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Article

Evolution of Wireless Communication to 6G: Potential Applications and Research Directions

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Abstract: The fifth-generation mobile network (5G), as the fundamental enabler of Industry 4.0, has facilitated digital transformation and smart manufacturing through AI and cloud computing (CC). However, B5G is viewed as a turning point that will fundamentally transform existing global trends in wireless communication practices as well as in the lives of masses. B5G foresees a world where physical–digital confluence takes place. This study intends to see the world beyond 5G with the transition to 6G assuming the lead as future wireless communication technology. However, despite several developments, the dream of an era without latency, unprecedented speed internet, and extraterrestrial communication has yet to become a reality. This article explores main impediments and challenges that the 5G–6G transition may face in achieving these greater ideals. This article furnishes the vision for 6G, facilitating technology infrastructures, challenges, and research leads towards the ultimate achievement of "technology for humanity" objective and better service to underprivileged people.

Keywords: 6G; 5G advanced; wireless communication

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1. Introduction

The evolutionary background can be traced back to the 1980s, with the advent of the first generation (1G) analogue cellular system. This was replaced in 1990 by the second generation (2G) digital network, better known as the "global system for mobile communications (GSM)", which incorporated services such as voice communication and text messages. However, the low data rates necessitated the inception of third generation (3G) in 2001, offering comparatively high speed data rates. By 2009, long term evolution (LTE) networks marked the commencement of the fourth generation (4G) broadband service. The inclusion of new technologies in 4G, such as "multi- input multi-output (MIMO)" and "orthogonal frequency-division multiplexes (OFDM)", altered the status quo, greatly multiplying the subscribers for various services, including the internet. This was followed by fifth generation (5G) in 2019, which marked the extension of mobile services from humans to things in industries, making the world become a global village. However, while it is being deployed, researchers have also focused on exploring sixth generation (6G) to meet future requirements of more data and bandwidth greedy applications [1,2]. In view of the foregoing evolutionary process spanning over a few decades—this signifies not only a mere development of communication technologies, it is a process of connecting people and nations, making the world a global village. This period of development also marks the rapid internet penetration. This decades-long 'revolution of wireless networks' i.e., from year 1980 to 2001, first–second generations, and year 2015 onward, third–fourth generation networks have unprecedentedly altered the global digital outlook making the world, being globally accessible from anywhere at anytime. The first and second generation revolutions led to a phenomenal growth, i.e., of millions of new voice subscribers by 2000. As it continued to evolve in succeeding third and fourth generations, the mobile broadband attracted billions of subscribers, continuing until the 2019 roll-out of 5th generation wireless mobile communications. High speed internet at the rate of multiple Gbps led to the growth of the internet of things (IoT) and, more specifically, industrial internet of things (IIoT), as the main pillars of Industry 4.0 [3].

The fifth-generation mobile network (5G) kick-started a new beginning, laying its foundation upon softwarization, with components such as (i) "the software defined networks (SDN)", (ii) "network functioning virtualization (NFV)", (iii) "network slicing (NS)", (iv) "mobile edge computing (MEC)", (v) "massive multiple-input/multiple-output (MIMO)", and (vi) "millimeter-wave (mmW)". More so, enhanced frequency capacities facilitated more coverage and improved speed. Despite catering to an intensive environment of densely-connected IoT-M2M wireless communications, 5G has enabled 100 times more connected interfaces. Moreover, 5G provides more "indoor coverage", with enhanced signal propagation capabilities and energy efficiency. Yet, a densely connected world (through high speed wireless and fully automated) appears to be a dream that must still come true. The objectives of economical, pervasive, every time, everywhere, fast, latency-less internet, with human-to-human cross environment (water, air, space, etc.) communication, is yet to become a reality with a 5G beyond scenario. While the 6G experience is expected in a few years, new impending challenges of meeting the key performance indicators of 6G necessitate extensive research initiatives [4]. Further addition of 5G "new radio (NR)" reinforcing factors, such as (i) "enhanced mobile broadband (eMBB)", (ii) "massive machine type communication (mMTC)", and (iii) "ultra-reliable low latency communication (URLLC)" aiming to yield higher data rates in "gigabits per second (Gb/s)", coupled with low millisecond latency. Moreover the "traffic density" will enhance spectral capacity and energy efficiency [5]. Moreover, this has spurred new technology paradigms, including "virtual reality (VR)", "augmented reality (AR)", "mixed reality (MR)", "autonomous vehicles", "internet of things (IoT)", and Industry 4.0, along with the introduction of "edge intelligence (EI)", "sub 6 GHz to THz communication", "non-orthogonal multiple access (NOMA)", "large intelligent surfaces (LIS)" etc. On the contrary, new emerging applications, such as "holographic telepresence (HT)", "unmanned aerial vehicle(s) (UAV)", and "extended reality (XR)", etc., are likely to reshape future trends. Yet being bandwidth greedy, these applications require maximum speed, real-time access, with minimal latency, etc., which are beyond the capabilities of 5G [6]. The entire 5th generation ecosystem is based on densely connected wireless devices from diverse application areas in health, industry, transport, etc. However, such devices, including the internet of everything (IoE), "wearable", and "smart cities", have challenging requirements. Simultaneously, connectivity of distant devices will 'ease' lives; this requires diverse backhauling strategies. We view the challenges as the core of 6G research, as 6G technological infrastructures have yet to be explicitly defined. Figure 1 depicts comparison of 5G and 6G. This leads towards future 6G research directions [7]. Table 1 provides a summary of some studies on B5G wireless mobile communication.

Table 1. Summary of studies on 6G wireless communication

Author (s)	Contribution
[5]	mmW millimeter-wave enabling technologies.
[6]	Developments toward 6G
[8]	Sixth generation (6G) wireless system and role of ML techniques.
[9]	Sixth generation (6G) drivers, use cases, usage scenarios, requirements, KPIs, architecture, and enabling technologies.
[10]	Energy, IoT, and ML in 6G.
[11]	Digital twins for wireless systems
[12]	Quantum search algorithms for wireless communications
[13]	Advancements in a DL-based physical layer (PHY) of 6G.
[14]	Wireless evolution toward 6G networks and related potential technologies.
[15]	Optimization frameworks and performance analysis methods for large intelligent surfaces (LIS).
[16]	Scalable and trustworthy edge AI systems.
[17]	Technology transformations to define 6G.

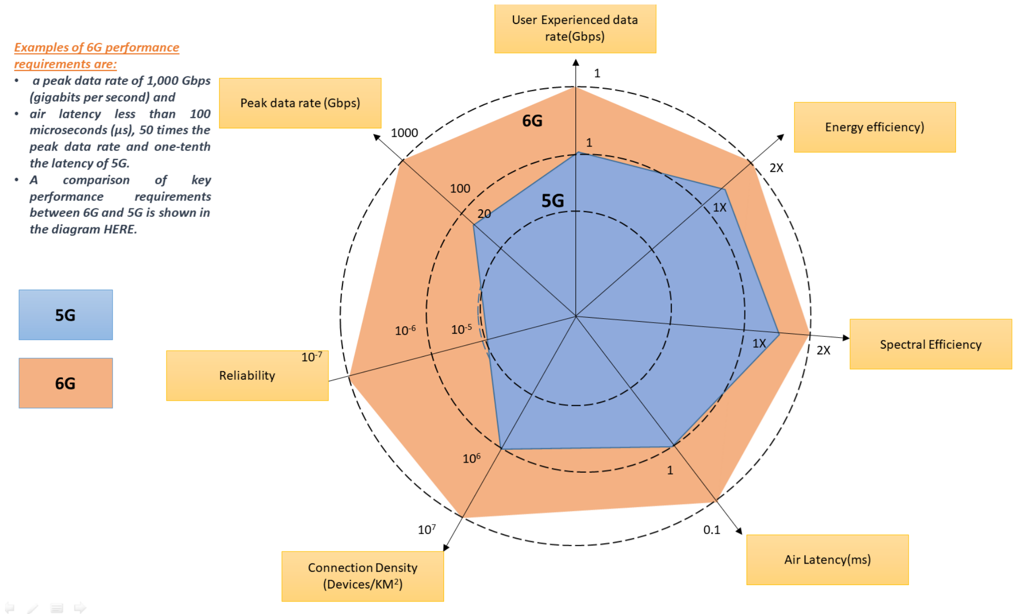

Figure 1. Comparison of Key Performance requirements between 5G and 6G [7].

For instance, Table 2 reflect a comparative scenario of the features of 5G advanced and 6G cellular networks.

Table 2. Evolution of wireless communication characteristics from 5G and envisioned for 6G [6].

Characteristics	5G Advanced	6G
Peak data rates	100 Gbps	1 Tbps
Latency	1 ms	<1 ms
Frequency bands	Sub 6 GHz, mmWave for fixed access	Sub 6GHz mmWave for mobile access, terahertz band, Non-RF e.g., VLC)
Device Services	Secure connectivity	Physical interaction in real-time scenarios
Network Type	SDN, NFV, Slicing	SDN, NFV, Intelligent Cloud, AI-based Slicing, Deep learning
Computing Techniques	Fog computing, Cloud computing	Quantum computing, Edge computing
Mobility	500 Km/h	>700 Km/h
Technology	D2D communication, Ultra-dense Network, Relaying, Small cell access, NOMA	Visible Llight Communication, Quantum Communication, Hybrid access, Haptic technology
Application types	Reliable eMMB, URLLC, mMTC, Hybrid	MBRLLC, mURLLC, HCS, MPS
Architecture	Dense sub-6 GHz small cells with	Cell-free smart surfaces, Temporary hotspots using drones base stations

1.1. Paper Motivation

The vision of 6G wireless systems revolves mainly around the idea of overcoming the limitations of 5G. For instance, providing a Gbps data rate through 5G mmWave will not meet the needs of data intensive applications such as IoE, UAVs, “3D video”, “VR”, “AR”, “XR”, etc. Moreover, intensive service needs of a new communication landscape with varied and dense networks are expected ahead, requiring the extension of global and cross environment coverage and enhancing spectral efficiency, ultra high data rates with AI-enabled management being a leap from “connecting things” to “connecting intelligence”, energy, and QoE and QoS issues. Furthermore, challenging the demands of data communication in the future, where confluence of the physical and digital world takes place. Amidst such a scenario, many candidate technologies, including the terahertz (THz) regime and other technologies powered by AI, have been discussed in [3,16,18–21]. There are a wide range of research studies and initiatives on the recent advances in wireless communication systems, future 6G vision with its candidate-enabling technologies, and use cases, including AI/ML, THz communication, edge intelligence, blockchain, molecular communication, V2X, IoE, UAVs, HT, XR [1,10,13,16,17,22–35]. However, while the 6G experience is expected in a few years, the new impending challenges of meeting the key performance indicators of 6G necessitate extensive research initiatives. This study has adopted a holistic approach of highlighting a major bottleneck, challenges, and research directions. Figure 2 shows comparison of 6G features with respect to 5G.

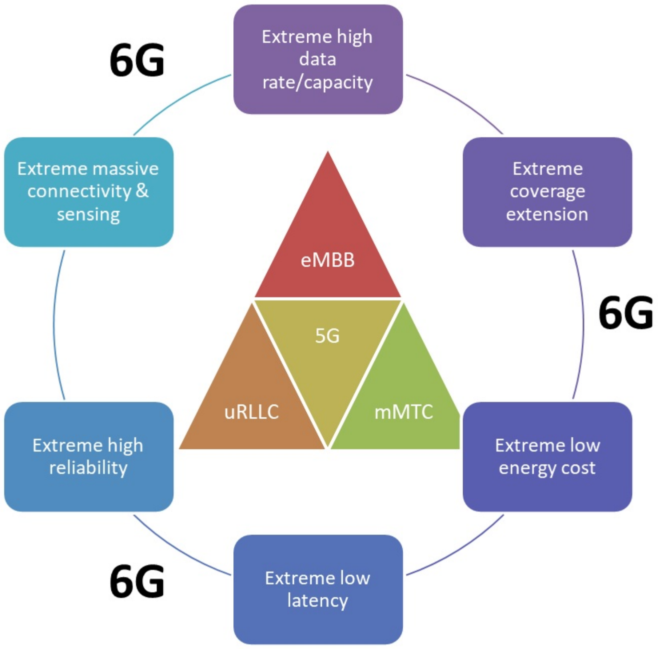

Figure 2. Comparison of 6G features with respect to 5G [36].

1.2. Paper Contribution

The main contributions of this survey study are as follows: (i) the evolution of mobile network architecture: this study presents the significance of architectural evolution while presenting suitable architectural adjustments for future technologies in order to achieve the objective of enhanced spectral efficiency, higher data rates, minimum latency, and CAPAX and OPEX. (ii) Post-2030 6G application landscapes: presents landscape of personal edge intelligence, 6G in the automotive sector, IoT supporting smart cities, autonomous ports and manufacturing, and biocybernetics-based identity. (iii) Country/region wise statistics of patents dedicated to 6G. (iv) Future 6G enabling technologies: presents key technologies, such as VLC, terahertz regime, molecular communication, biosignal processing, blockchain, and energy harvesting technologies enabling and facilitating beyond the 5G era. (v) Major challenges and research areas: highlights key 6G research and possible solution areas, such as data security and privacy, hybrid RN and VLC, cyber physical systems, quantum-based wireless designs, satellite communication, ethical responsibilities, RF interference, its effects on the human body, and multiple access and modulation techniques. (vi) Highlights AI/ML/Dl as key potential enablers of 6G. The structure of this study is shown in Figure 3.

Figure 3. Structure of study.

2. Evolution of Mobile Network Architecture

2.1. Core Network (CN) in 5G

The 5G architecture comprises components such as (i) the Core Network (CN) and (ii) the Radio Access Network (RAN). The Core Network in 5G is based on service based architecture (SBA). It incorporates fundamental functions, such as (i) session management (SMF), which is responsible for managing the protocol data units (PDU) sessions; (ii) Access and mobility management (AMF), which manages the device access and mobility; (iii) Application management (AF), which is responsible for managing application in 5G Network resources; (iv) User plane (UPF) manages user traffic flows and connectivity [37]. The evolution of mobile technology has led to the 5G underlying objective of connecting things, thereby facilitating the internet of things (IoT). This objective is achieved by 5G radio access network(s) (RAN); by connecting diverse and heterogeneous devices through wireless connectivity 5G beyond, using case applications, are highly strenuous. However, this requires appropriate locations of the base stations (BSs) in order to achieve the end user service requirements and maximize "spectrum efficiency". This would eventually impact QoE and QoS requirements and minimizations of CAPEX and OPEX [37,38]. The evolution and restructuring of RAN architecture in this regard is viewed as an important factor, as the optimization of RAN architecture is expected to achieve low latency maximum throughput. One idea is to deploy essential communication processes at the edge of the network. As a consequence, the end user will experience the minimum lowest latency and maximized throughput [38].

2.2. Ran Evolution of Mobile Networks

Regarding the stringent requirements of 5G and 5GB use cases and applications, the architectural evolution is an important issue. RAN architecture in the 5G network, in combination with "macrocell", "microcell", "femtocell", "picocell", and "unified multi-access technologies" utilizing fronthaul (FH) and backhaul (BH) resources, boost up cell edge effectiveness [38]. In 2G RAN, the "radio" and "baseband processing functions" were joined in the base station (BS). However, in 3G and 4G mobile networks, D-RAN deployment, the above scenario was changed to a more distributed one. Thus, two separate nodes were created, thereby splitting baseband and radio functions, i.e., (i) remote radio head (RRH) and (ii) baseband unit (BBU). This created a centralized C-RAN mechanism, thereby centralizing resources in BBU. The main objective of C-RAN architecture was to disintegrate the baseband units from the remote radio head. However, 5G incorporated the cloud computing (CC) feature to the C-RAN which has resulted in a centralization, virtualization/cloudification of RAN architecture [38]. As compared to previous generations, varied services and use cases are anticipated in 6G networks [39]. As a result, the user demands in such a scenario will increase. Thus, it necessitates "flexible", "dynamic", and "state-of-the-art" architecture [6]—a direction toward an architecture that is solely distributed and service-based in 6G and, therefore, a "service-based architecture (SBA)" that meets low latency user needs as an option for 6G. Architectural evolution of radio access network(s) (RAN) in 6G seems to offer opportunities whereby distributed, virtualization–cloudification functionalities will benefit heterogeneous service environments. Towards 6G, the processing capabilities at higher and reliable data rates will facilitate multiple and heterogeneous technologies. Moreover, evolution of architecture towards 6G has been foreseen as distributed and service-oriented RAN. This scenario will also be powered by AI/ML to further enhance the RAN performance in 6G [40]. Further, O-RAN foresees a more open, flexible, and multi-vendor-based selection of RAN interfaces, equipment, and software, and will further offer benefits in 6G, The O-RAN envisages interoperability of flexible, multivendor, and open interface equipment and software. Hence, 6G evolution would incorporate the overall end-to-end service-based architecture, enabling the CN and RAN with interoperability, flexibility,and networks scalability [40]. The 6G use case scenario depicts extensive use of IoT and other applications require data rates and reliability for the smooth provisioning of IoT services. The traditional IIoT architecture based on cloud computing is not suitable for the 6G era. Distributed mobile edge computing (MEC) is considered one of the promising solutions to support billions of IoT/IIoT devices in 6G. The scenario calls for architecture supporting possible future 6G use cases and evolution RAN and CN. Service-based architecture (SBA) is expected to continue through 6G [41].

2.3. Multi-Access Edge Computing (MEC)

Technologies that 6G mobile networks will benefit from include MEC for optimal performances for the provisioning of required resources. Thus, MEC can be a suitable paradigm in 6G as the distributed MEC architecture is foreseen as architecture for 6G. One of the architectural changes required to deal with future challenges of the data-intensive and traffic-intensive applications is a paradigm—multi-access edge computing (MEC). MEC relies on key enabling technologies, such as network function virtualization, software defined networks, network slicing, etc. The prominent 6G use cases benefiting from the above advantages of MEC include, (i) "AR/VR", (ii) "computational offloading", (iii) "internet of things (IoT)", (iv) video streaming etc., to name a few [38]. Moreover, 6G will leverage MEC to achieve the following advantages: (i) It brings services in the proximity of RAN, thereby bringing the end user close to the processing. (ii) "Ultra low latency"; (iii) "Higher bandwidth"; (iv) "Real-time access"; and (v) "Energy efficiency". Despite the great advantages of MEC in the 6G era, some challenges need to be considered, e.g., the location change of the mobile end user creates mobility and QoS issues, as it will ameliorate the burden of the edge server, which calls for mechanisms to deal with these issues effectively in order to ensure uninterrupted services to the end user [38].

2.4. Open-Radio Access Network (O-RAN)

Open-radio access network (O-RAN) is yet another architectural feature propounded by the open-RAN Alliance. It aims to add open source management and control [42]. The intensively demanding 5G network technologies, such as "eMBB", "uRLLC", and "mMTC" require more architectural reshaping. Given this scenario, the open radio access network (RAN) is considered a more viable opportunity. The O-RAN incorporates an opportunity of openness, competitiveness, multivendor deployment of "remote radio heads (RRHs)" and "baseband units (BBUs)", virtualization coupled with intelligence and a faster delivery of services to the end users, and support in 5G and beyond. The open RF interfaces, combining the intelligence making the radio access network (RAN) architecture more open, evolutionary, flexible, and scalable would enhance the performance of radio access networks in 5G and beyond. As stated above, the C-RAN offers cost-effectiveness whereby BBU remains centrally pooled with the baseband pool. However, the absence of openness and the proprietary software and hardware requirements have been a great challenge. The above stated features of O-RAN have been viewed as the solutions of the issues of earlier RAN architectures. Few key advantages of O-RAN include (i) mobility management; (ii) "traffic steering"; (iii) "QoE optimization"; (iv) "resource allocation"; (v) "energy saving"; (vi) "MIMO beam-forming optimization"; and (vii) "automated RAN operations", etc. [42].

2.5. Network Slicing

The concept of network slicing (NS) revolves around the idea of constructing different "logically-isolated" virtual networks, which are also called "the slices". Each service shall have a different slice over a physical network. However, despite its features, network slicing will face challenges in 6G, keeping in view the diversity of services that 6G is supposed to cater for in the future. One of the challenges in 'network slicing' is in dealing with the diversity of segments, in terms of the management of slices. In this regard, artificial intelligence can play a decisive role in intelligent management of slices, meeting all requirements of a diverse quality of service (QoS) [43]. Network slicing is the virtual distribution of network connections, a paradigm of a single connection into multiple different virtual connections. This results in allocating different resources to different connections. It is viewed as one of the most important and unique architectural features of the 5G and 6G future communication architectures. Mobile network operators (MNPs) will have great advantages (and ease) when dividing the networks into different slices, and they can dedicate each slice or portion for specific purposes, thereby allocating different resources to different wireless services. Slicing takes place over both RAN and CN; however, the challenges can range from the availability of radio resources to meeting the intensive requirements of diverse traffic [44].

2.6. xHaul Architecture

Fifth-generation (5G) has laid a necessary foundation for next generation 6G, as the architecture and infrastructure will be developed upon 5G with enhancements and additions to cope with the intensive requirements of 6G. As such, among various architectural and infrastructural components of preceding generations, 5G xHaul architecture will also be retained in 6G, as the flexibility required for B5G will be accommodated with the inclusion. xHaul is regarded as the amalgamation of front haul (FH) and backhaul (BH) in next generation mobile networks, to common and shared or common transport networks. It will enable and equip 6G with a flexible and software-defined reconfiguration of integrated network elements. xHaul architecture will also furnish service-oriented and unified management environments. The combination of "backhaul (BH)" and "front haul (FH)" will result in the evolution of RAN being more flexible. This will facilitate the network functions to be ubiquitously available and accessible and, thereby, they can effectively furnish access to edge and cloud computing resources [45]. This architecture would benefit 6G in terms of achieving high data rates and cost effectiveness. Table 3 provides summary of some studies related to xHaul.

Table 3. Summary of some studies on xHaul architecture.

Author (s)	Contribution
[33]	Reviewed xHaul architecture related standards and activities.
[37]	Reviewed "TSN-aware xHaul network"
[46]	Presented 5G-xHaul architecture features.
[47]	Presented implementation of a "multiband and photonically amplified fiber-wireless (FiWi)" xHaul.

3. Post 2030 Prospective 6G Application Areas

We should note that 5G wireless communications are going to provide the substance and groundwork of 6G, setting up the groundwork for future wired ecosystems for 6G. 6G vision are shown in Figure 4. However, it is not yet clear how the technology is going to digitally unroll towards the development of 6G targets toward robust physical–digital integration. It is also not clear how the lives are going to be fundamentally influenced by this physical digital confluence. Yet, we can envision the B5G era as a challenging discourse whereby providing the foundation for physical–digital confluence, making available 3D terrestrial communication, i.e., air, space, and under water. The era will mature to be trustworthy, resilient, smart, accurate developing extended reality, intelligent and smart IoTs/IIoTs.

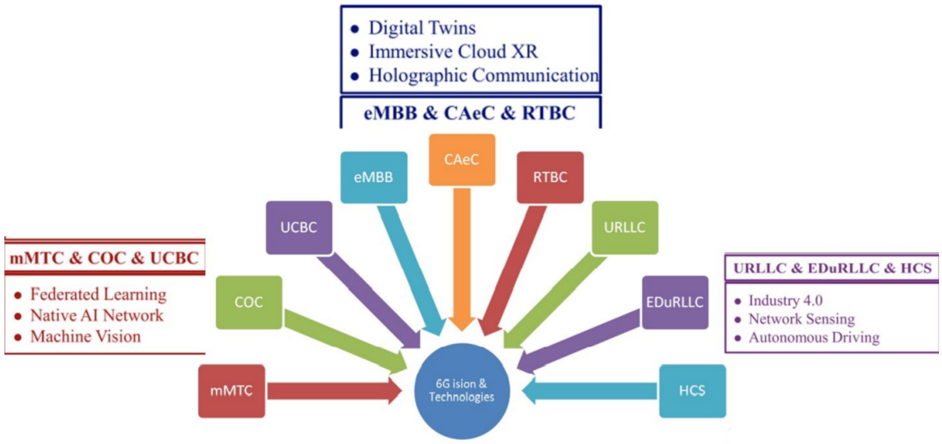

Figure 4. 6G Visions [48].

In this section, future technological landscape is depicted. Some of the key post-2030 era prospective technologies that have the potential to dominate the scenario are given below.

3.1. *Experiencing the Personal Edge Intelligence*

One of the important components absent in 5G is "edge intelligence", which is supported by artificial intelligence and will be an important component in 6G. The "edge intelligence" paradigm, has emanated from the idea of deploying the artificial intelligent added services in the proximity i.e., the "edge" of the network. This has many advantages as the solutions developed in the "edge" will provide swift processing of business services. This can offer economical, safe, secure, and rapid services thereby leading to more efficiency in businesses [49]. Thus, the fusion of advanced AI systems would be powering hundreds and millions of diverse "cross-platform" IoT devices. This will not only enhance the computational power and efficiency, it will achieve the objective of confluence of digital–physical worlds.

3.2. *Wireless Communication for Automotive Sector*

With the growth of the world population, more automobiles are coming about, which complicates the problems of "road accidents", "transport and mobility", and environmental hazards. Thus, there is a search for "environment friendly", intelligent "transport and mobility" solutions. Therefore, B5G envisions AI supported intelligently connected "autonomous vehicles (cars, trucks, ambulances, and drones)". The envisioned "autonomous vehicles" will have "sensors" and "cameras" installed coupled with "THz" data rates and AI algorithms will result in precision and accuracy, thereby greatly lowering the accidents and environment related risks [50].

3.3. Internet of Things (IoT) Supported Smart City Services

The smart city is a new paradigm that has emerged with the massive growths in internet of things (IoT) and intelligent and smart connected devices. The idea of the smart city revolves around densely connected and automated–artificial intelligence-powered digital services in urban life. The smart city massively utilizes digitization and IoT for providing diverse services to ease urban living. These services include, among others, "smart health", "smart transport, logistics and mobility", "smart education", "smart manufacturing", "smart availability of social services management", "smart firefighting", and "smart security systems", including smart policing, etc. The "International Data Corporation (IDC)" reported increased spending in smart city technologies. The idea has received reinforcement with the technologies envisaged in 6G. Entire 6G wireless communication ecosystems are expected to support and flip the idea of the growth in smart cities and smart living.

3.4. Autonomous Ports and Autonomous Manufacturing

Maritime navigation is an important area that can benefit from 6G automation and digitization developments. Innovative intelligent solutions for the Ports and Shipping Industry will streamline maritime navigation and transport in future. An important step in this direction has been taken by a "collaborative agreement" between "Rolls-Royce" and "the European Space Agency (ESA)". This agreement aims to employ an autonomous and "remote control"-based mechanism that will utilize the space based system. This will greatly enhance the capabilities of existing maritime navigational systems. This autonomous remote control-based maritime navigation system will rely on satellite communication, which makes one of the potential 6G application areas. The 6G future vision is likely to be instrumental in the materialization of this idea. The core enabling 6G technologies and computational power , such as "IoT", artificial intelligence, blockchain-based cybersecurity, and intelligent robotics will greatly facilitate the autonomous ports and shipping and maritime navigation as a whole.

3.5. Bio-Cybernetic Based Identity

Human–computer interaction (HCI) is a computational paradigm that seeks to achieve human computer confluence. The "Biocybernetics" is a novel adaptation approach that seeks to optimize the HCI. The vital information of human beings, "bio-signals" gathered and processed and interpreted in real time scenarios using computational power, more broadly, vital data of a person is collected and interpreted in real time by a computer to generate the "adaptive processes". The future industry will use the intelligent robotics and humans. Both will have their own unique features for identification for security and privacy objectives.

4. Statistics of the Patents Dedicated to 6G

The number of standard related (essential) patents in certain technology fields reflect the importance of the fields in each new generation. Yet, 6G technology is in an early pre-standardization phase. Therefore understanding on this topic is not based on facts but includes speculations and reflects aims of different 6G players, than reality. According to a survey involving around 20,000 patent applications for nine core 6G technologies conducted by Nikkei and the Cyber Creative Institute, China is leading the world in 6G patents. As shown in Figure 5, China is responsible for 40.3% of 6G patent filings mostly related to China's patent applications that are mostly related to mobile infrastructure, followed by the U.S. with 35.2%. Japan with 9.9%, Europe with 8.9% and South Korea with 4.2%.

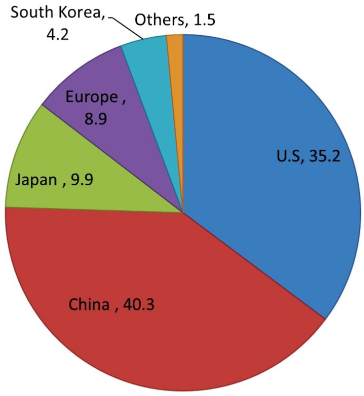

Figure 5. The 6G patent applications by country/region (As of August 2021, in percent) [51].

5. Future 6G Enabling Technologies

The technological advancements and unprecedented data requirements have led to the revolutionary foundations of 6G, taking the existing technology trends and further requirements that 6G will further use to enhance and develop, to enable ecosystems for wireless communication, the new service classes of "ubiquitous mobile ultrabroadband (uMUB)", "ultrahigh-speed-with-low-latency communications (uHSLLC)", and "ultra-high data density (uHDD)" [52]. While 6G is still in its conceptional stage, we envisage fundamental enabling technologies.

5.1. Big data and Deep Learning

The advancements in cellular technology have brought about everything at a distance within one touch. The social value added by digital services has enabled humans to use them for diverse services. The other side of this phenomenal growth is an increased number of connected digital devices, which in turn produce huge data. This poses a big challenge to handle these data efficiently. Big data powered by AI and ML techniques have been envisaged as key concepts to handle huge amounts of diverse data, thereby producing insights for further decision making processes. Big data are essentially large, huge, and entirely voluminous complex unstructured data forms gathered through diverse and heterogeneous sources, including video, images, social networks, sensors, etc. They are characterized by five Vs i.e., the volume, value, variety, velocity and veracity, which essentially define the whole of philosophy behind big data. Due to the complexity, huge volumes and unstructured nature of big data, traditional database management systems have limitations to process such data. Big data have become key components of 6G communication networks; the internet of everything (IoE) and other envisaged technologies produce and share huge and complex data. Big data analytics is yet another term derived from the complexity of data, whereby complex data are processed and analyzed, making the data meaningful and insightful for decision making. Big data, combining and leveraging the strength of deep learning mythologies, have great potential in handling the ever more complex data in 6G communication networks, e.g., finding the best optimum path and minimizing the E2E delay [34].

5.2. Quantum Communications

Quantum computing is a powerful way of processing information that surpasses the "classical communication and computation". There are several concepts and application areas that have attracted the attention of researchers. Quantum communication is one of several areas that is based on the quantum key distribution (QKD). To further explore applications of quantum communication in millimeter wave signals for 6G and beyond, there is ongoing research. The power of QC has inspired many researchers as one of the key enablers in the B5G era of wireless communication as it offers 'parallel processing' of multidimensional massive data along with security and higher data rates [53]. The road map to 6G envisions availability of quantum computing, the universal quantum computing approach based on Shore's algorithms. QC is powerful enough to crack the traditional cryptographic algorithms. Therefore keeping in view the requirements of 6G to ensure high data rates and security, QC-powered security mechanism will become essential [54]. The latest developments in quantum mechanics and quantum computing have reflected more improved and enhanced performances against traditional computing. However this signifies the need to develop quantum-based relevant communication hardware in view of the B5G requirements, since massive wireless data communication requirements of 6G necessitate superior capabilities for higher throughput. Moreover, a confluence of both 'quantum cryptography and advanced quantum communications' will be able achieve the underlying goals of 6G robust security and communication. However, transmission varies in traditional communication, whereby in quantum, communication-based mechanism qubits are transmitted through a mechanism of the quantum teleportation protocol instead of 'classical' bit transmission, which calls for developing relevant hardware and routing protocols [9]. Although quantum Key distribution offers photon-based qubit transmission with security, implementation of QKD in 'long-distance transmission' will be a demanding task and it requires further research [55,56].

6. Key Driving Technologies for 6G

6.1. VLC and terahertz Regime

We should note that 6G is progressing, to make a giant leap toward future wireless communication technologies, surpassing all previous limits and capabilities, such as the availability of huge amounts of superior bandwidth to meet the high requirements of Tbps data rates. Therefore, terahertz and massive MIMO have become potential candidate technologies toward 6G. For instance Table 4 gives some insights regarding some key characteristics of the THZ channel with effects on 6G wireless communication.

Table 4. Characteristics of the THZ channel with effects on 6G wireless communication. (Derived from [57]).

Parameters	**Frequency Dependence**	**effects on 6G THz**	**THz vs microwave and FSO**
Spreading Loss	Quadratic fluctuation with area and "frequency-dependent gains"	Distance Limitation	> microwave, < FSO
Atmospheric Loss	Frequency-dependent path loss peaks	frequency-dependent spectral windows with varying bandwidth	No perceptible impact on microwave frequencies, oxygen molecules at millimeter wave, water, and oxygen molecules at THz, water, and carbon dioxide molecules at FSO
Diffuse Scattering and Specular reflection	"Scattering increases" with frequency. Frequency-dependent reflection loss	Limited multi-path sparsity	Stronger than microwave, weaker than FSO
LoS prob, Diffraction, and Shadowing	Negligible diffraction, shadowing and penetration more losses with frequency increase. Frequency-independent loS probability	Low multi-path high sparsity and dense spatial reuse	more than microwave less than FSO
Weather Influences	Frequency-dependent airborne particulates scattering	Potential constraints in THz outdoor communications with heavy rain attenuation	> than microwave, < FSO
Scintillation Effect	Increase with frequency	Constraint in THz space communications	No clear effects at microwave, THz is less susceptible than FSO

It is highly anticipated that 6G will achieve the objective of more bits along with wider spectra and maximised network densification. This would furnish Tbps aggregated speed, but in small regions. The bit rates would be higher from 5G. This also signifies the achievement of the underlying objective of 6G, with terahertz technology being a key enabler towards it in future generation communication. terahertz frequency falls within the ranges of "electronics and optics", i.e., frequencies ranging from 300 to 3000 GHz, respectively. The secure terahertz radiation has great penetrability. The terahertz radiations also have high bandwidth characteristics. The unique characteristics of terahertz technology are also viewed as the potential facilitating factors of a wide array of application areas, such as healthcare, defence, security, and the telecommunication sector. Thus, it provides greater motivation to influence the upcoming 6G research trends to give special emphasis on diverse spectrum bands. The sub-THz and visible light bands are also included. This solution would provide an optical fiber-like performance, ranging from Gbps to Tbps. VLC is also anticipated to potentially furnish indoor connectivity for short ranges, to further increase up to Tbps. This is expected to be available for operations, achieving maturity by 2027. As such 6G is expected to exploit the terahertz (THz) bands (i.e., 0.1–10 THz). Besides meeting the requirements of 6G, terahertz bands would enhance precision in 'positioning', thereby enabling the accurate range between transmitter and receiver. The terahertz is a frequency band of 0.1–10 THz and can furnish huge "spectrum resources" thereby it is capable of enhancing the "peak rate", improving "user experience rate", higher "spectrum efficiency", greater "energy efficiency" and minimum latency etc. However, fundamentally it is expected to enable applications such as "wireless cognition", "sensing", "positioning", etc. [34,58,59].

6.2. THz Challenges

Further, terahertz frequency falls within the ranges of "electronics and optics", i.e., frequency ranges between 300 and 3000 GHz. The radiation from terahertz has greater safety (because of "non-ionizing nature") along with more potential penetrability, and high bandwidth characteristics. However, terahertz can also be viewed realistically with respect to challenges, such as 'path-loss and atmospheric absorption'. For instance, in comparison with 28 GHz, a link at 280 GHz has 20 dB of additional 'path-loss'. However such path problem can be solved by using ultra-massive multiple-input multiple-output (MIMO), having 'massive antenna arrays at base stations (BSs)'; in order to compensate the 'path-loss'. However these challenges are still open to be explored and researched [59]. Due to its characteristic and the key performance metrics (KPM), terahertz has been projected as an important technology for next generation wireless communications. As such, higher bands—95 GHz to 3 THz—are being considered for, in case of 6G. The vision is to make a leap to the higher frequency spectrum, i.e., from the "millimeter waves" to "terahertz waves". Due to its propensity to move in a linear path, the "terahertz waves" are not capable of propagating for longer distances. This necessitates further research to address this [57–60].

6.3. Molecular Communication

One of the novel interdisciplinary paradigms in communication is molecular communication (MC). Its research scopes are spread across biotechnology, nanotechnology and communication technology, biology, and computer science. It has a vast applications scope, ranging in several areas, such as healthcare. Molecular communication can leverage nanotechnology to urban health monitoring and as such, extensive research work is underway on communication through the use of chemical signals. The possibility of communications through chemical signal is being explored. An attempt has also been made in molecular communications to send text messages using chemical signals. The idea has received immense inspiration from the "biological system" of the human body, whereby communication takes place between transmitters and receivers through molecular chemical signals. This biological phenomenon is the foundation of inspiration for telecommunication engineers who compare this "information flow based on chemical reaction" inside the body with the telecommunication "radio or optical signals". As such, in recent times, research exploration has exceeded in finding solutions of molecular communication based “nano-(bio)-devices and nano-(bio)-networks”. As a matter of fact, the traditional communication uses electromagnetic (EM) waves for communication. However, electromagnetic (EM) waves are not viable in an environment, such as a human body. Thus possible solution is being explored to use these “biochemical signals” for communication, i.e., transfer the information to the receivers [14,61]. Thus, molecular communication is an option of communication in nano devices and nano sensors. The encoded information onto molecules at the sender side is propagated by molecules, to receivers, to be decoded and respond biochemically. As a result of molecular communication (MC), medicine and the healthcare application areas are going to witness huge transformation. MC will reshape and revolutionize 6G, thereby enabling mobile systems, which will further integrate the “bionano machines” for future communication.

6.4. Bio-Signal Processing

Advancements in wireless communication technologies have opened several vistas in different vital areas. The application of bio-signal processing will transform the outlook of healthcare; 6G wireless communication technology will enable real time health monitoring. With the featured robustness, 6G “real time healthcare monitoring system” can be implemented in distant areas, which are going to benefit rural life, elderly care, and clinical decision making in real time monitoring, and even early diagnosis. The computationally pre-programmed small embedded chips containing the bio-signaling processing can be integrated with mobile phones, “medical wearables” used by patients to communicate vital data of the human body, such as the pulse rate, blood pressures, etc., which can be monitored in real time for swift medical responses in emergencies.

6.5. Blockchain

Thriving wireless networks are causing “digital transformation”; consequently, massive data flows with unprecedented requirements, which current infrastructures are unable to sustain and fulfill. Thus, new technology solutions are being explored to meet the requirements of ‘beyond 5G era’. Among other technologies as discussed in this study, blockchain is one of the technologies of beyond 5G wireless “ecosystem”. Beyond 5G era is expected to have billions of connected internet of things (IoT) devices of heterogeneous nature. This intensive and massive scenario of wireless communication warrants privacy and security of massive data flow, among others. Thus, blockchain is considered to be one of such candidate technologies of future wireless communication, having potential of offering new security protocols of security, thereby enabling 6G IoT device data security in layered and decentralized manners. Blockchain unique characteristics make it a future “enabling technology” for 6G. The envisaged scenario depicts numerous IoT devices in the future, thereby requiring secure access and authentication mechanisms. Table 5 provides summary of some studies in blockchain.

Traditional centralized radio access networks (C-RAN) do not offer sustainable mechanisms for authentication. However, a blockchain based architecture is deemed to be secure architecture. Blockchain is regarded as one of the enabling technologies in a beyond 5G era wireless communication ecosystem. Blockchain is based on a peer-to-peer decentralized network mechanism. As a matter of fact, its a decentralized and distributed ledger technology that is primarily a dataset that is decentralized and distributed throughout numerous nodes. Having no central regulatory mechanism, every node or block owns and maintains a copy of a ledger. Blockchain is based on strong cryptographic mechanisms to ensure security [34]. Key characteristics of blockchain includes: decentralization, transparency, non-repudiation, immutability, resilience to cyber-attacks, etc. Thus, blockchain can provide multiple solutions to 6G networks, such as “intelligent resource management”, enhanced security in diverse application areas, such as industrial applications, seamless environment monitoring and protection, and healthcare [62]. Figure 6 gives an overview of the role of blockchain in 6G.

Table 5. Summary of some studies in blockchain.

No	Author (s)	Contributions
1	[34]	Presented comparison of "blockchain-based spectrum management" and legacy "centralized approach".
2	[57]	Proposed a novel consensus E-PoW, where MMC in AI training is integrated into the block mining process.
3	[58]	Presented a distributed watchdogs based on blockchain for securing IIoT
4	[59]	Propose a 'BlockEdge' (blockchain edge) framework that combines these two enabling technologies to address some of the critical issues faced by the current IIoT networks.
5	[60]	Reviewed blockchain and ML for IoT in 5G and beyond networks.
6	[62]	Proposed an "IoT and blockchain-enabled" optimized provenance system for Industry 4.0.
7	[63]	Presented an overview of blockchain as potential security solutions "edge computing".
8	[64]	Overviewed the blockchain technologies and protocols that can be used to implement blockchain-backed network asset trading over 5G and Beyond networks.
9	[65]	Examined the security problems with blockchain-enabled IoT with a 6G communication network.
10	[66]	Designed a new digital twin wireless network model—DTWN.

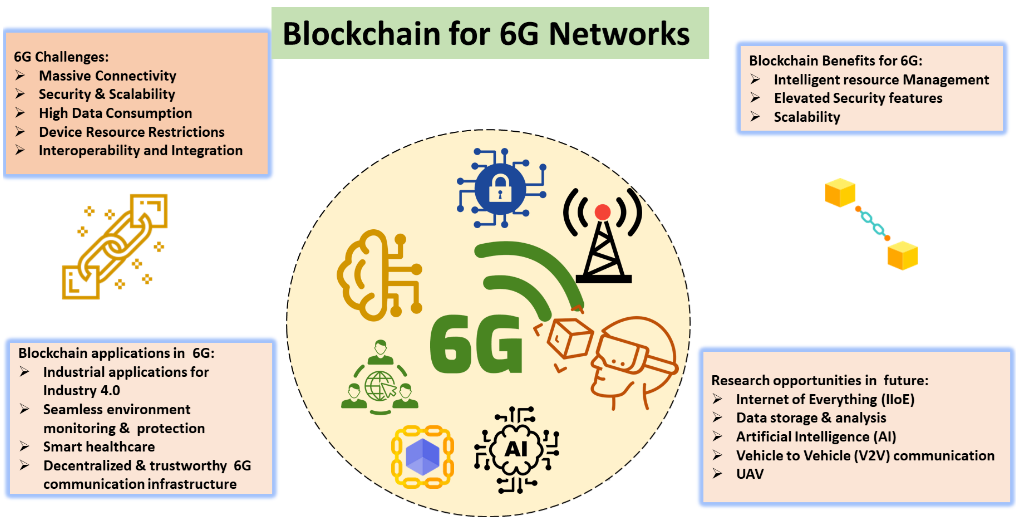

Figure 6. Role of blockchain for 6G networks [62].

Moreover, blockchain contains inherent characteristics of "decentralized" and "tamper-resistant" new technology paradigms for spectrum management. The traditional spectrum management faces challenges, such as security and "low allocation efficiency". It suits the 6G wireless communication by offering solutions to the existing challenges to traditional centralized spectrum management [60]. Table 6 provides comparison between centralized spectrum management and blockchain-based spectrum management.

Table 6. Comparison between centralized spectrum management and blockchain-based spectrum management [60].

S. No	Centralized Spectrum Management Issues	Benefits of Blockchain-Based Spectrum Management
01	Security risks	Distributed storage and encryption methods/algorithms are used for the security of the users' data
02	No incentive approach for spectrum sharing	The incentive mechanism (e.g., virtual currency) can attract nodes for spectrum sharing
03	Exposed to the threat of malicious attacks	Validation mechanisms offer security for the transactions
04	Low spectrum allocation efficiency	Distributed spectrum management offers effective and improved spectrum allocation
05	Expensive maintenance	Cost effective for maintenance as there is no centralized database to be maintained

Blockchain is a decentralized approach that offers "data integrity", "trust", and "security". The use of blockchain is not limited to a few application areas, but its use is spread across multiple fields including data communications, "healthcare", "supply chain management (SCM)", education, "internet of things (IoT)", industrial internet of things (IIoT) etc. Blockchain contains strong mechanism to ensure security triad i.e., the "confidentiality", "integrity", and "availability (CIA)", which make blockchain a critical candidate regarding 6G technology components [63,67,68]. Key characteristics of blockchain include: decentralization, transparency, non- repudiation, immutability, resilience to cyber-attacks, etc. Thus blockchain can provide multiple solutions to 6G networks such as "intelligent resource management", enhanced security in diverse application areas, such as industrial application, seamless environment monitoring, protection, and healthcare. Table 7 reflects Blockchain-based solution to address the challenges in AR/VR [67].

Table 7. Blockchain-based solution to address the challenges in AR/VR. [67].

No	Parameter	Description	Potential Benefits in AR/VR Applications
1	Decentralization	Decentralization of record maintenance eliminating the single-point risk of failure.	Blockchain offers the decentralization of different communication devices.
2	Tokenization	Facilitation users to exchange values on different networks.	Blockchain improves financial transactions using digital tokens.
3	Immutability	Consensus mechanism enables data storage in distributed ledger form, which provides unalterable and tamper-proof record maintenance. Consensus mechanism also provides the integrity of the end-to-end (E2E) system	Blockchain provides an improved way of sharing/exchanges of audio/video data between server and device in a secure way.
4	Scalability	Scalability provides increased transaction load and number of nodes in the network.	Blockchain provides an increase in the transaction size for all blocks for storing and peering data using an interplanetary file system.
5	Anonymity	provides trust mechanism among unknown nodes in network	Blockchain enables nodes create unique digital assets that cannot be copied.
6	Security	Offers security for possible attack against data by encrypting the data through cryptographic algorithms having no relationship for private and public keys.	Blockchain can offer improved scalability for AR/VR in tactical applications.

6.6. Energy Harvesting for Mobile Charging

In communication networks, “energy consumption” is of paramount importance [69]. Mobile phone charging and power are critical issues as the battery exhausts with excessive and continuous usage. Loosing power means dis-connectivity of a device. To resolve these issues of power issues of mobile devices, for continuous connectivity, researchers have focused their attention on "energy harvesting" techniques for continuous energy supply to the connected devices. Therefore, currently researchers explore how energy harvesting techniques can be applied for uninterrupted energy supply [70]. These options include,

(i) The energy obtained from an “ambient environment” can be utilized as a potential substitute of energy supply. This can also meet the energy requirements of radio access network(s) (RAN).
(ii) Moreover, radio frequency (RF) interference, “RF interference energy harvesting” has also been considered an option where the “ultra-dense” networks having numerous nodes can potentially produce interference energy.
(iii) The energy produced by “the artificial Jamming and noise” is also considered a resource for energy supply [70].

Among the above, the RF interference is an important energy source due to an overwhelmingly increasing number of RF devices and the resulting use of frequency bands (WiFi using 2.4 GHz, 5.8 GHz, cellular communication utilizing 700 MHz–2.7 GHz and Bluetooth 2.40–2.48 GHz) making RF energy use overwhelming. However energy harvesting requires the capable “rectenna”. Moreover, the “simultaneous wireless information and power transfer” (SWIPT) method proposed by [71], which is capable of obtaining information and energy simultaneously from RF signals [70].

7. Major Challenges and Research Areas for 6G

The 5G has setup the stage for next generation digital revolution. However, the road to the milestone still seems bumpy, with several challenges, as the emergence of disruptive technologies brings challenges. The challenges provide future research directions. Some of these challenges have been highlighted as the key research areas leading to 6G.

7.1. Data Security and User Privacy Challenges

Security and privacy flaws have remained issues in earlier mobile communication generations, amidst the envisaged hyper-connected dense ecosystem of future 6G wireless communication. However the 6G ecosystem is not for data communications only. It can be visualised as a framework of connected user specific services. Thus, “seamless security and user privacy” is a critical enabler for the 6G era [50]. Consider the security and privacy related experience and challenges of previous generations, i.e., 1G–3G, marked by authentication, availability and ‘physical attacks’, ‘eavesdropping’, ‘encryption issues’, ‘authentication’, and ‘authorization’, etc. Previous threat landscape also include ‘media access control (MAC)’ layer related threats such as ‘denial of service (DoS) attacks’, ‘eavesdropping’, ‘replay attacks’, and ‘malware’ attacks, etc. Moreover, 6G envisages confluence of AI/ML-based ‘connected intelligence’ and ‘telecommunication networks’, which may also inherit risks [1]. Moreover, 6G is expected to include ten times higher connectivity among the myriad number of connected heterogeneous devices enabling cyber–physical fusion, thereby necessitating trustworthy and reliable security mechanism against the aforementioned (and all other) threats. This requires a ‘holistic’ approach toward the issues at the very outset. [54]. In view of the above, exploration of the ‘privacy-enhancing computation’ (PEC) is actively on the cards, such as: (i) differential privacy, (ii) holomorphic encryption, and (iii) federated learning [72].

Privacy-Enhancing Computation (PEC)

Security and privacy of data hold fundamental positions in any data communication ecosystem. Hence, privacy enhancing commutation (PEC) technology is a mechanism used for secure communication of data. The areas for PEC being explored includes differential privacy whereby data can be shared while injecting random noise to scramble actual data into a database. Whereas, federated learning (FL) is a form of decentralized ML, where devices have local models to be trained and send updates to, to be synchronized with the global model [72].

7.2. Hybrid Radio Networks (RN) and Visible Light Communication (VLC)

Visible light communication is the latest technology paradigm, which was not available in existing mobile communication generation. Visible light communication (VLC) is still being explored with respect to strength and capacity. VLC being the future 6G technology, is researched from the perspective of limitations of millimeter wave and a wider range and coverage. There are limitations of millimeter wave. It has required bandwidth strength and capacity but it offers communication to comparatively limited areas. Thus, visible light communication (VLC) is a matter of extensive research from the perspective of suitability, capacity, and strength, to be deployed as a future technology. One of the cutting edge technologies envisaged for 6th generation wireless networks is light fidelity (LiFi), based on optical wireless technology, visible light communications (VLC), which offers cost and energy effective wireless solutions for 6G for 'extreme cell densification'. As compared to radio frequency (RF), VLC offers 'higher data rates', security, making availability of large spectrum and robustness. Moreover, it offers high speed secure ubiquitous connectivity in 'indoor', 'vehicular', and 'underwater communications'. This has some limitations, such as 'modulation bandwidth of the transmitting light-emitting diodes (LEDs)' and 'high dependency on the line-of-sight (LoS)', resulting in affecting the signal quality, which can be overcome with 'multiple-input multiple-output (MIMO) configurations' to enhance LiFi capability and signal quality. VLC is also vulnerable to confidentiality issues, such as eavesdropping attacks [1,72].

7.3. Wireless Networking for Cyber-Physical Systems (CPS)

We should note that 6G envisages a shift from physical and digital, from a confluence of a cyber–physical world. The concept does not only involve connecting the physical and digital ends, instead, a cyber–physical confluence connects the realities with "unified collaboration" and "immersive involvement" [73]. The cyber–physical systems (CPS) seeks to connect using computer algorithms to control them for automated operations.

7.4. Quantum-Based Wireless Systems Design

The challenges and inadequacies of existing wireless communication systems can be addressed by quantum-based computing, the term being inspired from photon-based quantum physics. The power of quantum communication algorithms can be applied to exponentially hard problems of optimization of the network and reduce the complexity of backhaul traffic problems. Table 8 provides summary of some studies on quantum communication. Figure 7 depicts user environment in QC.

Table 8. Summary of some studies on quantum communication.

Author (s)	Contribution
[9]	Presents attacks in optical networks and a solution through "quantum- secured blockchain".
[46]	Presented a scheduling algorithm for mmWave observation.
[74]	Studied the problem of optimal distribution of entanglement generation for multiple heterogeneous users in a quantum communication network.
[75]	Design and security analysis of the QKD protocol over FSO
[76]	Presents "Quantum Search Algorithms for Wireless Communications
[12]	Proposed "Quantum Learning Based Nonrandom Superimposed Coding for Secure Wireless Access in 5G URLLC"
[77]	Studied Quantum security authentication and key management in LTE.
[78]	Developed an integrated polarization beam splitter (PBS) module with silica planar lightwave circuit technology for use in QKD.

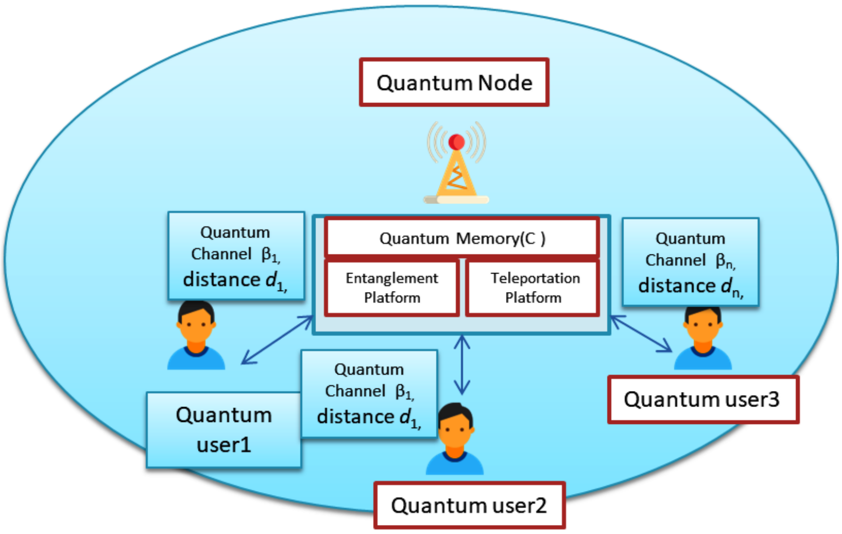

Figure 7. Quantum Communication (QC) derived from [9].

7.5. Multiple Access and Modulation Techniques

Efficient multiple access and modulation techniques could play essential roles in improving the data rate and reducing energy consumption of future 6G networks. Modulation techniques are viewed as key players in mobile communication with regard to enhancing the efficiency and performance. There are several modulation and multiple access schemes, such as:

(i) Frequency Division Multiple Access (FDMA);
(ii) Time Division Multiple Access (TDMA);
(iii) Code Division Multiple Access (CDMA); and
(iv) Orthogonal Frequency Division Multiple Access (OFDM).

The FDMA scheme was utilized in first generation Networks, TDMA was utilized in second generation networks, and CDMA scheme was witnessed in third generation networks, and the OFDM scheme being in 5th generation and later new radio (NR) wireless mobile communication networks. The 5GNR utilized the OFDM multiple access orthogonal scheme, which is viewed by researchers as the most prominent modulation scheme among all above. The reason for this being OFDM's efficiency against:

(i) "frequency selective fading";
(ii) "co-channel interference"; and
(iii) "impulse noise".

Further, the OFDM scheme offers several benefits, which includes enhanced "data rates", enhanced "spectrum efficiency", protective to the ISI (inter symbol interference), and offering "multipath delay spread". However, given its superior advantages among above, OFDM also suffers from certain bottlenecks as well, which include, greater "Peak to Power Ratio (PAPR)", etc. With this in mind, the researchers have proposed new schemes for the upcoming mobile network generations, such as "filter bank multi- carrier (FBMC)", "universal filtered multi-carrier (UFMC)", "filtered-OFDM (f-OFDM)", and "generalized frequency division multiplexing (GFDM)". However schemes suitable for future 6th generation networks need to be evaluated [35]. The 6G stringent requirements call for more research initiatives in the areas of "advanced modulation techniques" and "coding" to achieve maximum "throughput", "reliability", and modulation with no "shaping loss" [39].

7.6. Processing of Sensor Data at High Speed

Artificial Intelligence-based mechanisms can be developed for the processing of sensor data for various benefits, including "data analytics", "optimization", and "traffic mobility", etc. This will provide an added benefit of achieving a high performance.

7.7. Satellite Communication

Another important area that the existing mobile communication networks are not capable of providing is satellite communication. It is critically required to have an integration of satellite communication; 6G envisions achieving transformation of the "terrestrial 2D" to "global 3D connectivity". This will achieve the objective of limitless ubiquitous connectivity, thereby connecting land, sea, and air [73]. In order to achieve a wider global level of coverage, a post 6G scenario depicts wider usage of diverse "satellite communication" technologies. Thus 6G's vision for "ubiquitous connectivity", "wider global coverage" and "higher throughput" can be realized by integrating cellular networks with satellite communications. Further, in the 6G era, satellite-enabled communication can facilitate "UAV and satellite-assisted communication technologies" to provide global connectivity to facilitate the "smart-physical devices" and IoT for "reliable", "secure wider coverage", and "rapid rural deployment", etc. Moreover, 6G satellite-based communication can also facilitate "healthcare systems" and "navigation" applications, etc. Companies such as "Globalstar" and "Iridium Communications" have undertaken "satellite-based IoT" projects for the above-mentioned use case scenarios, which were challenging tasks for traditional "cellular communication systems" and "terrestrial technologies". Moreover, in the post 6G era, integration of "non-terrestrial technologies" the UAV, and satellite-assisted "communication technologies" will bring benefits of not only higher data rates, but facilitate the lives of people living in far flung regions, effective natural calamities, and disaster management opportunities [6,79,80].

7.8. RF Exposure and Related Human Health Concerns

The benefits offered by advanced wireless mobile technologies are innumerable; however, the challenges with regard to impacts on human lives, are issues. The negative impacts of the radio frequency radiations (RFR) cannot be overlooked. Thus, at the dawn of 6G era researchers should also focus and address human healthcare related concerns, with respect to human contact with RF radiations. Electromagnetic radiation-related issues have been under research for several years; however, 5G and beyond envisions mmWave environments, especially indoors, which is regarded as offering large data rates and bandwidth, yet the exposure to radiation has created major health concerns. The reason is that mmWave radiations are regarded as high frequency signals. This makes mmWave signals possible risks (i.e., of penetrating into the human body). The studies have shown exposure to the RF radiation leading to affect different body parts, including the skin and eyes [15,81].

7.9. Electromagnetic Compatibility

We should note that 6G is anticipated to use frequencies higher than 100 GHz [82]; 6G foresees a large number of varied devices connected through the wireless medium. This huge number of diverse nature-interconnected devices will require higher data rates as stated above. This however would result in an "overburdened and overloaded electromagnetic (EM) spectrum". In 6G, the problem of capability of wireless communication network requires a solution and mechanism, which, at the same time, sense and communicate through EM spectrum. Heterogeneity of devices calls for EMI compatibility. The requirements of EMI compatibility in B5G are also being explored by the researchers. B5G radio requirements call for a dynamic solution for spectrum sensing for sending and receiving RF signals to THZ bands. A transformation mechanism is needed [16,83], whereby the diverse devices can interact and share spectrum EM "dynamic sensing" and "multiband communication" for collocated devices [83]. The higher "bandwidth", "frequencies" and "co-location densities" have been considered challenging, which require devising mechanisms. The possible concerns as a result of EMC, with respect to the 6G KPI for collocated devices, may include (i) collocated devices having greater densities, demanding EM environments, (ii) the addition of more autonomous and flying objects may create unpredictability for collocated devices, (iii) radiated properties of new frequencies, (iv) VR glassed and body implants having sensors, and (v) integration of “3CLS” etc. [84].

7.10. Reshaping the Developing Economies, Last Mile

The advancements in digital wireless communication have also been viewed as factors of social change and in the growth of economic benefits leading towards poverty alleviation. In this regard, the 6G vision could help achieve poverty alleviation and social change (UN SDGs 2030 objectives). The cost effective means of wireless communication will obviously help individuals as well as collective economic development and growth. The wireless communication can boost the performance and achieve goals of economic growth in terms of easy and ubiquitous connections with individuals, financial institutions, banks for transactions, business owners, markets, agriculture, industry, transport, logistics and mobility of services, and goods, etc. 6G is expected to provide ample opportunities for the developing economies to benefit from the vision and, thereby, utilize the characteristics offered by 6G in ameliorating the living standards of people and growth of economies. From a small agricultural producer to small and medium industries, from small retail businesses to larger exports and imports of goods and services—all can benefit from the 6G vision for growth and prosperity. In short, 6G includes an opportunity for the development of new business models.

7.11. Ethical Responsibilities and User Awareness Programs

The disruptive technologies always bring some positive changes in society with an objective of benefiting people, social groups, industries, and economies. This change also puts social responsibilities of sensitizing that very change. The end user and other stakeholder sensitizations about the technological and economic benefits are therefore ‘socially responsibly’. Thus, it is imperative to mobilize user awareness programs for the above objectives.

8. Machine Learning Technologies as Potential Enablers of 6G Era

5G was envisioned to support eMBB and operate at high frequency millimeter wave (mmWave) frequencies as a key enabler of heterogeneous internet of everything (IoE), which resulted in 5G new radio (5G NR) coupled with 3GPP release. However, this has been impeded due to the limitations of the internet. The proposed 6G has been envisioned as the true successor of 5G to carry forward the underlying goals towards the achievements. Yet, much more regarding 6G is still being explored [21]. Figure 4 provides a vision of 6G. One of the key ideas that governs the wireless communication beyond 5G principles and alters the legacy fabric is the massiveness of data from heterogeneous sources. Given the limitations of the 5G setup, such massive operations require pervasive intelligence. The current mathematical models, though have clarity, have limitations to handle the complexity of massiveness of data communications. The new frequency bands, such as millimeter-wave (mmWave) and optical spectra coupled with the integration of licensed and unlicensed frequency bands, require intelligent setups to ‘cop-up’ with, as a significant increase in wireless data traffic that cannot be fully supported sufficiently by the current network, even with fifth generation (5G) systems [85]. In view of the above 6G envisions ‘transformations’, let us have a look at the following requirements [48,85]:

(i) “Very high data rates, up to 1 Tbps”;
(ii) “Very high energy efficiency capable of supporting ‘battery-free IoT devices”;
(iii) “Reliable ‘global/terrestrial connectivity”;
(iv) “Massive low-latency control (less than 1 msec E2E latency)”;
(v) “Very broad frequency bands’ (e.g., 73 GHz–140 GHz and 1 THz–3 THz)”;
(vi) “Ubiquitous always-on broadband global network coverage”;
(vii) “Connected intelligence’ powered by machine learning”.

Given the challenging requirements of 6G technology implementation, machine learning (ML)/deep learning (DL) can play vital roles to ensure the efficient and successful implementations of 6G wireless communication technologies. It is therefore expected that ML-driven state-of-the-art solutions are expected in physical as well as the upper layers. This also includes, among others, (i) 'Radio Interface Optimization' (RIO), (ii) 'Beam-forming' (iii) 'network management', and (iv) 'orchestration', etc. Simultaneous key 6G research directions for ML-driven intelligent solutions for the PHY layer, include: 'Channel coding', 'Synchronization', 'End-to-end (E2E) communication', 'UE Positioning', 'Channel estimation', 'Beam forming', 'Physical layer optimization (PLO)', and 'Physical later security (PLS)'. In addition to this, ML can play a vital role in upper layers as well [86]. As a result of the perpetual growth in wireless technology, new users, and demanding (and bandwidth greedy) applications being added, machine learning has been perceived as a key B5G/6G enabling technology. ML/Dl learns from scenarios, such as humans, and as such, can be helpful in several ways including making decisions about connecting devices and access points and resource allocation [8].

8.1. Machine Learning Approaches

Machine Learning approaches broadly falls under supervised learning (SL), unsupervised learning (USL), and reinforcement learning (RL). An associated subset of deep learning algorithms mimic human neurons. All above categories work in a centralized way and, thus, are considered vulnerable to security threat. Federated learning has emerged as a new technology. Federated learning (FL) is based on a decentralized approach and, hence, is called decentralized machine learning. In FL, each device has in own local model to learn. The local model is then uploaded for the synchronization with a global model. As such, no plain data are transmitted, making it a more secure learning approach.

8.2. ML/Dl Driven Solutions

There are several survey studies discussing the massive transformation processes and the evolution of wireless technologies from 1G to B5G/6G. However, few studies have discussed the state-of-the-art ML/DL/RL/FL solutions in order to provide insight into how machine learning technologies bring effective panacea to the requirements of upcoming wireless technology, set to achieve goals of turning today's fiction into a reality. In this section, we define some previous machine learning-based solutions for wireless communication. The author of [87] presented a federated learning (FL)-based solution for 'LEO-based satellite communication networks'. The author also reviewed different machine learning (ML) techniques, and then investigated possible ways of combining ML with satellite networks. The author of [88] developed a DL-based 'radar-aided beam prediction' approaches for mmWave/sub-THz systems. The author of [89] proposed an AI-based digital twin enabled network framework. The authors of [90] suggested 'Graph Attention Q-learning (GAQ) algorithm' for 'tilt optimization'. While the authors of [86] suggested a learning-driven detection scheme using lightweight convolutional neural network (CNN). The author of [8] suggested a federated learning (DFL) methodology for 'autonomous driving cars'. The author of [87] investigated 'accurate collaborative positioning' for 'autonomous vehicles'. The author of [88] demonstrated the ML method to detect the existence of the 'intermodulation interference' throughout several wireless carriers. Table 9 provides summary of sutdies related to AI/ML/DL/RL/FL approaches in wireless communication networks.

Table 9. Summary of AI/ML/DL/RL/FL approaches in wireless communication networks.

No	Author (s)	Contribution	Type
1	[8]	Proposed a federated learning (DFL) framework for autonomous driving cars.	FL
2	[21]	DL-based "radar-aided beam prediction" approaches for mmWave/sub-THz .	DL
3	[48]	Proposed a graph attention Q-learning (GAQ) algorithm for tilt optimization	RL
4	[72]	Presented FL in LEO-based networks. Reviewed LEO-based SatCom ML technique networks.	FL
5	[85]	Proposed an AI0based "digital twin enabled network framework"for 6G networks.	DL
6	[87]	Investigated the positioning for autonomous vehicles.	RL
7	[86]	Proposed a learning-driven detection scheme using lightweight CNN.	DL
8	[88]	A ML approach for intermodulation interference detection in 6G	ML
9	[89]	Computer vision-aided beam tracking in millimeter wave deployment	DL
10	[90]	Proposed to use a cell-free massive MIMO to ensure stable operation.	FL
11	[91]	Designed a DL-based LR channel estimation method—MIMO channel V2X.	DL
12	[92]	DL-based load balancing for QoS in 6G	DL

9. Conclusions

To many, the 6G era marks the dawn of a radical reshaping and complete transformation. Looking at the past provides a futuristic approach. Thus, in this paper, we traced the evolutionary background of wireless mobile communications. We explored the 'beyond 5G era', as having promising opportunity in the confluence of communication technology and humanity, connecting more people, and resulting in benefits to the neglected and underprivileged sections of global society. We revisited the major technical impediments and obstacles toward the transformation and discussed facilitating technology factors in 6G. In this paper, we observed that, despite several advancements, there are still several challenges. The goal of free, 24/7, ubiquitous ultra-high availability internet still seems a ticklish goal and presents many research 'directions'. There have been improvements introduced by 5G, yet cost effective, speedy, and latency-less internet, with cyber–physical fusion terrestrial communications (air, space), have yet to become a reality. Thus, we explored major issues and challenges of 5G , to be key obstacles for 6G, as leading research challenges. We conclude that the limitations of 5G will be addressed in 6G, toward a smooth transition, toward a new wireless communication ecosystem that entails novel technological innovations. We foresee a densely connected world of energy efficient, self-charging nodes, and devices that are intelligent and automated. In this article, we anticipated 6G as an era of new beginnings with hyper-digitization, in a hyper-connected world, bringing not only technological benefits, but simultaneously building upon the societal megatrends, such as the UN SDGs, green energy, clean atmosphere. Moreover, we anticipate that 6G will not only be about wireless data communication, it will be about facilitating and benefiting humanity, allowing businesses to grow and industries to flourish on the foundation of a fully connected intelligent and automated ecosystem. We anticipate that these years to come will usher in a new era, full of extensive research needs. It is observed that MC, Thz regime, molecular computing, quantum computing, deep federated learning, and blockchain will play roles in 6G, which requires strenuous and cogent research based findings. Thus, a whole new envisaged 6G ecosystem, new architecture, physical and upper layers, the atmospheric challenges, blockages, range issues of Thz, etc., need to be researched for the "machine-type communications" (MTC), smooth availability, transmission, security, economical, prudent, and judicious exploitation of "THz spectrums", coupled with sustainable "modulation and duplexing" mechanisms. Moreover, keeping in mind the existing digital divide, we conclude that 6G will benefit all of humanity, by furthering the UN's sustainable development goals (SDGs).

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Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
DOAJ	directory of open access journals
TLA	three letter acronym
LD	linear dichroism

References

1. Porambage, P.; Gur, G.; Osorio, D.P.M.; Liyanage, M.; Gurtov, A.; Ylianttila, M. The Roadmap to 6G Security and Privacy. *IEEE Open J. Commun. Soc.* **2021**, *2*, 1094–1122. [CrossRef]
2. Jiang, W.; Han, B.; Habibi, M.A.; Schotten, H.D. The road towards 6G: A comprehensive survey. *IEEE Open J. Commun. Soc.* **2021**, *2*, 334–366. [CrossRef]
3. You, X.; Wang, C.X.; Huang, J.; You, X.; Wang, C.X.; Huang, J.; Gao, X.; Zhang, Z.; Wang, M.; Huang, Y.; et al. Towards 6G wireless communication networks: Vision, enabling technologies, and new paradigm shifts. *Sci. China Inf. Sci.* **2021**, *64*, 110301. [CrossRef]
4. 6G Flagship Finland. Available online: https://www.oulu.fi/6gflagship/ (accessed on 27 February 2022).
5. Hong, W.; Jiang, Z.H.; Yu, C.; Hou, D.; Wang, H.; Guo, C.; Hu, Y.; Kuai, L.; Yu, Y.; Jiang, Z.; et al. The Role of Millimeter-Wave Technologies in 5G/6G Wireless Communications. *IEEE J. Microwaves* **2021**, *1*, 101–122. [CrossRef]
6. De Alwis, C.; Kalla, A.; Pham, Q.V.; Kumar, P.; Dev, K.; Hwang, W.J.; Liyanage, M. Survey on 6G Frontiers: Trends, Applications, Requirements, Technologies and Future Research. *IEEE Open J. Commun. Soc.* **2021**, *2*, 836–886. [CrossRef]
7. Available online: https://news.samsung.com/global/samsungs-6g-white-paper-lays-out-the-companys-vision-for-the-next-generation-of-communications-technology (accessed on 27 February 2022).
8. Kaur, J.; Khan, M.A.; Iftikhar, M.; Imran, M.; Ul Haq, Q.E. Machine Learning Techniques for 5G and beyond. *IEEE Access* **2021**, *9*, 23472–23488. [CrossRef]
9. Chehimi, M.; Saad, W. Entanglement rate optimization in heterogeneous quantum communication networks. In Proceedings of the 2021 17th International Symposium on Wireless Communication Systems (ISWCS), Berlin, Germany, 6–9 September 2021.
10. Mahdi, M.N.; Ahmad, A.R.; Qassim, Q.S.; Natiq, H.; Subhi, M.A.; Mahmoud, M. From 5G to 6g technology: Meets energy, internet-of-things and machine learning: A survey. *Appl. Sci.* **2021**, *11*, 8117. [CrossRef]
11. Lu, Y.; Huang, X.; Zhang, K.; Maharjan, S.; Zhang, Y. Low-Latency Federated Learning and Blockchain for Edge Association in Digital Twin Empowered 6G Networks. *IEEE Trans. Ind. Inform.* **2021**, *17*, 5098–5107. [CrossRef]
12. Botsinis, P.; Alanis, D.; Babar, Z.; Nguyen, H.V.; Chandra, D.; Ng, S.X.; Hanzo, L. Quantum Search Algorithms for Wireless Communications. *IEEE Commun. Surv. Tutor.* **2019**, *21*, 1209–1242. [CrossRef]
13. Ozpoyraz, B.; Dogukan, A.T.; Gevez, Y.; Altun, U.; Basar, E. Deep Learning-Aided 6G Wireless Networks: A Comprehensive Survey of Revolutionary PHY Architectures. *arXiv* **2022**, arXiv:2201.03866 .
14. Huang, T.; Yang, W.; Wu, J.; Ma, J.; Zhang, X.; Zhang, D. A Survey on Green 6G Network: Architecture and Technologies. *IEEE Access* **2019**, *7*, 175758–175768. [CrossRef]
15. Alghamdi, R.; Alhadrami, R.; Alhothali, D.; Almorad, H.; Helal, S.; Shalabi, R.; Asfour, R.; Hammad, N.; Shams, A.; Saeed, N.; et al. Intelligent Surfaces for 6G Wireless Networks: A Survey of Optimization and Performance Analysis Techniques. *IEEE Access* **2020**, *8*, 202795–202818. [CrossRef]
16. Letaief, K.B.; Shi, Y.; Lu, J.; Lu, J. Edge Artificial Intelligence for 6G: Vision, Enabling Technologies, and Applications. *IEEE J. Sel. Areas Commun.* **2022**, *40*, 5–36. [CrossRef]
17. Viswanathan, H.; Mogensen, P.E. Communications in the 6G Era. *IEEE Access* **2020**, *8*, 57063–57074. [CrossRef]
18. Khan, L.U.; Yaqoob, I.; Imran, M.; Han, Z.; Hong, C.S. 6G Wireless Systems: A Vision, Architectural Elements, and Future Directions. *IEEE Access* **2020**, *8*, 147029–147044. [CrossRef]
19. Alsharif, M.H.; Kelechi, A.H.; Albreem, M.A.; Chaudhry, S.A.; Zia, M.S.; Kim, S. Sixth Generation (6G) Wireless Networks: Vision, Research Activities, Challenges and Potential Solutions. *Symmetry* **2020**, *12*, 676. [CrossRef]
20. 5GIC. *6G Wirelss: A New Strategic Vision*; University Of Surrey: Guildford, UK, 2021.
21. Saad, W.; Bennis, M.; Chen, M. A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems. *IEEE Netw.* **2020**, *34*, 134–142. [CrossRef]
22. Noor-A-Rahim, M.; Liu, Z.; Lee, H.; Khyam, M.O.; He, J.; Pesch, D.; Moessner, K.; Saad, W.; Poor, H.V. 6G for Vehicle-to-Everything (V2X) Communications: Enabling Technologies, Challenges, and Opportunities. *arXiv* **2020**, arXiv:2012.07753.

23. Gupta, M.; Jha, R.K.; Jain, S. Tactile based Intelligence Touch Technology in IoT configured WCN in B5G/6G-A Survey. *IEEE Access* **2022**. [CrossRef]
24. Bourdoux, A.; Barreto, A.N.; van Liempd, B.; de Lima, C.; Dardari, D.; Belot, D.; Lohan, E.-S.; Seco-Granados, G.; Sarieddeen, H.; Wymeersch, H.; et al. 6G White Paper on Localization and Sensing. *arXiv* **2020**, arXiv:2006.01779.
25. Long, W.; Chen, R.; Moretti, M.; Zhang, W.; Li, J. A promising technology for 6g wireless networks: Intelligent reflecting surface. *J. Commun. Inf. Netw.* **2021**, *6*, 1–16.
26. Ali, Z.; Giupponi, L.; Miozzo, M.; Dini, P. Multi-Task Learning for Efficient Management of beyond 5G Radio Access Network Architectures. *IEEE Access* **2021**, *9*, 158892–158907. [CrossRef]
27. Vaca-Rubio, C.J.; Ramirez-Espinosa, P.; Kansanen, K.; Tan, Z.-H.; de Carvalho, E. Radio Sensing with Large Intelligent Surface for 6G. *arXiv* **2021**, arXiv:2111.02783.
28. Zhang, P.; Xu, W.; Gao, H.; Niu, K.; Xu, X.; Qin, X.; Yuan, C.; Qin, Z.; Zhao, H.; Wei, J.; et al. Toward Wisdom-Evolutionary and Primitive-Concise 6G: A New Paradigm of Semantic Communication Networks. *Engineering* **2022** *8*, 60–73. [CrossRef]
29. Liang, Y.-C.; Niyato, D.; Larsson, E.G.; Popovski, P. 6G mobile networks: Emerging technologies and applications Vision, enabling technologies, and new paradigm shifts. *China Commun.* **2020**, *17*, 90–91. [CrossRef]
30. Parsaeefard, S.; Leon-Garcia, A. Toward Efficient Transfer Learning in 6G. *arXiv* **2021**, arXiv:2107.05728.
31. Yazar, A. A Waveform Parameter Assignment Framework for 6G With the Role of Machine Learning. *IEEE Open J. Veh. Technol.* **2020**, *1*, 156–172. [CrossRef]
32. Liu Y.; Liu, X.; Mu, X.; Hou, T.; Xu, J.; Di Renzo, M.; Al-Dhahir, N. Reconfigurable Intelligent Surfaces: Principles and Opportunities. *IEEE Commun. Surv. Tutor.* **2021**, *23*, 1546–1577. [CrossRef]
33. De La Oliva, A.; Perez, X.C.; Azcorra, A.; Di Giglio, A.; Cavaliere, F.; Tiegelbekkers, D.; Lessmann, J.; Haustein, T.; Mourad, A.; Iovanna, P. xHaul: Toward an integrated fronthaul/backhaul architecture in 5G networks. *IEEE Wirel. Commun.* **2015**, *22*, 32–40. [CrossRef]
34. Chowdhury, M.Z.; Shahjalal, M.; Ahmed, S.; Jang, Y.M. 6G Wireless Communication Systems: Applications, Requirements, Technologies, Challenges, and Research Directions. *IEEE Open J. Commun. Soc.* **2020**, *1*, 957–975. [CrossRef]
35. Alsabah, M.; Naser, M.A.; Mahmmod, B.M.; Abdulhussain, S.H.; Eissa, M.R.; Al-Baidhani, A.; Noordin, N.K.; Sait, S.M.; Al-Utaibi, K.A.; Hashim, F. 6G Wireless Communications Networks: A Comprehensive Survey. *IEEE Access* **2021**, *9*, 148191–148243. [CrossRef]
36. Zong, B.; Fan, C.; Wang, X.; Duan, X.; Wang, B.; Wang, J. 6G technologies: Key drivers, core requirements, system architectures, and enabling technologies. *IEEE Veh. Technol. Mag.* **2019**, *14*, 18–27. [CrossRef]
37. Bhattacharjee, S.; Katsalis, K.; Arouk, O.; Schmidt, R.; Wang, T.; An, X.; Bauschert, T.; Nikaein, N. Network Slicing for TSN-Based Transport Networks. *IEEE Access* **2021**, *9*, 62788–62809. [CrossRef]
38. Tsukamoto, Y.; Saha, R.K.; Nanba, S.; Nishimura, K. Experimental Evaluation of RAN Slicing Architecture with Flexibly Located Functional Components of Base Station According to Diverse 5G Services. *IEEE Access* **2019**, *7*, 76470–76479. [CrossRef]
39. Filali, A.; Nour, B.; Cherkaoui, S.; Kobbane, A. Communication and Computation O-RAN Resource Slicing for URLLC Services Using Deep Reinforcement Learning. *arXiv* **2022**, arXiv:2202.06439.
40. Bernardos, C.J.; Uusitalo, M.A.; Anton, C.; Artuñedo, D.; Demestichas, P.; Fettweis, G.; Frascolla, V.; Hecker, A.; Kaloxylos, A.; Koumaras, H.; et al. *European Vision for the 6G Network Ecosystem*; 5G IA: Brussels, Belgium, 2021.
41. Kekki, A.; Li, A.; Arora, R.; Odgers, A.; Contreras, L.M.; Purkayastha, D.; Fang, Y.; Ranjan, A.; Featherstone, W.; Scarpina, S.; et al. *MEC in 5G Networks*; ETSI: Côte d'Azur, France, 2018; pp. 1–28.
42. Habibi, M.A.; Nasimi, M.; Han, B.; Schotten, H.D. A Comprehensive Survey of RAN Architectures Toward 5G Mobile Communication System. *IEEE Access* **2019**, *7*, 70371–70421. [CrossRef]
43. Kuklinski, S.; Tomaszewski, L.; Kolakowski, R. On O-RAN, MEC, SON and Network Slicing integration. In Proceedings of the 2020 IEEE Globecom Workshops (GC Wkshps), Taipei, Taiwan, 7–11 December 2020.
44. Niknam, S.; Roy, A.; Dhillon, H.; Singh, S.; Banerji, R.; Reed, J.H.; Saxena, N.; Yoon, S. Intelligent O-RAN for Beyond 5G and 6G Wireless Networks. *arXiv* **2020**, arXiv:2005.08374.
45. Wu, W.; Zhou, C.; Li, M.; Wu, H.; Zhou, H.; Zhang, N.; Shen, X.; Zhuang, W. AI-Native Network Slicing for 6G Networks. *IEEE Wirel. Commun.* **2021**, *29*, 96–103. [CrossRef]
46. Camps-Mur D.; Gutierrez, J.; Grass, E.; Tzanakaki, A.; Flegkas, P.; Choumas, K.; Giatsios, D.; Beldachi, A.F.; Diallo, T.; Zou, J.; et al. 5G-xHaul: A Novel Wireless-Optical SDN Transport Network to Support Joint 5G Backhaul and Fronthaul Services. *IEEE Commun. Mag.* **2019**, *57*, 99–105. [CrossRef]
47. Lima, E.S.; Borges, R.M.; Pereira, L.A.M.; Filgueiras, H.R.D.; Alberti, A.M.; Sodre, A.C. Multiband and Photonically Amplified Fiber-Wireless xHaul. *IEEE Access* **2020**, *8*, 44381–44390. [CrossRef]
48. Letaief, K.B.; Chen, W.; Shi, Y.; Zhang, J.; Zhang, Y.J.A. The Roadmap to 6G: AI Empowered Wireless Networks. *IEEE Commun. Mag.* **2019**, *57*, 84–90. [CrossRef]
49. Peltonen, E.; Bennis, M.; Capobianco, M.; Debbah, M.; Ding, A.; Gil-Castiñeira, F.; Jurmu, M.; Karvonen, T.; Kelanti, M.; Kliks, A.; et al. 6G White Paper on EDGE Intelligence. arXiv **2020**, arXiv:2004.14850.
50. 6G Flagship. *Key Drivers and Research challenges for Ubiquitous Wireless Intelligence*; University of Oulu: Oulu, Finland, 2019.
51. China Accounts for 40% of 6G Patent Applications: Survey. Available online: https://asia.nikkei.com/Business/Telecommunication/China-accounts-for-40-of-6G-patent-applications-survey (accessed on 13 March 2022).

52. Fraga-Lamas, P.; Fernández-Caramés, T.M. A Review on Blockchain Technologies for an Advanced and Cyber-Resilient Automotive Industry. *IEEE Access* **2019**, *7*, 17578–17598. [CrossRef]
53. Nawaz, S.J.; Sharma, S.K.; Wyne, S.; Patwary, M.N.; Asaduzzaman, M. Quantum Machine Learning for 6G Communication Networks: State-of-the-Art and Vision for the Future. *IEEE Access* **2019**, *7*, 46317–46350. [CrossRef]
54. Nakamura, T. 5G Evolution and 6G. In Proceedings of the 2020 IEEE Symposium on VLSI Technology, Honolulu, HI, USA, 16–19 June 2020.
55. Nguyen, V.L.; Lin, P.C.; Cheng, B.C.; Hwang, R.H.; Lin, Y.D. Security and Privacy for 6G: A Survey on Prospective Technologies and Challenges. *IEEE Commun. Surv. Tutor.* **2021**, *23*, 2384–2428. [CrossRef]
56. Akhtar, M.W.; Hassan, S.A.; Ghaffar, R.; Jung, H.; Garg, S.; Hossain, M.S. The shift to 6G communications: Vision and requirements. *Hum.-Centric Comput. Inf. Sci.* **2020**, *10*, 53. [CrossRef]
57. Han, C.; Wu, Y.; Chen, Z.; Wang, X. terahertz Communications (TeraCom): Challenges and Impact on 6G Wireless Systems. *arXiv* **2019**, arXiv:1912.06040.
58. Wedage, L.T.; Butler, B.; Balasubramaniam, S.; Koucheryavy, Y.; Jornet, J.M. Climate Change Sensing through terahertz Communications: A Disruptive Application of 6G Networks. *arXiv* **2021**, arXiv:2110.03074.
59. Samsung. *Samsung 6G Vision*; Samsung: Suwon, Korea, 2020. Available online: https://research.samsung.com/next-generation-communications (accessed on 13 March 2022).
60. Liang, Y.; Lu, C.; Zhao, Y.; Sun, C. Interference-Based Consensus and Transaction Validation Mechanisms for Blockchain-Based Spectrum Management. *IEEE Access* **2021**, *9*, 90757–90766. [CrossRef]
61. Mucchi, L.; Martinelli, A.; Jayousi, S.; Caputo, S.; Pierobon, M. Secrecy capacity and secure distance for diffusion-based molecular communication systems. *IEEE Access* **2019**, *7*, 110687–110697. [CrossRef]
62. Hewa, T.; Gur, G.; Kalla, A.; Ylianttila, M.; Bracken, A.; Liyanage, M. The role of blockchain in 6G: Challenges, opportunities and research directions. 2nd 6G Wirel. In Proceedings of the 2020 2nd 6G Wireless Summit (6G SUMMIT), Levi, Finland, 17–20 March 2020.
63. Kumar, T.; Harjula, E.; Ejaz, M.; Manzoor, A.; Porambage, P.; Ahmad, I.; Liyanage, M.; Braeken, A.; Ylianttila, M. BlockEdge: Blockchain-Edge Framework for Industrial IoT Networks. *IEEE Access* **2020**, *8*, 154166–154185. [CrossRef]
64. Lee, J.; Kwon, T. Distributed watchdogs based on blockchain for securing industrial internet of things. *Sensors* **2021**, *21*, 4393. [CrossRef]
65. Wei, Y.; An, Z.; Leng, S.; Yang, K. Connecting AI Learning and Blockchain Mining in 6G Systems. *arXiv* **2021**, arXiv:2104.14088.
66. Miglani, A.; Kumar, N. Blockchain management and machine learning adaptation for IoT environment in 5G and beyond networks: A systematic review. *Comput. Commun.* **2021**, *178*, 37–63. [CrossRef]
67. Bhattacharya, P.; Saraswat, D.; Dave, A.; Acharya, M.; Tanwar, S.; Sharma, G.; Davidson, I.E. Coalition of 6G and Blockchain in AR/VR Space: Challenges and Future Directions. *IEEE Access* **2021**, *9*, 168455–168484. [CrossRef]
68. Sekaran, R.; Patan, R.; Raveendran, A.; Al-Turjman, F.; Ramachandran, M.; Mostarda, L. Survival Study on Blockchain Based 6G-Enabled Mobile Edge Computation for IoT Automation. *IEEE Access* **2020**, *8*, 143453–143463. [CrossRef]
69. Ramírez-Arroyo, A.; Zapata-Cano, P.H.; Palomares-Caballero, Á.; Carmona-Murillo, J.; Luna-Valero, F.; Valenzuela-Valdés, J.F. Multilayer network optimization for 5G & 6G. *IEEE Access* **2020**, *8*, 204295–204308.
70. Lee, Y.L.; Qin, D.; Wang, L.C.; Sim, G.H. 6G Massive Radio Access Networks: Key Applications, Requirements and Challenges. *IEEE Open J. Veh. Technol.* **2021**, *2*, 54–66. [CrossRef]
71. Wu, Q.; Zhang, R. Weighted Sum Power Maximization for Intelligent Reflecting Surface Aided SWIPT. *IEEE Wirel. Commun. Lett.* **2020**, *9*, 586–590. [CrossRef]
72. Huawei. *Building a Fully Connected, Intelligent World*; Huawei: Shenzhen, China, 2021; pp. 120–121.
73. 6G—Connecting a Cyber-Physical World. February 2022. Available online: https://www.ericsson.com/en/reports-and-papers/white-papers/a-research-outlook-towards-6g (accessed on 13 March 2022).
74. Kim, J.; Kwak, Y.; Jung, S.; Kim, J.H. Quantum scheduling for millimeter-wave observation satellite constellation. In Proceedings of the 17th IEEE VTS Asia Pacific Wireless Communications Symposium, APWCS 2021, Osaka, Japan, 30–31 August 2021.
75. Sharma, P.; Bhatia, V.; Prakash, S. Securing Optical Networks using Quantum-secured Blockchain: An Overview. *arXiv* **2021**, arXiv:2105.10663.
76. Trinh, P.V.; Pham, T.V.; Dang, N.T.; Nguyen, H.V.; Ng, S.X.; Pham, A.T. Design and Security Analysis of Quantum Key Distribution Protocol over Free-Space Optics Using Dual-Threshold Direct-Detection Receiver. *IEEE Access* **2018**, *6*, 4159–4175. [CrossRef]
77. Xu, D.; Ren, P. Quantum Learning Based Nonrandom Superimposed Coding for Secure Wireless Access in 5G URLLC. *IEEE Trans. Inf. Forensics Secur.* **2021**, *16*, 2429–2444. [CrossRef]
78. Arul, R.; Raja, G.; Almagrabi, A.O.; Alkatheiri, M.S.; Chauhdary, S.H.; Bashir, A.K. A quantum-safe key hierarchy and dynamic security association for LTE/SAE in 5G scenario. *IEEE Trans. Ind. Inform.* **2020**, *16*, 681–690. [CrossRef]
79. Qadir, Z.; Munawar, H.S.; Saeed, N.; Le, K. Towards 6G Internet of Things: Recent Advances, Use Cases, and Open Challenges. *arXiv* **2021**, arXiv:2111.06596.
80. Shahraki, A.; Abbasi, M.; Piran, M.J.; Taherkordi, A. A Comprehensive Survey on 6G Networks: Applications, Core Services, Enabling Technologies, and Future Challenges. *arXiv* **2021**, arXiv:2101.12475.

81. Miller, A.B.; Sears, M.E.; Morgan, L.L.; Davis, D.L.; Hardell, L.; Oremus, M.; Soskolne, C.L. Risks to health and well-being from radio-frequency radiation emitted by cell phones and other wireless devices. *Front. Public Health* **2019**, *7*, 223. [CrossRef] [PubMed]
82. Skrimponis, P.; Hosseinzadeh, N.; Khalili, A.; Erkip, E.; Rodwell, M.J.W.; Buckwalter, J.F.; Rangan, S. Towards Energy Efficient Mobile Wireless Receivers above 100 GHz. *IEEE Access* **2021**, *9*, 20704–20716. [CrossRef]
83. Akyildiz, I.F.; Kak, A.; Nie, S. 6G and Beyond: The Future of Wireless Communications Systems. *IEEE Access* **2020**, *8*, 133995–134030. [CrossRef]
84. Electronic Environment. Available online: https://www.electronic.se/en/2020/02/25/how-will-6g-affect-emc/ (accessed on 11 April 2022)
85. Alraih, S.; Shayea, I.; Behjati, M.; Nordin, R.; Abdullah, N.F.; Abu-Samah, A.; Nandi, D. Revolution or Evolution? Technical Requirements and Considerations towards 6G Mobile Communications. *Sensors* **2022**, *22*, 762. [CrossRef]
86. Ali, S.; Saad, W.; Rajatheva, N.; Chang, K.; Steinbach, D.; Sliwa, B.; Wietfeld, C.; Mei, K.; Shiri, H.; Zepernick, H.-J.; et al. 6G White Paper on Machine Learning in Wireless Communication Networks. *arXiv* **2020**, arXiv:2004.1387.
87. Chen, H.; Xiao, M.; Pang, Z. Satellite Based Computing Networks with Federated Learning. *IEEE Wirel. Commun.* **2021**, *29*, 78–84. [CrossRef]
88. Demirhan, U.; Alkhateeb, A. Radar Aided 6G Beam Prediction: Deep Learning Algorithms and Real-World Demonstration. *arXiv* **2021**, arXiv:2111.09676.
89. Tariq, M.; Naeem, F.; Poor, H.V. Toward Experience-Driven Traffic Management and Orchestration in Digital-Twin-Enabled 6G Networks. *arXiv* **2022**, arXiv:2201.04259.
90. Jin, Y.; Vannella, F.; Bouton, M.; Jeong, J.; Hakim, E.A. A Graph Attention Learning Approach to Antenna Tilt Optimization. *arXiv* **2021**, arXiv:2112.14843.
91. Gecgel, S.; Kurt, G.K. Intermittent jamming against telemetry and telecommand of satellite systems and a learning-driven detection strategy. In Proceedings of the WiSec '21: 14th ACM Conference on Security and Privacy in Wireless and Mobile Networks, Abu Dhabi, United Arab Emirates, 28 June–2 July 2021.
92. Khan, L.U.; Tun, Y.K.; Alsenwi, M.; Imran, M.; Han, Z.; Hong, C.S. A Dispersed Federated Learning Framework for 6G-Enabled Autonomous Driving Cars. *arXiv* **2021**, arXiv:2105.09641.