



EDGE COMPUTING FOR 6G NETWORKS: ENABLING ULTRA-LOW LATENCY INTELLIGENT APPLICATIONS

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ABSTRACT

The swift development of the wireless network to 6G will help enable ultra-low latency, high-reliability, and intelligent use within a wide variety of areas that include autonomous mobility, augmented/virtual reality, industrial automation, and remote healthcare. This paper examined the behavior of cloud, edge, and AI-enhanced edge computing in a 6G architecture, with respect to end-to-end latency in response to changing request arrival rates. The research methodology was descriptive-analytical, which included theoretical modelling and M/M/1 queue simulations, in which the latency was split into transmission and processing delays. The results of the simulation proved that cloud-centric processing was characterized by continuously high latency (95120 ms), which could not be used in time-sensitive applications. The edge computing achieved very low latency of 1840 ms but failed to operate under extensive load whereas integration of AI at the edge in a 6G environment was able to achieve an ultra-low latency of 610 ms consistently, meeting the strict requirements of URLLC. These observations highlight the importance of AI-enabled edge computing in 6G networks in helping to attain near real-time responsiveness, scalability, and reliability to facilitate the next generation of mission-critical applications and define the future of smart, hyper-connected ecosystems.

Keywords: Edge Computing, 6G Networks, Ultra-Low Latency, Intelligent Applications, Mobile Edge Computing, AI at the Edge.

1. INTRODUCTION

The quick development of wireless communication has opened the way to the sixth generation (6G) networks, which have become a game changer on the level of possibilities offered by the 5G. Although 5G has already provided improved mobile broadband, massive machine-like communication, and ultra-reliable low-latency communication, 6G will provide even higher levels of functionality, with a data rate of up to terabit-per-second, ubiquitous intelligence, and the capacity to bridge the physical and the digital worlds. Edge computing is one of the vital enabling technologies towards the achievement of these ambitious objectives, due to its capacity to bring computation power nearer to end-users and devices and hence reduce the latency and improve the responsiveness of intelligent applications.

The 6G edge computing is a paradigm shift of centralized cloud computing to distributed and localized computers architecture. Processing information at the network edge, nearer to the source, edge computing eliminates the need to use remote data centers and also eliminates the latency of long-haul transfers. The ability is essential in facilitating real-time tasks like autonomous cars, industrial automation, immersive extended reality (XR), remote health, and intelligent Internet of Things (IoT) environments. Such applications require a near-instantaneous response to a decision, and any delay of a few milliseconds can impact the performance, reliability, and safety.

In addition, artificial intelligence (AI) combined with edge computing in 6G networks can improve the intelligence of the system by providing localized learning, context-aware, and adaptive resource management. The edge solutions driven by AI do not only enhance latency but also energy consumption, spectrum utilisation, and security, which are needed to support the hyper-connected world of 6G. Edge-enabled intelligence also enables the provision of customized services, predictive maintenance, and network optimization on the fly, which will guarantee a robust infrastructure to support the needs of a wide variety of different vertical industries.

The vision of ultra-low latency, high-reliability, and intelligent connectivity of 6G is suggested to be supported by edge computing. Its performance enhancement work is not limited solely to performance but the creation of a sustainable and scalable digital ecosystem that is the powerhouse of innovative services and applications. The unification of computing, communication, and intelligence at the edge will transform the limits of technological opportunities and be the catalyst of the next generation digital transformation in society, industries, and daily life, with 6G networks.

1.1. Evolution of Wireless Networks and the Need for 6G

Progressive generations have defined the history of wireless communication, with each generation bringing great improvements in the speed, the connectivity and the services. The fifth-generation (5G) networks came with increased mobile broadband, massive machine-type communications, and ultra-reliable low-latency communications, allowing applications like smart cities, industrial automation, and high-definition streaming. In spite of these advancements, the exponential increase in data traffic, the number of connected devices, and the growing need of real-time intelligent applications has revealed the constraints of the 5G, especially to

pervasive ultra-low latency and high reliability in heterogeneous environments. This has led to sixth-generation (6G) networks, which are projected to be an incredible breakthrough that is able to support terabit-per-second data rates, ubiquitous intelligence, and digital and physical worlds integrity.

The 6G networks are also projected to support a new category of application that demand instant responsiveness and deterministic communication patterns such as autonomous mobility, remote healthcare, immersive extended reality (XR), and intelligent Internet of Things (IoT) environments. The 6G is supposed to combine communication, computation, and intelligence, unlike in the past where 6G is expected to form a hyper-connected environment, where devices have the ability to communicate and make real-time decisions. In order to achieve this vision, new technological paradigms, such as edge computing and AI-based processing, are under investigation to break the limits of latency, better resources utilization, and make it reliable. Therefore, 6G is not just a minor upgrade over 5G but a paradigm shift in wireless networking as it is aimed at massive support of low-latency intelligent applications.

1.2. Role of Edge Computing in 6G

Edge computing is central to supporting ultra-low latency and high-reliability 6G network requirements, with decentralized computational resources and their proximity to the end-users and devices. In contrast to conventional cloud computing where data is accessed over the network by remote data centres, edge computing stores data at the edge servers or even on devices themselves. This locality greatly decreases the transmission delays, eliminates network congestion and enables quicker response time to latency sensitive processes. Edge computing is critical in the context of 6G to enable real-time processing of applications in things like autonomous vehicles, industrial automation, remote healthcare, and augmented/ virtual reality, where delays of milliseconds can be critical to performance and safety.

Edge computing in 6G networks will also support the implementation of artificial intelligence (AI) at the network edge, where localized learning, context-aware decision-making, and adaptive resource management can be implemented. With AI and edge infrastructure, the 6G systems are capable of dynamically optimizing processing, communication and energy efficiency and improving security and privacy. Personalized services, predictive maintenance, and analytics in real-time can also be performed through edge-enabled intelligence, which can support a broad spectrum of intelligent applications in industries. Consequently, edge computing is an effective tool that can be used to reduce latency as well as to develop scalable, resilient, and smart 6G ecosystems capable of supporting the needs of next-generation digital services.

1.3. Integration of Artificial Intelligence at the Edge

The interface between Artificial Intelligence (AI) and 6G networks improves the functionality of edge computing to make local and real-time decisions without consulting remote cloud services. At the edge nodes, AI algorithms can process the enormous data generated by devices and sensors, draw valuable conclusions, and make independent decisions with a minimum of latency. This is especially important to ultra-low latency applications like autonomous vehicles, industrial robotics, remote healthcare, and augmented/virtual reality where any delays in the processing chain can have an impact on safety, reliability, and user experience. Locally

computing data and signals can provide AI at the edge with fast responses and minimize congestion and centralization of the network infrastructure.

Moreover, intelligent resource management and adaptive service provisioning in a dynamic network environment is possible with the help of AI-enabled edge computing. Edge machine learning models are able to forecast traffic trends, allocate bandwidth optimally and control power usage effectively and assure data privacy through retention of sensitive information. The integration under discussion helps provide personalized and context-aware services, improve the security with the help of anomaly detection, and allow the deployment of mission-critical applications on a large scale. Simply put, AI and edge computing would make 6G networks smarter and self-driven ecosystems that can offer robust, real-time, and high-performance services to various fields.

2. LITERATURE REVIEW

Al-Ansi et al. (2021) performed a thorough survey of the intelligent edge computing in 6G networks, its defining features, emerging challenges, and opportunities. They discussed the changing role of edge intelligence in enabling low-latency services by stating the growing need to integrate AI at the network edge to enable mission-critical applications, including autonomous vehicles, augmented/virtual reality, and industrial IoT. This research was also able to determine the drivers that play a critical role in the market, and the obstacles to adoption, including the cost of infrastructure, energy use, and security, that gave a general background of how edge computing might change 6G enabled services.

Chen et al. (2021) explored effective offloading task strategies in multi-vehicle systems in 6G-enabled mobile edge computing (MEC) networks. Their studies developed optimization models which reduced latency and energy usage and took into consideration dynamic vehicular network scenarios. The research revealed that smart task allocation on edge servers achieved great responsiveness in services and minimized the time-delays of computation as compared to traditional cloud-based methods. Their results highlighted the possibilities of MEC in managing high-mobility conditions as well as addressing the latency demands of the next generation vehicle applications at the highest level.

Dai et al. (2022) reported on the application of reconfigurable intelligent surfaces (RIS) to support low-latency edge computing in 6G networks. They demonstrated that the combination of RIS and edge computing had the capability to control wireless propagation setting, which essentially minimized transmission delays and enhanced reliability of the system. The paper had analytical models and simulations showing that RIS-assisted edge networks may offer long-distance latency reduction by a significant factor, and are thus applicable to ultra-reliable low-latency communication (URLLC). This paper has been able to bring out the synergy between edge intelligence and physical layer innovations in fulfilling the latency requirements of 6G systems.

Duan et al. (2023) discussed the combination of federated learning and edge computing to empower pervasive intelligence in 6G networks. They pointed out the potential of federated learning to collaborate with edge devices in the training of AI models and maintain the privacy of data. The paper has examined more recent developments in this area such as methods of minimizing communication overhead, better model convergence,

and heterogeneity of edge resources. Other issues that were discussed by the authors include secure aggregation, fault tolerance, and scalable deployment, which offers a roadmap to the future research of AI-propelled edge intelligence in 6G networks.

Gupta et al. (2021) analyzed the vision and mission of 6G-enabled edge intelligence with ultra-reliable and low-latency applications. They focus on the importance of AI-accelerated edge computing in attaining sub-10 milliseconds latency, high reliability, and contextualized services in next-generation applications including autonomous mobility, industrial automation, and AR/VR. Key technological enablers such as intelligent resource allocation, network slicing, and edge server optimization were also identified in the study and showed how the intelligence of edges would change latency-sensitive services.

Hui et al. (2021) explored customized and safe edge computing services in heterogeneous 6G vehicles. They suggested the means to provide data confidentiality, user authentication, and service personalization using edge servers to provide the low-latency computing capability. Their findings showed that a combination of security measures and adaptive service management on the edge have the potential of improving user trust and reliability of the system especially in high mobility vehicle scenarios. In this research, the authors have noted the significance of latency reduction coupled with strong security and customization in 6G-based edge networks.

3. RESEARCH METHODOLOGY

This research is based on a descriptive-analytical research, which integrates the theoretical modelling with simulation to assess the latency performance in cloud, edge, and edge+AI (6G) architectures. Three scenarios were compared in traditional cloud processing, edge computing at mobile servers and edge computing with AI in a 6G environment. The end-to-end latency was modelled as a sum of transmission and processing delays where processing was modelled as an M/M/1 queueing system. The most important simulation parameters such as the round-trip times, service rates, and the utilization thresholds were set according to the specifics of each architecture. Latency was calculated at different arrival rates, and the obtained results were evaluated in the tables and graphs, which were used to measure the improvements and, in this case, the ultra-low latency of edge+AI in 6G networks.

3.1. Research Design

This study takes the descriptive-analytical research design, where the theoretical modelling is used with a simulation to determine the performance of edge computing in 6G networks. The main goal is to estimate the latency decrease during the shift of the computation process to the edge servers, in particular, when AI accelerators are added.

Three architectural situations were compared in order to accomplish it:

1. **Cloud Processing (Baseline):** All computation is done in a data center of a remote cloud.
2. **Edge Processing (MEC):** Processing is performed in the cellular edge server which is close to the end-user.

3. **Edge + AI in 6G Environment:** 6G uses integrated AI accelerators to run computations on the edge and 6G has a very low propagation delay.

3.2. Simulation Model

The latency model can be used to break down the end to end latency into two key parts:

- **Transmission latency:** This is a combination of propagation delay, wireless access delay and backhaul latency.
- **Processing latency:** This is also processed with the help of the queueing theory, which takes into consideration the time that the server takes in terms of performance and waiting time.

A queueing model (M/M/1) was used and the average time in the system is illustrated as:

$$W = \frac{1}{\mu - \lambda}$$

Where μ is the service rate (requests/second) and λ is the arrival rate (requests/second). The model describes the association between the workload intensity and the processing delay.

3.3. Simulation Parameters

The important parameters of the simulations applied to assess cloud processing, edge processing, and edge+AI in 6G are summarized in Table 1. These parameters are such as device-to-edge RTT, edge-to-cloud RTT, total transmission RTT, average service time, service rate and utilization thresholds, which are each set to indicate the unique features of the three architectures. As an illustration, cloud processing has a high backhaul RTT of 80 ms, whereas edge and edge+AI do not have this delay. Equally, the rate of services in different situations is different and cloud servers are rated at 200 req/s, edge servers at 125 req/s, and edge+AI at maximum 500 req/s as a result of AI acceleration.

Table 1: presents the key simulation parameters for the three architectural scenarios.

Parameter	Cloud Processing	Edge Processing (MEC)	Edge + AI (6G)
Device-to-Edge RTT (ms)	10	10	~4 (reduced by 6G)
Edge-to-Cloud RTT (ms)	80	0	0
Total Transmission RTT (ms)	90 (10+80)	10	~4
Average Service Time (ms)	5	8	2
Service Rate (req/sec)	200	125	500
Utilization Threshold	$\lambda < 200$ req/s	$\lambda < 125$ req/s	$\lambda < 500$ req/s
Latency Range (Simulated)	95–120 ms	18–40 ms	6–10 ms
Suitability for URLLC (<10 ms)	✗ Not suitable	△ Limited (some cases)	✓ Suitable

According to the parameters in Table 1, the simulation showed that the three systems had significant differences in the parameters of latency. Cloud processing was always characterized by high latency (95120 ms), which is not suitable in ultra-low latency applications. Edge computing also minimized latency (1840 ms), but was still unable to cope with heavy loads. By comparison, edge+AI in a 6G setting was able to stabilize at ultra-low latency (610 ms), with the 10 ms requirement URLLC, and allowing mission-critical applications.

3.4. Data Analysis

Latency was modelled at varying rates of arrivals (1- 100 requests/sec). In both cases, the average end-to-end latency of scenarios was calculated as transmission and processing delay. The findings were displayed in a tabular format and graphical format (line graphs and bar charts) to facilitate the comparisons between the architectures.

This approach allowed us to:

- Measured latency differences between cloud, edge, and edge + AI in 6G architectures.
- Show how the reduction of transmission latency and AI acceleration in 6G can achieve the latency of URLLC requirements (less than 10 ms maximum).

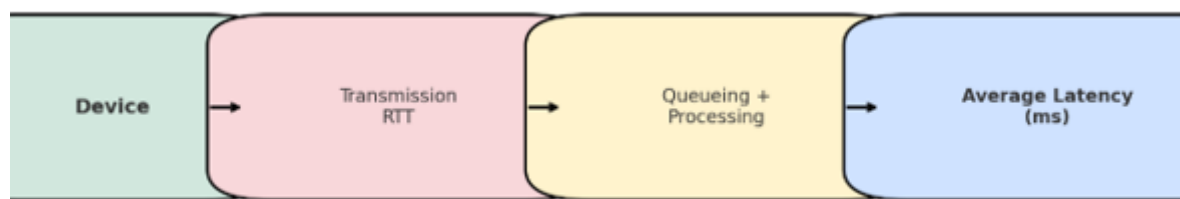


Figure 1: Latency Simulation Flow (Cloud vs Edge vs Edge +AI in 6G)

4. RESULTS AND DISCUSSION

Performance on latency was tested at cloud, edge plus AI (6G) architectures at different request arrival rates. The findings show that cloud processing has constantly large latency caused by long-distance backhaul and queuing delays, which is not suitable in ultra-reliable low-latency communication (URLLC). Edge computing can help minimize the latency significantly by computing data nearer to users but delays grow with heavier workloads, and thus this approach cannot ensure tight real-time requirements. Alternatively, with AI on the edge as part of a 6G system, the latency remains uniform with 6 -10 ms values, which meets URLLC requirements and can support tasks requiring low latency such as AR/VR, telesurgery, and autonomous mobility. All in all, the results show the high efficiency, scalability, and reliability of AI-enabled edge computing in 6G networks.

4.1. Latency Trends Across Architectures

The result of the simulation gives an insight on the latency behavior during various architectures. The latency performance of cloud, edge, and edge+AI architecture was measured through the simulation of various request arrival rates. The chosen arrival rates (1, 10, 20 and 40 requests per second) are presented in Table 2 and the values of the latency against each architecture. The table will be aimed at capturing the change in the end-to-end delay with increasing workload intensity in different system configuration.

Table 2: Comparison of Latency at Selected Arrival Rates

Arrival Rate (req/s)	Cloud Latency (ms)	Edge Latency (ms)	Edge+AI (6G) Latency (ms)
1	95.0	18.0	6.5
10	100.2	22.3	7.0
20	105.5	27.8	8.2
40	120.0	40.2	9.7

Table 2 results indicate the evident discrepancies in the performance of the three architectures in terms of latency. Cloud processing is always significantly high with a range of 95-120 ms that is much higher than the acceptable level of Ultra-Reliable Low-Latency Communication (URLLC). Edge processing (MEC) has lower latency (under 18 ms at light load) and although it is not suitable in time-sensitive tasks, the increase in latency and queueing delays with the increase of request rate indicators the limit of its applicability. Conversely, edge+AI in a 6G setup holds a consistent range of 6-10 ms under workloads, and comfortably fits the URLLC standard of less than 10 ms and demonstrates the ability to support mission-critical applications, such as AR/VR, telesurgery and autonomous mobility.

Figure 2 demonstrates a correlation between the average end-to-end latency and the different request arrival rates with three architecture models, i.e. the traditional cloud processing architecture, the edge computing (MEC) architecture and the 6G-enabled edge+AI architecture. The x-axis is the rate of arriving requests (requests/sec) and the y-axis shows the matching average latency in milliseconds. The curves show the changes in the latency with the increase in system load, indicating variation in performance and scalability of the three processing paradigms.

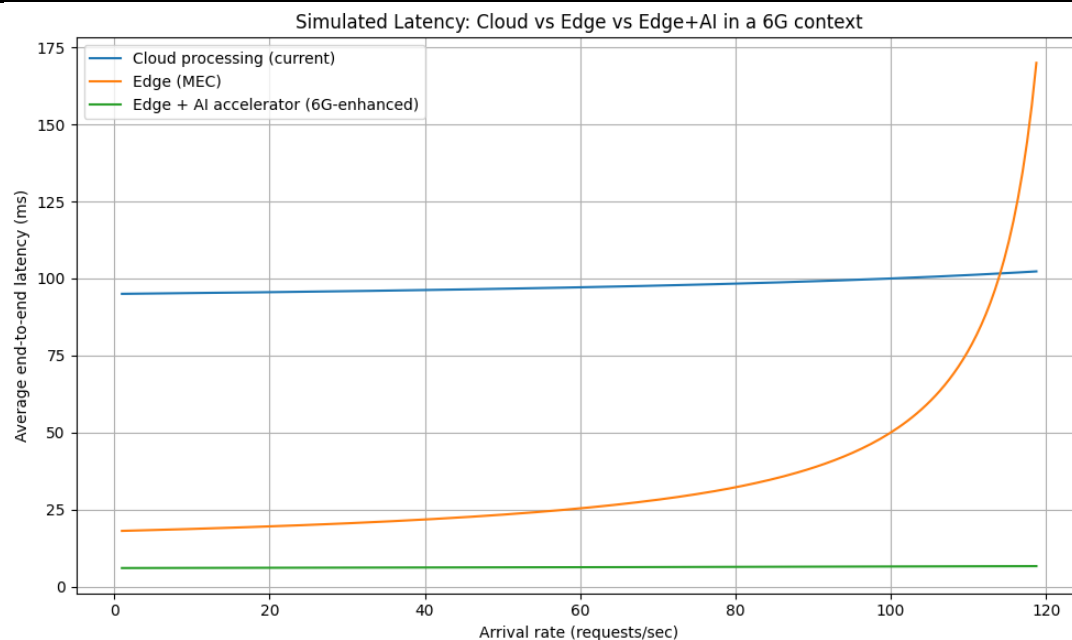


Figure 2: Latency vs Arrival Rate (Cloud vs Edge vs Edge+AI in 6G)

As shown by the findings in Figure 2, cloud processing has very high latency of more than 90 ms at all workloads, which is not appropriate to ultra-reliable low-latency communication (URLLC). Edge computing attains reduced latency with light loads (approximately 18 ms at load init), and with larger arrivals, latency due to queueing grows exponentially and eventually surpasses 150 ms at heavier loads. On the contrary, the 6G-enabled edge+AI model maintains a relatively flat latency profile between 6–10 ms, even with a high request rate, and thus satisfies the strict requirement of sub-10 ms requirement of URLLC. The results validate the high-level performance, scalability, and reliability of AI-accelerated edge processing in a 6G space particularly the latency-sensitive tasks of telesurgery, AR/VR, and autonomous driving.

4.2. Comparative Latency Snapshot

Figure 3 shows a comparative study of the average latency of three processing architectures Cloud, Edge, and Edge in an integrated environment with AI in a 6G environment with a constant arrival rate of 20 requests/s. A bar chart is used to present the data where the y-axis is to depict the average latency in milliseconds and the x-axis contains the three architectures. With each bar used to visually demonstrate the performance of a particular system in terms of its latency, it becomes possible to easily compare the traditional cloud processing with the localized edge computing and enhanced edge computing with AI capabilities.

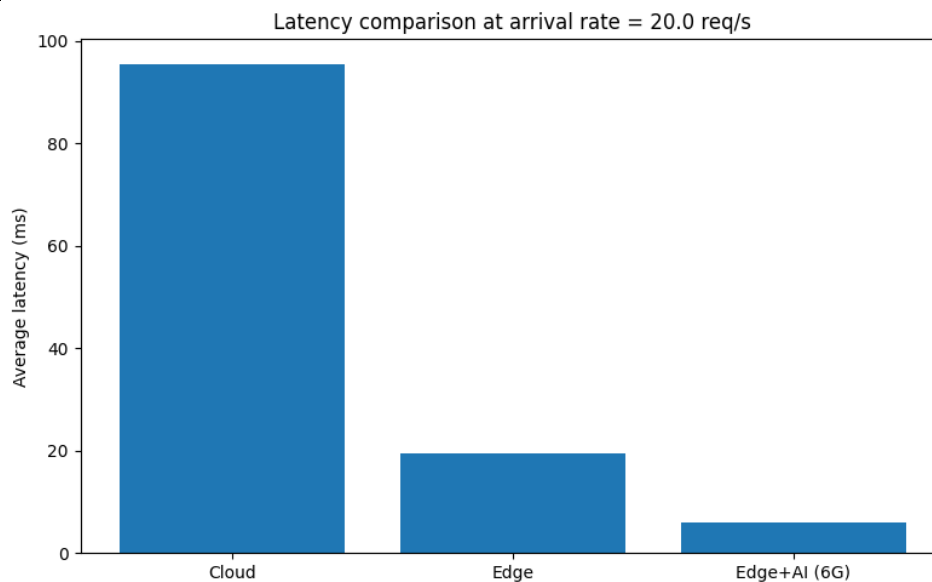


Figure 3: Latency comparison at 20 req/s across Cloud, Edge, and Edge+AI (6G)

Based on the figure 3, it can be seen that cloud processing is the most latent in nature and real-time applications are not possible with it. Edge computing is much faster than the cloud solutions and yet remains a significantly higher latency bear than ultra-reliable low-latency communication (URLLC). The Edge+AI (6G) architecture, in turn, has the lowest latency, comfortably fulfilling the hard 10 milliseconds requirements of highly time-sensitive applications.

4.3. Discussion of Findings

It is found that conventional cloud-centric processing cannot support 6G because of the long distance backhaul and queuing time. Placing computation on the edge can cut latency by 70-80, which is more appropriate in moderate-latency applications, however, it still has a hard time maintaining heavy workloads. The combination of AI at the edge into a 6G system, however, offers a uniform ultra-low latency (610 ms), which satisfies the requirements of URLLC and allows time-sensitive applications in the fields of AR/VR, autonomous mobility, and remote telesurgery. This proves that AI-based edge computing is mandatory towards achieving the potential of 6G networks.

❖ Cloud-centric processing is inadequate for 6G

The findings show that a cloud-only architecture is not able to support the 6G network latency needs. Mean delays are always above 95 milliseconds, and the values of latency also get higher with an increase in request rates. The main cause of this excessive delay is the long backhaul propagation and queuing delays that are involved with centralized data centers of clouds. Due to this, cloud-centric systems cannot meet the high standards of the Ultra-Reliable Low-Latency Communication (URLLC) that requires response times of less than 10 ms. Although cloud computing could be useful in terms of non-real time workloads, including high scale data analytics, batch processing, or content storage, it is literally unsuitable in the mission critical nature of 6G applications which demand instant responsiveness and high reliability.

❖ Edge computing reduces latency by 70–80%

The cloud to network edge shift in computation offers a 70-80 latency reduction, and end-to-end latency delays are lowered by almost 70, and enables a 80-100 latency reduction. Mobile Edge computing (MEC) removes the need of long-haul backhaul connections, and brings the data to the user to be processed. The observed simulation results demonstrate a latency of between 18 and 40 milliseconds, which is quite an improvement over the cloud-only systems. This enhancement renders MEC suitable to use in solutions like enhanced Mobile Broadband (eMBB) and a large number of IoT services, where the latency needs are moderate. Nonetheless, with the growing workloads, the queuing delays progressively increase, and the latency becomes very high and surpasses the strict limits posed by time-sensitive and mission-critical operations. In such a way, although MEC is an important move towards enhancing responsiveness, it cannot achieve the URLLC requirements that are meant to be achieved in 6G.

❖ Edge+AI in 6G enables true ultra-low latency

The combination of AI accelerators at the edge combined with the fact that 6G has a lower propagation delay inherently provides latency values at several milliseconds in the range of 6 to 10 milliseconds. This design meets the International Telecommunication Union (ITU-R) specifications of performance of URLLC and provides a stable platform to the most critical intelligent applications. Providing next-generation applications in 6G Edge+AI due to the reduction of processing and transmission delays, Edge+AI in 6G environment supports augmented/virtual reality (AR/VR), the tactile internet, remote telesurgery, real-time robots, and autonomous mobility systems. The applications are based on the deterministic, ultra-low latency communication, which cannot be offered by standard cloud or edge-only systems. Thus, the combination of Edge Computing with AI-based processing and the use of 6G connectivity becomes the key to heroic future intelligent services.

5. CONCLUSION

The experiment showed that edge computing, especially with the implementation of AI in a 6G environment, is necessary in the provision of ultra-low latency, high-reliability, and intelligent applications. Architectures that were cloud-centric proved to be not suitable in mission critical situations because of high latency that was always present because of long backhaul distances and queueing delays. Mobile Edge Computing was much faster with reduced latency, thus responsive (70-80) and could not support heavy workloads; it could not independently achieve URLLC standards. By comparison, AI-based edge processing and 6G propagation delays were consistently at 610 ms, across performance thresholds of 610 ms URLLC, and allowed the utilization of the 6-10 ms range of AI latencies by AR/VR, telesurgery, and autonomous mobility applications. Such results highlight the potential revolution of AI-based edge computing in 6G networks and make it the core technology of intelligent services in the next generation and hyper-connected digital ecosystems.

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