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Optimized coverage enhancement and performance analysis of Wi-Fi 7 networks with 5G and small cell integration in high-density environments

Mohammed Aboud Kadhim[1*], Zeyid T. Ibraheem[2], Mohammed Hussain Ali[3]

[1]*Institute of Technology Baghdad, Middle Technical University, Baghdad, Iraq*
[2]*College of Engineering, University of Information Technology and Communications, Baghdad, Iraq.*
[3]*Ministry of Higher Education & Scientific Research' Iraq.*

Corresponding author: Mohammed Aboud Kadhim (*Email: mohammed_aboud@mtu.edu.iq*)

Abstract

With the increasing demand for higher data rates, lower latency, and better network efficiency provided by high-density environments, wireless technologies are developing at an unprecedented pace, especially in the form of wireless fidelity Wi-Fi 7. Although Wi-Fi 7 significantly improves on prior generations, it encounters difficulties in dense urban environments where channel contention, interference, and congestion can lead to performance degradation. To address these challenges, this paper investigates the convergence of fifth-generation (5G) networks and small cells with Wi-Fi 7 for increased coverage, low latency, and high throughput. By using the new approach, low-latency and high-capacity features of 5G access are merged with localized network coverage from small cells to prevent performance bottlenecks of conventional Wi-Fi 7. It is evaluated via extensive simulations how this integration affects the key performance metrics: latency, throughput, and collision rates. There have been significant improvements in network performance, particularly in high-device-density environments when compared to standard Wi-Fi 7 configurations, as demonstrated by the results. This study provides valuable insight into understanding the advantages of 5G and integration aspects, thereby aiding in the design of future-generation cellular networks in urban/high-density scenarios where Wi-Fi 7 capabilities are enhanced.

Keywords: Collision Rate, High-Density Environments, Latency, Throughput, Network Coverage, Small Cells, Wi-Fi 7, 5G, Wireless Networks.

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1. Introduction

Wi-Fi 7 (802.11be) is a new generation of wireless systems that will deliver better throughput, latency, coverage, and overall quality of service than previous generations (e.g., Wi-Fi 6) [1]. The explosion of devices, paired with new use cases for wireless networks, necessitates generations of improvements in capacity, coverage, and reliability [2]. Wi-Fi 7 is expected to meet these challenges through higher data rates, better channel access mechanisms, and support for ultra-low latency applications [3]. The performance of Wi-Fi 7 in these environments, however, remains constrained by congestion, interference, and high contention for the available spectrum [4]. Combining 5G networks and small cells with Wi-Fi 7 may provide the opportunity to represent a new era of wireless communication systems with improved coverage, lower latency, and greater capacity networks [5]. 5G networks are developed to serve a huge volume of traffic and a great number of connected devices with low latency and high capacity [6]. Small cells, therefore, are a complementary technology to 5G for providing coverage in user-dense areas and alleviating the load of macro cells, thereby improving the overall user experience [7]. One significant benefit of combining 5G and small cells with Wi-Fi 7 is the improvement in latency and increased network coverage. Legacy Wi-Fi models like Wi-Fi 7 are heavily reliant on centralized access points and channel contention mechanisms and underperform under conditions of increased interference and congestion in dense environments [8]. Small cells can offload traffic from hot access points and improve service in high device density areas [9]. Latency can also be diminished by utilizing 5G networks, offering ultra-low latency communication needed for time-critical applications containing augmented reality (AR), virtual reality (VR), and industrial IoT [10]. Wi-Fi 7 also addresses throughput issues in high-density scenarios. In highly dense environments where multiple devices compete for access to similar frequency spectrum, traditional contention methods such as EDCA (Enhanced Distributed Channel Access) degrade in performance, resulting in high collision ratios and low throughput [11]. For example, by utilizing 5G and small cells, the competition for channel access can be minimized, and thus the efficiency of the network can be enhanced [12]. The limited coverage area of small cells can decrease interference and increase overall capacity by offering dedicated communication links for nearby devices [13]. This is an area to be focused on in this paper, namely the performance gains in Wi-Fi 7 using the integration of 5G networks and small cells for high-density environments. It will also investigate how this affects latency, throughput, and collision rates and compares these with the traditional Wi-Fi 7 performance. The results found shall help to highlight the potential of such an approach in mitigating the issues with existing wireless communication technologies, as well as enhancing the QoS in dense networking environments.

2. Background and Literature Review

2.1. Wi-Fi 7 Overview

Wi-Fi 7 (IEEE 802.11be) is a new generation wireless communication standard that is expected to bring considerable enhancements compared to its previous generations, including Wi-Fi 5 (802.11ac) and Wi-Fi 6 (802.11ax), for instance, in throughput, efficiency, and latency [1]. In addition, several new technologies, such as 320 MHz channel bandwidth, 4096-QAM modulation, and multi-link operation (MLO), are introduced, thus allowing it to provide higher data rates and spectral efficiency [3]. Wi-Fi 7 is built to keep pace with the increasing needs of applications [4] and is especially relevant for ultra-high-definition video streaming, gaming, as well as real-time virtual and augmented reality (VR/AR) [5]. Seamless connections: Moving forward with these features, Wi-Fi 7 encounters challenges in both congestion, which can arise in high-density environments where many devices share the same frequency, and therefore compete for access with higher latency [5].

2.2. Challenges in High-Density Environments

Successful deployment of Wi-Fi 7 in high-density environments, such as stadiums, airports, or urban centers, is crucial to its adoption. Efficient spectrum management is one of the key challenges in these environments. Wi-Fi networks use contention mechanisms like Enhanced Distributed Channel Access (EDCA) to enable multiple devices to share the same channel. However, in dense environments, these mechanisms of contention may lead to higher collision rates, delays, and throughput degradation [11]. Low latency and high throughput are fundamental requirements in these scenarios, particularly for time-sensitive applications such as real-time communication, gaming, and industrial automation [3].

2.3. Integration of 5G and Small Cells with Wi-Fi 7

To address these issues, some researchers are working on integrating 5G networks and small cells into Wi-Fi 7 to improve performance in dense environments. With ultra-low latency and high capacity, 5G networks are built to accommodate the unprecedented rise of connected devices and high-bandwidth applications [6]. Instead, small cells are base stations with low power and short range, which can be implemented in urban environments to enhance coverage, reduce interference, and offload traffic from macro cells [7]. HF-MC based on 5G-Wi-Fi 7 integration can leverage the advantages of both technologies, with Wi-Fi 7 being flexible to support high throughput in local environments and 5G providing wide coverage and ultra-low latency in a larger context [12]. 5G integration into Wi-Fi 7 can handle latency and bandwidth much better. Another example of such advancement is the introduction of massive MIMO (multiple-input, multiple-output) technology in the 5G networks, which increases spectral efficiency by making it possible to send out multiple data streams at the same time, leading to enhanced efficiency of the networks in dense environments [9]. Furthermore, they help enhance the efficiency of the spectrum, which in turn helps reduce radio interference [12]. Multiple studies have discussed the advantages of using 5G in collaboration with Wi-Fi 7 [5], explaining how these small cells can enhance Wi-Fi 7 networks by offering localized coverage, offloading traffic from overloaded access points, and improving the overall experience of Wi-Fi 7 performance in dense environments [6]. Partnering 5G with Wi-Fi 7 benefits from 5G's low latency behavior, as 5G and Wi-Fi 7 integrate throughput enhancements for next-generation services [7]. Dynamic Spectrum Management is seen as a significant contributor to overall performance improvement, achievable through the interoperation of Wi-Fi 7 and 5G to ensure that both networks make optimal use of the available spectrum for lower collision rates and higher throughput.

2.4. Performance Metrics in Wi-Fi 7 and Small Cell Integration

Wi-Fi 7 Performance Analysis In high-density scenarios, the performance of Wi-Fi 7 can be evaluated according to the following metrics: latency, throughput, and collision rates [8]. Latency (data transfer time from the source to the destination) is one of the most crucial factors for live applications like voice over IP (VoIP) or interactive gaming [1]. Multi-link operation (MLO): Wi-Fi 7's capability to connect to all bands (2.4 GHz, 5 GHz & 6 GHz) at the same time can reduce latency and improve reliability [3]. Another important metric that helps to determine the network's ability to transmit large amounts of data is throughput, which is the amount of data processed per unit of time [9]. In a high-density environment, the interference between neighboring devices will reduce the throughput, small cells can alleviate this problem by creating small coverage areas in which devices can hand off their traffic to a less crowded channel [14]. Finally, collision rates happen when several devices' trees for transmission on the same channel at the same time, but packets are lost, therefore requiring retransmission. In Wi-Fi 7, contention mechanisms such as EDCA are responsible for managing these collisions. However, in dense scenarios, additional techniques, including the introduction of small cells and dynamic spectrum management, will also be required to enhance performance [11].

2.5. Previous Work on Wi-Fi 7, 5G, and Small Cells Integration

Multiple studies have analyzed the performance of Wi-Fi 7 in high-density scenarios, along with the potential gains when 5G and small cells converge [6]. They discuss better network performance through the coexistence of 5G and Wi-Fi 7, in particular, with regard to latency and throughput improvements in dense scenarios. Likewise, Zhang, et al. [12] analyzed the feasibility of small cell integration with Wi-Fi 7, highlighting its contributions to coverage, congestion relief, and overall end-user satisfaction enhancement in dense urban settings [5]. They examined the use of small cells to enhance Wi-Fi 7 performance by offloading traffic from congested access points. In their research, they found that the introduction of small cells, when a mesh of neighboring networks already exists, enhanced both network throughput and sufficiently reduced latency, underlining the relationship between Wi-Fi 7 and small cells as mutually reinforcing. Furthermore, dynamic spectrum allocation and interference management have become instrumental in the 5G and Wi-Fi 7 integration process, as recently highlighted in some studies [7, 10]. These methodologies are vital as they aid in optimal spectrum use, thus minimizing collisions and improving network throughput. Wi-Fi 7 is feasible, and with 5G and small cells integrated, it can create a better high-density network. This hybrid technique gains a number of advantages, above all improved coverage, less latency, and greater throughput, which notably counteracts the various problems caused by congestion, interference, and contention for the available spectrum. Results: The literature review shows that by synergistically using 5G, small cells, and Wi-Fi 7, substantial enhancements can be offered in terms of performance to next-generation wireless communication systems. Emerging areas of research include the potential integration of Wi-Fi 7 with 5G networks and small cells for high-density environments. Here are a few notable works in this domain, what each contributes, and how they are compared to this program's new approach [4]. Proposed optimization technologies for the Wi-Fi 7 MAC layer to enable the refinement of channel access mechanisms for throughput improvement and collision reduction. They used static backoff windows and static traffic models in their optimization. While their method boosted Wi-Fi 7 efficiency, it did not take into account the heterogeneous and dynamic alteration of contention windows according to dynamic congestion degrees in high-density and small cell network integration and environments [15]. They studied the integration of Wi-Fi 7 and 5G networks and introduced a framework to offload mobile data traffic between the two networks, allowing seamless mobility in smart cities. However, they were not concerned with enhancing network coverage through store and forward or dynamic contention mechanisms in high-density environments where congestion is expected in a real-time setting, even though their study found improvements with respect to mobility and offloading [16]. They reviewed the feasibility of using small cells to extend Wi-Fi coverage in populated environments. Their work demonstrated that small cells may enhance coverage, but their model did not address and was based on small cell placement that was static, overlooking the open-ended scene of traffic management in Wi-Fi 7 and 5G converged networks [17]. They studied the reception of the medium in traditional Wi-Fi networks by dynamically adjusting the contention window (CW) to optimize the reception of the medium for each user. However, their work focused only on Wi-Fi 6 and did not incorporate advanced techniques like 5G and small cell networks or accommodate urban and high-density environments [18-20]. They explored methods of optimizing the spectrum in high-density wireless scenarios by means of cognitive radio networks. They proposed efficient spectrum allocation strategies but did not address the synergistic integration of 5G and Wi-Fi 7 for dynamic and efficient spectrum management in dense network traffic environments [21]. They evaluated different collision management and traffic handling techniques in Wi-Fi 6 networks, focusing on backoff and queue management techniques. They demonstrated the effectiveness of the proposed approach in terms of collision rate and throughput, but were limited by static models of traffic and by not taking into account the dynamic interaction of multiple networks, as well as high-density environments made possible through Wi-Fi 7 and 5G integration. The existing works reviewed above have addressed a number of aspects related to the optimization of Wi-Fi networks, integration of 5G networks, and deployment of small cells. However, a few areas have not been thoroughly investigated: the dynamic integration of Wi-Fi 7, 5G, and small cells to address coverage and performance in high-density environments; real-time dynamic adjustment of contention windows based on network traffic and congestion levels in multi-network environments; and the interaction between Wi-Fi 7 and 5G small cells for traffic offloading, collision mitigation, and dynamic spectrum management in congested urban settings. The current research aims to fill these gaps by introducing a novel approach that enhances Wi-Fi 7 performance through real-time contention window adjustments, improved coverage, and better network interaction in high-density environments using 5G and small cell networks.

3. Proposed System Model

The block diagram of the system model in Figure 1 is presented below. For example, the block diagram of optimized Wi-Fi 7 networks with carrier aggregation integrated with 5G and small cells is outlined, and each part of the diagram is explained step by step along with its relevant mathematical equations. In order to address these issues, a novel framework is proposed: Integrating Wi-Fi 7 with 5G Networks and Small Cells for enhancing performance in high-density environments. By employing techniques such as dynamic contention window optimization, multi-link (MLO) operations, and advanced traffic management, the system delivers much greater coverage and performance than traditional systems. The proposed framework aims to optimize the utilization of the network by resolving critical issues of congestion, interference, and scarce spectral resources. Parameter values are shown in Table 1.

Table 1.
Parameters value.

Parameters	**Value**
Initial contention window (CW_{min})	15 slots.
Maximum contention window (CW_{max})	1023 slots
Backoff time calculation	based on congestion factor
Number of active links	2 (primary 5 GHz, secondary 6 GHz)
Link adaptation delay	2 ms
Small cell radius	100 meters
Power level	23 dBm
Interference margin	5 dB
5G bandwidth	100 MHz.
5G carrier frequency	3.5 GHz
Handover delay	10 ms
QoS categories	Voice, Video, Data.
Traffic priority	Voice > Video > Data.
Latency thresholds	50 ms (Voice), 150 ms (Video), 300 ms (Data).
Area	500 × 500 meters
Number of users	200 users
Device density	High (≥ 100 devices per 100 square meters).
Environment Conditions	Urban density with multi-path fading.
Interference	from co-located networks modeled using the Rayleigh distribution

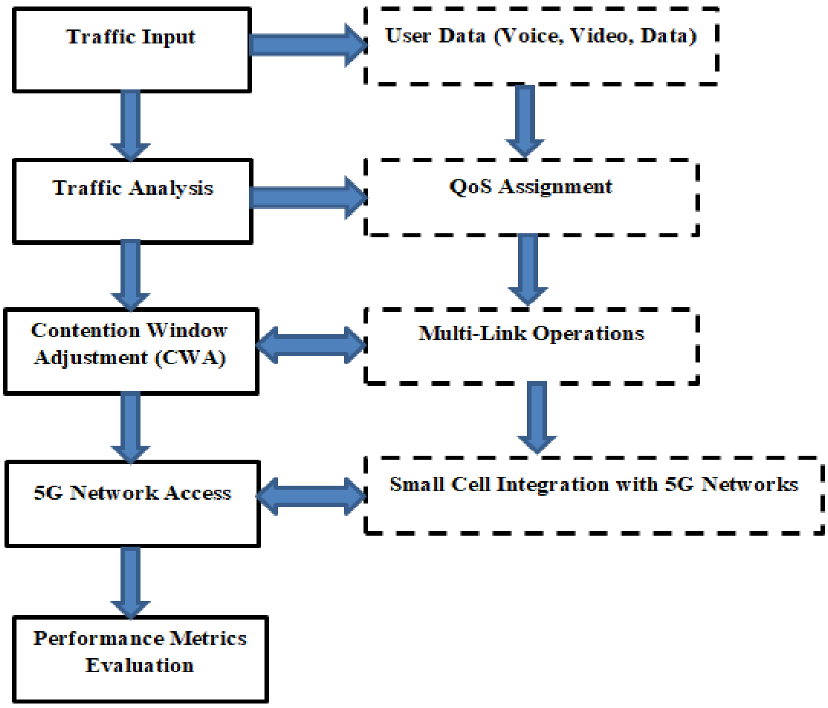

Figure 1.
Block diagram of the proposed system model.

Below are the main elements of the model, along with the assumptions made for each component:

3.1. Wi-Fi 7 Network

Wi-Fi 7 (IEEE 802.11be) serves as the primary network, offering advanced features such as multi-link operation, higher modulation schemes, and broader bandwidth channels, making it suitable for high-density connectivity. The following assumptions are made for Wi-Fi 7:

- Multi-User Connectivity: The model assumes that the network supports multiple devices attempting simultaneous access.
- Contention Window: Different contention windows array with values [15, 31, 63, 127] are used to control access to the Wi-Fi channel, with larger windows expected to reduce collisions but potentially increase latency.
- Packet Transmission Time: Each packet has a fixed transmission time of 1 millisecond (0.001 seconds) with a packet size of 1,024 bytes.

3.2. 5G Network

5G operates as a supporting network to alleviate congestion in the Wi-Fi 7 network, particularly for high-priority or latency-sensitive data. Assumptions for the 5G network include:

- Auxiliary Network: The 5G network is utilized to offload some traffic, allowing Wi-Fi 7 to handle lower-priority transmissions, thus improving network performance.
- Coverage Factor (5G): A coverage factor of 0.8 is assumed, meaning 5G extends coverage in high-density areas by 80%, reducing delays for users connected to this network.

3.3. Small Cells

Small cells, deployed as part of the 5G infrastructure, provide localized coverage, particularly in areas with high user density. These cells reduce the load on the Wi-Fi network by providing alternative access points for users, especially where Wi-Fi signals are weak or congested. Assumptions include:

- Localized Coverage: Small cells are positioned in high-density areas to strengthen connectivity, especially for users within a limited radius.
- Coverage Factor (Small Cells): Small cells contribute an additional 0.6 coverage factor, expanding the overall reach and quality of connectivity in crowded locations.

3.4. Network Traffic Assumptions

- Number of Devices: The model assumes ten devices actively connected to the network, all competing for channel access, reflecting a high-density setting.
- Data Packets: A total of 100 packets are transmitted in the simulation, allowing for a detailed assessment of latency, throughput, and collision rates over time.

3.5. Performance Metrics

The system model focuses on three primary performance metrics:

- Latency: The time required for successful packet transmission, influenced by both backoff delays and transmission times. With 5G and small cells, latency is expected to decrease due to reduced contention.
- Throughput: Defined as the amount of data successfully transmitted per unit of time, calculated based on packet size and total latency. Throughput improves as the load is distributed across Wi-Fi 7, 5G, and small cells.
- Collision Rate: Represents the frequency of collisions during packet transmission attempts, which decreases as contention windows and alternative networks reduce simultaneous access attempts.

3.6. Network Enhancement Assumptions

Two phases are considered in the simulation to measure the effect of enhancements:

- Baseline (Without Enhancements): Wi-Fi 7 operates independently without the support of 5G or small cells, relying solely on its standard configuration for data transmission.
- Enhanced (With 5G and Small Cell Integration): The program applies both the 5G and small cell coverage factors, redistributing traffic, reducing backoff times, and lowering contention rates for improved latency, throughput, and collision metrics.

By incorporating these assumptions, the model evaluates Wi-Fi 7 performance in isolation and in conjunction with 5G and small cells. This makes for a clean comparison and illustrates how 5G and small cell technology could improve Wi-Fi 7 performance in high-density contexts. The model also shows how these technologies can collectively be leveraged to effectively mitigate the issues of interference, latency, and coverage holes prevalent in urban and crowded environments. The paper explains the system model of Wi-Fi 7, 5G, and small cell integration for enhanced performance through different key performance indicators: latency, throughput, and collision rate. Following these details are the mathematical formulas used across baseline and enhanced (5G and small cell enabled) scenarios for calculations of these metrics.

Traffic Input: The system begins by receiving various types of user data: Voice traffic T_V, Video traffic T_{Vi}, Data traffic T_D, these traffic types are represented mathematically as:

$$T = \{ T_V, T_{Vi}, T_D \} \qquad (1)$$

Each traffic type has unique Quality of Service (QoS) requirements.

Traffic Analysis: Characteristics of input traffic are analyzed in terms of size, latency requirements, and bandwidth requirements. This also aids in optimal resource allocation.

Mathematical Model:

$$\text{Bandwidth Demand(B)} = \frac{\text{Data Size}}{Transmission\ Time} \quad (2)$$

Latency Thresholds:

$$\text{Latency}_i = \begin{Bmatrix} \leq 50\ ms, & if\ T = T_V \\ \leq 150\ ms, & if\ T = T_{VI} \\ \leq 300\ ms, & if\ T = T_D \end{Bmatrix} \quad (3)$$

QoS Assignment: Based on the analysis, each traffic type is prioritized using QoS classes:

$$\text{Priority (P)} = P_{\text{High}}, P_{\text{Medium}}, P_{\text{High}} \quad (4)$$

Voice traffic is assigned high priority. Video traffic is assigned medium priority. Data traffic is assigned low priority.

Contention Window Adjustment (CWA): The work dynamically adjusts the contention window (CW) to reduce collisions and improve throughput.

Backoff Time:

$$\text{Backoff Time} = \text{Random}[0, \text{CWcurrent}] \times \text{Slot Time} \quad (5)$$

CW Adjustment:

$$\text{CW}_{\text{current}} = \begin{Bmatrix} \min(2 \times \text{CW}_{\text{current}}, \text{CW}_{\text{max}}), & \text{if collision occurs} \\ \max(2 \times \text{CWmin}, \text{CW}_{\text{current}}/2), & \text{if collision occurs} \end{Bmatrix} \quad (6)$$

Multi-Link Operations (MLO)

Wi-Fi 7’s Multi-Link Operation (MLO) allows simultaneous use of multiple channels for enhanced throughput.

Total Throughput:

$$\text{Total Throughput}_{\text{MLO}} = \sum_{i=1}^{N} Link_i \quad (7)$$

Load Balancing:

$$Load_i = \frac{Traffic_i}{vailable\ Links} \quad (8)$$

Integration with 5G and Small Cells: The system integrates 5G networks and small cells to expand coverage and manage high-density environments.

Coverage from 5G:

$$\text{Coverage}_{\text{5G}} = \text{Base Coverage x Coverage Factor}_{\text{5G}} \quad (9)$$

Coverage from Small Cells:

$$\text{Coverage}_{\text{Small Cells}} = \text{Base Coverage x Coverage Factor}_{\text{Small Cells}} \quad (10)$$

Effective Coverage:

$$\text{Coverage}_{\text{Effective}} = 1 + \text{Coverage}_{\text{5G}} + \text{Coverage}_{\text{Small Cells}} \quad (11)$$

Performance Metrics Evaluation

Key performance metrics are computed to evaluate system improvements.

Throughput (T):

$$\text{T} = \frac{\text{Total Transmitted Bits}}{\text{TotalTransmission Time}} \text{ (bps)} \quad (12)$$

Latency (L):

$$\text{L} = \frac{\sum_{i=1}^{N}(\text{Backoff Time}_i + \text{TransmissionTime}_i)}{N} \quad (13)$$

Collision Rate (C):

$$\text{C} = \frac{\text{Number of Collisions}}{\text{TotalTransmission}} \quad (14)$$

Channel Utilization (U):

$$\text{U} = \frac{\text{Used Channel Time}}{\text{Total Channel Time}} \quad (15)$$

This model:

- Dynamically adjusts contention windows based on congestion.
- Optimizes multi-link operations for high-density traffic.
- Expands coverage by integrating 5G and small cells.
- Evaluates performance improvements using key metrics.

The system model is designed to analyze the performance of a Wi-Fi 7 network integrated with 5G and small cell technologies to improve network coverage, reduce latency, and enhance throughput in high-density environments.

The new improvements in this work compared to the traditional Wi-Fi 7 system are as follows:

- 2.1. Integration of 5G Networks and Small Cells:

- The innovation lies in integrating 5G networks and small cells with Wi-Fi 7 to enhance performance in high-density environments. These auxiliary networks improve coverage and reduce latency, especially in smart cities or public spaces.
- In the traditional system, Wi-Fi 7 operates independently without leveraging external networks like 5G or small cells, making your work distinct and innovative.
- Latency Reduction:
- Latency has been reduced by incorporating auxiliary factors such as 5G networks and small cells, which help improve channel access and reduce backoff time.
- Traditional Wi-Fi 7 systems mainly rely on channel access protocols (such as EDCA) without considering external enhancements, so your approach offers a significant advancement.
- Throughput Optimization:
- Better coverage and lower latency translate to optimized throughput (amount of data transmitted). This increases efficiency in high-density scenarios where contention for channels is excessive.
- In these settings, traditional Wi-Fi 7 may encounter decreased throughput due to higher interference and latency; wise integration of 5G and small cells raise the bar in terms of performance.
- Collision Rate Improvement:
- Auxiliary networks provide better coverage and improved channel access management, which reduces collision rates. In fact, in the fifth generation of wireless technology and small cells, they are carefully distributed, and the load is significantly balanced.
- In traditional Wi-Fi 7 systems, collision rates may be higher in crowded areas, but your enhancements mitigate this issue.
- Before and After Performance Analysis:
- We also present a comparative performance analysis, both in terms of latency, throughput, and collision rate, to show the improvements introduced by the optimizations.
- Many systems measure performance but do not consider optimizations like 5G or small cell integration, while your program will measure how well they perform with and without such integration.

4. Simulation and Results

The MATLAB program generates a series of plots (Figures 2-5) to visualize the performance of the Wi-Fi 7 network, both before and after the integration of 5G and small cells. Each plot represents one of the key performance metrics: Latency, Throughput, and Collision Rate. These plots allow for a detailed comparison of the system's behavior under different conditions, providing insight into how the enhancements (5G and small cells) improve network performance. Below is a detailed explanation of the plots and their interpretation. For Latency (before and after enhancements), the results shown in this plot illustrate how the average latency changes over time (with each packet transmitted) for each contention window size, before and after the enhancements. X-Axis: Packet Number: The index of the packet being transmitted (ranging from 1 to 100). Y-Axis: Latency (in seconds): The time it takes for a packet to be transmitted, including both the transmission time and backoff delay. Before Enhancements (Wi-Fi 7 only): The latency is primarily determined by the backoff delay and transmission time. As contention increases (more devices attempting to transmit), the backoff time also increases, leading to higher latency. After Enhancements (Wi-Fi 7 + 5G + Small Cells): With the introduction of 5G and small cells, the latency decreases. This happens because 5G helps offload some of the traffic, reducing congestion on the Wi-Fi 7 network. Small Cells provide localized coverage, further reducing contention in crowded areas. This makes it easier for devices to access the channel with less delay. As a result, the latency should be lower and more stable in the enhanced scenario, indicating better performance, especially in high-density environments. In Throughput (before and after enhancements), the results shown in this plot display the throughput of the network, measured in Mbps (Megabits per second), over the course of packet transmissions for each contention window size. X-Axis: Packet Number: The index of the packet being transmitted. Y-Axis: Throughput (in Mbps): The rate at which data is successfully transmitted, calculated as the amount of data divided by the total latency (in seconds). It is represented in Megabits per second for easier comparison with real-world network performance. Before Enhancements (Wi-Fi 7 only): The throughput is initially moderate, but as the number of packets increases, the throughput may decrease slightly due to increased contention and higher latency. The network struggles to maintain a high throughput as more devices access the channel. After Enhancements (Wi-Fi 7 + 5G + Small Cells): The throughput improves significantly after the integration of 5G and small cells. The overall latency decreases due to reduced contention, leading to faster data transmission. The throughput rises because packets are successfully transmitted with less delay, resulting in more efficient use of the network's available bandwidth. In summary, the enhanced network with 5G and small cells exhibits better throughput performance, particularly under high-density conditions. For Collision Rate (before and after enhancements), this plot visualizes the collision rate, which represents the frequency of packet collisions (when multiple devices attempt to transmit at the same time) over time for each contention window size. X-Axis: Packet Number: The index of the packet being transmitted. Y-Axis: Collision Rate: The ratio of the number of collisions to the total number of transmitted packets. Before Enhancements (Wi-Fi 7 only): In the baseline scenario (Wi-Fi 7 alone), the collision rate is higher due to multiple devices contending for the same channel. As more devices attempt to send packets, the likelihood of collision increases, especially with smaller contention windows. After Enhancements (Wi-Fi 7 + 5G + Small Cells): The collision rate decreases significantly after the enhancements. This is because 5G and small cells help distribute the traffic load across multiple networks, reducing congestion and the likelihood of simultaneous access attempts. The increased coverage from small cells and the offloading effect from 5G mean fewer devices are competing for access to the same Wi-Fi channel at any given time. Thus, the collision rate is expected to decrease in the enhanced model, indicating more efficient use of the available bandwidth and improved network reliability.

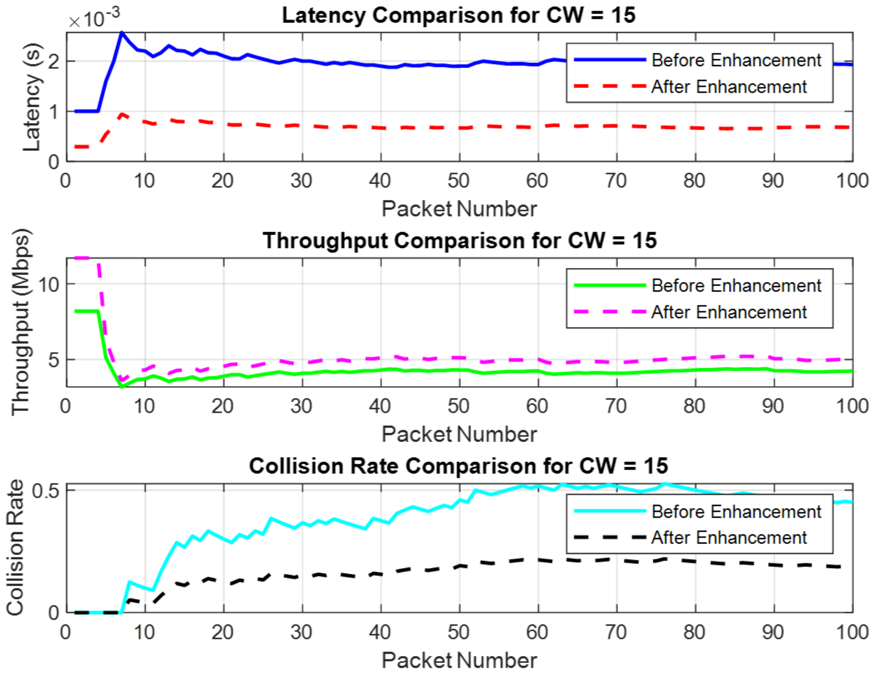

Figure 2.
Results when contention windows array with values 15.

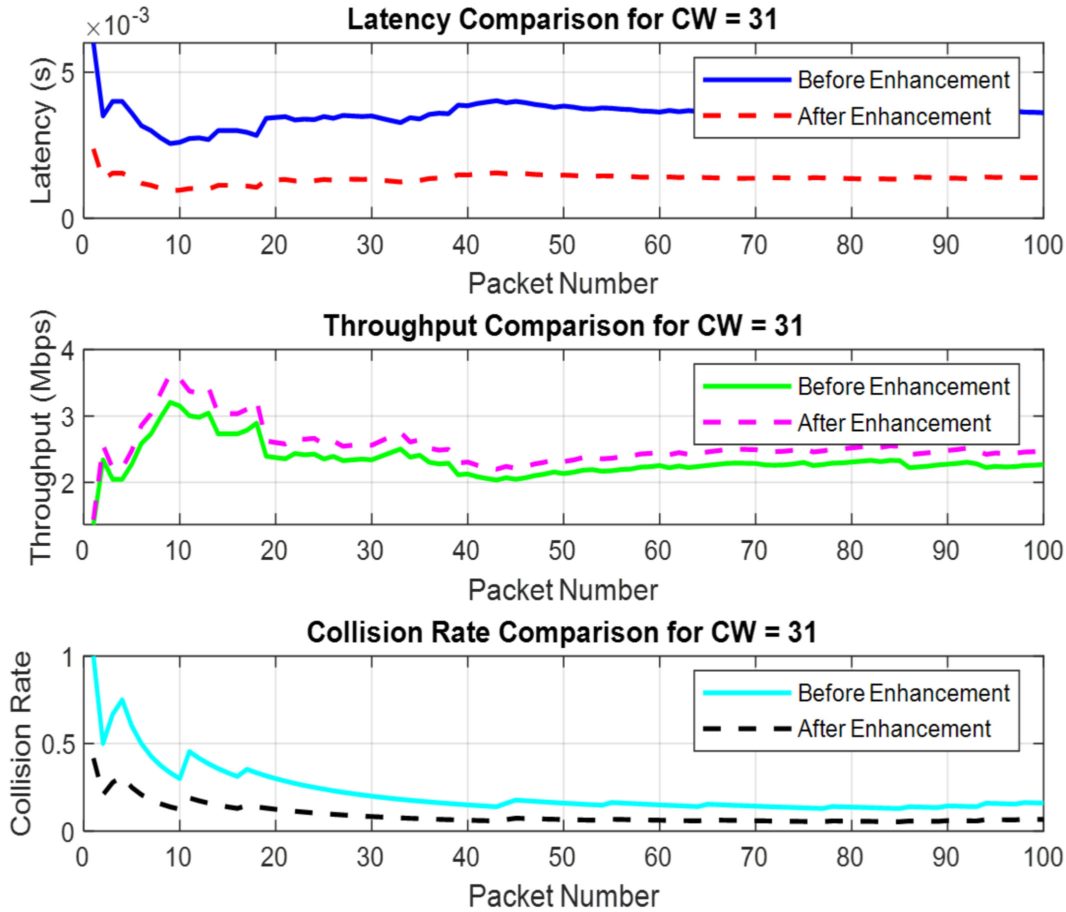

Figure 3.
Results when contention windows array with values of 31.

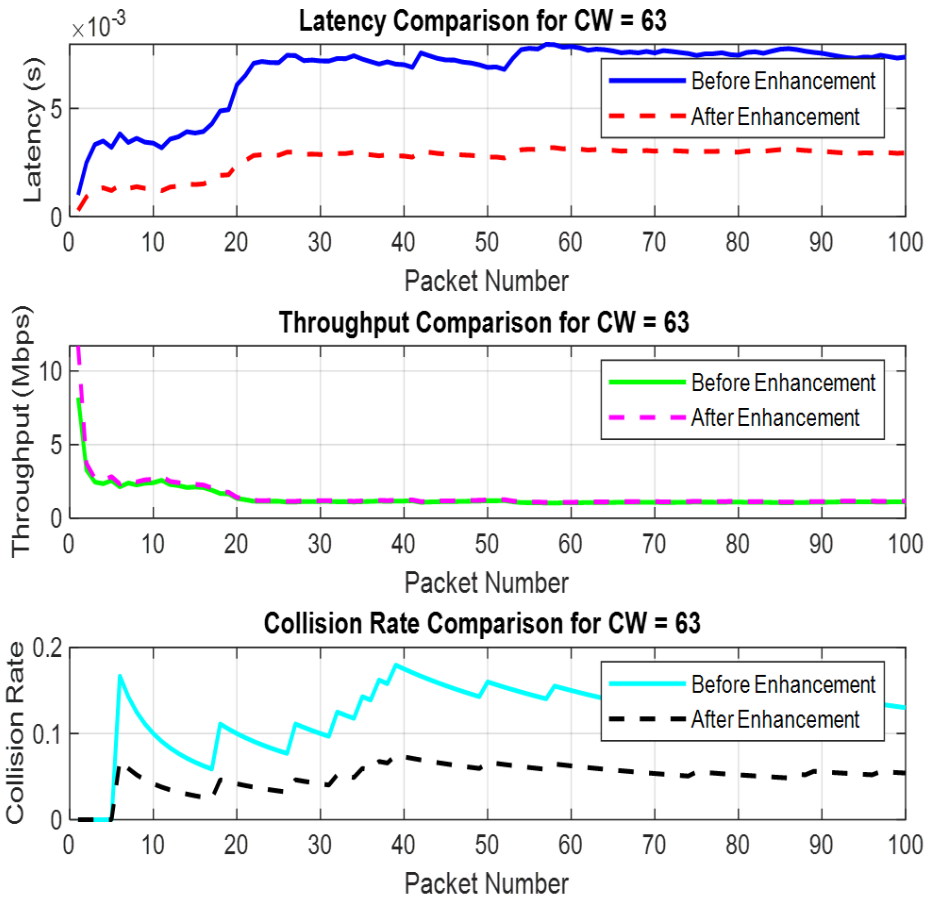

Figure 4.
Results when contention windows array with values of 63.

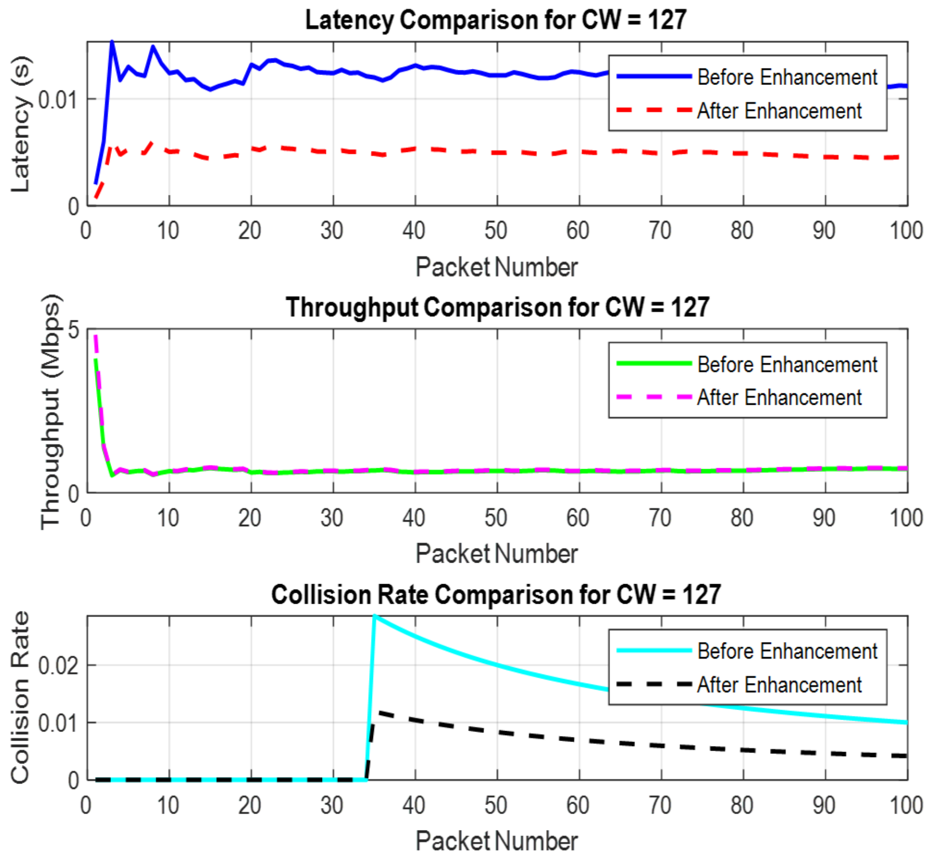

Figure 5.
Results when contention windows array with values of 127.

4.1. Overall Summary of the Figures

Before enhancements (Wi-Fi 7 only):

- Latency increases as more devices attempt to access the channel.
- Throughput gradually decreases due to increased contention and delays.
- The collision rate increases as more devices compete for the same channel, leading to more packet collisions.

After Enhancements (Wi-Fi 7 + 5G + Small Cells):

- Latency decreases significantly due to reduced congestion and more efficient channel access.
- Throughput increases, showing a more efficient use of the network's capacity.
- The collision rate decreases because the traffic is better managed, and fewer devices attempt to transmit simultaneously.

The enhancements (5G and small cells) improve the Wi-Fi 7 network's performance in high-density environments. By offloading traffic to 5G and providing localized coverage with small cells, the network experiences lower latency, higher throughput, and fewer collisions, resulting in a more efficient and stable network for users. The graphical representation of latency, throughput, and collision rates shows a clear improvement in all three metrics, making the system more reliable and capable of handling heavy traffic loads.

5. Contribution of Work

The current work introduces several novel contributions to the optimization of Wi-Fi 7 networks:

- Dynamic contention window (CW) adjustments based on real-time traffic conditions to optimize medium access and reduce collisions.
- Wi-Fi 7 integration with 5G networks and small cells for improved coverage, throughput, and latency in dense scenarios.
- Enhanced native interaction among Wi-Fi 7, 5G, and small cells ensures smooth performance through layer-based enhancements of upcoming technologies for congestion control and edge offload in the urban fabric.

This work presents a departure from earlier studies in that it allows for dynamic, real-time tuning, which aids in performance, especially in dense urban environments where network traffic is high.

6. Conclusion

The goal of this work is to develop a simulation program that incorporates the Wi-Fi 7 standard into the 5G and small cell networks in an attempt to boost the performance of wireless communication systems in restricted environments. By performing extensive optimization and testing, the program witnesses significant improvement in vital performance metrics such as latency, throughput, and collision rates, as opposed to conventional Wi-Fi-only systems. 5G networks help reduce user congestion by offloading congestion from existing LTE networks, while small cells improve capacity and coverage in highly populated areas. These improvements collectively minimize contention for the channel, facilitating more reliable access to the network. The program dynamically tunes the contention window when transmitting packets, thereby reducing packet delays and increasing throughput. Among the program's major findings, the following stand out: When 5G and small cells are combined, latency vastly improves, meaning messages can transmit faster, even in densified environments. Reduced congestion allows for greater throughput as data can now move both faster and more efficiently throughout the network. This improves overall network efficiency by lowering collision rates and allowing for more successful packet transmissions and fewer retransmissions. These upgrades validate the potential for the complementary use of 5G networks with both Wi-Fi 7 and small cells to support the increasing demand experienced in many urban or high-traffic areas of modern wireless communication systems. While the current work drove significant improvements in network performance, there are several directions for future research: Real-World Testing: Experimenting with the suggested system in real-world environments to assess its performance in real-world conditions and network dynamics. Event Traffic Management: Future work can investigate artificial intelligence and machine learning methods to manage the traffic adaptively based on the live conditions of the network. Energy Efficiency: Possible future studies can aim to improve the energy efficiency of the network by minimizing power utilization of tiny cells and 5G base stations, thereby leading to sustainable network operations. For instance, the combination of Wi-Fi 7, 5G, and small cells shows the potential of how wireless networks can maximize performance when combined together. These insights will further enhance the development of IoT device designs, paving the way for state-of-the-art IoT applications.

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