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Emerging Trends in 5G and Beyond-5G Wireless Networks

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Abstract

Wireless networks have evolved in the blink of an eye from 4G to 5G and are progressing towards beyond-5G (B5G) frameworks, leading to revolutionary changes in connectivity, speed, and network smarts. This review discusses trending features, challenges, and future trends of 5G and B5G wireless communications technologies. It presents the chief goals of 5G, such as ultra-low latency, high spectral efficiency, massive machine-type communication, and up to 10 Gbps user data rate. Furthermore, the article describes how machine learning (ML), artificial intelligence (AI), and edge computing are essential to handling the complexity of network demands and to facilitating real-time adaptability in 5G systems. A large body of literature reviews enabling technologies such as non-orthogonal multiple access (NOMA), cell-free massive Multiple-Input Multiple-Output (MIMO), and digital twins based on unmanned aerial vehicles (UAVs). The review also indicates the necessity of robust security architectures to neutralize new threats created by B5G technologies and increased device connectivity. Some of the primary challenges raised include ensuring quality of service (QoS), handover security, and ultra-reliable communication in highly dense and heterogeneous networks. This paper is an in-depth guide for researchers and professionals who want to know about today and the visionary path of wireless networking, offering insights into the technological innovation and infrastructural strategy that will be critical to the next-generation of mobile communications.

Keywords: 5G, wireless networks, machine learning, NOMA, MIMO, edge computing, network security, ultra-reliable communication, UAV, Beyond 5G (B5G)

INTRODUCTION

In addition to exceeding the International Mobile Telecommunications Advanced (IMT-A) limit, the fourth-generation long-term evolution network (4G-LTE) and its extension, long-term evolution-advanced (LTE-A), have handled high mobility of up to 100 Mb/s data rate and 1 Gb/s reduced mobility with Internet Protocol (IP) designed for all services. Over the past few years, mobile data subscribers have grown at a tremendous pace because of the need for speedy Internet access on the move [1]. It is projected by the Wireless World Research Forum (WWRF) in 2017, 7 billion people will be able to access approximately 7 trillion mobile devices, which is approximately 1000 times more people than currently inhabit planet Earth. On the other hand, Ericsson's 2017 technical mobility report predicts that by the year 2020, there will be approximately 29 billion devices on the planet, 18 billion of which will be linked to the Internet of Things (IoT) [2]. Other IoT uses include wearable AI devices, sensor networks, smart cities, smart homes, and grids. Therefore, the telecommunications industry is developing new mobile standards more carefully.

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The main aims of the 5G network are illustrated in Figure 1, and are less costly and more pervasive machine-type communication, quality of service (QoS), greater spectral efficiency (SE), ultra-reliable and better device battery life, and sustaining a 1000-fold capacity benefit and 10 gigabits per second available to an individual user. 5G networks' main challenge is addressing the ever-increasing demand for mobile data traffic. To cope with this, 5G technology, with its high throughput, ultra-low latency, and superior reliability, is well placed to transcend these barriers and provide a truly unlimited and seamless mobile experience.

5G is a term that reflects a great technological jump, with the "G" referring to generation. 1G and 2G marked the beginning of wireless phone technology, and by the early 1990s, companies made text messaging between cellular phones fascinating the globe. The advent of 3G enabled users not only to make calls and send texts, but also to browse the Internet at much higher speeds. 4G was based on this, allowing much more work to be done. Users can indulge in fast texting, voice calling, Internet use, and even rapid downloads and uploads of heavy video files [3]. To further enhance 4G use, firms embraced LTE, which is the fastest and most stable type of 4G technology. Even though WiMax is another innovative technology, LTE eventually became the standard in the industry. Although both technologies were designed to provide similar results, it was crucial to have a universal standard to guarantee cross-compatibility and a uniform user experience.

The Mobile Network of the Future

The following prerequisite for 5G networks is defined by alliances:

- Coverage speed.
- Higher data speeds.
- Improved spectrum efficiency over 4G.
- A simultaneous transmission of one gigabit per second to multiple workers on the same floor.
- An increase in signaling efficiency.
- Improved signaling efficiency, and a considerable reduction in legacy over LTE.

Globalization has significantly heightened the load on contemporary communication networks. To address these rising demands, cellular systems and wireless local area networks (LANs) are being installed at a record pace, frequently just a few hundred meters apart. With the unprecedented growth of mobile broadband services, new technologies, such as IoT and machine-to-machine (M2M) communications, are also adding to the volume of wireless traffic. The mass penetration of cellular connectivity has revolutionized the way users access mobile data in their daily lives. Owing to improvements in 3G, 4G, and 5G networks with low latency and high data rates, users have been able to access services such as video calling, online gaming, and social network sites such as Facebook, Twitter, and WhatsApp. These abilities have turned mobile technology into a central part of daily life and the basis of contemporary digital interaction [3].

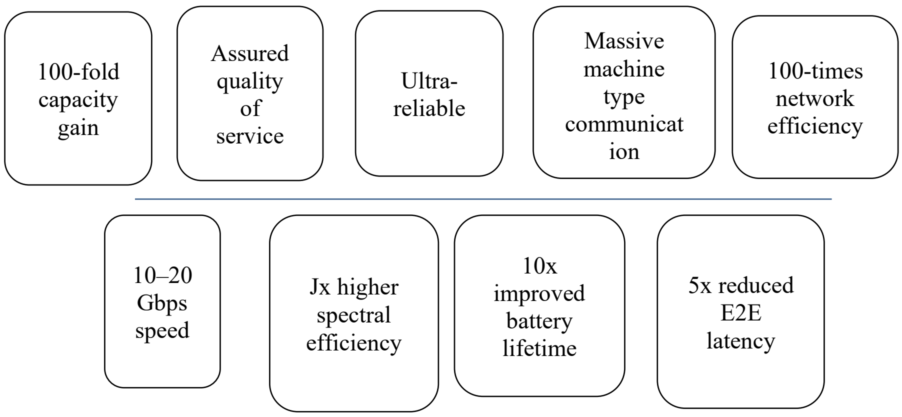

Figure 1. The main goal of 5G.

From 2017 to 2022, mobile traffic from smartphones is projected to increase tenfold, and the overall mobile traffic is projected to increase eightfold. As Figure 2 illustrates, both cellular data traffic and connected devices saw tremendous growth between 2017 and 2022. Cell phones are projected to account for over 90% of all mobile traffic by 2022. The management of this vast volume of wireless mobile data is a serious concern, particularly when relying on the limited capabilities of earlier generations of wireless infrastructure [4].

We introduce the 5G New Radio (NR) heterogeneous network architecture, where nearly everything is interconnected via the 5G Internet. DL, machine learning (ML), and AI technologies are considered fundamental enablers to unlock the complete potential of 5G (Figure 3). These smart methodologies are especially suited to support state-of-the-art use cases, including industrial automation, drone navigation, autonomous driving, mixed reality, and other delay-sensitive mission-critical applications. From social media websites to virtual personal assistants, ML is increasingly being used to provide solutions to many real-world issues. Solutions based on ML are effective in spam detection in emails, forecasting, surveillance through video, and intrusion detection and prevention, all with a minimal need for constant Internet browsing. ML has reached a point where it can considerably enhance network and service performance by analyzing and learning from various patterns of wireless network traffic. Current advancements have been largely spurred by the integration of modern networking paradigms, such as context-aware networking, mobile edge computing, edge caching, and big data analytics, and these create a strong foundation for ML-enabled 5G communication systems. Classic heuristic-based Radio Resource Management (RRM) techniques are becoming less capable of addressing the dynamic and complex needs of 5G networks because of their natural limitations. On the other hand, ML-based methods provide capable and adaptive solutions, especially tailored to address complex issues that would otherwise necessitate heavy manual intervention [5].

LITERATURE REVIEW

The fourth-generation (4G) network, as stated by Swami et al. [6], has been forced to change because of the increasing requirements for high data rates driven by the large-scale growth of multimedia services and increased wireless user traffic. These problems have opened doors to the innovation and use of fifth generation (5G) wireless networks. To improve 5G performance, various innovative technologies have been suggested, such as millimeter-wave (mmWave) communication, intelligent reflecting surfaces (IRSs), small-cell deployments (also referred to as heterogeneous networks or HetNets), and non-orthogonal multiple access (NOMA). Among these, multiple access (MA) technologies are still an essential part of the physical layer of wireless communication systems.

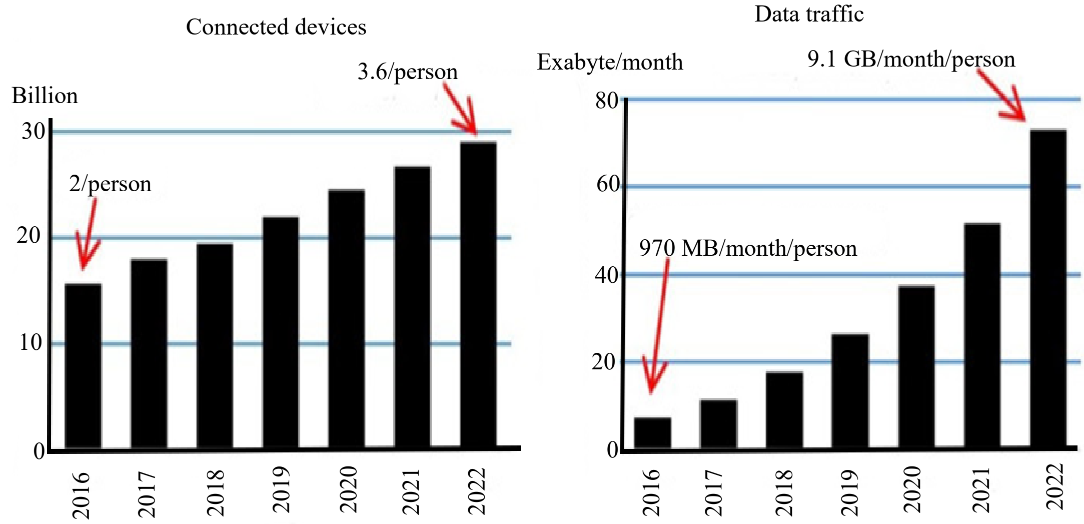

Figure 2. Growth of linked devices and worldwide mobile data traffic between 2017 and 2022.

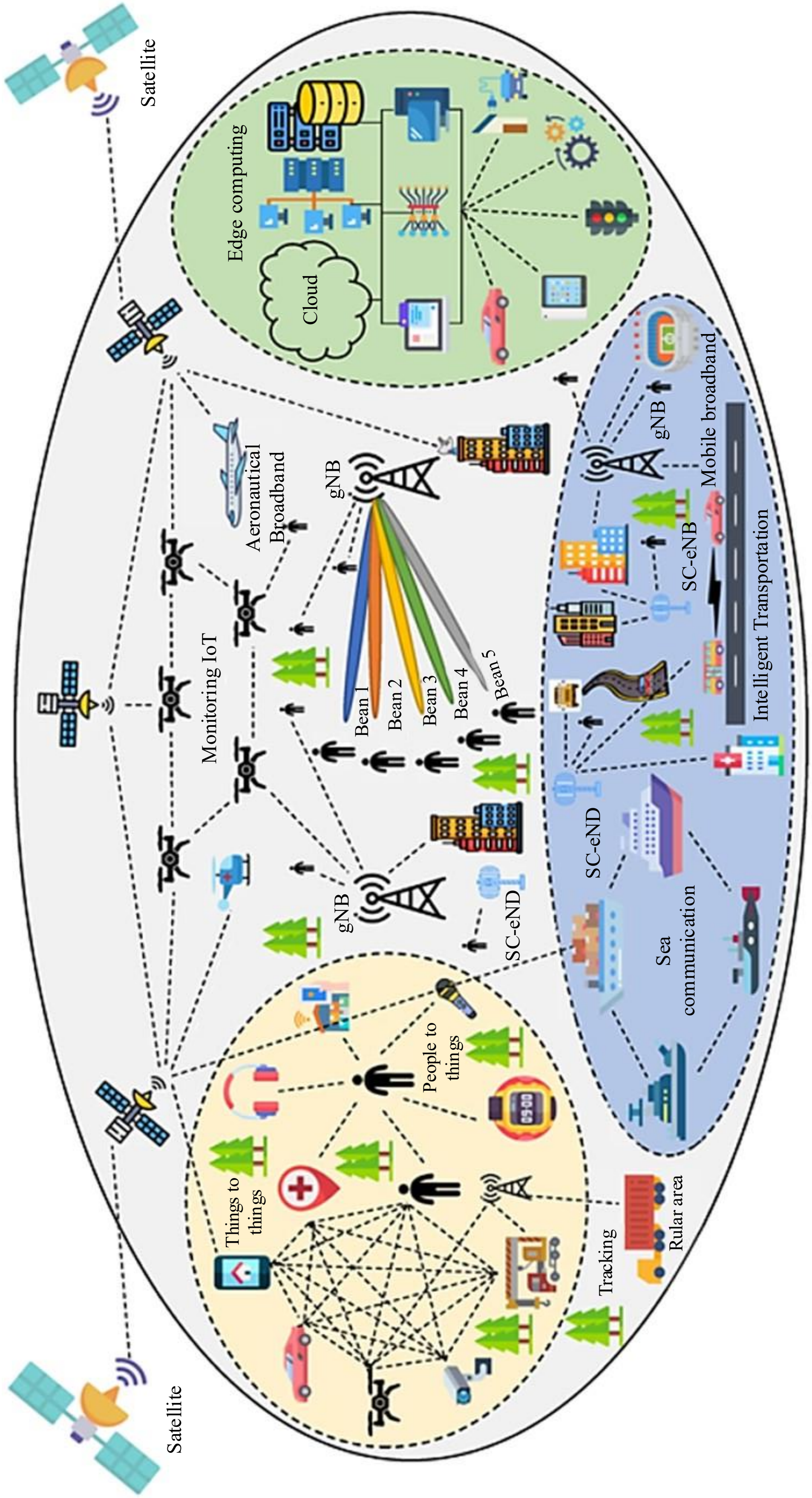

Figure 3. 5G network design.

MA techniques have been developed over generations, ranging from frequency-division multiple access (FDMA) during 1G to orthogonal frequency-division multiple access (OFDMA), which is extensively practiced in 4G, preparing the grounds for more sophisticated techniques such as NOMA in 5G. For 5G, NOMA is a contender that is considered because it deviates from the conventional orthogonality limitation and accommodates multiple users simultaneously. This leads to low latency and improved spectral efficiency, making NOMA the core concept behind the understanding and use of 5G and beyond. In addition, NOMA is fueled by other advanced technologies, such as IRS, mmWave, device-to-device (D2D) communication, and Honest systems. In this chapter, the integration of NOMA with these enabling technologies—a research topic drawing increasing scientific interest—is discussed. This chapter also accounts for an example of a heterogeneous cellular network (HCN) that comprises three tiers: the MacroBase station (macroBS) tier, the femto base station (femtoBS) tier, and the D2D communication tier. While both femtoBS and D2D tiers use NOMA, the macroBS tier does not. To relieve macroBS tier congestion, the workloads are shifted to the femtoBS tier. Furthermore, the offloaded macroUs from the macroBS tier are further assisted by the D2D tier in collaborative communication. This is especially helpful when femtoBS employing NOMA cannot identify a proper paired user for the offloaded macroU. To confirm the proposed system, the authors employed Monte Carlo simulations to examine and validate the theoretical higher and lower bounds of the outage probability.

Ahmad et al. [7] underscored the fact that fifth generation (5G) wireless networks quickly pick up speed in their quest to connect all dimensions of contemporary life, with ultra-high speeds, incredibly low latency, and pervasive connectivity. As these networks play a vital role in daily life, it is critical to secure users, infrastructure, and services. However, dramatic growth in 5G, both in the quantity of services and variety of technology, is significantly expanding the security threat environment. Before a full rollout, security measures must be conceived proactively to address a vast array of possible attacks on many services, new technologies, and mounting amounts of available user data. This article recognizes and examines the security risks inherent in the new technologies that are built into 5G, in addition to a general description of the wider threat landscape against 5G networks. In response, the authors suggested a range of mitigation measures and future directions for mitigating these security issues. This article also contains a summary of post-5G (XG) cellular technologies, describing their expected security issues. The paper then discusses both existing and future security threats in 5G networks and provides solutions for wireless communication security beyond 5G.

Lv et al. [8] examined the applications, effects, and limitations of unmanned aerial vehicles (UAVs) in 5G and beyond 5G (B5G) wireless and mobile communication networks. Their work presented a deep learning (DL)-enabled solution for designing a UAV Digital Twin (DT) communication channel model based on 5G connectivity. To counteract UAV-generated interference, this study integrates Coordinated Multi-point Transmission (CoMP) technology and uses an important algorithm at the physical layer to guarantee safe and secure information transmission. After the model was created, several simulations were performed to test its performance. The proposed deep learning methodology is contrasted with conventional deep neural networks (DNNs) in terms of different signal-to-noise ratios (SNRs), utilizing metrics such as the transmission error rate and estimation accuracy to measure effectiveness.

The findings point to the superior robustness and speed of convergence of the suggested method, with an estimation accuracy approximately 150 times superior to that of traditional methods. An additional comparison showed an accuracy of 82.39%, which is at least 3.2% greater than that of traditional ML techniques. In addition, the proposed algorithm has the lowest latency during transmission and the maximum Precision, Recall, and F1 measures compared with the competing methods. These results confirm that the constructed UAV DT communication channel model is not only extremely reliable but also efficient in handling UAV limitations, providing ample strength to enhance the performance of UAV systems in the future.

The growing demand for access to networks by end users and service providers has contributed tremendously to network operation and management complexity. Hireche et al. [9] focused on the recent advancements in automation, data analysis, AI, distributed ledger technology (e.g., blockchain), and data plane programming, which have driven research towards the development of trustworthy autonomous driving networks (SelfDNs). To this end, the authors presented a state-of-the-art framework for enabling fully distributed and reliable SelfDNs across various domains. The framework leverages programmable data planes to record in-network real-time telemetry, utilizes the P4 programming language along with AI for dynamically (re)programming the network component code, and uses policy enforcement to translate intent into an actionable effect. A relevant use case is presented to demonstrate the usefulness of the framework and the feasibility of implementing autonomous and intelligent networking.

5G and B5G networks offer ultra-low latencies, enhanced reliability, scalability, high data rates, and higher capacity to support applications such as device-to-device (D2D) communication, internet of everything (IoE), and vehicular communications [10]. Despite tremendous progress in 5G and Beyond 5G (B5G) technologies, there are still issues, more notably, issues regarding user privacy, resource management, and handover authentication. Handover connectivity security remains a prime issue, leading to the application of multiple machine learning (ML) methods to assist in target cell selection from factors such as signal quality and SNR. Nonetheless, many of these solutions sacrifice important security and privacy concerns in favor of efficiency. Conventional handover authentication methods tend to be latency-intensive and thus do not meet the requirements of real-time communication in 5G/B5G networks. In addition, dense base station deployment, which is necessary because of coverage constraints, triggers numerous handovers, which intensify performance, security, and privacy problems. To overcome these issues, this study proposes a privacy- and security-preserving handover approach with Multilayer Neural Networks (MLNNs). This approach maximizes quality of experience (QoE) and QoS through service requirements, user equipment (UE) capabilities, network states, and user satisfaction input into target cell selection. Security and privacy were maintained using random nonces, ephemeral keys, and timestamps. The robustness of the protocol was confirmed by a Burrows (Abadi) Needham logic-based security analysis with mutual authentication among the communicating parties. Additional analysis demonstrates that the protocol is secure against replay and impersonation attacks and fully preserves key secrecy. Performance analysis indicated improved handover success rates by 27.1%, ping-pong handover reduced by 24.1%, and minimal computational overhead and communication cost.

THE EVOLUTION OF 5G

A 5G mobile network has a highly dynamic and scalable architecture that is designed to interconnect all and everything anywhere. There are various major industry players, such as Do Communications Over the Mobile network (DOCOMO), Huawei, ZTE, Ericsson, Qualcomm, Samsung, Vodafone, and Nokia Siemens Networks, who have spent heavily financially and technologically on progressing with 5G development. These activities indicate widespread and optimistic dedication in the telecommunications industry to bring out the full potential of 5G. Overall, 5G can be broadly categorized into three significant domains, each of which addresses specific application contexts and use cases that cumulatively drive its overall paradigm-shifting effect on communication and connectivity.

- *Ultra-reliable low latency communication (URLLC)* used in smart factories and driverless cars, this technology is exceptionally fast and dependable, with 100% coverage and uptime.
- *Enhanced mobile broadband (MBB*) aims to provide wireless broadband services with gigantic devices, user capacity, and massive data applications.
- *Massive machine-type communication (MTC):* This technology increases energy efficiency, lowers the cost of devices per connection, and allows for a high density of wireless connections.

While the initial 5G rollouts in most nations are largely in the sub-6 GHz band, there is an increased drive to use higher band frequencies, including those above 6 GHz, to address the escalating need for higher capacity and SE. The Third Generation Partnership Project (3GPP) was formed in 1998 with the objective of standardizing mobile telecommunications technologies worldwide. Its main responsibilities are the writing of technical specifications and reports for 3GPP technologies, as well as establishing overall guidelines for implementation. The association consists of seven national or regional telecommunications standards organizations, which influence the development of mobile networks, such as 3G, 4G, 5G, and future networks. The technical reports and specifications that comprise each of the releases comprising the 3GPP specifications may have undergone numerous revisions. A recent publication presented both new and updated radio access technologies and showed the achievement of specific goals (Table 1).

Table 1. New developments in wireless communication technologies.

Main focus	Key contributions	Reference
Audio-Visual System	The suggestion of an intelligent and safe sensing and tracking architecture for AV systems based on BC. Dealing with concerns about data security and defense against intrusions. A comparison of traditional LTE-A and 5G communication networks with the proposed system.	[11]
Beyond 5G	The Multi-task Learning framework for modulation and signal categorization in wireless communication based on deep neural networks was introduced. Taking into account diverse wireless signals, including communication waveforms and radar. Tests and observations about model deployment and compression on edge devices with limited resources.	[12]
CF-MIMO	A summary of 5G and 6G wireless networks using cell-free massive MIMO (CF-m MIMO) technology. Talk about the main application areas, design concerns, and CF-m MIMO architecture. Investigation of the prominent characteristics in cell-free massive MIMO (CF-mMIMO) systems, such as simultaneous wireless information and power transfer (SWIPT), channel hardening, power control methods, non-orthogonal multiple access (NOMA), and other next-generation capabilities.	[13]
Evolution of 5G	A baseline strategy for the ten-year development of 5G New Radio (NR). Short-, medium-, and long-term timeline analysis of technology trends and target KPIs. To encourage dialogue and input from the wireless research community.	[14]
Development of 5G NR	A summary of the evolution of 5G New Radio (NR), emphasizing carrier aggregation (CA), numerologies, deployment scenarios, and frame structure. A focus on how crucial carrier aggregation is to 5G networks' capacity and coverage. Determining the difficulties and extent of the CA research.	[15]

Release 16 (Rel-16) and the newer Release 17 (Rel-17) expand on the solid foundation established by Release 15 (Rel-15), which not only achieves important 5G performance requirements but also provides extensive backward compatibility across future releases. Rel-16 and Rel-17 add features such as ultra-reliable communication, increased data rates, low latency, and improved security, paving the way for growth to even stronger and more feature-laden 5G networks. Rel-17 is an important milestone in the achievement of 5G-Advanced enhancements in connectivity, multi-access edge computing, and high-frequency bands above 52 GHz. Rel-17 further adds reduced capability (RedCap) user devices, proximity services, Industrial Internet of Things (IIoT) architectures, virtual reality, smart home automation, multicast/broadcast frameworks, non-terrestrial networks (NTNs), autonomous vehicles, and UAVs. Moreover, Rel-17 adds uplink functionalities in the form of new additions, such as physical uplink control channel (PUCCH) and physical uplink shared channel (PUSCH) additions.

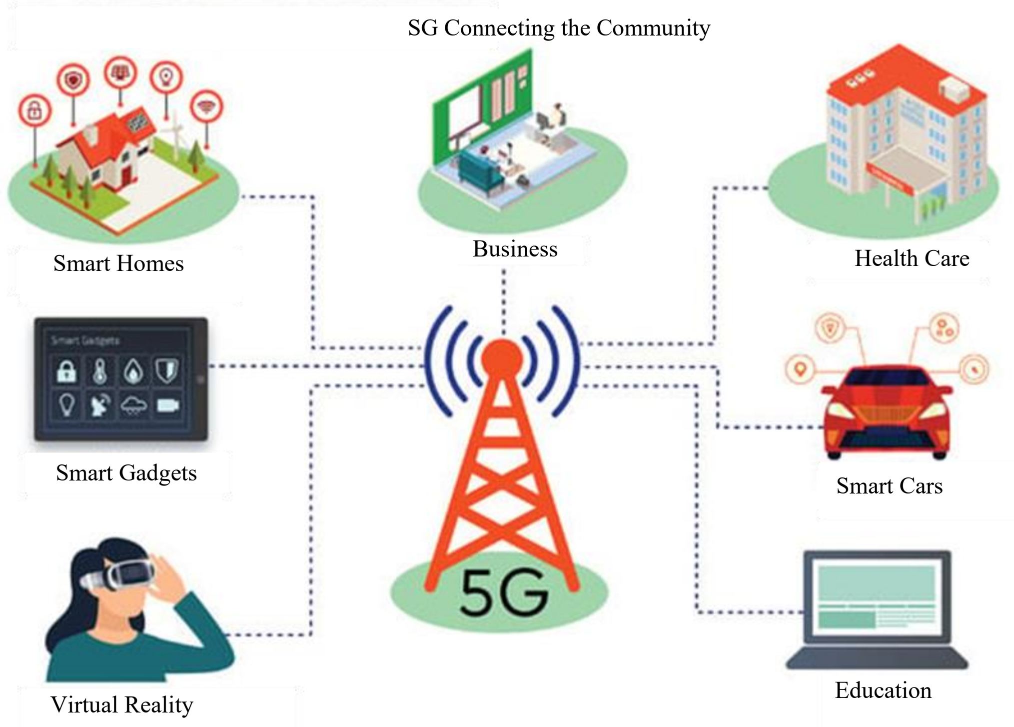

Figure 4. 5G, bringing the community together.

Encouraged by this pace, Release 18 (Rel-18) sets the stage for the official launch of 5G-Advanced with the central theme of introducing artificial intelligence (AI) and ML in network management. These technologies seek to maximize both real-time and non-real-time functionality through multidimensional optimization, automatic network administration, and intelligent decision-making features, paving the way for the next wave of clever, adaptive communication systems. To further improve uplink performance, future waveform technologies, such as DFT-spread OFDM (DFT-S-OFDM) and cyclic-prefix OFDM (CP-OFDM), are also actively researched and developed. These technologies provide greater spectral efficiency and stronger signal robustness, particularly under difficult wireless conditions. Commercial 5G services now have over 132,031 sites deployed globally, according to Ookla's 5G interactive map tracker, which is led by 216 operators in 220 pre-launch markets. A significant achievement in this worldwide deployment was made by Japan, with it being the first to commercialize 5G sub-6 GHz spectrum C-band aggregation. This was made possible through a joint effort between Qualcomm Technologies Inc. and NTT DOCOMO Inc. Table 1 compares the current 5G system performance targets and expectations for beyond 5G (B5G) networks, showcasing the ongoing development of wireless communication standards (Figure 4).

CONCLUSION

The rapid growth of mobile data subscribers and the increasing demand for high-speed mobile Internet have been addressed by the introduction of 4G-LTE and LTE-Advanced (LTE-A) networks. However, as the expansion of IoT applications and big data continues, there is an urgent need for new mobile standards to keep up with the runaway mobile traffic. 5G is a transformative technology that anticipates up to a 1000-fold increase in network capacity, 10 Gb/s user rates, guaranteed connectivity, and enhanced battery life. 5G is designed to address a wide range of applications and categorize itself into three primary service domains to handle diverse use cases and increase mobile transport needs. In the future, 5G's value will be further enhanced through collaboration with AI, network optimization methodologies, and extended reality (XR) technologies. Ultimately, 5G networks are fundamental for satisfying mobile data demand and uninterrupted connectivity with ever-growing pressure, launching a new era of communication, and making unprecedented technological innovations possible in a wide variety of industries.

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