6G as Support for IoE and Private Networks

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The emergence of the sixth generation of cellular systems (6G) signals a transformative era and ecosystem for mobile communications, driven by demands from technologies like the internet of everything (IoE), V2X communications, and factory automation. The primary goals of 6G include providing sophisticated and high-quality services, extremely reliable and further-enhanced mobile broadband (feMBB), low-latency communication (ERLLC), long-distance and high-mobility communications (LDHMC), ultra-massive machine-type communications (umMTC), extremely low-power communications (ELPC), holographic communications, and quality of experience (QoE), grounded in incorporating massive broad-bandwidth machine-type (mBBMT), mobile broad-bandwidth and low-latency (MBBLL), and massive low-latency machine-type (mLLMT) communications.

6G IoT

1. Introduction

The evolution of wireless communication has been marked by transformative leaps, each ushering in new paradigms of connectivity and interaction. Today, we face a new revolution, i.e., a new frontier. The emergence of sixth-generation (6G) technology promises to reshape connectivity and transcend the boundaries of its predecessors, unlocking unprecedented capabilities and enabling a plethora of applications that will change our perception of lifestyle, society, and business in ways that were once confined to the realm of “wishful thinking”.

The forthcoming mobile network generation, 6G, is poised to address novel and innovative challenges. It is envisioned as a self-contained artificial intelligence ecosystem, moving from a human-centric paradigm to a dual human- and machine-centric focus. It is expected that 6G will usher in near-instant, seamless wireless connectivity that knows no bounds [1].

Anticipated as the enabler for a globally connected ecosystem, 6G is poised to realize comprehensive connectivity. At the heart of 6G’s advancements lies edge intelligence (EI), a pivotal technology that amalgamates artificial intelligence (AI) with mobile multiple-access edge computing (MEC). This fusion unlocks the latent potential of intelligent, data -centric service at the edge. Furthermore, the integration of edge technology is imperative for the success of 6G, as it enables the convergence of cloud capabilities with intelligent devices in the proximity.

Expanding upon the foundation of 5G, the evolution to 6G is set to profoundly influence the progression of communication development’s intelligence. This evolution encompasses intelligent, deep, holographic, and ubiquitous connectivity [2]. In the standardization processes and procedures of 5G networks, three distinct scenarios were identified in the initial stages: enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (URLLC), and massive machine-type communications (mMTC). These scenarios served as key foundations for establishing the design guidelines of 5G technologies.

Sixth-generation (6G) technology promises to profoundly enhance communication networks, with the ambitious goal of establishing a worldwide connection using sustainable approaches, all geared towards the ultimate aim of enriching the quality of life.

The horizon of mobile communications and internet technologies is witnessing advancements that transcend current scientific boundaries. Complex concepts such as automated driving, augmented and virtual reality, and mMTC demand an elevated mobile infrastructure for successful implementation [3].

Many applications, because of 6G, will be redefined and restructured: the landscape of technology will be reshaped with the transformation of the internet of things (IoT) into the internet of everything (IoE), marking the onset of numerous innovative technologies: intelligent internet of medical things (IIoMT), intelligent industrial internet of everything (IIIoE) like the intelligent grid (EC-IoT SC: edge computing iot-based smart grid) [4]. This will transform the transition from smart to intelligent, i.e., with AI capabilities within 6G, the IoE will evolve smart devices into intelligent entities. These devices will authentically operate with AI-driven capabilities, enabling them to predict, make decisions, and share their experiences with other intelligent devices [5].

The advent of 6G is poised to profoundly influence the evolution of communication development's intelligence process, encompassing intelligent, extensive, deep, holographic, and ubiquitous connectivity.

Future time-critical applications' demands on 6G communication technology encompass very high bandwidth (≥1 Tbps), very high operating frequencies (≥1 THz), very low latency times (≤1 ms), extremely high reliability (10^{-9}), high mobility (≥1000 km/h), and wavelengths within the range of ≤300 μm [5]. It will be a paradigm shift in time-critical applications, entirely dependent on communication technology.

While the prospects of 6G communication technology bring forth many challenges and complexities, worldwide deployment is expected in 2030 [6][7]. Promising enhanced coverage and mobility through satellite communication, 6G technology highlights a crucial gap in the current landscape—poor rural coverage, the absence of data rates exceeding 1 Tbps, and the necessity for exceptional reliability and extremely low latency.

This inherent disparity requires a delicate balance so as not to compromise the quality of the system and services, nor affect user satisfaction. The International Telecommunication Union (ITU), in its Recommendation ITU-T P.10/G, defines two approaches to quality assessment: one is the measure of quality of service (QoS), and the other is the measure of quality of experience (QoE) [8]. Typically, within a communication system, the communication quality, and media signal quality components are concerned with users' perceptions of how effectively the system supports communication. It specifically emphasizes the quality attributes associated with aspects of communication. Within network and communication applications, QoS represents an evaluative measure of service quality provided by the network. This network-centric gauge assesses the quality of data transmission in communication networks. QoS measurement encompasses metrics evaluating the key performance indicators (KPIs) of a communication system. QoS indicator values are anticipated through an analytical model of the overall telecommunications system's performance, considering known parameters of user behavior and the technical characteristics of the telecommunications network [9][10]. However, there are other definitions of QoS, such as that used by the Internet Engineering Task Force (IETF), where QoS characterizes the performance of functional services in network layer models.

Discussions and research on 6G requirements are abundant [11][12][13], and multiple viewpoints and approaches propose different ways to meet these demands. Some proposals go towards exploring potential applications encompassing mobile broadband and low latency (MBBLL), massive broadband machine-type (mBBMT), and massive low-latency machine-type (mLLMT) communications [14]. Others emphasize issues such as further-enhanced mobile broadband (feMBB), extremely reliable and low-latency communications (ERLLC), umMTC, long-distance and high-mobility communications (LDHMC), and extremely low-power communications (ELPC) [15]. Still, others are also concerned with the following features: ubiquitous mobile ultra-broadband (uMUB), ultra-high-speed with-low-latency communications (uHSLLC), and ultra-high-data density (uHDD) [16].

Built upon an open network platform, 6G is poised to facilitate service-centric network slicing management on demand. This capability empowers service providers and industry-specific markets to swiftly deploy novel services as required.

Furthermore, incorporating AI algorithms for network monitoring and surveillance, data-driven business decisions, preventive maintenance, fraud detection, and robust blockchain-based security systems for data validation are also of utmost significance within the core of 6G.

Moreover, AI technology holds the potential to enable the dynamic orchestration and management of networks, caching, and computing resources, thereby enhancing the effectiveness of forthcoming network generations. Another crucial trend revolves around robust, endogenous network security spanning physical and network layers. Industry sectors such as cloud-based virtual reality (VR), IoT industrial automation, cellular vehicle-to-everything (C-V2X), digital twin body area networks, energy-efficient wireless network management and control, and federated learning systems collectively stand as driving forces, significantly propelling the advancement of 6G wireless communication networks.

The 5G Automotive Association (5GAA) is a collaborative initiative bringing together the automotive and telecommunications industries, driven by the overarching objective of expediting the worldwide implementation of C-V2X technology. This endeavor represents the initial stride towards realizing a seamlessly integrated intelligent transportation system that leverages the capabilities of 5G connectivity and beyond. The 5GAA has formulated a comprehensive framework, delineating various usage scenarios, methodological approaches, illustrative instances, and stipulated service-level requisites that are being followed by the industry and will continue its evolution towards

6G. In recent years, the automotive industry has witnessed the emergence of several pioneering applications rooted in C-V2X technologies. Furthermore, a continuum of such applications is anticipated in the ensuing years, poised to elucidate novel capabilities and augment the repertoire of connected vehicles. These forthcoming C-V2X use cases are poised to exert substantial influence, encompassing domains such as safety enhancement, vehicular operational management, vehicular software update (a particularization of the previous), convenience augmentation, autonomous driving, vehicular platooning, traffic optimization, ecological sustainability, and sociocultural integration [12].

In the 2024–2030 roadmap, 5GAA considers different types of V2X communication types (depending on the destination entity) in use cases that intend to achieve [17]:

- *V2X (Vehicle-to-Everything Communication*): V2X represents a comprehensive set of communication protocols developed under the 3GPP framework. The cellular-V2X (C-V2X) paradigm encompasses all V2X technologies standardized by 3GPP. As per the 5GAA documentation, the imminent maturation of 5G-V2X is anticipated to establish a global standard specifically tailored for automotive applications within the 3GPP 5G framework. This encompasses network-centric (Uu mode) and direct (PC5/Slidelink) communication modalities, with the potential of operating in conjunction or independently of LTE-V2X. It supports advanced vehicular functionalities and maintains previously established message types, ensuring seamless service continuity.

- *V2P (Vehicle-to-Pedestrian Communication)*: The emphasis on vulnerable road user (VRU) applications has been accentuated due to the escalating incidents involving pedestrians and cyclists. The 3GPP framework is being adapted to seamlessly integrate with contemporary smartphones and connected consumer devices. The current C-V2X specifications facilitate direct communication between vehicles, pedestrians, cyclists, and motorcyclists. As delineated in the 3GPP Rel. 17, future enhancements are geared towards optimizing power efficiency of C-V2X for handheld consumer devices, ensuring longevity and bi-directional communication efficacy.

- *Vehicle-to-Vehicle (V2V) Communication*: V2V encapsulates protocols that facilitate direct information exchange between vehicles, enabling them to share data regarding their operational state and immediate environment.

- *Vehicle-to-Infrastructure (V2I) Communication:* Recent legislative developments, such as the German Automated Driving (AD) L4 regulation, underscore the significance of V2I communication in the realm of autonomous driving. This legislation facilitates the deployment of AD L4 vehicles on predefined routes, contingent upon the presence of robust connectivity. Such regulatory frameworks pave the way for initiating automated valet parking (AVP) services, which relies intrinsically on a connected infrastructure and V2I communication modalities.

- *Vehicle-to-Network (V2N) Communication:* V2N refers to communication between a vehicle and a cellular or wireless network infrastructure. This paradigm enables vehicles to access cloud services, receive real-time traffic and road condition updates, and connect to remote servers for software updates or advanced driving analytics. Essentially, V2N facilitates the integration of vehicles into the broader IoT ecosystem, allowing them to leverage network-based resources for enhanced functionality and safety. Mobile operators have spectrum requirements to deliver advanced automotive V2N services efficaciously. Specifically, a minimum of 50 MHz of service-agnostic low-band spectrum (<1 GHz) is necessitated for V2N functionalities in rural topographies. Concurrently, a minimum of 500 MHz of service-agnostic mid-band spectrum (1 to 7 GHz) is imperative to meet the demands of high-capacity, urban advanced automotive V2N services.

- *Vulnerable Road User (VRU):* The VRU complex interactions scenario delineates a situation wherein a VRU communicates its intent before crossing a thoroughfare. Subsequent vehicular acknowledgments reassure the VRU of the safety of the maneuver. As the VRU traverses, continuous communication with stationary vehicles ensures vehicular awareness of the VRU's position and trajectory. The global emphasis on VRU applications is accentuated by the potential of cellular-V2X (C-V2X) to mitigate incidents involving pedestrians and cyclists. The 3GPP framework is evolving to ensure compatibility with contemporary communication devices, facilitating direct vehicular communication with pedestrians, cyclists, and motorcyclists.

Some of the V2X use cases, technological advancements, and evaluations that can be considered are the following [17]:

- *Evolution of 5G-V2X:* After its initial definition in the Rel. 14 with LTE-V2X and post the introduction of Rel.16, 3GPP has been meticulously defining the C-V2X direct communication protocols (PC5) predicated on the 5G NR radio access technology (RAT). This encompasses innovations such as truncated symbols to minimize latency, feedback channels to augment reliability, and an expanded capacity to support diverse transmission modes, including unicast, multicast, and broadcast. Regional variations may manifest in deployment strategies, potentially operating with or devoid of LTE-V2X.

- *Power Optimization for Direct Communication:* The burgeoning focus on VRU applications necessitates advancements in C-V2X to pre-emptively address potential incidents involving pedestrians and cyclists. The 3GPP framework is evolving to ensure compatibility with the latest generation of smartphones and connected devices. Current specifications facilitate direct vehicular communication with pedestrians, cyclists, and motorcyclists. Subsequent enhancements, as outlined in 3GPP Rel. 17, are poised to refine power consumption metrics of C-V2X, particularly for battery-dependent handheld devices.

- *Advancements in Mobile Network Positioning:* The automotive sector is currently probing the potential of 5G NR precise positioning to bolster position accuracy, especially in regions with compromised GNSS coverage. This initiative is pivotal for autonomous vehicular operations and V2X safety protocols. Certain autonomous vehicular applications necessitate stringent position accuracy metrics. In such scenarios, 5G NR is being assessed as a potential component of sensor fusion systems, supplementing GNSS and its corrective algorithms to enhance positional accuracy.

2. From 1G to 5G

The evolution of cellular wireless communications generations (#G) refers to significant changes in the infrastructure design architecture, speed, technology, bandwidth, and spectrum. Each generation introduces new standards, capabilities, techniques, and innovative or disruptive features that differentiate it from its predecessors [18]. The mobile generations have progressed in phases, with major milestones in 1981, 1992, 2001, 2010, and 2020, marking the advent of 1G, 2G, 3G, 4G, and 5G, respectively [19].

Throughout these evolutionary phases, several factors have undergone significant improvements. These include data speed, network service reliability, cost-effectiveness, network capacity enhancement, increased availability of network functions, energy-efficient design frameworks, cognition, security, and coverage [19]. These advancements have paved the way for developing more efficient and powerful mobile communication technologies, ultimately benefiting users, and expanding the capabilities of mobile devices and networks.

The evolution of inter-network services has brought about various changes in communication technology, from circuit-switching to packet-switching. Originally initiated with narrowband in 2G, the evolution advanced to broadband in 3G, ultra-broadband in 4G, and ultimately culminated in the wireless world wide web capabilities of 5G. These advancements have significantly impacted data transmission bandwidth, providing users with faster and more efficient communication experiences [20][21].

In the early stages, 1G utilized simple analogue assembly for communication, which later evolved to 2G and 3G, employing a 25 MHz bandwidth spectrum. The bandwidth was then expanded, reaching 100 MHz in 4G networks. The ambitious goal of 5G is to utilize an even broader spectrum, ranging from 30 GHz to 300 GHz, to establish communication networks with unprecedented capabilities [19].

These developments in bandwidth have been crucial in enabling the growth in both the quantity and complexity of advanced and complex services and applications that demand higher data rates and lower latency, i.e., they are time-critical, ultimately transforming how we connect and communicate in the modern world.

Over the past few decades, network speeds have experienced a gradual but significant transformation. The initial 1G networks offered a modest data transmission capacity of 2 Kbps, which saw a slight increase in 2G, reaching 64 Kbps. Subsequent advancements in 3G led to a remarkable boost in speed, providing up to 8 Mbps, and this progress continued with 4G networks offering speeds of up to 50 Mbps [22][23].

During this period, multiplexing and spectrum algorithms also experienced notable changes. In 1G, frequency division multiple access (FDMA) was the key multiplexing technique, while 2G adopted time division multiple access (TDMA), and 3G relied on wideband code division multiple access (W-CDMA). As 4G networks emerged, they utilized orthogonal frequency division multiplexing (OFDM), MIMO, and IoT-based schemes in their network operations [24][25][26][27].

With the advent of 5G, the standardization of new technologies has taken center stage: 5G networks incorporate extended LTE and various cutting-edge radio technologies, such as cmWave, mmWave, massive MIMO (mMIMO), radio access network (RAN), URLLC, mMTC, and extended mobile broadband services (eMBB) [19][28]. These innovations in 5G promise to revolutionize communication, offering unprecedented speeds and capacities that will power a new era of connectivity and enable a wide range of applications, from lightning-fast data transfers to reliable and ultra-low-latency services for critical systems and massive IoT deployments.

2.1. The First Generation (1G Analogue Technology)

During the first generation of mobile technology (1980–1990), data rates ranged from 1 Kbps to 2.8 Kbps, employing a circuit switch for communication. This era utilized analog phone service as its output technology, with a bandwidth of 40 MHz and a frequency range between 800 and 900 MHz, supporting only voice calls. The communication technique used during this time was FDMA [18].

Although it marked the initial steps in mobile communication, the first generation faced several limitations. Call quality was relatively low, and energy consumption was high. Users experienced poor voice connections, limited data capacity, a deficiency in security measures, and an unreliable transfer process [18][22]. Despite these drawbacks, the first generation laid the foundation for future advancements, paving the way for more sophisticated and capable mobile networks in subsequent generations.

2.2. The Second Generation (2G Digital Technology)

The foundation of 2G technology relies on the global system for mobile communications (GSM), primarily referred to as groupe special mobile, which was introduced in Finland in 1991. These networks marked a significant shift from analogue to digital cellular systems, providing substantial improvements over their predecessors, including enhanced standards and increased security [18].

The technologies of 2G marked the transition from analogue to digital communication networks, introducing encrypted services and data capabilities alongside voice services. This era brought features like SMS, and multimedia messaging services (MMS). Text messages were digitally encoded in the 2G realm, guaranteeing user privacy and data confidentiality during communication.

The advantage of digital encryption in 2G lies in its ability to protect data from being understood by unintended recipients. Three distinct types of 2G mobile techniques are available: FDMA, TDMA/GSM, and code division multiple access (CDMA). Each technique has different operational methods, characteristics, and terms [18][29]. These advancements in 2G technology laid the groundwork for further improvements and paved the way for more sophisticated mobile communication systems in subsequent generations. In the backend, this involved migrating away from a connection-oriented, public-switched telephone network to a packet-oriented network. Other functionalities allowed for structuring the network into a hierarchy that enabled mobility through handovers and roaming.

As in 2G, voice was the dominant service, the evaluation of user perception about performance and quality of service depended on the average opinion score (MOS). This subjective test was widely used in traditional telephone networks [30].

Following the advent of 2G, a subsequent iteration emerged known as 2.5G, a combination of 2G technology with general packet radio service (GPRS) and a set of novel attributes and functionalities. While retaining the foundational architecture of its predecessor, the 2.5G system embraced packet switching, departing from the circuit switching exclusive to prior generations and an IP-based core network. This evolution facilitated a surge in data transfer speeds, peaking at 144 kbps, propelled by advanced modulation techniques (GMSK and 8-PSK), a new encoding scheme (MCS-1 to MCS-9), and slot aggregation. The essential technologies characterizing this phase encompassed GPRS, and the enhanced data rate for GSM evolution (EDGE) was designated as 2.75G [31].

EDGE surpasses GPRS by accommodating three times the data subscribers or tripling the data rate for an individual user, achieved through a swift and economical implementation. Adding EDGE-capable transceivers and software is the sole requisite, aligning with WCDMA through the GERAN (GSM EDGE radio access network) standardization. Achieving data rates of up to 384 Kbps (downlink) and 60 Kbps (uplink), this system also supported functionalities like SMS, MMS, voice communication, and peer-to-peer (P2P) networking. EDGE aims to amplify system capacity for real-time and best-effort services, positioning itself as a foundational step towards 3G evolution and potential parity with other 3G technologies [31].

2.3. The Third Generation (3G)

In 2000, the 3rd Generation Partnership Project (3GPP) introduced the 3G mobile communication system, recognized as universal mobile telecommunications systems (UMTS) in Europe. The ITU-T refers to this standard as International Mobile Telecommunications-2000 (IMT2000), while, in the United States, it is called CDMA2000 [32].

The third generation of mobile transmission systems represents a significant leap forward, offering impressive speeds, to date, of up to 144 kbps up to 2 Mpps and beyond, ideal for high-speed mobile access and data transfer with internet protocol services. Certainly, 3G encompasses enhancements over its predecessors, focusing on features like “high-speed transmission, multimedia access, and global roaming capabilities” [18], improved QoS, and better voice call quality [32].

One of the primary applications of 3G is its widespread use in mobile phones and handheld devices, serving as a reliable means to connect these devices to internet protocol suite networks. This enables users to make voice and video calls, transfer data, and browse the web easily. The multimedia potential of 3G is evident, supporting full video streaming, video conferencing, and seamless internet access [33].

Data transmission in 3G networks is facilitated through a technology known as packet switching, which efficiently handles data packets, allowing for efficient data transfer. On the other hand, voice calls are handled using circuit switching for clarity and reliability. This modern communication process has evolved significantly over the past era, revolutionizing how we connect and communicate, and unlocking a world of possibilities for multimedia applications and seamless connectivity [18]. Exemplified by WCDMA, C2K, time-division synchronous CDMA (TD-SCDMA), and worldwide interoperability for microwave access (WiMAX), 3G has facilitated an array of data services encompassing video calls, internet access, and mobile television. Concurrently, there was a transformation in the network core toward the IP multimedia subsystem (IMS), introducing a perspective of data-switched communications using the session initiation protocol (SIP). This shift strengthened the connection between cellular network cores and the broader internet, enabling portable mobility across various radio interfaces.

The emergence of technologies like WCDMA, high-speed uplink/downlink packet access (HSUPA/HSDPA), and evolution-data only (EV-DO) led to the introduction of an intermediate wireless communication generation known as 3.5G, offering data rates ranging from 5 to 30 Mbps [31].

The transition in user engagement perception within 3G networks has altered the landscape of service evaluation in network management. Initially, network management and performance were contingent on quality of service (QoS) metrics, considering factors like delay, instability, and call drop rate. However, with 3G facilitating the integration of voice and multimedia content, the assessment of both the system and services now incorporates metrics rooted in quality of experience (QoE) [30].

2.4. The Fourth Generation (4G)

The introduction of 4G mobile communication in the late 2000s marked a significant advancement with its IP-based network framework. The primary goal of 4G innovations was to offer high-quality, high-capacity, cost-effective, and minimal-effort security administration services to voice, data, multimedia, and internet applications through IP services. This approach aimed to standardize all IP addresses, creating a unified platform for various technologies developed up to that point. It can support speeds ranging between 100 Mbps in mobile and 1 Gbps in nomadic mode, and it is all-IP with heterogeneous networks where multiple radio access technologies (RATs) or RANs interoperate since 4G networks deliver unparalleled performance [18]. The services of 4G include MMS, high-definition and mobile TV, digital video broadcasting (DVB), voice over IP (VoIP), multimedia on demand (MoD), gaming, and video chat [34].

To access the 4G mobile network, the user equipment must be equipped with multimodal capabilities to choose the most suitable wireless destination system intelligently. Terminal mobility played a crucial role in achieving the vision of wireless service anytime, anywhere, enabling seamless automatic roaming across different wireless networks (vertical handover, RAT handover). The 4G technology seamlessly integrated various existing and future wireless techniques, including MIMO antenna architecture, OFDM, the all-internet protocol (IP), Multi-carrier code-division multiple access (MC-CDMA), large area synchronous code-division multiple access (LAS-CDMA), network local multipoint distribution system (LMDS), reconfigurable systems, and the cognitive radio/network, providing users with the freedom to move and continuously roam between different technologies [3][18][35]. MIMO and OFDM technologies enable the reception and transmission capabilities of 4G. These technologies have alleviated network congestion by accommodating a more significant number of users through MIMO.

Long-term evolution (LTE) and WiMAX emerged as prominent 4G technologies. These innovative advancements played a crucial role in defining the 4G landscape and introducing novel communication prospects [18][36]. With smartphones and tablets becoming widespread, mobile communications have claimed a central role, providing substantial data throughput within 4G networks. Simultaneously, the transformative influence of accompanying information and communications technologies (ICTs) has been instrumental in reshaping society.

These modifications enabled the establishment of a fully packet-switched core, achieving speeds of up to 300 Mbps in the downlink (utilizing 4 × communications through four multiple-input multiple-outputs (MIMOs) with a 20 MHz allocation). The evolved packet core (EPC) played a pivotal role in creating a fully IP-based cellular network with mobility and billing management across various radio interfaces.

The 4G, known as LTE-advanced, witnessed substantial enhancements over LTE, particularly in access layer technology, resulting in a significant improvement in downlink rates (up to 1 Gbps). LTE-A facilitated the effective distribution of multimedia resources among the eNodeB, the evolved packet core (EPC), and content provider through multimedia broadcast multicast services (eMBMS). This innovation laid the groundwork for a novel business model founded on the LTE radio architecture [10].

Japan conducted the first successful field test of the fourth-generation technology in 2005, demonstrating its potential and setting the stage for the widespread adoption of 4G networks. The emergence of 4G technology revolutionized the mobile communication landscape, offering faster data rates and better performance and paving the way for more advanced services and applications in the mobile world.

An essential insight gleaned from the evolution is the emphasis on enhancing the mobile user experience by improving data rates. This shift involves aligning quality of experience (QoE) with a quality of service (QoS)-based approach in network management, distinct from isolated user perception considerations [30].

2.5. The Fifth Generation (5G)

In the realm of 5G research, there is a strong focus on advancing the “Worldwide Wireless Web (WWWW),” dynamic ad hoc wireless networks (DAWN), and other traditional wireless communication. Some of the most crucial techniques driving 5G technologies include 802.11 wireless local areas networks (WLAN), wireless metropolitan networks in urban areas (WMAN), ad hoc wireless personal area networks (WPAN), and other wireless networks to support digital communications. The introduction of 5G features has empowered portable devices with AI capabilities, unlocking new possibilities [18][36][37].

The wireless networks of 5G have brought about revolutionary technological concepts that bridge the gap between traditional IT domains and communication networks. Key innovations like cloudification and softwarization of networking technologies have enabled the deployment of a new range of use cases, services, and applications in wireless networks. From the physical layer’s mMIMO to the application layer’s machine learning (ML) technologies, 5G has significantly enhanced network capacities and capabilities. Despite these remarkable advancements, 5G still faces challenges in meeting the demands of emerging services like the IoE, primarily due to the intrinsic limitations within 5G systems [38][39]. During the initial deployment phase of 5G networks, operators and device manufacturers predominantly embrace the 3GPP 5G new radio (NR) standard, particularly in densely populated urban regions [40].

NR 5G enables mmWave spectrum access (24 to 100 GHz range), supplementing the initial sub-6 GHz spectrum commonly shared with 4G networks. The 20 Gbps requirement represents a substantial stride toward eMBB, alongside mMTC and URLLC. The advent of mMTC addresses the increasing reliance on IoT applications and aligns with IMT-2020 specifications for dense connectivity and low power consumption [30].

Operating within the 2–6 GHz spectra, the corresponding 5G network harnesses both mmWave and mMIMO technologies, albeit network densification initiatives might experience delays due to specific factors. Network slicing functionality plays a varying role in 5G mission-critical applications. The spectrum of services that benefit from 5G includes internet protocol television (IPTV), high-definition video streaming (HD-VS), high-speed mobility services, as well as foundational VR and augmented reality (AR) offerings.

Overall, 5G offers a high data transfer speed, very low latency, energy efficiency, and extensive connectivity. Its core services encompass eMBB to prioritize high throughput, capacity, and spectral efficiency; mMTC to deal with energy efficiency and massive connectivity; and URLLC to offer high reliability and low latency, to account for supporting diverse services [32][41]. To enhance user experience and network performance advanced technologies like mmWave, mMIMO, and device-to-device (D2D) communication are utilized. These innovations bolster both QoS and QoE for users [42].

Within 5G networks, softwarization facilitates the seamless instantiation of services across the entire network, ensuring resource allocation harmony and stability. This is supported by a two-tier cloud computing hierarchy, specifically the cloud edge, which divides physical network resources for various services such as eMBB, mMTC, and URLLC. The 5G core incorporates a network data analysis function (NWDAF) to address the growing reliance on resource sharing. This function plays a pivotal role in managing the increasing complexity of the network, particularly in executing autonomous policies or intent-based management [30].

The pursuit of 5G technology continues to push the boundaries of what is possible in wireless communication, and ongoing research aims to address the evolving requirements of an increasingly connected and data-driven world.

To meet the evolving demands for improved performance, portability, interoperability, elasticity, flexibility, reliability, scalability, and spectral and energy efficiency, the progression of mobile networks necessitates a software-driven approach [3][43], so the 5G core's softwarization capability allows the partitioning of functions into a layered architecture, showcasing remarkable flexibility. Key phases include virtualization—network function virtualization (NFV), service migration, orchestration, and service automation—like service function chaining (SFC) combined with software defined networking (SDN) [44], empowering network operators to maintain cost-effectiveness by minimizing both operational expenses (OPEX) and capital expenditures (CAPEX) [45], shaping the path to 5G and subsequent mobile paradigms [3]. As core and backhaul components of forthcoming mobile networks shift through software transformation, techniques like ultra-dense networks, mMIMO, and high-frequency communication play vital roles in enhancing wireless access networks. These advancements led to 5G's impressive 1000-fold capacity increase over its predecessor [3][37]. Key performance requirements for 5G encompass data rates of 1 to 10 Gbps, 1 ms RTT latency, heightened capacity for numerous connected devices via wide bandwidth channels, exceptional availability, pervasive connectivity, and a substantial 90% reduction in energy consumption to enhance battery life [3].

The 5G-PPP project introduces a comprehensive five-layered structure comprising infrastructure, network/control, orchestration, business, and services to establish the functional architecture of 5G. Within this framework, the orchestration layer is distributed across the other layers, and the services layer extends from the business layer [46][47]. The infrastructure layer embodies the RAN connectivity aspect, featuring RATs like non-orthogonal multiple access (NOMA), mMIMO, and coordinated multi-Point (CoMP) transmission to facilitate interface with high-data-capacity small-cells, and mmWave technologies. The control layer oversees network management, while the business layer is responsible for managing network and business services [3][48][49].

Nonetheless, the services offered by 5G are insufficient to effectively tackle the evolving needs of various applications, including health technologies and emergency scenarios. In the realm of health services, 5G plays a role by establishing internet connectivity for internet of medical things (IoMT) devices such as wearables and wireless body area networks (WBAN), along with internet of bio-nano things (IoBNT) via mMTC. It also facilitates superior video quality for telemedicine and AR/VR through eMBB, while simultaneously supporting unmanned aerial vehicles (UAV), unmanned ground vehicles (UGV), and autonomous vehicles through URLLC. Nevertheless, these technologies still have some limitations regarding privacy and security, ubiquitous communications in locations with poor infrastructure, connectivity for ultra-dense IoMT devices, and highly reliable and low-latency communications [41][50].

The 5G technologies offer ultra-reliable, low-latency communications. Still, its short-packet, sensing-based URLLC features hinder ultra-reliable, low-latency services with data-intensive applications like AR, mixed-reality (MR), and VR. The growing number of internet of everything applications calls for integrating communication, sensing, control, and computing functionalities, which are often neglected in the 5G context [16].

Recent progress enables the utilization of ML for tasks like radio-frequency (RF) signal processing, spectrum analysis, and RF spectrum mapping [51][52]. This integration of AI offers substantial support for precise capacity predictions, automated coverage optimization, efficient network resource scheduling, and network slicing.

Ongoing initiatives in 5G networks focus on developing standardized mappings of quality of experience (QoE) to network performance indicators. A notable challenge lies in transitioning from a management perspective rooted in quality of service (QoS) to one centered on QoE. The QoS viewpoint, being restrictive, confines network management to performance metrics like flow or packet priority, delay, jitter, bandwidth, etc., providing users with information about DiffServ/IntServ. Therefore, it remains crucial to further articulate the assumptions linked with QoE in a more comprehensive manner aligned with the functionalities and services provided by 5G [30].

The deployment of 5G networks will occur progressively, with the initial phase involving a modification in the radio interface. This involves linking 5G NR to the 4G network's EPC, termed the non-standalone phase. In the standalone phase, 5G NR will connect to the 5G core, enabling a dual-interface phone to execute handovers (or roaming) between the two networks.

eMBMS utilizes MIMO technology to deliver multicast/broadcast media content, ensuring a superior quality of experience (QoE), including high-definition video streaming for consumers. The introduction of 5G NR brings novel functionalities aimed at enhancing QoE, incorporating the integration of network slicing, edge computing, and 5G QoS Flow concepts [10].

3. Background and Current Development of 6G

The upcoming sixth-generation communications networks are poised to make a monumental leap beyond the capabilities of 5G, driven by the ever-evolving requirements of future services and societies. This transformative shift will revolve around processes that are data-centric, intelligent, and automated [53]. The progress of disruptive technologies across diverse domains will come together to meet the requirements of emerging applications and use cases [39].

The 5G Infrastructure Association (5GIA) envisions the next system generation, 6G, operating with flexible and on-demand infrastructure for mobile telecommunications systems [1]. It is anticipated that 6G will address various challenges and create an ecosystem deeply intertwined with artificial intelligence. The architecture of 6G should be sufficiently flexible and efficient, facilitating the integration and self-aggregation of connectivity and computing capabilities dynamically, heterogeneous types of resources of diverse elements such as a network of networks, joint communication and sensing, terrestrial and non-terrestrial networks, and novel AI-driven capabilities, including also local and distributed computing resources. The 6G framework is envisioned as a resource-as-a-service (RaaS), extending beyond bandwidth, time, power, and space considerations, emphasizing the imperative of optimizing infrastructure as a flexible and configurable resource tailored to meet distinct service demands. Furthermore, with the capabilities of dynamic network infrastructure management and service orchestration mechanism together, artificial intelligence (AI)-aware networking approaches, 6G can be viewed as an infrastructure-as-a-service (IaaS) [54][55]. The 5GPPP Architecture Working Group [56] states that to obtain its full potential, 6G needs to be AI- and computation-pervasive, which calls for the 6G architecture to be data-driven to enhance the optimization of its air interface—spanning physical layer setup, mobility management, resource allocation, and QoS guarantee, achieving a powerful and robust distributed AI platform, i.e., approaching the 6G network as AI-as-a-service (aIaaS). Because it is generally accepted that 6G systems necessitate the development of a strategy for the delivery and dissemination of services through a cloud-based framework to users and 6G applications [57], it is proposed that this objective can be achieved through an expanded interpretation of existing cloud-based service orchestration concepts, allowing for the organization and integration of diverse services to cater to the requirements of all types of 6G user applications, i.e., seeing 6G architecture as everything-as-a-service (EaaS).

The architects of the 6G network strive to supplant wired connections, ensuring reliability across diverse connectivity scenarios. These scenarios span from stationary, isolated devices to dynamic mobile groups, all of which necessitate seamless communication both among themselves and direct connectivity to the primary network. In other words, 6G is poised to build upon the techniques of the 5G systems while introducing advanced components such as enhanced RAT, terahertz (THz) communication [58][59] with abundant spectrum resources, molecular networking concepts, and integrated aerial and inter-terrestrial networks, urban air mobility (UAM), UAV, high-altitude platform stations (HAPS) and satellites of systems in low earth orbit (LEO) and geostationary orbit (GEO) [28][60][61][62], uncoordinated networks and the co-existence of RF—FM, TV, WiFi, visible light communication (VLC), energy-efficiency, and communication environment intelligence, ambient backscatter communication (AmBC) for energy savings, symbiotic communication radio, reconfigurable intelligent surface (RIS) for non-line-of-sight (nLoS) scenarios, a holistic security paradigm, physical layer security (PLS), and blockchain (BC) [63][64]. RIS equipped with computing resources seems to be a promising solution to dynamically reconfigure physical parameters for enhancing wireless system design and optimization. Their adaptability allows for improved signal propagation, channel modeling and acquisition, and creating intelligent radio environments that are advantageous for 6G innovative applications, i.e., the electromagnetic environment can be reshaped as needed.

Envisioned as a remarkable platform, 6G aims to integrate diverse network policies, devices, and algorithms, fostering cognitive-aware, user-centric mobile operations and mitigation strategies [14].

It is expected that 6G will demand an extensive spectrum allocation to support future mobile operations. Unlike the current range of existing 5G bands, which relies on mMIMO orchestration, which falls within the 1–30 GHz range, 6G is projected to rely on cell-free m-MIMO and utilize a spectrum extending from IR and visible light and 30–300 GHz, mmWave, or even beyond, THz wave, for its operations and for delivering efficient user-centric services [5][11][65].

The development of novel access methods is imperative to support extensive multiple access techniques in 6G. Among the noteworthy approaches from the literature review, researchers can underscore delta-orthogonal multiple access (D-OMA), filter bank multi-carrier (FBMC), and sparse code multiple access (SCMA). The D-OMA strategy leverages distributed large CoMP concepts, facilitating NOMA transmission through partially overlapping sub-bands within NOMA clusters [66]. SCMA prioritizes overall sum rates in cloud radio access network (C-RAN) scenarios, employing single-input single-output (SISO) systems and a low-complexity algorithm that considers individual user QoS, user association, and power constraints [67]. FBMC, compared to conventional OFDM systems, boasts diminished spectral side-lobes, granting it the capability for asynchronous transmission [68].

Novel breakthroughs in terahertz and optical communications will be crucial in unlocking unprecedented data transfer and communication speeds. Additionally, cell-less or poor coverage areas through integrated terrestrial satellite access technologies [69] will ensure seamless connectivity across vast areas, extending the reach of communication networks to remote and challenging locations [39].

The advent of 6G technology is set to profoundly reshape the landscape of communication progress, encompassing intelligent, deep, holographic, and pervasive connectivity, thus profoundly shaping the evolution of the intelligence process within communication [2].

Distributed end-user terminal-based AI [43][70] will bring intelligence and decision-making capabilities closer to the user, enabling personalized and context-aware services. Moreover, the integration of distributed ledger technologies (DLTs) [71] will enhance security, transparency, and efficiency in data handling and transactions across the network to fulfill the needs of emerging applications [39]. On the other hand, AI holds the potential to [4] enhance handover operation performance by considering network deployments and geographic conditions; optimize network planning by determining base station (BS) locations; lower network energy consumption; forecast, identify, and facilitate self-healing of network irregularities; predict channel coding for more extensive bit sequences, establishing resilient synchronization to meet 6G prerequisites, facilitating mobile positioning in nLoS environments with multiple paths, conducting non-linear and non-stationary channel estimation, and implementing adaptive, RT mMIMO beamforming to represent pivotal ML applications within the physical layer. DLT technologies drive the urgency for an intelligent self-organizing network (SON) capable of managing network operations, resources, and optimizations. So 6G will have to guarantee the transition from traditional SON, which adapts functions automatically to environment states, to a self-sustaining network (SSN). This SSN concept ensures continuous maintenance of key performance indicators (KPIs) within the intricate and dynamic environments spawned by diverse 6G application domains [72]. With regard to the 6G cellular network, the integration of connected robotics and autonomous systems (CRAS) and DLTs devices will necessitate the obligatory incorporation of SON and SSN. These mechanisms will be pivotal in governing network operations, resource allocation, and optimization.

As these diverse technologies converge, sixth-generation networks will usher in a new era of interconnectedness, empowering forthcoming services and societies with cutting-edge capabilities and revolutionizing how we interact, communicate, and utilize data. The journey towards 6G is set to push the boundaries of communication technology, shaping a more intelligent, efficient, and connected world. In short, 6G is poised to emerge as an authentic AI-driven communication network, imbuing the whole system with self-awareness, autonomous computation, and the capability to make independent decisions in various scenarios.

The potential of 6G lies in providing network performance that surpasses the limits perceivable by human senses. Quality of experience (QoE) is inherently connected to quality of service (QoS) measurements, and the state of the network is intertwined with and influences user experience. However, a crucial challenge is to shift the perspective from considering the network as the primary determinant in assessing QoE [30].

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