Robust Deterministic Backoff for Improving Wi-Fi Latency: Design and Coexistence Scenarios

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***Abstract*—The performance of Wi-Fi networks is strongly influenced by the backoff mechanism. The widely adopted exponential backoff (EB) mechanism exhibits limitations in throughput and latency, particularly in large and heterogeneous deployments. In this work, we design a robust deterministic backoff (DB) mechanism intended to address these issues while coexisting with legacy EB stations (STAs). We analyze the throughput and latency resulting from the coexistence of EB and DB mechanisms and, through extensive ns-3 simulations, identify DB parameter configurations that enable fair coexistence without requiring modifications to legacy STAs. The results show that DB preserves throughput fairness, improves throughput compared with EB-only configurations, and substantially reduces packet latency, with particularly pronounced improvements at the 99th percentile and beyond.**

***Index Terms*—Wi-Fi; latency; exponential backoff; deterministic backoff; network simulation**

I. Introduction

Reducing latency and improving predictability in IEEE 802.11 wireless local area networks (WLANs) has become increasingly important with the emergence of real-time and interactive applications, including cloud gaming, real-time communication, industrial automation, augmented reality, and time-sensitive networking (TSN) [1]. Unlike traditional best-effort traffic, these applications are sensitive not only to average delay but also to delay variability and occasional latency spikes, which can significantly degrade user experience and system performance. The Broadband Internet Technical Advisory Group (BITAG) identifies contention, queueing, and retransmissions as major contributors to latency in wireless systems [2]. Moreover, previous studies have shown that increasing network bandwidth alone provides limited benefits when latency remains high, emphasizing the importance of efficient medium access mechanisms [3]. Low-latency and deterministic wireless communication has also attracted interest in industrial networking, where strict timing constraints and high reliability must often be satisfied simultaneously [4].

WLAN performance is strongly influenced by the medium access control (MAC) backoff mechanism. The widely adopted exponential backoff (EB) mechanism (used, e.g., in IEEE 802.11's enhanced distributed channel access, EDCA) provides robustness under contention by increasing the contention window after a collision. However, it has well-known limitations in terms of latency, efficiency, fairness, and predictability, particularly in large-scale deployments and heterogeneous environments. These limitations become especially significant in dense networks, where collisions and uncertainty in channel access can cause substantial performance degradation.

Recent research has therefore investigated low-latency WLAN operation and more deterministic channel-access mechanisms for next-generation Wi-Fi systems. Several studies have considered enhanced scheduling, bounded-latency operation, and deterministic medium-access techniques for IEEE 802.11be and beyond [5]–[7]. These approaches seek to provide reliable and predictable communication in dense and heterogeneous wireless environments. Deterministic backoff (DB) mechanisms have also been proposed for coexistence between Wi-Fi and NR-U, demonstrating improved fairness and reduced contention overhead in unlicensed-spectrum environments [8], [9]. More recently, interruption-based contention window (CW) adaptation strategies have been introduced [10], further demonstrating the potential of contention mechanisms that adapt to current network conditions.

In contrast to EB, which selects the backoff randomly, DB schemes adjust the backoff deterministically according to observed channel activity. This behavior can provide more predictable channel access and reduce delay. Nevertheless, pure DB schemes may exhibit limited fairness and scalability, particularly when coexisting with EB stations.

In this paper, we design a robust DB mechanism in which the backoff is updated using a multiplicative factor determined by the number of interruptions observed during a prior backoff countdown, denoted as IPT. This approach enables each station (STA) to react directly to the measured contention level: the backoff increases when contention is high and decreases when contention is low. Consequently, the proposed mechanism maintains predictable access behavior while adapting effec-

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tively to network conditions and scaling from small to large deployments.

II. Robust deterministic backoff in Wi-Fi

In the following, we describe the DB protocol [9] when using a multiplier on IPT. Consider a medium access stage as beginning with the generation of a backoff value, and ending with an attempted transmission (which may or may not succeed). Let B_k denote the backoff at stage k, IPT_k the number of interruptions observed during stage k, and retry_k the retry counter at stage k. Additionally, let b and m denote the base backoff value and the IPT multiplier, respectively.

When a packet arrives to an empty queue, the STA initializes the process by selecting an initial backoff B_1 uniformly at random in the interval $[0, 15]$, and sets $\mathrm{IPT}_1 = 0$ and $\mathrm{retry}_1 = 0$. For subsequent stages $k > 1$, the backoff selection depends on the retry counter. If $\mathrm{retry}_k \bmod 7 < 3$ (i.e., for retry_k equal to {0, 1, 2}, {7, 8, 9}, etc.), the STA applies deterministic backoff and sets

$$B_{k+1} = b + m \cdot \mathrm{IPT}_k, \tag{1}$$

while resetting the interruption counter as

$$\mathrm{IPT}_{k+1} = 0. \tag{2}$$

Otherwise (i.e., for retry_k equal to {3,...,6}, {10,...,13}, etc.), the STA selects a random backoff

$$B_{k+1} \sim \mathrm{Uniform}(0, 6), \tag{3}$$

and keeps the interruption counter unchanged, i.e.,

$$\mathrm{IPT}_{k+1} = \mathrm{IPT}_k. \tag{4}$$

During the backoff countdown at stage k, the STA monitors the channel activity and increments the interruption counter for each interruption of its backoff, so that IPT_k represents the total number of interruptions experienced during that stage.

After each transmission attempt, the retry counter is updated based on the outcome. In case of a collision, the STA increments the retry counter as $\mathrm{retry}_{k+1} = \mathrm{retry}_k + 1$, whereas after a successful transmission the retry counter is reset to zero, $\mathrm{retry}_{k+1} = 0$.

In the presence of continued unsuccessful transmission, this mechanism results in an alternating behavior between deterministic and random backoff selections. In particular, DB is applied during the first three attempts within each cycle of seven retries, while random backoff is used in the remaining attempts to resolve persistent synchronization.

The value of b in DB emulates the average backoff of an EB node contending for channel access in similar contention conditions. For the case of a single contending node, the IPT is 0, and b is set equal to the average backoff value of a single EB node operating with a given $CW_{\min}$ (e.g., considering the default $CW_{\min} = 15$, and the average backoff of a single EB node at 7.5, the b value can be approximated to 8). Scaling to a larger number of STAs in mixed deployments using a fixed value of b is addressed by introducing IPT multiplier m. The value of m must be selected to ensure robust operation and fair coexistence with EB nodes. In our analytical study (not shown here) we found $m = 1.5$ to be provide good performance in coexistence scenarios, as we show next.

TABLE I
Simulation settings

Parameter	Value
PHY parameters	
Wi-Fi standard	IEEE 802.11ax
Frequency band	5 GHz
Channel width	20 MHz
Rate manager	ConstantRateWifiManager
Data rate	MCS 11
Control rate	MCS 2
Guard interval	800 ns
MAC parameters	
Access category	Best Effort
EDCA CWmin/CWmax	15/1023
EDCA AIFSN	3
EDCA TXOP limit	2528 μs
RTS/CTS threshold	0 B / 999999 B
Maximum retries	7
Traffic parameters	
Traffic direction	Uplink
Transport protocol	UDP
Traffic application	OnOffApplication
Offered rate	150 Mbit/s
Payload size	1450 B

III. Performance evaluation

A. Simulation setting

We implement the robust DB in ns-3 and observe that it preserves compatibility with the existing EDCA framework. The modifications leverage the existing ns-3 Wi-Fi architecture, integrating DB generation, interruption tracking during channel contention, and adaptive retry state management after transmission completion. The goal of the implementation is to reproduce deterministic contention behavior in which STAs adapt their backoff according to channel interruptions and transmission outcomes, instead of relying exclusively on the standard random backoff generation defined by EDCA.

The simulations evaluate the performance of the proposed robust DB algorithm in mixed IEEE 802.11ax environments where a subset of STAs employs the legacy EB mechanism. The analysis focuses on per-STA throughput and latency. Simulations were conducted considering an IEEE 802.11ax Basic Service Set (BSS) operating in the 5 GHz band. All nodes use a 20 MHz channel configuration with MCS 11 and a single spatial stream, but the dynamics of interaction between DB and EB STAs are not affected by these settings. The simulation parameters are summarized in Table I.

A portion of the STAs adopts the robust DB scheme, while the remaining STAs use standard EDCA with EB. For DB STAs, the contention window is computed as $B = b + m \cdot \mathrm{IPT}$, with parameters $b = 8$ and $m = 1.5$. For both DB and EB STAs, AIFSN is equal to 3, the TXOP duration is equal to 2528 μs, maximum retry limit equals 7. Simulations were performed both with RTS/CTS enabled and disabled. Traffic consists of saturated UDP uplink flows with constant offered

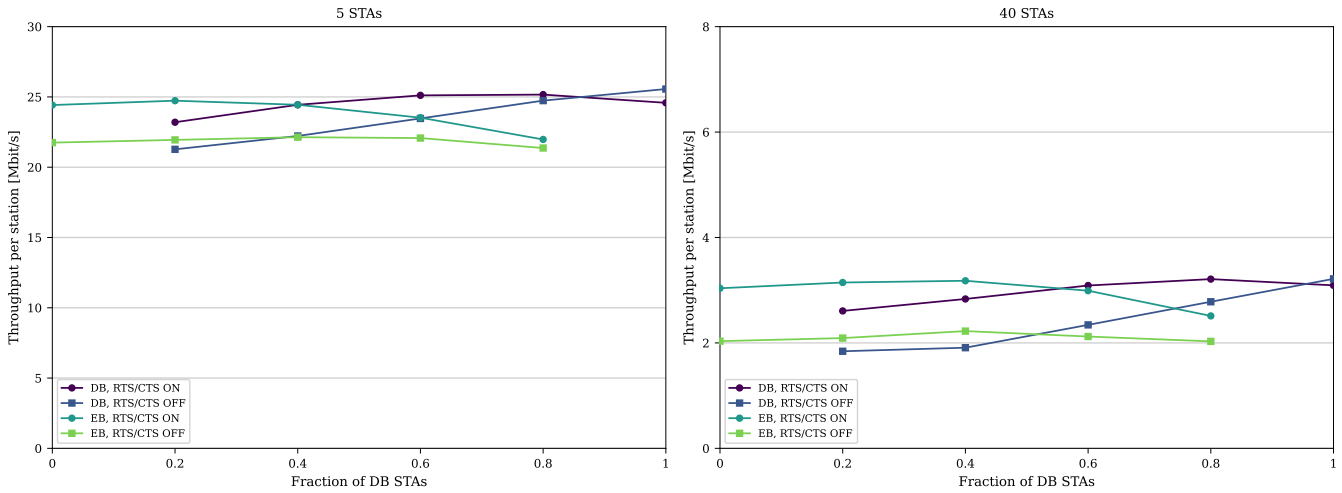


Fig. 1. System throughput for 5 and 40 active STAs, for fractions of DB STAs in [0, 1] and RTS/CTS enabled or disabled.

load equal to 150 Mbps per STA and payload size of 1450 B. Latency samples are collected after all STAs have joined the network and after an additional 30 s warm-up interval. Tail latency is evaluated through the complementary cumulative distribution function (CCDF) of the per-STA channel access delay, defined as the time interval between two consecutive successful TXOP transmissions after the warm-up phase.

B. Simulation results

Figure 1 shows the per-STA throughput for different fractions of DB STAs, with RTS/CTS either enabled or disabled. Results are reported for two deployments: a small scale scenario with 5 STAs (left figure) and a large scale scenario with 40 STAs (right figure). The fraction of DB STAs varies from 0 (all STAs using legacy EB) to 1 (all STAs using DB).

In all evaluated scenarios the robust DB process remained stable and did not exhibit throughput degradation. Furthermore, the results confirm that the introduction of DB STAs preserves stable and fair coexistence with EB STAs. In particular, increasing the fraction of DB STAs from 0.2 to 0.8 does not negatively affect throughput fairness between DB and EB nodes, both in small and large scale deployments. Therefore, the selected multiplier provides stable operation across both small and large scale deployments while preserving coexistence fairness.

Focusing on latency in the 5 STA scenario, Figure 2 shows the CCDF of the channel access latency for the all-EB case (left figure) and the all-DB case (right figure), highlighting the 90th, 99th, 99.9th, and 99.99th latency percentiles. The results show approximately one order of magnitude reduction in the 99th-percentile latency when moving from the all-EB scenario to the all-DB scenario, with 99th latency precentile decreasing from approximately 100 ms to about 10 ms. Moreover, the latency distribution in the all-DB scenario appears generally bounded, indicating significantly improved tail-latency behavior, due to the round-robin scheduling order and the virtual absence of collisions. Collisions with beacons may occasionally still occur (beacons are transmitted by the AP every 100 ms).

Figure 3 shows the CCDF of the channel access latency for the 40 STAs scenario, which confirms the reduction in the 99th latency percentile when moving from the all-EB scenario to the all-DB scenario, together with a latency distribution in the all-DB case that appears generally bounded.

IV. Conclusion and Future Work

We introduced a robust DB scheme and implemented it in ns-3 by extending the standard Wi-Fi MAC architecture with deterministic contention management, interruption tracking, and adaptive retry-state handling. Then, we investigated its coexistence with legacy exponential backoff mechanisms in IEEE 802.11 WLANs.

Extensive ns-3 simulations demonstrated that robust DB can coexist fairly with legacy EB STAs across both small to large deployments. Results showed that the proposed mechanism preserves throughput fairness while improving aggregate throughput compared to EB-only configurations. More importantly, robust DB significantly reduces channel-access latency and improves tail-latency behavior, achieving reductions in the 99th latency percentile in 5 STAs and 40 STAs scenarios. Additionally, latency appears generally bounded, indicating improved tail behavior. These findings indicate that robust DB represents a promising low-latency enhancement for next-generation Wi-Fi networks, particularly in heterogeneous and incrementally deployable environments.

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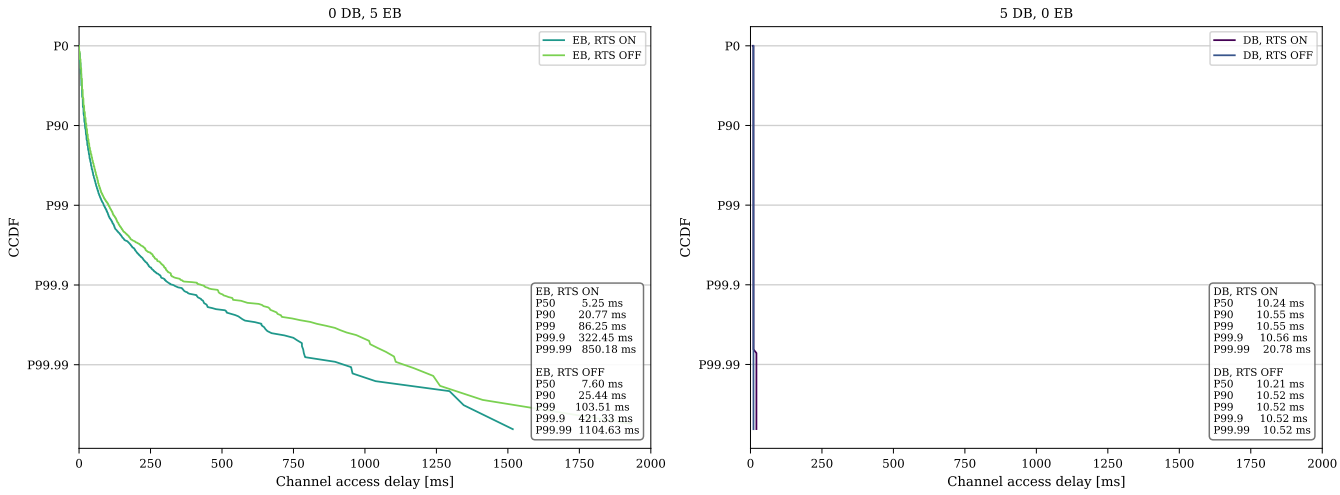


Fig. 2. System latency for 5 EB STAs and 5 DB STAs, and RTS/CTS enabled or disabled.

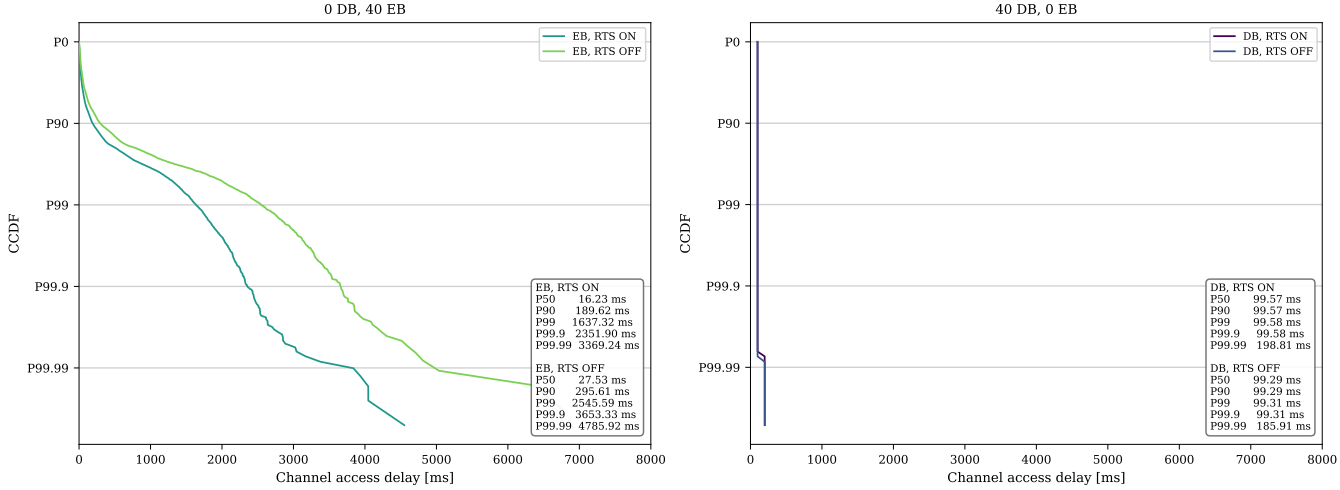


Fig. 3. System latency for 40 EB STAs and 40 DB STAs, and RTS/CTS enabled or disabled.

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