Protecting the Preamble: An Adaptive Scheduling Approach for Reliable Multi-Link Operation*

Ye-Sin Kim, Jin-Min Lee and Il-Gu Lee†

Sungshin Women's University, Seongbuk-gu, Korea
{20220965, iglee}@sungshin.ac.kr, csewa56579@gmail.com,

Abstract

The recent proliferation of Internet of Things and real-time streaming devices has spurred the widespread adoption of Multi-Link Operation (MLO) technology, which allows multiple wireless links to operate simultaneously in a shared space. Although MLO improves throughput and delivery reliability through parallel transmissions, interference from adjacent channels can corrupt the preamble, a component crucial for reception synchronization. This corruption forces the entire frame to be discarded and retransmitted, and in cases of intentional interference, it can lead to denial-of-service attacks. To address this vulnerability, the present study proposes an adaptive scheduling technique that protects the preamble by deferring transmissions when a collision with another preamble is anticipated. Before transmitting, a link determines if a neighboring link is sending its preamble. If a collision is anticipated, the transmission is briefly delayed to prevent interference. Experimental results under various traffic loads, frame lengths, and maximum retransmission counts demonstrate that the proposed technique reduces unnecessary retransmissions and decreases the average delay by up to 38.8% compared to existing methods.

Keywords: Multi-Link Operation (MLO), Adjacent Channel Interference (ACI), Preamble Protection, Latency Reduction

1 Introduction

The proliferation of real-time services, such as those for Internet of Things (IoT) devices, drones, autonomous vehicles, and smart factories, has created dense environments where multiple wireless devices operate simultaneously. In these settings, relying on a single communication link increases transmission delays and retransmissions, significantly degrading service quality (Carrascosa-Zamacois et al. 2023). To address these challenges, IEEE 802.11be (Wi-Fi 7) introduced Multi-Link Operation (MLO) technology, which enables a single station (STA) to utilize multiple frequency bands in parallel, thereby enhancing throughput and delivery reliability. However, in real-world radio-frequency (RF) environments, the spectra of adjacent channels often spread and overlap, causing adjacent channel

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† Corresponding author

interference (ACI) (George et al. 2023). This interference increases retransmissions and degrades overall network throughput. A wireless frame consists of two main parts: a preamble and a data section. The preamble, which allows the receiver to synchronize with the transmitter's signal, is highly sensitive to even minor interference and is difficult to recover once corrupted. By contrast, the data segment includes error correction codes capable of recovering from a certain level of signal error. Consequently, damage to the preamble is far more detrimental, forcing the entire frame to be discarded and retransmitted and causing greater delays than damage to the data segment (Carrascosa-Zamacois et al. 2023). This vulnerability can also be exploited for malicious purposes. For instance, if an attacker intentionally occupies an adjacent channel or injects preamble signals with the intention to disrupt reception synchronization, the receiver may discard the entire frame, which could result in a denial-of-service (DoS) attack, posing significant security risks in applications demanding real-time performance and stability, such as autonomous driving, telemedicine, and industrial control systems (Sun. 2024). To mitigate this issue, this study proposes an interference-aware scheduling technique that protects the preamble in realistic interference environments. This technique enhances performance and serves as a proactive countermeasure against security threats, contributing to a more stable and reliable wireless communication environment.

The primary contributions of this study can be summarized as follows:

- Considering the accumulation of adjacent channel interference (ACI) in Multi-Link Operation (MLO) environments, we propose a scheduling technique that defers transmission when preamble segments overlap, thereby avoiding potential interference.

- Experiments applying realistic interference under various traffic loads, frame lengths, and retransmission conditions demonstrate that transmission failure occurs almost entirely when the preamble is damaged.

The remainder of this paper is structured as follows: Section 2 analyzes existing research on interference detection and avoidance. Section 3 describes the proposed adaptive scheduling technique as a solution to the preamble interference problem in MLO environments. Section 4 evaluates and analyzes the performance of the proposed and conventional techniques under various conditions. Finally, Section 5 concludes the paper.

2 Related Work

Several studies have investigated the enhancement of MLO performance, focusing on delay analysis, resource optimization, and dynamic channel allocation. However, these approaches often fail to adequately address preamble protection in realistic ACI environments.

Shen et al. (2024) experimentally compared various traffic distribution strategies to analyze the increased delay from link contention in MLO, an issue they noted had been insufficiently studied. Their primary contribution was a simulation-based technique for identifying scheduling factors that affect transmission delay. However, their investigation did not include control strategies for interference or preamble protection.

Taramit et al. (2023) proposed a Markov decision process (MDP)-based queuing model to reduce resource wastage and delays when traffic with varying priorities coexists in MLO environments. This model derives a theoretically optimal policy by assigning the best link for each traffic class. However, it has a key limitation in that it fails to account for transmission delays caused by link-to-link interference or preamble loss.

Lian et al. (2025) introduced a resource management technique incorporating dedicated channel guarantees and link-number limitations to address resource contention and starvation when multiple basic service sets (BSSs) use MLO simultaneously. Although this approach balances fairness and interference avoidance, it does not directly resolve preamble collisions, a fundamental cause of interference. It may lead to inefficient resource utilization owing to its link restrictions.

Jeknić & Kočan et al. (2023) lacked a definitive strategy to prevent preamble damage in realistic ACI environments. To address this gap, this study proposes an adaptive scheduling technique that delays transmission when preamble collisions are anticipated. The proposed method helps reduce unnecessary retransmissions and mitigate transmission delays. However, it has limitations such as physical layer dependency, increased scheduler complexity, and insufficient handling of preamble collisions.

In summary, although prior research has significantly contributed to MLO optimization, a critical gap remains in strategies that explicitly protect the preamble in realistic ACI environments. This study aims to address this gap.

3 Adaptive Scheduling Technique for Reliable MLO

This study proposes a scheduling technique based on preamble protection to enhance communication performance in Wi-Fi 7's MLO environment. The primary goal is to avoid interference during the critical preamble interval of a wireless frame.

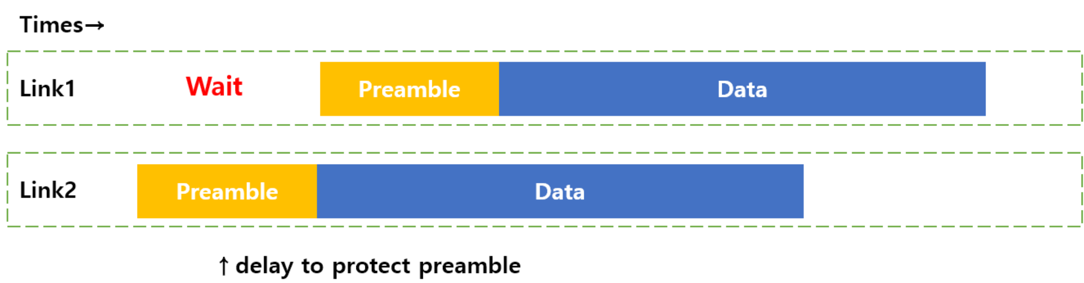

Figure 1: Time-domain illustration of the proposed preamble protection scheme

As illustrated in the conceptual diagram in Figure 1, the technique is designed to prevent preamble collisions when frames are transmitted simultaneously on two adjacent links (Link1 and Link2). A wireless frame consists of a preamble followed by a data section. The protection process works as follows: if Link1 detects that the adjacent Link2 is transmitting a preamble, it defers its own transmission. Once Link1 confirms that Link2 has finished its preamble and begun sending its data segment, Link1 initiates its own transmission. This strategic delay prevents the two sensitive preambles from corrupting each other.

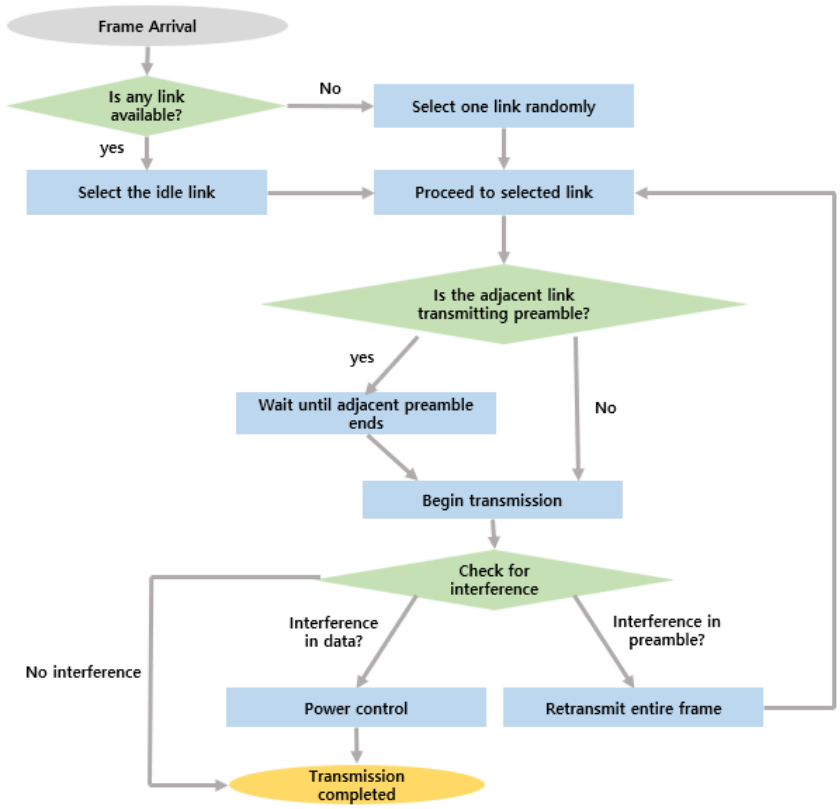

Figure 2: Flowchart of the proposed preamble interference avoidance algorithm

Figure 2 provides a flowchart illustrating the entire operational process of this algorithm. The process begins when a new frame is generated, at which point the transmitting node (AP or STA) checks for an available link and selects an idle one if possible. After securing a link, the node assesses the status of the adjacent link to adjust its transmission timing. If the adjacent link is transmitting a preamble, the node delays its own transmission until that preamble is complete, thereby preventing a collision. Conversely, if the adjacent link is idle or already transmitting data, the node can begin its transmission immediately. Once the transmission is initiated, the node monitors for interference. If interference corrupts the preamble, synchronization fails, and the entire frame must be retransmitted. By contrast, if interference affects the data segment, the node mitigates this by adjusting transmission power, allowing the receiver to recover the data without a retransmission. Any frame that requires retransmission is returned to the initial link selection phase to repeat the procedure. This entire process is designed to minimize retransmissions by prioritizing the protection of the vulnerable preamble.

4 Performance Evaluation

4.1 Evaluation Environment

To validate the performance of the proposed scheduling technique, we conducted simulation-based experiments using MATLAB (The MathWorks, Inc. 2024). The simulation environment was designed to model an MLO scenario assuming that communication would occur over adjacent channels, even in the presence of ACI. Specifically, Link1 was configured to use Channel 36 in the 5 GHz band, whereas Link2 used the adjacent Channel 40. The common simulation conditions are summarized in Table 1.

Features	Contents
Number of transmitted frames in AP	1000
Number of transmitted frames in STA	1000
Preamble Length	200 bits
Data Length	1,000 bits
frame generation rate	0.115 ms
Preamble Interference Threshold	Retransmit the entire frame
Data Interference Threshold	Recoverable by power control

Table 1: Simulation parameters for the evaluation environment

The simulation ran for a total of 2,000 frames, with 1,000 frames transmitted by the AP and STA. Each frame consisted of a 200-bit preamble and data section ranging from 500 to 1,500 bits, with an average frame length of approximately 1,200 bits. Frames were generated at a fixed interval of 0.115 milliseconds (ms) and transmitted at a constant rate of 24 Mbps, resulting in an average transmission time of approximately 50 microseconds (μs) per frame. A critical parameter of the simulation was interference handling: if interference occurred during the preamble, the entire frame was retransmitted; if interference affected the data section, it was assumed to be recoverable through power control, and no retransmission was required.

The experiments compared the performance of the proposed technique against two conventional scheduling methods: Round-Robin and Random. Each method differs in its approach to link selection, collision avoidance, and backoff mechanisms. A detailed comparison is provided in Table 2.

Scheduling Technique	Link Selection Rule	Key Characteristics
Round-Robin	The transmitting node (AP or STA) selects links in a fixed sequential order (e.g., AP: Link1 → Link2, STA: Link2 → Link1).	- Frames must be transmitted in the predetermined order; new frames wait for the previous one to finish- Ensures fair and balanced link usage (Shen et al. 2024).
Random	Selects a link randomly when a frame arrives.	- Before transmitting, it checks the adjacent link and defers its transmission if a preamble is detected.
Proposed	Selects the least busy (idle) link available.	- Manages data-segment interference with power control to avoid retransmissions - Achieves lower average delay, especially under heavy traffic.

Table 2: Comparison of the proposed and conventional scheduling techniques

The conventional Round-Robin method assigns links in a fixed, sequential order determined by the transmitting node (AP or STA). For instance, an AP transmits using the sequence Link1→Link2, whereas a STA uses the reverse order, Link2→Link1. A crucial constraint of this method is that frames must be transmitted in this predetermined sequence. Therefore, a subsequent frame must wait if the preceding one is still being transmitted. This approach ensures a fair and balanced utilization of system resources (Zhang et al. 2024). By contrast, the Random allocation method selects a transmission link at random upon each frame's arrival. However, if the selected link is already in use, it becomes temporarily unavailable, and the node must wait until the link becomes idle before it can transmit (Shen et al. 2024). The proposed technique is a more adaptive scheduling method that considers both link congestion and the risk of preamble collision. When a frame arrives, the transmitting node first checks for and prioritizes an idle link. Before sending, it verifies the status of the adjacent link. If the adjacent link is transmitting a preamble, the node briefly delays its own transmission to avoid a collision. If this timing adjustment fails and interference corrupts the preamble, the entire frame is retransmitted. Conversely, if interference occurs during the data segment, the node adjusts its transmit power to a level that allows for data recovery, thereby avoiding a retransmission.

4.2 Evaluation Results and Analysis

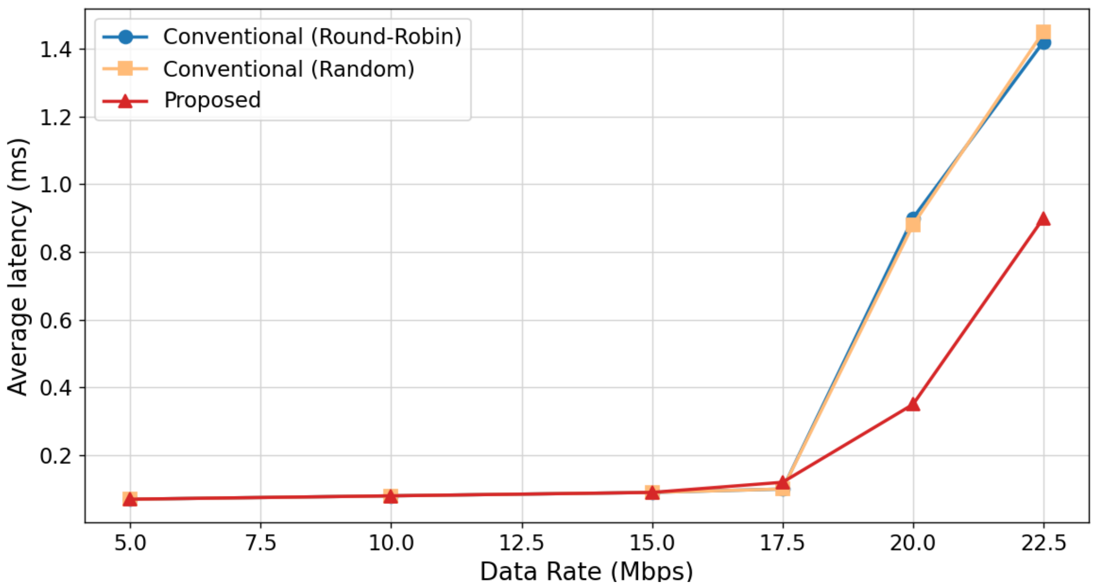

Figure 3: Average latency (ms) as a function of data rate (Mbps)

Based on an analysis of 1,000 repeated experiments for each condition, the evaluation results demonstrate the proposed technique's superior performance across various metrics. As illustrated in Figure 3, which shows the relationship between latency and data rate (megabits per second, Mbps), all three techniques performed similarly in the low data rate range, with latencies ranging from 0.07 to 0.08 ms. However, as the data rate approached 22.5 Mbps, the average delay for the Round-Robin and Random methods increased sharply to 1.45 and 1.47 ms, respectively. By contrast, the proposed technique maintained a significantly lower delay of approximately 0.9 ms, representing a reduction of 37.9% and 38.8% compared to the Round-Robin and Random methods, respectively. This advantage is attributed to the technique's prioritization of preamble collision avoidance, as data-segment interference can be recovered by adjusting transmit power, thereby mitigating the need for costly retransmissions as throughput increases.

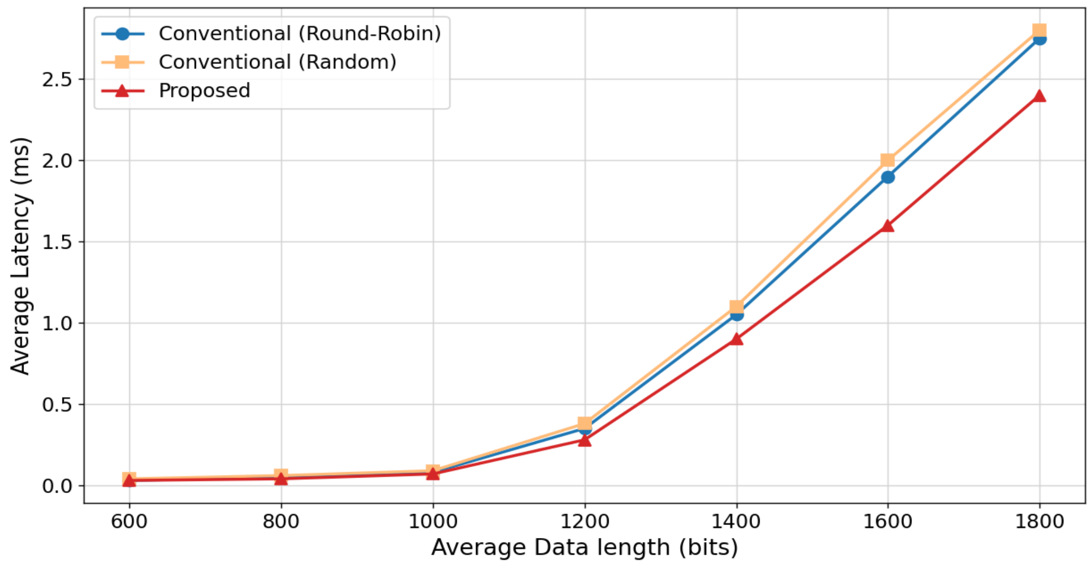

Figure 4: Average latency (ms) as a function of average data length (bits)

Similarly, Figure 4 shows that while the average delay for all methods increased with data length, the effect was more pronounced for the conventional algorithms. As preamble collisions accumulated, the delay for Round-Robin and Random increased from 2.6 to 2.7 ms when the data length reached 1,800 bits. By successfully avoiding these collisions and making data interval interference recoverable, the proposed technique achieved an average delay of just 2.4 ms under identical conditions. This represents a performance improvement of up to 15.3%, demonstrating its ability to maintain a lower delay in large-capacity data transmission environments.

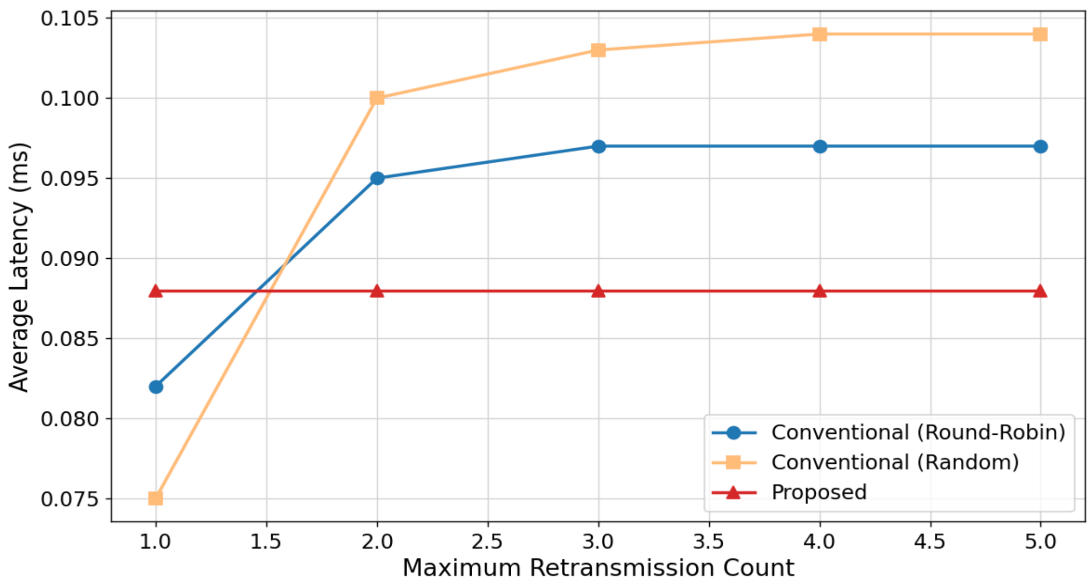

Figure 5: Average latency (ms) as a function of the maximum retransmission count

Finally, as illustrated in Figure 5, the average delay for each method was analyzed as a function of the maximum retransmission count, with results derived from 1,000 repeated experiments. For the Round-Robin configuration, the mean delay exhibited a consistent upward trend from 0.058 to 0.096 ms as the retransmission count increased, after which it stabilized. The Random method experienced a steeper delay increase owing to collision accumulation, reaching 0.10 ms at a maximum retransmission count of two before stabilizing. By contrast, the proposed technique prevented unnecessary full retransmissions by avoiding preamble collisions and recovering from data interference by adjusting transmit power. Consequently, as the retransmission count was raised from one to two, its delay only temporarily increased to 0.088 ms before stabilizing, demonstrating consistent performance. This result demonstrates the efficacy of the proposed technique in suppressing delay increases, even as the allowed retransmission count increases in a network environment.

These results confirm that the proposed technique reduces unnecessary retransmissions through preamble protection, thereby minimizing latency under various conditions.

5 Conclusion

The increasing proliferation of IoT devices, drones, and autonomous driving systems is making the wireless communication environment progressively more complex. Although Wi-Fi 7 introduced MLO to manage this complexity, real-world RF environments still suffer from ACI, which causes frame collisions and frequent retransmissions. This problem is particularly significant for the preamble interval, which is essential for receiver synchronization. If the preamble is corrupted by interference, the entire frame must be discarded, leading to performance degradation and creating vulnerabilities for DoS attacks via malicious interference. To mitigate these issues, this study proposed a scheduling technique based on preamble protection. This technique detects in real-time whether an adjacent link is transmitting its preamble and, if a collision is anticipated, temporarily delays its own transmission. This allows the data segments to be transmitted in parallel without risking preamble corruption. Our experimental results confirm that the proposed technique reduces average delay by up to 37.9%

compared to Round-Robin scheduling and up to 38.8% compared to Random scheduling. By effectively reducing unnecessary full-frame retransmissions, this technique enhances performance and serves as a preventative measure against security threats that exploit preamble vulnerability. Future research should analyze the impact of transmit power control on ACI strength in MLO environments with multiple STAs to develop additional interference mitigation strategies. Furthermore, future work will focus on strengthening the security resilience of the proposed scheme by conducting simulation experiments under defined threat models, including hostile preamble jamming and spoofing attacks.

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