Modeling the Performance of Wi-Fi Networks Using 5GHz, 6GHz, and Multi-Link Operation

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***Abstract*— The rapid expansion of wireless devices and the growing demand for high-speed data have made Wi-Fi networks indispensable in modern communication. However, traditional Wi-Fi networks operating in the 2.4GHz and 5GHz bands face challenges in high-density environments due to limited spectrum and increased interference. Recent advancements, such as the introduction of the 6GHz frequency band in Wi-Fi 6E and Wi-Fi 7, offer additional spectrum to alleviate congestion and improve performance. Additionally, Multi-Link Operation (MLO), introduced in Wi-Fi 7, allows devices to simultaneously operate on both the 5GHz and 6GHz bands, aggregating bandwidth to increase throughput and reduce delays. This study investigates the performance of Wi-Fi networks utilizing 5GHz, 6GHz, and MLO under varying STA densities. Using a simulation model, the study evaluates the impact of STA density on network performance, focusing on throughput and delay. The network's dynamic behavior, including transmission attempts, collisions, and backoff stages, is modeled using a Markov Chain to accurately simulate real-world transmission conditions. The results demonstrate that while 6GHz and MLO provide significant performance improvements, particularly in high-density environments, managing the interactions between the frequency bands and the challenges of interference and load balancing is crucial. The findings of this study offer valuable insights into how MLO can enhance network performance and reliability, contributing to the development of future Wi-Fi systems.**

Keywords*— Multi-Link Operation, Markov Chain, wireless networks

I. INTRODUCTION

The rapid growth of wireless devices and the increasing demand for high-speed data transmission have made Wi-Fi networks an essential component of modern communication. These networks are integral to a wide range of applications, from personal internet access and multimedia streaming to critical business operations and industrial automation. As Wi-Fi technology evolves, it faces significant challenges, particularly in high-density environments with a large number of connected devices. These high-density scenarios, such as urban areas, offices, and public venues, often suffer from network congestion, leading to degraded performance marked by low throughput, high latency, and frequent packet loss [1]. A major limitation of traditional Wi-Fi networks, especially those operating in the 2.4GHz and 5GHz bands, is the limited available spectrum. As the number of devices using these bands increases, so does the competition for available channels, which leads to interference and reduced network efficiency. This issue is compounded in environments where many devices operate in close proximity, creating additional congestion and interference. Such performance degradation negatively impacts applications that require high bandwidth or low latency, such as video conferencing, real-time gaming, and industrial control systems. To address these challenges, recent advancements in Wi-Fi technology have introduced the 6GHz frequency band [2], available in Wi-Fi 6E [3] and Wi-Fi 7 [4]. The introduction of the 6GHz band aims to alleviate congestion by providing additional spectrum and enabling the use of more available channels. This reduces interference in the 5GHz band and significantly improves throughput, making it especially valuable in high-density environments where traditional Wi-Fi networks struggle to maintain efficiency. However, the performance of the 6GHz band is still constrained by factors such as network congestion, interference between devices, and the complexities of managing a larger spectrum. In addition to expanding spectrum, Multi-Link Operation (MLO), introduced in Wi-Fi 7 [5],[6], is a key advancement that enhances Wi-Fi performance. MLO allows devices to operate on both the 5GHz and 6GHz frequency bands simultaneously, aggregating their bandwidth to increase throughput and reduce delays. This simultaneous use of multiple bands can mitigate congestion on a single band and offer more reliable connectivity, particularly in environments with many devices competing for bandwidth. While MLO holds great potential for improving network performance, it also introduces new challenges in managing interference, load balancing, and coordination between the two frequency bands. The interactions between 5GHz and 6GHz in a real-world environment are complex and require effective management to fully realize the benefits of MLO. Despite the promising advantages of MLO, the exact performance improvements in terms of throughput and delay under varying network conditions have yet to be fully explored. This is particularly important in high-density environments, where congestion, interference, and STA density significantly impact network performance. While much research has been conducted on 5GHz and 6GHz individually, and some studies have examined aspects of MLO, the combined effect of these two frequency bands operating simultaneously remains underexplored.

This study aims to bridge this gap by simulating the performance of Wi-Fi networks using 5GHz, 6GHz, and MLO, with a particular focus on throughput and delay. The network's dynamic behavior, including collisions, backoff stages, and resulting delays, is modeled using a Markov Chain [7], which accurately represents the random nature of transmission attempts in a shared wireless medium. By comparing the performance of the network under different conditions 5GHz, 6GHz, and MLO this study seeks to assess the practical benefits of MLO in high-density environments. The primary objectives of this study are to analyze the impact of STA density on throughput and delay, evaluate the

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performance improvements offered by MLO, and investigate the effects of combined frequency band operation in Wi-Fi networks. Furthermore, this research aims to provide insights into how MLO can be integrated into existing Wi-Fi networks to enhance capacity and reliability. The results of this study are expected to contribute to the design of future Wi-Fi systems, particularly those utilizing the 6GHz band and MLO, to meet the growing demands of high-density wireless environments.

II. Network Environment

In this study, the performance of Wi-Fi networks is evaluated through simulations involving stations (STAs) and access points (APs). The network environment is designed to reflect realistic conditions, considering key parameters such as the number of STAs, the number of APs, and the distance between each STA and its corresponding AP. Additionally, the network configuration incorporates both the 5GHz and 6GHz frequency bands, with a focus on evaluating the performance of MLO.

A. Network Configuration

The network configuration consists of several STAs and APs. In this study, each STA communicates with an AP, and the performance is evaluated across varying numbers of STAs. The density of STAs in the network ranges from 10 to 160 in increments of 10, allowing for a comprehensive analysis of how increasing network load influences key performance metrics such as throughput and delay. By varying the number of STAs, the study investigates the effects of STA density on network performance under different conditions. To simulate a more realistic environment, a fixed number of 5 APs are deployed within the network. These APs are evenly distributed across the environment, with each STA connecting to the AP that is closest to it. By maintaining a constant number of APs, the study isolates the impact of changing STA density on throughput and delay, allowing for a focused analysis of these factors without introducing variations in the number of APs. Additionally, the distance between each STA and its assigned AP is randomly generated within a range of 20 to 100 meters. This random distribution reflects the natural variability that occurs in real-world settings, such as urban or indoor environments, where the physical separation between users and APs can differ significantly. By modeling the network in this manner, the study simulates the dynamic conditions often encountered in real-world Wi-Fi deployments, where both the spatial arrangement of APs and the distribution of users are not uniform, adding to the complexity of the performance evaluation.

B. Frequency Bands

In this study, two primary frequency bands, 5GHz and 6GHz, are considered to evaluate their performance in terms of throughput and delay. The 5GHz frequency band is widely used in modern Wi-Fi networks, while the 6GHz band, introduced with Wi-Fi 6E and Wi-Fi 7, is relatively new and offers additional spectrum for higher throughput and reduced interference. By comparing these two frequency bands, the study aims to assess their individual performance, as well as the combined benefits of MLO, which aggregates the throughput of both frequency bands. The 5GHz band has become a cornerstone of modern Wi-Fi technologies, providing higher data rates compared to the 2.4GHz band. However, it suffers from a shorter range due to increased path loss, which makes it more susceptible to physical obstructions and environmental factors. This band is widely used for high-speed data transmission, but its coverage area can be limited in densely populated or obstructed environments. The 6GHz band, introduced with Wi-Fi 6E, provides an expanded spectrum that can support higher data rates with less interference compared to the 5GHz band. This additional spectrum allows for more channels, reducing congestion and improving overall network performance, especially in environments with many devices. The 6GHz band is expected to enhance the capacity and efficiency of Wi-Fi networks, particularly in high-density scenarios. In addition to evaluating the individual performance of the 5GHz and 6GHz bands, the study also investigates the potential benefits of MLO. MLO enables simultaneous communication on both the 5GHz and 6GHz bands, aggregating the throughput from each band. This approach could improve overall network performance by increasing bandwidth availability and reducing congestion, especially in high-traffic environments.

C. Markov Chain for State Transitions

In order to model the dynamic behavior of the network and account for the effects of contention, backoff, and collisions. Markov Chain models are used to simulate the state transitions of each STA. Each STA's behavior is modeled using a state machine, where each state represents a specific phase of communication (e.g., waiting to transmit, transmitting, or backoff due to collision). The transition probabilities between these states are determined by the parameters of the network, including the number of STAs, the level of congestion, and the likelihood of collisions.

States: The system includes several states, such as:

- Idle state: The STA is idle, waiting for a transmission opportunity.
- Transmission state: The STA is transmitting data to the AP.
- Backoff state: The STA is in backoff due to a collision or waiting for a clear channel.

The transition probabilities between these states are defined by a transition matrix, which specifies the likelihood of moving from one state to another based on the current network conditions. These probabilities are influenced by factors such as the number of STAs, the transmission success rate, and the probability of collision.

III. Methodology

This study employs a simulation model to evaluate the performance of Wi-Fi networks under varying conditions, focusing on throughput, delay, and the impact of dynamic network behavior, which is influenced by a Markov Chain model. The methodology integrates the calculation of key performance metrics, such as SNR, throughput, and delay, with the use of the Markov Chain to model the transitions between different states that represent transmission attempts, backoff, and collision events within the network. The simulation is set up to mimic a typical Wi-Fi network environment consisting of multiple STAs and APs. The network is designed to handle varying numbers of STAs, with each STA being assigned to the nearest AP, and the distances between the STAs and APs being randomly distributed. This configuration is representative of a real-world network where the physical layout and user distribution can vary significantly. The key parameters used in the simulation are the number of STAs, the number of APs, and the frequency bands used, which include 5GHz and 6GHz. The performance of the network is evaluated through the calculation of throughput and delay while incorporating the dynamic transitions of each STA using the Markov Chain model. To model the network's behavior, a Markov Chain is applied to simulate the transitions between the various states of each STA. The network is modeled using three primary states: the Idle state, where the STA is waiting for an opportunity to transmit; the Transmission state, where the STA is actively transmitting data; and the Backoff state, where the STA is in backoff due to a collision or waiting for a clear channel. The transition probabilities between these states are represented by a transition matrix, which dictates the likelihood of transitioning from one state to another based on the network conditions. The transition matrix can be expressed as:

$$P(i,j)=\begin{bmatrix} P(I,I) & P(I,Tr) & P(I,B) \\ P(Tr,I) & P(Tr,Tr) & P(Tr,B) \\ P(B,I) & P(B,Tr) & P(B,B) \end{bmatrix} \quad (1)$$

Where $P(i,j)$ represents the probability of transitioning from state i to state j, with the states being Idle (I), Transmission (Tr), and Backoff (B). The transition matrix reflects the changing probabilities of each STA's behavior based on the number of STAs in the network, the likelihood of collisions, and the channel availability. The key performance metrics used to evaluate the network's behavior include throughput and delay, both of which are affected by the Markov Chain model. Throughput (T) is a measure of the data rate that each STA can achieve. It is calculated based on the SNR, with the throughput increasing as the signal quality improves. The throughput is also influenced by the time each STA spends in the Backoff state due to collisions. The formula for calculating throughput is:

$$T=\frac{T_{\max}}{1+\log(\text{number of STA})}\times(1-\text{backoff time}) \quad (2)$$

In this equation, max throughput is the theoretical maximum throughput for the respective frequency band (100 Mbps for 5GHz and 120 Mbps for 6GHz). The term backoff time represents the time spent in the Backoff state due to collisions and network congestion, which reduces the overall throughput. Delay is another critical performance metric, representing the time it takes for data to be transmitted from the STA to the AP. Delay is inversely proportional to throughput, meaning that as throughput increases, the delay decreases. The delay is calculated as the inverse of the throughput:

$$\text{Delay}=\frac{1}{\text{Throughput}} \quad (3)$$

The collision probability is modeled using the Markov Chain by considering the likelihood of each STA moving into the Backoff state. As the number of STAs increases, the probability of collision also increases, leading to higher backoff times and reduced throughput. The collision probability is influenced by the number of STAs in the network, the current state of each STA, and the probability of moving to the Backoff state. The simulation also incorporates assumptions to simplify the modeling process.

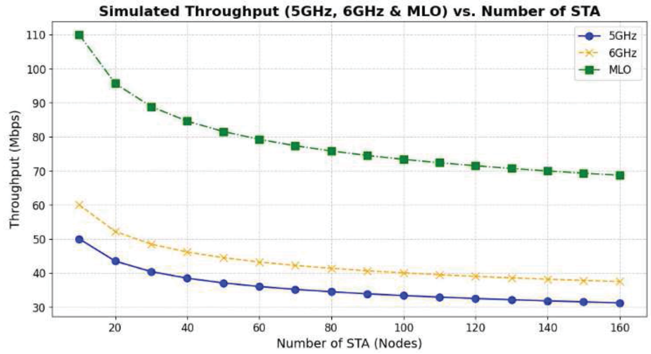

Fig.1. Saturation throughput for 5GHz, 6GHz, and MLO.

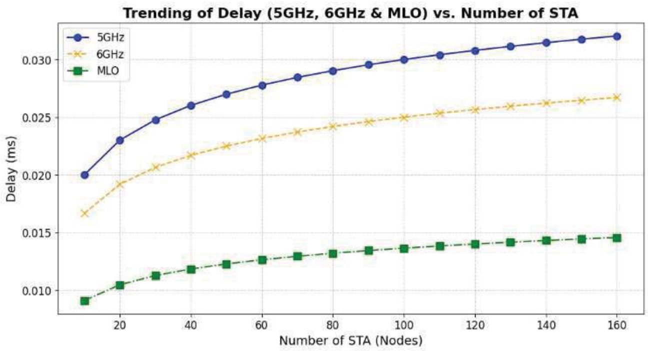

Fig. 2. Saturation delay for 5GHz, 6GHz, and MLO.

Ideal conditions are assumed, with no external interference or noise, other than the path loss caused by distance and frequency. The number of APs is kept fixed at 5 to isolate the effects of STA density on performance. Additionally, all STAs are treated equally, with no priority given to any individual STA.

IV. RESULT AND DISCUSSION

In this section, we present the results of the simulation for the throughput and delay of the Wi-Fi network under varying STA densities, with a particular focus on the comparison between the 5GHz, 6GHz, and MLO scenarios. The simulation results are analyzed to determine how network performance is affected by STA density and the use of different frequency bands.

The simulated throughput results for 5GHz, 6GHz, and MLO are presented in Fig. 1, where the throughput is shown as a function of the number of STAs. As observed, the throughput decreases with an increasing number of STAs, regardless of the frequency band used. This decrease is primarily due to the increasing contention for the shared wireless medium as more devices join the network. For the 5GHz band (blue line), throughput is significantly higher at low STA densities but drops more sharply as the number of STAs increases. This is due to the limited bandwidth of the 5GHz band and the increasing collisions between stations as the network becomes more congested. The 6GHz band (orange line), which offers additional spectrum, also shows a decline in throughput as the number of STAs increases. However, the throughput in the 6GHz band remains higher compared to 5GHz, even as the number of STAs increases, due to the broader available spectrum and less congestion. When MLO is enabled (green line), throughput is improved compared to the individual bands, as MLO aggregates the throughput from both 5GHz and 6GHz. This leads to a more stable throughput, which is less affected by the increase in STA density. However, as the number of STAs continues to rise, the throughput for MLO also decreases, but at a slower rate than for the individual bands. This result highlights the benefits of using MLO to increase network capacity, especially in high-density environments where the additional spectrum from 6GHz and the combined throughput from both bands help mitigate congestion.

Fig. 2 shows the trend of delay as a function of the number of STAs for 5GHz, 6GHz, and MLO. As expected, the delay increases with the number of STAs, which is indicative of the network becoming more congested as more devices contend for access to the wireless medium. For the 5GHz band, the delay increases significantly as the number of STAs increases. This is due to the higher likelihood of collisions in a crowded network, leading to longer backoff times and higher delays. The 6GHz band also experiences an increase in delay with increasing STA density, but the delay is lower compared to the 5GHz band. The additional spectrum in 6GHz reduces congestion, resulting in fewer collisions and lower delays for a given number of STAs. With MLO, the delay increases at a slower rate compared to the individual frequency bands. The aggregation of 5GHz and 6GHz helps to reduce the overall delay, especially in networks with higher STA densities. However, the delay still increases as the number of STAs rises, although it remains lower than in the 5GHz and 6GHz only scenarios. These results demonstrate that MLO can provide better network responsiveness and lower delays, particularly in dense network scenarios. The reduction in delay is beneficial for real-time applications that require low latency, such as video streaming and online gaming.

The results highlight the impact of backoff and collisions on network performance. As the number of STAs increases, both the probability of collisions and the time spent in backoff increase. This leads to a reduction in throughput and an increase in delay. The Markov Chain model used in the simulation accurately reflects the random nature of collision events and backoff stages, with the network moving between states of idle, transmission, and backoff based on the conditions of the channel. In dense network environments, where the number of STAs is high, the likelihood of collisions increases significantly, leading to longer backoff times and reduced throughput. This explains the steep decline in throughput and the corresponding increase in delay observed in the simulations as the number of STAs increases.

Although the results presented in this study provide valuable insights into the performance of 5GHz, 6GHz, and MLO in Wi-Fi networks, there are several limitations in the simulation setup that should be acknowledged. One of the key limitations is that the simulation was conducted using separate models for 5GHz and 6GHz, with MLO being treated as an aggregate of these individual simulations. While this approach offers a simple method to evaluate MLO, it does not fully capture the real-world complexity of multi-link operation. In reality, MLO requires simultaneous operation of both frequency bands, and the effects of using both bands together are more intricate than the sum of their individual performances. When 5GHz and 6GHz are used simultaneously, there are additional factors to consider, such as interference between the two bands, load balancing, and channel aggregation, which were not accounted for in the separate simulations. The current simulation assumes that the 5GHz and 6GHz bands operate independently, which simplifies the modeling process but overlooks the interaction between the two frequency bands. In a real-world MLO scenario, the coordination between the bands would have to be carefully managed to optimize throughput and minimize delay, especially in high-density environments. This would introduce more complexity into the simulation, as it would need to model how each STA interacts with both frequency bands simultaneously, accounting for factors like congestion and interference on each band, as well as the effect of MLO on the overall network load.

V. Conclusion

This study evaluated the performance of Wi-Fi networks using 5GHz, 6GHz, and MLO, focusing on throughput and delay under varying STA densities. The results demonstrated that while 5GHz throughput decreases significantly as the number of STAs increases, the 6GHz band provides higher throughput due to additional spectrum. MLO aggregates the benefits of both bands, improving throughput and reducing delay, particularly in high-density environments. However, the simulation modeled 5GHz and 6GHz separately, whereas in real-world scenarios, MLO requires simultaneous operation of both bands. The interactions between the two bands, such as interference and load balancing, were not fully captured. Future work should integrate these factors for a more realistic simulation of MLO performance.

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