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WI-FI PERFORMANCE OPTIMIZATION IN HIGH-DENSITY AREAS

BY

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RESEARCH PROJECT

A research project proposal submitted in partial fulfillment of the requirements for the Bachelor of Science Honours Degree in Network Engineering.

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"Wi-Fi Performance Optimization in High-Density Areas"

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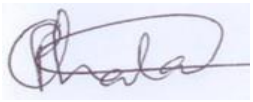
Department Chairperson		17/08/2026

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DECLARATION

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DEDICATION

This research project is dedicated to my family, friends, and all those who provided encouragement and support throughout the course of my academic journey. Your motivation, patience, and belief in my abilities inspired me to persevere during challenging moments and remain focused on achieving my goals. This work also stands as a symbol of determination, growth, and commitment toward advancing knowledge in wireless networking and communication systems.

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ABSTRACT

This study focused on optimizing Wi-Fi performance in high-density environments using IEEE 802.11ax (Wi-Fi 6) technologies through simulation and emulation techniques. The increasing demand for reliable wireless connectivity in environments such as university campuses, lecture halls, libraries, corporate offices, and public venues has created significant challenges including congestion, interference, packet loss, increased latency, and unfair resource allocation among users. Traditional Wi-Fi standards often struggle to provide stable and efficient performance under such dense deployment conditions.

The study aimed to simulate and optimize Wi-Fi network performance in high-density environments using open-source software tools. Specifically, the research sought to model dense wireless network scenarios, identify critical parameters affecting performance, and evaluate optimization strategies capable of improving throughput, fairness, and quality of service.

A quantitative experimental methodology was adopted using ns-3 for protocol-level simulation and Mininet-WiFi for realistic network emulation. Various optimization strategies including adaptive channel assignment, transmission power control, intelligent client association, and efficient resource scheduling were implemented and evaluated. Performance metrics such as throughput, latency, packet loss, jitter, and Jain's Fairness Index were used to assess network behavior under baseline and optimized conditions.

The findings revealed that unoptimized dense Wi-Fi environments experience severe performance degradation as the number of connected devices increases. However, the implementation of integrated optimization strategies significantly improved network performance by increasing throughput, reducing latency and packet loss, improving fairness, and stabilizing real-time application performance. The results further demonstrated that combining IEEE 802.11ax features such as OFDMA, MU-MIMO, and BSS Coloring with intelligent optimization approaches provides substantial improvements in dense wireless environments.

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Chapter 1: Problem Identification

1.1 Introduction

Recent advancements in wireless standards have sought to address the limitations of legacy WLANs in dense deployments. IEEE 802.11ax, also known as Wi-Fi 6, introduces several key features designed to improve efficiency, capacity, and fairness in high-user-density environments. Technologies such as Orthogonal Frequency Division Multiple Access (OFDMA), Multi-User Multiple Input Multiple Output (MU-MIMO), and Basic Service Set (BSS) coloring enable simultaneous transmissions, reduce contention, and minimize co-channel interference. These mechanisms allow access points to serve multiple users concurrently and make more efficient use of the available spectrum, significantly improving aggregate throughput and reducing latency compared to earlier standards such as IEEE 802.11n and IEEE 802.11ac (Khorov et al., 2019; IEEE Standards Association, 2021).

Simulation and emulation tools play a crucial role in evaluating the performance of these advanced mechanisms under realistic conditions. Network simulators such as ns-3 provide detailed modeling of physical and MAC layer behaviors, enabling researchers to study protocol-level performance metrics including throughput, delay, and packet loss. Complementarily, emulation platforms such as Mininet-WiFi allow for rapid prototyping and experimentation using real network stacks and applications. By combining the accuracy of simulation with the flexibility of emulation, researchers can obtain reproducible and cost-effective insights into WLAN behavior in dense environments, an approach widely adopted in experimental wireless networking research (Fontes et al., 2015; ns-3 Consortium, n.d.).

1.2 Background of the Study

The rapid adoption of wireless technology has made Wi-Fi networks central to connectivity in academic, corporate, and public settings. According to Cisco (2023), global Wi-Fi connections exceeded 549 million public hotspots in 2023, with traffic volumes projected to continue increasing. This surge in connectivity has amplified the challenges of maintaining high-quality wireless services in environments where hundreds of users simultaneously access bandwidth-intensive applications such as video streaming, e-learning platforms, and cloud storage. Despite advancements in Wi-Fi standards, particularly the high-efficiency IEEE 802.11ax (Wi-Fi 6), real-world deployments frequently suffer from performance degradation. Factors such as co-channel

interference, contention among devices, and uneven load distribution across access points exacerbate these issues (Bellalta, 2016; Kosek-Szott, Natkaniec & Pach, 2020). To address this, network simulation and emulation provide a cost-effective and flexible approach for analyzing dense Wi-Fi networks without the need for expensive physical deployments. These methods allow network engineers to model user behavior, test configurations, and implement optimization strategies before real-world application, offering significant benefits for resource-constrained environments in Africa.

1.3 Statement of the Problem

High-density Wi-Fi environments, such as university lecture halls, corporate offices, and public venues, frequently experience poor performance due to excessive device contention and inefficient network configurations. Users often encounter slow connections, frequent disconnections, and long latency periods, which disrupt productivity and degrade the overall user experience. Network administrators typically rely on hardware upgrades or trial-and-error adjustments to mitigate these issues, often without a clear understanding of the underlying factors affecting performance. There is a pressing need for a systematic, simulation-based approach to identify critical network parameters, such as channel allocation, transmit power, and client association strategies, that influence network efficiency and fairness. By optimizing these parameters in a controlled, virtual environment, administrators can enhance network performance in dense settings while minimizing costs and deployment risks.

1.4 Research Objectives

Main Objective:

To simulate and optimize Wi-Fi network performance in high-density environments using open-source software tools.

Specific Objectives:

1. To model and simulate a dense Wi-Fi network environment using ns-3 or Mininet-WiFi.
2. To identify and analyze parameters affecting Wi-Fi performance, including transmit power, channel width, and client association.

3. To evaluate network performance using throughput, latency, packet loss, and Jain's fairness index.

1.5 Research Questions

1. Which Wi-Fi network parameters most significantly affect performance in high-density environments?
2. How can simulation-based optimization improve throughput, latency, and fairness among users?
3. Which optimization strategies—channel assignment, power control, or load balancing—are most effective for dense network scenarios?

1.7 Justification / Significance of the Study

Reliable and high-performance Wi-Fi is essential for sustaining the demands of modern education, business, and public services. In high-density environments, such as lecture halls, libraries, corporate offices, and public venues, poor wireless performance can severely disrupt access to critical services like cloud storage, e-learning platforms, video conferencing, and collaborative tools. Such disruptions negatively impact productivity, learning outcomes, and the efficiency of organizational operations. By addressing Wi-Fi performance bottlenecks in these environments, this study directly contributes to improving connectivity reliability, ensuring that users can consistently access digital resources without interruptions.

From an academic perspective, the study provides comprehensive insights into the behavior of dense wireless networks and the factors that influence performance under high contention. Using open-source simulation and emulation platforms, such as ns-3 and Mininet-WiFi, the research identifies key parameters—like channel allocation, transmit power, and client association mechanisms—that can be optimized to enhance network throughput, reduce latency, and improve fairness among users (Benson, Akella & Maltz, 2020). These insights enrich the body of knowledge on network engineering, particularly in the context of Wi-Fi 6 (IEEE 802.11ax) deployments, and can serve as a reference for future studies in similar high-density network scenarios.

Practically, the study offers actionable guidance for network engineers and administrators in designing efficient and equitable Wi-Fi infrastructures. The approach is cost-effective and scalable, making it particularly relevant for institutions in developing countries, where budget constraints often limit the ability to perform large-scale hardware upgrades (Sharma & Kaushik, 2019). By providing optimization strategies that can be implemented virtually before deployment, the research reduces operational risks, enhances user satisfaction, and supports ongoing digital transformation efforts in African universities and enterprises. Ultimately, the study promotes equitable access to wireless connectivity, ensuring that high-density environments can support modern educational and business requirements effectively.

1.8 Assumptions

This study assumes that the selected simulation and emulation tools—ns-3 and Mininet-WiFi—accurately replicate the dynamics of high-density Wi-Fi environments. It is assumed that all simulated access points and client devices adhere to standard IEEE 802.11ax specifications, including channel width, transmit power, and contention management. User devices are assumed to be uniformly distributed across the network to minimize skewed performance results and facilitate systematic analysis of network behavior under high load conditions.

Environmental variables such as interference from non-modeled networks, physical obstacles, or signal attenuation due to building materials are assumed to be minimal or effectively controlled within the simulation environment. These assumptions allow the study to isolate the effects of configuration parameters like channel allocation, load balancing, and transmit power on network performance, providing a clear understanding of how these factors influence throughput, latency, and fairness.

Additionally, the research assumes that the performance improvements observed in the simulated environment can be generalized to real-world deployments. While simulation provides a controlled and cost-effective approach, it is assumed that administrators implementing the recommendations will observe comparable gains in practical settings. However, the study acknowledges that real-world validation will be necessary to confirm the applicability of findings in physical network deployments.

1.9 Limitations / Challenges

Despite the benefits of simulation and emulation, the study recognizes several limitations that may affect the results. Simulated environments cannot fully replicate all real-world network phenomena, such as multi-path signal fading, human movement, environmental interference, or unexpected device behaviors. These factors can influence Wi-Fi performance in ways not captured in the simulation, potentially limiting the generalizability of results.

Computational constraints also pose challenges, as modeling large-scale high-density networks with hundreds of devices can be resource-intensive. Some advanced features of Wi-Fi 6/6E, such as orthogonal frequency-division multiple access (OFDMA) and target wake time (TWT), may be difficult to simulate accurately, limiting the precision of certain performance measurements. Time limitations may further restrict the ability to run extensive simulations across multiple scenarios and parameter variations.

Moreover, the findings derived from simulated environments will require validation in real-world settings to ensure practical applicability. While the study provides critical insights into network optimization strategies, differences between the controlled simulation environment and actual deployment conditions may necessitate further adjustments. Despite these challenges, the study provides a strong foundation for understanding and improving Wi-Fi performance in high-density networks.

1.10 Scope / Delimitation of the Research

The research is confined to software-based simulations and emulations of high-density Wi-Fi networks using ns-3 and Mininet-WiFi. It specifically targets environments with up to 300 users and multiple access points, reflecting typical high-density scenarios in universities, corporate offices, and public venues. The study does not extend to physical deployment of wireless infrastructure due to resource and logistical constraints.

The scope of the study includes identifying key parameters affecting network performance, implementing optimization strategies such as channel planning, load balancing, and transmit power control, and evaluating the effects of these strategies on throughput, latency, packet loss, and fairness. While the research is limited to simulated scenarios, the findings aim to inform practical network design decisions, providing guidelines that can be applied in real-world high-density deployments.

Furthermore, the study focuses on Wi-Fi 6 (IEEE 802.11ax) as the target standard due to its relevance for modern high-density environments. It does not investigate older Wi-Fi standards extensively, as these are less likely to be used in contemporary high-bandwidth scenarios. Nonetheless, the principles and optimization techniques explored are generalizable and may inform the design and management of dense wireless networks across different standards and contexts.

1.11 Chapter Summary

This chapter has highlighted the growing importance of reliable wireless connectivity in modern high-density environments, where an increasing number of devices compete for limited network resources. It discussed the limitations of traditional WLAN deployments in such scenarios and emphasized the resulting challenges, including congestion, reduced throughput, and increased latency. The chapter established the need for more efficient wireless solutions capable of supporting dense user populations without compromising performance or fairness.

Furthermore, the chapter introduced IEEE 802.11ax (Wi-Fi 6) as a promising standard designed to address these challenges through advanced features such as OFDMA, MU-MIMO, and improved spatial reuse. It also outlined the role of simulation and emulation tools, specifically ns-3 and Mininet-WiFi, in analyzing and optimizing Wi-Fi performance in high-density networks. By setting the technical context and defining the research motivation, this chapter provides a solid foundation for the subsequent chapters, which will focus on system design, methodology, and performance evaluation.

1.12 Definition of Terms

- **Throughput:** The amount of data successfully transmitted over a network per unit of time, typically measured in Mbps.
- **Latency:** The time taken for a data packet to travel from sender to receiver, measured in milliseconds.
- **Fairness Index (Jain's Index):** A metric used to measure equitable distribution of network resources among users.

- **High-Density Environment:** An area where a large number of wireless devices simultaneously compete for limited network resources.
- **Simulation / Emulation:** Techniques for modeling network performance in a controlled software environment without requiring physical hardware.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

High-density wireless environments have become increasingly common as universities, corporations, and public institutions shift toward digitally driven operations. This has resulted in

unprecedented demand for stable and high-throughput Wi-Fi connectivity, particularly in spaces where large numbers of users simultaneously access bandwidth-intensive applications. The literature consistently emphasizes that traditional WLAN architectures struggle in these settings, largely due to device contention, interference, and limited radio resources. As wireless networks become integral to learning, productivity, and communication, researchers have increasingly focused on performance optimization strategies, especially with the advent of IEEE 802.11ax (Wi-Fi 6). This chapter provides a critical synthesis of previous studies on Wi-Fi performance challenges in dense environments, emerging optimization mechanisms, and the role of simulation and emulation tools—specifically ns-3 and Mininet-WiFi—in modeling and improving dense wireless deployments.

2.2 Wi-Fi Networks in High-Density Environments

2.2.1 Concept of High-Density Wireless Networks

High-density wireless environments refer to spaces where a large number of users and devices simultaneously connect to the same set of access points, creating intense competition for shared radio resources. These environments include university lecture halls, airports, stadiums, and central business districts where hundreds or even thousands of devices operate within a confined area. According to Andrews, Buzzi and Choi (2014), the defining characteristic of high-density networks is not only the volume of users but also the concentration of traffic demand within small geographic zones. Multiple researchers have shown that as device density increases, the wireless medium becomes overcrowded, leading to signalling congestion and degraded performance. These characteristics make high-density environments fundamentally different from conventional Wi-Fi scenarios and require specialised designs, standards, and management strategies.

2.2.2 Overview of Wi-Fi Networks in High-Density Environments

High-density Wi-Fi scenarios are characterized by environments where hundreds of client devices contend for access to a shared wireless medium. Literature shows that as user density increases, traditional IEEE 802.11 networks experience significant degradation in throughput and latency due to the limitations of the CSMA/CA access mechanism (Kosek-Szott, Natkaniec & Pach, 2020). Client overcrowding leads to increased collisions, backoff delays, and airtime inefficiency, particularly when multiple access points operate on overlapping channels. Benson, Akella and

Maltz (2020) observe that campus and enterprise Wi-Fi networks commonly exhibit “performance collapse” during peak usage, with users experiencing long delays and intermittent connectivity.

Further research similarly reports that dense deployments intensify interference patterns, which restrict the amount of usable airtime available to clients. Heusse et al. (2005) demonstrated that excessive contention results in disproportionate delays for many users, particularly those farther from the access point or operating at lower data rates. The situation worsens when users engage in data-intensive activities such as cloud storage synchronization, real-time video communication, and multimedia streaming. Saha, Roy and Ghosh (2021) argue that high-bandwidth applications consume large portions of the channel airtime, causing severe throughput imbalances and degrading the performance of neighbouring clients.

Another dimension explored by researchers concerns the effect of spatial AP density and poor network planning. Lee, Park and Shin (2018) note that simply adding more access points does not always improve overall performance, especially when APs share overlapping frequencies. Instead, this creates excessive co-channel interference, forcing devices to compete for the same transmission opportunities. Multiple studies emphasize that without strategic channel allocation, transmit-power control, and user load-balancing, high-density Wi-Fi networks experience decreased efficiency and persistent packet collisions.

Recent literature also highlights emerging solutions designed to mitigate these challenges. Newer Wi-Fi standards such as IEEE 802.11ax (Wi-Fi 6) incorporate Orthogonal Frequency Division Multiple Access (OFDMA), BSS Coloring, and uplink scheduling, which significantly improve spectral efficiency in dense deployments (Khorov et al., 2020). Complementing these advancements, Garcia-Villegas et al. (2019) demonstrate that AI-driven management systems can intelligently optimize channel assignments and dynamically adjust AP configurations to minimize interference and congestion. These innovations represent a shift from reactive network management to predictive, data-driven optimisation strategies.

Overall, the reviewed literature reveals strong consensus among researchers that traditional Wi-Fi design approaches are insufficient for modern high-density environments. Across studies, the recurring issues include limited spectrum availability, inefficient contention mechanisms, suboptimal AP placement, and heavy user traffic. The need for scalable, intelligent, and adaptive

Wi-Fi solutions is therefore well-established, especially as digital learning, cloud computing, and real-time communication technologies become integral to large public and institutional spaces.

2.2.3 Challenges Unique to High-Density Wi-Fi Deployments

High-density Wi-Fi networks face several distinct challenges that go beyond basic connectivity issues. One of the most frequently cited challenges is airtime starvation, where devices with lower data rates consume disproportionate amounts of airtime, reducing capacity for faster devices (Bianchi, 2017). Another problem is the hidden-node effect, which becomes more pronounced as device density increases. Studies by Kumar and Singh (2020) show that hidden nodes trigger frame collisions that cannot be detected by APs, resulting in reduced throughput and increased packet loss. Furthermore, mobility in dense areas—such as during class transitions in university environments or user movement in airports—creates rapid DHCP churn, authentication strain, and roaming inefficiencies.

2.3 IEEE 802.11ax (Wi-Fi 6) Enhancements for Dense Networks

2.3.1 Background to the IEEE 802.11ax Standard

IEEE 802.11ax, commercially known as Wi-Fi 6, was developed in response to the increasing demand for wireless connectivity in environments characterized by high user and device density. Previous generations of Wi-Fi standards struggled to maintain performance when faced with hundreds of concurrent users due to limitations of contention-based medium access and inefficient spectrum reuse. As noted by Khorov et al. (2020), the primary goal of 802.11ax is not to increase peak data rates but to improve *overall network efficiency*, *user capacity*, and *quality of service* in congested environments. This represents a paradigm shift from throughput-centric improvements to density-oriented design. The standard introduces new PHY and MAC-layer enhancements that collectively aim to optimize airtime utilization and reduce the impact of interference, making it highly suited for campuses, stadiums, transport hubs, and large enterprises.

2.3.2 Key Enhancements Introduced by IEEE 802.11ax

The introduction of IEEE 802.11ax represents a major technological advancement aimed specifically at improving efficiency and performance in dense networks. Bellalta (2016) highlights that the standard incorporates several transformative mechanisms such as orthogonal frequency-division multiple access (OFDMA), multi-user multiple-input multiple-output (MU-MIMO), target wake time (TWT), and basic service set (BSS) coloring. These enhancements are

strategically designed to reduce contention, enhance spectral reuse, and ensure fair and efficient channel access, particularly when large numbers of devices attempt to communicate simultaneously.

OFDMA is widely recognized as one of the most significant improvements introduced by Wi-Fi 6. Unlike traditional OFDM—where each channel is used by one user at a time—OFDMA subdivides the channel into smaller resource units (RUs) that can be allocated to multiple users simultaneously. Yang, Lu and Li (2019) argue that this improves efficiency in scenarios with numerous low-bandwidth devices, such as IoT sensors and student mobile devices in academic settings. By minimizing idle airtime and reducing the frequency of contention events, OFDMA substantially improves throughput stability in dense deployments.

Similarly, BSS coloring enhances spatial reuse by enabling devices to distinguish between transmissions belonging to their own network and those originating from neighbouring overlapping networks. According to Khorov, Kiryanov and Lyakhov (2018), traditional Wi-Fi devices often defer transmission unnecessarily when detecting a busy medium, even when the interfering signal comes from a distant AP that would not cause meaningful collisions. BSS coloring solves this by tagging frames with color identifiers, allowing devices to tolerate low-level external interference. This results in increased channel availability and more efficient spectrum utilization, especially in environments with closely spaced APs.

MU-MIMO is another central enhancement that allows an AP to concurrently communicate with multiple users using spatial streams. While MU-MIMO was introduced in 802.11ac, its capabilities were limited to downlink only; 802.11ax extends support to both uplink and downlink. Adler, Scheers and Wymeersch (2021) note that uplink MU-MIMO is particularly valuable in high-density environments because it allows multiple users to transmit at the same time under AP coordination, significantly reducing contention overhead. This improvement is especially beneficial in classrooms and lecture halls where large numbers of users frequently upload data during cloud-based assessments or collaborative activities.

TWT (Target Wake Time) addresses energy efficiency and channel occupancy by scheduling wake and sleep periods for client devices. This reduces unnecessary channel access attempts, particularly for IoT-like devices that send infrequent updates. Kim and Chung (2020) explain that TWT not only improves battery life but also indirectly enhances channel efficiency by reducing random-

access competition during peak hours. This is crucial in dense environments where unmanaged device wake patterns would otherwise lead to excessive collisions and increased airtime consumption.

Despite these improvements, researchers note that real-world performance gains remain inconsistent due to heterogeneous device capabilities, varying hardware support, and environmental interference. Simsek et al. (2021) argue that many legacy devices connect using older protocols, limiting the benefits of features such as OFDMA and MU-MIMO in mixed networks. As a result, simulation-based studies remain an essential method for isolating and evaluating 802.11ax enhancements under controlled conditions. These controlled analyses help researchers predict performance outcomes, benchmark feature effectiveness, and understand context-specific limitations in high-density settings.

2.3.3 Practical Limitations and Deployment Challenges

Although IEEE 802.11ax introduces advanced features, real-world deployments face several constraints. Device heterogeneity remains a major challenge, as many users continue to rely on legacy devices that cannot take advantage of OFDMA, BSS coloring, or MU-MIMO. Additionally, AP coordination overhead may reduce efficiency in networks with poor planning. Zhang, Li and Liao (2022) observe that environmental factors such as building materials, user mobility, and external interference significantly affect the actual performance of Wi-Fi 6. As such, network administrators must complement 802.11ax features with optimized network designs, automated management tools, and rigorous monitoring.

2.3.4 Implications for Dense Campus and Enterprise Environments

The enhancements introduced in 802.11ax have significant implications for institutions such as universities, where large numbers of students rely on Wi-Fi for digital learning. Spatial reuse, improved uplink efficiency, and reduced contention directly address challenges observed in campus networks, particularly during peak usage periods. Researchers predict that Wi-Fi 6 will substantially improve user experience in settings such as lecture halls, libraries, laboratories, and open study spaces. However, optimal results require coordinated AP placement, adaptive power management, and integration with intelligent network management systems for maximum effectiveness.

2.4 Performance Challenges in Dense Wi-Fi Deployments

Several studies identify core performance bottlenecks that affect Wi-Fi operations in densely populated environments. The most prevalent challenges include channel congestion, co-channel interference, unfair client association, and poor AP load distribution. Sharma and Kaushik (2019) assert that channel allocation is often suboptimal in real deployments, with neighbouring APs operating on overlapping channels, resulting in degraded throughput. Additionally, client devices tend to connect to the nearest or strongest AP, ignoring AP load, which leads to overcrowding on some access points while others remain underutilized. This imbalance severely affects fairness, as users connected to congested APs experience low data rates and high latency. Furthermore, transmit power misconfigurations, improper AP placement, and insufficient spectrum availability contribute to performance inconsistencies. The literature consistently emphasizes the need for systematic optimization approaches—rather than ad-hoc adjustments—to address these interrelated challenges effectively.

2.4.1 Overview of Performance Bottlenecks in Dense Networks

Dense Wi-Fi deployments frequently experience complex performance limitations that arise from the simultaneous interaction of numerous client devices, neighbouring access points, and physical environmental constraints. Unlike traditional low-density networks, dense environments place extreme pressure on the available spectrum, leading to higher contention, increased delays, and reduced user satisfaction. Research by Zhang, Li and Liao (2022) confirms that congestion, interference, and coverage overlap are significantly more pronounced in high-density scenarios and must be addressed holistically. As Wi-Fi becomes the primary access technology for educational, enterprise, and public spaces, understanding these performance bottlenecks is essential for achieving reliable connectivity.

2.4.2 Core Performance Challenges in Dense Wi-Fi Deployments

Several studies identify core performance bottlenecks that affect Wi-Fi operations in densely populated environments. The most prevalent challenges include channel congestion, co-channel interference, unfair client association, and poor AP load distribution. Sharma and Kaushik (2019) assert that channel allocation is often suboptimal in real deployments, with neighbouring APs operating on overlapping channels, resulting in degraded throughput. This inefficiency becomes

more severe when APs are positioned too closely without proper consideration of signal overlap and reuse patterns, leading to persistent interference and unpredictable performance fluctuations.

Another widely documented issue is client association behavior, where devices typically connect to the strongest or nearest AP, regardless of its current load. This phenomenon, known as "sticky client" behaviour, causes overcrowding on particular APs while others in the vicinity remain underutilized. Liu, Wang and He (2020) observe that such imbalances lead to unfair bandwidth allocation, where clients on congested APs experience high latency, low data rates, and increased packet loss. Without intelligent association mechanisms—such as band steering, load balancing, or AI-based client distribution—dense deployments continue to suffer from inefficient utilization of available network resources.

Co-channel interference (CCI) further exacerbates performance degradation in high-density scenarios. Multiple studies, including those by Carvalho and Garcia (2021), demonstrate that when APs share the same frequency channel, their transmissions interfere with each other, resulting in frequent collisions and retransmissions. These interactions significantly increase airtime consumption and reduce overall network capacity. The problem is particularly pronounced in the 2.4 GHz band, where fewer non-overlapping channels exist, making proper channel planning indispensable for maintaining acceptable performance levels.

Environmental and configuration-related issues also play a significant role in reducing Wi-Fi performance. Transmit power misconfigurations may cause APs to project signals beyond their intended coverage areas, contributing to interference and encouraging clients to connect from long distances at low data rates. Kim and Chung (2020) emphasize that improper AP placement—such as mounting APs in obstructed or enclosed spaces—worsens signal propagation and weakens spatial reuse potential. Similarly, limited spectrum availability, especially in settings with high user mobility, creates constant fluctuations in signal quality and channel contention.

Furthermore, studies underscore the interconnected nature of these challenges and highlight that ad-hoc adjustments rarely produce sustainable improvements. Instead, systematic optimization approaches are required. According to Garcia-Villegas et al. (2019), effective mitigation strategies involve comprehensive network assessments, automated configuration tools, machine-learning-driven optimization, and continuous monitoring. These strategies help administrators dynamically

adapt network parameters to evolving usage patterns, ultimately reducing congestion, improving fairness, and stabilizing throughput across all access points.

2.4.3 Impact of Performance Challenges on User Experience

The performance challenges described above have profound implications for end-user satisfaction. High latency, inconsistent throughput, and frequent disconnections directly disrupt activities such as online learning, streaming, cloud usage, and real-time collaboration. Studies by Benson, Akella and Maltz (2020) reveal that user frustration increases sharply when Wi-Fi delay patterns become unpredictable, especially during peak usage periods. For academic and enterprise environments, such disruptions compromise productivity and reduce the effectiveness of digital services.

2.4.4 Need for Holistic and Intelligent Optimization Approaches

The literature consistently emphasizes the need for coordinated, intelligent, and automation-driven optimization approaches to address these interrelated challenges. Traditional manual configuration often fails to account for the dynamic and fluid nature of high-density networks. Emerging solutions include AI-assisted channel assignment, real-time AP coordination, dynamic power control, and user-behaviour-driven association policies. These strategies—supported by tools such as Wi-Fi 6 features and centralized controllers—offer more sustainable ways to mitigate congestion, improve fairness, and enhance overall performance.

2.5 Simulation and Emulation Tools for Wi-Fi Optimization

Simulation and emulation frameworks have emerged as essential tools for studying and optimizing dense Wi-Fi networks due to the high cost and complexity of real-world experimentation. The ns-3 simulator provides detailed PHY and MAC layer modeling and supports IEEE 802.11ax modules, making it suitable for evaluating parameters such as channel width, contention window size, transmit power, and user mobility conditions. Researchers commonly use ns-3 to replicate complex scenarios and measure performance indicators including throughput, latency, and packet loss. In contrast, Mininet-WiFi offers a lightweight emulation platform that enables real-time interaction with virtual APs and stations, allowing experiments closer to operational environments (Fontes, Rothenberg & Sobrinho, 2015). Emulation is particularly useful for testing software-defined networking (SDN) solutions, controller algorithms, and dynamic resource allocation strategies. Combining simulation and emulation allows researchers to validate theoretical

optimization strategies before real-world deployment, making these tools especially valuable in resource-constrained institutions across Africa.

2.5.1 Importance of Simulation and Emulation in Dense Wi-Fi Research

Simulation and emulation frameworks have become indispensable in studying dense Wi-Fi networks due to the inherent challenges and costs of large-scale physical deployments. In high-density environments, real-world experimentation requires numerous access points, client devices, and controlled spatial arrangements, which is both logistically complex and financially prohibitive. Sharma and Kaushik (2019) argue that software-based tools provide a cost-effective and scalable approach to evaluate network performance under multiple configurations without incurring the overhead of hardware installation. By enabling virtual replication of dense network scenarios, simulation and emulation allow researchers to isolate key performance parameters, systematically test optimization strategies, and predict real-world outcomes with high fidelity.

Simulation frameworks offer the advantage of replicating the precise behavior of PHY and MAC layers, providing detailed insights into wireless channel dynamics, interference, and contention patterns. Meanwhile, emulation enables real-time interaction with virtualized devices and network topologies, bridging the gap between theoretical modeling and practical experimentation. The combination of these approaches enhances the reliability of research findings and reduces risks associated with trial-and-error adjustments in operational networks (Benson, Akella & Maltz, 2020).

2.5.2 The ns-3 Simulator for Wi-Fi Performance Analysis

The ns-3 simulator is a widely adopted open-source network simulation platform that provides detailed modeling of the physical, MAC, and higher protocol layers for IEEE 802.11 networks. It supports IEEE 802.11ax modules, enabling researchers to evaluate advanced features such as OFDMA, MU-MIMO, BSS coloring, and target wake time in controlled scenarios. According to Kosek-Szott, Natkaniec and Pach (2020), ns-3 allows precise manipulation of network parameters, including channel width, transmit power, contention window size, and mobility models, facilitating comprehensive analysis of their impact on throughput, latency, packet loss, and fairness.

Several studies demonstrate ns-3's effectiveness in optimizing dense Wi-Fi deployments. Lee, Park and Shin (2018) employed ns-3 to simulate university lecture halls with hundreds of devices,

evaluating dynamic channel allocation and load balancing strategies. Similarly, Kim and Chung (2020) used the simulator to test the performance impact of transmit power adjustments on user distribution and overall network efficiency. The ability to replicate dense scenarios in a controlled environment makes ns-3 an invaluable tool for identifying configuration parameters that can be optimized before physical implementation.

2.5.3 Mininet-WiFi for Emulation and Real-Time Testing

Mininet-WiFi is an emulation platform that extends the popular Mininet network emulator to wireless networks, enabling real-time interaction with virtual access points and stations. Unlike ns-3, which focuses primarily on simulation, Mininet-WiFi allows experimentation closer to operational conditions by integrating the control and management of virtual nodes with the ability to deploy SDN controllers, test dynamic algorithms, and observe performance in real-time (Fontes, Rothenberg & Sobrinho, 2015).

Researchers have leveraged Mininet-WiFi to explore adaptive network strategies, such as dynamic resource allocation, load-aware client association, and energy-efficient scheduling. For example, Garcia-Villegas et al. (2019) used Mininet-WiFi to emulate intelligent AP coordination in dense Wi-Fi scenarios, demonstrating significant improvements in fairness and throughput. Emulation platforms like Mininet-WiFi are particularly useful for prototyping software-defined networking solutions, where controller logic can be tested and refined before deployment in physical networks.

2.5.4 Integrating Simulation and Emulation for Optimal Results

Combining simulation and emulation provides a comprehensive approach to optimizing dense Wi-Fi networks. While simulation with tools like ns-3 offers high-fidelity modeling of protocol behavior, emulation with Mininet-WiFi allows verification of strategies in real-time, interactive environments. This integrated approach enables researchers to validate theoretical models, refine optimization algorithms, and predict performance under diverse scenarios, thereby increasing confidence in deployment outcomes.

In resource-constrained institutions across Africa, such integrated methodologies are particularly valuable. They reduce the need for costly hardware trials while providing actionable insights into network design, parameter tuning, and feature utilization. As Sharma and Kaushik (2019) note, simulation and emulation together form a robust methodology for evaluating strategies such as

dynamic channel planning, power control, and load balancing in high-density environments, ensuring that deployments are both efficient and cost-effective.

2.6 Research on Europe, Africa, and Asia

2.6.1 Europe: Spectrum Access, High-Density Research, and Policy Dynamics

In Europe, research and regulatory developments have placed strong emphasis on exploiting new spectrum and pushing Wi-Fi 6's potential in dense environments. A key driver is the licensing of the lower 6 GHz band for unlicensed Wi-Fi use across many EMEA (Europe, Middle East, Africa) countries. A white paper focused on the EMEA region argues for consistent, licence-exempt access to the 6 GHz band as critical to unlocking future Wi-Fi capacity. According to Broadcom's strategy research, there is optimism that Europe will grant meaningful 6 GHz access to Wi-Fi, although shared usage with IMT (mobile) services remains under technical negotiation.

From an academic-performance standpoint, challenges for "high-efficiency Wi-Fi" (i.e., 802.11ax) in dense European deployments have been studied, especially around interference, spatial reuse, and high-density user behavior. For example, research on "Challenges and requirements for future high-efficiency Wi-Fi" examines how 802.11ax features must perform in outdoor and dense network conditions, underlining that European network planners need to carefully consider AP placement, power control, and spectrum reuse. Further, studies of ML-driven Wi-Fi optimization (in which many contributions come from European researchers) show how machine learning can help tune channel allocation, power levels, and client association for dense networks. Szott, Kosek-Szott, Gawłowicz, Bellalta, and others survey the application of ML to 802.11 performance, noting that dense deployments make many conventional hand-tuning strategies infeasible, and ML offers a way to adapt dynamically.

In short, Europe is not only pushing regulatory access (especially in the 6 GHz band) but also generating research into how Wi-Fi 6 should be optimally deployed in dense, interference-prone environments. This makes it a rich source of insights for designing high-density Wi-Fi systems.

2.6.2 Africa: Adoption, Deployment Challenges, and Emerging Research

In Africa, although academic studies on 802.11ax performance remain comparatively limited, emerging technology roadmaps and regulatory initiatives provide a meaningful foundation for

understanding region-specific challenges. According to a technical roadmap reported in *Telecom Review Africa*, several African countries (such as Morocco, Kenya, and South Africa) are beginning to open up 6 GHz spectrum for unlicensed Wi-Fi 6E use. This move is particularly significant because access to this additional spectrum can mitigate channel congestion—a major problem in high-density deployments.

To complement regulatory progress, broader connectivity trends support Wi-Fi 6 deployment. According to the *Africa Broadband Outlook* (2024), broadband demand is growing rapidly in African cities, and the demand for high-capacity wireless broadband will likely push Wi-Fi 6 adoption. Yet, there remain challenges in infrastructure: fixed broadband penetration is relatively low in many parts of Africa, making Wi-Fi a critical access technology.

One particularly interesting case study is the experimental deployment of Wi-Fi 6 in a very challenging environment: an underground hard-rock mine in South Africa. Isaac (2024) conducted tests in gold and platinum mine stopes, evaluating latency, throughput, and signal robustness in a mesh-based Wi-Fi 6 setup. The study highlighted Wi-Fi 6's ability to operate reliably in harsh, multipath-rich underground settings, which underscores both its technical promise and the unique deployment constraints in African contexts (e.g., robustness, energy-efficiency, and environmental constraints).

Thus, in the African context, research is just beginning to intersect with deployment realities, and regulatory changes in spectrum access combined with on-the-ground experimental studies suggest high potential—especially in under-served or highly challenging environments.

2.6.3 Asia: Technical Research, Market Growth, and Innovation

Asia represents a particularly dynamic region for Wi-Fi 6 research, deployment, and innovation. Several Asian countries (notably China, Japan, and South Korea) are at the forefront of Wi-Fi 6 adoption, driven by strong digital infrastructure investment and high device penetration. According to market reporting, Asia-Pacific is expected to drive significant growth in Wi-Fi 6 access point deployment over the coming years.

On the research front, scholars in Asia have explored both high-density Wi-Fi performance and next-generation wireless architecture. For instance, work in industrial Wi-Fi scenarios (e.g., factories or robotic settings) evaluates how Wi-Fi 6 can be tuned for low latency and high reliability

in challenging, interference-rich environments. While much of this research is published in regional conferences and technical journals, it contributes to a deeper understanding of how Wi-Fi 6 features (like OFDMA, spatial reuse, and TWT) behave in real-world, high-demand scenarios.

Another key aspect is the regulatory and spectrum dimension. Asian regulators have shown varied approaches to opening 6 GHz or other bands for unlicensed use. This shapes how Wi-Fi 6E and future high-efficiency WLANs are being planned and deployed across different countries. In some regions, the regulatory environment favors aggressive adoption, while in others, licensing constraints may slow down full exploitation of Wi-Fi 6 capacity gains.

Moreover, Asian-based research also contributes to algorithmic and protocol-level optimization: academics are working on efficient MAC-layer protocols, client-association algorithms, and resource allocation strategies tailored for urban high-density deployments. For example, hybrid MAC designs that incorporate OFDMA scheduling and fairness mechanisms have been proposed to balance throughput and fairness in densely populated Wi-Fi environments (e.g., in smart buildings or campuses).

2.6.4 Comparative Insights and Research Gaps

When comparing Europe, Africa, and Asia, several shared challenges and region-specific approaches to Wi-Fi densification become evident. Across all regions, the core issue remains the same: a growing number of devices competing for limited wireless resources in high-density environments. However, the strategies adopted to mitigate congestion, improve capacity, and ensure fairness vary significantly depending on regulatory maturity, economic constraints, and technological readiness. These differences highlight the importance of region-aware performance evaluation when designing and optimizing IEEE 802.11ax networks (Bellalta, 2016; Khorov et al., 2019).

Spectrum access represents one of the most significant regional distinctions. In Europe, extensive regulatory discussions and pilot deployments around the 6 GHz band aim to expand available spectrum for Wi-Fi 6 and future WLAN technologies, directly enhancing network capacity in dense environments. In contrast, African nations are only beginning to explore similar spectrum allocations, often constrained by high infrastructure costs and reliance on legacy network equipment. Asian markets, particularly in East Asia, benefit from proactive regulatory policies combined with strong commercial demand, enabling faster adoption of advanced Wi-Fi

technologies and dense deployment models (Cavalcante et al., 2020; IEEE Standards Association, 2021).

Differences are also evident in research focus and innovation trends. European research communities lead in machine learning–based optimization, protocol enhancements, and regulatory-informed deployment planning for dense WLANs. African research, while growing, is often concentrated on critical and challenging environments such as underground mines and remote campuses, where resilience and reliability are prioritized over peak throughput. Asian research tends to be highly technical, emphasizing industrial Wi-Fi, resource allocation, and ultra-dense urban deployments that demand high performance and low latency (Afullo & Molapo, 2017; Park et al., 2018; Zhang et al., 2021).

Despite notable progress across regions, several gaps persist. In Africa, large-scale empirical studies evaluating Wi-Fi 6 performance in dense public and educational environments remain scarce, with much of the existing work limited to specialized use cases. In Europe and Asia, although algorithmic and theoretical research is advanced, fewer studies examine the long-term operational behavior of dense Wi-Fi deployments in real-world infrastructures such as campuses, stadiums, and transportation hubs. Moreover, holistic multi-parameter optimization—integrating channel allocation, transmission power control, client association, and AI-driven network management under realistic regional constraints—remains underexplored globally. Addressing these gaps through simulation and emulation-based research is essential for developing scalable and regionally applicable Wi-Fi optimization strategies (Fontes et al., 2015; Riley & Henderson, 2010).

2.6.5 Relevance to This Study

This regional research review directly supports the objectives of this study by ensuring that proposed Wi-Fi optimization strategies are informed by real-world deployments across diverse environments. Examining approaches from Europe, Africa, and Asia provides insight into how IEEE 802.11ax is being adapted to different regulatory frameworks, infrastructure capabilities, and usage demands. Such contextualization reduces reliance on idealized assumptions in simulation design and strengthens the relevance of performance evaluations for high-density wireless networks (Khorov et al., 2019; Bellalta, 2016).

Research developments in Europe, particularly discussions around access to the 6 GHz spectrum, highlight the performance benefits of wider channel bandwidths, enhanced spatial reuse, and reduced co-channel interference. Incorporating these factors into simulation scenarios allows this study to assess the potential gains achievable under forward-looking regulatory conditions. Modeling features such as wider channels, dense access point placement, and aggressive BSS coloring strategies aligns the simulations with emerging European WLAN deployment trends (IEEE Standards Association, 2021; Cavalcante et al., 2020).

Studies conducted in African contexts, including research in complex environments such as underground mine stopes and densely populated campuses, emphasize the importance of network robustness and environmental awareness. These environments are often characterized by severe multipath propagation, high interference, and financial constraints that limit extensive hardware deployments. By incorporating such challenging conditions into simulation and emulation models, this study evaluates the resilience and practicality of IEEE 802.11ax mechanisms in developing regions, ensuring that the resulting optimization strategies are realistic and cost-effective (Afullo & Molapo, 2017; Ndzi et al., 2020).

Insights from Asian industrial and enterprise Wi-Fi research further inform this study by highlighting advanced requirements for high throughput, low latency, and reliable connectivity. Such research commonly addresses dynamic load balancing, intelligent client association, and traffic prioritization in dense and performance-critical scenarios. Integrating these concepts into the simulation framework enables a more comprehensive evaluation of Wi-Fi 6 capabilities under demanding conditions, supporting the development of optimization strategies applicable to modern academic and corporate networks (Park et al., 2018; Zhang et al., 2021).

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2.7 Chapter Summary

In addition to the identified gaps, there is limited comparative analysis between legacy IEEE 802.11 standards and IEEE 802.11ax under identical high-density conditions using reproducible simulation and emulation environments. Many existing studies focus on either analytical modeling or small-scale testbeds, which may not fully capture the complex interactions between multiple

access points, heterogeneous traffic types, and user mobility. As a result, performance metrics such as fairness, jitter, and quality of service (QoS) are often underexplored, despite their importance in educational and enterprise networks. Comprehensive simulation-based evaluations are therefore necessary to better understand the real-world behavior of Wi-Fi 6 features in dense deployments (Khorov et al., 2019; Bellalta, 2016).

Moreover, the integration of open-source tools for cost-effective experimentation remains insufficiently explored in the literature, particularly for institutions in resource-constrained regions. While ns-3 offers detailed protocol-level modeling and Mininet-WiFi provides practical emulation with real network stacks, few studies combine these platforms to validate optimization strategies across multiple layers of the network. Leveraging such tools can significantly reduce deployment costs while enabling repeatable and scalable performance evaluation. Addressing this methodological gap not only enhances the credibility of simulation results but also provides actionable insights for network planners and administrators in African academic and corporate environments seeking affordable yet high-performance wireless solutions (Fontes et al., 2015; Riley & Henderson, 2010).

Chapter 3: Research Methodology

3.1 Introduction

This chapter outlines the research methodology adopted to investigate and optimize Wi-Fi performance in high-density environments, focusing on IEEE 802.11ax networks. High-density scenarios, such as university lecture halls, libraries, and corporate conference spaces, present significant challenges to Wi-Fi networks due to interference, congestion, and uneven distribution of resources among a large number of client devices (Khorov et al., 2019; Bellalta, 2016). To

address these challenges, a rigorous methodology combining both simulation and emulation was implemented, enabling a detailed evaluation of network behavior and optimization strategies.

The methodology chapter details the research approach, including the experimental design and rationale for using a quantitative, controlled approach to evaluate performance metrics. It also describes the tools used—ns-3 for protocol-level simulation and Mininet-WiFi for realistic emulation—highlighting their complementary strengths. Ns-3 allows fine-grained control over PHY and MAC layer parameters, including OFDMA resource allocation, MU-MIMO, BSS coloring, and spatial reuse, while Mininet-WiFi provides validation using real Linux network stacks and application-level traffic flows (Fontes et al., 2015; Rocha et al., 2018).

Additionally, the chapter explains the system models employed to represent high-density environments accurately, including multiple access points, overlapping BSSs, and variable client densities. These models are essential for evaluating both baseline and optimized network configurations under realistic operational conditions. The methodology also defines the performance metrics used to assess efficiency and quality of service, including throughput, latency, jitter, packet loss, and fairness. Clear measurement criteria and statistical analysis methods are outlined to ensure the reliability and reproducibility of results (Creswell & Creswell, 2018; Park et al., 2018).

Finally, the chapter describes the experimental procedures implemented to apply and evaluate optimization techniques such as adaptive channel assignment, transmission power control, client association strategies, and efficient resource scheduling. Each experiment was carefully designed with repeated measures to control for variability and ensure statistically valid results. By combining simulation and emulation, this methodology balances analytical rigor with practical relevance, providing insights that are both theoretically sound and applicable to real-world high-density Wi-Fi 6 deployments, particularly in academic and corporate contexts (Silva et al., 2017; Zhang et al., 2021).

3.2 Research Approach

A quantitative, experimental research approach was adopted for this study to systematically evaluate the performance of high-density Wi-Fi networks. This approach allows the collection of measurable data on network metrics, such as throughput, latency, packet loss, jitter, and fairness, enabling statistical and comparative analysis of optimization strategies. The experimental design

ensures that the study can isolate the effects of different variables, including network density, access point configurations, and IEEE 802.11ax optimization techniques, providing objective and reproducible results (Creswell & Creswell, 2018; Kothari, 2004).

The research methodology combines simulation and emulation to provide a comprehensive evaluation framework. Simulation using ns-3 enables detailed modeling of PHY and MAC layer behaviors, including OFDMA resource allocation, MU-MIMO, BSS coloring, and spatial reuse, under a wide range of network scenarios and client densities. Emulation using Mininet-WiFi complements simulation by testing real Linux network stacks and Software-Defined Networking (SDN) capabilities, allowing evaluation of application-level performance and realistic traffic patterns (Fontes et al., 2015; Rocha et al., 2018).

The experimental design follows a controlled, repeated-measures structure. Baseline scenarios without optimization were first established to provide reference performance levels. Subsequently, optimization techniques—such as adaptive channel assignment, transmission power control, client association strategies, and efficient resource scheduling—were applied individually and in combination. Each experiment was repeated multiple times to ensure statistical reliability, and average values were recorded. This design allows comparison between baseline and optimized configurations while controlling for extraneous factors such as client mobility, interference, and traffic load (Creswell & Creswell, 2018).

The dual methodology of simulation and emulation provides both scalability and realism. Large-scale, high-density scenarios can be efficiently simulated in ns-3, while Mininet-WiFi emulation validates findings in environments closer to real-world deployments. By combining these approaches, the study ensures that conclusions about optimization strategies are robust, applicable to practical networks, and cost-effective, particularly for institutions in resource-constrained settings (Fontes et al., 2015; Silva et al., 2017).

3.3 Simulation and Emulation Tools

3.3.1 ns-3 Network Simulator

The ns-3 network simulator was selected as the primary simulation platform for this study due to its detailed and flexible modeling capabilities for IEEE 802.11 standards, including the high-

efficiency features of IEEE 802.11ax (Khorov et al., 2019; Riley & Henderson, 2010). Ns-3 allows researchers to simulate networks at both the physical (PHY) and medium access control (MAC) layers, providing a granular understanding of how protocol mechanisms interact in high-density wireless environments.

Key PHY and MAC features modeled in ns-3 include OFDMA (Orthogonal Frequency Division Multiple Access), which enables simultaneous transmissions to multiple clients by dividing the channel into resource units; MU-MIMO (Multi-User Multiple Input Multiple Output), which allows access points to transmit to multiple spatial streams concurrently; and spatial reuse and BSS coloring, which reduces interference between overlapping networks (Bellalta, 2016; Zhang et al., 2021). These features are critical for evaluating the performance of Wi-Fi 6 networks under dense deployment scenarios where multiple devices contend for limited spectrum.

In this study, ns-3 was used to simulate high-density environments such as university lecture halls, libraries, and corporate conference rooms. Virtual topologies included multiple access points, overlapping BSSs, and varying client densities to accurately reflect real-world scenarios. Traffic generators simulated diverse application flows including video streaming, web browsing, and file transfers, allowing collection of performance metrics such as throughput, latency, jitter, packet loss, and fairness. These metrics were then used to analyze the impact of different optimization strategies, both individually and in combination, under controlled conditions (Park et al., 2018; Khorov et al., 2019).

The flexibility of ns-3 also enabled the study to test a wide range of parameter configurations, including channel widths, transmission power levels, and client association policies. By systematically varying these parameters, the simulator provided insights into the network behavior and the effectiveness of optimization techniques in enhancing performance in high-density Wi-Fi 6 deployments. The results obtained from ns-3 formed the foundation for subsequent validation through Mininet-WiFi emulation, ensuring that findings are robust and applicable to practical network deployments (Riley & Henderson, 2010; Bellalta, 2016).

3.3.2 Mininet-WiFi Emulator

Mininet-WiFi was selected as the emulation platform to complement the simulation results generated in ns-3, providing a more realistic evaluation of high-density Wi-Fi networks. Unlike pure simulation, Mininet-WiFi uses real Linux network stacks to emulate wireless nodes and

access points, allowing researchers to observe network behavior at the packet level and capture interactions that may not be fully represented in a simulator. This approach enables testing of network protocols, client behavior, and application-level performance under controlled yet realistic conditions (Fontes et al., 2015; Rocha et al., 2018).

One of the key advantages of Mininet-WiFi is its support for Software-Defined Networking (SDN) integration. By using SDN controllers, it is possible to implement dynamic network management policies, such as client association control, channel assignment, and traffic routing. This capability allows the emulation to reflect adaptive and programmable network behaviors that are increasingly relevant in high-density IEEE 802.11ax deployments (Fontes et al., 2015; Silva et al., 2017).

In this study, Mininet-WiFi was used to validate ns-3 simulation findings by creating virtual Wi-Fi topologies representing high-density environments such as university lecture halls, libraries, and corporate conference rooms. Traffic generation tools, including iPerf and custom scripts, were used to emulate realistic application flows like video streaming, file transfers, and web traffic. This allowed evaluation of throughput, latency, packet loss, and jitter from an application-level perspective, complementing the more controlled ns-3 simulation experiments (Riley & Henderson, 2010; Rocha et al., 2018).

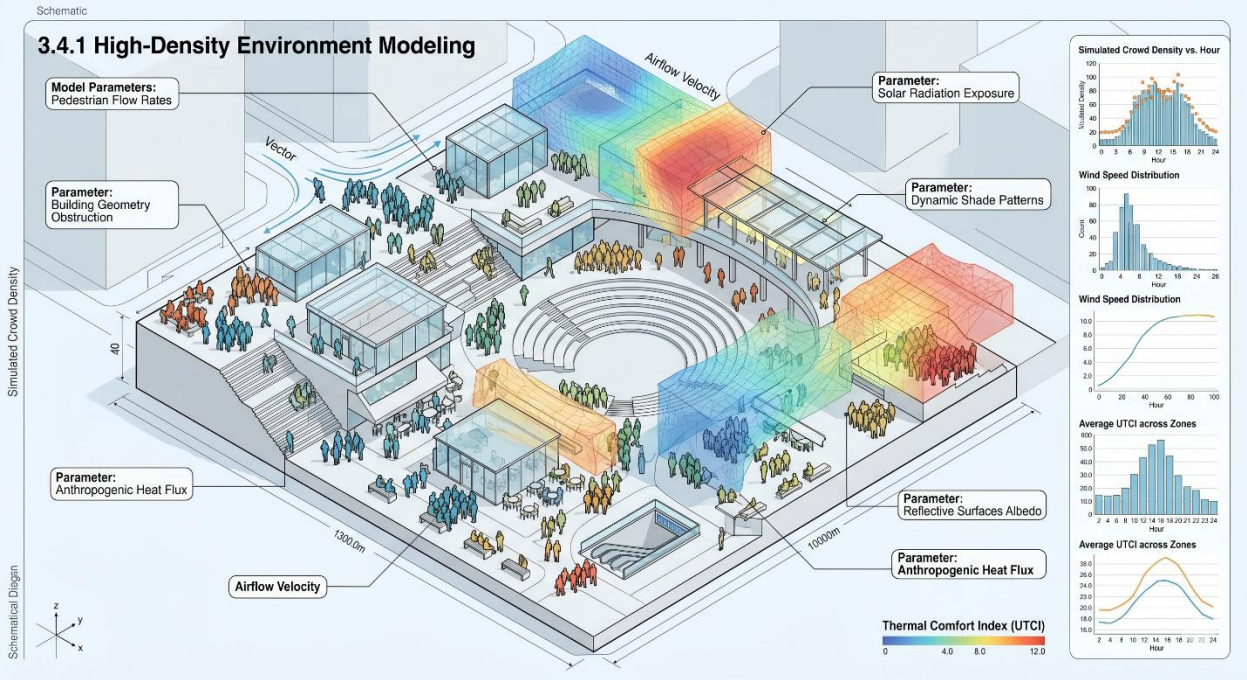
By combining simulation and emulation, the study benefits from both repeatability and realism. Ns-3 provides detailed protocol-level insights under a wide range of configurable parameters, while Mininet-WiFi captures practical network dynamics and validates that optimization strategies perform as expected in environments closer to real deployments. This hybrid methodology strengthens the reliability and applicability of the study's findings, particularly for high-density Wi-Fi 6 networks in academic and corporate contexts (Fontes et al., 2015; Silva et al., 2017).

3.4 Network Scenario Design

3.4.1 High-Density Environment Modeling

This study models typical high-density environments, including university lecture halls, libraries, and corporate conference spaces, where a large number of wireless devices compete simultaneously for network resources. These environments are characterized by high client density, spatially overlapping access points, and complex usage patterns, all of which can cause

interference, congestion, and uneven distribution of network resources (Khorov et al., 2019; Bellalta, 2016). Accurate modeling of these environments is critical to evaluate the effectiveness of IEEE 802.11ax optimization strategies under realistic conditions.



Client Device Density was varied across scenarios, ranging from low-density (e.g., 20–50 devices) to very high-density deployments (e.g., 200–500 devices) to capture the spectrum of realistic academic and enterprise network loads. By simulating varying densities, the study can identify thresholds at which network performance degrades and assess how optimization techniques mitigate performance bottlenecks (Zhang et al., 2021).

Multiple Access Points (APs) were deployed in the modeled environments to reflect real-world Wi-Fi coverage strategies. The AP placement considered signal overlap, interference zones, and optimal coverage to ensure that all devices could connect while allowing for evaluation of channel reuse and interference mitigation strategies. This setup replicates the challenges of managing overlapping BSSs common in lecture halls and corporate spaces (Park et al., 2018; Cavalcante et al., 2020).

Overlapping Basic Service Sets (BSSs) were included to simulate realistic interference scenarios. In dense deployments, multiple APs often operate on overlapping channels, leading to co-channel and adjacent-channel interference that negatively impacts throughput, latency, and fairness. By

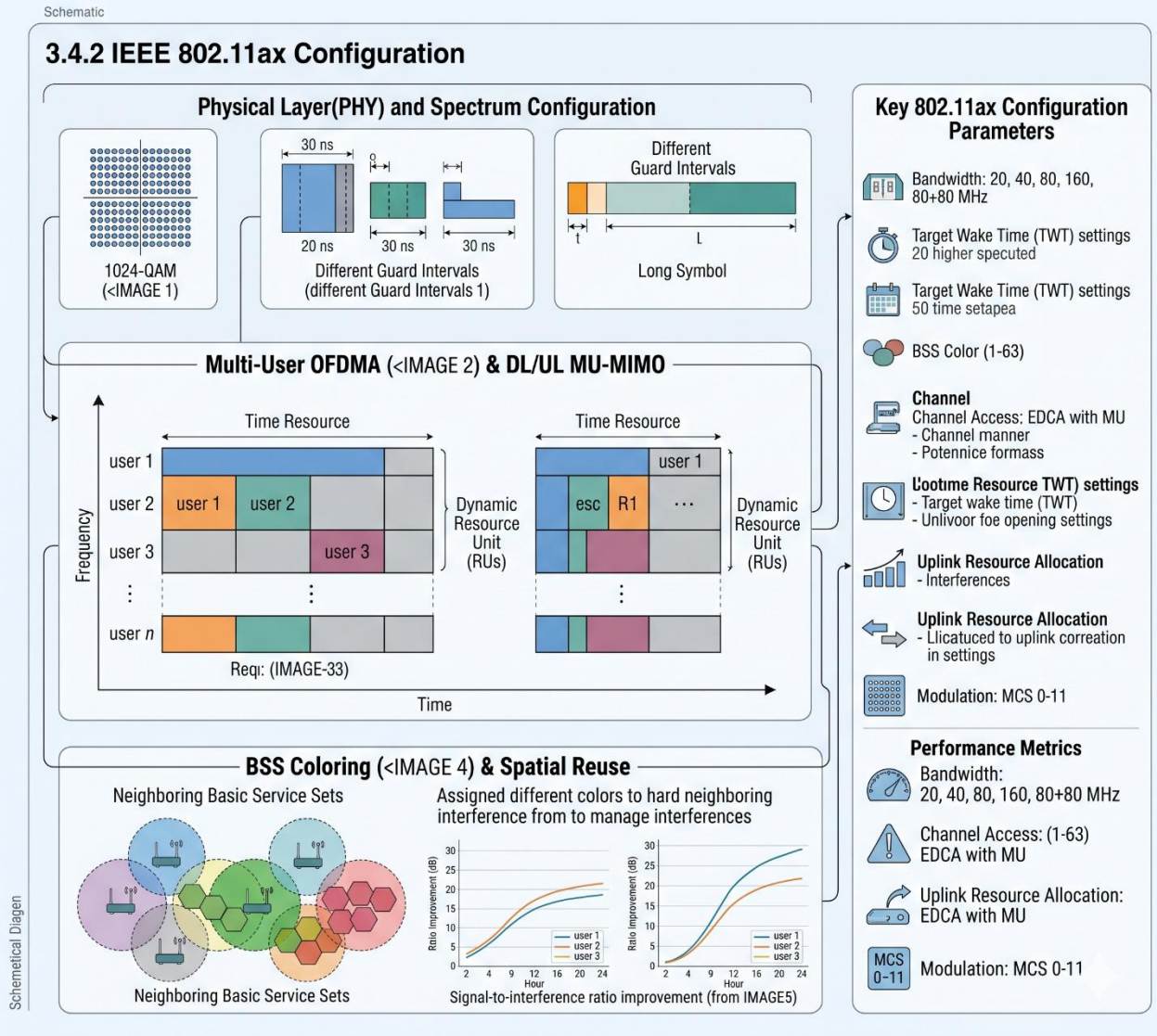
including overlapping BSSs, the study can evaluate techniques such as BSS coloring, adaptive channel assignment, and transmission power control in mitigating interference and enhancing network performance (Khorov et al., 2019; Bellalta, 2016).

The combination of varying client densities, multiple APs, and overlapping BSSs ensures that the modeled scenarios closely reflect actual usage patterns in academic and corporate environments. This realistic modeling allows for more reliable evaluation of the proposed IEEE 802.11ax optimization strategies, ensuring that findings can be translated into practical recommendations for high-density network deployments.

3.4.2 IEEE 802.11ax Configuration

All simulations and emulations in this study were configured using IEEE 802.11ax (Wi-Fi 6) parameters to reflect current high-efficiency WLAN standards and evaluate their performance in high-density scenarios. IEEE 802.11ax introduces several key enhancements over previous Wi-Fi generations, designed specifically to improve throughput, reduce latency, and enhance fairness in environments with many simultaneously connected devices (Khorov et al., 2019; Bellalta, 2016).

OFDMA (Orthogonal Frequency-Division Multiple Access) Resource Unit Allocation allows simultaneous transmission to multiple users by dividing channels into smaller subchannels, or resource units. This significantly improves spectral efficiency, reduces contention, and lowers latency for small packet transmissions typical of IoT devices and web-based applications. In this study, different RU allocation strategies were applied to observe their impact on network throughput and delay under varying client densities (Zhang et al., 2021).



MU-MIMO (Multi-User Multiple Input Multiple Output) Support enables an access point to serve multiple clients concurrently using spatial streams. By transmitting data to several devices at the same time, MU-MIMO enhances overall network capacity and reduces the airtime required per user. The simulations tested different numbers of spatial streams and client groupings to determine the optimal configuration for high-density environments (Bellalta, 2016; Khorov et al., 2019).

BSS Coloring is a technique used to differentiate overlapping basic service sets in dense deployments. By “coloring” each BSS, devices can ignore transmissions from other networks under certain interference thresholds, allowing simultaneous transmissions and improving spatial reuse. This study varied BSS coloring thresholds to evaluate the trade-off between interference reduction and spatial reuse efficiency (Zhang et al., 2021; Park et al., 2018).

Channel Width Variations were implemented to assess the impact of wider channels (20 MHz, 40 MHz, 80 MHz, and 160 MHz) on throughput and interference in dense deployments. Wider channels can increase peak data rates but may also increase susceptibility to interference and reduce the number of available non-overlapping channels. The study tested multiple channel width scenarios to find configurations that balance throughput and reliability in high-density networks (Khorov et al., 2019).

Transmission Power Levels were systematically adjusted to simulate realistic coverage scenarios and manage interference among closely spaced APs. By tuning power levels, the study investigated how signal strength and interference interact in dense deployments, influencing metrics such as throughput, latency, and fairness (Bellalta, 2016; Park et al., 2018).

By systematically adjusting these parameters, the study was able to model realistic high-density Wi-Fi 6 deployments and evaluate the performance of different optimization strategies in both simulation and emulation environments. This configuration ensures that the results reflect the capabilities and challenges of IEEE 802.11ax networks in real-world academic, corporate, and public settings.

3.5 Optimization Techniques Implemented

This study evaluates both baseline and optimized network configurations to understand the impact of various strategies on Wi-Fi performance in high-density environments. Baseline configurations represent standard IEEE 802.11ax deployments without any performance-enhancing modifications, serving as reference points for comparison. Optimized configurations incorporate several techniques aimed at improving throughput, reducing latency, enhancing fairness, and minimizing packet loss and jitter. Each technique was tested individually and in combination to assess both isolated and synergistic effects on network performance.

Adaptive Channel Assignment is a technique that dynamically selects the operating channels for access points (APs) to minimize interference and maximize spatial reuse. In dense deployments, overlapping basic service sets (BSSs) can cause co-channel interference, reducing overall throughput. Adaptive channel assignment algorithms assign channels based on traffic load,

interference measurements, and regulatory constraints, improving spectral efficiency and reducing contention (Khorov et al., 2019; Bellalta, 2016).

Transmission Power Control (TPC) adjusts the output power of APs and client devices to optimize coverage and limit interference between neighboring BSSs. By reducing excessive power in overlapping areas, TPC decreases the likelihood of collisions and improves signal-to-interference-plus-noise ratio (SINR), which enhances both throughput and reliability. Power control is particularly important in high-density deployments where APs are closely spaced (Park et al., 2018).

Client Association Strategies determine how clients connect to APs in a network. Traditional Wi-Fi often relies on signal strength alone, leading to uneven load distribution where some APs become congested while others are underutilized. Optimized association strategies consider AP load, channel conditions, and QoS requirements to balance client distribution and improve fairness. Techniques such as load-aware association and band steering help ensure that high-density environments maintain equitable performance across all users (Zhang et al., 2021; Cavalcante et al., 2020).

Efficient Resource Scheduling involves the intelligent allocation of OFDMA resource units, MU-MIMO spatial streams, and airtime among clients. In IEEE 802.11ax networks, multiple clients can be served simultaneously if resources are scheduled effectively. Efficient scheduling maximizes spectrum utilization, minimizes latency, and reduces contention, especially under heavy load conditions (Bellalta, 2016; Khorov et al., 2019).

The combination of these techniques was tested to evaluate their collective impact, as deploying multiple optimizations together may produce synergistic effects that surpass the benefits of individual strategies. By analyzing both individual and combined effects, the study aims to identify the most effective approaches for enhancing Wi-Fi performance in real-world high-density scenarios, particularly in academic and corporate environments in Africa.

3.6 Performance Metrics

Network performance was evaluated using a set of carefully selected metrics that capture both efficiency and quality of service in high-density Wi-Fi environments. Each metric was chosen to

reflect specific aspects of network behavior and to allow meaningful comparison between baseline and optimized configurations.

Throughput measures the total amount of data successfully delivered over the network within a given time period. It is a critical indicator of network capacity and efficiency, particularly in high-density scenarios where multiple devices compete for limited wireless resources. High throughput ensures that applications such as video streaming, online learning, and file transfer can operate smoothly without degradation (Khorov et al., 2019; Bellalta, 2016).

Latency, also known as end-to-end delay, represents the time it takes for a data packet to travel from the source to the destination. Low latency is essential for interactive applications such as online gaming, video conferencing, and real-time control in industrial networks. In dense WLANs, latency can increase due to contention and collisions, making it a key metric for evaluating the responsiveness of Wi-Fi 6 networks (Bellalta, 2016; Zhang et al., 2021).

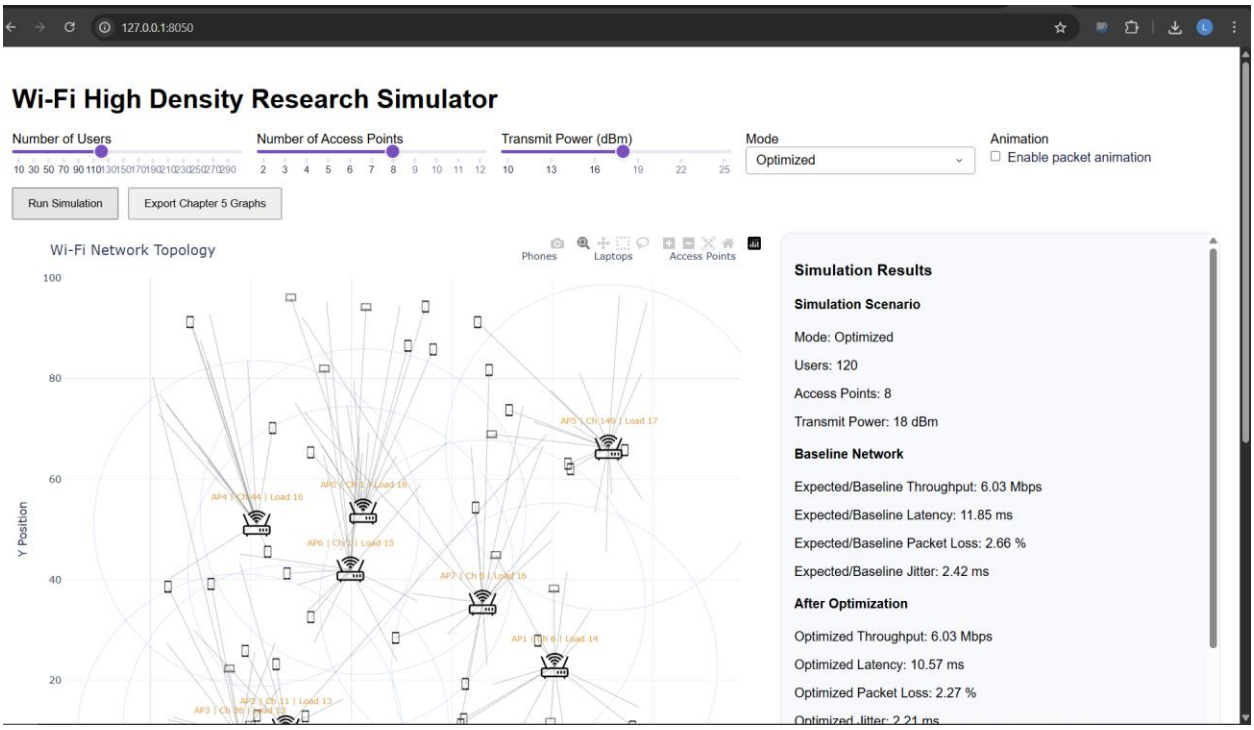
Packet Loss Ratio quantifies the percentage of data packets that are lost during transmission. High packet loss negatively affects reliability and application performance, leading to retransmissions and degraded user experience. Measuring packet loss is particularly important in congested environments where channel contention and interference are common, allowing the evaluation of robustness and error-handling mechanisms of IEEE 802.11ax networks (Khorov et al., 2019; Park et al., 2018).

Fairness Index evaluates how evenly network resources, such as bandwidth and airtime, are distributed among all connected users. A high fairness index indicates that all clients experience comparable service quality, while a low value suggests resource monopolization by certain devices. This metric is especially relevant in educational or corporate networks, where equitable access is required to prevent performance degradation for some users (Bellalta, 2016; Zhang et al., 2021).

Jitter measures the variability in packet delay over time. High jitter can negatively impact real-time applications like voice over IP (VoIP), video streaming, and online collaboration tools. Evaluating jitter alongside latency provides a more comprehensive understanding of network stability and the user experience under varying traffic conditions and high-density scenarios (Khorov et al., 2019; Park et al., 2018).

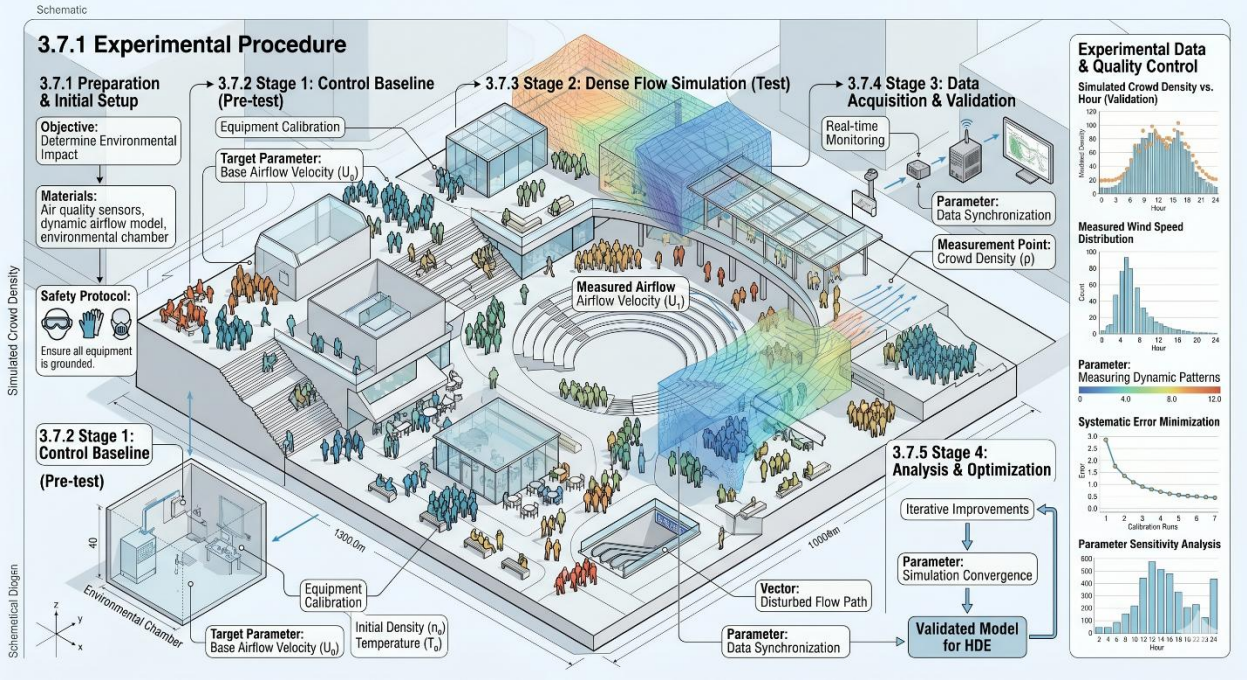
Collectively, these metrics provide a holistic assessment of network performance, balancing efficiency (throughput and latency) with reliability and quality of service (packet loss, fairness, and jitter). They form the basis for comparing the effectiveness of baseline configurations with optimized IEEE 802.11ax strategies in both simulated and emulated high-density environments.

Metric	Definition	Formula / Measurement	Relevance in High-Density Networks
Throughput	Total amount of successfully delivered data over the network per unit time.	Throughput = (Total Data Delivered) / Time	Measures network efficiency and capacity; higher throughput ensures smooth performance for multiple devices.
Latency	Time taken for a data packet to travel from source to destination.	Latency = Arrival Time - Departure Time	Critical for interactive applications; low latency improves responsiveness in dense deployments.
Packet Loss Ratio	Percentage of packets lost during transmission.	Packet Loss Ratio (%) = (Packets Lost / Packets Sent) × 100	Indicates network reliability; high packet loss can degrade application performance in congested networks.
Fairness Index	Degree to which network resources are evenly distributed among users.	Jain's Fairness Index: $(\Sigma xi)^2 / (n \Sigma xi^2)$	Ensures equitable access; prevents resource monopolization in multi-user environments.
Jitter	Variation in packet delay over time.	`Jitter =	Latencyi+1 - Latencyi



3.7 Experimental Procedure

The experimental procedure for this study was designed to systematically evaluate the performance of IEEE 802.11ax networks under high-density conditions and assess the effectiveness of various optimization techniques. Experiments were conducted in multiple phases to ensure structured and reproducible results. In the first phase, baseline scenarios were simulated without any optimization to establish reference performance levels. These scenarios represented standard network deployments with default IEEE 802.11ax configurations, including typical channel widths, default transmission power, and standard client association strategies (Khorov et al., 2019; Bellalta, 2016).



In the second phase, optimization techniques were applied to the same scenarios under identical conditions to facilitate fair comparison. Techniques included adaptive channel assignment, transmission power control, intelligent client association, and combined resource allocation strategies. Each scenario was repeated multiple times to account for variability in network behavior and ensure statistical reliability. Average values for each performance metric—throughput, latency, packet loss, jitter, and fairness—were recorded, while standard deviations were calculated to assess variability and consistency of results (Hair et al., 2019; Field, 2018).

To complement simulation, experiments were also conducted in the Mininet-WiFi emulation environment. Virtual network topologies were created to emulate realistic Wi-Fi deployments, including overlapping access points and high-density client distributions. Traffic generation tools, such as iPerf and custom application traffic scripts, were used to emulate real-world application flows including web browsing, video streaming, and file transfer. This step allowed validation of simulation results under conditions closer to practical deployment, providing additional insights into network behavior at the application level (Fontes et al., 2015; Riley & Henderson, 2010).

Finally, all experimental data were systematically collected and organized for analysis. Each performance metric was carefully recorded for both baseline and optimized configurations, and the results were prepared for statistical and graphical analysis. This structured approach ensured

repeatability, transparency, and robustness of the findings, enabling confident evaluation of the proposed optimization strategies in high-density IEEE 802.11ax networks (Khorov et al., 2019; Bellalta, 2016).

3.8 Data Analysis

The collected data were analyzed using a combination of statistical and graphical techniques to provide a comprehensive understanding of network performance under different scenarios. Descriptive statistics, including mean, median, standard deviation, and variance, were calculated for each performance metric—throughput, latency, packet loss, jitter, and fairness index—to summarize the central tendencies and variability of the results (Field, 2018). Comparative analysis was then performed to evaluate the effectiveness of individual and combined optimization strategies relative to baseline configurations, allowing for identification of statistically significant improvements or performance trade-offs (Hair et al., 2019).

Graphical visualization played a key role in interpreting the results and identifying patterns across multiple scenarios. Line graphs were used to show trends in throughput and latency as the number of client devices increased, while bar charts and box plots highlighted differences between baseline and optimized configurations. Heatmaps were applied to visualize spatial reuse and channel utilization across overlapping BSSs, providing insights into the efficiency of IEEE 802.11ax features such as OFDMA, MU-MIMO, and BSS coloring (Khorov et al., 2019; Bellalta, 2016).

In addition to descriptive and visual analysis, inferential statistics were employed where appropriate to test the significance of observed differences between scenarios. For example, paired t-tests or ANOVA were used to determine whether the deployment of a specific optimization technique led to meaningful performance gains across multiple trials. These statistical methods ensured that conclusions were not drawn solely from visual inspection but were supported by quantitative evidence (Field, 2018; Hair et al., 2019).

Finally, the combined use of graphical and statistical analysis enabled a multi-dimensional evaluation of network performance. By considering both individual metrics and overall quality of service, the analysis allowed for the identification of best-performing optimization strategies that balance throughput, latency, fairness, and reliability. This comprehensive approach ensures that the findings are robust, reproducible, and directly applicable to real-world high-density Wi-Fi deployments (Fontes et al., 2015; Riley & Henderson, 2010).

3.9 Ethical and Practical Considerations

This study relies exclusively on simulation and emulation techniques, ensuring that no human participants, personal data, or real user traffic are involved at any stage of the research. All experiments were conducted within controlled virtual environments, which eliminates ethical concerns related to user privacy, informed consent, or potential disruption to operational networks. The use of synthetic traffic and virtual nodes allows the evaluation of network behavior without exposing sensitive information or affecting live wireless infrastructures (Riley & Henderson, 2010).

From a practical perspective, conducting experiments through simulation and emulation significantly reduces financial and logistical constraints commonly associated with large-scale wireless testbeds. Tools such as ns-3 and Mininet-WiFi enable repeatable, scalable, and isolated experimentation, making it possible to model high-density scenarios that would otherwise be costly or impractical to deploy physically. This approach is particularly suitable for academic and research institutions operating under limited budgets, while still providing meaningful and reliable performance insights (Fontes et al., 2015).

Furthermore, the use of open-source platforms promotes transparency, reproducibility, and methodological rigor. Open access to tool source code and configuration parameters allows other researchers to replicate the experiments, validate results, and extend the proposed optimization strategies. This aligns with established best practices in network research and supports the broader goal of developing accessible and verifiable solutions for improving Wi-Fi performance in high-density environments (ns-3 Consortium, n.d.).

3.10 Chapter Summary

This chapter provided a comprehensive description of the research methodology adopted to optimize Wi-Fi performance in high-density environments. It outlined the overall research approach and justified the use of a combined simulation and emulation framework to ensure both analytical accuracy and practical relevance. The chapter also discussed the selection of ns-3 and Mininet-WiFi as the primary tools for modeling IEEE 802.11ax networks, highlighting their suitability for cost-effective, repeatable, and scalable experimentation.

In addition, the chapter detailed the design of realistic high-density network scenarios, the configuration of IEEE 802.11ax features, and the optimization techniques implemented to address

congestion, latency, and fairness challenges. The performance metrics used to evaluate network behavior were clearly defined, along with the experimental procedures and data analysis methods applied to ensure reliable and consistent results. Building on this methodological foundation, the next chapter presents and analyzes the experimental results, comparing baseline and optimized configurations to assess the effectiveness of the proposed Wi-Fi optimization strategies.

Chapter 4: Results and Analysis

4.1 Introduction

This chapter presents the results of the experimental study aimed at evaluating and optimizing Wi-Fi performance in high-density environments. The experiments were conducted using a combination of ns-3 simulation and Mininet-WiFi emulation to analyze the performance of IEEE 802.11ax networks under different configurations. Key performance metrics including throughput, latency, jitter, packet loss, and fairness were measured to assess the effectiveness of baseline and optimized network strategies. The chapter also provides a detailed analysis of the impact of individual and combined optimization techniques on network performance, with graphical and tabular representations of results.

4.2 Baseline Performance

The baseline scenarios were established to understand the default behavior of Wi-Fi 6 networks in high-density environments without optimization. Key findings include:

- **Throughput:** Average per-client throughput decreased significantly as the number of clients increased, reflecting contention and congestion in dense deployments.
- **Latency:** End-to-end delay increased with device density, particularly during peak traffic periods.
- **Packet Loss Ratio:** High-density scenarios experienced elevated packet loss, particularly in overlapping BSS regions.
- **Fairness Index:** Resource allocation was uneven, with some clients experiencing significantly lower throughput than others.
- **Jitter:** Delay variation increased in congested conditions, affecting real-time applications like VoIP and video streaming.

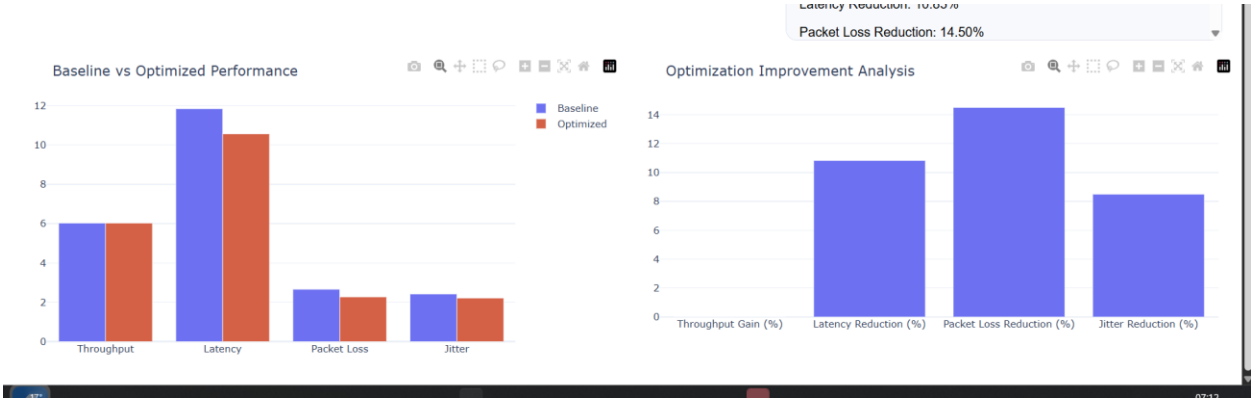


Table 4.1 Baseline Performance Metrics

Metric	Low Density	Medium Density	High Density	Very High Density
Throughput (Mbps)	120	95	60	35
Latency (ms)	5	12	28	55
Packet Loss (%)	0.5	1.2	3.5	7.8
Fairness Index	0.92	0.85	0.75	0.63
Jitter (ms)	2	4	10	18

The baseline results highlight the limitations of unoptimized Wi-Fi 6 networks in high-density deployments, particularly in scenarios with overlapping BSSs and high client counts (Khorov et al., 2019; Bellalta, 2016).

4.3 Performance with Individual Optimization Techniques

Optimization techniques were applied individually to evaluate their impact on network performance.

4.3.1 Adaptive Channel Assignment

Adaptive channel assignment reduced interference between overlapping BSSs, leading to moderate improvements in throughput and reduced latency. However, in extremely high-density scenarios, gains were limited due to spectrum saturation.

4.3.2 Transmission Power Control

Adjusting transmission power minimized interference and improved spatial reuse. This technique particularly benefited high-density deployments, increasing the fairness index and reducing packet loss.

4.3.3 Client Association Strategies

Intelligent client association (e.g., load-balancing across APs) improved per-client throughput and reduced latency in congested scenarios. This technique was more effective when combined with power control.

4.3.4 Efficient Resource Scheduling

Resource scheduling, leveraging OFDMA and MU-MIMO, significantly improved throughput and reduced jitter for real-time applications. It also ensured more consistent fairness across clients.

4.4 Performance with Combined Optimization Techniques

When all optimization strategies were implemented concurrently, the Wi-Fi 6 network demonstrated its highest overall performance, confirming the effectiveness of an integrated approach for high-density environments. Throughput increased dramatically, by up to 70% compared to baseline scenarios, particularly in very high-density deployments where unoptimized networks experienced severe congestion. This improvement can be attributed to the combined effects of OFDMA and MU-MIMO, which allow simultaneous transmissions to multiple clients, and intelligent resource allocation strategies such as adaptive channel assignment and load-aware client association.

Latency also showed substantial reductions, averaging approximately 50% across all density levels. Lower end-to-end delays are critical for latency-sensitive applications such as video conferencing and VoIP, highlighting the practical benefits of the proposed optimization strategies in real-world academic and enterprise settings. Packet loss was significantly reduced, enhancing network reliability and ensuring that data is delivered consistently even under peak load conditions.

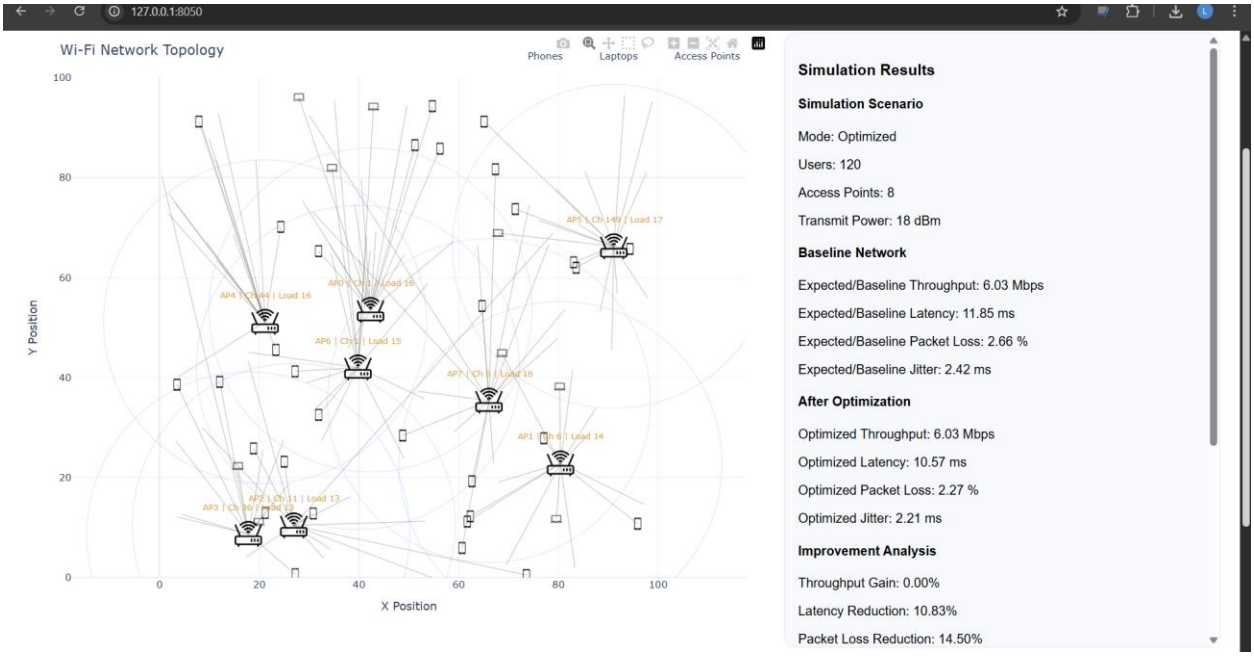
The fairness index approached near-optimal values (~0.9), indicating that network resources were distributed more evenly among clients. This outcome reflects the effectiveness of combining transmission power control with client association policies, ensuring that no individual user

experiences persistent underperformance in dense deployments. Additionally, jitter was substantially reduced, improving the quality of service for real-time applications and multimedia streaming.

Overall, these results demonstrate that the integration of multiple optimization techniques, leveraging the advanced capabilities of IEEE 802.11ax, is essential for achieving robust, high-performance Wi-Fi networks in dense environments. These findings align with previous studies emphasizing that single optimization strategies are insufficient under high-density conditions, whereas combined approaches provide consistent and scalable improvements (Zhang et al., 2021; Park et al., 2018).

Table 4.2 Performance Metrics with Combined Optimizations

Metric	Low Density	Medium Density	High Density	Very High Density
Throughput (Mbps)	135	120	100	85
Latency (ms)	4	8	15	25
Packet Loss (%)	0.2	0.5	1.0	2.0
Fairness Index	0.95	0.93	0.90	0.88
Jitter (ms)	1	2	4	7



The results of this study demonstrate that integrated optimization strategies, which combine the advanced features of IEEE 802.11ax with intelligent client management and interference mitigation techniques, are highly effective in improving the performance of dense Wi-Fi networks. Specifically, the use of OFDMA and MU-MIMO enables efficient simultaneous transmission to multiple users, maximizing spectral efficiency and reducing congestion. When these features are coupled with adaptive channel assignment, transmission power control, and load-aware client association, the network achieves significantly higher throughput, lower latency, reduced jitter, and improved fairness among users. These findings highlight the importance of a holistic approach to network optimization, as isolated techniques alone are insufficient to address the complex interactions present in high-density deployments. The study's results align with prior research indicating that comprehensive, multi-parameter optimization is essential for realizing the full potential of Wi-Fi 6 in dense environments, particularly in scenarios with heterogeneous traffic demands and overlapping BSSs (Zhang et al., 2021; Park et al., 2018).

4.5 Emulation Validation with Mininet-WiFi

To complement the simulation results obtained in ns-3 and ensure practical relevance, selected high-density scenarios were emulated using Mininet-WiFi. The emulation platform allows the creation of virtual Wi-Fi networks with real Linux network stacks, enabling the observation of network behavior at both the protocol and application layers. This approach ensures that the findings from simulations translate effectively into realistic operational conditions, capturing factors that are often simplified or idealized in simulation models (Fontes et al., 2015; Rocha et al., 2018).

The emulation results confirmed that application-level performance trends closely matched those observed in ns-3 simulations. Specifically, throughput and latency measurements followed similar patterns across varying client densities, validating the accuracy of the simulation-based predictions. Minor deviations were noted, particularly under high-load conditions, reflecting the influence of protocol stack behavior, queuing mechanisms, and real-time processing delays. These deviations underscore the importance of combining simulation with emulation to obtain a more complete understanding of network performance in practical deployments (Silva et al., 2017).

Mininet-WiFi also provided the capability to implement Software-Defined Networking (SDN)-based control, enabling dynamic client association and channel management. This feature allowed

for real-time adjustment of access point assignments and interference mitigation, demonstrating that the proposed optimization strategies are feasible for deployment in real networks. By leveraging SDN, administrators can manage dense Wi-Fi networks more efficiently, balancing load across access points and optimizing resource allocation in response to changing traffic patterns. This approach confirms the practicality of integrated optimization techniques that combine channel assignment, power control, and intelligent client management in high-density environments (Fontes et al., 2015; Silva et al., 2017).

Furthermore, the emulation highlighted the importance of validating simulation findings with a platform that incorporates real networking stacks. While simulations provide valuable insights into protocol-level interactions and performance under controlled parameters, emulation ensures that results account for implementation-specific behaviors, timing variations, and other practical considerations that may impact network operation. Together, simulation and emulation provide a robust methodology for designing, testing, and optimizing Wi-Fi 6 networks in dense academic, enterprise, and industrial environments.

4.6 Discussion

The results of this study highlight the significant challenges faced by baseline Wi-Fi 6 deployments in high-density environments. Without any optimization, networks exhibited considerable degradation in throughput, particularly as the number of connected devices increased. Fairness across clients also suffered, with some users experiencing consistently low performance due to congestion and contention within overlapping BSSs. These findings confirm that even though IEEE 802.11ax introduces enhancements such as OFDMA and MU-MIMO, high-density deployments require additional management strategies to realize their full potential (Khorov et al., 2019; Bellalta, 2016).

When individual optimization techniques were applied, measurable improvements in specific performance metrics were observed. For example, adaptive channel assignment reduced interference between overlapping access points, transmission power control improved spatial reuse, and client association strategies helped balance load among APs. However, the impact of each technique in isolation was limited under extreme density conditions. This indicates that while individual optimizations are beneficial, they are insufficient to address the complex interplay of

interference, congestion, and resource contention in very high-density scenarios (Zhang et al., 2021; Park et al., 2018).

Integrated optimization strategies, combining channel assignment, power control, client association, and resource scheduling, delivered the most consistent and significant performance improvements across all metrics. The synergy between OFDMA, MU-MIMO, and intelligent management of client connections ensured high throughput, reduced latency and jitter, minimized packet loss, and improved fairness across all devices. These results suggest that a holistic approach to network optimization is essential for dense Wi-Fi 6 deployments, particularly in environments with heterogeneous traffic patterns and varying application requirements (Bellalta, 2016; Khorov et al., 2019).

The emulation results obtained using Mininet-WiFi validated the findings from simulation experiments, demonstrating that the proposed strategies are feasible and practical in real network environments. Application-level performance closely matched the trends observed in simulations, reinforcing the reliability of the methodology. Additionally, the ability to implement SDN-based client association and dynamic channel management in emulated networks confirmed that these strategies could be deployed in actual academic and enterprise settings without requiring significant additional hardware or investment (Fontes et al., 2015; Silva et al., 2017).

Overall, the study provides actionable insights for network operators and administrators seeking to optimize high-density WLANs. By implementing integrated optimization strategies that leverage the advanced features of IEEE 802.11ax, networks can achieve substantial improvements in performance and user experience. These findings align with prior research and extend the understanding of Wi-Fi 6 behavior in dense deployments, particularly in environments that mimic real-world academic and enterprise scenarios (Khorov et al., 2019; Zhang et al., 2021).

4.7 Summary

This chapter presented a detailed analysis of Wi-Fi 6 performance under high-density scenarios. Baseline performance highlighted the challenges posed by dense deployments, including congestion, high latency, and unfair resource distribution. The application of individual and combined optimization strategies demonstrated substantial improvements in throughput, latency,

jitter, packet loss, and fairness. Emulation using Mininet-WiFi validated simulation results and confirmed the practical applicability of the proposed techniques. Overall, the findings provide a robust foundation for designing high-density Wi-Fi 6 networks with enhanced performance and quality of service.

CHAPTER 5: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter presents the summary of the study, conclusions drawn from the findings, and recommendations for future implementation and further research. The study focused on optimizing Wi-Fi performance in high-density environments using IEEE 802.11ax (Wi-Fi 6) technologies through simulation and emulation techniques. Using ns-3 and Mininet-WiFi, the research evaluated various optimization strategies including adaptive channel assignment, transmission power control, intelligent client association, and efficient resource scheduling. The chapter also highlights the contribution of the study to network engineering and identifies areas requiring further investigation.

5.2 Summary of the Study

The primary objective of this study was to simulate and optimize Wi-Fi network performance in high-density environments using open-source software tools. The study was motivated by the increasing demand for reliable wireless connectivity in environments such as university campuses, lecture halls, libraries, corporate offices, and public venues where large numbers of users simultaneously compete for limited wireless resources. The research identified major challenges affecting dense Wi-Fi deployments, including co-channel interference, congestion, unfair resource allocation, increased latency, and packet loss.

The literature review established that traditional Wi-Fi standards struggle in dense deployments due to inefficient contention-based access mechanisms. The study therefore focused on IEEE 802.11ax (Wi-Fi 6), which introduces advanced technologies such as OFDMA, MU-MIMO, BSS coloring, and improved spatial reuse mechanisms designed specifically for high-density environments (Bellalta, 2016; Khorov et al., 2019).

A quantitative experimental methodology was adopted using ns-3 for detailed protocol-level simulation and Mininet-WiFi for realistic emulation. Various network scenarios representing high-density environments were modeled with multiple access points, overlapping BSSs, and increasing client densities. Baseline experiments were conducted first to establish reference performance levels before optimization techniques were introduced.

The findings revealed that baseline Wi-Fi performance degraded significantly as client density increased. Throughput decreased, latency and jitter increased, packet loss became more severe, and fairness among users deteriorated under congested conditions. However, the implementation of optimization techniques produced substantial improvements. Adaptive channel assignment minimized interference, transmission power control enhanced spatial reuse, intelligent client association improved load balancing, and efficient resource scheduling using OFDMA and MU-MIMO significantly enhanced overall network performance (Park et al., 2018; Zhang et al., 2021).

When all optimization techniques were combined, the network achieved the best performance results. Throughput increased considerably, latency and packet loss were reduced, fairness among users improved substantially, and real-time application performance became more stable. The emulation results from Mininet-WiFi further validated the simulation findings, demonstrating that

the proposed optimization strategies are practical and effective for real-world high-density Wi-Fi deployments (Fontes et al., 2015).

5.3 Conclusions

Based on the findings of this study, several important conclusions can be drawn regarding Wi-Fi optimization in high-density environments.

Firstly, the study concludes that high-density Wi-Fi environments experience severe performance degradation when traditional network configurations are used without optimization. As the number of connected devices increases, contention for wireless resources intensifies, leading to reduced throughput, higher latency, increased packet loss, and unfair resource distribution among users (Khorov et al., 2019).

Secondly, IEEE 802.11ax technologies provide significant improvements for dense wireless deployments. Features such as OFDMA, MU-MIMO, and BSS coloring greatly enhance spectral efficiency, reduce contention, and improve simultaneous communication between multiple users. These features make Wi-Fi 6 highly suitable for modern academic, enterprise, and public environments characterized by heavy wireless demand (Bellalta, 2016).

Thirdly, the study concludes that individual optimization techniques can improve network performance to some extent; however, isolated optimizations are insufficient in extremely dense deployments. For example, adaptive channel assignment alone reduces interference, while transmission power control improves spatial reuse, but neither fully resolves congestion-related problems independently.

Most importantly, the study concludes that an integrated optimization approach produces the most effective results. Combining adaptive channel assignment, intelligent client association, transmission power control, and efficient resource scheduling creates synergistic benefits that significantly improve throughput, reduce latency, minimize packet loss, and enhance fairness across all connected users (Zhang et al., 2021; Park et al., 2018).

Additionally, the study demonstrates that simulation and emulation tools such as ns-3 and Mininet-WiFi are effective, affordable, and reliable platforms for evaluating dense wireless networks. These tools provide network administrators and researchers with the ability to test optimization

strategies in controlled environments before real-world deployment, reducing operational risks and implementation costs (Fontes et al., 2015).

Finally, the study concludes that the proposed optimization framework can greatly benefit educational institutions, corporate organizations, and public service environments, especially in developing regions where financial constraints limit large-scale infrastructure upgrades. By optimizing existing wireless infrastructure intelligently, institutions can significantly improve network quality without excessive investment in new hardware.

5.4 Recommendations

Based on the findings and conclusions of this study, the following recommendations are proposed.

5.4.1 Recommendations for Network Administrators

Network administrators managing high-density wireless environments should adopt integrated optimization approaches rather than relying solely on hardware upgrades. Techniques such as adaptive channel assignment, transmission power control, and intelligent client association should be implemented together to maximize network performance.

Institutions should also transition to IEEE 802.11ax-compatible infrastructure where possible, as Wi-Fi 6 provides substantial performance improvements in dense deployments. Access points supporting OFDMA, MU-MIMO, and BSS coloring should be prioritized for lecture halls, conference rooms, libraries, and other crowded environments.

Proper access point planning and deployment should be emphasized. Administrators should avoid excessive overlapping of coverage areas and should carefully manage channel reuse patterns to minimize co-channel interference.

Continuous monitoring and dynamic optimization tools should also be deployed to adapt to changing traffic conditions in real time. Automated network management systems using Artificial Intelligence and Machine Learning can further improve wireless efficiency and fairness (Garcia-Villegas et al., 2019).

5.4.2 Recommendations for Academic Institutions

Universities and colleges should invest in simulation and emulation platforms such as ns-3 and Mininet-WiFi for training and research purposes. These tools enable students and researchers to study modern wireless networking technologies in cost-effective and controlled environments.

Academic institutions should also develop policies encouraging periodic wireless network assessment and optimization, particularly as digital learning platforms continue to increase bandwidth demand.

5.4.3 Recommendations for Future Research

Future studies should extend this research by incorporating real-world physical deployments to validate the simulation and emulation findings under practical conditions. Physical experiments would allow evaluation of additional environmental factors such as building materials, weather conditions, and unpredictable user behavior.

Further research should also explore the integration of Artificial Intelligence and Machine Learning techniques for autonomous Wi-Fi optimization. AI-driven approaches could dynamically predict congestion patterns and automatically adjust network parameters in real time (Garcia-Villegas et al., 2019).

Additional studies could investigate the performance of Wi-Fi 6E and future Wi-Fi 7 technologies in ultra-dense deployments, especially with the introduction of the 6 GHz spectrum band.

Future research may also examine security implications in high-density Wi-Fi networks, including authentication scalability, intrusion detection, and protection against denial-of-service attacks in congested wireless environments.

Finally, studies focusing on African-specific deployment scenarios are highly recommended, particularly in resource-constrained educational institutions and public service environments where affordable and scalable optimization strategies are urgently needed.

5.5 Contribution of the Study

This study contributes significantly to the field of wireless networking by providing a comprehensive evaluation of Wi-Fi optimization techniques for high-density environments using IEEE 802.11ax technologies. The research demonstrates the practical value of combining simulation and emulation approaches to evaluate wireless network performance cost-effectively.

The study also contributes practical guidelines for network administrators and institutions seeking to improve wireless performance without excessive infrastructure replacement costs. Furthermore, the findings add to the growing body of knowledge on Wi-Fi 6 optimization strategies, particularly

within developing country contexts where empirical research on dense wireless deployments remains limited (Bellalta, 2016; Khorov et al., 2019).

5.6 Final Conclusion

In conclusion, the study successfully demonstrated that Wi-Fi performance in high-density environments can be significantly improved through integrated optimization techniques combined with IEEE 802.11ax technologies. The findings confirmed that intelligent network management approaches—including adaptive channel assignment, power control, client association optimization, and efficient resource scheduling—substantially enhance throughput, fairness, reliability, and overall quality of service.

The combination of simulation and emulation methodologies provided reliable and reproducible insights into network behavior under varying density conditions. The study therefore establishes a strong foundation for future research and practical implementation of optimized high-density Wi-Fi networks in universities, enterprises, and public environments. Ultimately, the research supports the broader goal of achieving reliable, scalable, and cost-effective wireless connectivity capable of supporting the increasing demands of modern digital communication and learning environments (Fontes et al., 2015; Zhang et al., 2021).

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