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RESEARCH ARTICLE

Enterprise Approach: Performance Analysis of Wi-Fi 6 and 5G Private LAN With Micro-Slicing Feature

VANLIN SATHYA[1], LYUTIANYANG ZHANG[2], ONUR SAHIN[3], AND MEHMET YAVUZ[1]
[1]Celona Inc., Campbell, CA 95008, USA
[2]University of Washington, Seattle, WA 98195, USA
[3]Izmir Turk College, 35280 Izmir, Türkiye

Corresponding author: Lyutianyang Zhang (lyutiz@uw.edu)

ABSTRACT This study presents a comprehensive comparison of the performance indicators, namely latency, packet drop, and throughput, for commercial Wi-Fi and 5G LAN systems in both enterprise and warehouse environments. This pioneering assessment marks the first evaluation of actual commercial hardware products in such critical settings. The study focuses on both downlink (DL) and uplink (UL) data flows, employing Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) within these networks. The results from these real-life deployments indicate that Wi-Fi networks, when subjected to increased UL/DL traffic, tend to experience stability issues. This is particularly evident in the form of significant packet drops and increased latency, adversely affecting traffic that is sensitive to delays. Mobility scenarios, which involve device transitions between multiple Wi-Fi Access Points, further intensify these challenges. In contrast, the 5G LAN systems showcased remarkable performance in both stationary and mobile conditions. They consistently maintained a low rate of packet drops. This robust performance can be attributed to the efficient use of TDD frame allocation and Medium Access Control (MAC) scheduling techniques. Notably, micro-slicing feature in the 5G LAN setups was instrumental in ensuring reduced latency across various testing scenarios, proving its efficacy in diverse operational contexts.

INDEX TERMS Unlicensed, 5G LAN, shared spectrum, private networks, IoT, enterprise deployment, warehouse deployment.

I. INTRODUCTION

In the rapidly evolving landscape of cellular and Wi-Fi industries, meeting the demands of human traffic (voice, video, and data applications) is increasingly intertwined with automation technologies like Automated Guided Vehicles (AGVs), robots, and drones. Performance metrics like latency and network throughput are critical in enterprise environments and traditional human-centric applications. Presently, Wi-Fi deployments, especially Wi-Fi 6 [13] and 6E featuring 802.11 ax standards [14], excel in indoor environments, catering to mobile users' needs for high data rate applications like Virtual Reality and Augmented Reality (VR/AR). Conversely, cellular operators, leveraging 4G Long-Term Evolution (LTE) and 5G New Radio (NR [16]) technologies [15], primarily deploy small cells outdoors due to the high costs associated with Distributed Antenna System (DAS)-based indoor solutions. These traditional cellular networks typically remain separate from enterprise local area networks (LANs). A LAN is a network that connects devices within a limited area such as a building, enabling efficient communication and resource sharing.

However, both traditional Wi-Fi [11], [12] and traditional cellular approaches struggle to meet the stringent requirements of industrial Internet-of-Things (IoT [1]) and other machine-critical use cases. These domains demand exacting standards on latency, throughput, and packet error rates, which differ markedly from consumer applications.

An alternative involves using Licensed Assisted Access (LAA [4]) or New Radio Unlicensed (NR-U) in unlicensed

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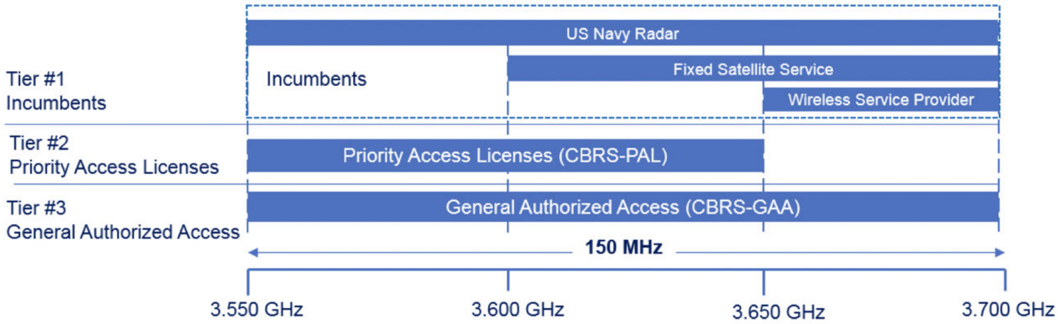


FIGURE 1. Three tier framework for 5G LAN band.

systems. However, as network load increases, User Equipment (UE) encounters more channel contention and collisions, leading to higher packet drops, jitter, and latency - all detrimental to sensitive or mission-critical applications like automated manufacturing or healthcare systems. Dedicated cellular licensed spectrum solutions, though effective, are marred by complexity and high costs.

Against this backdrop, the Citizenship Broadband Radio System (CBRS [17]), a recent release in the locally available clean spectrum, is gaining traction for private and public deployments, including parking lots where traditional Wi-Fi falls short. The 5G LAN technology, occupying 150 MHz bandwidth divided into 15 channels of 10 MHz each, offers private entities an opportunity to construct enterprise infrastructure services without hefty licensing fees [18], [19]. This development facilitates the deployment of advanced applications ranging from autonomous vehicles to IoT sensors and ultra-low latency applications, independent of commercial mobile carriers. The 5G LAN band is categorized into three tiers to mitigate interference and classify devices and communications: Incumbents, Priority Access License (PAL), and General Availability Access (GAA [2]). Figure 1 shows the three-tier framework for 5G LAN bands [26].

The Incumbents tier, reserved for entities like governmental agencies and navy ships, enjoys protection from interference. Commercial businesses can acquire PAL licenses through 5G LAN auctions, while the GAA tier, being the lowest, is subject to interference from the higher tiers but is accessible for a wide range of devices like mobile phones and small cell towers. The PAL licensing process, accessible via FCC auctions or secondary markets, and the GAA tier's flexibility are pivotal for enterprises planning mobile deployments.

For initial Base Station (BS) operations within this spectrum, it is essential to communicate specific requirements like transmission power and operating frequency to the Spectrum Access System (SAS [20]), a cloud-based spectrum coordinator. The SAS, utilizing environmental sensors, plays a crucial role in preventing interference, assigning power, and assessing spectrum availability [22], [23]. However, as the SAS cannot proactively connect with cellular access points [21], these must be designed and FCC-approved for operation within this spectrum. The OnGo Alliance, an industry group of over 100 technology and communication companies, champions the technological advancement of 5G LAN-powered networks and advocates for efficient spectrum utilization across various industries.

This study delves into the first real-time warehouse deployments using Wi-Fi and 5G LAN [3], [48], [49], [50] technologies. We specifically examine the impact of mission-critical applications like ping, in terms of latency, jitter, packet drop, and throughput, on actual data transmissions over TCP and UDP for both Uplink (UL) and Downlink (DL). Our observations reveal that with increasing system load and user numbers, Wi-Fi struggles to maintain performance, particularly in comparison to the more robust 5G LAN system.

II. LITERATURE REVIEW

The coexistence performance of 5G and Wi-Fi 6 systems, as explored through simulations assessing throughput, BER, and latency, forms the core of the study highlighted by [5]. Our research contrasts sharply with this approach by unveiling the real-world performance of 5G O-RAN and Wi-Fi systems based on actual commercial products. Emphasizing the 5G O-RAN system, our work identifies it as the industry's leading state-of-the-art private LAN solution. The cornerstone of our evaluation is the utilization of real commercial products, with a focus on detailed AP deployment that scrutinizes latency, throughput, and jitter.

Moreover, the simulation-based evaluation of critical IIoT applications' performance within the 5G and Wi-Fi domains, as noted by [6], serves as a precursor to our more ambitious project. Our paper elevates the discussion by assessing the performance of critical IIoT applications through real commercial products, spotlighting Wi-Fi systems and the 5G O-RAN as the latest in private LAN solutions.

Further diverging from the approach taken by the research using real products from Qualcomm and MediaTek to evaluate BER, Packet Loss Ratio, Latency, and data rate for video transmission over Wi-Fi or 5G C-band, as mentioned in [7], our study redirects the focus towards the CBRS band. Utilizing the 5G O-RAN system, we compare its performance against Wi-Fi systems, with a particular emphasis on broader applications enabled by the micro-slicing solution.

Additionally, the comparison of the overall number (utilization) and network architecture between 5G and Wi-Fi systems, as touched upon in [8], does not delve into the specifics of key performance indicators such as throughput. Our research takes significant strides beyond this by employing 5G O-RAN technology and includes an extensive data analysis of the KPIs collected from both the 5G O-RAN and Wi-Fi systems.

Furthermore, the study by [9] introduces a novel approach towards the design and implementation of a radio-aware multi-connectivity concept using a layer-4 scheduling mechanism. Two packet scheduling mechanisms, packet duplication and best path scheduling, are presented. This multi-connectivity solution significantly improves performance, cutting down system latencies to 30-80 ms at the 99.9%-ile of reliability. The proposed schemes fully mitigate Wi-Fi handover delays, allowing for seamless roaming in mobile conditions.

Lastly, the study by [10] evaluates a wireless Manufacturing Execution System (MES) for Industry 4.0, utilizing self-configuring multi-access gateways for seamless transport of delay-tolerant industrial Ethernet control data over LTE or Wi-Fi. The wireless MES solution was deployed at Aalborg University's Smart Production Lab, demonstrating reliable support for production control operations at the MES level, despite increased latency and packet loss compared to Ethernet.

III. SPECTRUM CHARACTERISTICS: WI-FI AND PRIVATE NETWORK (5G LAN)

Building on our introduction's context, this section delves into the fundamental mechanisms of Wi-Fi and cellular technologies, specifically focusing on Wi-Fi and 5G LAN [24], [25]. We aim to elucidate the distinct differences between these two technologies, both in terms of their protocols and from a mathematical perspective. This comparative analysis is essential to understanding the distributed nature of Wi-Fi systems and the centralized architecture inherent to Cellular systems.

A key aspect of our study is the qualitative analysis that intertwines with the experimental section, where we discuss the outcomes derived from real-world deployments of Wi-Fi and 5G LAN setups. This analysis not only provides a theoretical foundation but also serves to rationalize the empirical results obtained from our deployment experiences.

Wi-Fi operates within the WLAN 5GHz spectrum, a crucial component for understanding its performance and limitations. Figure 2 illustrates the WLAN 5GHz Spectrum Allocation Chart, providing a visual representation of how the spectrum is organized and utilized. This allocation chart is instrumental in comprehending the operational environment of Wi-Fi networks and their interaction with various frequency bands.

Wi-Fi 6, also known as 802.11ax, operates within the 2.4 GHz and 5 GHz bands and introduces several enhancements over previous Wi-Fi standards, including improved efficiency, greater capacity, and lower latency. The 5 GHz band, utilized by Wi-Fi 6, is particularly relevant due to its ability to support higher data rates and reduce interference, thus enhancing overall network performance. Licensed Assisted Access (LAA) is a feature of LTE and 5G technologies that enables the use of unlicensed spectrum, such as the 5 GHz band, to augment the licensed spectrum. This allows cellular networks to offload traffic onto the unlicensed bands, improving throughput and efficiency. The coexistence of Wi-Fi 6 and LAA [4] within the 5 GHz spectrum necessitates effective spectrum management to minimize interference and optimize the performance of both Wi-Fi and cellular networks, facilitating a more seamless and efficient communication environment.

A. WI-FI MECHANISM AND MEDIUM ACCESS CATEGORIES

In the realm of wireless local area networks (WLAN), the predominant protocol for managing data transmission is Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Under CSMA/CA, a station (or node) is permitted to transmit data only if it perceives the channel as idle, and no recent transmission has been completed. If the channel is occupied during the Distributed Coordination Function (DCF) Interframe Space (DIFS) sensing period, or if the station is attempting to transmit following a successful data transfer, it must continue to monitor the channel. Once the channel is idle for a DIFS duration, the station then engages in a random back-off process. This process involves selecting a back-off counter randomly within the range of $[0, 2^i \times W_0 - 1]$, where i denotes the back-off stage (starting at 0) and W_0 represents the initially chosen minimum contention window. Should a transmission fail due to packet collision, the back-off stage i increases by 1 (following the binary exponential back-off or BEB principle), and the node counts down from this newly selected back-off value. Upon successful unicast transmission, the recipient station acknowledges the receipt by transmitting an Acknowledgment frame (ACK) after a Short Interframe Spacing (SIFS) duration.

The WLAN system is also engineered to support various traffic categories, including background, best effort, video, and voice. Further delving into the practical aspects of WLAN, Table 1 provides a comprehensive overview of the experiment parameters employed in our study. This includes the number of WLAN Access Points (APs), their allocated channels, the frequency and bandwidth of operation, the transmission power settings, the method of channel selection, the number and type of WLAN client devices, and the tools used for monitoring and data transmission testing. This detailed experimental setup aids in a thorough evaluation of the WLAN mechanism under various conditions,

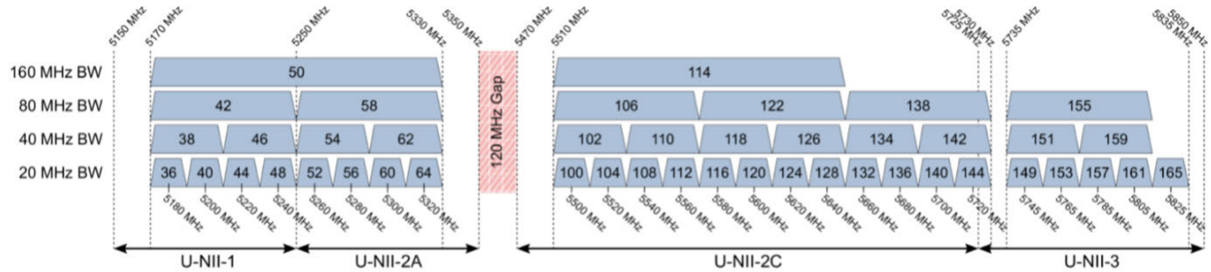


FIGURE 2. Wi-Fi 5GHz spectrum allocation chart.

contributing to a deeper understanding of its capabilities and limitations in real-world scenarios.

B. LTE AND 5G NR QUALITATIVE ANALYSIS

Contrasting with Wi-Fi's distributed CSMA mechanism, LTE and 5G NR employ a centralized approach to radio resource allocation, fundamentally differentiating their operational dynamics. In Wi-Fi, clients must compete for medium access for both UL/DL transmissions. However, in LTE and NR, user equipment (UEs) are allocated radio resources based on MAC layer scheduling algorithms, eliminating contention and inefficient spectrum usage. This centralized scheduling ensures optimal resource utilization to cover UEs' needs in LTE and NR environments [29].

The channel allocation strategy in 5G, often an adaptation of the Proportional Fairness (PF) algorithm, is designed to maximize network throughput while ensuring proportional fairness over time. The PF algorithm considers both the UL/DL data buffer and the channel spectral efficiency in its scheduling decisions. UEs with higher data rates, resulting from better channel spectral efficiency $\mathbf{C}_n$ or larger buffered UL/DL data, receive a larger share of scheduled resources. Conversely, UEs with lower channel spectral efficiency receive proportionally fewer resources, thus preventing resource wastage. Nonetheless, the channel spectral efficiency can still influence the overall network throughput.

The PF scheduler algorithm operates by maintaining an average data rate $R_t(n)$ for each UE over a time window T, updating it as follows:

$$R_t\left(n\right) = \left(1 - \frac{1}{T}\right) R_{t-1}\left(n\right) + \frac{1}{T} x_{t-1}\left(n\right), \qquad (1)$$

where $x_{t-1}(n)$ denotes the actual data rate of UE n at time $t-1$. The PF scheduler prioritizes the UE with the highest ratio of achievable instantaneous data rate to the average received data rate for resource allocation:

$$n^* = \arg\max \{P_t\left(n\right)\}, \qquad (2)$$

where

$$P_t\left(n\right) = \frac{C_t\left(n\right)}{R_t\left(n\right)}, \qquad (3)$$

with $C_t(n)$ representing the achievable instantaneous data rate for UE n at time t. The scheduler allocates resources to the UE with the highest $P_t(n)$, continuing this process until all Resource Blocks (RBs) in the current slot are allocated.

C. WI-FI AND 5G PRIVATE LAN: PROS AND CONS

Through this comparison, we endeavor to offer a nuanced understanding of how Wi-Fi and 5G private LAN functions, spotlighting their unique attributes and the implications they carry in various practical applications.

- **Spectrum Coordination:** Wi-Fi operates on an unlicensed spectrum shared with other technologies [47], covering 563 MHz and extending to 1.2 GHz in the 6 GHz bands, which includes protection measures for incumbents in the 5 and 6 GHz bands. On the other hand, 5G LAN benefits from a well-orchestrated spectrum allocation, managed by the Spectrum Access System (SAS), providing a total of 150 MHz bandwidth. This centralized and regulated allocation by SAS's Environmental Sensing Capability (ESC) minimizes interference and optimizes spectrum usage [28].
- **Coverage Range:** Wi-Fi, with its lower transmit power, has a more limited coverage range compared to 5G LAN [45]. The Wi-Fi noise floor depends on the channel width, ranging from 20+20 MHz to 80+80 MHz, using OFDM sub-carriers at 15 KHz. In contrast, 5G LAN's higher transmit power allows for broader coverage, making it suitable for extensive outdoor environments. For an illustrative depiction of Wi-Fi's operational environment in indoor scenarios.
- **Traffic Handling:** Wi-Fi networks handle traffic with distributed contention between clients and Access Points (APs), enabling dynamic allocation in both directions. In contrast, 5G LAN employs a scheduled allocation of radio resources based on weighted upload and download profiles, leading to more efficient and predictable traffic management [33].
- **Quality of Service (QoS):** Wi-Fi networks typically use statistical prioritization, which can be enhanced with optional RF loops. In contrast, 5G LAN offers deterministic QoS support, thanks to its scheduling mechanism

and mandatory RF feedback loops such as Channel Quality Indication (CQI) and Signal-to-Interference-plus-Noise Ratio (SINR), ensuring consistent service quality.

- **Density Handling:** Wi-Fi supports Single Factor OFDMA with the widely used legacy OFDM technology, mitigating co-channel interference through the CSMA protocol. 5G LAN, using Dual Factor OFDMA (Frequency and Time Domains), effectively manages co-channel interference, making it more suitable for high-density environments.
- **Mobility:** Wi-Fi networks rely on client-initiated off-channel scanning for roaming decisions, which can be less efficient. In contrast, 5G LAN employs infrastructure-controlled handover decisions, precisely timed for seamless mobility.
- **Security:** 5G LAN networks use SIM technology for device authentication, providing a more secure, whitelist-only approach. This stands in contrast to Wi-Fi's reliance on password-based security, which is less secure and poses risks, especially in scenarios where network integrity is critical [34], [35].
- **Capacity:** 5G LAN networks, with their structured traffic scheduling, accommodate a larger number of devices more efficiently than Wi-Fi networks, which can suffer from collisions and interference due to their dependence on random access backoff algorithms.
- **Latency:** Wi-Fi typically offers low latency in low-traffic scenarios but can face significant delays during high-traffic periods. 5G LAN networks, however, consistently maintain low latency, even under heavy traffic conditions, making them ideal for real-time data processing applications.
- **Speed:** Both Wi-Fi and 5G LAN offer competitive speeds suitable for a range of business applications. Wi-Fi can achieve speeds up to 1Gbps, while 5G LAN speeds vary from 25 Mbps to 1 Gbps, depending on whether 4G or 5G cellular technology is used.
- **Cost:** For outdoor deployments, 5G LAN provides a cost-effective solution due to its wide coverage per radio unit. In indoor settings, the implementation costs of a 5G LAN network are comparable to those of Wi-Fi, particularly when considering advanced solutions like cloud networking.

In summary, Wi-Fi and 5G LAN each present a set of distinct advantages and challenges. Wi-Fi offers ease of deployment and widespread accessibility but faces limitations in terms of coverage, traffic handling, and density management. Conversely, 5G LAN stands out for its efficient spectrum use, extensive coverage, and superior handling of traffic, QoS, and network security. These contrasting attributes underscore the different operational characteristics of each technology, emphasizing their suitability for varied applications and settings.

IV. 5G LAN AND WI-FI END-TO-END ARCHITECTURE

This section explores the architectural details of 5G LAN and WLAN systems, providing a thorough understanding of their end-to-end connection frameworks. We aim to articulate the complex processes and components involved in these systems, from the initiation of connections to their successful termination. An illustration of the comprehensive architecture of 5G LAN, encompassing all critical elements from SIM cards to cloud orchestration, is provided in Figure 3.

A. 5G LAN END-TO-END ARCHITECTURE

The 5G LAN architecture presents a holistic approach to setting up a private mobile network. This architecture consists of several integral components, each playing a crucial role in the network's functionality. Figure 3 illustrates the end-to-end architecture of 5G LAN, showcasing the seamless integration of its diverse elements. The key components of this architecture include:

- **SIM Cards**: Utilized for authenticating and connecting devices to the network [36].
- **Radio Access Network (RAN)**: Comprising both indoor and outdoor private LTE/5G access points, the RAN forms the backbone of the network's connectivity [37].
- **On-site Edge Computing Services with Evolved Packet Core (EPC)**: This setup facilitates local data processing and management of core network functions [38].
- **Cloud-based Orchestration**: Centralizes network operations, enabling efficient management and scalability [39].
- **Integration with Spectrum Access System (SAS)**: Ensures regulatory compliance, particularly in spectrum usage [40].

The 5G LAN architecture streamlines the typically intricate process of procuring and integrating components from multiple vendors into a unified system. Each component is supported and managed via the cloud, enhancing operational efficiency and ease of use. The edge computing setup is crucial for tunneling and securing wireless traffic, while the access points are designed for zero-touch deployment in enterprise environments. The cloud-hosted orchestrator plays a pivotal role in managing configurations and automating essential tasks such as radio frequency selection. This is achieved through advanced machine learning algorithms that enhance Self-Organizing Network (SON) functions.

The SON system, a standout feature of this architecture, is adept at adjusting to shared spectrum allocations. It ensures that the network remains compliant with frequency channel usage regulations. This capability is particularly beneficial for enterprise IT departments, as it automates the coordination and frequency assignment of AP radios, negating the necessity for separate licensing or complex integration with government-certified spectrum-sharing frameworks [41].

In our experiment, understanding the 5G LAN architecture is crucial as it helps us set up the network in a manner

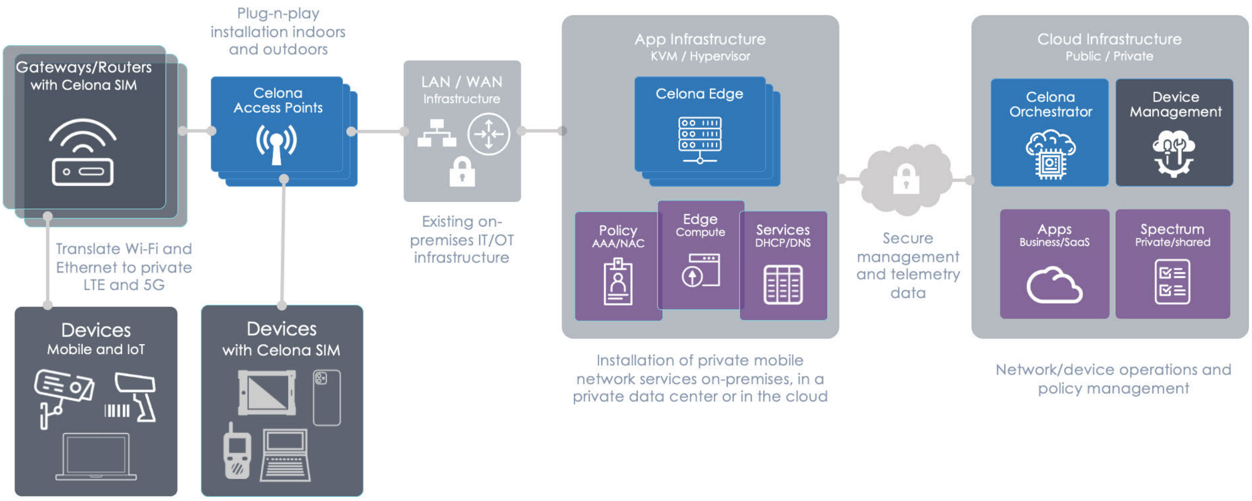


FIGURE 3. End-to-end architecture of 5G LAN, highlighting the integration of key components ranging from SIM cards to cloud orchestration.

that optimizes performance metrics such as latency, packet drop, and throughput. The use of advanced SON functions and cloud-based orchestration ensures stable and efficient operations during high traffic conditions.

B. MICRO SLICING

Micro-slicing technology represents a significant advancement in the allocation of network resources and services. This innovative approach offers precise control over network segments for various applications and devices, particularly those with strict requirements for latency and reliability. Figure 4 illustrates the concept of micro-slicing, highlighting the allocation of dedicated network segments to specific groups of devices and applications. Managed by the enterprise orchestrator, micro-slicing facilitates:

- Tailoring of application-specific Service Level Agreements (SLAs) to ensure optimal bandwidth, latency, and error rates for each application [42].
- Customized network provisioning for individual applications, enhancing overall performance.
- Advanced tracking of app-level Key Performance Indicators (KPIs) utilizing AI/ML technologies, enabling the system to learn and adapt to application behaviors over time [43].

This technology not only provides comprehensive visibility of device performance but also significantly improves network efficiency and cost-effectiveness. Micro-slicing adeptly manages network resources, preventing unnecessary occupation of these resources, thereby ensuring optimal utilization. Figure 4 demonstrates the intricate workings of the micro-slicing feature.

In our experiments, micro-slicing is crucial for maintaining low latency and high throughput in diverse testing scenarios. This feature allows us to allocate network resources dynamically, ensuring that critical applications receive the necessary bandwidth and low latency they require, thereby improving overall network performance.

C. WI-FI END-TO-END ARCHITECTURE

Wi-Fi's widespread adoption is largely attributed to its operation in the unlicensed spectrum, which facilitates its extensive deployment. Despite this, challenges such as interference and network collision, especially in dense environments, are inherent to Wi-Fi networks.

To enhance security and reliability, Wi-Fi networks often incorporate centralized encryption and sophisticated authentication methods, including RADIUS. In larger deployments, network segmentation is a common practice, serving to isolate guest networks from private ones.

A significant challenge for Wi-Fi networks, particularly in large-scale deployments, is managing device mobility across different APs. Wi-Fi's dependence on connected devices to make AP switching decisions can lead to unpredictable latency and data transfer speeds in high-traffic scenarios. This issue is more pronounced in enterprise environments where consistent network performance is crucial.

Comparing the architectures of 5G LAN and Wi-Fi reveals distinct approaches to connectivity, resource management, and overall network operations. 5G LAN offers a structured and advanced setup, featuring innovations like micro-slicing, while Wi-Fi provides the advantage of easy deployment but faces challenges in managing high-density networks [44]. This contrast highlights the unique operational characteristics and suitability of each technology for varying applications and environments.

In our experiments, these architectural differences are critical in evaluating performance metrics under varying conditions. Wi-Fi's decentralized *i.e.*,, CSMA-based approach leads to noticeable performance degradation under high traffic, while 5G LAN's centralized management maintains stable performance.

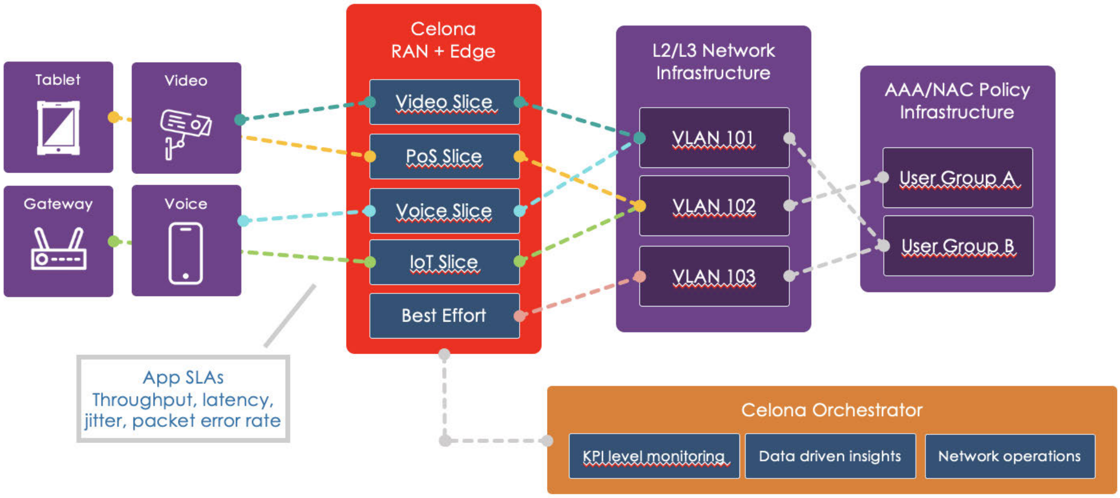


FIGURE 4. Depiction of micro slicing, emphasizing the targeted allocation of network resources for diverse applications and devices.

V. ENTERPRISE EXPERIMENT ENVIRONMENT AND CONFIGURATION

This section outlines the experimental setup for evaluating Wi-Fi and 5G LAN systems in an enterprise environment. The experiments were conducted at a dedicated test facility in the USA, using an open-air commercial wireless network testbed. The key parameters of the deployment, radio technology, and experiment details are summarized in Table 1.

Table 1 consolidates the key parameters for both Wi-Fi and 5G LAN systems, providing a clear comparison of their configurations in the experiment.

- **Carrier and Operating Frequency**: Wi-Fi operates in the 5 GHz band, while 5G LAN utilizes the 3.5 GHz band, highlighting the different spectrum environments.
- **Number of APs and Clients**: Both setups use a similar number of access points and clients, ensuring a fair comparison.
- **MIMO Configuration and Antenna Pattern**: Both systems use a 2×2 MIMO configuration and omni-directional antennas, standardizing the hardware setup.
- **AP Placement**: APs are placed on the roof ceiling in both scenarios to provide consistent coverage.
- **Bandwidth and Transmission Power**: Both systems use a 40 MHz bandwidth, with Wi-Fi transmission power ranging from 15 to 17 dBm and 5G LAN transmission power set at 23 dBm. The transmission power specifications are applicable to the base station.
- **Channel Selection and Spectrum Management**: Wi-Fi uses a centralized controller for channel selection, while 5G LAN channels are allocated by the SAS, reflecting their respective spectrum management strategies.
- **Client Devices and Traffic Tools**: Both setups involve similar client devices and use Iperf and Ping for traffic testing, maintaining consistency in the evaluation metrics.
- **Micro Slicing and QoS**: 5G LAN employs micro-slicing to enhance performance under varying traffic conditions, while Wi-Fi uses standard QoS mechanisms.

Table 1 is crucial for understanding the experimental conditions under which Wi-Fi and 5G LAN systems were tested. By standardizing key parameters and highlighting differences in technology and management strategies, this setup allows for a direct comparison of performance metrics such as throughput, latency, and packet drop. This comparative analysis helps identify the strengths and weaknesses of each system in handling enterprise-level traffic demands.

A. WI-FI ENVIRONMENT AND CONFIGURATIONS

The WLAN network under investigation comprises three production WLAN Access Points (APs) strategically deployed across the office floor. These APs provide comprehensive indoor coverage for a variety of devices, including mobile phones, laptops, printers, and televisions. All APs are connected to a centralized controller, which manages key network parameters such as channel selection, transmission power, and operating bandwidth. The setup is as follows:

- **Channel Allocation**: The WLAN controller allocates channels 44, 108, and 124 with 40 MHz bandwidth to the three WLAN APs, using both UNII-1 and Dynamic Frequency Selection (DFS) bands. This choice is influenced by the crowded state of the unlicensed channels in the UNII-1 and UNII-3 bands.
- **Transmission Power:** The experiment observes varying transmission power levels depending on the WLAN band. Specifically, 15 dBm is noted for channels 44 and 48 (40 MHz bandwidth), 15 dBm for channels 108 and

TABLE 1. Experiment setup parameters.

Parameter	Wi-Fi	5G LAN
Carrier	5 GHz	3.5 GHz
Number of APs	3	2
MIMO Configuration	2x2	2x2
Antenna Pattern	Omni	Omni
AP Placement	Roof Ceiling	Roof Ceiling
Operating Frequency	2.4 and 5 GHz	3.55 to 3.7 GHz
Bandwidth	40 MHz	40 MHz
Transmission Power	15-17 dBm	23 dBm
Channel Selection	MIST Centralized S/W Controller	Spectrum Access System (SAS)
Number of Clients	5	5
Client Devices	Google Pixel	Samsung S21, Google Pixel
Micro Slicing	No	Yes
Wi-Fi QoS	Yes	-
Tools	Iperf, Ping	Iperf, Ping
Monitoring Software	Wireshark	Wireshark

112 (40 MHz bandwidth), and 17 dBm for channels 124 and 128 (40 MHz bandwidth). [1]

B. 5G LAN ENVIRONMENT AND CONFIGURATION

For the 5G LAN setup, two APs are installed to ensure strong signal coverage across the entire office floor. Each AP is linked to the wireless LAN backhaul (i.e., WAN network), which in turn connects to a nearby edge network. The configuration is as follows:

- **Bandwidth and Channels**: The APs are set up with a 40 MHz bandwidth using 5G LAN channels allocated by the Spectrum Access System (SAS) at the time of request grant.
- **Seamless Handover**: Seamless handover refers to the process of smoothly transitioning user equipment (UE) from one 5G LAN access point (AP) to another without application interruptions. In our experiment, the handover algorithm is specifically designed to minimize packet drops, jitter, and latency during this transition. This ensures that even mission-critical applications, which require high reliability and low latency, experience minimal disruption. Although there is some slight increase in latency during handovers, it remains within acceptable limits (below 60 ms), ensuring the overall network performance remains stable and unaffected.

C. TRAFFIC ENVIRONMENT: TCP IPERF AND PING APPLICATION

The network is subjected to both Downlink (DL) and Uplink (UL) traffic through our own deployed server at the edge, minimizing any additional delays over the backhaul network. The experiment includes:

- **TCP Traffic**: Both DL and UL traffic are TCP-based. The network is loaded with multiple (i.e., 60) TCP connections via iperf, simulating an environment with 25 to 39 UEs in various DL and UL combinations.
- **Ping Tests**: Ping packets are transmitted at 10 ms intervals, with a time to live of 64 hops and operating in ICMP mode. The timeout duration for ping packets is set to 1000 ms.
- **Experiment Test Cases**: A detailed description of the test cases for the experiment is provided in Table 2.

D. EXPERIMENTAL SETUP FOR STATIC AND MOBILITY SCENARIOS

This subsection describes the experimental setups designed to evaluate the performance of WLAN and 5G LAN systems under both static and mobility scenarios.

1) EXPERIMENT SETUP

The static experiment is designed to evaluate the performance of WLAN clients positioned in an area with strong signal strength, which is a common scenario in enterprise environments. The specific aspects of this setup are as follows:

- **WLAN Client Deployment**: All WLAN clients are located in an area with proper signal coverage. However, due to the nature of WLAN, these clients have to contend for access to the unlicensed spectrum, leading to a high likelihood of channel contention and collision.
- **Air Medium Utilization**: In dense WLAN client deployments, a significant portion of the air medium (approximately 60-70%) is typically occupied by control packets (BACKs), management frames (beacons, probes, association, authentication), and data packets.

2) 5G LAN EXPERIMENT SETUP

For the 5G LAN segment of the experiment, the setup focuses on assessing the performance of band 48 support clients under optimal signal conditions:

- **Client Placement**: Clients are strategically placed within the good coverage signal area of the 5G LAN APs, specifically AP1 and AP2, as depicted in Figure 5.
- **Micro-Slicing Configuration**: The 5G LAN APs are configured with a micro-slicing feature. This advanced capability, managed by the network orchestrator, allows for the allocation of dedicated resource slices to meet

[1] To maintain realism, we do not force the Wi-Fi to operate at 23 dBm, as this could hinder performance and would not reflect typical enterprise settings. This approach ensures that the experiment accurately represents an actual enterprise Wi-Fi environment, with the CBRS network overlaying this existing network.

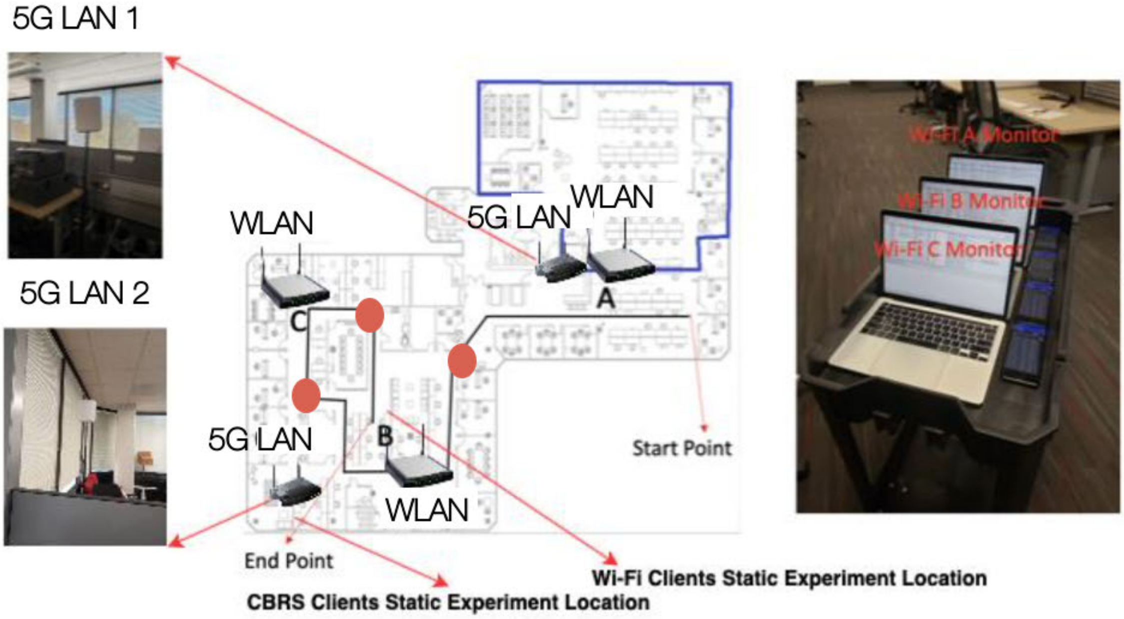


FIGURE 5. Wi-Fi and 5G LAN experiment setup.

TABLE 2. Experiment test cases.

Scenarios	Description
1 Ping	Only one UE running the ping test
5 Ping	Five UEs start the ping test (Approx. at the same time)
1 DL 1 Ping	All two UE traffics (DL, Ping) running ipref and ping on the air
1 UL 1 Ping	All two UE traffics (UL, Ping) running ipref and ping on the air
1 DL 1 UL 1 Ping	All three UE traffics (DL, UL, Ping) running ipref and ping on the air
2 DL 1 Ping	All three UE traffics (2 DL, Ping) running ipref and ping on the air
2 UL 1 Ping	All three UE traffics (2 UL, Ping) running ipref and ping on the air
2 DL 2 UL 1 Ping	All five UE traffics (2DL, 2UL, 1Ping) running ipref and ping on the air

specific needs of different 5G LAN device groups, such as ensuring low latency for delay-sensitive devices.

- **Traffic Configuration**: In our experiment, ping traffic is configured as real-time and delay-sensitive, to test the efficacy of micro-slicing in managing and prioritizing different types of network traffic.
- **Resource Allocation**: The experiment aims to observe how effectively 5G LAN can manage mixed traffic transmissions while still guaranteeing the specific requirements of different device groups, a capability that is crucial in dense network environments.

Unlike a Distributed Antenna System (DAS), each 5G LAN small cell has its own radio, cellular protocol stack, availability, and processing capacity. This configuration offers high capacity with good RF coverage and high throughput. In a DAS setup, a single base station signal is distributed across multiple antennas throughout the building, which ensures good RF coverage but does not match the capacity of a 5G LAN setup.

This experimental setup provided insights into how WLAN and 5G LAN systems handle network traffic under static conditions, particularly in terms of managing air medium utilization, contention, and collision, as well as resource allocation for varied traffic types.

The mobility experiment is designed to evaluate the performance of WLAN and 5G LAN systems during device movement across different coverage areas. This setup aims to assess how each system manages handovers between Access Points (APs) and the impact on network performance, particularly in terms of packet loss and latency:

- **WLAN Handover Mechanism**: In WLAN networks, handovers between APs typically follow a break-and-make approach. This method can result in increased packet loss or heightened latency during transitions from one WLAN AP to another. The efficiency of these handovers is a key focus of our investigation.
- **5G LAN Handover Efficiency**: Conversely, the 5G LAN system utilizes a make-and-break handover mechanism, which is generally more efficient in mobility scenarios. This setup tends to result in lower packet drop rates, a crucial advantage in maintaining consistent network performance.
- **Observation on Channel Usage**: A higher packet count is observed on WLAN channel B, which can be

attributed to the experiment's journey path predominantly covering the B AP's area, as indicated in Figure 5.

- **Analyzing Network Performance**: The experiment's objective is to analyze how effectively each system manages mobility, with a specific focus on network performance during AP handovers and the distribution of network traffic across different channels.

Through this mobility experiment setup, we aim to gain a deeper understanding of the comparative efficiency of WLAN and 5G LAN systems in handling device movement across multiple APs, especially in terms of handover mechanisms and their impact on network stability and performance.

E. RESULT DISCUSSION

This section discusses the results of the experiments conducted to compare the performance of 5G LAN and Wi-Fi systems.

1) PING RESULT DISCUSSION

The experiment is structured to evaluate the latency performance of both 5G LAN and Wi-Fi networks under varying load conditions. The following observations and analyses are drawn from the conducted ping tests:

- **Latency and Packet Drop in WLAN**: Figure 6 illustrates the latency comparison between 5G LAN and WLAN, highlighting the inconsistencies and delays in WLAN as the network load increases. As network load intensifies, there is a noticeable linear increase in latency that peaks at more than 200 ms for WLAN mobility case and 145 ms for WLAN static case, while 5G LAN remains almost constant at around 50 ms. This can be attributed to the contention and collision inherent in the WLAN, particularly evident during simultaneous UL/DL transmissions. Packet drop in WLAN setup also increases approximately in linear form and peaks at almost 20 for both static and mobility cases; however, for 5G setup, there is almost no packet drop (0%) for all test cases. Both traditional and slicing 5G LAN configurations maintain these low latencies and minimal packet drops, with slicing demonstrating even better stability under high load conditions.
- **Jitter Impact**: Figure 7 shows the comparative impact of jitter on both 5G LAN and WLAN systems. Jitter, along with latency, significantly influences packet drops within the network, as depicted in Figure 8. Traditional and slicing 5G LAN configurations both exhibit lower jitter compared to WLAN, but slicing configurations show an enhanced capability to maintain lower jitter levels as network load increases, offering a more stable performance.
- **Real-World Warehouse Deployment Scenario**: In a typical warehouse setting with a high network load, it is expected that latency in the WLAN system could escalate to approximately 700 to 1000 ms, based on our observations. Such high latency, coupled with increased packet drop rates, particularly in mobility scenarios, exacerbates the challenges in WLAN networks. Additionally, WLAN APs operating on the Dynamic Frequency Selection (DFS) band face more complex handover processes compared to those on other Unlicensed National Information Infrastructure (UNII) bands.
- **Comparison of Micro-Slicing and Traditional 5G LAN Performance:** Our comparison between traditional and micro-slicing 5G LAN results against Wi-Fi reveals that both traditional and micro-slicing configurations outperform Wi-Fi significantly in terms of latency, packet drop, and jitter, especially under increased load conditions. While traditional and micro-slicing 5G LAN show similar performance with low latency, minimal packet drop, and low jitter under low load, the benefits of micro-slicing become more pronounced as the load increases. Under high load conditions, micro-slicing maintains lower latency, reduces packet drop, and minimizes jitter more effectively than traditional 5G LAN, demonstrating its superiority in replicating a realistic enterprise environment with higher network performance demands.

In contrast to WLAN, the 5G LAN network utilizes scheduling based on Quality of Service Class Identifier (QCI) and slot fairness. Moreover, the micro-slicing feature in 5G LAN plays a significant role in ensuring Quality of Service (QoS) for delay-critical traffic, such as Ping, by establishing dedicated bearers. This analysis underscores the contrasting performances of 5G LAN and WLAN in handling network traffic under various load conditions. While 5G LAN exhibits more stable and consistent performance due to efficient scheduling and micro-slicing, WLAN struggles with increased latency and packet drops, particularly in high-load and mobility scenarios.

On the other hand, the 5G LAN network is an infrastructure-based control and constantly takes measurement feedback from the UEs in the order of milliseconds. This helps to make the right choice of when to make the handover decision. Also, for WLAN, the transmission opportunity (TXOP) is higher (*i.e.,* 6 ms for A-MPDU enabled system) compared to real-time ping traffic (*i.e.,* 2 ms), and ping traffic needs more frequent opportunities to pass through the air medium. In WLAN, when the AP is wholly occupied or loaded in each (traffic bucket) Queue because of no frequent access to the medium, then the real-time ping traffic (in ms intervals) cannot be guaranteed due to late transmission or timeout packets.

The distinct approaches of WLAN and 5G LAN to managing network traffic, particularly in terms of handling TCP streams and ensuring timely ACK packet transmission, highlight the advanced capabilities of 5G LAN in ensuring consistent and reliable network performance.

2) USE-CASES RESULT DISCUSSIONS

This section delves into the analysis of various real-time traffic use cases in an enterprise environment, encompassing

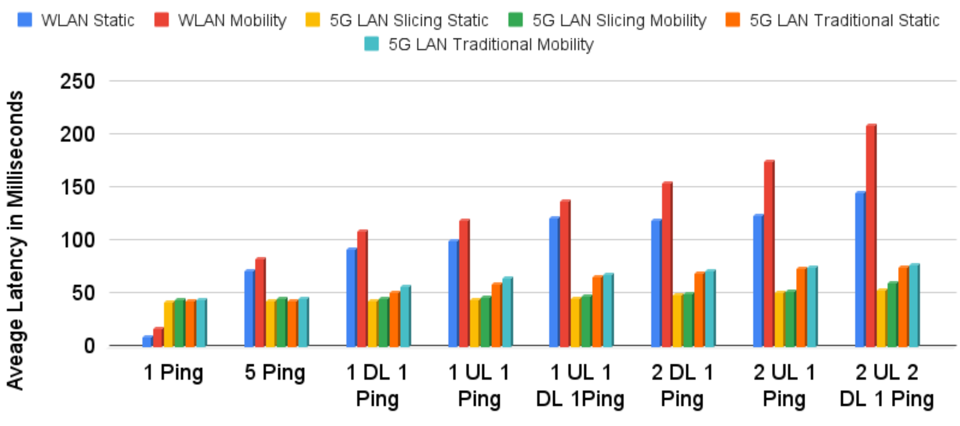


FIGURE 6. Comparison of 5G LAN and Wi-Fi in latency in ms.

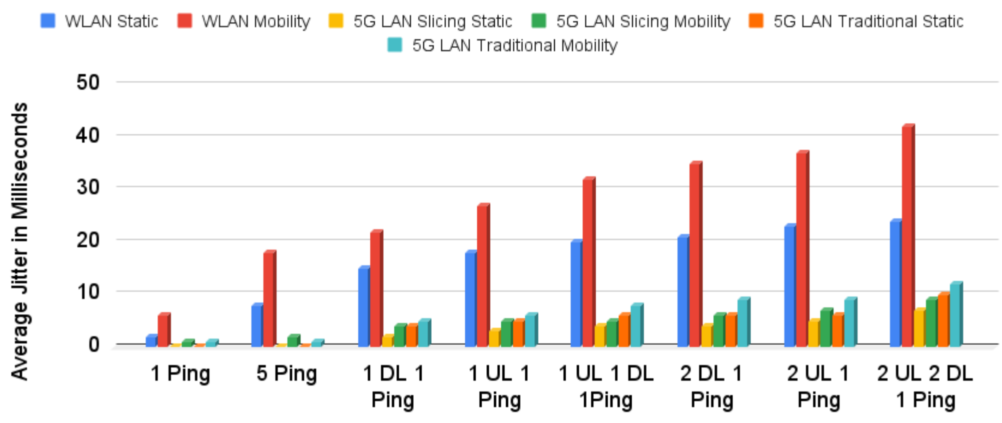


FIGURE 7. Comparison of 5G LAN and Wi-Fi in jitter in ms.

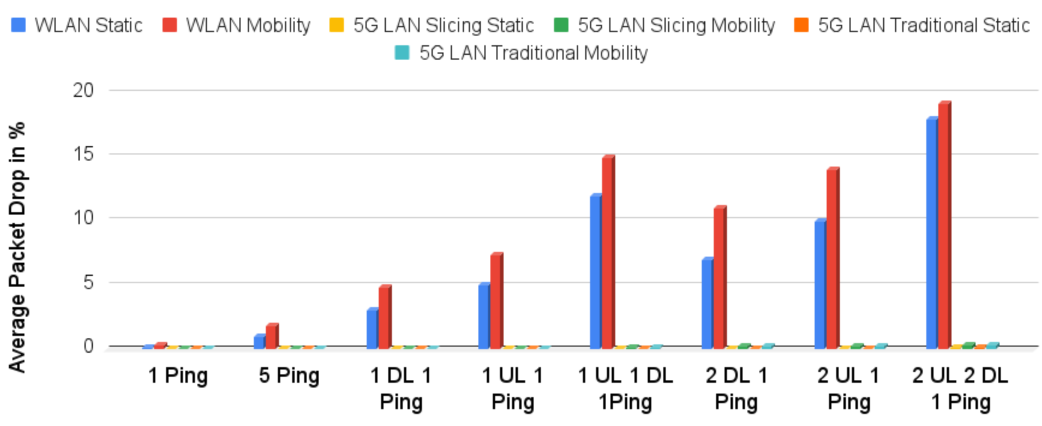


FIGURE 8. Comparison of 5G LAN and Wi-Fi in packet drop in %.

both WLAN and 5G LAN systems. Table 3 provides an overview of how different use cases impact these networks under static and mobility conditions, both loaded and unloaded. The score (Bad, OK, and Good) for different applications is based on the performance experienced by the end-device. The Bad score (*i.e.,* 1 to 3) is determined when the application is not usable for the end-user due to more packet drop and increase in latency. The OK score (*i.e.,* 4 to 7) is determined when the application is usable but the end-user can experience notable latency in the deliverables. The Good

(a) Zoom (b) Barcode (c) 5G LAN Camera (d) Wi-Fi Camera

FIGURE 9. Zoom, barcode and camera performance on Wi-Fi and 5G LAN.

TABLE 3. Different usecase performance between Wi-Fi and 5G LAN.

APPs	Unloaded Static		Loaded Static		Unloaded Mobility		Loaded Mobility	
	Wi-Fi	5G LAN	Wi-Fi	5G LAN	Wi-Fi	5G LAN	Wi-Fi	5G LAN
Zoom	OK	Good	Bad	Good	OK	Good	Bad	Good
Barcode	Good	Good	Bad	Good	OK	Good	Bad	Good
VoIP	Good	Good	Bad	Good	Bad	Good	Bad	Good
Camera	OK	Good	Bad	Good	Bad	Good	Bad	Good

Score: Bad → 1-3, OK → 4-7, Good → 8-10

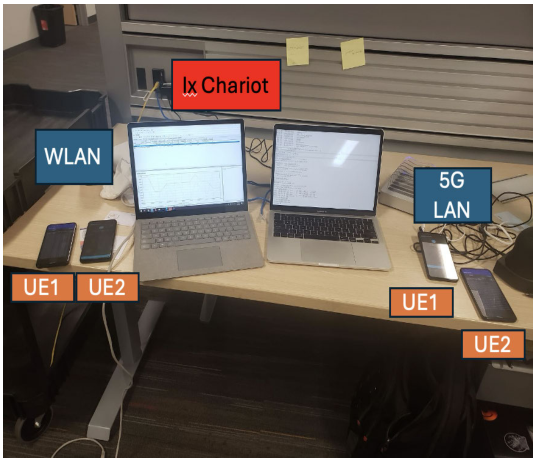
score (*i.e.,* 8 to 10) is determined when the application experience is flawless for the end-user. The key observations from our experiments in 9 are summarized below, with a focus on the behavior, characteristics, and performance of each use case:

- **Performance in Static Scenario**: In static scenarios where both WLAN and 5G LAN clients are near the access points, WLAN in itself performs better when it is unloaded compared to when it is loaded. However, 5G LAN consistently outperforms WLAN in both unloaded and loaded scenarios. Overall, 5G LAN is superior in all conditions.
- **Zoom Call Experiment**: Conducted with a laptop client, this experiment compares Zoom call performance on 5G LAN (using a Quanta dongle for 5G connectivity) and WLAN (connecting to a MIST WLAN AP). Both networks have specific features enabled to optimize Zoom traffic, such as WLAN's WMM and 5G LAN's micro-slicing. The Zoom application's statistics provide insights into latency, jitter, and packet loss for real-time traffic. Figure 9(a) showcases the setup for this experiment. As network load increases, the Zoom call quality on WLAN deteriorates significantly, marked by high latency, jitter, and packet drops.
- **Barcode Scanner Experiment**: Utilizing the Scan-IT to Office application (Figure 9(b)), this test involves scanning barcodes to input data into Excel spreadsheets in real-time. With a target of ten scans in ten seconds, the experiment reveals a decrease in successful scans within the allotted time on the WLAN network under loaded conditions.
- **VoIP Experiment**: Employing the IxChariot Keysight voice call application (Figure 10(a)), this test assesses VoIP call quality on both networks. In this setup, there are two UEs (UE 1 and UE 2 represented in Green and Red) making the VoIP call on WLAN and 5G LAN systems. While the 5G LAN AP operates on a $(20+20)$ MHz configuration, the WLAN AP uses a 40 MHz DFS spectrum. The experiment involves running iperf UL and DL traffic in parallel to the VoIP calls. The results show that even with minimal UL traffic, the WLAN system struggles to maintain VoIP quality, as evidenced by the Mean Opinion Score (MOS) of 1.4 (Figure 10(b)), compared to 5G LAN's superior MOS close to 4.3 (Figure 10(c)).
- **Camera Experiment**: In this setup, a Camera AXIS is connected to a 5G LAN via a CPE device (Figure 9(c)), and to a WLAN network through a MIST AP (Figure 9(d)). During active frame transmission at 30 FPS using the H.264 encoding scheme, Wireshark is used to monitor network traffic. This experiment highlights more dropped frames in the WLAN system compared to 5G LAN, particularly during image buffering and encoding processes.

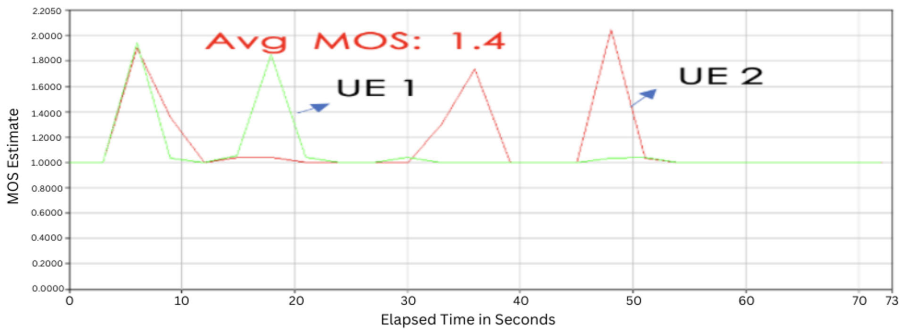
These experiments illustrate the varying effectiveness of WLAN and 5G LAN systems in handling different types of real-time enterprise traffic. While 5G LAN consistently provides stable and high-quality service, WLAN shows susceptibility to performance degradation under increased network load, particularly in dynamic and real-time traffic scenarios. Figure 10 shows the performance of the voice call on WLAN and 5G LAN systems. We notice similar result correlation on the performance of VoIP compared to Table 3.

3) THROUGHPUT RESULT DISCUSSIONS ON NON-CO-CHANNEL AND CO-CHANNEL SCENARIOS

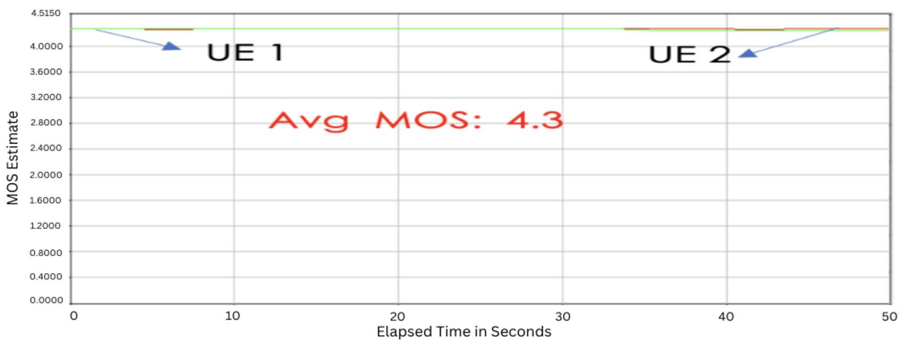
The experiments conducted focus on comparing the Downlink (DL) and Uplink (UL) throughput performance of



(a) VoIP Exp. Setup



(b) Wi-Fi VoIP MOS



(c) 5G LAN VoIP MOS

FIGURE 10. VoIP performance on Wi-Fi and 5G LAN.

TABLE 4. Aggregate throughput (in Mbps) for Non co-channel Scenarios between Wi-Fi and 5G LAN.

Scenarios	5G LAN	Wi-Fi
1 DL	DL: 148 Mbps	DL: 196 Mbps
1 UL	UL: 26 Mbps	UL: 66 Mbps
1 DL 1 UL 1 Ping	DL: 100 Mbps, UL: 22 Mbps	DL: 36 Mbps, UL: 17 Mbps
2 DL 2 UL 1 Ping	DL: 102 Mbps, UL: 21 Mbps	DL: 22 Mbps, UL: 10 Mbps

WLAN and 5G LAN systems under various channel configurations. The findings are detailed in Tables 4, 5.

In scenarios with non-co-channel allocations, the WLAN system shows high throughput (up to 200 Mbps) when operating with a single UE in DL. This high throughput, however, decreases significantly as the number of DL users increases. The cause of this decline can be attributed to the increased control and management packets in the network,

TABLE 5. Aggregate Throughput (in Mbps) for co-channel scenarios between Wi-Fi and 5G LAN.

Scenarios	5G LAN	Wi-Fi
1 DL	DL: 110 Mbps	DL: 86 Mbps
1 UL	UL: 18 Mbps	UL: 50 Mbps
1 DL 1 UL 1 Ping	DL: 82 Mbps, UL: 16 Mbps	DL: 28 Mbps, UL: 10 Mbps
2 DL 2 UL 1 Ping	DL: 78 Mbps, UL: 14 Mbps	DL: 17 Mbps, UL: 8 Mbps

TABLE 6. Average throughput (in Mbps) for Wi-Fi system.

Scenarios	AP 1			AP 2			AP 3		
Wi-Fi DL (Mbps)	UE1: 12	UE2: 8	UE3: 15	UE1: 16	UE2: 12	UE3: 15	UE1: 6	UE2: 10	UE3: 12
Wi-Fi UL (Mbps)	UE1: 6	UE2: 2.5	UE3: 5	UE1: 3	UE2: 4	UE3: 7	UE1: 4	UE2: 6	UE3: 5

TABLE 7. Average throughput (in Mbps) for 5G LAN system.

Scenarios	AP 1					AP 2			
5G LAN DL (Mbps)	UE1: 24	UE2: 26	UE3: 22	UE4: 20	UE5: 21	UE1: 30	UE2: 28	UE3: 31	UE4: 27
5G LAN UL (Mbps)	UE1: 4	UE2: 4.1	UE3: 3.9	UE4: 3.2	UE5: 3.5	UE1: 1.5	UE2: 4.8	UE3: 5.2	UE4: 4.7

reducing the available medium for actual data transmission. In the co-channel scenario (Tables 4 and 5), similarly, 5G LAN produces less throughput than the Wi-Fi system with 1 DL/UL. This is because Wi-Fi can perform optimally with zero medium contention. When there is more than one STA, 5G LAN can perform 3 times better than Wi-Fi and 50% better than Wi-Fi. For 5G LAN, the impact on throughput performance with increased device load is much less severe than WLAN. This difference in performance can be linked to the CSMA protocol used in WLAN, which leads to more contention and collision with increased load. In contrast, 5G LAN's slot-based radio resource allocation or scheduling facilitates better performance under loaded conditions.

When examining co-channel allocations, the static UEs are placed in overlapping regions of 5G LAN APs to evaluate the impact of channel reuse on neighboring APs. Here, WLAN systems exhibit more significant performance degradation compared to 5G LAN, mainly due to increased contention and channel sharing among WLAN clients and APs.

4) CAPACITY PERFORMANCE RESULTS

In this experiment, in order to ensure a fair comparison, the WLAN and 5G LAN systems are configured with as many similar parameters as possible. All three WLAN APs are configured to their optimal channels (DFS 40 MHz) as determined by the centralized controller. The two 5G LAN APs operate on distinct 40 MHz frequencies (20 + 20 MHz), thereby avoiding co-channel interference. The WLAN system is configured with a flexible format for downlink and uplink. Similarly, the 5G LAN system is configured with an uplink-heavy configuration as 3U-1S-1D and a downlink-heavy slot configuration as 3D-1S-1U. The total number of devices in this setup is 9, with each WLAN AP associating with three WLAN clients, totaling nine WLAN clients.

On the 5G LAN side, we have two APs, so one AP manages five clients, while the other handles four. As the number of connected devices increases, the 5G LAN system demonstrates a more reliable packet allocation compared to the WLAN system. The performance stability of the WLAN network diminishes with increased load, in contrast to the more stable 5G LAN network, as indicated in Tables 6 and 7. In 5G LAN, throughput distribution among UEs is more equitable due to the scheduling mechanism. In contrast, WLAN's throughput varies based on contention among the Station (STAs) or WLAN clients, resulting in less equal throughput distribution compared to 5G LAN.

VI. CONCLUSION AND FUTURE WORK

This section presents the conclusions drawn from our study and outlines potential directions for future research.

A. CONCLUSION

The comprehensive study of WLAN and 5G LAN networks in various deployment scenarios leads to the following conclusions:

The WLAN system, burdened with a large volume of control and management packets, shows susceptibility to delays in applications like Zoom, scanners, VoIP, and cameras. This leads to more frequent packet drops and higher latency, particularly under increased load. In contrast, the 5G LAN system, leveraging clean spectrum, TDD-based scheduling, and micro-slicing features, assures minimal latency, no packet drops, and equitable distribution of radio resources. 5G LAN exhibits superior performance due to its slot-based transmission, which eliminates contention and delays in uplink ACK packet transmission. The clean frequency channel, devoid of contention on the spectrum, and the efficient scheduling algorithm at the MAC layer contribute to a significant reduction in packet drops. Consequently, 5G LAN is capable of maintaining minimal latency even under increased load, offering a fair share of radio resources among users.

B. FUTURE WORK

To further enhance the understanding and capabilities of WLAN and 5G LAN networks, the following areas of future work are proposed:

- Advanced Congestion Management in WLAN: Develop more efficient congestion control algorithms for WLAN to handle high-density deployments and reduce latency and packet drops.
- Enhanced QoS Mechanisms: Implement advanced QoS mechanisms in WLAN to better support real-time applications, especially in loaded scenarios.
- Integration of AI and ML: Integrate artificial intelligence and machine learning techniques to optimize network performance, particularly in dynamic environments with varying traffic patterns.
- Cross-Layer Optimization: Explore cross-layer optimization strategies for WLAN to improve coordination between the MAC and network layers, enhancing overall network efficiency.
- 5G LAN Network Expansion: Investigate the scalability of 5G LAN networks in larger and more complex deployment scenarios, including urban settings and IoT applications.
- Latency Reduction Techniques: Innovate techniques specifically aimed at reducing latency in WLAN networks, especially for applications requiring real-time data processing.

Through these future endeavors, the goal is to advance the technological capabilities and applications of WLAN and 5G LAN networks, catering to the evolving demands of modern communication and connectivity needs.

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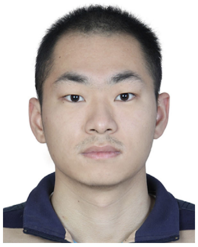
VANLIN SATHYA received the B.E. degree in computer science and the M.E. degree in mobile and pervasive computing from Anna University, Chennai, India, in 2009 and 2011, respectively, and the Ph.D. degree in computer science and engineering from IIT Hyderabad, India, in 2016. He is a System Engineer with the CTO Office, Celona Inc., USA. Previously, he was a Postdoctoral Scholar with the University of Chicago, focusing on 5G and LTE-Wi-Fi coexistence. His research interests include interference management, LTE network, device-to-device communication, and private 5G networks.



LYUTIANYANG ZHANG received the B.E. degree in electronic communication from The Australian National University and Beijing Institute of Technology, in 2017, and the M.S.E.E. and Ph.D. degrees in electrical and computer engineering from the University of Washington, in June 2019 and June 2023, respectively. His research interests include resource allocation problems in Wi Fi networks, 5G, and mobile edge computing (MEC) networks.

ONUR SAHIN is a high school Student with a strong passion for machine learning research and wireless networks. He has published papers in various IEEE conferences and journals, including IEEE Access and IEEE VTC. As a Data Scientist Intern with Veritus.ai, he worked on processing academic PDF files (April 2024–August 2024). He plans to pursue a degree in computer science for his undergraduate studies, with the aim of further advancing technology and contributing to academic research in these fields. His research interests include 5G, private 5G, 6G, private 6G, Wi Fi, and the applications of machine learning in wireless networks.

MEHMET YAVUZ received the M.S. and Ph.D. degrees in electrical engineering from the University of Michigan, Ann Arbor. He is the Co-Founder and the CTO with Celona Inc., where he is responsible for the technology vision of its innovative platform for private mobile networks. Previously, he was the CTO of Ruckus Wireless and a VP of engineering with Qualcomm Corporate Research and Development. While at Qualcomm, he has led LTE Small Cells Group and 1000x Initiative with Qualcomm Research, including areas such as self-organizing networks, neutral host services, LTE in unlicensed or shared bands, and the work on 5G Internet of Things (IoT) networks for industrial IoT applications. He has more than 160 issued patents with USPTO. He received Qualcomm IP Excellence Award, in 2013.