral efficiency, and more flexible spectrum use. The implementation of OFDMA on the downlink and single-carrier FDMA (SC-FDMA) or DFT-spread OFDM(A) on the uplink seemed it became the most popular, however, several alternative approaches were still on the table **[14]**.

In summary, 3G networks constituted a substantial advancement in mobile telecommunications technology, enabling users to access the internet and use advanced applications on their mobile devices by providing faster data speeds. They necessitated significant infrastructure upgrades, such as the installation of new base stations and network equipment, and paved the way for the deployment of 4G networks. Users may experience even higher connection rates with 4G, allowing smooth live streaming of videos, online gaming, and other apps that demand much information. While 3G networks are no longer the most advanced mobile technology available, they still provide critical connectivity in many parts of the world, bridging the digital divide and connecting people in even the most remote locations.

2.4 Fourth generation or 4G mobile networks

In June 2005, Japan hosted the first productive field experiment for 4G. At a downlink speed of roughly 20 km/h, NTT Do Co Mo was efficient in attaining 1 Gbps packet delivery immediately. To access 4G offerings, a variety of modes of user terminals are required to be able to select the target wireless systems. In prevailing GSM systems, base stations routinely send signaling instructions to mobile devices requesting that they subscribe to services. Due to variations in wireless technologies and access protocols, this process becomes more challenging in 4G diverse and complex systems. Terminal mobility is a necessity in 4G architecture to provide mobile connectivity at any moment and from any location. By virtue of terminal mobility, mobile clients can traverse the physical borders that surround wireless connections.

The two most significant problems with terminal mobility are control of position and handoff. The technology follows and locates a mobile terminal utilizing location management to make sure an association can be established. Through location management, you can manage all of the data regarding moving terminals, involving their initial and present cell locations, authentication specifics, and so on. Even though the terminal itself roams, handoff management maintains constant contact. Mobile IPv6 (MIPv6) is a mobile protocol based on IP for IPv6 wireless networks. Within this arrangement, each terminal got its own IPv6 home address. When a terminal leaves the local network, its home address becomes invalid, and it is issued a new IPv6 address (often referred to as a care-of address) in the network that was visited.

The 3GPP established the basic principles for the next Long-Term Evolution (LTE) advanced protocols through designing and optimizing incoming wireless access strategies and the growth of the present system. Maximum spectrum effective targets for LTE Advanced networks were fixed at 15 Bps/Hz for uplink transfer and 30 Bps/Hz for downlink transfer. The coordinated multipoint (CoMP) transmission method, which involves considerable coordination between many cell sites, and improved multiple-input multiple-output (MIMO) channel transfer methods were acknowledged as the key LTE approaches in addition to multiple access strategies **[8]**.

To optimally utilize the available bandwidth for high-speed transmission with the least amount of interference, 4G networks use OFDM and OFDMA. OFDM suppresses interference by maintaining the independence of all sub-carriers. Besides, because the OFDM layout does not need guard bands, effective spectrum utilization is guaranteed. The 4G multi-carrier transfer technique known as Orthogonal Frequency Division Multiplexing (OFDM) divides the overall carrier bandwidth divided into 15 kHz sub-carriers. OFDM is strong and effective in both the time and frequency aspects. Additionally, it provides the best receiver intricacy for 4G networks' spatial multiplexing MIMO antenna technology. The multi-user form of OFDM is Orthogonal Frequency Division Multiple Access (OFDMA). In regards to the path of downlink, OFDMA can simplify communication with several users at once.

Moreover, 4G employs SC-FDMA, which is OFDMA-like but DFT-precoded to accomplish more power-effective for usage in communication through the uplink. Single Carrier Frequency Division Multiple Access (SC-FDMA) is a unique variation of the OFDM-based multiple access system that uses a single carrier as opposed to multiple carriers like OFDMA. Also, because of its power efficiency, SC-FDMA is utilized in uplink communication, resulting in longer battery life for mobile phones and a reduced level Peak-to-Average Power Ratio (PAPR) than OFDMA. Before performing the Inverse Fourier Transform (IFT), which lowers the PAPR, the symbols in SC-FDMA are first converted by a Discrete Fourier Transform (DFT) **[15]**.

4G networks have relied heavily on Multiple Input Multiple Output (MIMO) antenna technologies. On top of that, to increase data throughput and signal quality in 4G networks, the MIMO architecture has undergone numerous improvements. MIMO is a 4G LTE antenna technology that employs several antenna components at the sender and the recipient to enhance data rates and signal quality. Also, to increase network quality and data throughput, MIMO uses spatial multiplexing, diversity, and beamforming techniques **[16]**.

A radio wave can be directed at its target via a process called beamforming. Normally, once a signal leaves the antenna, it spreads out and loses most of its intensity in the process. With beamforming, the focus of the signal is narrowed and travels straight to the connected device. The absence of multi-path interference helps maintain the signal's intensity. A key component of LTE, MIMO technology is used in beamforming. High data rates can now be transmitted thanks to this. Beamforming uses the same method as communications with numerous antennas. The beamforming feature on devices directs their frequencies in the direction of each recipient **[17]**.

The introduction of 4G cellular networks was a watershed moment in the history of mobile communication. These networks enabled the broad adoption of multimedia applications and mobile internet browsing by providing faster data transfer rates and reduced latency than their predecessors. 4G networks also cleared the way for IoT, and the exponential rise of multimedia applications, however, the increasing number of intelligent devices put a strain on them. To address the increased need for higher data rates and capacity, new technologies and improvements to current ones were critical. The development of 5G cellular systems attempts to address the shortcomings of 4G networks by providing networks with lower latency, improved service quality, faster data rates, and expanded capacity. The introduction of 5G networks heralds a new era in mobile communication, allowing new applications and technologies and paving the way for a more connected and smarter society.

2.5 Fifth-generation or 5G mobile networks

The fifth-generation or 5G cellular communication network, which supports IPv6, MC-CDMA, LAS-CDMA, Network-LMDS, UWB, and OFDM, is today's true wireless world. Since 5G has no restrictions, it might be referred to as the ideal actual wireless world or World-Wide Wireless Web (WWWW). IPv6 is the most important standard for both 5G and 4G networks. 5G intends to give everyone in the world unrestricted information accessibility and the freedom to exchange data at any moment, anywhere. All the innovative characteristics that render 5G mobile technology the most potent and in high requirement now are covered by IPv6. For the exact purpose of mobile and wireless network interoperability, 5G mobile is IP-based **[18]**.

As already mentioned, for OFDM to function, the electromagnetic signal must be divided into various shorter sub-signals that are then concurrently delivered to the recipient at various frequencies. Large Area Synchronized Code Division Multiple Access (LAS-CDMA) is a standard that expands voice capacity and permits data transmission at high speeds. It is intended for international areas as well. Multi-Carrier Code Division Multiple Access (MC-CDMA) is intended to operate over a large region known as a macro cell. Broadband wireless networking is employed to transmit data on the internet, as well as video conferencing services in the 25 GHz spectrum and above is called Local Multipoint Distribution System (Network-LMDS) and is made of micro-cells.

Within the integration of the MC-CDMA WLAN network, data services are offered by means of 5G true wireless multimedia internet access on mobile devices. As a result, the fundamental parts of the CDMA-WLAN packet dominance design are altered. Mobile nodes (MN), access points (AP), packet control functions (PCF), base stations (BS), packet data service nodes (PDSN), and packet data interworking functions (PDIF) make up the architecture. MN's primary system elements can include a personal digital assistant, phone, laptop, tablet, etc.; they can all operate under the entire TCP/IP protocol suite with information and concepts of applications for multimedia. MN's radio interface and radio connection management are provided by the BS and the AP. Furthermore, they both offer connectivity to the PCF and PDIF **[19]**.

When discussing 5G and the latest developments in LTE, the keywords massive MIMO (mMIMO) and beamforming are frequently utilized in the telecommunication sector. As is already known in MU-MIMO, the base station uses the same time-frequency resources to deliver multiple data streams, one per-user equipment. As a result, MU-MIMO boosts cell capacity by increasing overall cell throughput. One antenna port is required in each UE, and the BS has as many antenna connectors as UEs collecting information concurrently. The definition of mMIMO that is most often used is a system in which there are more antennas than users. Massive in this context refers to the base station having 32 or more rational antenna connectors. 5G is anticipated to launch with at most 64 rational antenna connectors.

Sometimes, the phrases beamforming and mMIMO are used synonymously. To put it another way, beamforming is a part of mMIMO or is employed in mMIMO. Further, by ensuring that the magnitude and phase of each antenna input are correctly balanced in an array of numerous antennas, beamforming often employs many antennas to regulate the direction of a wavefront. In other words, the same signal is transmitted using numerous antennas with enough distance (at least a wavelength) between them. The receiver will consequently pick up many duplicates of the identical signal in any given location. The signals could be constructively summed up if the many copies are in the same phase, destructively averaging each other out if they are in different phases, or anywhere in between depending on where the receiver is **[20]**.

High-band, ultra-wide mmWave spectrum is used in 5G Ultra-Wideband (UWB) to provide the best performance and the quickest 5G speeds. You can stream movies with excellent picture quality, play games with no lag, and conduct video calls thanks to 5G Ultra-Wideband's near-zero lag experience. The 5G Ultra-Wideband's capabilities are excellent. Also, without affecting local data transfers, the 5G ultra-wideband can provide phone users with excellent data transmission speeds. Healthcare, entertainment, public works, and the automobile industries have all been shown to be transformed by 5G UWB. Large capacities are supported with ultra-wideband 5G. This suggests that this network delivers dependable performance in some areas **[21]**.

As 5G is being constructed, its coverage primarily will rely on beam-based technology, which marks a departure from the conventional cell-based approach utilized in earlier generations of cellular networks. There isn't a reference channel that can be used to measure a cell's coverage. In contrast, Synchronization Signal Block Beam (SSB) beams are present in one or more numbers in each cell. SSB beams always point in the same direction and are either semi-static or just static. The entire cell area is covered by a grid of these beams. The UE maintains a set of candidate beams and searches for and measures the beams. Multiple cells' worth of beams could be included in the potential set of beams. For each beam, the measurements are SS-RSRQ, SS-RSRP, and SS-SINR. The identifications separating beams from one another are beam ID and Physical Cell Identification (PCI). These metrics can be measured in the field using test UE as well as scanning receivers. Therefore, in the field measurements, SSB beams appear as a sort of new coat of smaller cells inside each cell. Naturally, it must be remembered that 5G can function without beamforming. In this situation, an individual SSB beam would spread across the entire cell region. Because the SSB beam corresponds to the cell, every aspect of coverage evaluation techniques would revert to those used in LTE **[20]**.

The commercial entry of 5G networks in 2020 was driven by the need to significantly improve mobile network features, especially the Quality of Service (QoS). The primary objective of 5G engineers became the virtualization of network services, which are accountable for the administration and handling of QoS in the network. This is because the principles of QoS handling are being maintained during the 4G to 5G conversion. Algorithms for traffic classification, which will support market developments, including changes in the requirements for services and customers' wants, will be another area of research. Video services and services based on the widespread use of M2M devices in most businesses and customers' homes will be the focal points of future mobile services **[22]**.

The development of 5G provides seamless connectivity throughout the wireless community. Numerous difficulties are created by this innovative technology, and it is anticipated that mobile terminals with constrained resources will be able to access more individualized and interactive services. Mobile Cloud Computing (MCC), which is currently being developed in the setting of 5G, can overcome this restriction and enable numerous demanding of resources and services for customers on the move by utilizing mobile big data transportation and cloud-assisted computation. Intelligent 5G technologies make it possible seamless connectivity to the wireless world. 5G mobile networks are opening the path for developing software-intensive applications that make use of complicated enormous amounts of data assisted by cloud computing with MCC **[23]**.

A significant enabling technology for 5G network operators to deliver a variety of customized services on-demand and sustainably is network slicing based on cloud computing and Network Functions Virtualization (NFV). To fulfill the ambitious objectives of the 5G system, numerous technological challenges still need to be resolved **[24]**. A shared network domain is a grouping of shared network and computing assets and is layered with several virtual networks through the process of network slicing. The expression "network slicing" usually appears in conversations about 5G networks, owing to the fact that this capability is demanded by the specification for 5G, whereas it wasn't available and was unable to be accommodated by 4G and previous generations of mobile services for communication. Each of the sections of a network can have its own conceptual architecture, rules regarding safety, and operational attributes within the constraints established by its foundational network infrastructure. Various slices may be allocated to various assignments, including separating flow for particular customers or device classes or ensuring that a specific application or service has the highest priority when it comes to capacity and transmission **[25]**.

The fifth-generation mobile networks are expected to be succeeded by the sixth-generation networks. The forthcoming 6G technology promises significantly enhanced bandwidth and network speed compared to 5G networks, primarily due to its ability to operate at higher frequencies. According to predictions, 6G aims to provide internet access points with an incredibly low latency interval, estimated to be one thousand times quicker than the one-millisecond latency offered by 5G. The deployment of 6G is anticipated to bring substantial advancements in visual and display technologies, as well as location awareness. It is important to note that 6G is not currently functional technology. While some vendors are preparing for its implementation, the availability of 6G-capable network services may still experience occasional downtime due to ongoing challenges within the industry **[26]**.

Chapter 3

Building the Foundation for 6G

3.1 Introduction to 6G Technology

The focus of the network shifts with each new generation of communication technology. The 2G and 3G eras were focused on human-to-human communication via voice and text. The 4G era lauded a huge transformation toward massive data usage, whereas the 5G era has transitioned its focus to linking the Internet of Things and manufacturing automation systems. The electronic, physical, and sentient worlds will merge seamlessly in the 6G era, triggering extrasensory experiences. Insightful information systems will also be merged with rigorous simulation competencies to render people infinitely more productive and to reframe how we continue living, working, and caring for the planet. Despite the fact that there has yet to be a great deal of progress in 5G with the introduction of the latest 5G-Advanced standards, experiments on 6G have already officially started in hopes of making it available to consumers by 2030.

5G is currently the winner of telecommunications, but 3GPP and many network experts have already started concentrating on 6G. Although 6G may be as many as eight or more years away, this shouldn't be too surprising. That's because, regardless of the fact that details are questionable right now, a prospect with 6G networks offers incredible opportunities. The field's specialists are ecstatic about the technological breakthroughs associated with 6G. In support of the limited collection of authorized security needs, public and private enterprises will be obligated to comply with protective measure evaluation criteria, along with the smallest entity in the end-to-end distribution chain. Global 6G proposals and correlating investment opportunities paint a very bright potential for its advanced design.

There has been an increasing number of 6G technology research projects trying to investigate what would be possible alongside what's required. The real template for 6G will be determined by how 5G evolves and where its gaps appear to be. There are currently numerous unique use cases proposed, yet only in the future will determine what the utilization is and how 5G is being used. It is predicted to be progressively utilized within IoT, and even for inter-vehicle connectivity for self-driving cars. It remains uncertain how this entire situation plays out. If there are inconsistencies in 5G, these can be addressed in 6G propositions. Moreover, among the regions that are expected to be a major aspect of 6G is using Terahertz for sharing information. Massive bandwidth utilization will become obtainable using these incredibly high frequencies, however, the system for achieving this currently isn't operational yet.

3.2 Developing 6G Standards for Efficiency

The merging of the real and virtual worlds in all measurements will serve as the key driver behind future 6G wireless systems. People, computers, robotic systems, and their digital equivalents require pervasive in-time and on-time network connectivity that extends from the earth to the atmosphere, space, beneath, and deep water. 6G systems are highly distributed computing systems that can include multiple sensors, handling, stockpiling, information exchange, and computational power. Building pervasive and smart 6G systems that can manage QoS requirements, provide such a wide variety collection of communication mechanisms as multicast, in-cast, unicast, and group-cast, and endorse mobile applications centered on customers is challenging.

A way of communicating known as multicast involves sending information from one source to a number of recipients. This is helpful when distributing identical data to numerous people, such as during video streaming or conferences. Numerous sources transmit data to many different recipients through an in-cast communication technique, but just a portion of the sources' data must be received by each recipient. When substantial quantities of data must be moved among servers in data center systems, this is helpful. Data can also be transferred from a single point to one recipient in a form of communication known as unicast. This is the most popular form of correspondence on the internet and is frequently utilized for activities like sending emails or browsing the web. A group-cast way of communication involves sending data from one sender to a designated set of recipients. Identical to multicast, but with a more condensed and fewer number of recipients. Applications like services that use location or alerts for emergencies can employ group-cast **[27]**.

As already discussed, the primary focus of 6G wireless communications' goal is the concept of surpassing 5G's capabilities. In the case of Internet of Everything (IoE) applications like UAVs, 3D videos, VR, AR, etc., a Gbps data rate provided by 5G mmWave is unlikely to be enough to satisfy their requirements. Anticipated advancements in the future include global expansion and enhanced coverage, increased spectrum efficiency, ultra-high connection speeds, and the integration of AI-enabled management. These advancements mark a significant leap from "interconnected devices" to "connecting intellect." Additionally, they address concerns related to Quality of Experience (QoE) and Quality of Service (QoS). Moreover, addressing the difficulties associated with information exchange in the long term, when the physical and digital sectors collide is another concern **[28]**.

The Quality of Experience (QoX or QoE) serves as a measure of a provider's ability to satisfy customers. QoS, which illustrates the concept that both software and hardware attributes are measurable, enhanced, and possibly assured, is linked to QoE but is distinct from it. The phrase "quality of life" (QoL) refers to a person's general sense of well-being and fulfillment in life. Physical and mental health, social connections, economic position, and environmental elements are all part of the multifaceted idea of quality of life **[29]**. Excellent QoL communication technology will be made possible with 6G technology. Despite not being an indispensable part of 6G technology for communication, QoL shall be critically important to smart medical facilities. Great QoE and the envisioned QoL indicators are likely to be supplied by 6G.

Massive multiple-input multiple-output (MIMO) networks are used in cell-free massive MIMO communication systems, a developing technology that seeks to overcome the limits of conventional cellular networks. Cell-free networks have a distributed architecture with several access points dispersed throughout the service area, in contrast to typical cellular networks where base stations are built in a grid-like pattern. By doing away with the idea of discrete cells, this method enables a more adaptable and effective use of network resources. Cell-free massive MIMO networks may simultaneously serve multiple users with high spatial multiplexing gains and increased spectrum efficiency by utilizing many APs outfitted with a gigantic array of antennas. Advanced methods for signal processing are used in these networks to reduce interferences, allocate resources optimally, and improve overall network performance. Cell-free mMIMO networks possess the capacity to serve a huge number of devices and offer seamless connectivity, allowing them to carry out the rising needs for future wireless telephone networks **[30]**.

6G wireless telecommunication networks are expected to extend capabilities to the higher mmWave band between 100 and 300 GHz and the terahertz (THz) band between 300 and 3000 GHz. Upcoming 6G technologies will aim for maximum speeds of up to terabits per second with reduced transmission delay. Communication bandwidths must be substantially greater than what current 5G networks and bandwidth restrictions under 100 GHz can supply. It is obvious that the move from the low frequency mmWave zone to THz is going to require important scientific advances in fields ranging from hardware to software. When developing standards for 6G, it is critical to take into account these possibilities comprehensively and plausibly.

Transmitter power production competence, recipient noise, and employed antenna gains among the two link sides influence range. Given that radio frequency power production possesses become less frequent as an indicator of frequency because of semiconductor tools, the incredibly excessive transmission reduction associated with THz frequencies needs to be reimbursed primarily by extremely powerful antennas. The limited width of the beam of powerful antennas is caused by their orientation. Even modest movement turns difficult, necessitating the use of adjustable antenna suggestions, such as switching beam lens antennas, as well as advanced beam collection and monitoring procedures. Due to antennas being huge and their beams being quite narrow, long-distance connections appear to be practical only for designated transceivers with particularly high antenna profits **[31]**. However, the utilization of narrow beams in 6G networks, despite their advantages such as increased spectral efficiency, can lead to higher transmission costs, thereby posing challenges in network design.

Plenty of investigations were considered and published in the past few years involving the utilization of various high-frequency bands for rapid communications, which are indicated as possible options for 6G **[32]**. Specifically, a group of the Defense Advanced Research Project from the IBM Corporation, and Intel have concentrated their efforts on researching the utilization of 140, 220, and 340 GHz frequencies. They delivered a comprehensive examination of the terahertz spectrum in the region between 0.1 to 10 THz for enabling terabit-per-second transmissions at lightning speeds back in 2014 **[33]**. Terahertz spectrum transmission has also advanced because it is capable of supporting purposes that are both large-scale and small-scale, like terabit WLAN and nano-sensor systems **[32]**.

A great deal of end devices could effortlessly function in a network thanks to 6G's predicted extension of 5G's capabilities when it comes to minimal latency and high speed of data. As opposed to this, ultra-reliable low-latency communication (URLLC) offers a very high degree of network durability and just a small packet transmission latency. Both features make URLLC an important consideration for 6G services given that it offers data transfer in a couple of milliseconds or microseconds with outstanding reliability. For a number of sectors, including medical care, transport, production, and energy, URLLC will likely be a breakthrough in 6G. In general, it is believed that URLLC will create a broad spectrum of opportunities for mission-critical applications that rely on excellent dependability and low delay **[34]**.

Among the main motives behind the development of 6G systems is the implementation of edge computing. Mobile (or Multi-access) edge computing (MEC) is being viewed as an intriguing strategy to make cloud-based computing features inside the framework of the radio access network (RAN) more accessible to the end-users because of the remarkable rise in the amount of traffic and processing workloads for forthcoming connections. There appears to be a lot of study on MEC including its possible uses, although nothing has been done to shed light on the crucial aspects of MEC implementation that need to be considered in order to satisfy the various requirements for possible uses **[35]**.

Regarding the upcoming wireless technologies, like 6G, to be ubiquitous and pervasive, intelligent communication environments are necessary. These settings go beyond conventional network optimization techniques and concentrate on exerting control over wireless signal propagation. Intelligent communication environments use cutting-edge technologies to actively shape and manage electromagnetic waves in both indoor and outdoor settings, in contrast to earlier systems where the environment for wireless communication only had a supporting function. These settings provide better signal quality, less interference, greater coverage, and effective spectrum usage by intelligently managing how waves interact with their surroundings. The creation of strong, dependable, and high-performance wireless networks that can adapt to changing environmental circumstances and provide seamless connectivity experiences across numerous usage scenarios is made possible by intelligent communication environments in 6G **[30]**.

IEC stands for "Intelligent Edge Computing" and it was developed by the Industry Specification Group (ISG) of the European Telecommunications Standards Institute (ETSI) to improve the edge of a network's preservation and computation capabilities. Additionally, IEC's characteristics support movement, offer determining and mobile connectivity, and facilitate sharing of information at all times and any place. IEC is regarded as a mobile connectivity architecture that enables effective and seamless interaction among various mobile equipment. Additionally, IEC is a framework that brings the assets that are needed in proximity to the networks that rely on them in order to decrease the capacity and delay. This assertion's foundation relies on the optimistic assumption of fewer capital investments and the future introduction of more amenities, which might be supplied independently but might be released at any time **[36]**.

The Self-Evolving and Transformative (SET) protocol structure, proposed by Xiangyu Ren, Xuemin Shen, Wenjun Yang, Lin Cai, and Jianping Pan **[37]**, has the potential to offer a wide range of functionalities for various types of 6G applications and communication environments. The protocol structure can be altered throughout the course of a flow, allowing for modifications in response to changing inputs. Network protocols can now be designed using a flexible, object-oriented, and domain-specific technique thanks to the suggested SET standard architecture. The standard can adjust to the 3D environment and deliver a wide range of features by utilizing clever Protocol Control Agents (PCAs). The data plane and the control plane protocols make up the two planes of the protocol architecture as you can see in Figure 1 the proposers made. To administer data plane protocols in real-time, the control plane focuses on packet stream and control by using specific functions, AI, and machine learning.

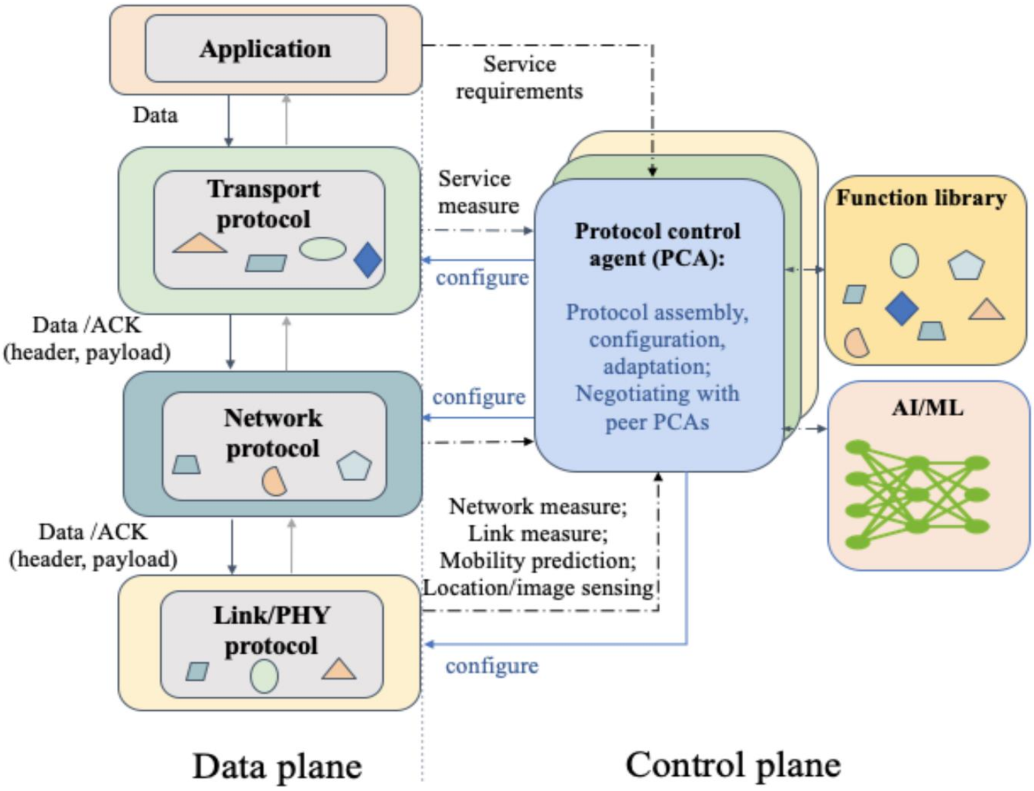

Figure 1. SET protocol architecture **[37]**

Protocol function composition and protocol assembly by PCAs in accordance with service constraints and network metrics, as well as the creation of advanced control functions for PCAs to maximize the performance of routing protocols, are the three steps in the development of SET. Unwanted redundancy and repetition can be eliminated by breaking down protocol functions into separate and self-contained blocks. This enables the flexible assembly of selected building components into comprehensive, distinctive protocols according to the corresponding layer in the data plane. SET offers distributed and independent in-network intellect, adaptive spectrum, movement scheduling, QoS assistance, and ubiquitous intellectual ability thanks to combined detection, interaction, storage, computing, and management **[37]**.

An innovative architecture proposed by Tao Sun, Huanxi Cui, Xianbin Cao, Ning Zhang, Jun Zhang, Yuhui Geng, Qihui Wu, Zhenyu Xiao, and Jiajia Liu for the sixth 6G mobile communication network, is called the Space-Air-Ground Integrated Network (SAGIN) **[38]**. Based on the limits of the current 5G network, SAGIN intends to convene the needs of new uses of technology, such as ubiquitous coverage, the Industrial IoT (IIoT), pervasive AI, and digital twins (DT). A flexible and adaptive network that seamlessly combines communication capabilities from space, air, and ground is what SAGIN envisions. SAGIN assures ubiquity of coverage, even in distant or difficult situations, by fusing satellite-based connectivity, unmanned aerial vehicles (drones), and terrestrial base stations. In addition to meeting the enormous connection, high bandwidth, and low latency requirements of IIoT, ubiquitous AI, and digital twins, SAGIN caters to real-time applications, such as autonomous vehicles and telesurgery, with a focus on low latency and effective resource allocation. To accommodate the changing demands of upcoming mobile networks and to make a variety of cutting-edge applications possible, the suggested SAGIN architecture offers a potential road forward.

Also, in the context of a distributed 6G network architecture, research by Gianluca Reali and Mauro Femminella focuses on suggesting a gossip-based approach for exchanging monitoring data pertaining to service functions (SFs) **[39]**. The authors stress the necessity of a data distribution and monitoring function that offers a current snapshot of the network's resource state. They introduce local monitoring agents (MAs), which are collocated with each orchestrator in computer clusters and facilitate a distributed monitoring procedure. Using a gossip protocol, the MAs collect data about SF status and service capability and share it with other MAs. Each local orchestrator can have an up-to-date view of the entire network or slice thanks to this method. The suggested gossip protocol integrates a discovery function into the monitoring protocol itself, obviating the need for a separate mechanism, and it makes use of packet interception capabilities to increase operational efficiency. Overall, the suggested strategy provides a distributed and reliable approach to deal with the 6G networks' dynamic nature.

Shuo Wang, Tao Sun, Hongwei Yang, Xiaodong Duan, and Lu Lu from the "China Mobile Research Institute" **[40]** presented a novel perspective on the highly distributed, autonomous, and globally unified structure of the 6G network in their research. The proposed network design approach places a priority on top-heavy distribution, multi-way growth, a stable size-free form, and vertical distribution. It was motivated by the effective organization of ant nests. By extending the deployment of network functions from the core network to the edge and creating a multilevel network architecture with centrally heavy function distribution, the goal is to increase network efficiency and scalability. Using this strategy, it's feasible to use both robust and sophisticated network methods in the core network as well as basic functions at the network's edge that provide proximity services to user terminals and reduce the stress on the core and backhaul networks. The authors present the concept of a distributed autonomous network as the 6G network structure which is presented in Figure 2.

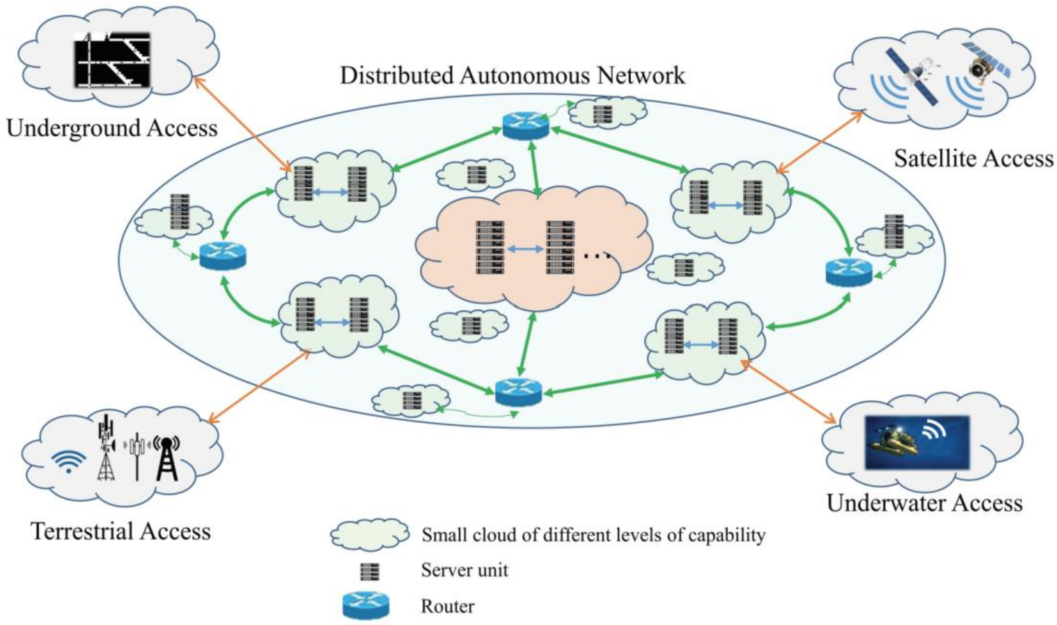

Figure 2. Distributed Autonomous 6G Network **[40]**

Additionally, the article of the proposers emphasizes the significance of globally converged network design to control the growing quantity of traffic and device diversity. The suggested design includes numerous access clouds that cover the terrestrial, satellite, subsurface, and underwater domains to accomplish this. A distributed autonomous network with distributed homogeneous small cloud units

(SCUs) with various levels of capacity connects these access clouds. Each access cloud establishes a connection to the autonomous network through the nearest SCU, and all transmissions within and between SCUs use a uniform end-to-end simple protocol. The ultimate objective is to offer universal accessibility and standardized end-to-end data forwarding methods for a variety of communication systems, including Wi-Fi, terrestrial mobile networks, fiber networks, and satellite communication **[40]**.

In comparison to their predecessors, 6G networks are anticipated to be significantly more complex due to the abundance of linked devices and services that would produce enormous volumes of data. 6G networks are projected to largely rely on artificial intelligence technology to manage this complexity and assure the effective use of network resources. By forecasting traffic patterns, discovering congestion hotspots, and dynamically allocating network resources, AI can be used to enhance the functionality of 6G networks. This can lower latency and packet loss while increasing the network's overall efficiency and dependability. AI is perhaps utilized to optimize the routing of online movement while taking into consideration variables like bandwidth accessibility, delay, and network bottlenecks. This can aid in reducing delays and lowering the possibility of network faults by ensuring that traffic on the system is routed effectively. AI can be employed to keep track of the condition of a system's architecture and forecast when upkeep or upgrades are necessary. This can aid in lowering interruption and enhancing the network's total dependability **[41]**.

Artificial intelligence that is widely included in 6G's design and operation is referred to as being “pervasive.” In order to improve many facets of performance and functionality, entails the deployment of AI algorithms and techniques throughout the network infrastructure. Pervasive AI in 6G offers intelligent resource allocation, network optimization, and adaptive decision-making, improving the effectiveness, dependability, and scalability of the wireless communication system. 6G networks can dynamically adapt to shifting network conditions, effectively manage network resources, and offer improved connectivity experiences by utilizing AI capabilities. Pervasive AI in 6G aims to build intelligent and adaptable wireless networks that can successfully handle the rising demands of various applications and user requirements **[30]**.

3.3 Utilizing Techniques for 6G Safety

As mobile networks evolve and 6G networks are being designed, security will become an even greater problem, which is why we need to discuss blockchains. Blockchains are distributed ledgers that are kept running by a peer-to-peer (P2P) network of machines. As suggested by its title, a blockchain is made up of a number of transactional pieces that are mathematically connected or chained altogether to generate an electronically stored log. A “block” is subsequently generated out of confirmed actions that occurred during a specific time frame. Due to this, there is a set of possible actions within every block. These blocks have rational connections according to the creation order determined by hashes of cryptography. Accordingly, the “previous block hash” section of every single block contains the message digest of the prior block. The “genesis block” is the first block and contains zero antecedents. The genesis block's previous block hash section is consequently set to zeros **[42]**.

The use of blockchain in current networks, as well as distributed databases overall, has recently picked up steam and has been welcomed by academic and industrial institutions all around the world for future networks like 6G. A few benefits of blockchain computing include decentralized management, which gets rid of the necessity for service providers and centralized trusted third-party administrators, but also being open with confidentiality; and, origin and refusal of the transactions created, including the permanence and tamper-proofing of the public record's material. In addition, its other use is removing just one point of inability with enhancing resilience and resentencing to hacking attempts like distributed denial-of-service (DDoS) attacks, as well as relatively less analyzing postponement blockchain is therefore viewed as a crucial tool for establishing reliability in potential systems **[43]**.

Blockchain, the underlying technology for Blockchain-based integrated security measure (BISM), serves as a crucial component in ensuring secure internet connections and user confidentiality. It stands as one of the supporting techniques in 6G communications for enhancing safety in various applications. The accessibility and privacy-related security procedures have been adjusted to handle dispersed virtual assets in the 6G context. There is a considerable likelihood of illegal utilization of virtualized assets that masquerades as linked user security. Additionally, because of unlawful access, abuse of resources in terahertz transmission technologies is prevalent. The goal of asset duplication is defeated if a third-party user seizes control of the virtualized asset, which results in the main resources being indifferent. In order to avoid unwanted access to the complete virtual asset system, BISM emphasizes safeguarding end virtualized assets **[44]**.

Blockchain technology can improve security by offering tamper-proof and secure data storage and movement. Blockchain ensures data integrity and immutability by applying cryptographic methods. It is very challenging for hostile actors to alter or manipulate the data since transactions recorded on a blockchain are encrypted and linked together in a chain. Blockchain is suited for applications where security and reliability are crucial, such as in financial transactions, supply chain management, and medical data, thanks to this property. Additionally, the distributed structure of blockchain lessens reliance on a single centralized authority and increases its resistance to attacks by distributing data across a network of computers.

Blockchain can provide pseudonymity and transparency in terms of privacy. Although most blockchain transactions are visible to the public, users can still protect their privacy by using cryptographic keys. Individuals are able to manage their identities and release information only when they want to. People can authenticate their identification, for instance, in a blockchain-based digital identity system without disclosing any personal information, maintaining their privacy. Blockchain can also provide secure, permissioned data sharing where users retain control over their data and can grant access to certain parties while protecting their privacy from others.

It can be guaranteed that 6G networks will accommodate cutting-edge applications with difficult measurement requirements, made possible by innovative technological advancements and network design concepts. In the past few years, quantum information technology (QIT) has evolved fast across the fields of quantum telecommunications and quantum computation, paralleling the growth of cellular networks beyond 5G to 6G. As we already know, quantum computing is a revolutionary way of calculating that employs basic scientific concepts to tackle highly challenging issues rapidly. That is why QIT is projected to help facilitate and enhance upcoming 6G technologies simultaneously from a connectivity and computation standpoint. Reliable quantum interactions, like quantum key exchange, it may be used to boost 6G safety.

Quantum information technology is divided into four different groups: quantum physics, quantum interactions, quantum computation, and quantum detection and measurement. Quantum physics offers the mathematical underpinnings and fundamental components for quantum interactions, quantum computation, quantum detection, and measurement. Entanglement, for instance, may be used for not simply quantum telecommunications yet additionally quantum computation and detection. Furthermore, quantum interaction and quantum computation can complement one another and be combined to transform the traditional Web into the eventual quantum Internet. As one of the fundamental quantum interaction protocols, quantum teleportation holds the potential to facilitate the transfer of quantum information among quantum machines in the context of 6G technology **[45]**.

The convergence of blockchain and quantum computing could, however, provide certain challenges. The potential risk that quantum computing poses to the safety of conventional encryption techniques is one of the primary challenges. Current encryption techniques may be vulnerable to quantum computers' capacity to answer some mathematical problems exponentially quicker than traditional computers. This puts the safety of blockchain systems that rely on conventional cryptography at risk. To combat this, work has been made to develop resistant cryptographic algorithm assaults from quantum computers that are quantum resistant.

The scalability of blockchain networks presents another challenge. The network may slow down and perform less effectively as users and transactions grow. This is due to the possibility of bottlenecks caused by the requirement for many network nodes to evaluate and record each transaction. To overcome this difficulty and enable blockchain to manage a bigger volume of transactions without compromising security and privacy, sharding and layer-two protocols are being investigated. Furthermore, many blockchain networks, particularly those that use proof-of-work consensus methods, raise questions about energy consumption. Energy-intensive computing may be needed to verify transactions and maintain the blockchain. To lessen this environmental impact, attempts are being made to create more energy-efficient consensus procedures.

Chapter 4

Emerging Applications and Use Cases for 6G

4.1 Exploring the Real-World Applications of 6G

As our reliance on mobile technology rises, technology firms are already anticipating 6G networks and their potential to transform the mobile technology field. 6G networks, which have faster speeds, more capacity, and lower latency than their predecessors, generate new use cases and applications in fields like virtual and augmented reality, autonomous vehicles, remote education and training, and financial services. Furthermore, the predicted benefits of 6G systems are the acceleration and integration of artificial intelligence and the growth of the IoT, opening fresh possibilities for innovation and economic expansion. The boundless potential of 6G networks appears to be transforming the future of cellular networks, making it an exciting moment to be a part of this industry. Some of its fundamental applications are addressed in more context below.

4.1.1 Virtual and Augmented Reality

Augmented Reality and Virtual Reality are significant concepts in today's growing technologically advanced world. Despite the fact that these are two distinct inventions, the phrases are frequently used interchangeably. Augmented Reality (AR) merges the digital and physical worlds. It is a type of technology that may be used on smartphones and desktop computers. The thing that distinguishes it is the ability to mirror digital elements in reality. The primary distinction that exists between AR and VR is that VR is generated by a computer representation. This implies that actuality or an alternate universe is created visually. It may be feasible to totally engage the consumer in the digital environment through the use of suitable equipment. VR hardware necessitates perceptual sensors that convert actual body motion into a simulated environment. As a result, there are significant distinctions between AR headsets and VR headsets.

The goal of virtual reality aims to create an alternate world. An individual can see and participate within the online environment through the use of a VR display. This necessitates the placement of glasses separating the individual using it and the display. The lenses detect how the eyes move and adjust personal motion to the environment of VR. As a consequence, substantial equipment is required in this situation to separate the person using it from his/her true surroundings. The integration of AR and VR creates a symbiotic relationship between great technologies. While they can be used alone, when paired together, they provide consumers with a more enriched and enjoyable journey. The idea is to build an imaginary dimension that can nevertheless relate to the actual world around it **[46]**.

The upcoming breakthrough in technology is mixed reality, which will be accompanied by computer systems, PCs, and cell phones. For customers as well as businesses, mixed reality is gaining popularity. Supplying simple interactions with information within our residences and with those we love, allows us to discover things outside the constraints of screens. The best elements of VR and AR are combined in mixed reality (MR/XR). It's all about creating an absorbing, engaging fusion of virtual and real-world content. In mixed reality, virtual items blend in seamlessly with the real environment and hide behind them. The shadows and lighting of virtual stuff can also be affected by real items. The seamless integration of the real and virtual worlds in 6G enables the exploration of novel solutions that were previously inconceivable with VR or AR alone **[47]**.

For the impending 6G mobile communication network, particularly stringent networking requirements have been established by the development of virtual reality (VR), augmented reality (AR), and extended reality (XR) applications. To provide smooth and immersive user experiences, these immersive technologies significantly rely on real-time and extremely low latency connectivity. A major improvement in networking capabilities is required to support the exceptionally high data speeds, very low latency, and stable connectivity demanded by VR/XR/AR applications. 6G networks must provide an exceptionally minimal delay of communication, ultra-high-speed wireless communications, and reliable access even in highly dynamic surroundings in order to enable realistic and engaging experiences. For VR/XR/AR technologies to reach their full potential and offer users immersive and fascinating experiences in the future, it will be imperative to meet these strict networking criteria.

The arrival of 6G networking has the potential to transform how we communicate through virtual and augmented reality software. With the upcoming version of cellular communications technology, 6G guarantees far more rapid speeds and more information capacity than current 5G systems. This might encourage the adoption of AR and VR programs for deeper, more realistic, and more engaging interactions. 6G systems are intended to provide a maximum of one terabit per second rate, meaning they're roughly twenty times quicker than 5G connections. Consumers may be able to take advantage of AR and VR applications with close to zero delay and without buffering as a result of this. Furthermore, 6G technologies are projected to provide improved reception, allowing consumers to participate in AR and VR activities in a wider range of places.

Both enhanced speed and capacity of 6G connections may potentially render further developed use cases for AR and VR technologies conceivable. Also, 6G connectivity may support multiple users' virtual reality adventures alongside more intricate, lifelike visualizations and dynamics. 6G connections may potentially enable more complex AI methods, such as human speech understanding and face identification, to be deployed with AR and VR apps. Additionally, 6G may enable the creation of AR and VR software considerably quicker and more effectively. Using faster connectivity, programmers can reduce time by swiftly downloading and uploading information, as well as evaluating their programs instantaneously. The above has the potential to render the task of designing AR and VR applications considerably easier and less time-consuming, which would potentially be extremely beneficial to developers **[48]**.

4.1.2 Autonomous Vehicles

One of the major applications that are anticipated to considerable profit from the improvements in 6G networks is autonomous vehicles. Self-driving cars will need extremely dependable and low-latency communication networks to ensure safe and effective operation as they become more common. By having ultra-low latency and high-speed connectivity, 6G networks can supply the foundation required to support autonomous vehicles. This enables real-time data interchange between vehicles, infrastructure, and the cloud. This would make it possible for autonomous vehicles to exchange vital information like road conditions, traffic patterns, and potential hazards as well as converse with one another and make choices in concert. Additionally, 6G networks can make employing of cutting-edge innovations like edge computing and network slicing to improve the functionality and effectiveness of autonomous vehicle networks, ensuring dependable and uninterrupted communication even in highly dynamic and demanding circumstances. Overall, the adoption of autonomous vehicles with 6G networks possesses the capability to completely make them safer to change the way we travel, more effective, and less harmful to the environment.

In the most recent iterations of the automated driving network, autonomous driving cars (AVs) are anticipated to detect the objects around them by processing a sizable volume of data collected through a number of onboard sensors in close immediately. Due to this, the AVs will incur significant computing costs while processing tasks using the implemented machine learning model, and inference correctness might not always be assured. Considering this, multi-access edge computing (MEC) and machine learning are projected to be made available to AVs in close vicinity thanks to the development of edge intelligence (EI) and WLAN of the sixth generation **[49]**.

4.1.3 Healthcare

The fast creation of mobile applications is accelerated by developments in wireless technology. Our lives will change dramatically and fundamentally as a result of the impending mobile revolution. It will have an impact on how we act, how we live, and how we maintain our health as the experts say. Mobile applications give the healthcare sector an exciting opportunity in providing patients with improved care and services, as well as a more adaptable and mobile means of connecting with suppliers and patients. Vital immediate information will be made available through mobile apps to patients, doctors, insurance companies, and providers. In addition, it will change how doctors and patients interact, and it will fundamentally change how data is managed in the healthcare industry **[50]**.

Around 2030 and from then on, the entire health business will be dominated by the promised 6G communication technology. It will rule a variety of industries in addition to the health industry. Healthcare is one of the many industries that 6G is predicted to transform. The future of healthcare would be based on AI and reliant on 6G connectivity technologies, altering how we view lifestyle. The main obstacles to health care today are time and distance, which 6G will eventually be capable of removing. Additionally, 6G will demonstrate its potential as a revolutionary technology for healthcare. In light of this, we imagine a medical network for the 6G future of interacting technologies.

Aspects of quality of life (QoL), intelligent wearable devices (IWD), the intelligent internet of medical things (IIoMT), hospital-to-home (H2H) providers, and unique approaches to companies, are all considered in many types of research as necessary innovations to improve our way of living. We can additionally explore how 6G technology for communication is used in telesurgery, epidemics, and pandemics **[51]**.

A component of the Internet of Things (IoT), the Internet of Healthcare Things (IoHT), enables distant information interchange for actual tasks like tracking the patient's progression of treatment, inquiry, and discussion. The IoHT framework, which provides preventive or precautionary medical treatments at a lower cost, is fundamentally characterized by the simplicity of time-independent interaction at geographically remote locations. In IoHT networks, a variety of lightweight biological detectors with constrained computing resources provide interaction, unity, calculation, and compatibility **[52]**.

A greater quality of medical care is required by the Internet of Healthcare Things, which calls for extensive and intelligent communication, enormous bandwidth, a low delay, and astonishingly high speeds. The forthcoming 6G telecommunication is envisioned to offer Intelligent IoHT (IIoHT) assistance anywhere at any moment to enhance humanity's standard of living, in contrast to the current 5G cellular system. The structure of 6G mobile systems and their incorporation of multidimensional communication technologies like systems for visual wireless interaction, cell-free connectivity systems, backhaul networks, and quantum connectivity, are used in the context of IIoHT **[53]**.

A developing surgical technique called telesurgery or remote surgery allows surgeons to execute surgery from a distance. Holographic interaction, AR, and robotics are being combined in telesurgery to control robot-assisted cutting and guarantee the virtual presence of medical professionals. The approach minimizes the main limitations of successful medical procedures, like a lack of skilled medical experts, the difficulty of accessing excellent services due to geography, the need for post-operative recovery, a heavy cost burden, and long-range journey. The main obstacle of remote surgery yet is immediate interaction with a very short response time in auricular transmission, graphical, and even physical data input among the two far-off places because any retardation could cause serious surgical errors and pose a hazard to human life. Traffic, disruption, and network routing issues are the main causes of elevated delays. Using the rapid transmission of data and rapid-speed complicated processing of information of the 6G goal, doctors will be able to connect medical equipment and remotely engage in some ways that are still unimaginable. The broad use of telesurgery in medical environments will become increasingly practical after 6G is implemented, and any geographic restrictions will vanish **[54]**.

4.1.4 Education and Training

The introduction of intelligent education will additionally be rendered possible by 6G networks through the use of cutting-edge techniques including AI, hologram interactions, and mobile edge computing. These cutting-edge techniques will enable anyone that wants to learn to explore a variety of constructions and designs in a 3D form and assist the educator in delivering the material from faraway places, resulting in engaging and realistic online learning. Additionally, intelligent classifications could be implemented, in which sensor information is transferred to the cloud or edge cloud for examination. Learners' input may be used later to assess the gathered data and make improvements to schooling **[55]**.

Training in many aspects of every field may be done using 6G VR communication or even hologram communication between a teacher and many trainees. VR simulations like that can be used in various types of training like training for police forces as the research with the title “Impact of Full-Body Avatars in Immersive Multiplayer Virtual Reality Training for Police Forces” was proposed at the end of the year 2022. As the article says, police forces can train particular abilities in hostile, hazardous, and difficult circumstances without risking their lives in the actual world just by using these simulations. It is obviously important for virtual simulations to generate feelings, involvement, and anxiety in addition to having realistic activities **[56]**. However, as we already discussed, for a more superior and accurate virtual reality experience faster speeds need to be utilized. This is where 6G networks come to solve the problem and make education easier and affordable for everyone.

A hypothetical use case called "Multi-Sensory Holographic Teleportation" imagines a new form of communication that is superior to current technologies like virtual reality (VR) and augmented reality (AR). Holographic teleportation aims to offer a genuinely fascinating adventure by including all five senses, as opposed to AR and VR, which largely rely on visual and auditory stimuli. Users of this cutting-edge technology would be able to interact with lifelike holographic representations of people, things, and settings since it operates in a true three-dimensional realm. However, 5G systems are currently unable to meet the requirements of holographic teleportation, which include nearly 5 Tbps of data rates and less than 1 ms of end-to-end latency **[30]**.

4.1.5 Financial Services and Security

The confidentiality and safety of the 6G systems and the apps must be guaranteed in addition to the enhanced communication and special applications. Blockchain and other distributed database technologies of 6G networks are one way to improve software privacy and security. A distributed ledger, or blockchain, which serves as the foundation and vital component of Bitcoin, can make sure that the data from every transaction is unchangeable and everlasting thanks to an encrypting method. The nodes that make up the blockchain network do not have to be trustworthy of one another and they might not be members of a single group. Each of the nodes in a blockchain cooperatively preserves information, and every node has access to a complete duplicate of all entries. Blockchain utilizes a distributed financial model in contrast to typical bookkeeping techniques.

The private blockchain, public blockchain, and consortium blockchain are the three categories that divide blockchain technology. Anybody can join a public blockchain, whereas a private blockchain is only accessible to a certain business or organization. Agreement on the Consortium blockchain is managed by chosen peers. The consensus method and intelligent contracts are two blockchain-related advances in technology. A consensus system, such as proof of stake (PoS) or proof of work (PoW), assures that all endpoints concur on the veracity of a document. Smart agreements, which can be utilized in sectors including healthcare, financial services, telecommuting, and power, constantly carry out established rules according to validated data kept on a distributed ledger. For instance, in the financial services field, a predetermined reimbursement rule can be incorporated into a smart agreement, and when an individual experiences an inconvenience, the smart agreement immediately verifies for validity and offers reimbursement. It is important to emphasize the value of consensus mechanisms and smart agreements for improving reliability and security across a range of businesses **[57]**.

4.1.6 Smart Cities

In recent years, increasing population growth has made the development of society, the environment, and the economy necessary for cities in order to greatly strengthen the Quality of Life and introduce the “Smart City” scheme. Urban challenges are addressed by combining IoT, Information and Communication Tools (ICT), and other technologies. Making the most effective utilization of the resources that are at hand to create smart cities is the main priority. IoT-enabled systems play a significant role in this, but it has numerous safety, confidentiality, delay, and reliability problems with just one point of failure. By virtue of its number of features, including openness, trustlessness, decentralization, permanence, and more, the creation of blockchain technology is able to address the previously mentioned security and privacy concerns even though providing superior services. The 6G wireless communication system offers unique characteristics that effectively address delay and dependability challenges in smart city environments, ensuring improved performance and reliability of 99.99999% **[58]**.

Smart Cities powered by 6G transform urban life by utilizing cutting-edge connection and data capabilities. A seamless integration of IoT devices, autonomous vehicles, and smart infrastructure is made possible by 6G's breakneck speeds, incredibly low latency, and vast device capacity. These cities use the power of 6G to improve a variety of facets of urban life, including public safety, energy management, transportation, and environmental sustainability. Smart cities enhance traffic flow, cut down on energy use, and boost emergency response capabilities through real-time data collecting and analysis. The ultra-reliable and secure 6G networks lay the groundwork for ground-breaking applications like AR, VR, and immersive city experiences. Smart cities can now deliver effective and sustainable services, raising the standard of living for their citizens, thanks to 6G's seamless communication and intelligent resource allocation capabilities.

Thanks to the estimated quick advancements in neuromorphic chip design as well as dispersed and prevalent AI, which can imitate human thinking and make decisions through combined information from a variety of (nano) sensors incorporated into every component, the majority of the things around us will eventually have intelligence. The majority of the Institute of Information Technology (IoIT) network will be controlled by movement, speech, and other sensory forms of interaction. For a genuinely smart city, 6G will use a combined, comprehensive strategy **[59]**.

4.1.7 Entertainment and Media

The blistering speeds and extremely low latency of 6G networks are predicted to possess a significant favorable effect on the field of entertainment. 6G may present new opportunities for playing games, live performances, and remote communication due to its ability for excellent real-time streaming of complex material, such as virtual reality and augmented reality activities but also . Additionally, the concurrent connection of a huge number of gadgets over 6G may enable the development of expansive thrilling experiences. For example, a shared virtual environment for several users could be created by connecting several VR headsets. This possesses an ability to complete the manner we absorb entertainment, and as 6G connectivity develops, we can expect a major shift in this area.

The media sector could undergo a change because of 6G technical developments. The rapid transmission of big media files could be the possibility of 6G's lightning-fast speeds and very little latency, enabling the seamless delivery of high-definition movies and TV shows. Additionally, 6G might make it easier for new media types and delivery systems to evolve. For instance, cutting-edge technology like holographic virtual presence in addition to real-time distance communication on media initiatives might be made available. A genuinely connected media experience might be made possible by new applications with 6G's power to connect many devices working together simultaneously, such as a seamless combination of smart home gadgets. Overall, 6G technology is anticipated to significantly alter the media landscape, and we may anticipate the emergence of novel new experiences and applications.

Chapter 5

Conclusions

5.1 The Power of Innovation: How 6G Technology is Reshaping the Wireless Landscape

It is now clear the telecommunications industry will be undergoing considerable change because of 6G networks, which will provide quicker downloading and uploading speeds, better connection coverage, more dependability, higher efficiency of energy, and fresh applications and use cases. One of 6G's main benefits is its capacity to accommodate speeds of up to one terabit per second. The applications requiring high-bandwidth, minimal latency connectivity will allow higher download and upload speeds. The effortless connection in isolated and rural locations, as well as in heavily inhabited urban areas, will be made possible by 6G systems' enhanced data speeds and their usage of an assortment of satellite, terrestrial, and aerial networks.

On top of that, it is anticipated that 6G networks would be developed with increased resiliency and durability, as well as self-treatment and redundancy features, to guarantee that networks continue to function regardless in the face of natural catastrophes, cyberattacks, or other disturbances. The new networks will use cutting-edge technology like massive MIMO and beamforming to cut the quantity of energy required for transferring data, making them more environmentally friendly than earlier generations of wireless networks. They are going to become more ecologically friendly and sustainable as a result. Finally, it is believed that 6G would allow access to new use cases and applications that wouldn't have been conceivable with earlier cellular network technologies. Autonomous automobiles, smart cities, virtual and augmented reality, and cutting-edge healthcare systems are some of them. In fact, 6G networks have the capacity to entirely change every aspect of the way we operate and reside by bringing us fresh instruments and possibilities that were formerly unthinkable.

Innovation is key to the creation of 6G networks since it helps to make these developments possible with the support of the technologies that already exist in 5G. The emergence of the 6G system is being aided by advancements in digital signal processing, antenna layout, network structure, and energy conservation. In order to promote innovation and advance the implementation of 6G technology, collaboration between academics, businesses, and even governments is also essential. In conclusion, the invention of the 6G has the potential to drastically alter the cellular industry. Improved download and upload speeds expanded network reach, higher dependability, increased energy economy, and fresh applications will all be provided. As a result, the wireless industry is experiencing an exciting period, and we may anticipate major advancements in the years that lie ahead.

5.2 Balancing Innovation and Responsibility: Ethical Considerations for 6G Technology

There are various moral concerns that need to be taken into account throughout the creation of emerging technologies like 6G. Privacy, especially for smart cities, constitutes one of those issues. It is necessary to protect user privacy given the rising use of wireless networks to convey sensitive data. To address privacy issues, effective encryption methods and restrictions on gathering and storing information must be put in place. Security is another important factor not only for smart cities but also for financial services. It is critical to make certain that 6G connections are safe and secured from cyberattacks because they are sending sensitive information such as money transfers, medical records, and private data. To reduce the dangers of cyber-attacks, new security protocols, and guidelines must be created.

Access and equity pose significant moral problems. There is a technological gap between individuals who have a connection to fast internet compared to those that are unable to have an opportunity to expand to faster internet speeds with the 6G development. In order to make sure that 6G networks are egalitarian and available to all, measures need to be taken to reduce the digital gap and guarantee that all individuals have access to cost-effective and dependable wireless internet. An additional significant ethical issue related to 6G technology is its effect on the environment. The mobile networks, data centers, and other types of facilities needed for the implementation of the 6G network may still consume a substantial amount of energy. Therefore, it is crucial to consider how 6G networks will environmentally impact and create more energy-saving solutions to cut down on carbon emissions.

There are major moral concerns that are raised by the possible use of 6G networks for telesurgeries. While the idea of remote surgery has the potential to increase access to specialist medical care, it also raises challenging ethical issues. In telesurgeries, it is crucial to ensure patient protection, data privacy, and dependable internet access because any communication hiccup or delay could result in serious repercussions. Signed permission grows increasingly essential since patients must completely comprehend the nature of remote procedures, including the use of robotic devices and any potential drawbacks they may have. The need for near-zero latency, which is defined as a delay of below one millisecond, is essential for enabling immediate input and precise control of robotic surgical systems. It is crucial that ethical principles and legislation address this requirement, especially considering that higher latency is predicted for 6G than the desired one. To solve these issues, protect the rights of patients, and guarantee that the advantages of 6G-enabled telesurgeries surpass the hazards, ethical standards, and laws must be created and put into place. This is why navigating the potential adoption of telesurgery across healthcare systems requires a balance between technological improvements, patient safety, and ethical considerations, which I believe will be difficult to achieve in the coming years.

Another important factor in the growth of 6G networks is ethical AI. It is essential to make assured that AI and machine learning algorithms are created and used ethically because 6G networks will rely on them to permit novel uses and improve connectivity for all their applications. To avoid prejudice, discrimination, and numerous other unethical problems, ethical AI principles, and rules must be established. Collaboration among researchers, businesses, and politicians is required to guarantee the ethical and accountable creation and utilization of 6G infrastructure. It is possible to create 6G technology that is simultaneously creative and morally upright by taking seriously the above-mentioned ethical constraints. The secret to the efficient creation and application of the 6G network is striking the right balance between innovation and stewardship.

5.3 Requirements for the 6G Applications

In 6G, three additional dimensions will be added to the interaction capabilities of ultra-reliable low latency communications (uRLLC), enhanced mobile broadband (eMBB), and massive machine-type communication (mMTC): ubiquitous mobile ultra-broadband (uMUB), ultra-high data density (uHDD), and ultra-high-speed with low latency communications (uHSLLC) as you can see in Figure 3. uMUB makes it possible to transmit intended outcome across the space-aerial-terrestrial-sea field. Very large speeds and extremely minimal delay are accomplished using uHSLLC, and uHDD offers exceptional data density and dependability. A thorough collaboration in communication, sensing, and processing possibilities is required for the creation of these prospective services in uMUB, uHDD, and uHSLLC, to be able to satisfy the prerequisites of future applications.

Real-time broadband communication (RTBC), uplink-centric broadband communication (UCBC), and harmonized communication and sensing (HCS) are the three key use cases that 5.5G improves in order to improve the current 5G use cases. This update advances the Internet of Everything (IoE) and makes it possible for intelligent IoE, which is in line with Huawei's vision and goal. The sixth generation will inherit some features and technologies from the fifth generation while improving modern methods to transmit in response to future demands, according to important 5G, 5.5G, and 6G scenario comparisons. Furthermore, 6G is projected to revolutionize some technologies like the ones we discussed in Chapter 3, to fulfill the particular demands of anticipated use cases.

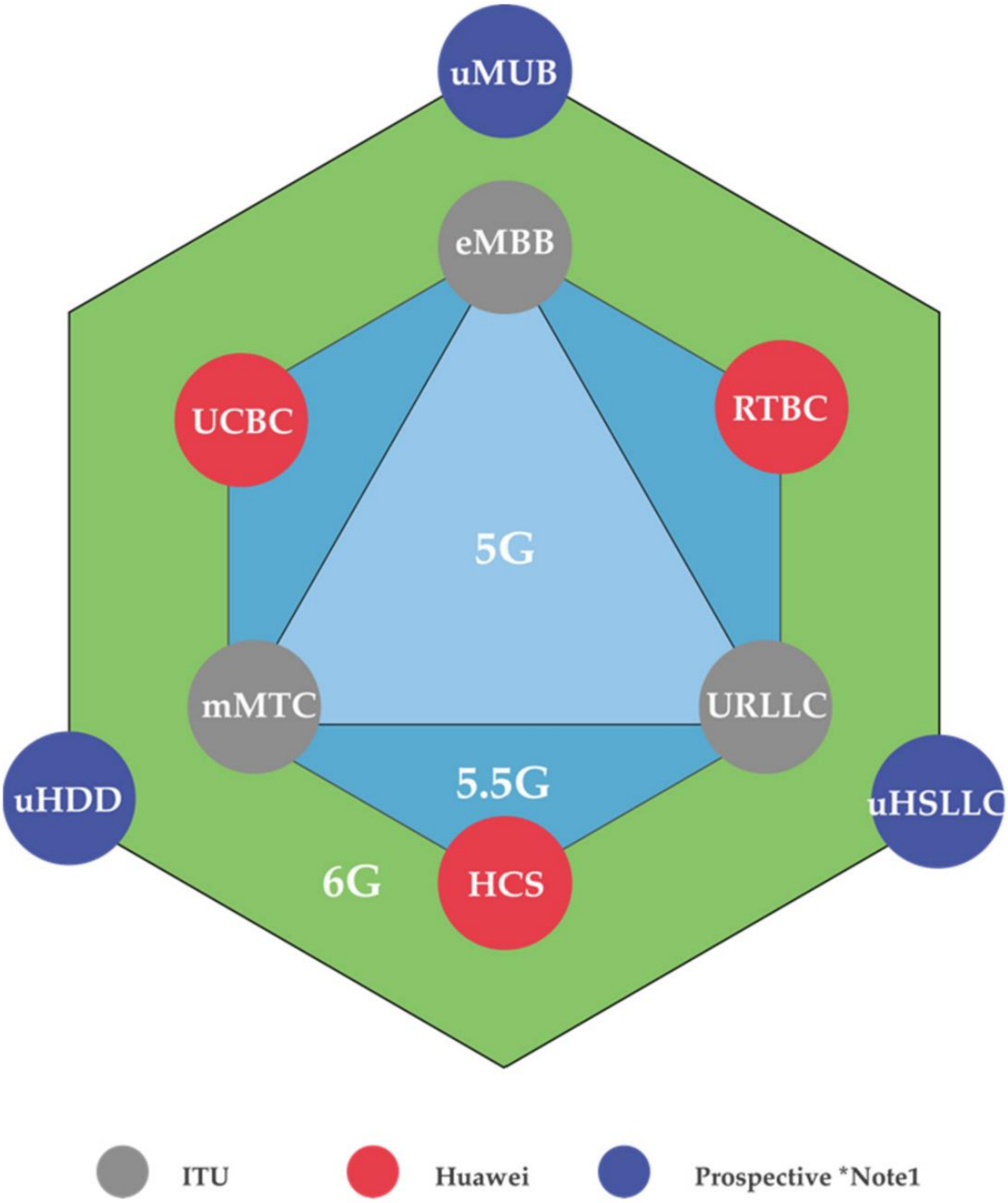

Figure 3. Comparisons of applications for 5G, 5.5G, and 6G networks **[60]**

The projected focal guidelines for 6G include ecological responsibility, coverage, coordination, geographic location, and dependability, in contrast to 5G's emphasis on latency, speed, dependability, and mass connectivity. 6G intends to integrate numerous items in both the virtual and real worlds, in contrast to 5G, which does not provide guaranteed time synchronization. The timing disparities and communication links between these objects must stay within a specified range in order to allow for natural reaction and interaction. In addition, time jitter and precise geolocation are essential for achieving 6G's goals. Another significant obstacle for 6G is connectivity, which calls for not just ultra-high-speed connectivity but also durability, adaptability, and customization. Smart algorithms, including AI-based compression approaches, are required to optimize bandwidth utilization and anticipate future needs for demanding applications like 4D video transmission, which entails sending terabits of data.

Low latency large backhaul is required to enable comprehensive data transport. Additionally, 6G calls for precoding for distributed mMIMO systems, superior-quality channel status information (CSI), and flexible spectrum access. Uplink with high capacity, enhanced connection quality and capacity for portable cloud extended reality, and placement with low power and high precision are further connection goals. Bridging the digital gaps and ensuring that everyone has access to network services, regardless of geography, is one of 6G's primary goals. Additionally, the development of a prompt, effective, and dependable data transport mechanism is required for the efficient communication of large numbers of low-powered devices, or Internet of Things, as well as resource utilization for high connection density. Regarding performance, 6G aims to offer incredibly high peak transmission speeds of 1–10 Tbps and incredibly low latency ranging between 10 to 100 seconds **[60]**. However, to accomplish these goals, energy usage must be drastically reduced, both as a percentage of total power use and as a unit of data.

For the creation of an intelligent information society by 2030, 6G capabilities are essential. When comparing the technical specifications of 6G and 5G, the following characteristics of 6G become clear: 10 times more density of connectivity than 5G (supporting up to 107 devices per area), significantly higher spectrum efficiencies (5 to 10 times higher than 5G), peak data rates of at least 1 Tbps (and up to 10 Tbps in some cases), user-experienced data rates of 1 Gbps (or even up to 10 Gbps in certain scenarios), a wireless network capable of accommodating various and sometimes conflicting requirements, high mobility and low latency for acceptable quality of experience, and these specifications illustrate the high standards and developments anticipated for 6G technology **[60]**. You can see this in Table 1 below which enumerates the variations between 5G and 6G. It demonstrates how 6G will fundamentally alter mobile connectivity. The connectivity density, data rate, latency, and spectrum of 6G will be up to 10-100 times greater than those of 5G, it can also be deduced.

Characteristic	5G	6G
Operating frequency	3 GHz–300 GHz	Up to 1 THz
Peak data rate	20 Gbps	1 Tbps
Latency	1 ms	10–100 μs
Mobility	500 km/h	>1000 km/h
Available spectrum	30 GHz	10–100 times higher than 5G
Spectral efficiency	30 bps/Hz	100 bps/Hz
Energy efficiency	High	Ultra-high
Connection density	106 devices/km^2	107 devices/km^2
Coverage	99.99%	99.9999%
Positioning precision	Meter precision	Centimeter precision
Satellite integration	Partial	Fully
Automation integration	Partial	Fully
Network awareness	Partial intelligibility	Ubiquitous intelligence
Reliability	$1–10^{-5}$	$1–10^{-9}$
Service level	VR/AR/3D	Tactile
XR	Partial	Fully
Haptic communication	Partial	Fully
Smart city components	Separated	Integrated
IRS	-	Yes
Standards	5G/NR	-
Core network	IoT	IoE
HetNets	Flexible	Ultra-flexible
Usage scenarios	EMBB, URLLC & mMTC	uMUB, uHSLLC & uHDD
Main technologies	mmWave, mMIMO, UDN, SDN	THz, SM-MIMO, Laser and VLC, Quantum, Blockchain, AI/ML
Applications	VR/AR/360° videos, UHD videos, V2X, IoT, Smart city/factory/home, telemedicine, and wearable devices	Holographic, tactile/haptic internet, full-sensory and reality, fully automated driving, industrial internet, space travel, deep-sea sightseeing, and Internet of bio-nano-things
Flexible spectrum	Flexible duplex	Free duplex

Table 1. Comparison of 5G and 6G characteristics **[60]**

5.4 Future Work and Research Directions

Since 6G technologies haven't been developed yet, it's noteworthy to identify certain key research directions. Firstly, the utilization of THz frequencies for wireless transmission in 6G is an intriguing research field for terahertz communications. Since THz waves have greater bandwidths than existing microwave frequencies, they could sustain transmission speeds upwards of terabits per second. In order to improve THz interaction, researchers in this field can investigate the creation of THz transmitters, receivers, antennas, and signal engineering methods. Secondly, to improve network speed, lower latency, and improve customer satisfaction in 6G systems, artificial intelligence, and machine learning may constitute crucial factors. The creation of AI-powered network topologies, the mix together of AI/ML algorithms with 6G, and the embrace of AI to handle network assets might all be the subject of special research. 6G networks could become more sophisticated and productive through the incorporation of AI and ML.

Additionally, edge computing and IoT are both connected ideas that are foreseen to be important parts of 6G network infrastructures. Edge computing is capable of being utilized for processing data regionally, lowering latency and network traffic, as 6G connections are contemplated to accommodate a sizable number of connected gadgets and sensors. The creation of edge computing structures for 6G systems, the pairing of IoT devices with 6G connections, and the application of AI/ML algorithms for handling information might all be interesting areas of research. Also, quantum computing has the ability to completely transform communication systems, especially 6G systems, as we discovered through the study for this thesis. The progression of quantum interaction protocols, the application of quantum cryptography for encrypted communications, and the combination of quantum computing alongside 6G networks could potentially be a focus of research in this area of science. 6G networks may be able to operate more securely and effectively by using quantum computing.

Lastly, as previously presented, security and privacy issues in 6G connections is going to be essential due to the rising quantity of linked devices and the volume of personal information being transferred. The creation of safe edge computing architectures, the application of blockchain technological advances for the confidentiality of data, and the establishment of reliable communication techniques are all possible topics for research in this discipline. These precautions are vital for defending against possible hazards and guaranteeing the safety and confidentiality of information in 6G wireless networks.

Bibliography

[1] European Telecommunications Network Operators' Association (ETNO), "State of Digital Communications | 2022," pp. 15, February 2, 2022. Available at: https://etno.eu/library/reports/104-state-of-digi-2022.html

[2] Petroc Taylor, "Development periods of 3G, 4G, 5G, and 6G mobile broadband technologies," Statista Research Department, November 6, 2020.

[3] Petroc Taylor, "5G mobile subscriptions worldwide 2019-2027, by region," Statista Research Department, November 10, 2022.

[4] 3GPP Website, 3GPP: A Global Initiative, "Introducing 3GPP," 2022. Available at: https://www.3gpp.org/about-us/introducing-3gpp

[5] L. Woodland, "The importance of 5G technology - Why do we need 5G for connectivity and data?", Airbus Secure Communications Website, 2022. Available at: https://securecommunications.airbus.com/en/meet-the-experts/the-importance-of-5g-technology

[6] Verizon News Archives, "Why is 5G important? - Reasons 5G is important," May 2019. Available at: https://www.verizon.com/about/our-company/5g/why-5g-important-discover-importance-5g-technology

[7] P. Rajkotia, "The 6G Future: How 6G will transform our lives," Incompliance Website, September 30, 2022. Available at: https://incompliancemag.com/article/the-6g-future-how-6g-will-transform-our-lives/

[8] P. Sharma, "Evolution of Mobile Wireless Communication Networks-1G to 5G as well as Future Prospective of Next Generation Communication Network," International Journal of Computer Science and Mobile Computing, vol. 2, no. 8, pp. 48-49, August 2013.

[9] J. R. Churi, T. S. Surendran, S. A. Tigdi, and S. Yetwale, “Evolution of Networks (2G-5G),” In International Conference on Advances in Communication and Computing Technologies (ICACACT), vol. 51, no. 4, pp. 9-11, 2012.

[10] A. Lamba, J. Yadav, and G. U. Devi, “Analysis of Technologies in 3G and 3.5G Mobile Networks,” 2012 International Conference on Communication Systems and Network Technologies, pp. 330, 2012.

[11] Team of Electronics Notes, “UMTS UTRA / UTRAN: radio network subsystem RNS,” Incorporating Radio-Electronics Website, 2022. Available at: https://www.electronics-notes.com/articles/connectivity/3g-umts/radio-access-network-utra-utran.php

[12] J. Lister, “What is WCDMA?”, in Easy Tech Junkie Website, December 18, 2022. Available at: https://www.easytechjunkie.com/what-is-wcdma.htm

[13] G. Sharma, and G. S. Kumar, “Moving towards HSUPA (high-speed uplink packet access): A complete 3.5G wireless system,” In 2005 IEEE International Conference on Personal Wireless Communications, pp. 174, 2005.

[14] Anttila, Lauri, M. Valkama, and M. Renfors, “3.9 G radio reception with SC-FDMA waveforms under I/Q imbalance,” In 2007 IEEE International Symposium on Circuits and Systems, pp. 25, 2007.

[15] A. Ghayas, “Difference Between OFDM, OFDMA And SC-FDMA In 4G LTE,” in COMMSBRIEF Website, February 5, 2021.

[16] A. Ghayas, “MIMO In LTE: What Is Multiple-Input-Multiple-Output In 4G?”, in COMMSBRIEF Website, October 10, 2021.

[17] G. A. Darrell, “Beamforming and LTE,” in Medium Website, Jun 20, 2018. Available at: https://medium.com/@artiedarrell/beamforming-and-lte-cbc6d12b812e

[18] G. A. Uttam, “An overview on Evolution of Mobile Wireless Communication Networks: 1G-6G,” International Journal on Recent and Innovation Trends in Computing and Communication, vol. 3, issue. 5, pp. 3131-3132, May 3, 2015.

[19] X. Li, R. Salleh, A. Aani, and O. Zakaria, “Multi-Network Data Path for 5G Mobile Multimedia,” In 2009 International Conference on Communication Software and Networks, pp. 584, 2009.

[20] Matti Passoja, “5G NR: Massive MIMO and Beamforming – What does it mean and how can I measure it in the field?” RCR Wireless News, September 12, 2018. Available at: https://www.rcrwireless.com/20180912/5g/5g-nr-massive-mimo-and-beamforming-what-does-it-mean-and-how-can-i-measure-it-in-the-field

[21] Team of AYMING PCB & ASSEMBLY Website, **“**5G Nationwide Vs 5G Ultra-Wideband – Which Offers Higher Performance?” December 2021. Available at: https://www.raypcb.com/5g-nationwide-vs-5g-ultra-wideband/#:~:text=5G%20Ultra%20Wideband%20provides%20very,at%20a%20very%20fast%20speed.

[22] A. R. Abduljabbar, N. H. Alkhazaali, S. Q. Jabbar, and D. J. Kadhim, “Quality of service (QoS) for 5G networks,” in International Journal of Future Computer and Communication 6, no. 1, pp. 27-30, March 1, 2017.

[23] M. Chen, Y. Zhang, Y. Li, S. Mao, and V. C. M. Leung, “EMC: Emotion-aware mobile cloud computing in 5G,” in IEEE Network, vol. 29, no. 2, pp. 32-33, April 2015.

[24] S. Zhang, “An Overview of Network Slicing for 5G,” in IEEE Wireless Communications, vol. 26, no. 3, pp. 111-117, June 2019.

[25] J. Burke, “Network Slicing,” Nemertes Research, in TechTarget Website - Enterprise 5G: Guide to planning, architecture, and benefits, May 2022.

[26] G. Kranz and G. Christensen, “What is 6G? Overview of 6G networks & technology,” in TechTarget Website - Enterprise 5G: Guide to planning, architecture, and benefits, April 2022.

[27] M. Z. Asghar, S. A. Memon, and J. Hämäläinen, **“**Evolution of Wireless Communication to 6G: Potential Applications and Research Directions,” in MDPI platform, May 23, 2022.

[28] G. Fairhurst, “Unicast, Broadcast, and Multicast,” in notes of University of Aberdeen, March 10, 2020. Available at: https://erg.abdn.ac.uk/users/gorry/course/intro-pages/uni-b-mcast.html

[29] TechTarget Contributor, “Quality of Experience (QoE or QoX),” TechTarget Website - Customer service and contact center, April 2008.

[30] I. F. Akyildiz, A. Kak, and S. Nie, “6G and Beyond: The Future of Wireless Communications Systems,” in IEEE Access, vol. 8, pp. 133995-134030, doi: 10.1109/ACCESS.2020.3010896, July 31, 2020.

[31] K. Rikkinen, P. Kyosti, M. E. Leinonen, M. Berg, and A. Parssinen, “THz Radio Communication: Link Budget Analysis toward 6G,” in IEEE Communications Magazine, vol. 58, no. 11, pp. 22-27, November 2020.

[32] P. Yang, Y. Xiao, M. Xiao and S. Li, "6G Wireless Communications: Vision and Potential Techniques," in IEEE Network, vol. 33, no. 4, pp. 70-75, doi: 10.1109/MNET.2019.1800418, July/August 2019.

[33] I. F. Akyildiz, J. M. Jornet, and C. Han, “Terahertz band: Next frontier for wireless communications,” in Science Direct platform - Physical Communication, vol. 12, pp. 16-32, ISSN 1874-4907, September 2014.

[34] M. Adhikari and A. Hazra, “6G-Enabled Ultra-Reliable Low-Latency Communication in Edge Networks,” in IEEE Communications Standards Magazine, vol. 6, issue 1, pp. 67-74, doi: 10.1109/MCOMSTD.0001.2100098, March 2022.

[35] M. Ishtiaq, N. Saeed, and M. Asif Khan, “Edge Computing in IoT: A 6G Perspective,” in IEEE Network, pp. 1-9, May 15, 2022.

[36] 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, vol. 13, Issue 5, doi: 10.3390/fi13050118, April 30, 2021.

[37] 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, vol. 57, no. 8, pp. 84-90, doi: 10.1109/MCOM.2019.1900271, August 2019.

[38] H. Cui et al., “Space-air-ground integrated network (SAGIN) for 6G: Requirements, architecture and challenges,” in China Communications, vol. 19, no. 2, pp. 90-108, doi: 10.23919/JCC.2022.02.008, February 28, 2022.

[39] M. Femminella and G. Reali, "Gossip-based Monitoring Protocol for 6G Networks," in IEEE Transactions on Network and Service Management, doi: 10.1109/TNSM.2023.3263542, March 31, 2023.

[40] L. Cai, J. Pan, W. Yang, X. Ren, and X. Shen, “Self-Evolving and Transformative (SET) Protocol Architecture for 6G,” in IEEE Wireless Communications, pp.1-12, August 22, 2022.

[41] H. H. Pajooh, S. Demidenko, S. Aslam, and M. Harris, “Blockchain and 6G-Enabled IoT,” Inventions, in MDPI Website, vol. 7, issue 4, doi: 10.3390/inventions7040109, November 28, 2022.

[42] T. Hewa, G. Gür, A. Kalla, M. Ylianttila, A. Bracken and M. Liyanage, “The Role of Blockchain in 6G: Challenges, Opportunities, and Research Directions,” 2nd 6G Wireless Summit (6G SUMMIT) in 2020, pp. 1-5, doi: 10.1109/6GSUMMIT49458.2020.9083784, May 4, 2020.

[43] Caserman, Polona, P. Schmidt, T. Göbel, J. Zinnäcker, A.Kecke, and S. Göbel, “Impact of Full-Body Avatars in Immersive Multiplayer Virtual Reality Training for Police Forces,” in IEEE Transactions on Games, vol. 14, issue 4, pp. 706-714, December 2022.

[44] C. Wang and A. Rahman, "Quantum-Enabled 6G Wireless Networks: Opportunities and Challenges," in IEEE Wireless Communications, vol. 29, no. 1, pp. 58-69, doi: 10.1109/MWC.006.00340, February 2022.

[45] Team of Empower Frontline Workers, “Augmented Reality vs Virtual Reality,” in TeamViewer Website, April 12, 2022. Available at: https://www.teamviewer.com/en/augmented-reality-ar-vs-virtual-reality-vr/

[46] Team of Contributors in Microsoft Website, “What is mixed reality?” in Microsoft Learn platform, January 25, 2023. Available at: https://learn.microsoft.com/en-us/windows/mixed-reality/discover/mixed-reality

[47] Administrator of ISP.PAGE, “The Impact of 6G on Virtual and Augmented Reality,” in Internet Providers, March 18, 2023. Available at: https://isp.page/news/the-impact-of-6g-on-virtual-and-augmented-reality/

[48] S. Wang, T. Sun, H. Yang, X. Duan, and L. Lu, “6G Network: Towards a Distributed and Autonomous System,” 2nd 6G Wireless Summit (6G SUMMIT) in 2020, pp. 1-5, doi: 10.1109/6GSUMMIT49458.2020.9083888, May 4, 2020.

[49] B. Yang et al., "Edge Intelligence for Autonomous Driving in 6G Wireless System: Design Challenges and Solutions," in IEEE Wireless Communications, vol. 28, no. 2, pp. 40-47, doi: 10.1109/MWC.001.2000292, April 2021.

[50] K. Siau and Z. Shen, “Mobile healthcare informatics,” in Medical Informatics and the Internet in Medicine, pp. 89, doi: 10.1080/14639230500095651, June 27, 2006.

[51] S. Nayak and R. Patgiri, “6G Communication Technology: A Vision on Intelligent Healthcare,” Part of the Studies in Computational Intelligence book series, vol. 932, pp. 1-2, January 31, 2021.

[52] M. A. Khan, M. H. Alsharif, and A. Irshad, “Securing the Internet of Health Things (IoHT) with Lightweight Security Schemes,” Journal of Healthcare Engineering - Hindawi Website, December 1, 2022. Available at: https://www.hindawi.com/journals/jhe/si/579329/

[53] M. Shamim Kaiser, N. Zenia, F. Tabassum, S. Al Mamun, M. A. Rahman, Md. Shahidul Islam, and M. Mahmud, “6G Access Network for Intelligent Internet of Healthcare Things: Opportunity, Challenges, and Research Directions,” Part of the Advances in Intelligent Systems and Computing book series, vol. 1309, pp. 317-318, December 17, 2020.

[54] Kaiser, M.S., Zenia, N., Tabassum, F., Mamun, S.A., Rahman, M.A., Islam, M.S. and Mahmud, M., “6G access network for intelligent internet of healthcare things: opportunity, challenges, and research directions,” in Proceedings of International Conference on Trends in Computational and Cognitive Engineering: Proceedings of TCCE 2020, vol. 1309, pp. 317-328, December 17, 2020.

[55] S. Iyer, R. J. Pandya, R. Kallimani, K. Pai, R. Khanai, D. Torse, and S. Mavinkattimath, “Survey on Internet of Things enabled by 6G Wireless Networks,” Cornell University, pp. 6, March 16, 2022.

[56] W. Li, Z. Su, R. Li, K. Zhang, and Y. Wang, "Blockchain-Based Data Security for Artificial Intelligence Applications in 6G Networks," in IEEE Network, vol. 34, no. 6, pp. 31-37, doi: 10.1109/MNET.021.1900629, November/December 2020.

[57] G. Manogaran, B. S. Rawal, V. Saravanan, P. M. Kumar, O. S. Martínez, R. G. Crespo, C. E. Montenegro-Marin, and S. Krishnamoorthy, “Blockchain-based integrated security measure for reliable service delegation in 6G communication environment,” in Computer Communications, vol. 161, pp. 250, September 1, 2020.

[58] A. Kumari, R. Gupta, and S. Tanwar, “Amalgamation of blockchain and IoT for smart cities underlying 6G communication: A comprehensive review,” in Computer Communications, vol. 172, pp. 102, April 15, 2021.

[59] Tariq, F., Khandaker, M.R., Wong, K.K., Imran, M.A., Bennis, M. and Debbah, M., “A speculative study on 6G,” in IEEE Wireless Communications, vol. 27, issue 4, pp.118, August 18, 2020.

[60] S. Alraih, I. Shayea, M. Behjati, R. Nordin, N. F. Abdullah, A. Abu-Samah, and D. Nandi, “Revolution or Evolution? Technical Requirements and Considerations towards 6G Mobile Communications,” in Sensors 22, no. 3: 762, pp. 3-9, January 20, 2022.

ANNEX A: Table of Abbreviations

Abbreviation	Definition
3GPP	3rd Generation Partnership Project
AP	Access Point
AMPS	Advanced Mobile Phone System
AI	Artificial Intelligence
AR	Augmented Reality
AS	Autonomous System
BS	Base Station
BISM	Blockchain-based integrated security measure
CSI	channel status information
CDMA	Code Division Multiple Access
CoMP	Coordinated Multi-Point
DFT	Discrete Fourier Transform
DDoS	Distributed Denial-of-Service
8PSK	Eight Phase-Shift Keying
EDGE	Enhanced Data rates for GSM Evolution
EGPRS	Enhanced General Packet Radio Service
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
GPRS	General Packet Radio Service
GSM	Global System for Mobile communication
HCS	Harmonized Communication and Sensing
HSCSD	High-Speed Circuit Switched Data
HSDPA	High-Speed Downlink Packet Access
HS-DSCH	High-Speed Downlink Shared Channel
HSUPA	High-Speed Uplink Packet Access
H2H	Hospital-to-Home
IMTS	Improved Mobile Telephone Service
IIoT	Industrial Internet of Things

ISG	Industry Specification Group
ICT	Information and Communication Tools
IEEE SA	Institute of Electrical and Electronics Engineers Standards Association
IoIT	Institute of Information Technology
iDEN	Integrated Digital Enhanced Network
IEC	Intelligent Edge Computing
IIoHT	Intelligent Internet of Healthcare Things
IIoMT	Intelligent Internet of Medical Things
IWD	Intelligent Wearable Devices
IS-136	Interim Standard 136
IS-95	Interim Standard 1995
IMT	International Mobile Telecommunications
IMT-SC	International Mobile Telecommunications Single Carrier
IoE	Internet of Everything
IoHT	Internet of Healthcare Things
IoT	Internet of Things
IP	Internet Protocol
IPv6	Internet Protocol version 6
ISP	Internet Service Provider
IFT	Inverse Fourier Transform
LAS-CDMA	Large Area Synchronized Code Division Multiple Access
LMDS	Local Multipoint Distribution System
LTE	Long-Term Evolution
M2M	Machine to Machine
mMTC	massive Machine-Type Communication
mMIMO	massive Multiple Input Multiple Output
MR/XR	Mixed Reality
MCC	Mobile Cloud Computing
MEC	Mobile Edge Computing
MIPv6	Mobile IPv6
MN	Mobile Node

MA	Monitoring Agent
MC-CDMA	Multi-Carrier Code Division Multiple Access
MMS	Multi-media MessageS
MIMO	Multiple Input Multiple Output
MU-MIMO	Multi-User Multiple Input Multiple Output
NFV	Network Functions Virtualization
NTT	Nippon Telephone and Telegraph
NMT	Nordic Mobile Telephones
OFDMA	Orthogonal Frequency Division Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
PCF	Packet Control Function
PDIF	Packet Data Interworking Function
PDSN	Packet Data Service Node
PAPR	Peak-to-Average Power Ratio
P2P	Peer-to-Peer
PDC	Personal Digital Cellular
PCI	Physical Cell Identification
PoS	Proof of Stake
PoW	Proof of Work
PCA	Protocol Control Agent
QoE/QoX	Quality of Experience
QoL	Quality of Life
QoS	Quality of Service
QIT	Quantum Information Technology
RAN	Radio Access Network
RNC	Radio Network Controller
RNS	Radio Network Subsystem
RTBC	Real-time broadband communication
RSRP	Reference Signal Received Power
RSRQ	Reference Signals Received Quality
RTT	Round Trip Time
SET	Self-Evolving and Transformative

SF	Service Function
SMS	Short MessageS
SIR	Signal-to-Interference Ratio
SINR	Signal-to-Interference-plus-Noise Ratio
SC-FDMA	Single Carrier Frequency Division Multiple Access
SCRTT	Single-Carrier Radio Transmission Technology
6G	Sixth generation
SCU	Small Cloud Unit
SAGIN	Space-Air-Ground Integrated Network
SSB	Synchronization Signal Block Beam
TV	television
TDMA	Time Division Multiple Access
TACS	Total Access Communication Systems
TCP	Transmission Control Protocol
uHDD	Ultra-High Data Density
uHSLLC	Ultra-High-Speed with Low Latency Communication
uRLLC	Ultra-reliable low latency communication
URLLC	Ultra-Reliable Low-Latency Communication
UWB	Ultra-Wide Band
UTRA	UMTS Terrestrial Radio Access
UTRAN	UMTS Terrestrial Radio Access Network
UMTS	Universal Mobile Telecommunications System
UAV	Unmanned Aerial Vehicle
UE	User Equipment
VR	Virtual Reality
WCDMA	Wideband Code Division Multiple Access
WAP	Wireless Application Protocol
WLAN	Wireless Local Area Network
WWW	World Wide Web
WWWW	World-Wide Wireless Web

ANNEX B: List of Figures and Tables