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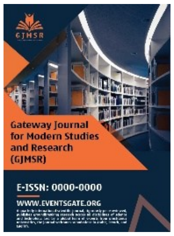

Scientific Events Gate
مجلة البوابة للدراسات والأبحاث الحديثة
GJMSR
Gateway Journal for Modern Studies and Research
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A Comprehensive Overview of 6G Communication Systems and Emerging Technologies

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Received: 10 Aug. 2024 – Accepted: 11 Nov. 2024 Available online: 27 Nov. 2024

Abstract: The sixth generation (6G) of communication systems represents the next leap in wireless technology, promising ultra-fast speeds, greater efficiency, and revolutionary new applications. Building on the evolution from 1G's analog systems to today's 5G, 6G will integrate advanced technologies such as artificial intelligence (AI), virtual reality (VR), the Internet of Everything (IoE), and terahertz (THz) communications to deliver terabit-level data rates and ultra-low latency. This will enable applications like autonomous vehicles, immersive digital realities, industrial automation, remote healthcare, and smart cities. Research shows that 6G will focus strongly on security, privacy, and user experience, addressing challenges like network capacity and reliability. Studies highlight the vital role of machine learning, edge computing, massive MIMO, and mmWave/THz spectrum in realizing 6G's vision. Extensive surveys by various scholars have explored 6G's potential for integrating quantum computing, AI-driven network optimization, UAV networks, space and deep-sea connectivity, and bio-nano communications. Ultimately, 6G aims to connect billions of devices globally, bridging connectivity gaps in remote regions and enabling transformative services across industries. By overcoming technical and societal challenges, 6G is expected to redefine global communication infrastructure and support unprecedented levels of interconnectivity and innovation.

Keywords: 6G Communication Systems, Terahertz Technology, Artificial Intelligence (AI), Internet of Everything (IoE), Ultra-Low Latency Networks

1. Introduction

The sixth installment of Internet and communication systems, commonly referred to as 6G, signifies a remarkable advancement in technology that is set to completely transform connectivity and communication. Expanding on the progress made by previous generations, 6G is anticipated to deliver heightened speed and efficiency, while also introducing cutting-edge services and applications that will revolutionize our interaction with technology.

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A fundamental aspect of 6G lies in its emphasis on user-friendly features, prioritizing security, privacy, and confidentiality to create a more engaging and personalized user experience. Key technologies like artificial intelligence (AI), virtual reality (VR), 3D media, and Internet of Everything (IoE) systems are crucial for the development of 6G networks.

Furthermore, the transition from 5G to 6G will usher in new usage scenarios and technological trends that will enable groundbreaking applications across various industries. These include touch/haptic internet, comprehensive digital sensing and reality experiences, fully autonomous driving, industrial internet, space exploration, deep-sea exploration, and Internet of Bio-Nano-Things.

Facilitating technologies like terahertz communication will play an essential role in unlocking the full potential of 6G networks. Terahertz band communication boasts high data rates and broad bandwidths, making it a promising technology for achieving terabit-level data transmission rates necessary for future ultra-dense networks.

Looking ahead towards the future of communication systems with the introduction of 6G technologies, it is evident that society stands to reap significant benefits from improved connectivity in remote regions, enhanced telemedicine capabilities for better access to healthcare, and innovative smart city applications that will redefine urban living. (Alsharif, et. al., 2020) and (Aslam, et. al. 2021).

2. Evolution of Internet and communications systems

The evolution of Internet and communication systems has been a remarkable journey marked by significant technological advancements. Beginning with analog FM cellular systems in 1981, the transition from 1G to 2G introduced digital networks, enhancing speeds and paving the way for innovations such as SMS and MMS. The progression to 3G further increased speeds up to 2Mbps, allowing for the integration of smart technologies into everyday life. With the arrival of 4G, download speeds improved significantly, ranging from 100 to 300 Mbps, while 5G is expected to reach speeds of up to 1 Gbps.

Recent years have seen exponential growth in wireless communications, leading to the rise of data-intensive applications like multimedia streaming and online gaming. The widespread adoption of mobile Internet technology has equipped users with a variety of personalized services, including mobile shopping, smart homes, and mobile gaming. Looking forward, the anticipated sixth generation (6G) of wireless communication is on the horizon.

6G technology aims to connect billions of Internet of Things (IoT) devices and users around the globe. It seeks to provide low-latency computing resources both at the edge and in the cloud, facilitating seamless machine-to-machine communication in diverse environments. The potential impact of 6G networks spans critical services across industries such as transportation, healthcare, and manufacturing.

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As we advance toward a future dominated by 6G technology, addressing technical challenges related to network capacity, connectivity, and security will be crucial. The integration of advanced technologies like millimeter wave, massive MIMO, and artificial intelligence will be essential in shaping the next era of wireless systems. Each generation builds upon the successes and innovations of its predecessors, continuously redefining connectivity and transforming the digital landscape. (Aslam, et. al., 2021) and (Gill, et. al., 2024).

Table 1: A comprehensive survey on 6G communication networks. (Banafaa,2023)

Author year	Main objective of research
(Nawaz, et. al., 2019)	Presented a comprehensive review on B5G applications, issues, use cases and potential benefits of quantum computing and machine learning.
(Saad, et. al., 2019)	A comprehensive performance requirement of 6G technology and its proposed application trends are elaborated.
(Strinati, et. al., 2019)	Analysis the research gap of previously used technology and predicting the 6G roadmap for future communication.
(Salehi, and Hossain, 2019)	The challenges associated to UAV network related to temporal correlation for distribution and success probability is presented.
(Huang, et. al., 2019)	Wireless communication technology that provides solutions for the bottlenecks that limit the capability of the integrated space and terrestrial network (ISTN) are proposed.
(Elliott,, et. al., 2019)	Future cellular networks and short range communication is discussed.
(Ji, et. al. 2019)	A detailed survey on 5G/B5G wireless communication for UAVs.
(Letaief, et. al. 2019)	A comprehensive discussion on AI enabled 6G applications and optimized network architecture using state-of-the-art technologies.
(Yang, et. al., 2019)	6G techniques and future research trends to improve it are analyzed
(Chowdhury, et. al., 2019)	A detailed overview on 6G enabled AI wireless communication
(Zhang, et. al., 2019)	Incorporating the three main aspects, AI, IoT and mobile ultra-broadband for evolving 6G technology.
(Lovén, et. al., 2019)	6G wireless communication and role of Edge AI is elaborated for future.
(Clazzer, et. al., 2019)	Recent advances in modem random access and uncoordinated medium access for different IoT applications in 6G paradigm is discussed.

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(Giordani, et. al., 2020)	6G use cases and their requirements are presented.
(Viswanathan and Mogensen, 2020)	A detailed overview and performance requirement for 6G technology transformation is discussed. Highlighting the privacy issues, latency, reliability, sensing capabilities, spectrum bands, network architecture and spectrum methods.
(Tariq, et. al., 2020)	Extending the vision of 5G to provide step changes for enabling 6G.
(Mahmood, et. al., 2020)	Different machine type communications, trending technologies and performance indicators for 6G are discussed.
(Dang, et. al., 2020)	Explores the Challenges associated with 6G deployment and a future vision is incorporated.
(Zhang, et. al., 2020)	Wireless evolution towards 6G communication is surveyed. Enhanced network architecture, ubiquitous 3D coverage, protocol and persuasive AI is highlighted.
(Zhang, et. al., 2020)	Categorizing the current technologies and extending the drive force by AI-enabled intelligent communication.
(Gui, et. al., 2020)	6G requirements are achieved using the five 6G core components. Additionally, how to enable KPIs and centricities are discussed in detail to address these components.
(Zhang, et. al., 2019)	Incorporating the three main aspects, AI, IoT and mobile ultra-broadband for evolving 6G technology.
(Tomkos, et. al., 2020)	A comprehensive overview of the transformation of IoT technologies towards 6G networks is presented.
(Yaacoub and Alouini 2020)	A survey on connectivity for rural areas is presented. Additionally, backhaul and front haul techniques are analyzed using cost efficiency and energy requirements.
(Kato, et. al., 2020)	The IoT networks for 6G are discussed, where the IoT devices are connected using different frequency bands, such as mmWave and THz
(Shafin, et. al., 2020)	A comprehensive overview on the applications, challenges and future research direction for B5G and 6G networks are presented.
(Gui, et. al., 2020)	A survey on the machine learning techniques for network, security and communication of 6G vehicular technology is presented.
(Zhang, et. al., 2020)	Low latency networks are supported using reinforcement learning framework and a heterogeneous multi-layer edge computing is presented.
(Chowdhury, et. al., 2020)	A comprehensive literature review on the probable 6G technologies, the requirements, applications and technologies that are expected to evolve in the near future for the 6G networks. Moreover, the associated

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	challenges with these emerging technologies have also been elaborated.
(Kim, 2021)	Provides an elaboration of the main components, description of enabling technologies, current research and possible applications of the 6G wireless communication systems to IoT based services/technologies
(Allam and Jones, 2021)	Presents the scope and emerging directions for the 6G applicability to the Digital Twins and Immersive Realities. Provides an extensive overview of 6G, associated concepts, and relations in context of the future Smart, Digital and Sustainable Cities
(Padhi and Charrua-Santos 2021)	The synthesis of 6G, IoT, IoE, industrial Internet of Everything (IIoE) is presented here. This study also reports a novel theoretical framework for 6G-enabled IIoE (6GIIoE) system.
(Yang, et. al., 2021)	It embodies the key requirements for the application of federated learning (FL) to the wireless communication systems.
(Wang, et. al., 2021)	A security scheme based on the Internet-of-Vehicles (IoV) devices that request services from the edge nodes anonymously is presented here.
(Shahraki, et. al., 2021)	The article highlight the importance of 6G networks, its requirements, major trends, latest research, performance indicators, and applications relevant to 6G networks. Moreover, the study provides the depiction of various unresolved challenges for the future utility of the 6G.
(Imoize, et. al., 2021)	The enabling technologies, emerging 6G applications, technology mediated challenges, possible solutions and other issues (social, psychological, commercialization) relevant to the vision of 6G are elaborated in detail.
(Wang, 2021)	The application scenarios of data mining (in subjects/contents) for online teaching (quality control) based on the 6G networks are described here.

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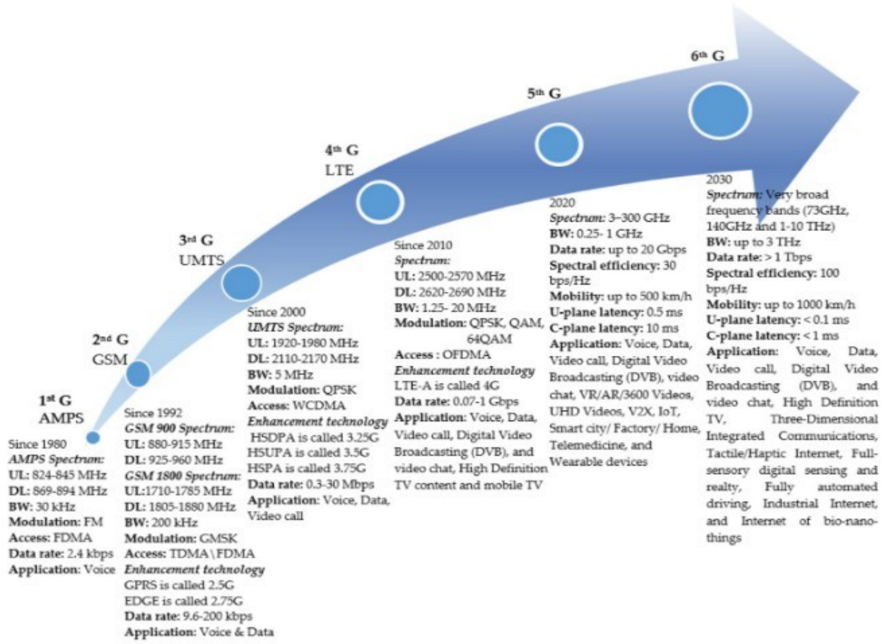

Figure 1: Major milestones for different generations of communications (1-6G). (source: (Gill, et. al., 2024))

3. Features of the sixth generation of communications

3.1 Increased speed and efficiency

The advent of the sixth generation in Internet and communication systems is set to transform connectivity through technological advancements that ensure increased speed and efficiency. Transitioning from 5G to 6G will bring significant improvements, including a dramatic rise in individual device speed, soaring from 20 GBps in 5G to an impressive 1 terabyte per second (Tbps) in 6G. Additionally, latency will see a substantial decrease, falling from 10 milliseconds in 5G to just 1 millisecond (ms) in the upcoming sixth generation.

The full implementation of artificial intelligence (AI) and extended reality (XR) technologies will be achieved within 6G, paving the way for innovative services and applications. The mobility support in 6G networks will also experience a considerable enhancement, increasing from 500 km/hr in 5G to an astonishing speed of 1000 kilometers per hour (km/hr) in the new generation. Advanced technologies such as Terahertz (THz) communication, visible light communication (VLC), and others will significantly contribute to improving the efficiency and performance of sixth-generation networks. These innovations will enable not only ultra-high data rates but also low-latency computing for real-time applications.

The transition to sixth-generation networks promises unparalleled speed, efficiency, and connectivity for society as a whole. The reduction in latency combined with technological advancements will open up new opportunities for various industries, driving innovation and

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progress like never before. (Aslam, at. al., 2021), (Wikipedia, 2024) (Alsharif, et. al., 2020) and (Becher, et. al., 2023).

Table 2: 6G evaluation in CR networks communication from 5G to 6G. (Becher, et. al., 2023).

Problem	5G	6G
Per device speed	20 GBps	1 terabytes per second (Tbps)
Latency E2E	10 ms	1 millisecond (ms)
AI	Partial	Fully
XR	Partial	Fully
Mobility support	500 km/hr	1000 kilometer per hour (km/hr)
Higher spectral efficiency	30 bps/HZ	100 bit per second/hertz (bps/HZ)
Haptic communication	Partial	Fully
Autonomous vehicle	Partial	Fully
Delay jitter	NA ms	10^{-3} millisecond (ms)
Energy efficiency	NA	1 terabyte/joule (Tb/J)
Packet error rate	10-5	10-9
Higher channel bandwidth	1 GHz	100 gigahertz (GHz)

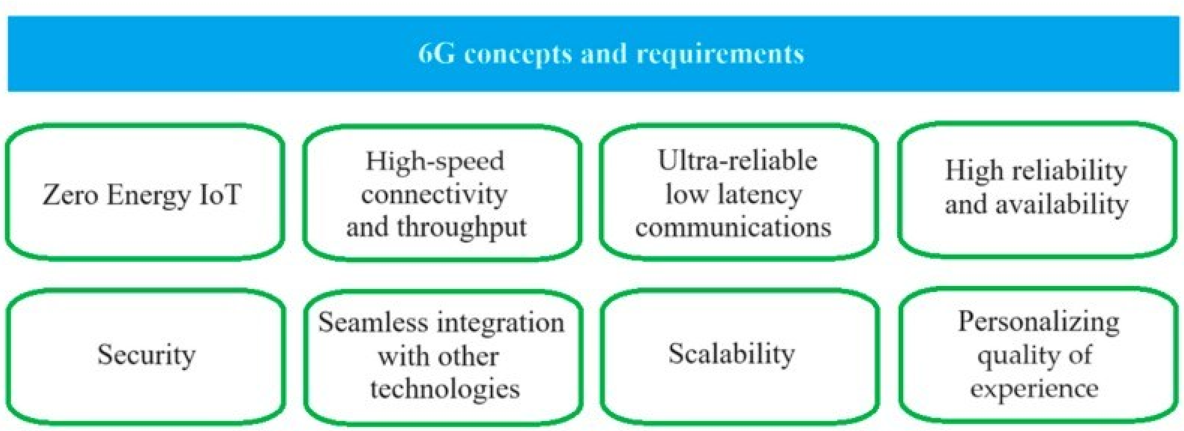

Figure 2: 6G visions and requirements. (Alsharif, et. al., 2020)

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Table 3: Comparisons of capabilities of 4G, 5G, and 6G systems. (Alsharif, et. al., 2020)

Parameter	**Fourth-Generation (4G)**	**Fifth-Generation (5G)**	**Sixth-Generation (6G)**
Mobility [km/h]	350	500	>1000
Latency [ms]	<100	<10	<0.1
Connectivity density [devices/km^2]	10^5	10^6	10^7
Area traffic capacity [Gbps/m^2]	0.001	0.01	1
Parameter	**Fourth-Generation (4G)**	**Fifth-Generation (5G)**	**Sixth-Generation (6G)**
Peak data rate [Tbps]	0.002	0.02	>1
User experiences data rate [Gbps]	0.01	0.1	1

Table 4: Comparison of use cases for 5G, 5.5G, and 6G systems. (Alsharif, et. al., 2020)

Technology	**5G**	**5.5G**	**6G**
Ultra-reliable and low-latency communications (URLLC)	+	+	
Massive machine-type communications (mMTC)	+	+	
Enhanced mobile broadband (eMBB)	+	+	
Uplink centric broadband communication (UCBC)		+	+
Real-time broadband communication (RTBC)		+	+
Human-centric services (HCS)		+	+

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Ubiquitous mobile ultra-broadband (uMUB)			+
Ultra-high data density (uHDD)			+
Ultra-reliable low latency communications (uHSLLC)			+

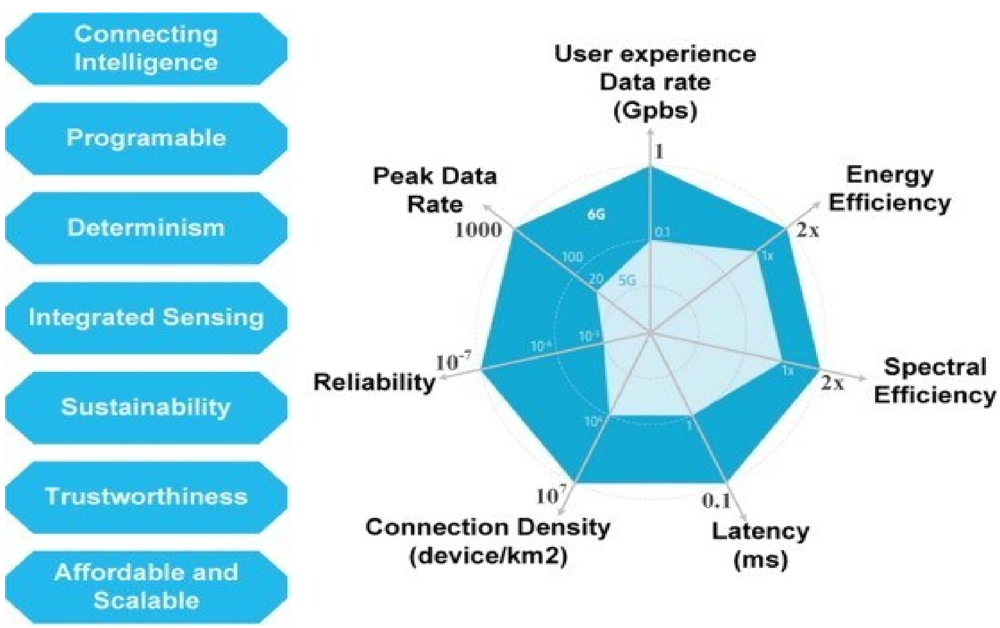

Figure 3: Key enhancements of 6G technology. (Aslam, at. al., 2021)

Table 5: Comparison of 6G with 4G and 5G mobile communication systems. (Aslam, at. al., 2021),

KPIs	4G	5G	6G
Peak data rate /device	1 Gbps	10 Gbps	1 Tbps
latency	100 ms	1 ms	0.1 ms
Max. spectral efficiency	15 bps/Hz	30 bps/Hz	100 bps/Hz
Energy efficiency	< 1000x relative to 5G	1000x relative to 4G	>10x relative to 5G
Connection density	2000 devices / km^2	1millon devices /km^2	>10millon devices/km^2

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Coverage percent	< 70 %	80 %	>99 %
Positioning precision	Meters precision (50 m)	Meters precision (20 m)	Centimeter precision
End-to-end reliability	99.9 %	99.999 %	99.9999 %
Receiver sensitivity	Around −100dBm	Around −120dBm	< −130dBm
Mobility support	350 km/h	500 km/h	≥1000 km/h
Satellite integration	No	No	Fully
AI	No	Partial	Fully
Autonomous vehicle	No	Partial	Fully
Extended Reality	No	Partial	Fully
Haptic Communication	No	Partial	Fully
THz communication	No	limited	Widely
Service level	Video	VR, AR	Tactile
Architecture	MIMO	Massive MIMO	Intelligent surface
Max. frequency	6 GHz	90 GHz	10 THz

4. Modern services and applications

Cutting-edge advancements in the sixth generation of Internet and communication systems go beyond mere speed and connectivity. The integration of artificial intelligence (AI) is poised to redefine our interaction with technology, enabling networks to autonomously make decisions and facilitate seamless communication at all levels.

A particularly exciting aspect is the inclusion of virtual and augmented reality experiences, which will transform machine-to-machine communication and enhance interoperability in the era of smart Internet-of-Things. With 6G, users can expect immediate data transfers without interruptions or delays, paving the way for innovative applications such as networked vehicles, smart factories, and collaborative virtual and augmented reality experiences.

Furthermore, robust cybersecurity measures are essential components of modern services in the sixth generation of communications. As the number of interconnected devices increases, protecting data security and privacy becomes increasingly critical. 6G networks will require strong cybersecurity protocols to defend against potential threats.

Ultimately, modern services and applications in the sixth generation of Internet and communication systems promise a future where the combination of artificial intelligence, virtual

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and augmented reality experiences, and enhanced cybersecurity measures creates a connected ecosystem that is faster, more efficient, and more secure than ever before. (Aslam, at. al., 2021), (Alsharif, et. al., 2020) and (Qian, et. al., 2024).

5. Benefits to society

5.1 Improved connectivity for remote areas

Enhanced connectivity in remote locations plays a crucial role in the sixth iteration of Internet and communication systems. This technological advancement aims to bridge the gap in digital access by delivering reliable, high-speed connectivity to previously underserved areas. A notable example is the Faroe Islands, which have an advanced communication network covering the entire nation, including remote and sparsely populated regions. The unique geographical conditions of the Faroe Islands have positioned local companies as experts in providing digital communication solutions to such areas.

Similarly, the Solomon Islands have experienced growth in mobile services, with the introduction of 3G services in 2010 leading to increased adoption of mobile broadband. However, fixed broadband services are primarily accessible to government bodies, businesses, and educational institutions due to the substantial investments required for telecommunication infrastructure. Despite efforts from international organizations like the World Bank and the Asian Development Bank to enhance communication services in rural regions, internet and broadband penetration rates remain low. The recent establishment of the Coral Sea Cable System, which connects Papua New Guinea to the Solomon Islands, has significantly strengthened broadband infrastructure.

Additionally, Tokelau is set to benefit from a new submarine cable linking it to New Zealand, enabling high-speed internet access for the first time. This initiative will ensure affordable internet connectivity and improved digital service platforms for Tokelauan residents. In summary, enhanced connectivity in remote areas through sixth-generation technologies will not only improve access to essential services but also lay the groundwork for economic growth and social empowerment in these regions. (Qadir, et. al., 2023)

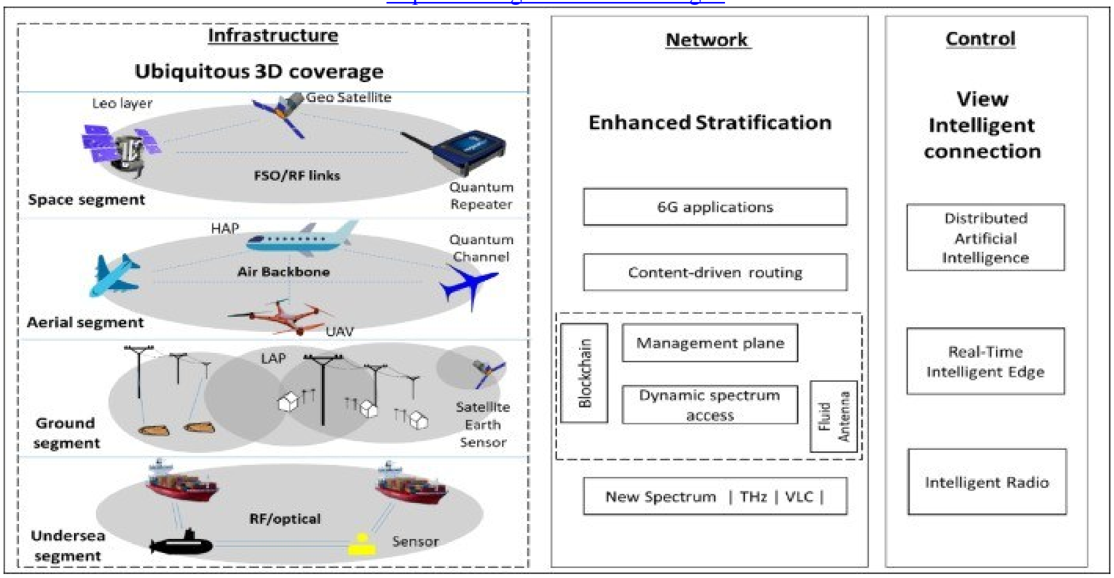

Figure 4: Overview of the 6G architecture. (Becher, et. al., 2023)

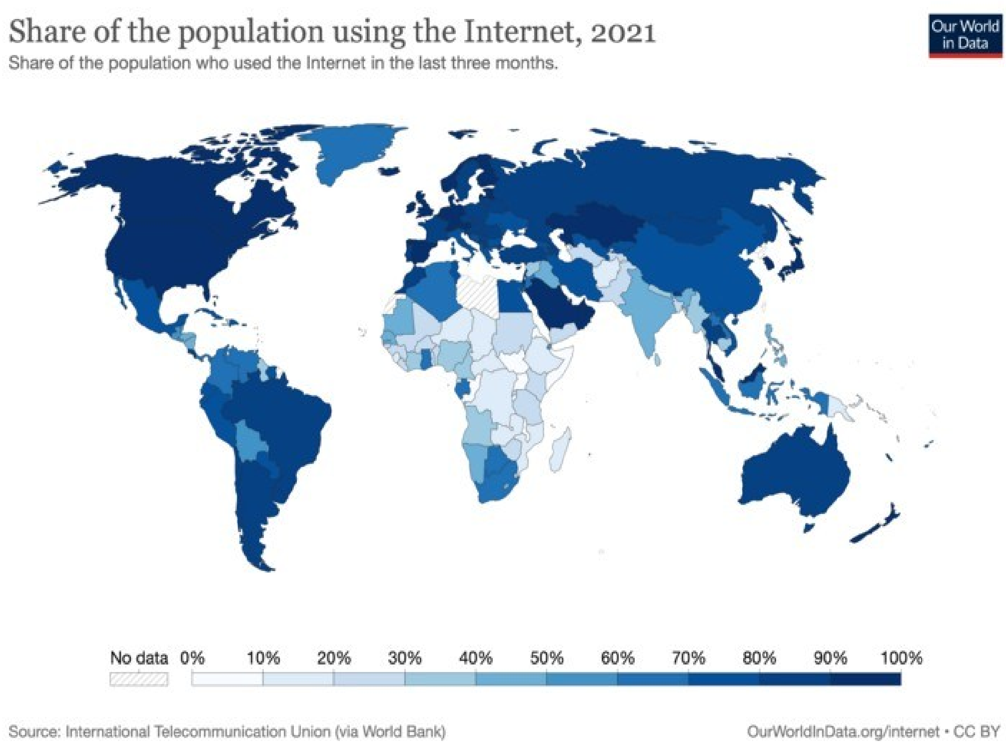

Figure 5: Internet users in 2021 as a percentage of a country's population Source: Our World in Data. (Kumar, et. al., 2019)

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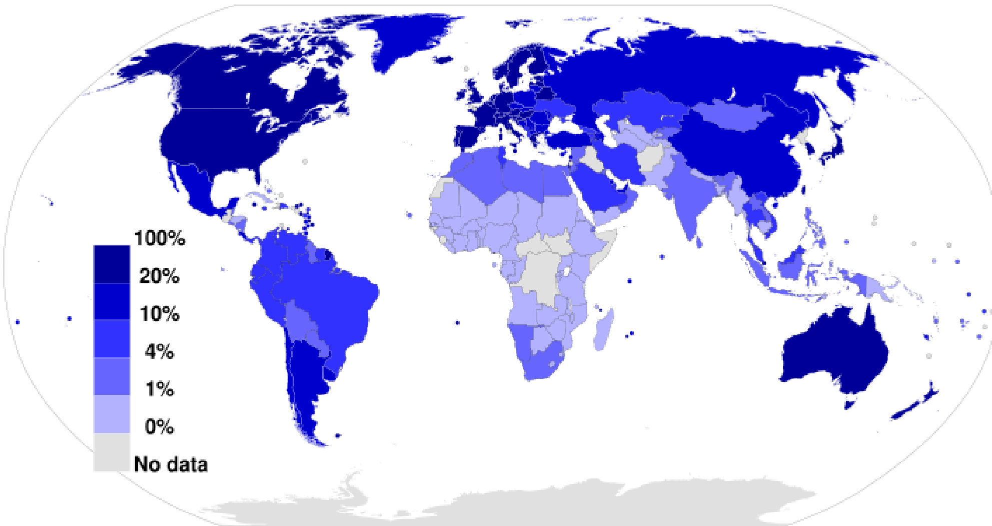

Figure 6: Fixed broadband Internet subscriptions in 2012 as a percentage of a country's population Source: International Telecommunication Union. (Kumar, et. al., 2019)

5.2 Enhanced telemedicine capabilities

Telehealth has become a fundamental aspect of healthcare, particularly in remote areas with limited access to medical facilities. The latest version of Internet and communication systems, known as 6G, is poised to further enhance telehealth capabilities. With advancements in 6G technology, telehealth services are expected to achieve greater reliability, reduced latency, and faster data speeds. This will enable healthcare professionals to effectively monitor patients remotely and even perform surgeries using teleoperating systems.

The integration of wearable body sensors and implantable devices with 6G technology will allow for the seamless transmission of medical data, ensuring that patients receive timely and accurate care regardless of their location. Additionally, the incorporation of molecular communication into 6G technology will significantly improve telehealth capabilities by providing secure channels for sensitive medical information.

Moreover, the increased speed and efficiency offered by 6G networks will facilitate real-time consultations between patients and healthcare providers, thereby decreasing the need for in-person appointments and reducing wait times for medical advice. This will be especially beneficial for individuals living in rural or underserved regions who face difficulties accessing traditional healthcare services.

The advanced telehealth capabilities enabled by the sixth generation of Internet and communication systems possess the potential to transform healthcare delivery. They will enhance access to care, improve the efficiency of medical consultations, and support innovative remote surgical procedures. As we look toward the future of telehealth with 6G technology, it is evident that the societal benefits will be extensive and transformative. (Aslam, at. al., 2021) and

(Becher, et. al., 2023).

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Table 6: The security evolution of mobile communications from 1G to 6G. (Alsharif, et. al., 2020)

Generation	Network Services	Security Solutions
1G	Voice services	Unencrypted telephone services
2G	Voice services and short messages	One-way authentication, unauthorized access
3G	High-speed Internet, web browsing	Internet protocol (IP) privacy, wireless interface threats
4G	Improved spectrum efficiency, reduced latency	Media access control (MAC) layer attacks, threats from new devices
5G	High-speed Internet, more secure systems	Non-terrestrial networks (NTN), software-defined networks (SDN), cloud threats
6G	Ultra-low latency, variety of applications, extremely reliable and low-latency communication (ERLLC), Internet of Everything (IoE)	AI/ML threats, system attacks

6. Smart city applications

Smart city initiatives play a crucial role in the sixth iteration of Internet and communication systems. A key focus area where this technology is making a significant impact is in the realm of intelligent homes within smart cities. Smart residences leverage IoT-enabled gadgets such as household appliances, air conditioning units, security systems, and more to interact with each other through a central control hub. This connectivity enhances convenience and safety while also reducing energy usage, leading to financial savings for homeowners.

Additionally, smart vehicles represent another fundamental element of smart cities that benefit from the sixth generation of communication technology. By employing intelligent devices and sensors to manage various aspects of modern automobiles, communication between vehicles and drivers ensures proactive maintenance and secure driving experiences. Advancements in IoT solutions for smart energy management further contribute to the evolution of smart cities by promoting energy conservation and cost-effectiveness.

The integration of UAVs (Unmanned Aerial Vehicles) into wireless communication networks stands out as another groundbreaking innovation that significantly impacts smart city applications. UAVs provide high data rates and wireless connectivity, making them ideal for offering cellular coverage during emergencies or natural disasters when traditional infrastructure may be ineffective or economically unviable. From enhancing network connectivity to aiding in disaster response, monitoring pollution levels, conducting security surveillance, and more, UAVs play a vital role in improving the functionality of wireless networks within smart cities.

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The sixth generation of Internet and communication systems ushers in a new era for smart city applications by enabling seamless communication among diverse devices and systems. The integration of IoT-enabled technologies, smart homes, smart vehicles, and UAVs transforms urban settings, fostering greater efficiency, safety measures, and sustainability. (Banafaa, et. al., 2023) and (Rojek, et. al., 2024).

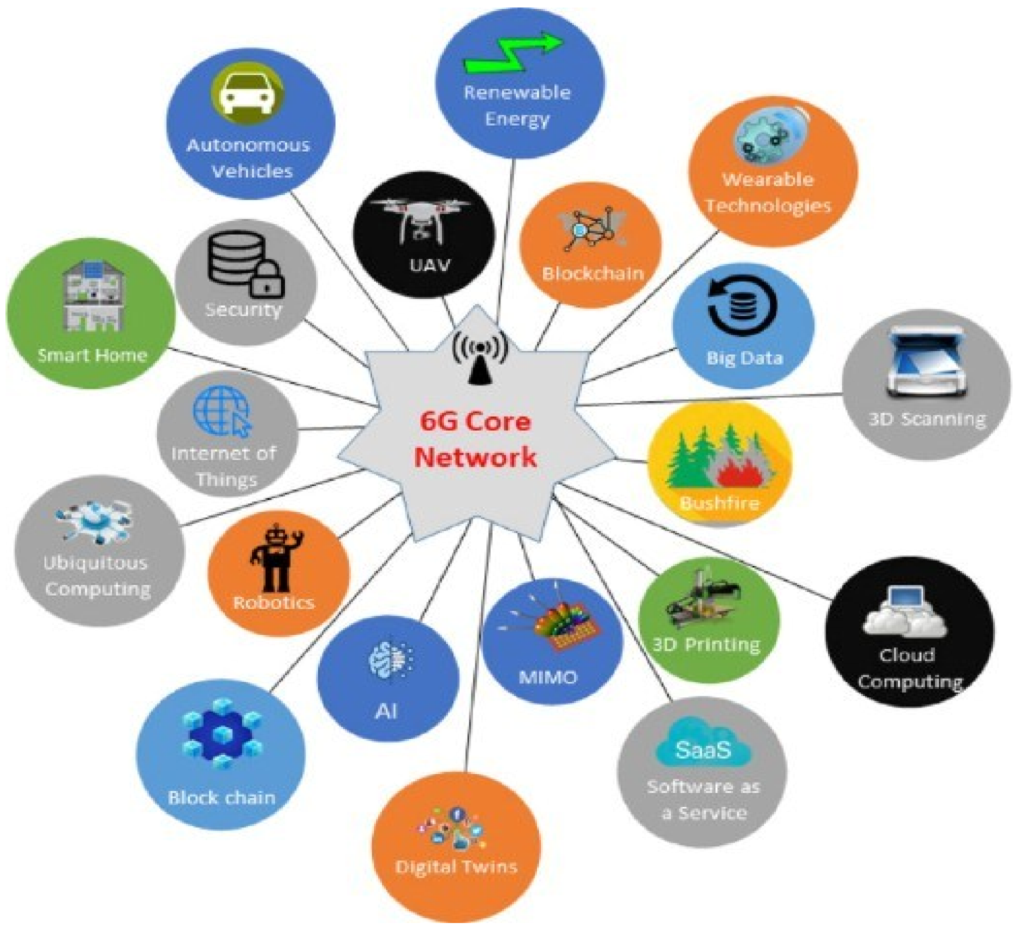

Figure 7: Envisioned 6G based applications. (Banafaa, et. al., 2023)

Table 7: Details on the use cases for the comparative analysis of the 5G and 6G networks. (Banafaa, et. al., 2023)

Use case	**5G**	**6G**
Centre of gravity	User-centric	Service-centric
Augmented reality for industry in terms of Peak rate and capacity	Low resolution and high level tasks	High resolution with multi sensing and comprehensive level tasks

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Tele-presence in terms of capacity	Limited scale and a high video quality	Mixed reality
Security surveillance, detection of defects in terms of positioning and sensing	External sensing with limited automation	Fully automated through the integrated radio sensing
Dynamic digital twins and virtual worlds	No	Yes
Data center wireless in terms of capacity and peak rate	No	Yes
Automation, distributed computing in terms of time synchronization	Micro second level tasks	High precision tasks at nano second level
Ultra-sensitive applications	Not feasible	Feasible
Zero energy devices	No	Yes
Groups of robots or drones in terms of low latency	Might be	‘Yes
Bio-sensors and AI	Limited	Yes
True AI	Absent	Present
Reliability	Not extreme	Extreme
VAR	Partial	Massive scale
Time buffer	Not real-time	Real-time
Capacity	1-D (bps/Hz) or 2-D (bps/Hz/m2)	3-D (bps/Hz/m3)
VLC	No	Yes
Satellite integration	No	Yes
WPT	No	Yes
Smart city components	Separate	Integrated
Autonomous V2X	Partially	Fully

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Table 8: Features comparison of 4G, 5G, and 6G mobile communication systems. (Aslam, at. al., 2021)

Empty Cell	**4G**	**5G**	**6G**
Usage Scenarios	Mobile Broadband (MBB)	eMBB, uRLLC, mMTC, FeMBB, ERLLC umMTC	FeMBB, muRLLC, umMTC, eRLLC, MBRLLC, uHDD, uHEE, uHS
Applications	• High-Definition Videos • Voice • Mobile TV • Mobile Internet • Mobile Pay	• VR/AR/360° Videos • UHD Videos • V2X • IoT • Smart City/Factory/Home • Telemedicine • Wearable Devices	• Holographic Verticals and Society • Tactile/Haptic Internet • Full-Sensory Digital Sensing and Reality • Fully Automated Driving • Industrial Internet • Space Travel • Deep-Sea Sightseeing • Internet of Bio-Nano-Things
Network	Flat and All-IP	• Cloudization • Softwarization • Virtualization • Slicing	• Intelligentization • Cloudization • Softwarization • Virtualization • Slicing
Characteristics	People	Connection (People and Things)	Interaction (People and World)
Technologies	• OFDM • MIMO • Turbo Code • Carrier Aggregation • HetNet • ICIC • D2D Communications • Unlicensed Spectrum	• mm-wave Communications • Massive MIMO • LDPC and Polar Codes • Flexible Frame Structure • Ultra dense Networks • NOMA • Cloud/Fog/Edge Computing • SDN/NFV/Network Slicing	• THz Communications • SM-MIMO • LIS and HBF • OAM Multiplexing • Laser and VLC • Blockchain-Based Spectrum Sharing • Quantum Communications and Computing • AI/ML

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Table 9: The envisioned variances between 5G and 6G network architecture. (Aslam, at. al., 2021).

Parameters	**5G**	**6G**
Type of service	Point to point QoS transport	Point-to-multipoint transport, including configurable logical network overlay topologies with managed quality properties and net-app awareness, with compute services, sync services, AI services
Type of resources	Communication	Communication + compute + sensing
Architecture scope	Radio access network (RAN) + Core network (CN)	Terminal + RAN + CN
Cloud-native	Only control plane (CP) in 5G core	E2E and cross-plane (User plane / Control plane / Management plane)
Microservices	No	Yes, E2E, all planes
Resource awareness	Only air interface	compute, transport, wireless
Trustworthiness	Trustworthy nodes	Trustworthy adaptive services/ network of networks
Ai/ml integration	Over-the-top	Natively integrated
Admission control	Access control	Execution control
Device/node disaggregation	Centralized unit (CU)/ distributed unit (DU), integrated access and backhaul (IAB)	Fully flexible

7. Impacts on various industries

7.1 Education sector

The forthcoming 6G technology is set to revolutionize education in significant ways. With its focus on delivering extremely high data rates, integrating artificial intelligence, providing low latency, and connecting numerous devices, 6G has the potential to completely transform how education is accessed and delivered.

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One of the main advantages that 6G offers to the education sector is improved accessibility to educational resources across all learning levels. From pre-school to post-doctoral studies, the Internet already provides a wealth of educational materials. However, with advancements in 6G networks, these resources will become even more accessible, facilitating distance learning, independent study opportunities, and research initiatives across various fields.

Additionally, collaboration in educational environments will be enhanced due to the improved connectivity and efficiency that 6G networks provide. Students and educators will have access to real-time communication tools, file-sharing capabilities, and interactive platforms that enable smooth group projects and research collaborations.

The introduction of 6G technology in education will also create new opportunities for virtual laboratories and remote research initiatives. Researchers from different disciplines will be able to conduct experiments and studies remotely through virtual platforms, leading to groundbreaking scientific discoveries and improved knowledge dissemination.

Overall, implementing sixth-generation networks in education presents immense potential for enhancing access to educational resources, fostering collaboration among students and educators, and driving innovation in research efforts. As we look forward to future advancements in seventh-generation technologies, it is clear that the education sector stands to gain significantly from the ongoing evolution of Internet and communications systems. (Kumar, et. al., 2019) and (Alsharif, et. al., 2020).

7.2 Healthcare industry

The healthcare sector is set to gain significant benefits from the latest advancements in sixth-generation Internet and communication systems. With faster speeds, improved efficiency, and modern services, healthcare professionals can expect enhanced connectivity in remote areas, expanded telemedicine capabilities, and the integration of smart city applications. By leveraging the potential of sixth-generation networks, healthcare providers can overcome geographical barriers and deliver timely care to individuals in underserved regions. The high-speed connections enable seamless video consultations and remote monitoring, resulting in more effective diagnosis and treatment planning. Additionally, the use of cutting-edge technologies like virtual reality for surgical training and artificial intelligence for medical image analysis can improve patient outcomes.

Moreover, the implementation of sixth-generation networks in the healthcare industry has the potential to transform how medical data is securely stored, accessed, and shared. The enhanced connectivity facilitates real-time collaboration among healthcare professionals, leading to faster decision-making and improved patient care. Through the integration of smart city applications, hospitals can optimize resource allocation, streamline operations, and enhance overall efficiency.

The sixth-generation Internet and communication systems hold immense promise for revolutionizing the healthcare industry by providing advanced tools for diagnosis, treatment, and patient care. Adopting these state-of-the-art technologies allows healthcare providers to achieve

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superior outcomes for patients while maximizing operational efficiency. (Banafaa, et. al., 2023), (Das Sharma, et. al., 2022) and (Wikipedia, 2024).

7.3 Transportation sector

The transportation industry is on the brink of a major transformation with the introduction of sixth-generation Internet and communications systems. By incorporating cutting-edge communication technologies like the Internet of Vehicles (IoV) and Internet of Drones (IoD), vehicle fleets are expected to achieve enhanced connectivity and operational effectiveness. Vehicle social networks (VSNs) will allow vehicles to establish connections on the road, improving passenger comfort, safety, and trust in the transportation of goods. These networks must meet specific criteria, including reduced latency, increased connection density, and extensive coverage.

Furthermore, the deployment of blockchain-based collaborative distributed intrusion detection (BCDID) and dynamic bandwidth throttling (DTS) will enhance security within VSN networks by preventing cyber-attacks. These security features are essential for maintaining uninterrupted communication services and ensuring reliability in vehicle-to-everything (V2X) interactions. Additionally, distributed intelligent reflecting surfaces (IRSs) will be key in enhancing the dependability of 6G transmission within the transportation sector. Despite potential complexities from multiple IRSs, efficient resource management strategies such as pairing IRS arrays with user equipment using intelligent-reflecting surface-user equipment association algorithms will lead to faster transmission rates.

Integrating sixth-generation technologies into transportation holds the promise of transforming connectivity, safety, and efficiency in vehicle operations. By leveraging advanced communication systems and innovative security protocols, the industry is primed for significant progress that will benefit both passengers and logistics operations alike. (Alsharif, et. al., 2020) and (Banafaa, et. al., 2023).

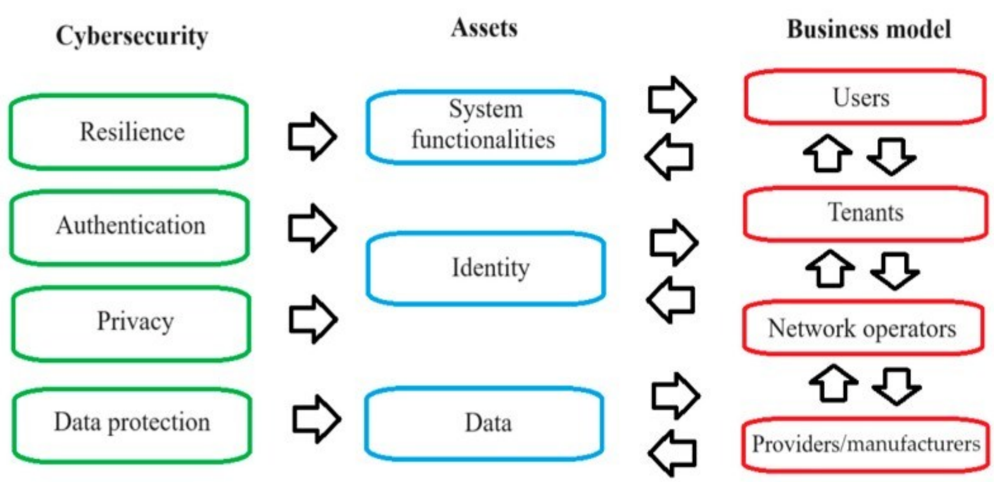

Figure 8: Security requirements, assets, and business relationships model. (Alsharif, et. al., 2020).

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8. Challenges and limitations

8.1 Infrastructure requirements for implementation of sixth-generation networks.

The integration of sixth-generation networks requires significant attention to infrastructure development to support their advanced features and capabilities. A crucial aspect of deploying 6G networks is creating a robust core network architecture that can seamlessly integrate terrestrial wireless mobile communication, medium and low orbit satellite mobile communication, and short-distance direct communication. This innovative 3D core network architecture aims to ensure ubiquitous global coverage of high-speed mobile communications across various environments including air, space, land, and sea.

To achieve this ambitious goal, substantial investments in infrastructure deployment will be essential. Building the necessary base stations and network equipment for 6G networks will demand considerable financial resources and time. Logistical challenges may also emerge when installing infrastructure in remote or difficult geographical areas. Furthermore, integrating systems presents a critical challenge, as many industrial facilities still use outdated equipment that may not be compatible with 6G technology. Upgrading or replacing these systems to facilitate 6G machine-to-machine (M2M) communications will incur additional costs and complexities.

Additionally, ongoing standardization efforts for sixth-generation technology are in progress, with complete definitions of standards yet to be finalized. The development and standardization process might take several years, potentially causing delays in the widespread adoption and implementation of 6G networks. Moreover, utilizing higher frequency bands in 6G networks could result in challenges related to interference from environmental factors such as buildings, vegetation, and weather conditions. This interference may affect the reliability and performance of M2M communications within industrial environments.

By addressing these infrastructure requirements for implementing sixth-generation networks will be crucial in unlocking the full potential of 6G technology across different industries and sectors. (Alsharif, et. al., 2020) and (Aslam, at. al., 2021).

Table 10: Limitations of 6G in M2M communication. (Alsharif, et. al., 2020)

Limitation	**Description**
Infrastructure deployment	Deploying 6G infrastructure, including base stations and network equipment, will require significant investment and time. Building the necessary infrastructure to support 6G networks in industrial environments can pose logistical challenges, especially in remote or difficult geographic locations.

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Systems integration	Many industrial facilities still use legacy equipment and systems that may not be compatible with 6G technology. Updating or upgrading existing infrastructure to support 6G M2M communications may involve additional costs and complexity, requiring careful planning and investment.
Standardization	Sixth-generation technology is still in its early stages of development and standards have not yet been fully defined. The process of developing and standardizing 6G technology could take several years, which may lead to delays in widespread adoption and deployment.
Interference and signal attenuation	The higher frequency bands used in 6G networks are prone to higher signal attenuation and are more susceptible to interference from environmental factors such as buildings, foliage, and weather conditions. This may impact the reliability and performance of M2M communications, especially in outdoor industrial environments with complex topology.
Spectrum availability	Sixth-generation networks are expected to use higher frequency bands, including terahertz (THz) frequencies, to achieve higher data rates and capacity. However, these frequency bands pose challenges in terms of propagation and coverage characteristics, requiring innovative antenna technologies and deployment strategies. Additionally, spectrum allocation and regulatory issues may hinder the availability of appropriate frequencies for 6G deployment.
Power	The higher data rates and increased processing requirements of
consumption	6G networks may result in higher power consumption compared with previous generations. This may pose a challenge for battery-powered devices and IoT sensors deployed in industrial settings, where energy efficiency is crucial for long-term maintenance-free operation.
Security and privacy	Sixth-generation networks may be susceptible to security breaches, hacking and privacy breaches. Providing robust security mechanisms and protocols to protect M2M communications in Industry 4.0 environments will be essential to mitigate these threats and build trust in the reliability and integrity of 6G networks.

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8.2 Potential cybersecurity threats.

The advancement of wireless communication technologies, particularly within the energy sector, has paved the way for new cybersecurity risks. The escalating instances of global cyberattacks targeting power grids present a substantial danger to the secure functioning of energy networks. The emergence of the energy Internet has made systems vulnerable to exploitation by cybercriminals, who can manipulate monitoring commands to cause potential power failures. Wireless networks are especially susceptible to breaches when compared to optical fibers due to their proneness to external influences and unstable transmission channels.

The erratic nature of conventional wireless channels can lead to compromised signal quality and intermittent communication disruptions, impacting the secure management and regulation of an energy Internet. Cyber attackers well-versed in wireless communication protocols can exploit these weaknesses to pilfer data from energy consumers or introduce false information into the systems. Scholarly experts have put forth various strategies to counter cyber threats, with power researchers emphasizing the use of power system models for detecting false data and IT specialists advocating for security measures like network segregation, identity verification, encryption, and access control.

While cutting-edge wireless communication technologies enhance the efficiency of energy systems, they also bring about security vulnerabilities such as network intrusions. As we progress towards the sixth generation of networks, it is essential to proactively tackle cybersecurity risks by implementing robust security protocols tailored to the unique challenges posed by wireless communication in energy systems.

Ultimately, fortifying against cyber dangers in sixth-generation networks will necessitate a blend of inventive security tactics and a comprehensive defense-in-depth approach. By confronting these cybersecurity obstacles head-on, we can guarantee the dependability and durability of our forthcoming communication systems in an increasingly interconnected world. (Hussein, et. al., 2020).

Table 11: Summary of general challenges in 6G. (Aslam, at. al., 2021)

Challenges	Restrictions/Relevant research questions
Sustainability and green	There are numerous challenges that must be investigated and addressed in order to achieve a potentially sustainable network, such as: • Green communication requires advanced power transfer and energy harvesting techniques from heterogeneous devices. • Ensure network sustainability for users with varying levels of processing power. • Ensure that Super Energy efficient algorithms are used for a large number of devices.

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	• Ensure advanced 6G system provides reconfigurable intelligent surfaces for sustainable communication.
Trustworthiness –security	The deployment of security, privacy, and trust measures is challenging due to the massive scale of 6G networks, applications, and services. Several questions are listed as follows and need to be addressed: • How to implement security and privacy measures in the undefined 6G architecture? • When new network elements can be instantiated on-demand in 6G applications, how should authentications be performed? • What security and privacy issues are associated with such technologies that have not yet been fully expected or identified? Another issue is what happens when AI-based tools are used to launch attacks? • How to design and build a privacy-enabled AI model that protects users' privacy while making their data as useful as possible?
Coverage	Some interesting research questions that must be addressed in order to achieve the 6G vision of extreme global coverage: • How to smartly handle smooth 3D navigation while moving vertically up (in air or space) or down the ground level? • How can power radiation and system efficiency be improved while obtaining global coverage? • How to create an automated, open, and decentralized wireless sector that encourages entrepreneurs to take part in order to achieve global coverage?
Applications and performance	• The key restrictions and related research questions that must be clarified in order to achieve the ultimate mobile experience originally envisioned with 6G are as follows: • • How can Tbps data rates be provided to enable FeMBB, extreme availability and reliability in the 99.99999 percent range, and ultra-low latency of less than 1 ms? • How can neighboring devices work together to have a powerful edge intelligence operation with <10 ns latency issues? • How can sensors and interfaces be integrated into the environment to deliver smooth gadget-free interaction? • How to connect and handover data from up to 1 million connected devices/km2?

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	• What is the best way to ensure a high customer satisfaction in services such as holographic telepresence (HT) and XR?
Integrating systems	For hyper-intelligent networking in 6G, several obstacles and research questions must be overcome. • How to make standard and high-quality data sources for active learning in networks with varying characteristics (for example, cognitive radio technologies, channel modeling, and densification level)? • How can hybrid centralized-distributed AI solutions be provided to leverage the effective computing capabilities of centralized cloud servers along with the computing resources available at massive IoT devices at the edge of the network? • How can AI solutions be used to empower networks to be fully programmable in order to support flexible and software-based 6G system implementation? • How to build predictive orchestration strategies to support a few billion IoT devices, zero-latency services, and extremely high capacity.
Device capability	Some 6G features may not be supported by 5G devices, and the cost of 6G devices may rise as their capabilities improve. Another challenge in light of these developments is How to harmoniously combine two new yet different technologies into a single device?
Enabling satellites	• How to effectively control and manage a swarm of LEO and VLEO satellites while also enabling them to communicate in a secure and cost-effective manner? • What are the time-efficient solutions that can help mitigate the Doppler shift and Doppler variation challenges caused by the relative movement of the earth and LEO satellite? • How to deal with the receiver sensitivity, signal detection quality, and receiving performance challenges associated to Transmission Technology for Inter-Satellite Link (ISL)?

9. Comparison with previous generations

9.1 Speed performance comparison.

When analyzing the speed and performance of the sixth generation of Internet and communications systems in comparison to its predecessors, it becomes clear that 6G is on track to completely transform data transmission. While 5G laid the groundwork for improvements in connectivity, 6G aims to surpass current technology in every aspect. The projected data rates and latency enhancements in 6G are striking, with speeds anticipated to reach 1-10 Tbps and latency dropping as low as 0.1 ms. The frequency spectrum allotted for 6G exceeds that of all previous generations, indicating higher transmission rates made possible by THz frequencies. Furthermore, the performance indicators of 6G showcase a significant increase in spectrum and energy efficiency compared to 5G. With commitments to enhanced coverage percentages, reliability levels, positioning accuracy, and receiver sensitivity, it is evident that 6G will establish a new benchmark for wireless communication networks. Additionally, the incorporation of AI applications in 6G networks will distinguish it from its predecessors by enabling autonomous functions that were previously unachievable.

The shift from a user-centric model in 5G to a service-centric approach in 6G represents a move towards machine-to-machine communication driven by improved speed and efficiency. Through the utilization of technologies like haptic communication and extreme reality experiences, 6G will open up new possibilities such as tactile communication and fully automated processes through integrated radio sensing.

The comparison of speed and performance highlights that the sixth generation of Internet and communications systems is poised to redefine connectivity standards far beyond what was previously imagined. (Aslam, at. al., 2021), (Banafaa, et. al., 2023), (Qian, et. al., 2024) and (Becher, et. al., 2023).

Table 12: A detailed comparison of 6G with the previous mobile communication technologies. (Banafaa, et. al., 2023)

Specifications	1G	2G	3G	4G	5G	6G
Data rate	2.4 kbps	64 kbps	2 Mbps	100–1000 Mbps	≈ 20 GBPS	≈ 1 TBPS
End-to-end latency	20–200 s	10–100 s	1 s	100 ms	10 ms	1 ms
Highest spectral efficiency	1 bps/ HZ	0.5 bps/ HZ	2.5 bps/Hz	15 bps/Hz	30 bps/Hz	100 bps/Hz
Network mobility support	Up to 15 m/hr	Up to 50 km/hr	Up to 150 km/hr	Up to 350 km/hr	Up to 500 km/hr	Up to 1000 km/hr
fmax	–	–	–	5 GHz	90 GHz	10 THz

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XR	–	–	–	NO	Partial	Full
THZ communication	–	–	–	NO	Very Limited	Wide
Services	–	–	–	Video	VR, AR	Tactile
System Architecture	–	–	–	MIMO	Massive MIMO	Intelligent surface
AI	NO	NO	NO	NO	Partial	Full
Autonomous vehicle	NO	NO	NO	NO	Partial	Full
ER (Extreme Reality)	NO	NO	NO	NO	Partial	Full
Haptic Communication	NO	NO	NO	NO	Partial	Full
SI (Satellite integration)	NO	NO	NO	NO	NO	Full

Table 13: Impact of FBER on Retry Probability, Bandwidth Loss, and FIT in PCIe 6.0 x16 Links. (Zhang, et. al., 2022)

FBER/ Retry Time	**10^{-6}/ 100ns**	**10^{-6}/ 200ns**	**10^{-6}/ 300ns**	**10^{-5}/ 200ns**
Retry probability per flit	5×10^{-6}	5×10^{-6}	5×10^{-6}	0.048
B/W loss with go-back-n (%)	0.025	0.05	0.075	4.8
FIT	4×10^{-7}	4×10^{-7}	4×10^{-7}	4×10^{-4}

9.2 Efficiency comparison.

Comparing the efficiency of the sixth generation (6G) of Internet and communications systems with its predecessors reveals remarkable advancements. One notable improvement is in the data rate, where 6G excels with an impressive data transmission speed of around 1 terabyte per second (TBPS). In contrast, 5G offers speeds of approximately 20 gigabytes per second (GBPS), indicating a significant leap in data transfer capabilities.

Moreover, the end-to-end latency of 6G networks is drastically reduced to just 1 millisecond

(ms), far surpassing the latencies of previous generations like 5G, which ranged from 10 ms to 100 ms. This latency reduction enhances real-time communication and response times, making 6G ideal for applications that require instant data transmission.

Additionally, the spectral efficiency of 6G networks is notably higher at about 100 bits per

second per Hertz (bps/Hz), outperforming earlier generations such as 5G, which offered spectral efficiencies ranging from 30 bps/Hz to 15 bps/Hz. This enhanced efficiency allows for more data to be transmitted over the available bandwidth, resulting in improved network performance and capacity.

The comparison of efficiency between the sixth generation and previous iterations underscores the substantial technological advancements in terms of speed, latency, and spectral efficiency. These enhancements position 6G networks as a transformative force in facilitating high-speed, low-latency communication across various sectors and paving the way for innovative applications and services. (Banafaa, et. al., 2023) and (Qadir, et. al., 2023).

Table 14: Optimum values for SNR, λ top and λ top− elec to target FEC BER threshold of 3.8 × 10 −3. Collapse (Telecommunication systems, 2024).

QAM Type	SNR	λ_{top}	λtop−*elec*
8-QAM	16.7 dB	1.899	4.76
16-QAM	19.6 dB	2.1964	5.5056
32-QAM	22.3 dB	2.4526	6.1478
64-QAM	25.1 dB	2.6652	6.6807

10. Future Outlook

10.1 Expected advancements in seventh-generation technologies.

The upcoming seventh-generation technologies are poised to transform the landscape of communication and connectivity in the digital realm. Expanding on the groundwork set by its predecessor, 7G is projected to introduce even speedier and more effective communication systems tailored to meet the ever-changing demands of society.

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A primary focus of 7G technologies will center on enhancing connectivity in remote areas. By harnessing state-of-the-art innovations like terahertz waves and advanced artificial intelligence, 7G networks will ensure seamless connectivity even in the most isolated locations. This not only bridges the digital gap but also empowers individuals and communities with access to a wide array of services and opportunities.

Moreover, advancements in telemedicine capabilities are set to revolutionize the healthcare sector. The integration of sophisticated AI algorithms and high-speed communication networks will facilitate real-time monitoring, diagnostics, and treatment options for patients irrespective of their geographical location. This will reshape healthcare delivery, rendering it more accessible and efficient than ever.

Furthermore, smart city applications driven by 7G technologies will play a pivotal role in shaping our urban landscapes. From intelligent traffic management systems to energy-efficient infrastructure, 7G networks will empower cities to become more sustainable, resilient, and responsive to the needs of their residents.

In essence, the anticipated strides in seventh-generation technologies carry immense potential for society. They stand to foster innovation across various sectors, enhance quality of life, and generate fresh avenues for economic growth and progress. (Aslam, at. al., 2021), (Banafaa, et. al., 2023) and (Das Sharma, et. al., 2022).

Table 15: Summary of computing traits. (Das Sharma, et. al., 2022)

Trait	**Description**
Focus/Paradigms	We discuss well-established computing paradigms, from client–server to quantum computing, which have been explored in the last decade.
Technologies/Impact Areas	We cover key research that has grown over time by utilizing these well-established computing paradigms and how this has led to many breakthroughs in the underlying technology.
Trends/Observations	The new trends, such as large-scale machine learning, digital twins, edge AI, bitcoin currency, 6G & Beyond and quantum Internet and biologically-inspired computing, for the next generation of computing, have come to light due to these advances in computing paradigms and technology.

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Table 16: Summary of Trends/Observation for modern computing along with future reading. (Das Sharma, et. al., 2022)

Trends/ Observation	Open challenges and future directions	Further reading
AI-driven Computing	How to optimize the management of resources using the latest AI/ ML models in computing systems?	Elsevier IoT
Large Scale Machine Learning	How can businesses mitigate the risks associated with the proliferation of sensitive information that arise as a result of the proliferation of data produced by AI and ML systems?	IEEE TKDE
Edge AI	What strategies should be employed to oversee the simulation and information transmission among peripheral devices and other systems? What network infrastructures should be utilized to enable this communication?	Elsevier IoT
Bitcoin Currency	How can computing be utilized to maximize the efficiency of computation or processing capacity usage in cryptocurrency for cloud mining?	Elsevier JNCA
Industry 4.0	How can AI, the cloud, and edge computing be used to do predictive analysis that involves company resources?	IEEE COMST
Intelligent Edge	How to deal with big problems that come up when designing system-level, algorithm-level, or architectural-level developments or innovations for integrated cognitive ability, like making decisions in real-time, keeping AI training and inference environmentally friendly, and deploying protection?	IEEE COMST
XAI	How can the forecasting of resource and power consumption and SLA variances, as well as the implementation of promptly proactive action, reduce SLA violations and enhance QoS using XAI?	ACM CSUR

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Exascale Computing	How to make energy-efficient computing as power-hungry as the supercomputers that do calculations and transfer data within the computing environment nowadays?	ACM CSUR
6G and Beyond	What role 6G may play in reducing latency and improving reaction times by transmitting data between edge devices at high speeds?	IEEE COMST
Quantum AI	What steps should be taken to build the AI cloud-based quantum computing infrastructures that are expected to be the foundation for our usage of quantum computers and simulators, which will supplement our existing classical computing hardware?	Wiley SPE
Quantum Internet	How can the benefits of quantum networking be preserved while integrating the quantum Internet into currently operating conventional technology that will have to exist alongside and communicate effortlessly with today's Internet services?	IEEE COMST
Analog Computing	How is it that analog computers can do complicated computations faster and more accurately than their digital equivalents, which utilize ML methods?	Nature Electronics
Neuromorphic Computing	How might neuromorphic systems, which model the brain's structure and function and use analog circuits to do AI tasks, pave the way for creating incredibly adaptable, self-learning machines?	Nature Computational Science
Biologically-inspired Computing	What can researchers take away from brain cells concerning ways to minimize the energy needed for computation, AI, and ML, given that these cells can easily combine smaller tasks to execute larger	Elsevier ESA

Digital Twins	How can network digital twins aid in speeding up preliminary installations by preparing navigation, protection, digitization, and evaluation in simulation while offering the scalability and interoperability of complex networks?	IEEE COMST
Net Zero Computing	How can companies mitigate the negative ecological impact of their IT infrastructure by constructing environmentally friendly data centers and improving energy effectiveness, given that these centers use significant quantities of electricity and release enormous quantities of waste heat while also providing powerful computing services?	IEEE COMST

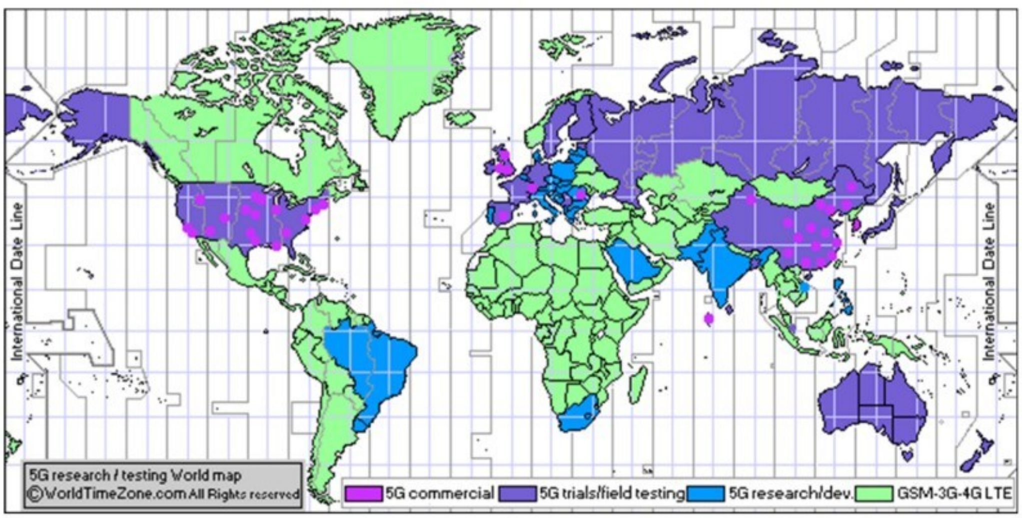

Figure 9: 5G commercial network world coverage map (December 2019). (Gill, et. al., 2024)

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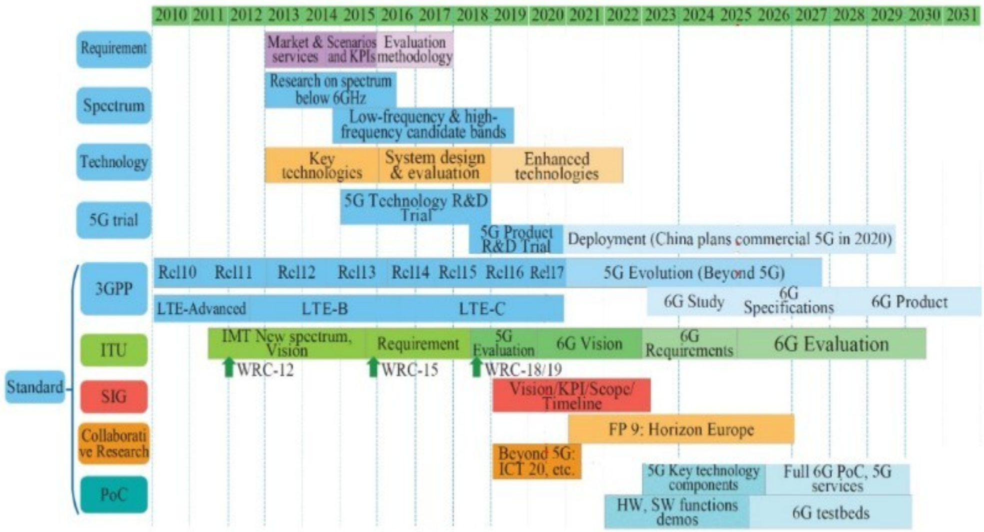

Figure 10: Timeline of 6G wireless networks. (Gill, et. al., 2024)

10.2 Potential societal impacts and benefits.

The sixth wave of Internet and communication systems, characterized by holographic, tactile, and human-bond interactions, is on the verge of significantly impacting society in numerous ways. Holographic interactions are poised to transform our engagement with 3D technology, providing immersive experiences that can enhance teleoperation and interpersonal dialogue. Tactile interactions will facilitate the real-time transmission of virtual imagery, creating opportunities for teleoperation and cooperative automated driving. Furthermore, human-bond interactions will introduce a new level of connection focused on the human experience by engaging all five senses in communication processes.

These advancements in communication technologies have the potential to improve many aspects of society. For instance, in healthcare, tactile interactions can streamline remote medical consultations and diagnoses by transmitting physical characteristics securely. In education, holographic interactions can enrich virtual learning experiences through interactive 3D images and video content. Additionally, in smart city applications, these technologies can support urban planning efforts by allowing real-time data transmission for effective city management.

However, challenges such as developing innovative physical layer schemes and protocols tailored to these advanced communication technologies must be addressed. Interdisciplinary research collaborations will be vital in creating hybrid communication technologies that can effectively replicate human senses. Moreover, ensuring secure communication channels for transmitting biometric profiles and sensitive information will be essential for protecting user privacy.

The sixth wave of Internet and communication systems presents significant promise for society by enabling groundbreaking communication methods that address human-centric needs. By overcoming challenges and effectively leveraging these advancements, we can realize the full

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potential of these technologies to benefit various industries and enhance connectivity in remote areas. (Aslam, at. al., 2021) and (Gill, et. al., 2024).

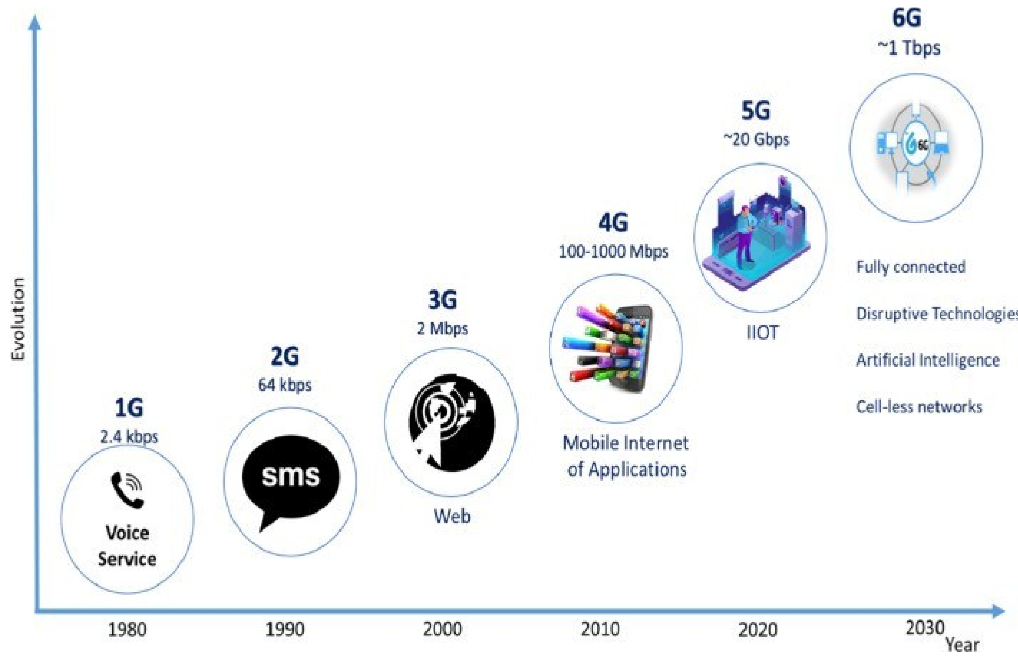

Figure 11: Existing and expected mobile wireless communication evolution till 2030. (Banafaa, et. al., 2023)

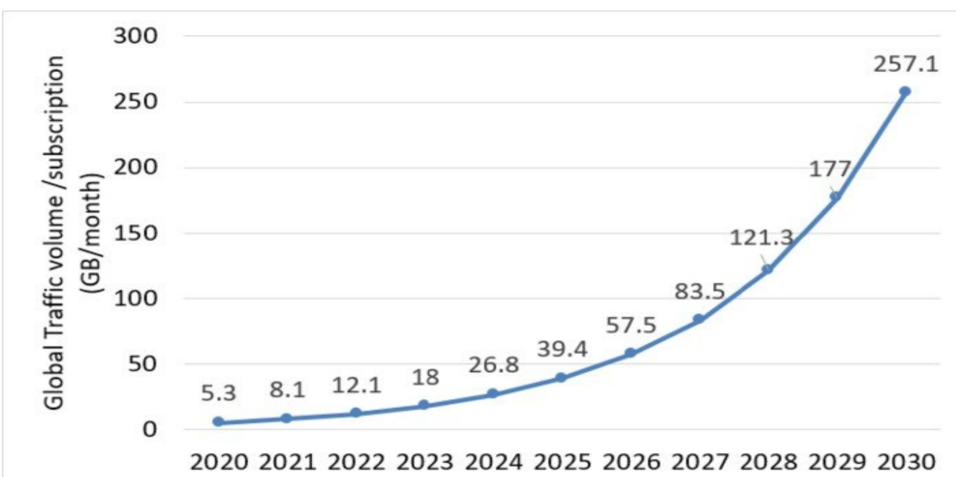

Figure 12: The growth depicts worldwide connectivity during the years 2020-2030, in terms of the total global traffic volume. (Banafaa, et. al., 2023)

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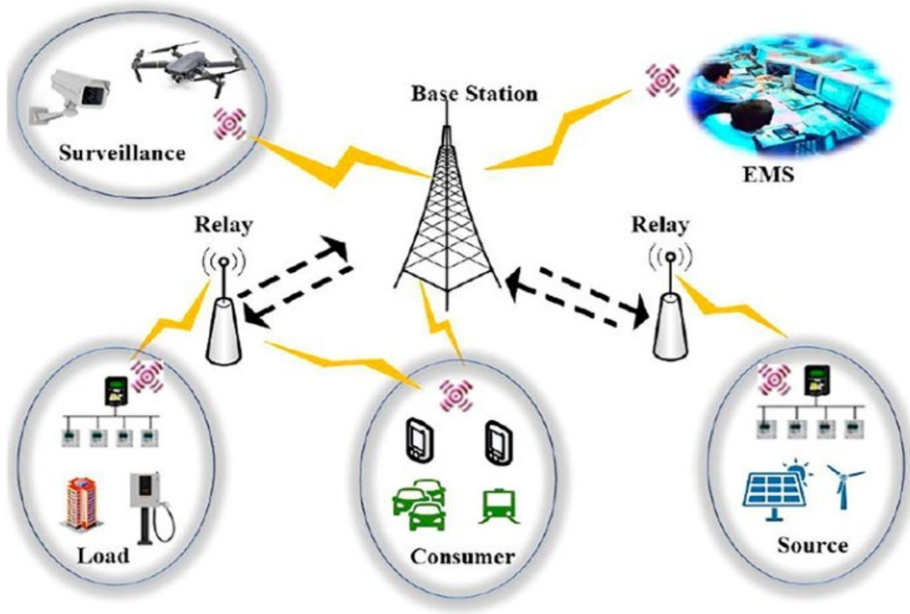

Figure 13: Architecture of an energy Internet communication network. (Hussein, et. al., 2020)

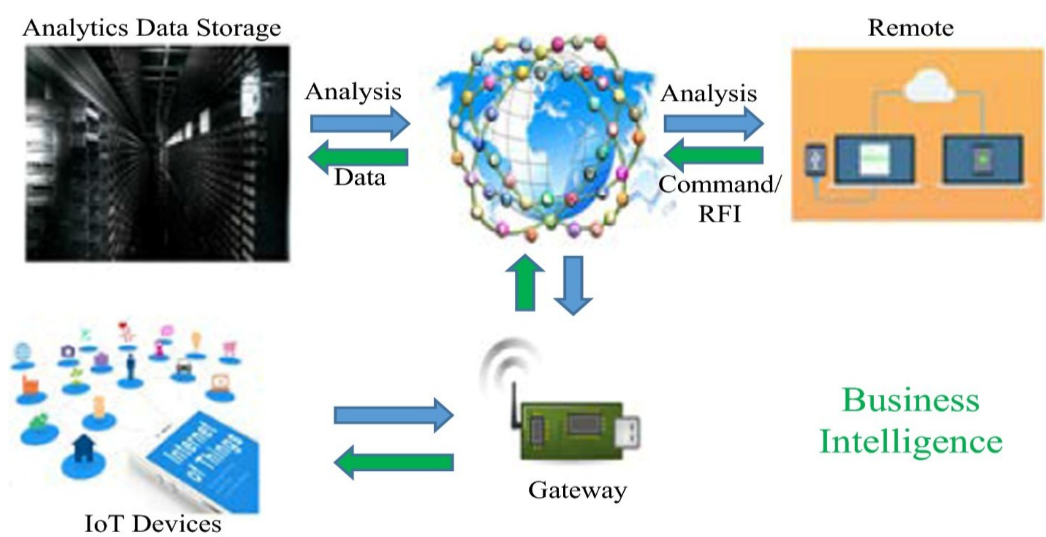

Figure 14: General architecture of IoT (Rojek, et. al., 2024)

11. Conclusion

The sixth wave of Internet and communication systems marks a significant advancement in technology and connectivity. With each decade bringing new developments in communication systems, the progress made in 6G networks is poised to greatly enhance speed, efficiency, and overall capabilities compared to its predecessors. The shift from 5G to 6G networks will introduce fresh services, applications, and features aiming to revolutionize our interaction with digital platforms. The advantages of the sixth generation of communications are wide-reaching and substantial. Enhanced connectivity in remote regions, upgraded telemedicine capabilities, and smart city applications are just a few illustrations of how society can benefit from these advancements. Various sectors like education, healthcare, and transportation will witness positive changes due to the integration of 6G networks. Despite the numerous benefits brought forth by 6G technologies, there exist challenges and limitations that demand attention. Infrastructure needs for implementing network systems present a significant obstacle, along with potential cybersecurity risks associated with advanced communication technologies. Nonetheless, with strategic planning and innovative solutions, these obstacles can be overcome to fully harness the potential of sixth-generation networks. When comparing 6G with its predecessors, it becomes evident that there is a substantial improvement in speed performance and efficiency. The future outlook for seventh-generation technologies appears promising, with anticipated advancements set to further amplify societal impacts and benefits. Overall, the sixth generation of Internet and communication systems signifies a momentous leap in technological progress. With its capacity to transform various industries and enhance global connectivity, 6G networks hold immense promise in shaping the future of communication technology.

References

Alsharif, M. H., Kelechi, A. H., Albreem, M. A., Chaudhry, S. A., Zia, M. S., & Kim, S. (2020, April). Sixth Generation (6G) wireless networks: Vision, research activities, challenges and potential solutions. *Symmetry*, *12*(4), 676. https://www.mdpi.com/2073-8994/12/4/676

Aslam, M. M., Du, L., Zhang, X., Chen, Y., Ahmed, Z., & Qureshi, B. (2021, January). Sixth Generation (6G) Cognitive Radio Network (CRN) application, requirements, security issues, and key challenges. *Security and Privacy*, Article ID 1331428. https://onlinelibrary.wiley.com/doi/10.1155/2021/1331428

Banafaa, M., Shayea, I., Din, J., Azmi, M. H., Alashbi, A., Daradkeh, Y. I., & Alhammadi, A. (2023, January). 6G mobile communication technology: Requirements, targets, applications, challenges, advantages, and opportunities. *Ain Shams Engineering Journal*. https://www.sciencedirect.com/science/article/pii/S111001682200549X

Becher, B., & Urwin, M. (2023, October). 6G: What is it? When can we expect it? *Built In*. https://builtin.com/hardware/6g

Das Sharma, D. D. (2022, November). The evolution of the PCI Express specification: On its sixth generation, third decade and still going strong. *PCI-SIG Blog*. https://pcisig.com/blog/evolution-pci-express-specification-its-sixth-generation-third-decade-and-still-going-strong

Gill, S. S., Wu, H., Patros, P., Ottaviani, C., Arora, P., Pujol, V. C., ... & Buyya, R. (2024, January). Modern computing: Vision and challenges. *AI Open*, *5*, 100113. https://www.sciencedirect.com/science/article/pii/S2772503024000021

https://doi.org/10.61856/eme16g83
Hussein, A. F., & Elgala, H. (2020, June). Design and spectral analysis of mixed-carrier communication for sixth-generation networks. *Proceedings of the Royal Society A*, *476*(2239), 20200165. https://royalsocietypublishing.org/doi/abs/10.1098/rspa.2020.0165

Internet. (2024, September). *Wikipedia*. https://en.wikipedia.org/wiki/Internet

Kumar, S., Tiwari, P., & Zymbler, M. (2019, September). Internet of Things is a revolutionary approach for future technology enhancement: A review. *Journal of Big Data*, *6*, Article 111. https://journalofbigdata.springeropen.com/articles/10.1186/s40537-019-0268-2

Qadir, Z., Le, K. N., Saeed, N., & Munawar, H. S. (2023, January). Towards 6G Internet of Things: Recent advances, use cases, and open challenges. *Internet of Things*, *22*, 100677. https://www.sciencedirect.com/science/article/pii/S2405959522000959

Qian, Y. (2024, September 5). Internet of Things and next generation wireless communication systems. *IEEE Xplore*. https://ieeexplore.ieee.org/document/9535460

Rojek, I., Kotlarz, P., Dorożyński, J., & Mikołajewski, D. (2024, January). Sixth-generation (6G) networks for improved machine-to-machine (M2M) communication in Industry 4.0. *Electronics*, *13*(10), 1832. https://www.mdpi.com/2079-9292/13/10/1832

Telecommunication systems. (2024, September 5). *The World Factbook*. https://www.cia.gov/the-world-factbook/field/telecommunication-systems

Zhang, X. (2022, April). Advanced wireless communication technologies for energy internet. *Frontiers in Energy Research*, *10*, 889355. https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2022.889355/full