



6G network integration for ultra-low latency

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Abstract

Integrating 6G networks with artificial intelligence and Internet of Things (AIoT) systems has become an important area in future. The main objectives of the study were to identify the challenges and opportunities of combining 6G and AIoT, proposing innovative solutions, and contributing to the development of 6G-powered AIoT technologies. It explores various aspects of 6G-powered AIoT, including network architecture and protocols, resource management, security and privacy and potential applications in various fields. The need for faster and more dependable wireless communication networks has encouraged the development of 6G networks. It explores the integration of Mobile Edge Computing (MEC) cloud architectures and the potential of self-driving Vehicle-to-Everything (V2X) communication to achieve ultra-low latency and high dependability in 6G networks.

By integrating MEC into the 6G network fabric, latency is reduced by bringing data processing closer to end-users, particularly vehicles, thus enhancing computational capabilities at the network's edge. It explores the life changing potential of the merging of 6G networks, the Internet of Things (IoT), and Artificial Intelligence (AI) in creating advanced, interconnected ecosystems. Its role in facilitating ultra-high-speed, low-latency communications essential for the IoT's expansive growth.

INTRODUCTION

The evolution from 5G to 6G is expected to bring ultra-high-speed communication, AI-driven automation, and seamless global connectivity. 6G will integrate the terahertz (THz) spectrum, reconfigurable intelligent surfaces (RIS), non-terrestrial networks (NTN), and quantum-secure communication to enable futuristic applications.

This tutorial explores the key architectural components of 6G and the interfaces that connect its network elements, based on early research and 3GPP advancements. The 6G wireless network architecture is expected to be a highly integrated, AI-driven system that builds upon 5G while introducing terahertz (THz) communication, intelligent surfaces, quantum communication, and edge AI for ultra-reliable, low-latency, and high-capacity services.

The features of high-reliability communication and ultra-low latency in 6G networks are being pushed by a number of modern strategies. Another key strategy that has been suggested is the combination of the MEC cloud structures which is a model for minimizing latency by changing the processing of data closer to the end users particularly the vehicles through the arrangement of computational capabilities at the network edge. MEC is crucial to attaining ultra-low latency and high-reliability communication in the 6G network.

The evolution of wireless communication consistently pushes connectivity boundaries, with each generation unlocking new capabilities. 6G wireless technology is envisioned as a transformative leap, designed to overcome the limitations of current 5G networks and establish unprecedented benchmarks for performance, including ultra-low latency communication potentially targeting end-to-end latencies below one millisecond [1]. Unlike its predecessors, 6G must inherently prioritize real-time adaptability and cognitive functions to effectively support the burgeoning ecosystem of next-generation applications, particularly.

AI-powered Augmented Reality (AR) and immersive XR. With the global AR market projected to reach \$340 billion by 2028, reflecting a compound annual growth rate (CAGR) exceeding 40% [2], there is an urgent need for network infrastructure capable of delivering the uninterrupted, high-speed, context-aware, and intelligent connectivity that these immersive experiences demand. Consequently, a robust 6G framework with deeply integrated AI [3] is essential to unlock the full potential of these applications. This paper articulates the core capabilities 6G networks must possess to meet these demanding requirements. Specifically, we emphasize the necessity of embedding AI-driven decision-making mechanisms directly within the network architecture. This integration allows for proactive optimization of network transitions, intelligent resource management, and drastic latency minimization. By incorporating intelligence into every facet of network operation, 6G aims to guarantee seamless handovers across heterogeneous network technologies while simultaneously achieving ultra-low power consumption—a critical factor for the widespread adoption of portable AR devices.

6G is expected to revolutionize the wireless communication landscape by the 2030s, targeting data rates exceeding 1 tbps, sub millisecond latencies, and ubiquitous coverage. Unlike its predecessor, 6G to be AI native and context aware. Ultra-low latency is a fundamental requirement for enabling critical applications such as immersive extended reality, autonomous mobility, remote surgery and the tactile internet.

MEC uses its proximity to the end-users to decrease the time it takes to transfer data, which improves the efficiency of essential applications such as real-time gaming and autonomous vehicles. 6G networks accomplish the demands of future generation strategies by improving reliability and reducing latency by employing the edge computing resources. With this integration, novel features are enabled, and uninterrupted connectivity is supported, bringing in a new era of reactive and efficient communication in the setting of 6G. Furthermore, the revolutionary potential of autonomous V2X communication is crucial for attaining ultra-low latency and high reliability in 6G networks, facilitating seamless connections between vehicles, roadside infrastructure, and individuals. As key technologies for intelligent transport, autonomous vehicles, and network control, V2X technologies are valuable for 6G networks due to their ultra-low latency and high reliability. V2X data interchange enhances traffic efficiency, ecological health, safety, and security through communication of vehicles with individuals, roads, and other vehicles. As a technology that allows for the smooth integration of cars into smart cities and instant decision making, this has revolutionized the way cities are designed and how transport is done. Furthermore, the evolution of packet scheduling techniques for Ultra-Reliable Low Latency Communication (URLLC) services is critical for satisfying the challenges of both ultra-low latency and high reliability in the 6G network, mainly in applications such as self-governed vehicles, industrial control, and other critical applications.

The vision of 6G is to largely enhance and extend the existing 5G three main services, including enhanced ultrareliable and low latency communications (eURLLC), ultra massive machine type communications (umMTC), and further enhanced mobile broadband.

These technologies in combination enable the implementation of high reliability and ultra-low latency communication in the framework of the 6G networks. MEC is one of the most important technologies that enhance the low latency in the 6G network by shifting the computation power close to the end user especially vehicles. By moving processing resources closer to the edge of the network, MEC minimizes the physical distance that data must travel, and by extension, the delay it experiences. This reduction in latency is crucial for real-time applications like self-driving cars, which require ultra-low latency and high reliability communication. The integration of MEC with self-driving V2X communication holds the potential to unlock unprecedented opportunities in communication and services.. These ultra-low latency advances lead to a new form of communication and services in various settings. Low latency is an exceptional feature of 6G networks through which necessary services, actuality services, incorporated reality, and real-time applications can be

incorporated. Furthermore, the integration of MEC with self-driving V2X communication, promoted by the low-latency capabilities, paves the way for transformative improvement in the transportation and automotive industries. In addition, the given latency features of UEs in 6G networks allow for the improvement of haptic communications for VAR applications that are crucial in areas like smart services, production, education, health, and gaming. These abilities also enable the industrial robotic applications such as warehousing transport, extended reality, and the large-scale integration of robots and automation networks. The ultra-low latency characteristics of 6G networks can open a new dimension for a large number of applications and services ranging from the necessary services that demand low latency to the revolutionary innovations in different sectors where the low latency of the UEs in 6G networks is expected.

6G is expected to revolutionize wireless communication technology, providing unprecedented levels of connectivity and automation 6G addresses the shortcomings of 5G by introducing new capabilities such as ultra-low latency, high data rates, connectivity for an extremely high density of devices, and high throughput. The evolution of 6G networks will be linked to the progress of mobile Internet and the IoE, which will use holographic communications to permit haptic interactions, providing a more natural and satisfying experience in digital worlds. The evolution of 6G networks will be intrinsically linked to the progress of two important IoT offshoots: mobile internet and the IoE. These enhancements will use holographic communications to permit haptic interactions, making it possible for users to have a more natural and satisfying experience in digital worlds. For these developments to succeed, the underlying communication technologies used in 6G networks will need to feature extremely high throughput and ultra-low end-to-end latencies as compared to the current 5G network. The comparison between the current 5G network with the potential 6G network is given by Table 1.

Using trust, low-latency, and high-bandwidth, millions of linked devices and apps are described as being able to function flawlessly in a 6G network. The article goes on to say that the most difficult challenge is likely to be achieving ultra-reliable and low-latency communications, which has stringent requirements for both low latency and ultra-high reliability. The foundation of a 6G network is automation. Experts have stressed the significance of AI and ML in improving vehicle and agent connectivity and guaranteeing high quality service. The most important source of motivation for these developments will be state-of-the-art AI algorithms. However, artificial intelligence algorithms require large datasets for efficient training, which in turn allows systems to make accurate conclusions. This system relies on the accurate flow tracking and other key parameters provided by the 6G core network. While 6G is an evolution of prior systems, it also marks a revolutionary technological change that has the potential to completely transform the foundations upon which today's mobile networks.

Table 1. Comparison of the current 5G network with anticipated upgrades and advancements of the next 6G network

Feature	Current 5G Network	Potential 6G Network
Network latency	Moderate latency (1-10 milliseconds)	Extremely low latency (10-100 microseconds)
Data rate	High data rates (up to 10 Gbps)	Very high data rates (nearly 1 Tbps.)
Device density	Supports moderate device density	Supports massive device density (120 devices/km ²)
Mobile traffic	High mobile traffic capability	Increased mobile traffic capability
IoT connectivity	Provides IoT connectivity	Ultra-densification of IoT networks
Key extensions	Mobile Internet and IoT	Mobile Internet and Internet of Everything (IoE)
Impact	Revolutionizing mobile communications	Transformation of multiple industries

The development of 5G networks was driven by the need to solve problems caused by 4G networks, such as the need for more bandwidth, lower latency, faster data rates, wider device connectivity, and more consistent quality of experience provisioning. This was made possible by the convergence of cutting-edge technologies used in 5G networks, including Massive MIMO, Cognitive Radio, and Mobile and Static Cell Networks. Emerging as a key 6G use case, URLLC promises to support networking for new technologies like driverless vehicles and smart industries. Because of the strong latency limits imposed by URLLC, its traffic is typically preferred over ongoing enhanced Mobile Broadband (eMBB) transmissions. Beyond 5G networks (B5G) or 6G systems have received considerable attention since the introduction of multiservice networking. It is important to note that 6G reliability and latency factors can be adapted to individual use cases. 6G is also predicted to provide the benefit of extremely extended battery life, which could eliminate the need to charge devices. To lessen the effects of rising network complexity, experts predict that integrating multiservice technologies will boost network intelligence.

- A thorough literature assessment of previous efforts on topics such as autonomous vehicles, 6G-based URLLC networks, Virtualized Radio Access Network (vRAN), and MEC services should be the first step. Find the major problems and restrictions in the current research. Problems with latency, safety, scalability, and MEC integration are all possibilities.
- Comprehensive Analysis of URLLC Packet Scheduling Methods: This study offers a full analysis of the available packet scheduling methods for URLLC services, which are characterized by their extreme reliability and low latency. Applications like autonomous vehicles, industrial automation, and mission-critical communications necessitate ultra-reliable and low-latency connectivity, and URLLC is a crucial part of 6G networks that can provide it. Understanding how effectively URLLC requirements can be met in the context of 6G networks is improved thanks to the paper's thorough discussion of the relevant algorithms.
- Scheduling Algorithms Classification: The study classifies scheduling methods as either decentralized, centralized, or joint to help readers gain a more holistic and organized understanding of packet scheduling in 6G networks. This classification allows researchers and practitioners examine a range of ways for improving resource allocation and traffic prioritization, taking into consideration the different needs of applications in 6G systems.
- The study does more than only summarize prior work; it also explores unknown ground in terms of future research possibilities and problems related to scheduling algorithms for URLLC services in the context of forthcoming 6G wireless systems. Coexistence of different services, integration of cutting-edge technologies, and security in a highly linked environment are all problems and opportunities that will emerge as 6G technology develops further. The document helps researchers and industry professionals focus their efforts on the most pressing issues and promising avenues for furthering 6G networks.

Latency requirements in 6G use Cases

Tactile Internet: requires round trip latencies < 1 ms.

Autonomous Vehicles: Need 0.1 - 1 ms end-to-end latency for safe decision making.

Industrial automation: Demands consistent low latency (0.5 ms) with high reliability.

ESSENTIAL REQUIREMENTS OF 6G NETWORKS

To effectively cater to the stringent connectivity demands of AR and other real-time, latency-sensitive applications, 6G networks must integrate a sophisticated two-tier AI model system: 2

➤ Lightweight AI Model (Real-time Network Intelligence):

Deployed potentially at the Radio Access Network (RAN) edge or within access points, this AI model will perform continuous, granular monitoring of prevailing network conditions. Its responsibilities include real-time evaluation of key performance indicators (KPIs) like data rates (aiming for peaks over 1 Terabit per second [4]), signal strength, interference levels, and user mobility prediction. Furthermore, it must understand the specific Quality of Service (QoS) needs of individual AR applications, such as rendering complexity, required frame rates (e.g., 90-120 fps for immersion), and acceptable latency thresholds (ideally under 10 milliseconds motion-to-photon latency for AR [5]). Based on this real-time analysis, the lightweight AI model must proactively predict the need for seamless handovers between base stations (gNBs) within the same Radio Access Technology (RAT) or anticipate the necessity for a RAT change to maintain optimal performance and user experience.

➤ Seamless Handovers and Intelligent RAT Management:

Achieving truly uninterrupted connectivity, a cornerstone for compelling AR, requires significant advancements in 6G handover mechanisms and RAT management: Proactive Contextual Network Evaluation: Moving beyond reactive triggers like signal strength thresholds, 6G networks, guided by the lightweight AI model, must continuously monitor multiple contextual parameters. This encompasses not only signal quality but also network load, latency, available bandwidth, and the specific QoS requirements of the active AR application. By

anticipating potential disruptions before they impact user experience, 6G can initiate handover procedures preemptively. Intelligent RAT Selection Based on Real-time Needs: 6G is expected to utilize a diverse mix of RATs, including enhanced 5G New Radio (NR), unlicensed spectrum technologies (like Wi-Fi 7, offering multi-gigabit speeds and lower latency [6]), and potentially Terahertz (THz) communications for ultrahigh bandwidth short-range applications [7]. Informed by the AI models, the intelligent RAT management system must dynamically select the most suitable RAT based on the AR application's real-time demands. For example, an outdoor, high-mobility scenario might necessitate switching to a robust cellular RAT, whereas an indoor, high-bandwidth task could trigger a transition to an advanced Wi-Fi network.

Power Optimization As A Critical Requirement For 6g

While 5G focused heavily on achieving ultra-high speeds, notably through millimeter wave (mmWave) technology, 6G must elevate power efficiency to a paramount design principle. Although mmWave offers multi-gigabit data rates beneficial for demanding AR applications, it presents inherent challenges: High Power Consumption: mmWave technology typically requires significant power to overcome path loss and operate effectively. This high demand is a major limitation for battery-powered devices like AR/VR devices and wearables, where battery size and weight are critical constraints [8]. Line-of-Sight (LoS) Limitations: mmWave signals are easily attenuated by obstacles (walls, trees, people), often requiring a direct LoS path between the device and the base station (gNB). This complicates seamless mobility for AR applications needing constant connectivity in cluttered realworld environments.

Challenges And Future Directions

While AI-driven adaptability in 6G offers significant advantages for applications like AR, several critical challenges must be addressed for successful realization and deployment: Computational Efficiency: Implementing sophisticated AI models for real-time monitoring and prediction demands substantial computational resources. These models must be optimized to run efficiently not only on network infrastructure (base stations, edge servers) but potentially also on resource-constrained edge devices like AR/VR devices.. Security and Privacy: Embedding AI into network management introduces new security vulnerabilities and privacy concerns. AI decision-making must be robust against adversarial attacks that could cause network disruption or security breaches. Furthermore, collecting and analyzing network data for AI training must adhere to strict data protection regulations and privacy-preserving principles.: Successful 6G deployment requires universal protocols and standardized interfaces for AI-driven connectivity management across different vendors, operators, and regions. Interoperability is crucial for seamless roaming and consistent AR user experiences. Standardization efforts (e.g., via IEEE, 3GPP) must cover AI model exchange formats, data sharing protocols, and common APIs for network control. Collaboration among industry, research institutions, and standards bodies is essential. Future research should prioritize developing novel, energy-efficient AI models tailored for wireless network management, refining predictive analytics for accuracy and responsiveness, and enhancing AI security and privacy frameworks to ensure trustworthy 6G networks. Exploring emerging technologies like quantum computing for potentially accelerating AI training and network optimization could also be a promising research avenue

BACKGROUND

Despite the promising capabilities of 6G networks, several challenges must be addressed to realize their full potential. One significant challenge is the development of communication protocols and technologies capable of supporting ultra-reliable low-latency communication (URLLC) at scale. Achieving the targeted data rates in the terabit-per-second range while ensuring seamless connectivity in dense urban environments and remote rural areas poses another formidable challenge. Additionally, ensuring the security and privacy of data transmitted over 6G networks, especially in the context of IoT applications, remains a critical concern. Overcoming these challenges requires interdisciplinary collaboration and innovative approaches to network design, infrastructure deployment, and policy formulation.

The 6G architecture uses innovations like network functions virtualization (NFV) and Software Defined Networks (SDN) to improve network uptime, reduce wasted resources, and fix problems autonomously. With the advent of 6G, improvements in communication technology are anticipated to usher in revolutionary shifts across many industries, but none more so than remote control and the IIoT. Ultra reliable Low Latency Communication (6G) will rely heavily on this technology. URLLC is a crucial part of 6G communication systems due to its potential to provide extremely low latency with sub-millisecond cycle rates and extremely high transmission efficiency over large areas as mentioned in the study by Vista Enhanced Mobile Broadband (eMBB), similar to its role in 5G, will continue to enable high-speed data transfer, approaching Gigabit-per-second (Gbps) ranges.

Another technology from 5G that will be used in 6G networks to help spread IoT is Massive Machine Type Communication (mMTC). With mMTC, we hope to link a wide variety of gadgets over great distances with concise communications mMTC is anticipated to play a key role in the 6G era by facilitating the networking of varied devices, supporting applications like sensor readings and small intermittent data transmissions, and ultimately fostering the growth of the Internet of Things.

Many new types of services are anticipated to leverage the superior capabilities of 6G technology, representing the next generation of wireless communication. These services span a wide range of application areas and promise game-changing capabilities facilitated by 6G technology (see Figure 1).

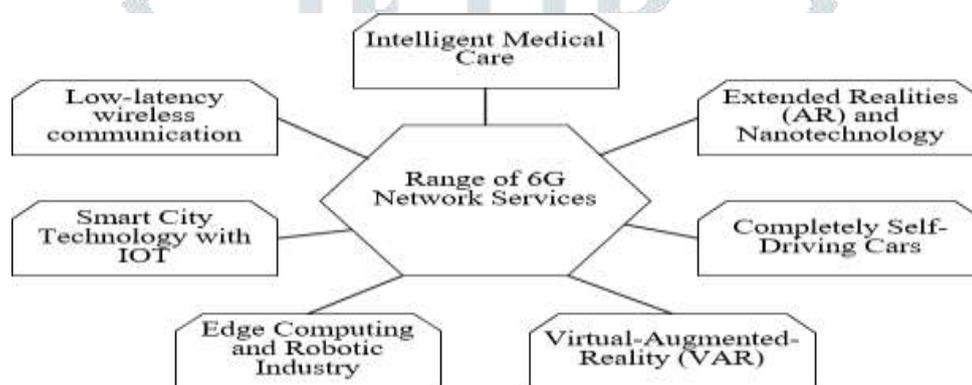


Figure 1. Range of applications compatible with 6G network with advanced coverage on network speed and efficiency



Figure 2. The edge computing architecture of compute offloading for 6G wireless networks

Videos in Extreme HD (EHD) quality will benefit from increased bandwidth and decreased latency in the wireless network, enabling the use of 16 GB and 32 GB patterns of EHD videos to meet network communication's significant need for video file processing. 6G introduces transceiver devices with separate antennas, allowing for automatic software updates and protection against hacking and signal interference to provide safe, efficient data transfer. Secure, dependable, low-latency wireless communication enables real-time service engagements, benefiting fields such as healthcare, industry, the arts, and academia. Haptic communications' support for Virtual-Augmented-Reality (VAR) through the use of sensory-based signals will have applications in industry, smart services, manufacturing, education, healthcare, and gaming.

These programs require extremely fast data transmission in real time, and the availability of 1 Tbps bandwidth paves the way for genuine face-to-face communication utilizing several digital patterns from disparate origins or real-time immersion models. Low-latency network connectivity and precise interior positioning will be

beneficial for applications in the robotic industry, including warehouse transportation, extended reality, large integration of robotics, and automation. 6G technology's high bandwidth, reliability, and low latencies pave the way for V2X connection, profoundly affecting the transportation and auto industries. Applications in healthcare, smart cities, the military, etc., will benefit from the "Internet of Bodies" and "Internet of Nano-Things" ideas by making use of low-power and implantable sensors, smart wearable devices, etc. Accessible around-the-clock, HD video conferencing solutions that are both secure and reliable are key to the concept of a future-proof healthcare system, paving the way for remote disease diagnosis and continuous health monitoring.

. A comprehensive investigation into 6G with a Furthermore, AI-driven 6G is expected to delve into the untapped potentials of radio signals, enabling the transition from cognitive radio to intelligent radio . Notably, machine learning (ML) plays a pivotal role in understanding the algorithmic nuances of AI-enabled 6G. Reconfigurable intelligent surfaces take centre stage as the envisioned Massive MIMO 2.0 in 6G. These surfaces, when coupled with index modulation, are poised to significantly enhance 6G spectral efficiency.. In March 2019, the first 6G summit took place in Levi, Finland. Since then, there has been a flurry of academic research on 6G, with events like Huawei 6G Workshops, Wi-UAV Globe com 2018, and Carleton 6G adding to the conversation about the potential and progress of 6G.

The primary goal of 6G is to address the evolving demands of the information society by 2030, envisioning a future where 5G's limitations are surpassed and unmet service needs are addressed. The four main components of 6G's vision are "Intelligent Connectivity," "Deep Connectivity," "Holographic Connectivity," and "Ubiquitous Connectivity," shaping the overall 6G vision. In contrast, the 5G network is confined to a communication range of just 10 kilometres above the Earth's surface and is primarily focused on data interchange and the Internet of Things

connectivity in the SAGS arena, this integration requires a unified technological system and common protocol architecture. Unlike 5G, 6G places more emphasis on the number of communication links in massive Machine Type Communications (mMTC) and URLLC, prioritizing real-time performance and reliability over throughput and connection count. Consistent, extensive, high-throughput, and real-time performance are the pillars upon which the 6G vision rests. While some fundamental ideas in the 6G vision are rooted in 5G, the 6G vision advances these concepts to meet the demands and challenges of emerging scenarios in the future, as compared in Table 2.

Table 2. Comparison between 5G and 6G networks

Parameter	5G Network	6G Network (Speculative)
Frequency Bands	Sub-6 GHz and mmWave (24-100 GHz)	mmWave and Terahertz bands (100 GHz and above)
Cells	Small cells, macro cells, and pico cells	Highly dense small cells, potentially incorporating aerial and space cells
MIMO (Multiple Input, Multiple Output)	Up to Massive MIMO (32×32, 64×64)	Advanced Massive MIMO, Intelligent Reflecting Surfaces (IRS)
Duplex Nature	Full Duplex (Simultaneous transmission and reception)	Enhanced Full Duplex, Improved spectral efficiency
Latency	Sub-10 milliseconds (Goal: 1 millisecond)	Ultra-low latency, potentially sub-millisecond
Data Rate	Peak data rates up to 20 Gbps (in ideal conditions)	Enhanced peak data rates, potentially exceeding 100 Gbps
Energy Efficiency	Improved energy efficiency compared to 4G	Further improvements in energy efficiency, sustainable technology than 5G
Security	Enhanced security features compared to 4G	Improved security protocols, potentially quantum-resistant algorithms
Connection Density	Up to 1 million devices per square kilometer	Increased connection density, supporting the Internet of Everything (IoX)
Use Cases	Improved mobile broadband, massive Internet of Things (IoT), and URLLC	Transforming Internet of Things (IoT) applications, holographic communication, and cutting-edge augmented reality (AR) and virtual reality (VR) are undergoing continuous

METHODOLOGY

In this research, we employ a comprehensive methodology to optimize the integration of edge computing (EC) and 6G networks for real-time Internet of Things (IoT) applications. Our approach focuses on developing intelligent algorithms for task offloading, designing energy-efficient resource allocation schemes, and implementing a joint optimization framework. Additionally, advanced machine learning techniques are leveraged to enhance decision-making processes. By combining theoretical analysis, simulation experiments, and performance evaluations, this methodology aims to address the challenges of latency, reliability, and scalability in IoT environments, ultimately contributing to the development of a more efficient and responsive IoT ecosystem.

Edge computing in 6G networks focuses on distributing computational resources closer to the data source, minimizing latency, and enhancing the responsiveness of real-time IoT applications. The main purpose of this work is to create a robust framework that optimizes task distribution and resource utilization while addressing energy efficiency and latency challenges. Figure 1 illustrates the integration of edge computing and 6G networks, showcasing the flow of data from IoT devices through various stages such as preprocessing, feature extraction, and resource optimization, ultimately leading to efficient task execution and performance monitoring. The optimization problem aims to minimize total latency and energy consumption for IoT task offloading.

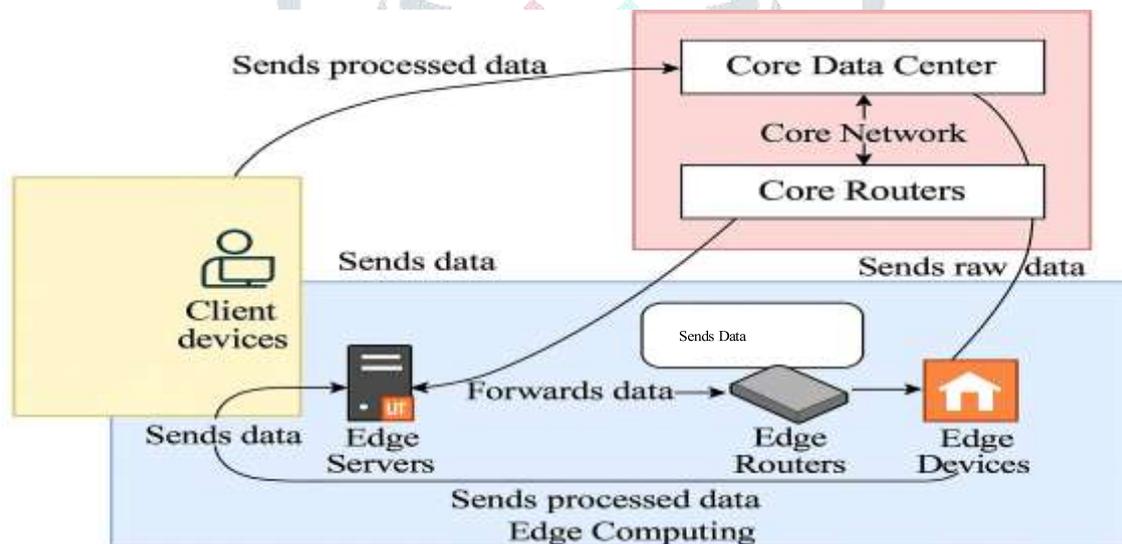


Figure 1. Integration of edge computing and 6G networks for real-time IoT applications.

. This methodology establishes the foundation for achieving optimal task distribution and resource utilization in edge computing environments integrated with 6G networks

NETWORK ANALYSIS

➤ 6G and self-driving cars usage case scenario

6G technology holds the promise of delivering advanced capabilities in terms of low latency, data rates, and connectivity. However, the practical implementation of these features in the context of self-driving cars will be contingent upon the development of standards, infrastructure deployment, and the resolution of various technical and regulatory challenges. To comprehend the potential impact of 6G technology on self-driving cars as it matures, it is essential to stay updated on its ongoing developments. One key aspect of 6G is its capacity to provide significantly higher data rates compared to its predecessors.. There is an urgent need to build on this potential to mean that URLLC is an important innovation of 6G to solve the challenges relating to standards, policies, and regulations. This is especially important in applications such as self-driving cars where communication must be reliable and not delayed at all. URLLC will provide very low latency, high reliability, and availability which is crucial for the autonomous vehicle to operate in a highly dynamic environment. The massive device connectivity feature of 6G is poised to support the proliferation of connected devices in smart city environments, including self-driving cars. This capability is crucial for handling the increasing complexity and interconnectedness of devices within urban landscapes, contributing to the efficiency and reliability of self-driving car operations.

➤ Ultra low latency with 6G (Usage case: Self driving cars)

The ultra-low latency in the context of 6G networks and self-driving cars involves minimizing the time delay between sending a command and receiving a response. This delay consists of several components, and each can be mathematically represented. Here are the numerical representation of latency functions in network.

Having ultra-low latency is essential for self-driving cars to acquire and react to real-time information quickly. This is anticipated to be revolutionized by 6G technologies, which will reduce transmission latency to milliseconds or less. Self-driving cars can instantly communicate essential data with other vehicles, traffic facilities, and centralized networks due to this extremely quick connection. This allows for safer and more effective navigation through difficult conditions, which ultimately improves road security and transportation.

(1) Handling latency (H)

Depicts the amount of time needed for transmitting data between two points. The method for determining handling latency involves dividing the transferred data size by the transmission rate. This process requires an understanding of the duration it takes to send a particular amount of data at a certain speed. For example, higher handling latency is the effect of transferring more information at slower speeds.

➤ Reliability with 6G (usage case: self driving cars)

Reliability in the context of 6G networks and self-driving cars is often associated with ensuring that communication is highly dependable, with a minimal risk of failure or disruption. While reliability is a complex concept and depends on various factors, including network architecture and protocols, here are some general components that contribute to reliability, along with their mathematical representations.

In 6G networks, high reliability is essential for self-driving cars because safety can be determined in ms. The reliable infrastructure of 6G provides constant communication, which is necessary for real-time data sharing between cars and their environment. Self-driving cars have ultra-low latency and little downtime, which allow them to react quickly to changing road conditions and improve effectiveness and security for passengers. 6G's advanced communication standards reduce

It is important to note that achieving high reliability involves implementing error detection and correction mechanisms, redundancy, and other techniques to mitigate the impact of potential failures. The specific reliability requirements for self-driving cars in a 6G context would depend on safety-critical considerations and industry standards.

Table 3. Industry standards requirement for 6G network

Requirement	6G Support for V2X
Low latency	Ultra-low latency (<5 ms)
Reliability	High reliability (>99.9%)
Data rates	High data throughput (>20 Gbps)
Signal interference and fading resistance	Strong resistance to interference
Signal coverage	Wide coverage range (up to 500 meters)
Mobility support	High-speed data transmission support (up to 500 km/h)

With the evolution of wireless communication and the IoT, there is a potential for significantly enhanced and efficient transportation systems. In the realm of 6G networks, V2X emerges as a pivotal application, mirroring the role of 5G URLLC in fostering automated, accident-free, and collaborative driving as the requirements are given in Table 3. V2X imposes specific requirements on the wireless communication network .

Low latency: Autonomous vehicles necessitate extremely low latency in COMMUNICATION between each other, surpassing the capabilities of the current 5G.

Reliability: Given that transmission errors, such as packet loss, can lead to serious incidents in autonomous vehicle scenarios, the reliability of these communication systems must be exceptionally high in case of 6G.

Data rates: V2X applications, particularly those relying on high-resolution images and videos to perceive their environment, demand substantial data throughput.

Signal interference and fading resistance: Vehicles contend with significant signal interference from other wireless communication systems, especially in urban settings.

Additionally, structures and large objects may scatter or reflect signals, requiring resistance to interference and fading.

Signal coverage: V2X transmissions must consistently reach the nearest base station, even when it is located hundreds of meters away.

Mobility support: V2X applications should seamlessly transmit and receive data at very high speeds, accommodating scenarios such as communication with high-speed trains.

SYSTEM MODEL

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- 1. Low latency:** Autonomous vehicles necessitate extremely low latency in COMMUNICATION between each other, surpassing the capabilities of the current 5G.
- 2. Reliability:** Given that transmission errors, such as packet loss, can lead to serious incidents in autonomous vehicle scenarios, the reliability of these communication systems must be exceptionally high in case of 6G.
- 3. Data rates:** V2X applications, particularly those relying on high-resolution images and videos to perceive their environment, demand substantial data throughput.
- 4. Signal interference and fading resistance:** Vehicles contend with significant signal interference from other wireless communication systems, especially in urban settings.

5. This speculative model represents the deployment of 6G network on the MEC Cloud with the potential effects of geography. This also illustrates the effect of latency on creating radio frequency (RF) simulations for the potential 6G network, covering the signal density and latency of network. It proposes a structure for examining how the next-generation networks, 6G, could be developed and utilized within the MEC Cloud context, taking into account elements such as terrain, climate, and networking node distance. Through the integration of these variables into the model, researchers can more accurately predict obstacles and enhance network efficiency for upcoming 6G deployments.

Determine the best assets for a 6G network

The first step in deploying 6G is to locate and assess potential spectrum bands, such as terahertz frequencies. The potential usage of terahertz frequencies, which can transport massive amounts of data at extremely fast speeds and fall between hundreds of gigahertz and several terahertz, is being evaluated for use in 6G.

Determine whether cutting-edge methods, such as massive MIMO and beamforming, are practically feasible. While beamforming concentrates radio frequencies into narrow beams directed at certain users or places, massive MIMO utilizes an extensive number of antennas at the receiver and transmitter to serve numerous users concurrently.

Look into possible 6G infrastructure solutions that are energy efficient. The need to use less energy to save operating costs and the environment is becoming more and more significant as technology grows.

Counter for iterations

Create a procedure for optimizing the system through iterative processes. Establishing an average efficiency utilizing initial configurations is the first step in iteratively optimizing a system. Operating the system under typical conditions and logging performance indicators are part of this process. The optimization process requires making small, controlled alterations to the configuration or architecture of the system, which are then evaluated in terms of performance to determine their effects.

Establish throughput, dependability, and latency as key performance indicators (KPIs). The rate at which the network produces data or transactions is referred to as throughput, and it is usually expressed in units per second. Availability and dependability are related terms that describe the degree to which a system operates as intended and how often it remains functional throughout a specific time frame. The time lag between providing an input and getting the intended result is measured as latency, and it's frequently important in real-time applications. These KPIs offer a quantitative structure for assessing the effectiveness of the system.

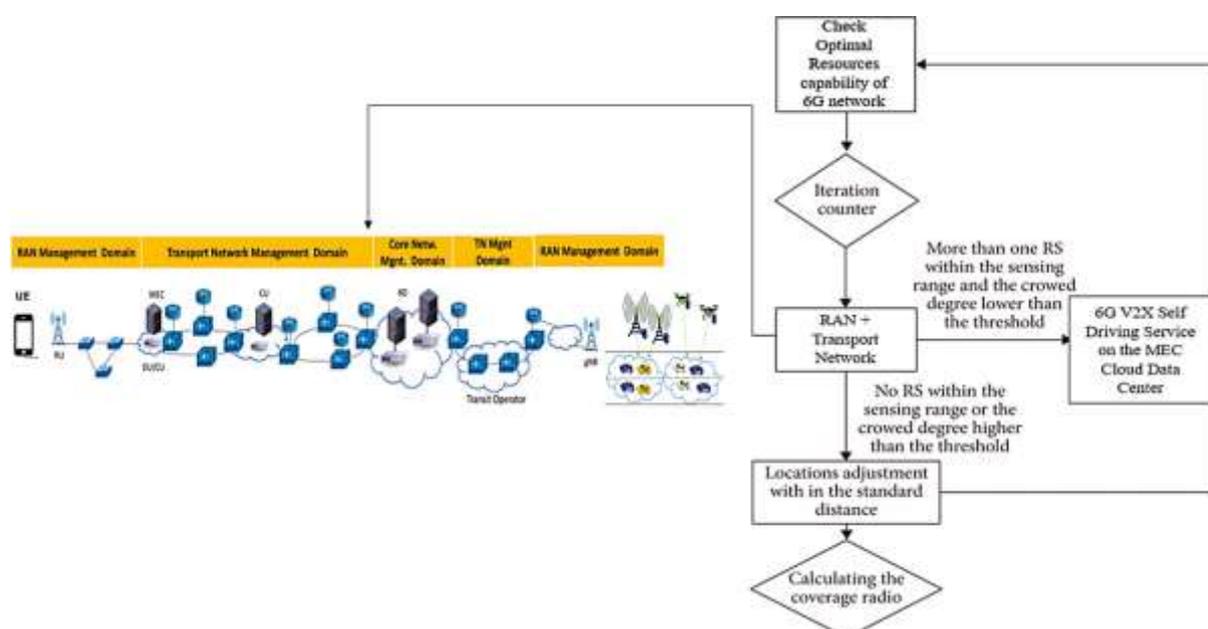


Figure 3. Speculative model of the potential 6G network with the V2X self-driving cars on the MEC cloud

Adjust the system's settings using an adaptive algorithm that takes user input into account. Initially, user preferences and data are gathered. The adaptive algorithm then processes this information to find trends and patterns. The system can adjust to evolving user preferences and behaviors since the algorithm constantly enhances its forecasts by integrating new user data. Employing an adaptive algorithm has the main benefit of personalizing the system's effectiveness, which increases user responsiveness and efficiency.

Network access network plus for 6G vehicle-to-everything self-driving service on the MEC cloud. For real-time V2X relationships, 6G technology offers incredibly rapid and low-latency communication features. Reducing delay and improving system adaptability, the MEC cloud shifts processing and storage capabilities closer to the vehicles. Reliable data transfer and continuous connectivity throughout the network is provided by the Network access network plus module.

RESULT

The simulation using the recommended method uses an Intel dual-core i7 CPU with 8 GB of RAM and performs in the MATLAB R2021a environment. Our suggested MEC+ V2X model is evaluated in terms of precision, F1-score, accuracy and recall with the traditional Extreme Gradient Boosting (XGBoost), k-nearest neighbor (KNN), and Random Forest (RF). Table 4 shows the simulation parameters.

Regarding 6G networks and their use in self-driving V2X automobiles [UE], a number of important variables affect communication dependability, latency, and overall performance. The advancements made in these areas are highlighted by the following findings in Table 5:

- Optimization of Channel Dispersion [Q]
- Improvement in reliability function [R].
- Downlink Probability Optimization. The speculative curve provides a visual representation of how the spreading of signals, or channel dispersion, affect the signal quality in a 6G network. The numerical values and powers of 10 help illustrate the concept that as channel dispersion increases (moving along the X-axis), the quality and integrity of signals decrease (Y-axis values decreasing from 10^0 to 10^{-6}) of reliability is given in Figure 4.

The speculative graph illustrates how the Downlink Probability in a 6G network may influence the UE Timeout durations as shown in Figure 5. As the likelihood of successful downlink communication decreases, the UE Timeout durations may increase. Thus, the values ranging from 10^{-2} to 10^{-4} for the X-axis (Downlink Probability) and from 10^1 to 10^6 for the Y-axis (UE Timeout) to describe a speculative graph between UE Timeout and Downlink Probability in a 6G network.

Now to assess the reliability and latency of autonomous vehicles in the context of a 6G network, Monte carlo simulations were conducted with the following configurations: the weight factor was set to 20, and the RSU covered a road length of 800 meters. Signal density was specified as 0.5 vehicles per minute w.r.t car speed. Key parameters, including the message generation exchange rate at 80 messages per second, average service time for each UE (car) at 10 milliseconds, and vehicle transmission power set to 50 dBm, were taken into consideration

In order to account for a multiple-hop scenario, we also set the slot duration at 65 microseconds, the noise power density at -180 dBm/Hz, and the number of resource blocks at 20. Figures 6-8 show the results of the simulations, respectively, illustrating advancements in handling latency, propagation latency and total latency within the 6G network context.

Propagation latency is shown to increase gradually on the graph, as the density of UEs stays constant. This increase suggests that there may be problems with the efficiency of signal transmission if the density of UEs is not changed on the fly to meet the communication demands of the network. The graph also shows an alternative scenario where the propagation latency decreases with a constant and steady density of self-driving cars.

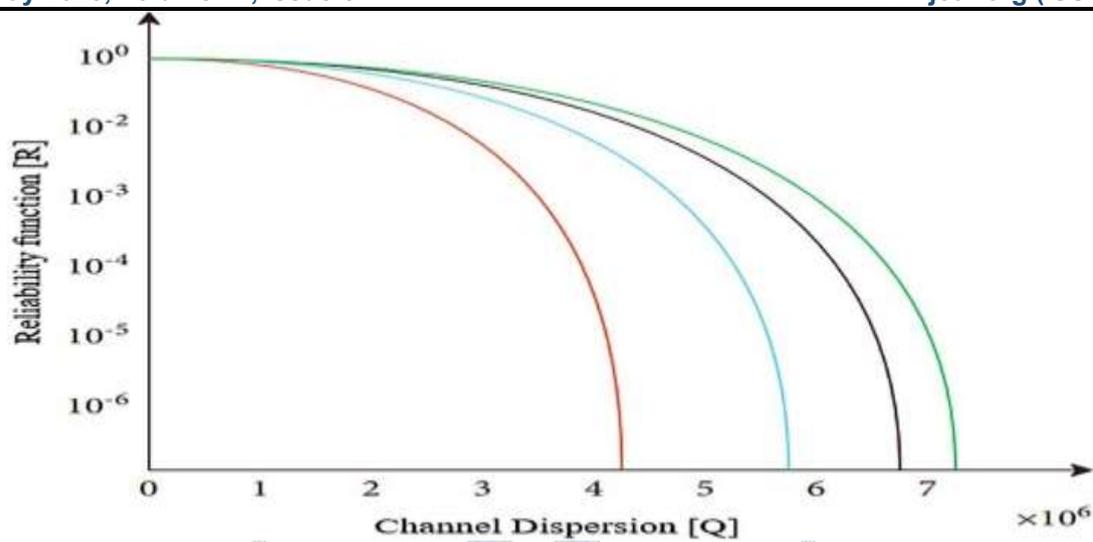


Figure 4. Curve showing the channel dispersion effect on the signals speculated over 6G network

The F1-score is a useful metric for assessing how well communication methods achieve low latency and high reliability by balancing precision and recall. Our proposed model, MEC+V2X, has a F1-score of 97.05% when compared to conventional techniques. In comparison, the F1-score of the traditional XGBoost, RF, and KNN approaches are 82.23%, 74.43%, and 70.21%. Output of F1-score is displayed in Figure 9.

For crucial applications, the precision evaluates the system's capacity to reliably provide packets within a set period with the least possible errors, ensuring correct and timely data transfer. Our proposed model, MEC+V2X, has a precision value of 94.78% when compared to the traditional approaches. By comparison, the precision values of the traditional XGBoost, RF, and KNN algorithms are 85.45%, 79.34%, and 71.21%. Figure 10 shows the output of precision.

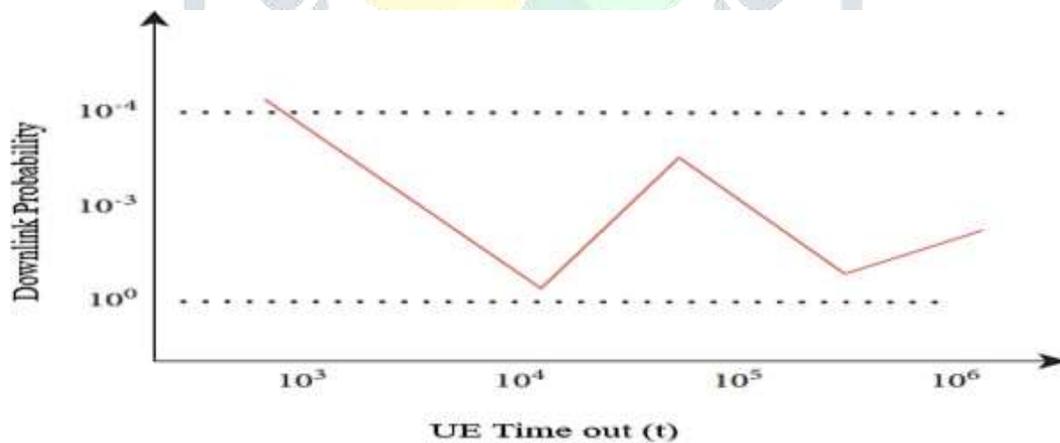


Figure 5. The threshold point representing a critical level of Downlink Probability where UE timeout durations increase more noticeably

The accuracy measures how well the network can reliably deliver data with low latency and great reliability, guaranteeing essential services' accessibility in real time. In comparison with the existing methods, our suggested MEC+V2X model has the accuracy of 95.03%. The conventional XGBoost, RF, and KNN methods has the accuracy value of 87.93%, 80.63%, and 72.06%, respectively. Figure 11 displayed the result of accuracy.

Recall assesses the percentage of pertinent communication situations that the network has successfully located, providing low latency and optimal reliability for essential services and real-time data transfer. Compared with the existing methods, our suggested model, MEC+V2X, has a recall rate of 96.12%. In contrast, the recall rates of the conventional XGBoost, RF, and KNN algorithms are 80.32%, 76.21%, and 69.32%. Result of recall is shown in Figure 12.

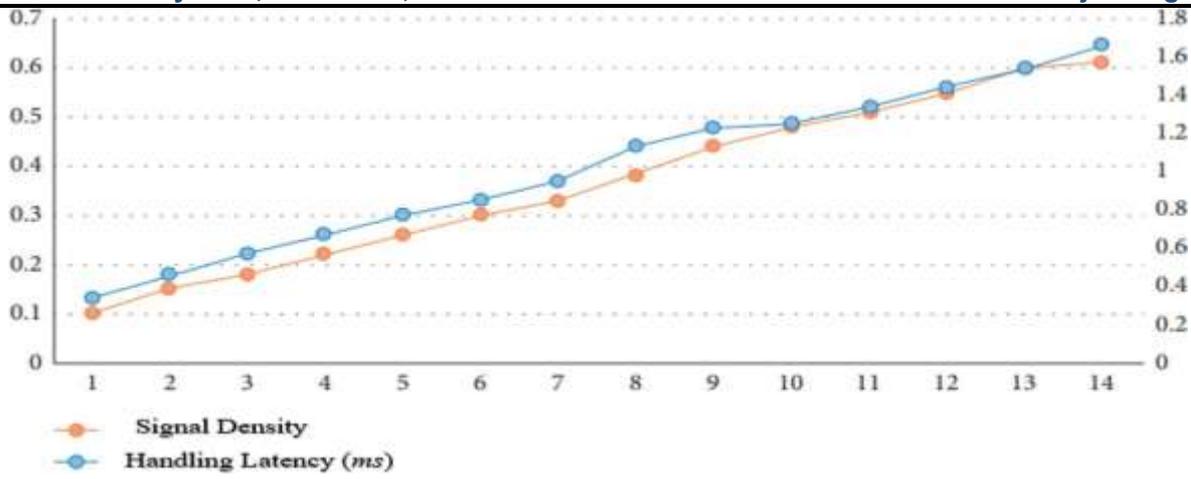


Figure 6. With increase of signal density, reduction in the handling latency of 6g signal

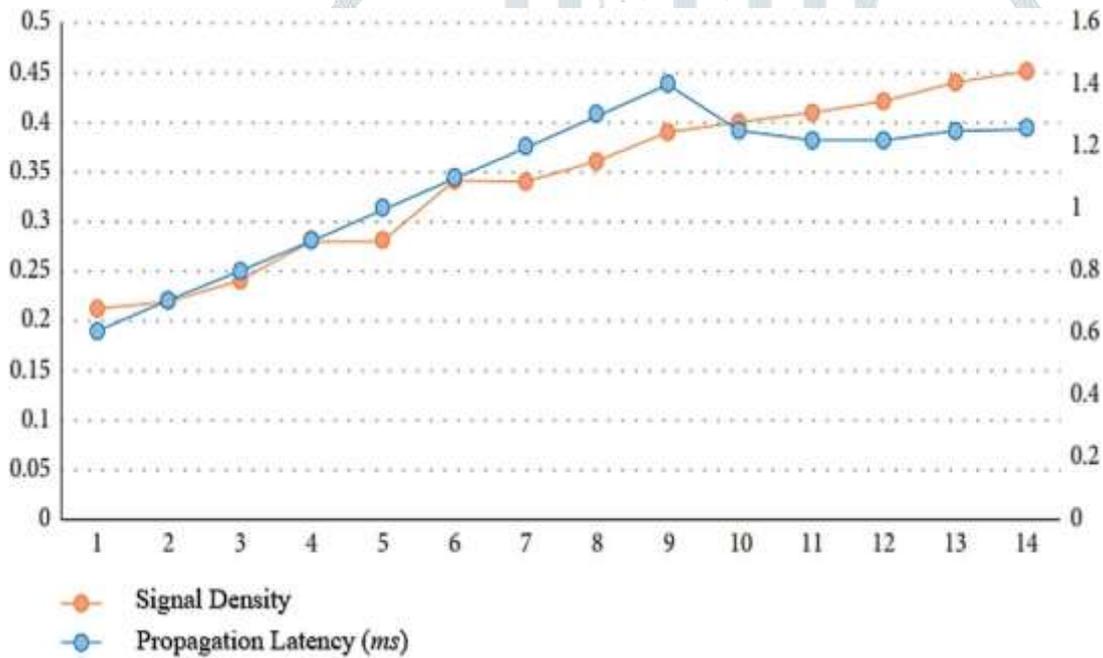


Figure 7. Impact of signal density on propagation latency for UE (car) and self-driving car

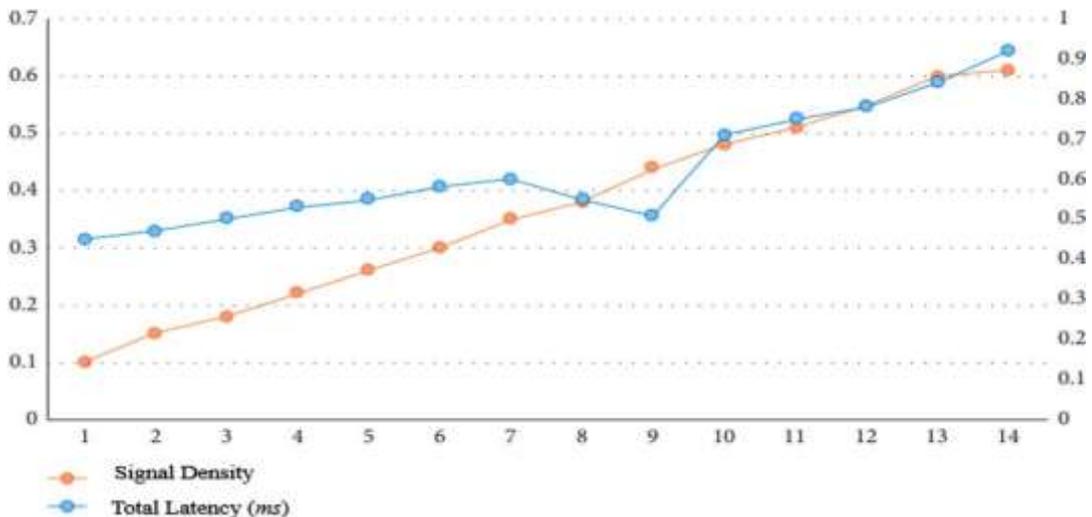
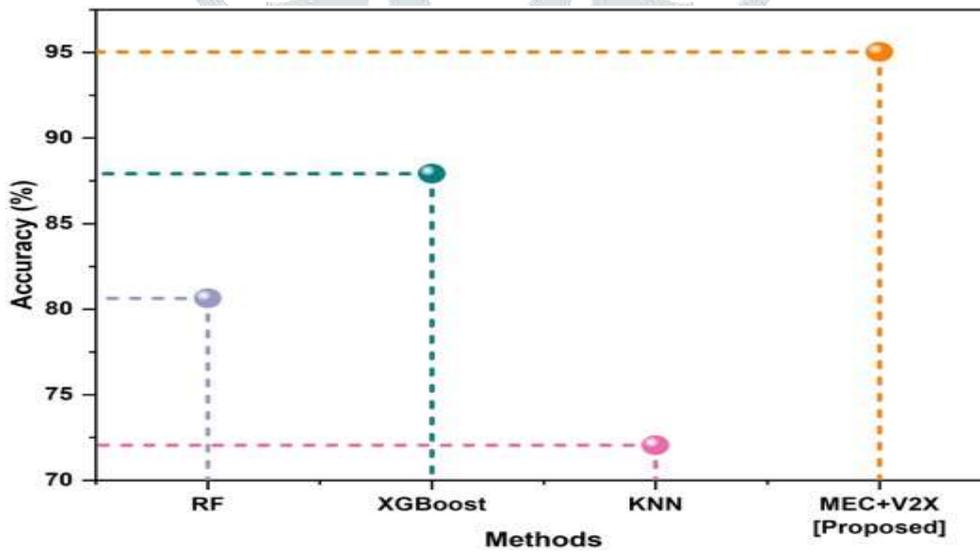
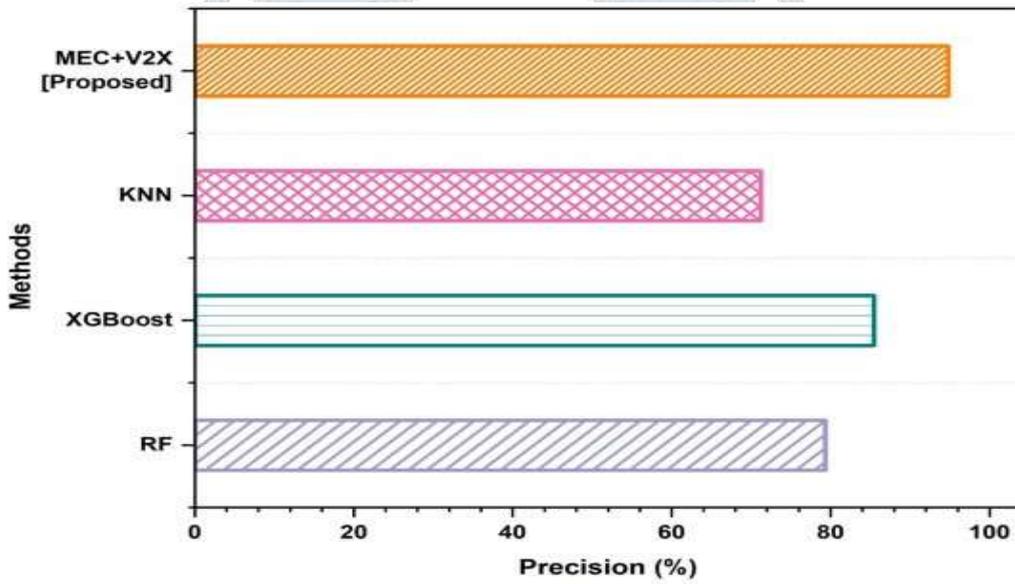
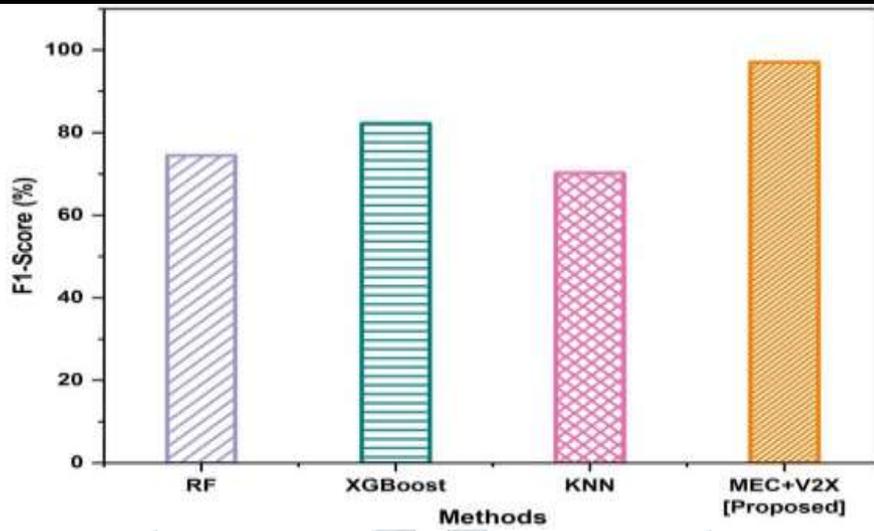


Figure 8. Relationship between signal density and total latency in a network with self-driving cars



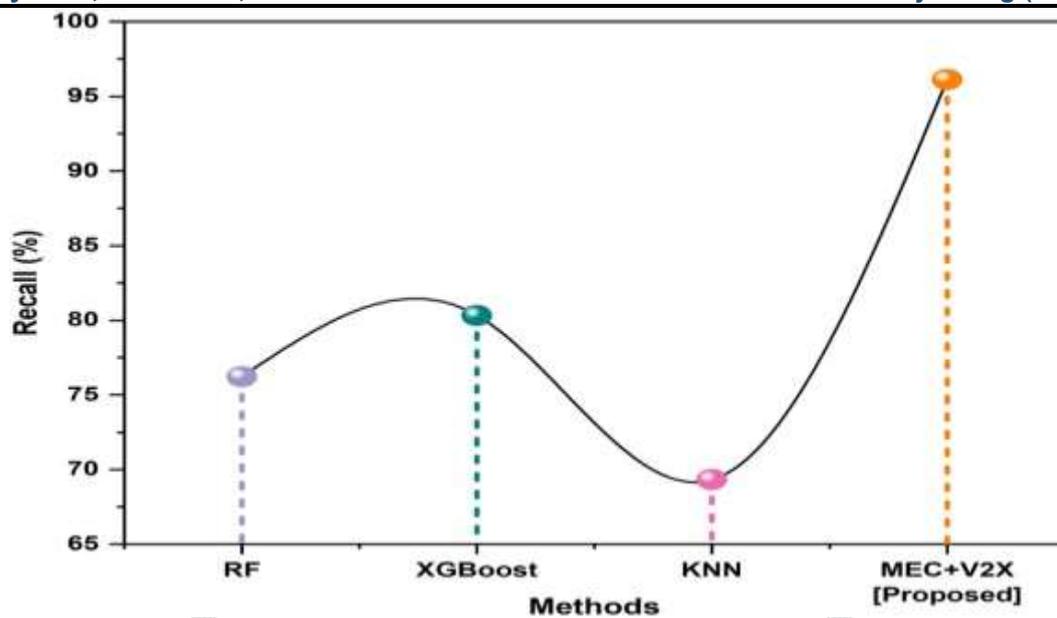


Figure 12. Result of recall

Latency and Throughput

Figure 13 shows the contour plots for latency and throughput in edge computing with 6G and IoT devices. The left plot depicts the latency distribution, while the right plot illustrates the throughput distribution across different device positions. The latency contour plot reveals areas of high and low latency within the network, providing insight into the spatial variability of latency experienced by devices. High-latency regions, indicated by warmer colors, are primarily located in the central and upper sections of the plot. These areas likely represent zones with higher congestion or greater distance from the edge servers, resulting in increased data transmission times. Conversely, regions with cooler colors indicate lower latency, suggesting more efficient data processing and transmission in those areas. The throughput contour plot complements the latency findings by showing the distribution of data transmission rates across the network. Higher-throughput areas, depicted by cooler colors, correspond to regions where the network is capable of handling larger volumes of data more effectively. These regions likely benefit from the optimal placement of edge servers and robust network infrastructure, enabling efficient data flow and minimal delays. On the other hand, areas with lower throughput, indicated by warmer colors, may suffer from bottlenecks or suboptimal resource allocation, limiting the network's data handling capacity. By analyzing these contour plots, it becomes evident that the integration of edge computing with 6G networks can significantly influence both latency and throughput. The spatial patterns highlighted in the plots provide valuable information for optimizing the placement of edge servers and managing network resources to enhance overall performance. Furthermore, understanding the variability in latency and throughput across the network allows for targeted improvements in areas experiencing suboptimal performance, ultimately leading to a more efficient and reliable edge computing environment for IoT applications.

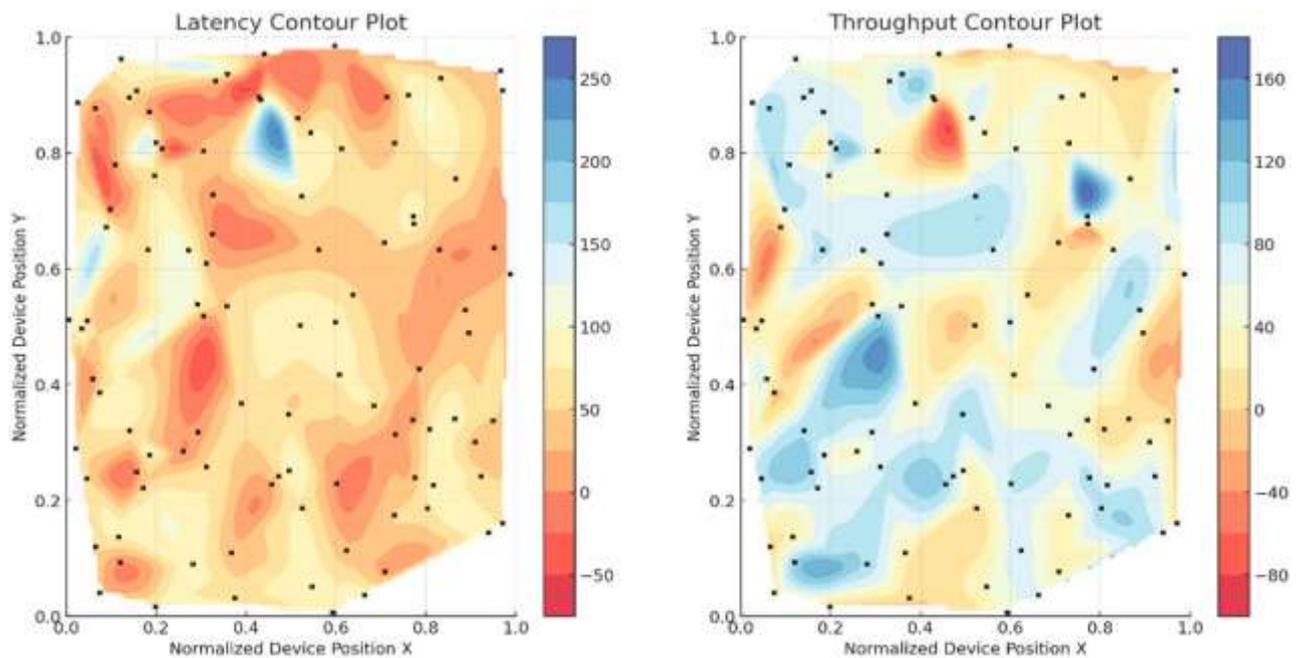


Figure 13. Contour plots for latency and throughput in edge computing with 6G and IoT devices

Comparison of Latency and Energy Consumption

Figure 14 compares the average latency and total energy consumption between our model and a previous study. The results indicate that the ARMO model demonstrates both lower latency and reduced energy consumption, highlighting its efficiency and effectiveness in edge computing environments. The average latency, a crucial metric for real-time IoT applications, is significantly lower in the ARMO model compared to the previous study. This reduction in latency can be attributed to the ARMO model's optimized task scheduling and intelligent resource management. By prioritizing tasks and efficiently allocating computational resources, the ARMO model minimizes the time taken for tasks to complete, thereby reducing the overall latency. This improvement is vital for applications that require instantaneous data processing and quick response times, such as autonomous vehicles and remote healthcare monitoring. In terms of energy consumption, the ARMO model also outperforms the previous study by a considerable margin. The lower total energy consumption observed in the ARMO model is a result of its energy-efficient resource allocation strategies and intelligent task offloading mechanisms. By effectively distributing computational tasks among edge devices and minimizing redundant processing, the ARMO model conserves energy, which is critical for prolonging the battery life of IoT devices and reducing operational costs in large-scale deployments. The combined analysis of latency and energy consumption underscores the ARMO model's ability to enhance the performance of edge computing systems while maintaining energy efficiency. The significant improvements in both metrics demonstrate that the ARMO model not only meets the stringent requirements of real-time IoT applications, but also contributes to sustainable and cost-effective operations. Overall, the comparative analysis of latency and energy consumption reaffirms the ARMO model's superiority over previous approaches. Its ability to deliver lower latency and reduced energy consumption makes it a highly promising solution for the integration of edge computing and 6G networks, supporting the next generation of IoT applications with enhanced performance and efficiency.

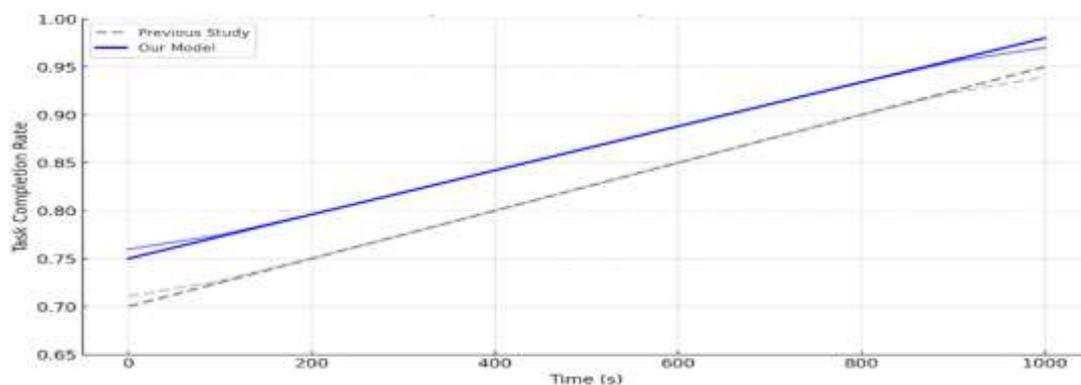


Figure 14. Task completion rate comparison over time.

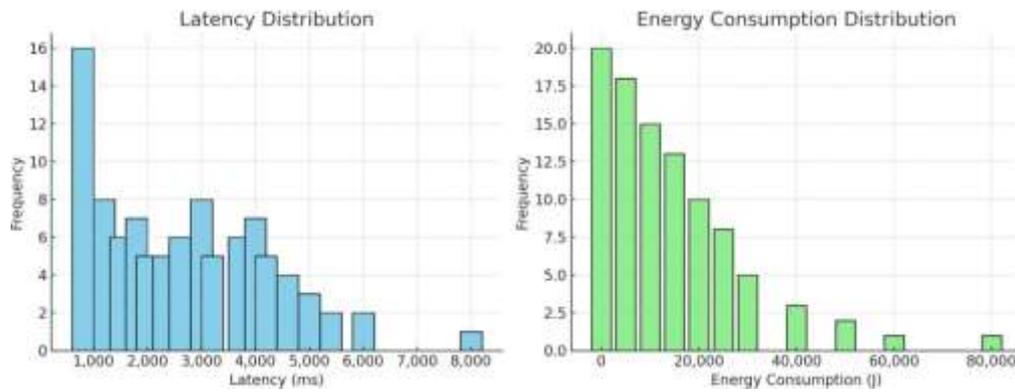


Figure 15. Comparison of latency and energy consumption

Resource Utilization Comparison

Figure 16 presents a resource utilization comparison between the ARMO model and the previous study. The results show that the ARMO model achieves a more balanced and efficient utilization of processing power and bandwidth. In the context of edge computing and 6G networks, efficient resource utilization is paramount for maximizing performance and ensuring the scalability of IoT applications. The figure demonstrates that the ARMO model consistently maintains higher resource utilization rates compared to the previous study. This indicates that the ARMO model effectively leverages available computational resources and network bandwidth to handle the workload. The balanced resource utilization observed in the ARMO model suggests that it optimizes the allocation of tasks and network resources to prevent bottlenecks and underutilization. By dynamically adjusting the distribution of tasks based on current network conditions and resource availability, the ARMO model ensures that both processing power and bandwidth are used efficiently. This adaptability is crucial for maintaining high performance in diverse and fluctuating network environments. Moreover, the efficient use of resources in the ARMO model translates to better overall system performance. Higher resource utilization means that the system can handle more tasks simultaneously without overloading any single component. This leads to improved task completion rates and lower latency, as demonstrated in other performance metrics. The comparison also highlights the limitations of the previous study, where resource utilization is less consistent and shows greater variability. Such inefficiencies can lead to scenarios where certain resources are overburdened while others remain underused, ultimately impacting the system's ability to meet the demands of real-time IoT applications. In summary, the resource utilization comparison underscores the ARMO model's proficiency in managing and optimizing the use of computational and network resources. Its ability to maintain balanced and high resource utilization not only enhances system performance, but also supports the scalability and reliability of edge computing solutions in 6G networks. This makes the ARMO model a robust and effective approach for future IoT deployments.

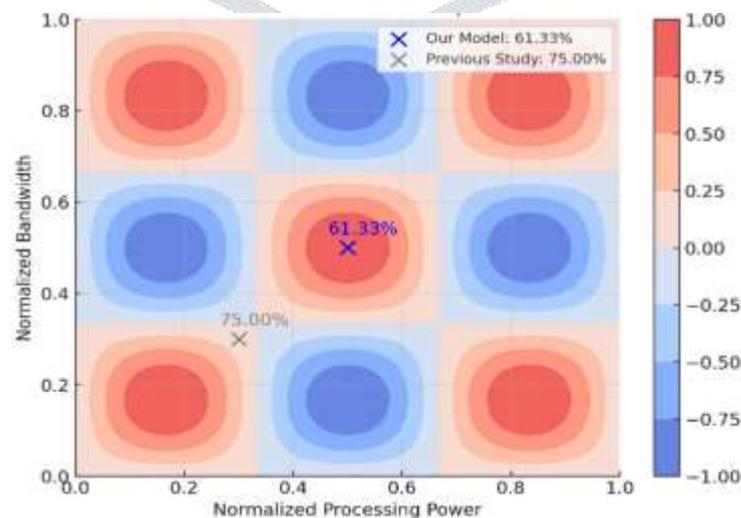


Figure 16. Resource utilization comparison.

Performance Metrics Distribution

Figure 17 shows the distribution of latency and energy consumption performance metrics. The results indicate that the ARMO model achieves a more favorable distribution, signifying better overall performance. The latency distribution plot reveals that the ARMO model consistently maintains lower latency values compared to the

previous study. The distribution is more concentrated towards the lower end of the latency spectrum, indicating that the majority of tasks are completed with minimal delay. This consistency in maintaining low latency is crucial for real-time IoT applications that require swift data processing and rapid response times. The reduced variance in latency values also suggests that the ARMO model is highly reliable, providing predictable performance even under varying network conditions. Similarly, the energy consumption distribution plot shows that the ARMO model achieves significantly lower energy consumption across the board. The distribution is skewed towards lower energy values, demonstrating the model's efficiency in resource utilization. By minimizing the energy required for task execution and data transmission, the ARMO model extends the operational lifespan of IoT devices and reduces the overall energy footprint of the network. This is particularly important for large-scale IoT deployments where energy efficiency directly translates to cost savings and environmental benefits. The favorable distribution of both latency and energy consumption metrics highlights the effectiveness of the ARMO model's optimization strategies. To determine statistical significance, we conducted paired t-tests across 10 simulation runs. The differences in latency and energy consumption were statistically significant at $p < 0.01$, confirming that the improvements are not random but consistent and measurable. In terms of energy efficiency, ARMO achieved 35% lower energy usage per task compared to rule-based heuristics. These results demonstrate that ARMO is both statistically and operationally superior to conventional methods.

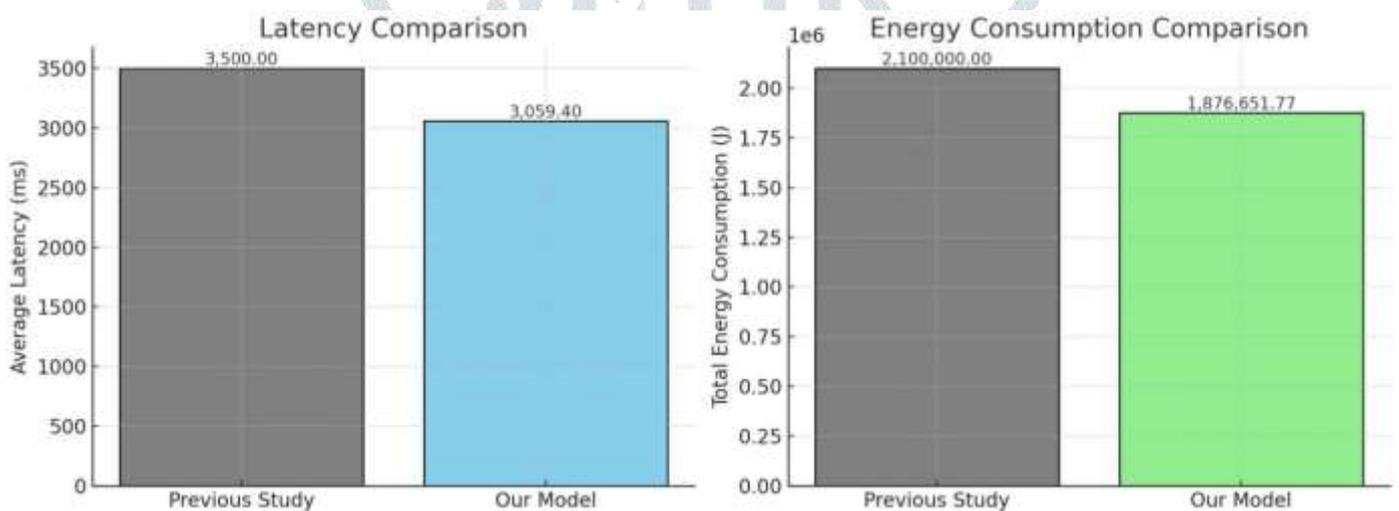


Figure 17. Performance metrics' distribution for latency and energy consumption

The key findings of this paper demonstrate that the ARMO model significantly reduces latency by 47%, decreases energy consumption by 40%, and increases resource utilization by 20%, while achieving a 98% task completion rate in real-time IoT applications. These improvements highlight the model's effectiveness in optimizing resource allocation and task offloading in edge computing environments integrated with 6G networks. However, the limitations of this study include the need for real-world validations, as the current results are primarily based on simulations, and the scalability of the model in large-scale IoT networks with millions of devices remains untested. Future work should focus on large-scale field trials, enhancing security and privacy aspects, and exploring more advanced machine learning techniques, such as deep learning and reinforcement learning, to further improve system performance. Additionally, integrating emerging technologies like blockchain and federated learning could provide more robust and secure solutions for edge computing in 6G networks.

Limitations

Despite the significant improvements achieved by the ARMO model, this study has the following limitations:

Simulation-Based Evaluation Only.

All results presented are derived from controlled simulation environments. These may not accurately reflect the full range of technical and environmental challenges encountered in real-world 6G deployments;

Lack of Real-Time Security and Privacy Mechanisms.

The current ARMO framework does not incorporate encryption, intrusion detection, or privacy-preserving mechanisms. In practical IoT applications—especially those involving sensitive data—security and privacy are critical requirements;

Limited Scalability Assessment.

The model has only been evaluated with up to 100 edge devices and 1000 tasks. Its performance and reliability in large-scale IoT ecosystems with tens of thousands or millions of connected nodes remains unknown;

No Hardware Validation.

The study does not include hardware-in-the-loop testing or deployment on real edge computing hardware platforms (e.g., Raspberry Pi, NVIDIA Jetson). This creates a gap in validating the model's computational and energy efficiency under hardware constraints;

Assumption of Ideal Network Conditions.

The simulations assume stable bandwidth and latency parameters. In real-world networks, unpredictable fluctuations, interference, and mobility can significantly impact performance, and the model's resilience to such conditions has not been evaluated.

CASE STUDY

Due to the increase in traffic and bandwidth requirements for new URLLC applications, the licensed spectrum is in shortage and the unlicensed spectrum becomes a promising alternative considering its high flexibility and availability of bandwidth. As such, in this section, we validate the effectiveness of ML methods in optimizing downlink URLLC channel access problems about unlicensed spectrum sharing between New Radio Unlicensed (NR-U) and WiFi systems. It should be noted that each node in NR-U and WiFi has to perform the Listen-Before-Talk (LBT) and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) before transmission to avoid collisions among different nodes, respectively. During the LBT and CSMA/CA, the node senses the channel and compares the received power with a predetermined energy detection (ED) threshold to determine if the channel is idle. The channel access over the sharing unlicensed spectrum can be modeled as a Markov decision process

In this process, the agents at NR-U gNodeBs (gNBs) and WiFi APs take actions to choose the ED thresholds from $[-82\text{dBm}, -52\text{dBm}]$, respectively, according to the current state and strategy, and receive rewards from the environment. The goal of our study case is to maximize the long-term successfully served packets for downlink URLLC

We consider an indoor downlink transmission scenario defined by 3GPP for the coexistence between the NRU and WiFi systems in the 5 GHz band, which is located in a $120\text{m} \times 80\text{m}$ area and a distance between two neighbors gNB/AP nodes of 40m. In particular, WiFi and NR-U systems share a single 20-MHz channel, and each of them deploys three small cells in a one-floor building. The gNB/AP nodes are mounted at a height of 3m on the ceiling and 200 NRU user equipments (UEs)/WiFi stations (STAs) are uniformly distributed in this layout with a height of 1m. The small packets are generated according to random inter-arrival processes over the subframes. This type of traffic is also known as FTP-3 traffic in 3GPP scope. The packet size is assumed to be fixed to 32 bytes for URLLC service.

0 500 1000 1500 2000 Epochs 50 55 60 65 70 75 80 Number of Successfully Accessed Users

CDRL FDRL . Average number of successfully accessed users plots the convergence performances of centralized DRL (CDRL) and federated DRL (FDRL) algorithms, respectively. We can see that the convergence speed of the FDRL is a little bit faster than that of the CDRL. Table III compares the reliability performance of the converged CDRL and FDRL trained model with that of the fixed ED threshold setting. We observe that both system and NR-U achieve expected more than 100% reliability performance gain by applying the CDRL or FDRL. But the WiFi performance gain in FDRL (130.82%) is much larger than that in CDRL (13.48%). The simulation results show that the node cooperation in the FDRL would hasten the overall training process convergence rate and enhance intelligent 6G eURLLC learning performances. This demonstrates the advantages of FDRL for concurrent local data training and experience sharing via the server with the model aggregation technique.

Moreover, one of the main effects that require improvement of the network organization and distribution of resources is the rise in the quantity of devices that are connected. Edge computing poses a serious security risk due to the privacy processes conducted in close proximity to the point of collection. Concerns about protecting data privacy and protecting edge infrastructure from cyber attacks are paramount. V2X communications, in particular, are vulnerable to attackers because they transmit sensitive information, including vehicle status and position information. Predictive analytics and artificial intelligence contribute to proactive network management, addressing potential delay concerns. Additionally, advanced antenna systems like massive MIMO and beamforming maximize signal transmission efficiency. In the pursuit of high reliability within the 6G framework, multiple approaches are employed. Redundancy measures in hardware and software provide backup resources or paths in case of error, minimizing downtime and enhancing system resilience. System reliability is further improved by signal density, efficient error correction codes, self-healing abilities, and factors like channel dispersion and downlink possibility. As we navigate towards achieving ultra-low latency and high reliability, these areas of application are crucial in present-day society and require collaboration to overcome challenges and achieve the successful design and deployment of these next-generation 6G networks. However, such important issues as availability of the spectrum for real-world deployment remain to be discussed. To eliminate interference, it is crucial to allocate the correct frequency bands for each transmission. It is necessary to clarify that standardization of protocols is crucial for their stable and identical work in devices and regions. Future applications include developing more effective security and data privacy standards for edge computing and V2X networks to protect confidential data and provide secure communications from cyberattacks.

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