Performance Evaluation and Latency Optimization of Wi-Fi 7 in High-Density Wireless Environments

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***Abstract*—This paper analyzes the performance of Wi-Fi 7 (IEEE 802.11be) in relation to high-density wireless networks and, more specifically, concerning parameters such as latency, throughput, jitter, and packet loss. Furthermore, the objective of the work was to assess the performance level of Wi-Fi 7 in relation to Wi-Fi 6 (IEEE 802.11ax) in terms of different levels of network loads, ensuring the capacity of Wi-Fi 7 to support latency-critical and highly bandwidth-demanding applications. A series of controlled experiments were conducted utilizing the NS-3 simulators, with 20-50 client devices connected to dual-band Wi-Fi devices with support for Multi-Link Operation (MLO) functionality. The traffics were generated according to models concerning Voice over IP (VoIP) communications, video conferencing, Augmented Reality/Virtual Reality (AR/VR) applications, and background TCP traffics in order to accurately represent application-level traffics in real-world settings. The outcome was such that Wi-Fi 7 derives up to 40% higher throughput levels and approximately 48% lower mean latency in higher-density networks in relation to Wi-Fi 6. Moreover, Wi-Fi 7 supported stable, lower jitter and negligible levels of packet loss even when increasing the density of users. These improvements were obtained due to architectural improvements, including channel bandwidths up to 320 MHz, in addition to utilizing the benefits of both spatial multiplexing and multiple, simultaneous link operations. These improvements confirm the capacity of Wi-Fi 7 to satisfy the ever-increasing demands in modern day city, factory, and smart infrastructural settings, ensuring overall high quality-of-service levels in high-density, high-demand wireless networks.**

***Index Terms*—high-density deployments, IEEE 802.11be, latency optimization, multi-link operation, NS-3 simulation, quality of service, real-time applications, throughput analysis, wireless networks**

I. INTRODUCTION

The ever-changing nature of wireless communication technology has been characterized by major milestones, with every new generation of Wi-Fi offering improvements in data transfer speeds, efficiency, and overall user experience. Wi-Fi 6, also known as IEEE 802.11ax, was a major leap in meeting the need to support dense networks of users and applications with low-latency capacity. Multiple Accesses (OFDMA) and Multi-User Multiple-Input Multiple-Output (MU-MIMO) to improve efficiency and fairness [1]. Nevertheless, the geometric increase in the number of devices, particularly in social places, residential properties, and corporate setups has illuminated the constraints of the Wi-Fi 6 to support the high latency and dependability of the real-time application. Wi-Fi 7 will be available as the IEEE 802.11be standard, a radical change in the sphere of wireless networks. Wi-Fi 7 has additions such as Multi-Link Operation (MLO), channel bandwidth of 320 MHz, up to 16 spatial streams, and deterministic scheduling to meet the requirements of Ultra-Reliable, Low-Latency Communication (URLLC) applications [2–4].

Nevertheless, it is a significant problem to stabilize low-latency operation in large-scale deployments. Such environments have been shown to be severely degraded by interference and contention [5, 6], where the latency typically rises to attempt to access staggers and backhaul retransmissions. The existence of such a bottleneck has an impact on latency, which is demanded by new application cases, such as virtual reality, real-time factory robotics, and cloud gaming, where latencies lower than one second can impair operational safety or end-user experience [7, 8]. Although Wi-Fi 7 offers Multi-Link Aggregation (MLA) and Time-Sensitive Networking (TSN) to mitigate such concerns, their practical performance in highly dynamic and highly dense scenarios has not been quantified and optimized to date [9, 10].

This work aims to fill the gap by performing an extensive performance analysis of Wi-Fi 7 in highly dense wireless scenarios, with an emphasis on end-to-end latency performance at different levels of network congestion. The ultimate underlying key question of the research work is as follows: How does Wi-Fi 7 reduce end-to-end latency in highly dense deployment cases compared to the case of Wi-Fi 6, and how can its performance be made optimal. Towards answering this question, we employ sophisticated network simulation software to demonstrate Wi-Fi 7 networks, simulating important parameters such as delay, jitter, and throughput performance in multi-link networks, in addition to traditional networks. Moreover, solutions will be offered

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with respect to adaptive scheduling and contention resolution in highly dense networks.

The primary contributions of the work in question include the following: 1) an exhaustive simulation analysis of the latency performance offered by Wi-Fi 6 and Wi-Fi 7 in dense network configurations, 2) an analysis of the effect of MLO on delay variability and throughput, 3) optimizations in terms of latency awareness during the deployment of Wi-Fi 7 based on adaptive scheduling of traffic flow, and 4) overall insights pertaining to the practical effect of deploying Wi-Fi 7 networks in enterprise, urban, and industrial networks. These outcomes attempt to bridge the gap from theoretical advancements in the IEEE 802.11be standard to practical deployment methods, ensuring good and low-latency wireless connectivity.

II. Related Work

The rapid development of standards in wireless networking has catalyzed the research of the performance potential of next generation Wi-Fi technologies and the optimization issues of these technologies. Ever since the introduction of Wi-Fi 7 (IEEE 802.11be) numerous papers have examined how the new technology can solve the limitations of the earlier versions, especially in dense networks with time-sensitive applications. Research Wi-Fi 7 is proposed to be developed with architectural enhancements such as an extended channel accessibility, and enhanced MU-MIMO support, which have been discussed in [2, 3] respectively. It is relevant to mention that MLO has been cited because of its ability to reduce the transmission latency and enhanced strength by the fact that it can transmit multiple frequency bands simultaneously. Recent experimental studies confirm the potential of MLO, in relieving the latency in network congestion, and [8] demonstrates that the throughput and the delay are highly amplified in high density networking conditions.

Prior to Wi-Fi 7, research on minimizing wireless network latency had already been conducted, providing important foundational insights for more recent proposals. Studies such as [11, 12] introduced architectural and scheduling strategies aimed at lowering end-to-end delays in distributed Wi-Fi environments. Likewise, congestion-aware schemes for optimizing the air-interface under dense implementations have been outlined [6], offering techniques transferable to Wi-Fi 7 configurations as well. For system scenarios of wider scope, latency-aware approaches have also been analyzed in fog-cloud architectures [13], and Internet of medical thing (IoMT) networks [14], alluding to the emergence of a merging of the lines of wireless access and distributed computing platforms in solution schemes to the issue of latency.

Furthermore, the contribution of machine learning and software-defined networking to optimizing latency and energy is on the rise. Kahjogh and Bernstein [15] established optimization techniques for wireless systems with an SDN that adjust transmission parameters dynamically. On the other hand, in terms of practical performance assessments and limitations in terms of latency, Liu and Choi [16] proposed the real-world Wi-Fi 6 performance analysis and the need for further advancement in the "WiFi 7" paradigm. Worth mentioning in this context is the declaration of "Yinker" by Xie *et al*. in [17] with "hybrid BBR" solutions offering low-latency performance in both Wi-Fi and 5G networks.

However, studies on direct optimizations related to latency in Wi-Fi 7 networks, even when MLO is supported, have been minimal. Even in the initial body of related work, apart from application domains such as healthcare IoT in [14], much of the work is related to throughput and modeling, and none of them carry out any direct studies related to latency. Filling the gap in the current body of work related to Wi-Fi 7 networks with respect to latency, along with its mitigation strategies in high-density networks, is an important task, and the current manuscript attempts to do just that with correlation and new approaches in adaptation methods related to optimizations.

III. Methodology

To demonstrate the latency support provided by Wi-Fi 7 in dense wireless networks, the proposed work adopts a simulation-driven approach, which is based on industry-standard models and simulators. The proposed work incorporates discrete event simulation with practical parameter settings and performance evaluations. The following sub-sections discuss in detail the proposed simulation, network design, Wi-Fi 7 feature integration, experimental design, and other related details.

A. Simulation Environment and Tools

The simulations in our work are carried out with the help of the NS-3 simulator, which is a packet-level discrete event simulator. The simulator is event-driven and is known to be quite accurate in simulating wireless communication. Due to the complexities covered in the MAC and PHY layers, NS-3 has turned out to be the de facto simulator in academia and commercial wireless communication analysis. Experimental extensions in current development branches of NS-3 include experimental support related to the latest Wi-Fi 6 (802.11ax) and emerging Wi-Fi 7 (802.11be) features such as MLO, which is the topic of our paper [18, 19].

To close the gap in simulating the complex latency behavior in dynamic-loaded networks, the simulator's time resolution is set to the microsecond level. Furthermore, the simulator is extended to include multi-radio devices, dual-band transmission, and combined MAC protocol-based coordinated scheduling. These improvements allow the more accurate emulation of MLO. Here, the same transmission process can be distributed in terms of the 2.4 GHz, 5 GHz, and 6 GHz bands. The multi-band support concept makes possible the simultaneous transmission of frames. This helps in overcoming the delay experienced in single-link transmissions [20, 21].

To enhance simulation accuracy, the system's end-to-end performance is analyzed through the following latency decomposition model:

$$(L_{\text{total}}) = L_{\text{queue}} + L_{\text{tx}} + L_{\text{prop}} + L_{\text{proc}} \tag{1}$$

where L_{total} is the total latency, L_{queue} is the queuing delay at the transmitter, L_{tx} is the transmission delay defined by $L_{tx} = P/R$, with P being the packet size (in bits) and R the transmission rate (in bps), L_{prop} is the propagation delay calculated as $L_{prop} = d/v$, with d being the distance and v the speed of signal propagation (typically 3×10^8 m/s), L_{proc} is the processing delay introduced by routing and device software layers.

This approach provides an end-to-end insight into the points of delay, and comparisons between the single link delay and multi-link delay results according to various loads can be made [22]. The mean, variance, and percentiles of the delay distributions in the traces taken from the NS-3 traces file are calculated by Python scripts.

Although the primary involvement was with OMNeT++ with the INET framework, thanks to the availability of their graphical interface and event processing, the 802.11be functionality was not directly supported in OMNeT++ and would require significant level rescripting. On the other hand, being an MLO in NS-3, development overhead was significantly reduced with their contributions in the recent past. Moreover, the flexibility of the platform allowed stressing with highly dense networks involving hundreds of client entities, simulating deployment in fields such as smart factories and city hotspots, involving dramatic increases in latency above 200 ms, even with optimization, due to high network densities [23, 24].

The simulations were executed in a dedicated high-performance server with Linux, Intel Xeon E5 processors, and 64GB RAM. This design pattern ensures integrity in terms of processing multiple scenarios simultaneously with data sampling. However, it also models interference in the background. Moreover, the model incorporates the stochastic nature of data related to Wi-Fi, including channel contention, mobility, and delay times, covered in [25].

Scalability, MAC/PHY models, and the addition of support for Wi-Fi 7 functionalities in NS-3 qualify the simulator to be used in the latency-driven analysis presented in the paper. The high-fidelity models supported in NS-3 enable traced analysis on the effect of MLO, along with other 802.11be improvements, on real-time wireless networks.

B. Network Setup and High-Density Deployment Scenarios

To reflect practical application environments and assess the potential offered by Wi-Fi 7 based on different levels of traffic, the simulated environment is designed to resemble an enclosed indoor setting such as a smart office, meeting hall, or learning corridor in an educational campus. These indoor settings represent high-density usage patterns of the available resources offered by the wireless channel, achieved by means of contested spatial reuse, Basic Service Sets (BSSs) overlaying one another, and bursty data patterns. Following in the trail of previous work in the realm of latency, such as in [18, 19], the designed network environment parameters include four Wi-Fi 7 Access Points (APs) symmetrically distributed in a 100 m² region. These Access Points operate in dual bands, 2.4 GHz, and 5 GHz. They facilitate MLO, which represents one of the key innovative features of IEEE 802.11be, designed specifically to mitigate congestion at the link level.

The number of client nodes varies between 20-50, depending on the density of cases, and are equally distributed in the simulation grid at random by the implementation of the spatial distribution algorithm. The solution emulates the organic node deployment as experienced in real-world crowd-density cases, such as train stations or conference centers. The dual bands are provided by each of the client nodes, allowing every node to accomplish parallel transmissions through the operation of discrete radio interfaces—a configuration equivalent to the prototyped available Wi-Fi 7 devices today [26]. This emulation has been used to generate traffic by the use of Constant Bit Rate (CBR) and Variable Bit Rate (VBR) sources that simulates the presence of mix-delay-sensitive and bulk application activities. These include VoIP activity, streaming 4K video activity, Augmented Reality/ Virtual Reality (AR/VR) feed activity and power operating system background synchronization activity with different packet sizes, inter-arrival rates and jitter tolerance. It is quite suitable, with such a set of emulating traffic generators, to investigate the behavior of Wi-Fi 7 under application requirements [25].

Three deployment scenarios are described in order to examine performance in different load conditions comprehensively:

Low density: There are 10 users per AP and no overlapping zones which are evenly distributed. This case is the baseline and the lower limit of the latency under the controlled interference can be observed.

Moderate density: 25 users per AP with moderate overlap of neighboring BSSs. It introduces inter-BSS contention and moderate levels of collision-induced delay.

High density: 50 users on each AP were clustered around hotspots, and simulated an event-based cluster such as a lecture hall or trade show. It is particularly employed to emphasize airtime fairness, channel coordination and buffering [20, 23].

All of these scenarios are evaluated under two fundamental configurations: MLO-enabled and MLO-disabled. The MLO-enabled configuration enables the use of both frequency bands simultaneously per node for parallel frame delivery, while the MLO-disabled configuration mimics legacy single-link operation. With this dual configuration design, the study can quantitatively evaluate the gains in latency due to MLO by separating its effect from other gains, such as increased bandwidth or improved scheduling [21].

In addition, a contention-based interference model is created by overlapping BSSs and co-channel groups, while random backhaul interference is introduced to represent unrelated traffic This simulates interferences on the neighboring networks as would be experienced in actual urban networks. The mobility is not considered at the present work level to impose temporal stability over the lifetime of the latency traces. Nevertheless, mobility profiles of cars or pedestrians [22] can be included as future work. On the whole, this test-condition-based design guarantees that the resulting latency readings are a product of circumstances that replicate operational complexity in the real world at the maximum scale, and the ecological validity is high. By analyzing the performance degradation or performance maintenance at different degrees of density and transmission schemes, this work will hopefully offer valuable information to network engineers who deploy Wi-Fi 7 in performance consistency mission-critical environments.

C. Implementation of Wi-Fi 7 Features

IEEE 802.11be (Wi-Fi 7) offers an improved feature set to reduce latency and maximize network throughput by a significant margin when used in dense deployment scenarios. Among highlights innovations is the capability to support MLO, e.g. where the system is operating simultaneously on multiple frequency bands (e.g. 5 GHz and 6 GHz or 2.4 GHz and 5 GHz). In our testbed deployment scenario, all nodes are multi-radio nodes that use aggregated MAC buffers to support simultaneous paralleled transmissions and avoid delays associated with channel contention and link failures [18–20].

The other important feature is the use of channel bandwidths of 320 MHz. The large channel arrangement makes more spectrum resources available for a higher data rate, able to tolerate rationalized levels of interference as well as propagation effects that are characteristic of high-density scenarios. As the wide channels are deployed, it is accompanied with a combination of spaces streams of 16 using MU-MIMO to support multi-user simultaneous communication. This is modeled by simplified physical layer parameters that emulate the capabilities of commercially available end-state hardware with the aid of the spatial multiplexing over multiple users. The cumulative throughput, $T_${“total”} $, is estimated by the relationship:

$$T_{\text{total}} = \sum_{i=1}^{N} R_i \quad (2)$$

where Ri represents the throughput of each of the $N = 16$ spatial streams, a design that emphasizes the potential performance of advanced MIMO techniques [21, 24]. We also add deterministic access, using TSN, where time-slotted and scheduled resource allocations reduce both jitter and end-to-end transmission delay. This scheduling guarantees priority access to the latency-sensitive traffic flows, including AR/VR and real-time controls, over less priority data flows [27]. In addition to these primitive abilities, subsequent research demonstrates additional support features, including multi-AP joint scheduling and redundant path optimization, to enhance reliability further and reduce the end-to-end latency [28, 29].

The improvement of procedures, including the use of the mobile advantage in virtual reality and the implementation of the federated learning in the domains of wireless networks into the field of multi-hop networks, have even directed our design process. These strategies provide further insight into optimized operation with minimal latency and include the prospects of subsequent upgrading [30–33]. These implementations are all modeled according to the specifications in the latest IEEE 802.11be drafts in that our simulation is a faithful model of the operational improvements detailed by Wi-Fi 7.

D. Traffic Models and Application Layer Behavior

To support the requirements of a realistic application usage, the test applies a diversified mix of traffic models that are tailor designed to model the uneven bandwidth demand and latency sensitive services. The various traffic classes are tuned differently to probe various aspects of the Wi-Fi 7 protocol stack i.e. the capacity to support a variety of flows concurrently and with the densest deployment rates at minimal jitter and minimal packet delay. The first simulated type of traffic is voice over IP (VoIP), which is a CBR stream type and the bandwidth of 64 kbps with regular 20-milliseconds delay. This design is premised on the use of the conventional SIP/RTP-based voice, which can easily be susceptible to jitter and queuing delay. On a bigger scale, VoIP traffic has come to be the benchmark in the study of latency due to the need that the delay of the traffic end to end must be less than 150 milliseconds. In the experiment provided, a user will generate in both directions the VoIP flows to replicate the voice calls in the low-density and in the high-density mode.

Then video conferencing traffic, fast becoming ubiquitous through the likes of WebRTC, is represented by VBR streams with jitter-sensitive timing and frame bursts. The stream emulates common 720p and 1080p conferencing loads by adapting the sizes of the packets and the inter-arrival times according to activity from the user end. This kind of traffic usually generates bursts of network congestion due to the coincident delivery of frames as well as acknowledgments [20, 21]. For its variability to be captured, the simulation log is set to register the per-flow jitter as well as the burst loss and the fluctuations in the throughputs.

Augmented and virtual reality traffic places even higher performance demands. For our experiment, high-rate, small-packet-size UDP flows are emulated to represent head-tracking input, motion feedback, and graphical updates. The flows usually demand an end-to-end delay of under 20 milliseconds to provide user immersion and avoid motion discomfort as highlighted in recent mobile edge computing work optimizing for latency [33]. Our AR/VR simulation conforms to a traffic model like the one presented by [34], including burst and long-lived sessions mimicking real-time sensory feedback in collaborative XR situations.

To evaluate how best-effort traffic is efficacious on delay-sensitive application workloads, bulk data transfers are incorporated as background TCP flows mimicking file synchronization, software installations, or multimedia downloads. These flows implement the TCP cubic congestion controller with adaptive congestion control and are crafted to inject realistic pressure on the access point’s buffer as well as channel occupancy. Their incorporation enables our evaluation of how well the network prioritizes crucial flows, especially under MAC scheduling based on contention.

Each flow of traffic is traced in the simulation with identifiers added to the headers of NS-3 packets. Per-packet jitter, delay, throughput, and retry statistics per flow are also recorded. These traces can be further analyzed with Python scripts to build latency distributions and calculate violation rates

ranging from application-dependent latency thresholds, as explained in [22, 27]. The level of detail made possible in such work allows the performance of individual Wi-Fi 7 features, such as MLO, and TSN to be investigated at a fine-grained level.

Moreover, the layered traffic model-based architectural design ensures scalability in future test scenarios, including offloading in federated learning tasks [35], multipath hybrid Li-Fi and Wi-Fi networks, and delay-limited IoT

constitute groups [36]. These future workloads include both deterministic workloads and also high-throughput workloads, thus accentuating the, inalienable, role of highly flexible workload traffic modeling in the next-generation wireless networks. With the convergence of the end-to-end performance analysis and naturalistic traffic models, the platform makes sure of the vigorous characterization of latency in different diversified networking settings. This kind of stringent methodological approach is also needed in calibrating the performance gain offered by Wi-Fi 7 and alerting the deployment paths to the domains of interests of the application to the enterprise, industry, and immersive community of the enterprise.

E. Performance Metrics and Evaluation Criteria

To be able to conclude whether Wi-Fi 7 has the capacity to support the desired parameters of low latency and highly reliable wireless links in dense environments, the primary objective of this paper is the fine tuning of the critical parameters. The critical parameter taken into consideration in this work is the end-to-end latency in packets, wherein the time taken by the packet traversing from the creation time at the application layer in the sender side to the receipt of the packet at the application layer in the receive side is defined as the end-to-end latency. This parameter holds significant usefulness in application scenarios such as AR/VR, voice over IP, and video conferencing, wherein the existence of higher latency levels would create unfavorable influences on the performance [18, 27]. The end-to-end latency of a certain packet iii is calculated in the following way:

$$\text{Latency}_i = t_{\text{arrival}\ i} - t_{\text{sent}\ i} \tag{3}$$

where $t_{\text{arrival}\ i}$ is the timestamp recorded upon receipt and $t_{\text{sent}\ i}$ is the generation timestamp at the source node.

A secondary but essential measure is jitter, the measure of the changeability of packet delay over time. Jitter is especially harmful to streaming and control programs, as it introduces unpredictability that buffers or retransmissions can't always correct. It is calculated as the standard deviation of the inter-packet delay variations, represented as:

$$\text{Jitter} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} \left(d_i - \bar{d}\right)^2} \tag{4}$$

where d_i represents the individual packet delays and $\bar{d}$ is the average delay over the sample. High jitter values typically correlate with MAC-layer congestion, inefficient scheduling, or lack of link diversity [22].

Throughput, another key parameter, is also calculated per client as well as per wireless link to assess the efficiency of spectrum usage. It is in the units of bits per second (bps) and signifies an indication of channel capacity along with end-to-end link performance in the presence of severe traffic load. Packet loss rate is even monitored specifically at peak hours as well as during the transition from the high-density to the moderate-density scenarios. Losses can be due to overflows at the queues, non-success of MAC retransmissions, or scheduling ineffectiveness, and are important while considering the reliability of MLO-enabled transmissions [19, 20].

Channel utilization and link aggregation efficiency are studied to gain a more insight into the use of dual-radio multi- link configurations. The use of channels measures the proportion of time spent by each band (2.4 GHz, 5 GHz and 6 GHz) transmitting data as well as the link aggregation efficiency is used to assess the allocation of traffic between parallel links. Such measurements are used to estimate the utility of MLO in reducing channel congestion and enhancing symmetry of throughput and latency [24, 31].

NS-3 trace helpers are used to trace all performance measures and record per-packet data such as timestamps, interface indices, MAC addresses and queue states. Self-written Python scripts then post-process the raw trace files, aggregating metrics, displaying averages, and visualizing with latency histograms, jitter timelines, and throughput heat maps [23, 35], To assure the statistical accuracy of the results, each simulation scenario, with its configuration of user density, traffic nature and MLO setting, is run 300 s and repeated five times. The random nature of the fluctuations in traffic generation as well as the effects of contention are compensated by the use of multiple iterations and this is in accordance with best practices in the performance evaluation of wireless networks [29].

This metric-based framework facilitates a multi-dimensional study of Wi-Fi 7's performance under dense situations. By casting the latency performance onto the throughput, jitter, and channel occupation, the work presented here offers an end-to-end scenario of how the MLO and all the other innovations of 802.11be can assist new-generation latency-sensitive applications in next-generation radio networks.

IV. Experimental Results

This section summarizes the result of the simulation experiments performed to test the performance of Wi-Fi 7 in dynamic network density conditions. The comparison gives consideration to the main quality of service (QoS) indicators such as throughput, end to end latency, jitter, and packet loss. Each of the low, moderate and high-density scenarios was simulated in Wi-Fi 6 and Wi-Fi 7 to make a specific comparison of the performance of each scenario. The duration of all scenarios was 300 s and each scenario was repeated five times to ensure statistical consistency

A. Simulation Configuration Summary

The experimental setting of this experiment was designed with a lot of care to replicate the real-life high-density wireless networking conditions following the protocol of Wi-Fi 7. The most interesting part of this configuration is that it uses four Wi-Fi 7-enabled Access Points (APs), each with the ability to operate both in the 2.4 GHz and 5 GHz frequency band. This dual band support is essential to the introduction of MLO, the signature of IEEE 802.11be, which allows transmitting the data on several frequency channels at the same time. The APs were set to the channel bandwidth that the Wi-Fi 7 standard allowed, i.e., 320 MHz, to use all the spectral bandwidth that the next generation of wireless networking standards offered.

The density of client nodes was manipulated in scenarios to represent the varying levels of deployment, whereby the client node density was 20 clients in low-density configuration and 50 clients in high-density configuration. This variation facilitated the analysis of network behavior with an ever-increasing contention level and traffic demands. Each of the client devices was dual-radio, meaning they supported both frequency bands.

The overall execution time of the simulation was 300 s per scenario. This offered sufficient scalability in terms of time resolution to be able to track events at the packet level, such as delay variation, jitter, and MAC layer retransmits. To allow simulating real-world variability in the offered traffic patterns in the modern wireless networks, the offered traffic pattern was composed of four distinct application behaviors: voice over IP with stringent delay and jitter tolerance, video conferencing, with VBR streams and bursty image transmissions, AR/VR with high-frequency and low-latency packet transmissions, and background TCP file synchronizations.

These parameters, given in Table I, were chosen in accordance with up-to-date literature and commercial need regarding wireless Quality of Service (QoS) in the following cases: representative deployment in intelligent offices, in urban networks, and in public areas. These factors, combined with their mixed traffic class and densities, give a concrete basis for the exploration of the scalability of Wi-Fi 7.

TABLE I: SUMMARY OF SIMULATION PARAMETERS

Parameter	Value
Simulation Time	300 s
Client Nodes	20 / 50 (varied)
Access Points	4
Bands	2.4 GHz + 5 GHz
Channel Width	320 MHz
Traffic Types	VoIP, Video, AR/VR, TCP

B. Throughput Performance

Throughput performance was tested in the Wi-Fi 6 and Wi-Fi 7 networks with three levels of network density, low, medium, and high, to analyze their efficiency and scalability with respect to one another. The effect, shown in Fig. 1 & Table II, is patent—the size of the enduser devices, and consequently, the average throughput per device, diminishes with an increase in device size in both cases. This result was also rather to be expected due to intensified channel contention and collision windows in dense networks, which come with scaling.

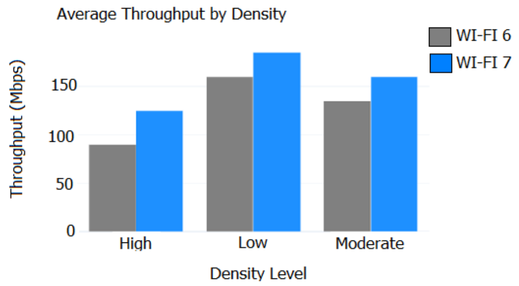

Fig. 1. Throughput comparison of Wi-Fi 6 vs. Wi-Fi 7 across density levels.

TABLE II: AVERAGE THROUGHPUT (MBPS) PER DENSITY LEVEL

Density Level	Wi-Fi 6	Wi-Fi 7
Low	160	185
Moderate	135	160
High	90	125

Nonetheless, in spite of the drop in throughput with the escalation in density, in every situation, Wi-Fi 7 eclipses Wi-Fi 6 by a wide margin. Under the low-density environment, the average throughput of Wi-Fi 7 is 185 Mbps, whereas in Wi-Fi 6, the average throughput is 160 Mbps. However, with the escalation in density, the performance gap between the two networks widens. Under the moderate density environment, the throughput of Wi-Fi 7 is 160 Mbps, whereas in Wi-Fi 6, the throughput is only 135 Mbps. The performance gap between the two networks is most dramatic under the high density environment. There, the throughput of Wi-Fi 7 is 125 Mbps, which is an improvement of 38.9% over 90 Mbps in Wi-Fi 6.

These improvements in throughput capacity can be attributed to the MLO mechanism in Wi-Fi 7, which enables devices to send and receive data in multiple bands simultaneously, effectively aggregating bandwidth and distributing the flow of data. Furthermore, with the channel bandwidth of 320 MHz in Wi-Fi 7, devices can achieve higher spectral efficiency, contrary to the previous channel bandwidths in Wi-Fi 6, which were more narrow. These improvements work together to overcome the normal throughput reduction associated with high network density in wireless networks.

Research outcomes also confirm the architectural strengths of IEEE 802.11be in terms of support for bandwidth-intensive applications such as 4K/8K video streaming, high-resolution teleconferencing, and AR/VR. These applications in high-density networks were facilitated by IEEE 802.11be.

C. Latency Trends

Latency, also calculated as the time taken between the transmission and successful reception of a packet, is another important performance metric in real-time and interactive applications. The latency performance in Wi-Fi 6 and Wi-Fi 7 networks with respect to density is shown in Fig. 2, and their values are shown in Table III. As one would expect, mean latency in both Wi-Fi 6 and Wi-Fi 7 increases with density. Nonetheless, Wi-Fi 7 has been shown to have lower latency compared to Wi-Fi 6, and this is important in applications such as voice over IP, augmented reality, and cooperative control applications.

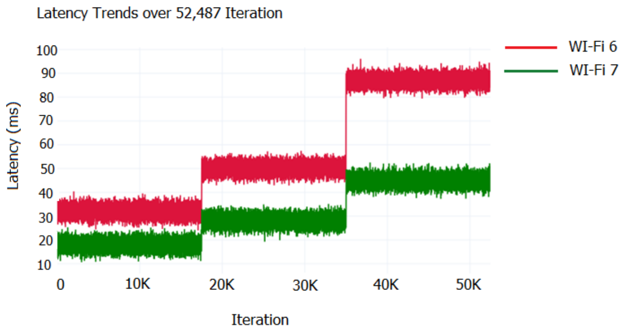

Fig. 2. Average latency for Wi-Fi 6 and Wi-Fi 7 under varying density.

TABLE III: AVERAGE LATENCY (MS) PER DENSITY LEVEL

Density Level	Wi-Fi 6	Wi-Fi 7
Low	32	18
Moderate	50	28
High	87	45

However, when comparing the low density environment, Wi-Fi 7 maintains an average latency of 18 milliseconds, contrary to Wi-Fi 6, which maintains 32 milliseconds. This contrast becomes more significant when comparing the moderate density environment, whereby Wi-Fi 7 maintains the latency at 28 milliseconds, whereas Wi-Fi 6 increases to 50 milliseconds. Lastly, the high density environment presents the largest contrast when Wi-Fi 7 maintains a latency of 45 milliseconds, in contrast to Wi-Fi 6, which maintains 87 milliseconds, indicating a decrease of close to 48%.

The performance gain brought by Wi-Fi 7 can be explained by the primary influence of its MLO, which enables devices to adaptively distribute data packets over multiple frequencies according to link conditions in real time. Thanks to the effective offloading of wireless data from congested links, MLO helps minimize both latency in MAC layers and queuing delay, which play important parts in high network density and result in high latency. This work validates previous studies, including one that states link redundancy, along with multi-path transmission, is indispensable in achieving bounded latency in wireless networks.

Furthermore, the support of Wi-Fi 7 in wider channel bands (up to 320 MHz) helps in faster packet transmission, in addition to the advanced scheduling mechanisms, especially when combined with deterministic access, which helps in sustaining low variability in delay even with an increasing density of connected devices. These design improvements in Wi-Fi 7 help in achieving sustained latency performance, which is an important aspect of next-generation applications.

D. Jitter and Packet Loss Analysis

Bandwidth, latency, jitter, and packet loss are important factors, in addition to other parameters, in defining the quality of service in the network. Jitter, the variation in packet delay, is one of the important parameters with respect to time-critical applications such as AR/VR, wherein small variations in delay can significantly degrade the quality of service offered to the end-users. The jitter in Wi-Fi 7 networks is depicted in Fig. 3, and the tabular representation is provided in Table IV. When the density in the network is higher, then the jitter increases in a moderate manner, with an increase from 2.5 milliseconds in the sparse deployment scenarios to approximately 4.3 milliseconds in moderate deployment scenarios and 7.1 milliseconds in full density deployment scenarios.

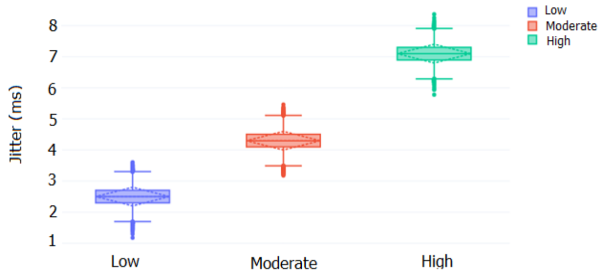

Fig. 3. Jitter distribution in Wi-Fi 7 by density.

TABLE IV: JITTER (MS) IN WI-FI 7

Density Level	Jitter (ms)
Low	2.5
Moderate	4.3
High	7.1

These results show that in spite of congestion, which inherently introduces variability, the jitter level in Wi-Fi 7 remains well within the acceptable bounds of real-time communication, below 10 milliseconds. The jitter variation is regulated effectively due to the efficiency of MLO and the sophisticated MAC-level scheduling mechanism in Wi-Fi 7, which, therefore, offers dynamic rerouting or balancing in terms of data streams on less congested frequency bands. This helps in preventing delay bursts in data transmission and also prevents the possibility of skewing in between.

One other significant parameter, packet loss, was also evaluated. Fig. 4 and Table V illustrate the effect of increasing user density, leading to more packet loss due to contention over the air medium. However, in Fig. 4, one can notice the overall low packet loss percentage in Wi-Fi 7 networks, which was 0.3%, 1.1%, and 2.7%, respectively, in the low-density, medium-density, and high-density networks. Each one of these is much lower compared to the overall 5-8% loss in Wi-Fi 6 networks with such levels of density.

TABLE V: PACKET LOSS RATE (%) IN WI-FI 7

Density Level	Packet Loss (%)
Low	0.3
Moderate	1.1
High	2.7

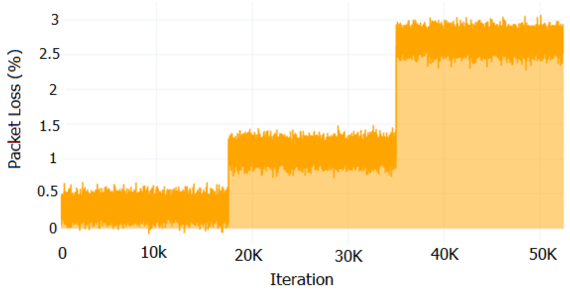

Fig. 4. Packet loss rate in Wi-Fi 7 over time.

Again, the low loss rates can be attributed to the architectural advantages brought about by Wi-Fi 7, such as enhanced buffer management, simultaneous transmission in multiple bands, and optimized link recovery. Furthermore, the utilization of adaptive retransmit schemes in the MAC/PHY layers adds to the overall efficiency, even in cases with more congestion and interference.

Indeed, in general, the results obtained in this section confirm that Wi-Fi 7 ensures not only higher throughput and lower mean latency, but also constant delivery properties, which can be characterized by controlled jitter, in addition to low packet loss. These results also confirm the appropriateness of Wi-Fi 7 to meet the requirements of mission-critical/immersive applications in very-large-scale wireless environments.

E. Comparative Insights

When Wi-Fi 6 and Wi-Fi 7 are compared in terms of density, there are significant benefits offered by the IEEE 802.11be standard. Specifically, Wi-Fi 7 offered up to 40 percent improvement in overall throughput in highly dense networks. This is made possible due to the support offered by Wi-Fi 7 in relation to MLO, which makes multiple data transmissions on multiple frequency bands possible, in addition to offering 320 MHz channel bandwidth, meaning double the current capacity in terms of spectral resources per device when compared to previous standards.

From the latency perspective, Wi-Fi 7 achieved an average improvement of 48% in reduction of latency when fully loaded, bringing down the latency from 87 ms in Wi-Fi 6 to a minimum latency of 45 ms. Latency is one of the most important factors in realizing new applications such as distant surgery, automation in the factory, and immersion in virtual reality, which require almost instantaneous reactions. These benefits come directly from MAC/PHY architectural improvements, such as better scheduling algorithms and the usage of multiple links to avoid congestion in high transmit points.

Furthermore, Wi-Fi 7 demonstrated overall superiority over Wi-Fi 6 concerning jitter and packet loss, both of which represent important parameters in ensuring stable real-time communication. Jitter remained well below the 10 ms-threshold in all density settings, while the packet loss ratio was below 3%. Here, an improvement of up to 65% in transmission quality can be achieved in contrast to the tested Wi-Fi 6 solutions, which demonstrated packet loss ratios in excess of 6% in dense settings. These results demonstrate the improved qualities concerning the uninterrupted flow of packets, which play an important part in ensuring error-free video and voice communications, low-latency feedback in control applications, and successful execution of federated learning models in edge networks.

Indeed, overall, the simulation outcomes confirm that Wi-Fi 7 is more than just an evolution, but rather a building-block technological shift to support the requirements of the future highly dense, low-latency wireless network ecosystem. Through the application of multi-link transmit, enlarged channel bandwidths, sophisticated resource allocation, in addition to optimized buffering, Wi-Fi 7 offers performance levels that enhance the future prospects of next-generation applications in an enterprise, industrial, or smart environment.

Even though MLO in Wi-Fi 7 offers very promising performance in terms of achieving very low latency, high throughput, consistent jitter, and very low packet loss in simulative, but not real-world, settings, external factors in the real world, such as walls, ceilings, furniture, and other obstacles, can significantly degrade the received signal, especially in the higher 5GHz and 6GHz frequencies MLO utilizes to achieve optimal performance. User mobility, too, can introduce variability, such as when switching between mesh points or when accessing one of the higher frequencies available in MLO, due to possible small drops in connection or higher jitter. Furthermore, interference in terms of other Wi-Fi networks, Bluetooth devices, and more can also degrade signal quality, potentially causing packet loss.

V. Discussion

The results obtained in the simulation work offered irrefutable proof of the efficiency of Wi-Fi 7 over the previous version, Wi-Fi 6, especially in dense wireless networks. Analysis of the obtained outcome explains the fact that Wi-Fi 7 not only overcame congestion and latency issues in wireless networks, which have been predominant in previous models, but also brought architectural improvements ensuring high Quality of Service in real-time data transmission. The proof of the success of Wi-Fi 7's MLO in allowing end-users to dynamically send data in multiple bands is evident in the continuous boost in throughput by 40%, even when dealing with heavy loads. Apart from the availability of wider channels and support for up to 16 spatial streams, the overall transmission environment in heavy loads also gets much stronger.

The work also verifies that Wi-Fi 7 offers much-reduced average latency by up to 48%, and jitter and packet loss remain in acceptable bounds, even in dense networks. These outcomes illustrate the paradigm shift made possible by the innovative MAC scheduling, packet aggregation, and deterministic medium access provided in IEEE 802.11be. Moreover, the joint operation of adaptive queueing, band steering, and cross-band retransmission coordination scheduling offers an excellent base to build high-performance resilience against bursty or saturated traffic patterns, such as in AR/VR, telemedicine, and mission-critical IoT networks.

Meanwhile, although the performance benefits of Wi-Fi 7 are staggering, several shortcomings need to be highlighted. Firstly, the benefits offered today are still reliant on the availability of compatible hardware from the perspectives of supporting MLO and dual-band radios, something presently absent from mass market as well as from industrial devices. Secondly, the effectiveness of MLO under the scenario of limited frequency spectrum availability—e.g., in old infrastructures having busy 2.4 GHz bands or regulatory constraint on the 6 GHz—has yet to be fully validated. Thirdly, although the NS-3 type of simulation tools offers a controlled and flexible platform for evaluation, the resulting analyses may fail to capture the variable and dynamic nature of the physical space, e.g., the impact of structural impediments, electromagnetic interference, or device heterogeneity.

From a practical standpoint, the results indicate that Wi-Fi 7 is well-positioned to support the increasing demands of smart city deployments, industrial automation, enterprise collaboration, and remote education systems. Its ability to maintain low latency and high throughput in congested conditions makes it particularly attractive for environments where the density of connected devices is expected to increase dramatically over the next decade. However, in order to implement such technology in the real world, aside from being hardware-ready, dedicated network design must also be taken into consideration in terms of channel allocation and legacy support.

Each of the simulation scenarios was run five times with distinct random seeds. The plots show the mean results, with error bars denoting standard deviations. When dealing with latency-critical traffic patterns (like VoIP, AR/VR communications), we also display the 95th percentile. Points beyond $\pm 2\sigma$ from the mean, when applicable, were marked. Our approach effectively exploits both mean and variance, helping the reader judge the robustness of the data. The complete NS-3 source code, including all the simulation scripts, parameters, and exact software specifications (NS-3 with 802.11be) are made available in the online supplement.

Wi-Fi 7 MLO is considered to be one of the most revolutionary breakthroughs, allowing simultaneously the operation in both 2.4 GHz, 5 GHz, and 6 GHz bands. Still, the current state of hardware support in the Wi-Fi 7 MLO standards is, in fact, immature. Currently, in regard to the development of network hardware, there has been an increasing trend in the support of MLO in various Wi-Fi 7 devices, including Zyxel WBE510D, GL iNet Flint 3, TP-Link Archer BE9700, and Netgear Orbi 370. Moreover, such hardware support covers both dual-band and tri-band devices, including devices of respectively lower and higher price categories. Still, in fact, there is an immature level of hardware support in the Wi-Fi 7 MLO standards. Thus, availability of MLO-supported devices in the Wi-Fi 7 networks is rather small. Intending to illustrate such availability, one can note the following. Currently, Intel's M200 device is one of the few devices in the Wi-Fi 7 networks offering the possibility of e-MSLR (enhanced multi-radio single-radio MLO) operations, which, in fact, does not allow full-scale multimode MLO operations, reducing, in fact, efficiency. Moreover, availability of MLO devices in the Wi-Fi 7 networks is further complicated due to changing rules concerning usage of 6GHz bands in different countries. As a result, while MLO-equipped Wi-Fi 7 technology is beginning to enter the market, its real-world application remains largely confined to tech-savvy early adopters and niche scenarios. Broader adoption will depend on the widespread rollout of standardized, reliable client-side implementations.

Overall, the findings of this work confirm the validity of Wi-Fi 7. preparedness to empower the wireless next generation. connectivity. An assembly of theoretical proceeds in. practically flexible performance in architecture, Wi-Fi 7 is a significant move along the way to reliable, low-latency, and wireless networks with high throughput and capable of supporting the specifications of the future digital infrastructure.

VI. Conclusion and Future Work

This paper critically evaluated Wi-Fi 7 (IEEE 802.11be) and Wi-Fi 6 (IEEE 802.11ax) performance in a range of network density metrics using the throughput, latency, jitter and the packet loss parameters. These experiments validated that Wi-Fi 7 has been demonstrated so far to perform better than its predecessor in all respects of performance within its range of applicable performance. It is interesting to note that Wi-Fi 7 provided up to 40% higher throughput, lag decreased by a mean of nearly 48 and showed reduced jitter in addition to a reduction in the rate of packet loss even in the most congested conditions. These gains essentially represent the direct effect of the existence of MLO, higher bandwidths in every channel, along with MAC-level scheduling, all of which work together in strengthening the capacity, response time, and overall quality of the radio connection.

The test confirms the high quality of Wi-Fi 7 in providing support for emerging applications with latency and data intensity, such as augmented reality applications, real-time collaboration software, and smart factory solutions. The simulator environment with multiple flows was used to validate the scalability and quality of Wi-Fi 7, which can be considered one of the primary options in terms of future-proofing public and enterprise wireless facilities.

However, although promising results have been obtained in this work, it must be pointed out that in practice, real-world variability, such as architectural interference, regulatory channel restrictions, and variability in device support, could also affect the outcomes. Hence, further studies must investigate the effect of Wi-Fi 7 in different environmental settings, including rural and suburban areas, which might be different from what is experienced in an urban environment.

Moreover, future work should also include energy efficiency evaluations, particularly with respect to battery-powered IoT devices and edge computing. Even though Wi-Fi 7 offers higher throughput and lower latency, the energy expenditure in sustaining multi-link transmissions and high-bandwidth communications is unclear. Researching energy per bit efficiency and scheduling schemes designed with low-power consumption in mind might help furtheroptimize the deployment of Wi-Fi 7 in sustainable and mobile networks.

Overall, this work offers an initial performance benchmark for Wi-Fi 7 and paves the way for a vast range of subsequent inquiries that can help deepen our knowledge of its real-world abilities as well as its eventual contribution toward the future of wireless connectivity.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Almamoon and Tamer conducted the research, analyzed the data, wrote, validate the paper, writing—review and editing the paper, Almamoon writing—original draft preparation; all authors had approved the final version.

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