Real-time Channel Adaptive Guard Interval Adjustment and Secondary Data Transmission Framework*

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Abstract

This paper proposes an adaptive GI management and secondary data transmission framework that reflects real-time channel characteristics to improve the inefficiency of fixed GI (Guard Interval) used to cope with channel delay spread in wireless communication systems. The proposed model

measures the channel delay spread in real time to calculate the minimum required GI for primary data protection. It enhances transmission efficiency by utilizing the remaining space within the fixed GI for secondary data transmission. Furthermore, it prioritizes primary data reliability by suspending secondary data transmission when channel conditions deteriorate. Simulation results on Wi-Fi 6 networks demonstrate that this technique achieves a 22% transmission efficiency improvement indoors and a 121.5% improvement outdoors while maintaining a 0% Bit Error Rate, completely suppressing Inter-Symbol Interference. Furthermore, it highlights potential security and privacy risks associated with the secondary data transmission segment and discusses future scalability through hardware implementation and integrated security measures.

1 Introduction

In recent wireless communication technologies, a Guard Interval (GI) is essential to prevent Inter-Symbol Interference (ISI) caused by multipath propagation. However, the fixed-length GI used conventionally does not sufficiently reflect the variability of the channel environment. Consequently, it is often set longer than the average delay spread actually required, leading to reduced transmission efficiency or inefficient resource utilization[1].

As next-generation wireless communication environments evolve toward 6G and high-frequency bands, higher transmission speeds and lower latency performance are increasingly demanded. Consequently, research on the efficient design and dynamic adjustment of GI is actively underway[2]. Particularly in UAV environments and various applications, including systems employing MU-MIMO-OFDM technology, GI optimization based on theoretical system capacity under varying channel conditions has been proposed. Some studies have suggested approaches that tolerate ISI with minimal GI while compensating for performance through equalization and precoding [3]. Furthermore, while the latest standards consider guidelines for selecting GI based on the environment, they cannot fully account for the diversity of real-world conditions [4].

* Proceedings of the 9th International Conference on Mobile Internet Security (MobiSec'25), Article No. 74, December 16-18, 2025, Sapporo, Japan.

As such, existing studies propose various approaches to improve the inefficiency caused by fixed GI settings[5]. However, most apply the same reliability level only to primary data, and the balancing issue between efficiently utilizing the surplus GI space existing in the channel's spare time and ensuring reliability has not been sufficiently addressed. Furthermore, there is a lack of system designs that flexibly respond to real-time changing channel conditions while ensuring efficient transmission of additional data.

This paper proposes an adaptive GI adjustment framework that measures channel delay spread in real time, adaptively adjusts and uses the minimum required GI, and utilizes the remaining space for additional data transmission. If the channel situation deteriorates and the required GI exceeds the fixed GI, additional data transmission is suspended to prioritize the reliability of primary data.

The main contributions of this paper are as follows.

- First, we enhanced transmission resource utilization efficiency by dynamically adjusting GI values based on real-time channel characteristics.
- Second, we propose an adaptive transmission technique that ensures reliability according to data importance.
- Third, we designed a frame structure that enables software-based implementation and offers high compatibility with standards and applicability.

This paper consists of six chapters. Section 2, Related Research, analyzes existing prior studies relevant to this research and identifies their limitations. Section 3, Proposed Model, details the design and operational principles of the adaptive GI adjustment and secondary data transmission framework. Section 4, Evaluation, presents and analyzes the experimental setup and results under various channel conditions. Section 5, Application Examples, presents specific use cases demonstrating the applicability of the proposed model. Finally, Section 6, Conclusion, summarizes the research and discusses its significance and future research directions.

2 Related Works

In recent high-speed wireless communication environments, GI optimization for OFDM (Orthogonal Frequency Division Multiplexing) systems has emerged as a critical research topic. GI is employed to prevent inter-symbol interference caused by multipath and to compensate for channel delay spread; however, excessive GI insertion degrades transmission efficiency and spectral efficiency [5]. Consequently, channel adaptive guard interval adjustment techniques have been proposed to improve the transmission efficiency and transmit the secondary data.

In 5G and Beyond 5G environments, fixed GI faces limitations due to the Doppler effect from vehicle mobility and variable channel characteristics. Consequently, adaptive GI and frequency-division subcarrier spacing adjustment techniques are being actively researched to address these challenges. In research to enhance communication quality and data rates in Vehicle-to-Everything environments, Hasan et al.[2] proposed an Adaptive Numerology Scheme (ANS) that simultaneously optimizes the subcarrier spacing and GI based on real-time channel state information and speed information. To validate ANS performance, spectrum efficiency, and BER (Bit Error Rate) were compared across multiple environments. Experimental results demonstrated a maximum 2.8-fold improvement in spectrum efficiency and a 2.56-fold increase in data rate compared to conventional methods. Furthermore, it maintained a BER below 0.001, demonstrating stability. However, consideration of high-frequency bands and performance verification were not conducted, and standardization application was not considered.

Meanwhile, research on channel access control and scheduling for strict QoS assurance has been conducted in IEEE 802.11ad/ay mmWave Wi-Fi environments. Sahoo et al.[4] proposed an admission control and Earliest Deadline First scheduling algorithm considering GT (Guard Time) overhead. This algorithm achieves stable scheduling and resource allocation efficiency in real system environments, including GT. Simulation results show that without reflecting GT overhead, Allocation Efficiency degrades by up to 35%, admission rate decreases by up to 25%, and delay and fragmentation increase by up to 30%. The proposed algorithm overcomes these issues, demonstrating more efficient and stable system performance. However, increased algorithm complexity and limited applicability to isochronous traffic remain areas for future improvement.

In another study, Sudhakar et al.[1] proposed an adaptive CP (Cyclic Prefix) selection technique based on wireless channel randomness for OFDM systems. By analyzing the signal strength of the channel's frequency response, it dynamically adjusts the optimal CP length per OFDM symbol, thereby improving spectrum efficiency and security. Experiments demonstrated a spectrum efficiency improvement of approximately 38% compared to the existing fixed CP, and BER performance improved by approximately 99% compared to the conventional method. However, this research faces challenges: uncertainty in adaptive CP calculation increases when channel estimation accuracy deteriorates in real high-speed mobile environments, and real-time computation complexity makes implementation difficult.

Furthermore, Wang et al.[3] proposed the RGI (Reduced Guard Interval) OFDM technique to overcome the drawbacks of CP-free OFDM, combining the advantages of conventional CP-OFDM and CP-free OFDM. By selecting the optimal RGI length based on a genetic algorithm and combining it with decision feedback equalization, it effectively eliminates ISI. Compared to conventional ZP-OFDM, it achieves up to an 80% increase in spectral efficiency in high delay spread environments, a 33% increase on the experimental channel, and improved BER performance at SNRs above 15 dB. However, genetic algorithm-based optimization incurs high computational costs and has limitations for real-time applications. It also suffers from optimization cycle adjustment issues and performance degradation under severe channel variations.

Analysis of existing studies reveals that to address the performance inefficiencies of fixed GI and CP environments, various techniques have been proposed, including adaptive parameter adjustment, scheduling techniques, admission control, and waveform enhancement methods. However, conventional studies only consider specific environments or frequency bands and cannot simultaneously guarantee transmission efficiency, reliability, and security in highly mobile real-world environments. Therefore, this study aims to overcome these limitations and propose an efficient and highly reliable wireless communication framework that includes adaptive GI adjustment and additional data transmission.

3 Proposed Model

This chapter proposes an adaptive GI management framework that transmits secondary data by utilizing unused space within GI while maintaining the existing data transmission method. This model calculates the minimum required GI needed to protect primary data by measuring the channel's delay spread in real time, thereby improving transmission efficiency by utilizing the spare space within the fixed GI for additional data transmission. The flowchart of the proposed model is shown in Figure 1.

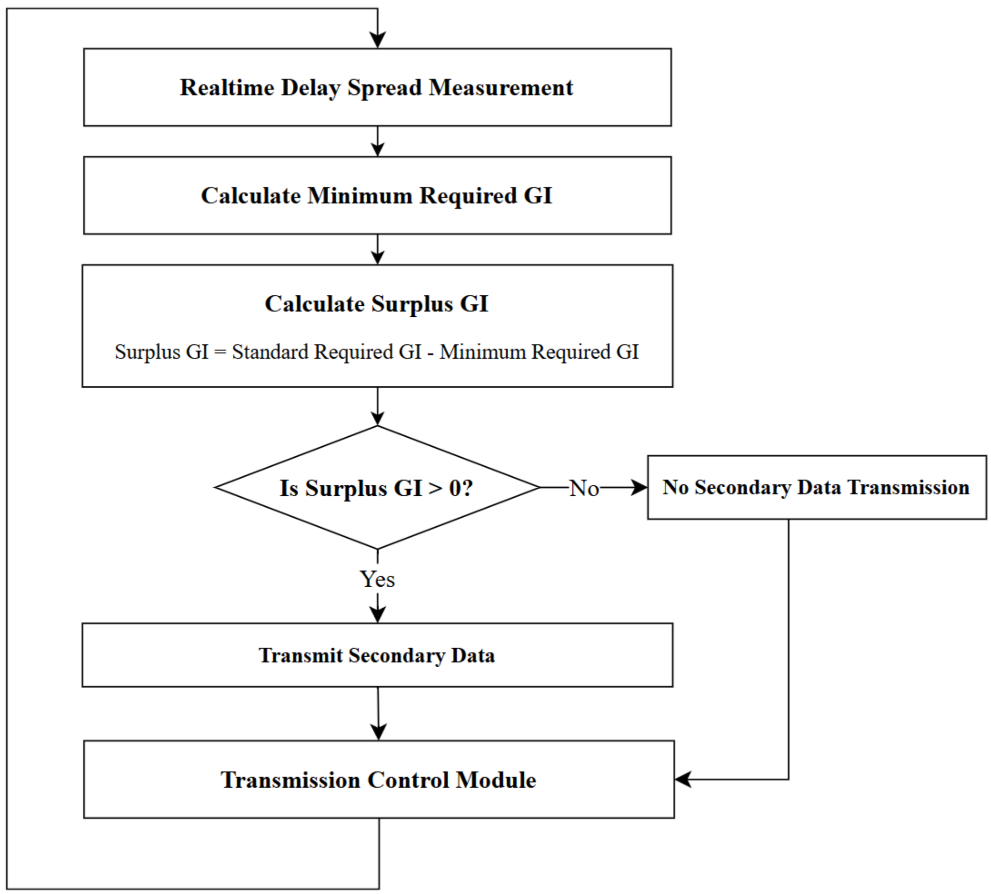

Figure 1. Flowchart of the Proposed Model

The operation process of the proposed model is as follows. First, the channel measurement module measures the delay spread of the wireless channel in real time. The key in this process is to accurately calculate the minimum required guard interval length to prevent inter-symbol interference occurring in multipath fading environments. Based on the measured delay profile, the GI management module calculates the minimum GI length required for primary data transmission under the current channel conditions.

Next, the Surplus GI is calculated by subtracting the minimum required GI from the standard GI length. The formula Surplus GI = Standard GI - Minimum Required GI quantitatively evaluates the size of the available surplus interval under the current channel state. After determining whether the calculated Surplus GI is positive, additional data transmission is performed only if surplus space exists.

If Surplus GI exists, the frame configuration module allocates this interval for Secondary Data transmission. During this process, appropriate separation techniques are applied to prevent interference between primary and secondary data, ensuring secondary data is transmitted without compromising the transmission quality of primary data. Conversely, if the Surplus GI is zero or less, the channel state is deemed poor, and no Secondary data transmission is performed. All GI is then used for protecting the primary data.

The transmission control module continuously monitors and controls this entire process. It detects real-time changes in channel conditions to automatically regulate the start and stop of secondary data transmission, ensuring system stability. Particularly when channel conditions deteriorate rapidly, requiring GI exceeding the standard GI, it immediately halts secondary data transmission and focuses on ensuring the reliability of primary data.

Through this dynamic GI management, the proposed model offers several advantages. When channel conditions are favorable, it efficiently utilizes surplus intervals within the GI to enable additional data transmission, thereby enhancing the overall system throughput. Simultaneously, during poor channel conditions, it guarantees transmission reliability by concentrating all resources on protecting primary data. Furthermore, it achieves performance improvements without fundamentally altering the existing standardized frame structure, offering compatibility advantages. Therefore, the proposed model provides a practical solution that simultaneously satisfies transmission efficiency and reliability in wireless communication systems.

4 Evaluation

This chapter evaluates the performance of the proposed dynamic GI adjustment and secondary data transmission framework by comparing it with fixed GI models and variable GI models. Experiments were conducted based on the Wi-Fi 6 wireless LAN standard, IEEE 802.11ax, considering all three GI options supported by Wi-Fi 6: 0.8μs, 1.6μs, and 3.2μs. The data transmission size was fixed at 10MB, and the delay spread was continuously varied across 16 conditions ranging from 0.02μs to 5.0μs. This simulation reflected both indoor low-delay environments and outdoor high-delay environments. The indoor environment exhibits relatively low delay spread, allowing sufficient reliability to be achieved even with short GI. Conversely, the outdoor environment shows characteristics requiring long GI due to significant multipath effects and delay spread. This environmental distinction enabled a comprehensive verification of the adaptability of Wi-Fi 6-based GI management and the dynamic GI framework across various channel conditions.

4.1 Experiment Configuration

In the simulation, all models were assumed to accurately measure delay spread. This excludes the effects of channel estimation errors or measurement delays, enabling a comparison of the pure GI management algorithm's performance. The comparison comprises three models. The fixed GI model uses a fixed GI of 0.8μs, while the variable GI model selects the appropriate GI from the Wi-Fi 6 standard options of 0.8, 1.6, or 3.2μs based on the measured delay spread. The proposed model calculates the minimum required GI for ISI prevention in real-time based on the delay spread for each transmission and transmits additional secondary data using the time saved compared to the maximum standard GI.

The evaluation metrics used were BER and Throughput. BER is defined as the error rate caused by ISI when the delay spread exceeds the GI, and Throughput is the number of successfully transmitted bits divided by the transmission time. Furthermore, the proposed model distinguishes between Primary and Secondary data, measuring the throughput for each separately.

4.2 Results

In the delay spread range of 0.02μs to 0.6μs corresponding to indoor environments, the proposed model demonstrated a significant throughput improvement compared to both fixed and variable GI models. Specifically, while the fixed and variable models achieved average throughputs of 815.26 Mbps and 87.65 Mbps, respectively, in the indoor delay spread range, the proposed model recorded an average throughput of 1032.86 Mbps, demonstrating a performance improvement of approximately 22%. This superior performance stems from the proposed model adaptively allocating only the minimum GI required by the actual channel environment and utilizing the saved time resources to perform secondary data transmission.

In sections with delay spreads of 1µs or more, corresponding to outdoor environments, the throughput differences between models became even more pronounced. Particularly at a delay spread of 5µs, the fixed GI model exhibited a very low throughput of 0.71Mbps due to severe ISI, while the variable GI model achieved 166.80Mbps, and the proposed model achieved 588.84Mbps. On average, the fixed model and variable model achieved 31.87 Mbps and 461.84 Mbps, respectively, while the proposed model achieved 688.52 Mbps. This signifies an outstanding 180% performance improvement for the proposed model. Figure 2 below shows the throughput comparison of the three models as the delay spread varies.

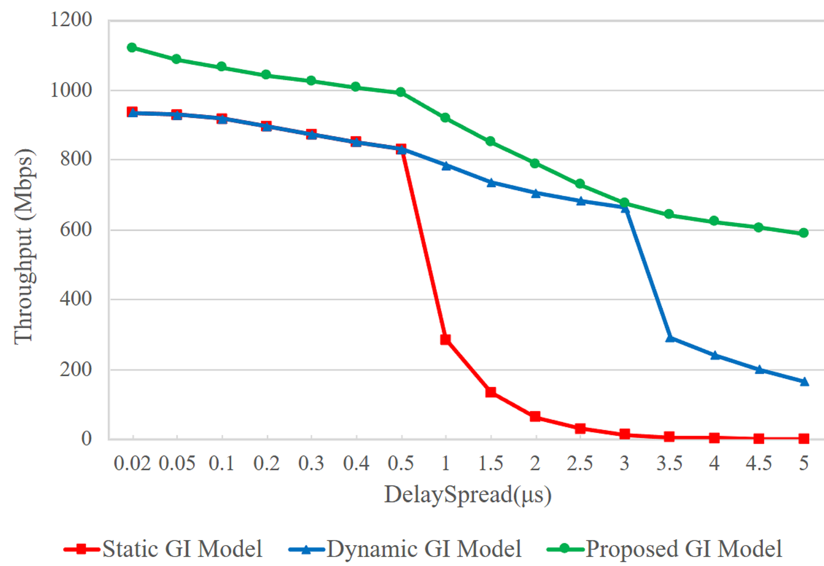

Figure 2. Throughput Comparison of Static, Dynamic, and Proposed Models over Delay Spreads

In terms of reliability, BER analysis results confirmed that all three models recorded a BER of 0% across the range of delay spread from 0.02µs to 0.6µs in the indoor environment, enabling perfectly error-free communication. This is because the GI applied by each model in this range was sufficiently larger than the actual delay spread, preventing any ISI from occurring. Therefore, all models can guarantee high reliability in indoor environments.

However, in the outdoor environment where the delay spread is 1µs or greater, significant performance differences emerged between models. For the fixed GI model, ISI began to occur as the delay spread exceeded the fixed GI value of 0.8µs, causing the BER to rise sharply. Specifically, it exhibited a high BER of 61.1% at a delay spread of 1µs and recorded an extremely high error rate of 99.7% at 5µs. The variable GI model showed relatively superior performance, maintaining a BER of 0% up to 3.5µs, but thereafter exhibited a high BER ranging from 54.5% to 71.5%. In contrast, the proposed model consistently maintained a BER of 0% across all delay spread intervals, demonstrating perfect ISI suppression performance and communication reliability. These results show that the proposed model achieves an average performance improvement of 31.5%, proving that the adaptive

GI control mechanism operates effectively in all channel environments. Figure 3 below details the comparison of BER changes for the three models as the delay spread increases.

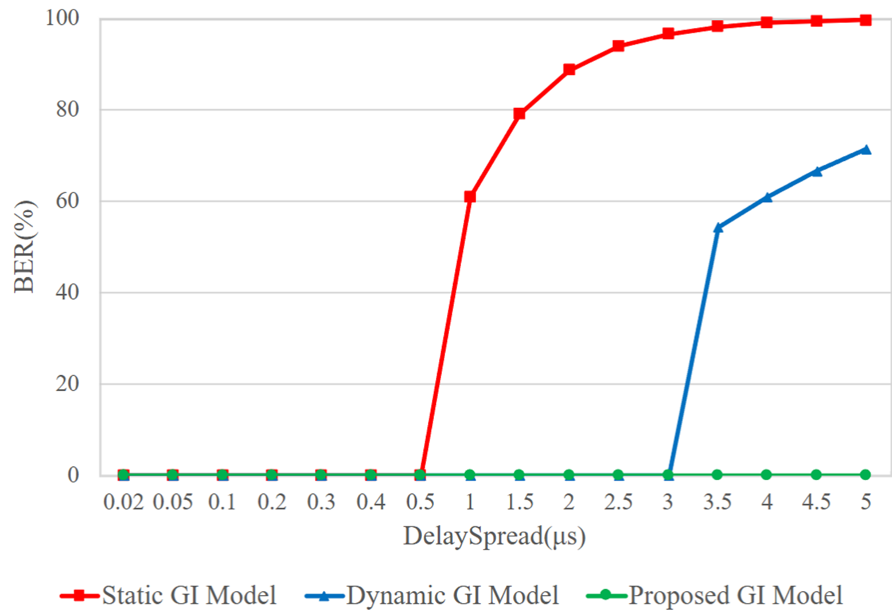

Figure 3. BER Comparison of Static, Dynamic, and Proposed Models over Delay Spreads

5 Usage Model

The dynamic GI adjustment and secondary data transmission framework can significantly improve the transmission efficiency of wireless communications by utilizing unused GI intervals to transmit additional data. However, this simultaneously carries a security risk: the secondary data segment could be exploited by the transmitter. The core risk of this method lies not in inadequate encryption or authentication, but in the fact that the entity controlling transmission could intentionally insert sensitive personal information, authentication credentials, or corporate secrets into the secondary data segment for external leakage. Indeed, recent reports indicate repeated incidents of large-scale leaks of subscriber information, authentication keys, and unique device identifiers within mobile communication networks and industrial wireless environments, perpetrated by insiders. Cases have also been confirmed where this information was covertly transmitted in the form of supplementary data. Given that the Secondary data transmission method is applied across diverse wireless communication environments—such as IoT, smartphones, industrial automation, and public safety networks—malicious exploitation by transmitters could cause extensive harm, including personal privacy violations, industrial espionage, and threats to national security. The inherent difficulty of detecting or controlling data flows externally due to wireless characteristics further exacerbates the problem. Therefore, comprehensive security measures—such as access control, transmission history monitoring, insider behavior surveillance, and real-time anomaly detection—must be implemented alongside this framework.

Simultaneously, the secondary data channel holds innovative potential as a confidential communication channel. For instance, in smart grid SCADA (Supervisory Control And Data Acquisition) environments, encrypted hash values embedded in Secondary data can enable real-time integrity verification between remote terminals. In autonomous vehicle V2X (Vehicle-to-Everything) communications, sensitive location and identity authentication information can be covertly transmitted, effectively blocking MITM (Man-in-the-Middle) attacks and location manipulation attempts. In manufacturing PLC (Programmable Logic Controller)–HMI (Human Machine Interface) communication, integrity tags verifying the tampering status of production parameters and system commands can be securely exchanged to prevent industrial espionage and sabotage threats. To implement these security features, a multi-layered encryption system combining AES-256 (Advanced Encryption Standard 256-bit) and ECC (Elliptic Curve Cryptography)-based key exchange must be integrated. Adaptive security level management dynamically adjusts encryption strength based on network risk levels and service quality requirements, and AI-based traffic anomaly detection analysis modules to monitor threats in real time and automatically block them. This enables expansion beyond simple efficiency improvements into a comprehensive and secure communication infrastructure for diverse future wireless communication environments such as IoT (Internet of Things), smart grids, autonomous driving, and Industry 4.0.

6 Conclusion

This study originated from the problem that fixed GI schemes fail to reflect channel environment changes, leading to reduced transmission efficiency. While previous studies proposed GI optimization methods, they had limitations in real-time adaptability and utilization of residual intervals. Therefore, this paper proposes a dynamic GI management framework to improve the inefficiency of existing fixed GI schemes. This framework calculates the minimum required GI based on real-time channel delay spread measurements and utilizes the surplus interval for secondary data transmission. Simulation results confirm that the proposed model can enhance transmission efficiency by approximately 22% in indoor environments and up to 121.5% in outdoor environments while maintaining the reliability of primary data. Notably, it completely suppresses ISI across various delay spread environments and demonstrates high applicability to Wi-Fi 6-based wireless systems by increasing resource utilization through secondary data transmission.

The significance of this research lies in three aspects: first, designing a GI management technique that adapts in real-time to channel changes; second, enabling differential reliability assurance based on data importance; and third, proposing a frame structure compatible with existing standards. This demonstrates the feasibility of simultaneously achieving the high efficiency and high reliability demanded by next-generation high-speed wireless communications.

However, a limitation exists in the actual implementation stage: additional channel estimation and signal processing modules are required for accurate real-time measurement of delay spread. Furthermore, as discussed in this paper, if the secondary data transmission segment is exploited, it could lead to security and privacy threats, making countermeasures essential.

Future research should validate the performance and complexity of the proposed model through actual hardware-based implementation and conduct performance evaluations in various wireless access networks and mobility environments. Furthermore, it is necessary to combine access control and anomaly detection techniques to mitigate the security risks of the secondary data transmission channel, thereby expanding it into a complete framework that guarantees high reliability, high efficiency, and high security.

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