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The 6G Ecosystem as Support for IoE and Private Networks: Vision, Requirements, and Challenges

Carlos Serôdio [1,2,3], José Cunha [1,4], Guillermo Candela [4], Santiago Rodriguez [4], Xosé Ramón Sousa [4] and Frederico Branco [1,5,*]

[1] Department of Engineering, School of Sciences and Technology, Universidade de Trás-os-Montes e Alto Douro, 5000-801 Vila Real, Portugal; cserodio@utad.pt (C.S.); jcunha@optaresolutions.com (J.C.)
[2] Center ALGORITMI, Universidade do Minho, Campus de Azurém, 4800-058 Guimarães, Portugal
[3] CITAB, Universidade de Trás-os-Montes e Alto Douro, 5000-801 Vila Real, Portugal
[4] Optare Solutions, Parque Tecnológico de Vigo, 35315 Vigo, Spain; gcandela@optaresolutions.com (G.C.); srodriguez@optaresolutions.com (S.R.); xrsousa@optaresolutions.com (X.R.S.)
[5] INESC TEC—Institute for Systems and Computer Engineering, Technology and Science, 4200-465 Porto, Portugal
* Correspondence: fbranco@utad.pt

Abstract: 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. To support this connectivity, mission-critical applications are emerging with challenging network requirements. 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. In attaining its objectives, 6G faces challenges that demand inventive solutions, incorporating AI, softwarization, cloudification, virtualization, and slicing features. Technologies like network function virtualization (NFV), network slicing, and software-defined networking (SDN) play pivotal roles in this integration, which facilitates efficient resource utilization, responsive service provisioning, expanded coverage, enhanced network reliability, increased capacity, densification, heightened availability, safety, security, and reduced energy consumption. It presents innovative network infrastructure concepts, such as resource-as-a-service (RaaS) and infrastructure-as-a-service (IaaS), featuring management and service orchestration mechanisms. This includes nomadic networks, AI-aware networking strategies, and dynamic management of diverse network resources. This paper provides an in-depth survey of the wireless evolution leading to 6G networks, addressing future issues and challenges associated with 6G technology to support V2X environments considering presenting +challenges in architecture, spectrum, air interface, reliability, availability, density, flexibility, mobility, and security.

Keywords: 6G; IoT; IoE; private networks; V2X

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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 ($\geq$1 Tbps), very high operating frequencies ($\geq$1 THz), very low latency times ($\leq$1 ms), extremely high reliability (10^{-9}), high mobility ($\geq$1000 km/h), and wavelengths within the range of $\leq$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. This paper adopts an approach that defines the characteristics of both a network-centric system and an end-to-end system. Quality of experience (QoE), in which the latter serves as the benchmark for high quality, and driven by user-centric communications, addressing the whole user experience. QoE refers to the extent of user satisfaction or dissatisfaction with an application or service. The assessment, representation, prediction, and utilization of QoE play a crucial role in evaluating the overall performance of the relationship between the user and the system or service. This process hinges on various dimensions, including user experience, technology, context, environment, application, resources, and network QoS impairments [11,12].

This will be realized through augmented reality, virtual reality, holographic communications, and the tactile internet, which necessitate very high data rates coupled with exceptionally low latency.

Discussions and research on 6G requirements are abundant [13–15], 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 [16]. 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) [17]. 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) [18].

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 [14]. We also have some use cases related to local hazard and traffic information, hazard information collection sharing, basic safety, intersection safety, sensor sharing, and tele-operated driving (ToD) including AVP [19]. This paper, we will dive into two of these use cases: (i) vehicle operations management (i.e., vehicular software update, one of its particularizations) and (ii) the cooperative adaptive cruise control (CACC) use case regarding safety [20].

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 [19]:

- *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 topogra-

phies. 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 [19]:

- *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.

This survey and comprehensive analysis explore the significant advancements introduced by 6G technology, comparing them to preceding 5G technologies. It assesses crucial aspects like data rate speed, system capacity, latency, and additional enhancements such as optimal coverage for very high-mobility, mobile edge computing, augmented reality (AR) facilitation, and enhanced connection reliability. Additionally, the paper delves into the pivotal enabling technologies essential for 6G support development environments based on V2X, evaluating feasibility, advantages, challenges and, consequently, implementation solutions.

This paper is organized as follows: Section 1 provides a concise overview of 6G technology, emphasizing key features and the V2X roadmap. Additionally, Section 2 reviews the cellular systems evolution from 1G to 5G, while Section 3 presents the background and ongoing evolution of 6G. Section 4 examines the requirements and enabling technologies of 6G, and Section 5 explores the broad applications of 6G, detailing its impact on healthcare, high-performance precision agriculture, intelligent transportation systems, and logistics and supply chains. In Section 6, the focus shifts to the impact of 6G communications infrastructure and technology on supporting the V2X applications addressing critical evaluation, challenges for the future and implementation solutions. Finally, Section 7 offers a comprehensive conclusion.

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 [21]. 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 [22].

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 [22]. 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 [23,24].

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 [22].

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 [25,26].

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 [27–30].

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) [22,31]. 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 [21].

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 [21,25]. 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 [21].

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 [21,32]. 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 [33].

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 [34].

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 [34].

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 [35].

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" [21], improved QoS, and better voice call quality [35].

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 [36].

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 [21]. 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 [34].

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) [33].

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 [21]. 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 [37].

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 [3,21,38]. 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 [21,39]. 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 $\times$ 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 [33].

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 [21,39,40].

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 [41,42]. 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 [43].

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 [33].

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 [35,44]. 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 [45].

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 [33].

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 [3,46], 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) [47], empowering network operators to maintain cost-effectiveness by minimizing both operational expenses (OPEX) and capital expenditures (CAPEX) [48], 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 [3,40]. 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 [49,50]. 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 [3,51,52].

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 [44,53].

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 [18].

Recent progress enables the utilization of ML for tasks like radio-frequency (RF) signal processing, spectrum analysis, and RF spectrum mapping [54,55]. 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 [33].

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 [56]. The progress of disruptive technologies across diverse domains will come together to meet the requirements of emerging applications and use cases [42].

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) [57,58]. The 5GPPP Architecture Working Group [59] 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 [60], 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 [61,62] 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) [31,63–65], 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) [66,67]. 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 [16].

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 [5,13,68].

The development of novel access methods is imperative to support extensive multiple access techniques in 6G. Among the noteworthy approaches from the literature review, we 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 [69]. 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 [70]. FBMC, compared to conventional OFDM systems, boasts diminished spectral side-lobes, granting it the capability for asynchronous transmission [71].

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 [72] will ensure seamless connectivity across vast areas, extending the reach of communication networks to remote and challenging locations [42].

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 [46,73] 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) [74] will enhance security, transparency, and efficiency in data handling and transactions across the network to fulfill the needs of emerging applications [42]. 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 [75]. 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 [33].

4. The Requirements of 6G

The emergence of 5G has ushered in remarkable technological achievements, distinguished by exceptional transmission speeds, minimal latency, efficient power usage, and a wide-reaching connectivity capability. This innovation stands ready to serve many purposes, from individual consumers to various sectors and industries. This transformative progress takes form through three central scenarios: eMBB, mMTC, and URLLC [2,76,77].

It is anticipated that 6G will attain data rates of 1 TBPS or higher. Diverging from the two-dimensional communication structure of 5G and B5G, 6G will adopt a three-dimensional approach encompassing time, space, and frequency. Emerging technologies like edge computing, AI-aware, cloud computing, and blockchain will support this novel paradigm. The communication network of 6G is projected to be seamlessly integrated and omnipresent [78].

Envisioned as a comprehensive solution, 6G is poised to expand coverage extensively, spanning device-to-device, terrestrial, and satellite communications. The overarching objective is to fuse computation, navigation, and sensing within the communication network. Furthermore, in the core of security, 6G aims to address safeguarding, secrecy, and privacy of the vast amounts of big data generated by countless smart devices [79].

The architecture of the 6G communication network must address challenges stemming from the constrained computation capacity of mobile devices. A potential solution is offloading computation tasks to more potent devices or servers. The network demands hyper-fast data rates and ultra-low latency to facilitate real-time computation task offloading.

The specifications for the end-to-end latency, radio delay, and processing in 6G are defined as $\leq$1 ms and $\leq$10 ns, respectively, ensuring real-time communication. Additionally, 6G is positioned as an authentic AI-driven communication technology [14]. The integration of satellite technology will be fundamental to 6G's capabilities. Furthermore, intelligent radio (IR) is anticipated to replace NR-Lite [80].

Anticipated to bring about a fully interconnected global environment, 6G is projected to establish a heterogeneous network that encompasses ground, air, space, maritime, and underwater communications. Enhanced by AI capabilities, artificial intelligence (AI)-driven communications will develop in a way that "the 6G is about the 6th sense" [81]; the network entities within 6G will possess the ability to perceive and dissect multi-dimensional data, thereby enabling the effortless interlinking of terrestrial devices and onboard systems. The incorporation of pervasive artificial intelligence allows the achievement of large-scale network automation. In the age of 6G, each edge device is anticipated to be connected to the internet and regularly employ AI software. Many AI applications rely on data, raising concerns about the security and privacy of the collected information [82].

The autonomous management capability of 6G systems is improved to meet diverse application requirements, such as MBBLL, mBBMT, and mLLMT communications [16,83]. Furthermore, other proposals indicate that the path to this evolution will also pass through the focus on feMBB, ERLLC, umMTC, LDHMC, and ELPC [17]. The upcoming 6G service classes of uMUB, uHSLLC, and uHDD stem from eMBB, URLLCs, and mMTC, mobile broadband reliable low-latency communication (MBRLLC), massive URLLC (mURLLC), human-centric services (HCS), multi-purpose services (MPS) [18,75]. As the spectrum of requirements continues to broaden, 6G envisions the rise of more sophisticated service categories that are shaped by clustering applications with comparable needs, such as big communications (BigCom), secure ultra-reliable low-latency communications (SuRLLC), unconventional data communications (UCDC), and three-dimensional integrated communications (3D-InteCom) [84]. These classes, respectively, provide extensive coverage and performance across diverse domains; ultrahigh rates with low latency, and high data density with ultra-reliability.

These technologies enhance robust communication infrastructure, ensuring ultra-massive connectivity, extreme reliability, and connection continuity, enabling pervasively intelligent, reliable, scalable, flexible, adaptable, and secure terrestrial wireless. Hence, 6G systems require a cellular communication redesign that offers exceptional flexibility, surpassing the existing scope through three key strategies: (i) leveraging various sensing mechanisms, including artificial intelligence (AI), to comprehend diverse facets of the communication network and environment, (ii) improving or revolutionizing technology options, and (iii) achieving optimal resource utilization by considering real-world sensing capabilities alongside awareness.

Quality, performance, and alignment with the specifications of 6G communication systems are evaluated by establishing key performance indicators (KPIs). These KPIs are currently in the process of formulation and finalization by entities like the ITU Telecommunication Standardization Sector (ITU-T) and various industry stakeholders. Although still under development, the existing literature points to several overarching areas often taken into account [66]:

- *Data Rate and Capacity:* associated with system throughput. Measures of how much data can be transferred within a given time interval, reflecting the high-speed, high-capacity, peak and experienced spectral efficiency, maximum channel bandwidth, traffic capacity per geographic coverage area, and connection density. Must be fulfilled at 95% of all user locations. QoS and QoE will manage trade-offs between data transmission capacity or spectral efficiency and other concurrent metrics like energy efficiency and service latency.
- *Latency:* Defines the end-to-end latency and jitter, aiming for ultra-low latency to enable delay-sensitive real-time applications.
- *Reliability:* Defined by the metric for the duration of uninterrupted operation of infrastructure, and related to the orchestration and management of networks, ensuring robust and dependable communication, especially for critical applications like remote surgery or autonomous vehicles.
- *Energy Efficiency:* Focus on reducing energy consumption to prolong device battery life and promote sustainability.
- *Coverage:* Ubiquitous mobile ultra-broadband will be available everywhere, extending connectivity to remote and underserved areas, potentially through satellite networks.
- *Spectral Efficiency:* Maximizing data transmission over limited frequency bands.
- *Mobility Support:* Seamless communication while moving at high speeds, such as in high-speed trains or vehicles.
- *Connection Density:* Accommodating a high, or even a massive, number of devices within a certain geographic area is important for the IoT.
- *Security and Privacy:* Implementing strong security procedures to protect users and data.
- *Sustainability:* Ensuring that 6G networks and devices are environmentally sustainable and minimize their ecological footprint.

A 6G network requires a service-based end-to-end (E2E) architecture with key roles played by software-defined networking (SDN), network function virtualization (NFV), and network slicing. These technologies enhance network programmability, enabling the creation of multiple logical networks on a shared physical infrastructure. Anticipated benefits include higher data rates, improved spectral and energy efficiency, broader coverage, wide bandwidths, extremely high reliability, ultra-low latency, and dynamic QoS management across all network segments. Dynamic QoS management is crucial for flexible network resource utilization. However, common SDN implementations often statically provide required QoS through resource reservation based on predefined rules in forwarding engines, mapping packets into existing queues with assigned priorities [85,86].

4.1. Network Architecture

In the future, networks are expected to integrate diverse RAN technologies, including macro and small cells with high-capacity short-range links. The extensive use of AI/ML is foreseen to enhance network performance as a service across applications, impacting air interface design, data processing, network architecture, and management for superior performance. The 6G era will bring a new network architecture paradigm, decomposing the system into platform, functions, orchestration, and specialization for increased efficiency. The convergence of RAN and core networks aims to reduce complexity, while dynamic offloading and flexible instantiation of sub-networks drive increased specialization. Future scenarios rely on a flexible, scalable, secure, and reliable transport network accommodating distributed and centralized/cloud RAN with AI-powered programmability. The 6G network-of-networks will cover various scales of physical and virtual networks to address local and specialized needs [59].

The technology of 6G must be prepared to enable the IoE, ensuring connectivity for multiple smart devices across its communication network, including every smart device, from small and compact gadgets like smartwatches and smartphones to expansive applications such as mobile healthcare, robotics, and vehicular communications systems. The IoE, eMBB, and mMTC services will intricately link these devices to one or more interfaces of wireless networks based on different technologies equipped with numerous access points (APs) or base stations (BS) that will be strategically positioned in high-density or ultra-dense configurations within the 6G network, generating overlapping coverage areas, which results in a need for the management and efficiency in frequency spectrum allocation, management and minimization of interference, handoff efficiency, and the use of transmission multiplexing or transmission coordination. All this results in a distributed, cell-less massive MIMO network topology. The infrastructure must ensure access to cloud computing services or multi-access edge computing to support services.

Assuming that the 6G data-rate requirement is about 1 Tbps [83] to enable applications like [6] smart cities, smart electric cars, smart healthcare, and virtual/augmented reality, among others, the system must be focused on QoE and provide an extremally high data-rate and low latency. To achieve QoE, it needs low latency, which will be obtained through small data packets and reliable transmission served by efficient forward error correction (FEC) schemes, high-level diversity channels, efficient control algorithms, neighbor-discovery algorithms, and efficient MAC protocol over a flat network architecture [14]. To increase reliability, 6G must enhance the URLLC of 5G to obtain ERLLC.

The requirements grow exponentially for the transition from 5G to 6G. Many features of 6G may be constrained or hampered by the current underdeveloped technology that could dramatically evolve 5G technology to 6G. Indeed, the network's optimal utilization can be achieved through softwarization. Substantial enhancements are imperative within software-defined radio (SDR), SDN, and NFV of 5G technology to attain the objectives of 6G. For instance, as 6G is a truly ubiquitous and distributed AI-driven communication technology, from the physical layer to the application layer, AI will have to be deployed in all 5G layers [48,87]. Softwarization, cloudization, virtualization, and slicing remain crucial attributes of autonomous networks. Consequently, SDN, NFV, and NS continue to constitute a significant toolkit for shaping the design of 6G. The synergy of AI-enabled with SDN/NFV/NS culminates in dynamic and zero or self-network orchestration, optimization, and administration. AI-enabled network orchestration adeptly manages network infrastructure, and slices and harmonizes diverse radio access technologies, resulting in liquid networks catering to ever-evolving service needs. AI-enabled network optimization continuously monitors KPIs in real time, swiftly adapting network parameters to ensure an exceptional QoE.

In 6G, native-AI will significantly influence the network's physical layer, enhancing tasks such as estimation or prediction of channel conditions, modulation classification, adaptative coding, and security [54,88]. Deep reinforcement learning will be employed for resource allocation at the data link layer [89], while the transport layer will see the application of algorithms for route computation and intelligent traffic prediction [16]. The design of 6G should aim for a genuine convergence of communication and computing, enabling users' diverse devices to tap into the network's available computational resources effortlessly.

The H2020 EU-funded Hexa-X proposes an architecture based on three layers: infrastructure, network service, and application [59]. The infrastructure layer, which provides physical resources to host network service and application layer, incorporates network RAN, network CN, and transport networks based on radio equipment like non-virtualized radio functions such as radio units (RUs), distributed units (DU), and BS, switches, routers, communication links, data centers, and cloud infrastructure. Based on the new features of RAN enhancements, it enables a high data rate, extremely low latency, high reliability, availability, high capacity, affordable coverage, high energy efficiency, high localization accuracy, and integrated sensing functionalities. Within the framework of 6G architecture, a diverse array of (sub)network solutions converge to form a comprehensive network of networks. This dynamic structure possesses the innate ability to conform to novel topologies readily and flexibly, effectively addressing the demands for exceptional performance and extensive global service coverage.

The 6G network service layer is designed with a foundation in the cloud and microservice-based technology, utilizing services that span from the central cloud to the far edges, encompassing devices beyond the RAN. This expansion of microservices across network functions, operations, and applications lays the groundwork for a softwarised, AI-driven, and efficient 6G architecture. To create an intelligent network, support for AI in 6G and AIaaS is crucial, alongside advancements in programmability and network automation. Embracing a cloud-native approach further simplifies RAN and CN architectures, reducing complexity by eliminating redundant processing points for specific messages and minimizing duplication of functionalities among functions. In the era of 6G, there is a significant and anticipated focus on merging the functionalities of both 5G RAN and its core components. This consolidation aims to streamline functional elements, culminating in a core-less RAN structure that offers enhanced precision in the user plane [64]. Cloud-native technologies will be crucial in establishing edge-based cloudlets, enabling seamless communication between applications and functions. This capability will serve many interconnected assets while accommodating dynamic and flexible mesh topologies to deal with the highly heterogeneous network of devices and technologies, encompassing variations in both hardware and software.

Security and privacy mechanisms are intrinsic components of the comprehensive architecture, impacting every network layer along with the management and orchestration domain [59].

Pursuing the elevated spectrum and energy efficiency mandates the integration of novel air interface and communication technologies. This encompasses the adoption of new waveforms, diversified multiple-access methods, advanced channel encoding techniques, multi-antenna technologies, and the strategic amalgamation of these diverse approaches. Concurrently, evolution necessitates innovative network architectures. These include paradigms like SDN and NFV, dynamic network slicing (DNS), service-based architecture (SBA), cognitive service architecture (CSA), and cell-free (CF) architectures.

The 5GPPP Architecture Working Group proposes an architecture based on a multi-dimensional approach, with five horizontal layers [59]: infrastructure and environment, user plane network functions, control plane network functions, the management plane, and vertical service providers. It has a vertically designated orchestration profile which deals with responsibilities related to: the network intelligent stratum, security stratum, sensing stratum and network stratum. The network intelligence stratum coordinates functions across the entire network, managing network functions intelligently and autonomously through data and analytics gathered from the infrastructure and environment layer. The security stratum oversees all cybersecurity and data privacy aspects throughout the network, coordinating functions across planes and domains, up to the vertical service provider by distributed data and AI/ML pipelines, with automated closed-loop network operations and orchestration to meet end-to-end service KPIs.

The cloudification trend is anticipated to persist in 6G, introducing innovative network designs, such as cloud-optimized procedures that involve network functions (NFs) capable of accessing network information with minimal hierarchical interactions [90].

AI is projected to optimize 6G communication and operate as AI-as-a-service across various network entities and layers of the radio stack. The potential applications of AI include optimizing the physical layer, mobility algorithms, network management, QoS, and more. As 6G approaches, the trend involves deeply integrating AI as a fundamental enabler for communication, influencing the behavior and communication of network components, in contrast to its role in previous generations as a tool for parameter optimization.

4.2. Spectrum

The realm of 6G spectrum management can be distinguished into two primary categories of challenges: the efficient reuse of spectrum and the adoption of either novel spectrum bands or innovative transmission technologies. For the reuse part, techniques similar to 5G can be used, sharing temporally underutilized spectrum to maintain the availability and reliability [5], or communications can be conducted using cognitive radio (CR) techniques [73] and, in this case, the devices can access a shared or underused spectrum using interference detection and allocation management mechanisms. Another innovative technique of spectrum sharing is symbiotic radio (SR), which supports and bolsters intelligent and diverse wireless networks while enhancing the effectiveness of spectrum sharing in a mutualistic and competitive way [91,92]. The efficiency of THz signals can be enhanced through spectrum reuse and sharing strategies. Among the techniques available for spectrum sharing and reuse, CR stands as a notable example. When considering spectrum sharing, temporally underutilized or unlicensed spectrum upholds availability and dependability. A novel SR technique has emerged to facilitate intelligent and diverse wireless networks.

The promise is that 6G will be based on THz communications, meaning high-frequency communication and a high data rate. However, the THz signal could be either a pulse or continuous type, but 6G transmission needs a continuous wave THz signal, which is very difficult to generate and comes at the expense of greater complexity in antenna/transmitter design. This presents a paradox as generating THz signals is costly, whereas 6G asserts to provide low-cost communication services.

However, other communication techniques are being considered: VLC uses light-emitting diodes (LEDs) to achieve high-frequency (HF) bands [93]. Nonetheless, VLC has some constraints in terms of coverage and noise interference [94], whereby its application within confined spaces devoid of interference from other light sources. Molecular communication [64,65], whose signals are biocompatible, has low energy consumption because needs low power to obtain the signal as well as for transmission, and can support high data rates [95]. In quantum communication, based on the application of quantum principles, information is encoded and stored in a quantum state (utilizing photons or quantum particles) and cannot be retrieved or copied without causing changes to the data, making it a major challenge for them to be accessible by unauthorized entities. This approach offers notable benefits, including robust security, high data rates, and efficient long-range transmission capabilities. However, this technique is still at an embryonic stage [95]. Overall, 6G offers an intelligent eco-system enabling a wireless propagation environment with active signal transmission and reception and an all-spectrum reconfigurable dynamic spectrum access [66]. A comprehensive hyperspectral and full-spectral system is anticipated, encompassing a spectrum ranging from visible light, microwave, mmWave, and terahertz frequencies to laser-based free-space optical communication.

5. Use Cases and Applications

Leveraging the power of current and upcoming wireless networks, 6G holds immense potential to enable a wide range of applications, particularly for energy-efficient devices reliant on symbiotic communication. This is especially pertinent in regions densely populated with passive sensors, offering effective harnessing of their capabilities. Additionally, 6G's role extends to serve various sectors such as building and factory automation, manufacturing, e-health, intelligent transport systems (ITS), smart and precision agriculture, surveillance, and the smart grid. These applications are vital components of Industry 4.0, anticipated to drive profound paradigm shifts.

5.1. Healthcare

Envisioned as a catalyst for progress in healthcare, 6G technology is poised to revolutionize robotic-assisted surgery, telemedicine, and integrate interconnected devices for deep-body implants. These medical applications necessitate the seamless collection and transmission of continuous health data, predominantly supported by low-power, battery-operated wireless devices, and sensors.

Wireless data transfer in medical devices, facilitated by active radios, can substantially deplete battery life. However, these devices have the potential to harness the signals of pre-existing wireless systems, such as WiFi APs found in hospitals or residential environments, to ensure reliable communication without draining power. Additionally, medical devices often transmit data to centralized servers, necessitating a localized network gateway. In the context of using symbiotic radio solutions, medical devices can effectively transmit their information online via WiFi, further streamlining the communication process [44,96].

Holographic teleportation emerges as the inherent evolution from AR and VR-based solutions. It stands apart by functioning within a genuine three-dimensional domain and harnessing all five senses—sight, hearing, touch, smell, and taste—to deliver an unparalleled immersive experience. This advancement finds diverse applications, particularly in advanced healthcare, encompassing remote diagnosis, telemedicine and surgery, high-resolution sensing for distant exploration, and lifelike video conferencing. However, 6G must evolve in a way that guarantees very high throughput (Tbps) and ultra-low latencies (<1ms), which can be obtained in the new design of eMBB and URLLC [66].

Current transport network architecture is ill-equipped to handle the required $\leq$1 ms latency, which requires a profound re-evaluation of network design. The solution will involve virtualizing the existing fiber infrastructure, facilitated by modern SDN and virtualization techniques and methodologies. Simultaneously, the main functions of the network will be structured in a microservices architecture capable of dynamic activation.

5.2. High-Performance Precision Agriculture

The synergy between environmental data collection and agriculture finds realization within an IoT-driven ecosystem. In precision farming, IoT devices and sensors are strategically positioned on plants, such as within intelligent greenhouses, to facilitate data acquisition. The paramount requirements for these devices include compact size, energy efficiency to enable ultra-dense deployment, and prolonged operational longevity [91].

Existing communication technologies for wireless sensor networks, for example, IEEE 802.15.4-based protocols, are energy-intensive and large, so they can be combined with nano UAVs or UGVs to support real-time and high-performance precision farming applications for online crop or soil monitoring tasks. Creating this communications scenario, focused on symbiotic communications and ubiquitous wireless access, between traditional WSNs, cellular and UAVs, or UGVs can improve active radios' energy efficiency and operating time, countering the usual coverage gaps in rural areas [66,97].

5.3. Intelligent Transport Systems

The field of transportation is experiencing transformative growth through integrating information and communication technologies into ITS. Innovations such as autonomous driving, remote driving, collision prevention, driver assistance, and mobility management actively enhance road safety and curtail accidents. Using sensors permits these systems to gather and analyze environmental data to enact essential measures. Additionally, this data is exchanged with neighboring vehicles and infrastructure through communication technologies like IEEE 802.11p and C-V2X, further advancing the ITS landscape. In vehicular networks, battery-powered IoT sensors and devices play a crucial role by transmitting active radio signals for data exchange. The increasing scale of transportation systems worldwide anticipates a substantial proliferation of sensors, leading to heightened demand for frequent data transmission.

Consequently, the forthcoming ITS landscape necessitates communication radios with power efficiency and advanced resource management capabilities. Using a symbiotic scenario, intelligent transportation systems (ITS) can be elevated, leveraging the cooperative potential of C-V2X and IEEE 802.11p networks, promoting communication efficiency regarding spectrum utilization and energy consumption [91]. Vehicles will possess genuine

AI-driven capabilities, learning from real-world experiences facilitated by the truly real-time communication prowess of 6G. Integrating such communications becomes paramount within the framework of 6G, as they lay the foundation for ensuring high-reliability and low-latency interactions and the secure exchange of massive driving data and the surrounding environment [98]. Applications such as autonomous driving, vehicle-to-vehicle (V2V), and V2X or integrating numerous sensors on upcoming vehicle models may lead to a collective data rate of 1 Gb/s. This data capacity can be harnessed for V2V and V2X interactions.

5.4. Intelligent Industrial Automation

Founded on the principles of supply chain management and optimization, autonomous machinery, additive manufacturing processes, data analytics, and the IoT, Industry 4.0 [99] has ignited the shift toward industrial automation. Conversely, the emerging Industry X.0 paradigm [100] aims to synergize industrial automation's diverse facets by integrating artificial intelligence. Interconnected factories are central to this vision as crucial hubs of significant big data, pivotal for guiding decision-making processes. Thus, it can be expected that future factories will require assured high-throughput connectivity for thousands of devices, frequently with sub-millisecond latency.

Enabled by symbiotic technology, the deployment of industrial IoT facilitates real-time monitoring, predictive maintenance, automation, and the realization of smart factory systems, revolutionizing manufacturing processes for enhanced efficiency, productivity, and scalability, with symbiotic connections with diverse radio systems, combining a variety of manufacturing processes, thereby raising efficiency and scalability to a comprehensive level, and ensuring the safety of safety-critical systems and operators. This kind of solution allows the digitization and automation of the manufacturing industry, promoting efficient, intelligent, and sustainable practices [67,91].

Intelligent driving and industrial transformations drive essential 6G needs, culminating in uMUB, uHSLLC, and uHDD service categories. These emerging services necessitate holistic communication, sensing, and computation integration, inspiring the fusion of photonics and AI [18].

The URLLC service classes encompass a wide range of use cases within upcoming ITS, future industrial facilities, and the management of unmanned swarms of aerial vehicles or robots. Within the realm of ITS, the integration of sensors, cameras, radars, AI/ML, and V2X technologies finds prominence. V2X assumes a pivotal role by furnishing AI-equipped vehicles with contextual information from smart roads, automated highways, and intelligent autonomous intersections.

5.5. Logistics and Supply Chains

Symbiotic technology enhances communication and operational efficiency in logistics and supply chain management. This frequently entails the incorporation of RFID tags into products, enabling efficient tracking and streamlined management for improved outcomes.

This kind of solution could be valuable for RT asset location and tracking and inventory management within warehouses, utilizing existing WiFi APs to identify and oversee inventory for indoor applications or outdoor real-time shipment tracking using the cellular network [91].

6. The 6G Network Infrastructure to Manage V2X Application Lifecycles

This section explores the evolution and potential of vehicular ad hoc networks (VANETs) in a 6G network environment, emphasizing the incorporation of air and space networks to ensure seamless vehicle communication across global locations. We delve into vehicle-to-everything (V2X) communications, exploring the developments from vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications, towards a broader spectrum of interaction within the vehicular network. The section further discusses the technical demands posed by the integration of numerous sensors in contemporary vehicles and proposes advancements in 6G to accommodate these demands. Critical evaluations of three use cases and a proposal of implementation strategies and future work in the 6G-V2X domain are also presented.

As autonomous driving technology and automotive applications advance, the existing infrastructure and geographical coverage of ground networks might fall short of meeting the demands of future vehicular ad hoc networks (VANETs). In 6G, it is expected that VANETS will evolve beyond ground-based limitations and expand into a comprehensive 3D network encompassing a space–air–ground network. The incorporation of air and space networks will ensure seamless vehicle communication across global locations, addressing the limitations posed by ground-based networks [101]. The 6G VANET primarily consists of vehicles and surrounding infrastructure elements, including BSs, buildings, traffic lights, streetlamps, and more, each equipped with computing and communication capabilities. Within this setup, vehicles can communicate with all intelligent nodes in the 3D vehicular network, a communication paradigm referred to as V2X communications.

Initially, onboard units (OBUs) were integrated into vehicles, enabling direct communication with stationary roadside units (RSUs) via vehicle-to-infrastructure (V2I) wireless connections or between vehicles using V2V links. In the contemporary landscape, advancements in the automotive industry have allowed cars to exchange data with a broader spectrum of entities, including pedestrians' handheld devices, bicycles, ground stations (GNs), UAVs, and more. This evolution is achieved through V2X communication, enabling vehicles to engage and communicate with their surrounding environment [102].

Current vehicles are outfitted with an extensive array of up to 200 sensors, such as video and infrared cameras, automotive radars, light detection, and ranging systems—including RADAR and LIDAR, along with global positioning systems, as well as others—all demanding significantly elevated data rates up to 1 Gbps, which is well beyond the capability of digital short-range communication (DSRC), so using 6G they can be served by bands below 6 GHz for high reliability and mmWave bands to achieve Gbps low data rate latency, sharing a mobile edge compute (MEC) through a uRRLC network [103,104].

V2X adaptation enhances ITS, focusing on vehicular networks (VNs) within the 5G landscape. MEC or similar edge paradigms are essential for V2X applications due to their need for ultra-low latency and reliability [87,105–107]. The 3GPP-defined connected vehicle technology improves safety, reduces congestion, senses vehicle behavior, and supports vehicular services by offloading computational tasks to roadside BSs or infrastructure, enabling data-connected autonomous driving with reduced latency [3]. AI edge intelligence is implemented using AI/ML algorithms to deal with data and services in edge nodes.

Given the extensive implementation and deployment of service-oriented 5G networks, research is now focusing on the intelligence-driven 6G to enable a fully connected world, particularly emphasizing edge intelligence [108,109]. Therefore, 6G presents an integrated framework encompassing communication networks, artificial intelligence, and mobile MEC. MEC, an evolution of previous edge computing technologies [106,110,111], has emerged as a paradigm shift by decentralizing some functions from centralized mobile cloud computing (MCC) and placing them closer to edge devices within the RAN. It means that MEC is focused on communication originating from mobile devices like 5G terminals and IoT devices within the immediate environment. MEC was designed with mobile communication as its primary consideration. This approach delivers efficient services for computation-intensive or latency-critical tasks, striking a balance between uploading data to a central cloud server and processing it on resource-constrained mobile devices [106,112]. Challenges like propagation delay, i.e., ultra-low latency, network congestion, optimal performance, connectivity feasibility and reliability, scalability, robust security, and privacy concerns, all while facilitating high-speed communication and computations, are effectively tackled through well-designed AI-MEC schemes [113,114].

V2X is a crucial enabler for autonomous vehicles, potentially significantly enhancing road safety and traffic efficiency [115]. Within this context, C-V2X emerges as a standardized V2X solution specified by 3GPP. C-V2X offers communication capabilities with low latency, very high reliability, and a high data rate. It caters to various communication scenarios, encompassing V2V, vehicle-to-pedestrian, vehicle-to-infrastructure, and vehicle-to-cloud interactions. The 3GPP-defined MEC architecture is adaptable for V2X applications. MEC servers can be positioned within the cellular network or at the roadside, linked to the network—a decision influenced by business models and policies. MEC enables C-V2X to facilitate cooperative perception, computing, and decision-making for autonomous vehicles.

Vehicle density is a key aspect in V2X communications, especially considering the crucial nature of managing and facilitating communication in environments with varying vehicle densities. In the realm of 6G V2X communications, the network infrastructure must exhibit proficiency in handling high-density scenarios. This entails ensuring low-latency and reliable communication even in heavily populated vehicular networks. Additionally, positioning accuracy stands paramount in V2X communications. It is essential to ensure safe and effective interaction among vehicles and between vehicles and infrastructure. As we progress into the age of 6G, there is a pressing need to enhance localization accuracy to accommodate the stringent demands of various V2X use cases, especially those pivotal for safety and autonomous driving.

Another dimension of challenges revolves around interoperability (Table 1). Ensuring diverse systems, perhaps originating from different manufacturers or developers, can work cohesively is a significant hurdle. The 6G V2X communication framework should ideally promote interoperability, facilitating seamless interaction among disparate systems and technologies. Furthermore, navigating through and complying with various regional and global regulations and standards becomes imperative. The 6G framework must ensure that V2X communications are compliant and standardized, adhering to regulatory requisites and promoting global operability.

Table 1. Present Situation and Proposed Changes in 6G V2X Communications.

Aspect	Present Situation	Proposed Changes
Use Case Descriptions and Roadmaps	Currently, the focus is on developing and describing use cases for V2X communications, as documented across multiple volumes and white papers by 5GAA	Proactively, the focus may pivot towards the enhancement and progression of cellular vehicle-to-everything (C-V2X) use cases, delving deeper into facets such as autonomous vehicular navigation and the direct communication interface between vehicular units and network infrastructures.
Technical Requirements and Challenges	The dominant narrative highlights an array of technical prerequisites and obstacles inherent in the deployment of V2X communications.	For forthcoming 6G implementations, a meticulous elucidation of specific technical enablers and strategies to address identified challenges is imperative.
Regulations and Standards	The current dialogue touches upon compliance with regional and global regulations and standards, ensuring that V2X communications are standardized.	The future discourse could delve deeper into how 6G can navigate through and ensure adherence to evolving regulations and standards.
Interoperability	Presently, interoperability among systems from diverse manufacturers or developers is acknowledged as a significant challenge.	Looking ahead, outlining specific strategies, technologies, or frameworks to enhance interoperability in 6G V2X communications will be vital

Diving deeper into use cases, enhancing safety aspects through V2X communications might involve scenarios like collision avoidance and emergency vehicle warning. These use cases necessitate reliable and rapid communication facilitated by 6G. Vehicle operations management pertains to managing vehicle operations effectively through V2X communications and primarily focuses on use cases related to fleet management and vehicle diagnostics. On the convenience front, V2X communication involves use cases related to parking management and infotainment services, necessitating high data rates and low-latency communication in the 6G era. Furthermore, facilitating autonomous driving through V2X communication brings forth use cases related to cooperative maneuvering and autonomous navigation, demanding stringent communication reliability and accuracy in 6G networks.

As AI's rapid integration accelerates, the evolution of autonomous functionalities and vehicle intelligence becomes increasingly evident. Thus, the next-generation C-V2X technology should establish a comprehensive solution to foster collaboration among essential stakeholders within an ITS.

Several technology challenges and corresponding solutions have been documented, and some issues deserve more attention and resolution (Table 1), such as [116]:

- C-V2X architecture, spectrum, and air interface: C-V2X needs to introduce mMIMO, VLC, THz, and radar communications to enable reliable sensing and V2X communication to support cooperation among ITS players.
- Handover control, efficient network discovery/selection: The high mobility of vehicles gives rise to frequent handovers, leading to multiple transitions between points of attachment (PoA) in conventional systems, known as vertical handovers, and these events could present a considerable challenge in terms of resource allocation, resulting in notable overhead and latency. When a vehicle transits from an RSU-covered area to a BS-covered region, or vice versa, data is transferred using distinct PoAs with varying access control protocols. The use of cell-free communications, characterized by the absence of cell borders, has the potential to facilitate continuous vehicle mobility with the help of machine learning-assisted techniques [102].

6.1. Vehicle Operations Management

Vehicle operations management in C-V2X is an example of a use case focused on leveraging C-V2X to enhance and optimize vehicle operations within a connected environment. Vehicle operations management is an intelligent platform utilizing C-V2X communication to coordinate and improve various driving and vehicle performance aspects.

The Vehicle Operations Management use case can be split into several steps:

1. Traffic and Coordination: The vehicle operations management system receives real-time traffic information and communicates with other vehicles and traffic infrastructure through C-V2X. It optimizes routes and adjusts speeds to enhance traffic flow.
2. Collision Prevention: Using C-V2X data, the vehicle operations management system detects potential collision situations with other vehicles and alerts the driver. It takes actions such as speed adjustment to avoid collisions.
3. Emergency Response: Vehicle operations management employs C-V2X to alert nearby vehicles and emergency services about the situation in emergencies. This improves response times and road safety.
4. Fleet Optimization: In commercial fleets, vehicle operations management uses C-V2X to track vehicle locations, monitor efficiency, and coordinate routes and maintenance schedules.
5. Dynamic Traffic Light Control: Using C-V2X, the vehicle operations management system communicates with traffic lights to optimize their timing based on traffic conditions, reducing congestion, and improving travel efficiency.
6. Parking Assistance: Through C-V2X, the vehicle operations management system guides drivers to available parking spaces, simplifying parking search and enhancing traffic flow.
7. Remote Maintenance and Software Updates: Utilizing C-V2X, the vehicle operations management system conducts real-time remote diagnostics and sends software updates without requiring a physical workshop visit.

A. Critical Evaluation

Feasibility in 6G: 6G's capabilities to support a vast array of IoT devices and ensure high-reliability communication lay a robust foundation for advanced vehicle operations management. With features such as network slicing, 6G can allocate dedicated network resources to manage vehicle operations efficiently and reliably.

Advantages: Implementing 6G would facilitate enhanced real-time monitoring, control, and optimization of vehicle fleets, thereby improving logistical operations and reducing operational costs.

Challenges: Ensuring secure and consistent communication across various geographic locations and terrains presents a significant hurdle, alongside managing the voluminous data generated by vehicle fleets.

B. Implementation Solutions

Technical Framework: Develop a 6G-enabled IoT framework where vehicles continuously communicate operational data to a centralized management system, facilitating real-time monitoring and decision-making.

Addressing Challenges: Implement advanced cybersecurity protocols and utilize machine learning algorithms to process and analyze the data efficiently.

Practical Considerations: Explore aspects such as initial setup costs, adapting existing vehicles to the new system, and training personnel to manage the 6G-enabled operations management systems.

6.2. Over-the-Air (OTA) Software Updates

Regarding the last step of vehicle operations management, we have the particularization of vehicle software update, which encompasses the over-the-air (OTA) software updates that represent a process in which software enhancements are transmitted remotely from a cloud-based server via a cellular connection to a connected vehicle. The primary objective is to furnish the vehicle's software systems with new features and updates, and it represents a paradigm shift in how vehicles receive software upgrades, eliminating the need for physical interventions and ensuring timely updates. This mechanism enhances vehicle performance and features and addresses potential vulnerabilities, ensuring robust vehicular cybersecurity. These updates encompass potential modifications to any software governing the vehicle's physical components or electronic signal processing systems. In practice, OTA updates predominantly impact user interfaces, such as infotainment screens, navigation systems, and vehicle maps. The execution of OTA updates empowers continuous enhancement and upkeep of a vehicle's performance and features. The necessity for physical visits to repair or service centers is obviated by leveraging advanced data analytics and automated, remote service delivery. Two user stories are associated with the OTA scenario:

- Scheduled Updates: In this scenario, users can schedule updates during off-peak hours or when the vehicle is not in use, ensuring minimal disruption.
- Incremental Updates: Rather than fetching the complete software package, vehicles exclusively retrieve the modifications from the previous version, resulting in quicker update times and decreased data usage.

Considering different variables like current and predicted future network coverage, number of surrounding vehicles impacting the available bandwidth, remaining battery life, available storage, and others, the vehicular operations management system can decide to schedule the update according to off-peak hours, prioritize the updates based on urgency, have redundancy mechanisms ensuring continuous operation and implement robust and encryption and authentication protocols that guarantees the security of OTA updates., Additionally, this technological evolution in updates allows vehicle manufacturers to rejuvenate and refine their products continuously remotely. Notably, the effectiveness of the firmware over-the-air (FOTA) process hinges significantly on C-V2X technology, which facilitates efficient and scalable wireless communication between vehicles and software management platforms.

OTA software updates, as a component of vehicle operations management, highlight the significance of ongoing software improvements in the automotive sector. As vehicles become more interconnected and reliant on software, these methods guarantee peak performance and security.

A. *Critical Evaluation*

Feasibility in 6G: The advent of 6G and its inherent capabilities, such as eMBB and URLLC, pave the way for efficient OTA software updates in vehicular networks. The expansive bandwidth of 6G facilitates the rapid transmission of large software update files, ensuring vehicles receive pertinent updates in a timely manner.

Advantages: Using 6G for OTA updates ensures that vehicles are always equipped with the latest software features and security patches, enhancing functionality and safeguarding against potential vulnerabilities.

Challenges: Key challenges encompass ensuring the integrity and security of software updates, managing the simultaneous update of numerous vehicles without overwhelming the network, and ensuring that updates are installed and implemented successfully without inducing system errors.

B. *Implementation Solutions*

Technical Framework: Implement a cloud-based vehicle management system that leverages the 6G network to transmit OTA updates securely and efficiently. Vehicles could be equipped with a system that checks for updates during non-operational hours, downloads, and installs them autonomously while ensuring that the new software is compatible and stable.

Addressing Challenges: Employ end-to-end encryption for data transmission to ensure security. Implement a robust testing and validation process for new software updates to ensure compatibility and stability. Additionally, schedule updates during off-peak hours to manage network load effectively.

Practical Considerations: The practicality of implementing OTA updates via 6G also hinges on regulatory compliance, ensuring that software updates adhere to vehicular safety and operational standards, and managing user perceptions and trust regarding autonomous updates.

6.3. Cooperative Adaptive Cruise Control (CACC)

Cooperative adaptive cruise control (CACC) represents a pivotal advance in vehicular communication, aiming to enhance safety and driving convenience. It is a sophisticated vehicular communication mechanism that seeks to bridge the gap between the host vehicle (HV) and the leading vehicle (remote vehicle—RV). By ensuring a safe and adaptive distance, CACC paves the way for smoother vehicular maneuvers and anticipates undetectable behaviors, such as sudden accelerations or decelerations. The CACC use case is versatile, with applicability spanning across various terrains and settings, including urban, rural, and highway environments. The primary objective of the HV in the CACC scenario is to modulate its speed efficiently, aligning its reactions to the behaviors of the RV. Notably, this function retains its efficacy even when not all vehicles ahead can communicate status messages. Two user stories are associated with the CACC scenario:

- ACC with Status Messages: Incorporating status messages from surrounding vehicles into the existing adaptive cruise control (ACC) framework facilitates enhanced behavioral adaptation.
- ACC with Control Information: This variant of ACC leverages specific control messages from the RV's system, offering preliminary insights into acceleration or deceleration patterns, thereby refining ACC's adaptability.

The defined service level requirements associated with the CACC scenario are the following:

- Range: The practical operational distance is determined to be 800 m, considering vehicle speeds and the possible gaps between vehicles.
- Data Transmission: Vehicles are required to regularly transmit kinematic and positional data, with an average data size of 300 bytes.
- Vehicle Density: The system is engineered to accommodate a wide range of traffic scenarios, supporting densities of up to 10,000 vehicles per square kilometer.
- Positional Accuracy: The focus is on precise longitudinal positioning, with a defined accuracy threshold of 0.5 m (Xσ).
- Standardization and Regulation: To establish inter-vehicle distances, the CACC framework requires compatibility among various original equipment manufacturers (OEMs), standardized protocols, and regulatory supervision.

The CACC use case highlights the transformative power of V2X communication in reshaping vehicle safety and the driving experience. As vehicle networks become increasingly complex, such innovations will be crucial in influencing the trajectory of ITS in the future.

A. *Critical Evaluation:*

Feasibility in 6G: CACC leverages V2V communication, and 6G, with its URLLC and high-mobility communication capabilities, can ensure that vehicles exchange data in real-time, enabling cooperative decision-making even at high speeds.

Advantages: Implementing CACC via 6G could enhance road safety, optimize traffic flow, and contribute to a more pleasant driving experience by reducing the burden on the driver.

Challenges: Developing algorithms that can manage diverse and dynamic traffic scenarios while ensuring that communication between vehicles is not only fast but also exceedingly reliable is crucial.

B. *Implementation Solutions:*

Technical Framework: Establish a system where vehicles utilize 6G to communicate data regarding speed, distance, and road conditions to each other, employing AI algorithms to make cooperative decisions regarding speed adjustments and lane changes.

Addressing Challenges: Ensure that the AI algorithms are robust enough to manage varied traffic scenarios and implement redundant communication channels to enhance reliability.

Practical Considerations: Address issues related to user adoption, update current vehicular communication systems to be 6G-compatible, and navigate regulatory compliance related to autonomous driving features.

6.4. Technical Requirements, Challenges and Future Work

In the pursuit of implementing 6G-enabled V2X applications, a meticulous analysis of technical requirements is paramount. The network infrastructure demands a robust architecture capable of supporting the voluminous data generated by vehicular and IoT devices, ensuring ultra-low latency and reliable connectivity, which are vital for real-time decision-making and data transmission in V2X applications. When it comes to hardware, vehicles need to be equipped with 6G-compatible communication modules, sophisticated sensors, and potent computing capabilities. Concurrently, the network infrastructure must be fortified with advanced base stations and edge computing devices to proficiently manage 6G connectivity.

The software realm necessitates the development of efficient communication protocols and intelligent algorithms to optimize data processing and manage communications effectively in V2X applications. Security encompasses another pivotal facet, demanding end-to-end data security through comprehensive encryption and secure data transmission protocols. Network security measures need to be fortified to thwart cyber-attacks and unauthorized access, ensuring the safety and integrity of the network and data.

Interoperability stands as a cornerstone to facilitate seamless communication between devices from different manufacturers, necessitating adherence to industry standards and the uniformity of communication protocols.

Embarking on the 6G journey introduces a spectrum of challenges. Network reliability stands out prominently, wherein ensuring continuous and steadfast connectivity, particularly in geographically challenging areas, becomes crucial. Upholding data integrity during transmission also becomes vital to prevent data corruption and ensure the reliability of communicated information. Scalability emerges as another formidable challenge, necessitating the network and V2X systems to efficiently manage increasing connected vehicles and data volumes.

Delving into security and privacy, safeguarding user and vehicle data, and protecting the network against cyber threats is paramount to uphold user trust and regulatory compliance. The implementation cost looms as a significant hurdle, entailing substantial investments in establishing 6G infrastructure and adapting vehicles to be 6G-compatible. Regulatory compliance further complicates the implementation, as V2X applications must adhere to strict safety and data protection standards.

To navigate through the elucidated challenges, adopting edge computing can be pivotal, enabling data processing closer to the source, thereby alleviating latency and bandwidth usage. Network slicing could be employed to dedicate network resources for specific V2X applications, ensuring consistent performance. Robust cybersecurity measures, such as advanced encryption and intrusion detection systems, need to be at the forefront to safeguard against cyber threats.

As we gaze into the future, enhancing the AI capabilities of V2X systems to adeptly manage complex scenarios and decision-making will be crucial. Further research into exploring alternative network technologies and architectures could pave the way for the evolution and enhancement of 6G V2X applications.

7. Conclusions

Ultimately, 6G is a pivotal communication technology poised to unlock many novel innovations. This article comprehensively explores the essential parameters of 6G technology, revealing substantial challenges that must be surmounted to realize these desired benchmarks and fulfill the envisioned potential. Wireless networks based on 6G promise to deliver a substantial increase in QoS while also emphasizing sustainability. This assurance is underpinned by a new architectural paradigm shift around existing and emerging spectrum technologies such as THz, VLC, molecular, and quantum communication. This paradigm also encompasses integrating terrestrial and non-terrestrial networks, fostering intelligent connections made possible by pervasive AI, and bolstering the network's protocol stack framework.

V2X scenarios are challenging, and the use cases presented highlight the transformative potential of V2X communication in reshaping the automotive industry. As the industry moves forward, addressing potential challenges, including cybersecurity risks and network bandwidth limitations, ensuring universal applicability across diverse terrains and settings will be imperative.

The presented vehicular operations management (VOM) system, leveraging C-V2X communication technology, underscores the paradigm shift toward a more connected and intelligent vehicular ecosystem. The system enhances driving experiences and optimizes vehicle performance and safety, presenting a holistic vehicular management.

As a subset of VOM, introducing OTA software updates represents a significant advancement in vehicular maintenance, eliminating the need for physical interventions and ensuring vehicles are always equipped with the latest software enhancements and security patches. This not only augments vehicle performance but also fortifies vehicular cybersecurity.

The effectiveness of both the OTA updates and CACC hinges significantly on C-V2X technology. This technology facilitates efficient and scalable wireless communication, making it indispensable for the future of vehicular operations and establishing C-V2X as the backbone.

CACC, as a sophisticated vehicular communication mechanism, plays a pivotal role in enhancing safety and driving convenience. Ensuring a safe and adaptive distance between vehicles paves the way for smoother vehicular maneuvers, potentially reducing traffic congestion and accidents.

Some future Implications must be considered as vehicles become increasingly interconnected and reliant on software. The methods and systems discussed will guarantee optimal vehicle performance, safety, and user convenience. The continuous evolution and refinement of these systems will shape the future of transportation, making it more efficient, safe, and user-centric.

The need for standardization and regulatory oversight, especially in frameworks like CACC, cannot be overstated. As vehicular communication systems become more intricate, ensuring compatibility among various original equipment manufacturers (OEMs) and defining inter-vehicle distances will be paramount.

The presented systems and use cases highlight the transformative power of V2X communication in reshaping the automotive sector. As the industry progresses, addressing potential challenges, including cybersecurity threats and network bandwidth limitations, and ensuring universal applicability across diverse terrains and settings will be imperative.

The bottom-up approach in designing and implementing 5G needs a shift towards considering the requirements of future applications as a cornerstone for successful 6G infrastructure. High-demand verticals, like vehicular applications, will be crucial in establishing the primary performance requirements for future 6G deployments.

In conclusion, 6G is positioned to bring about a revolutionary transformation across various domains, establishing itself as a paradigm-shifting technology with profound impacts.

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