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Collision-Based Window-Scaled Back-Off Mechanism for Dense Channel Resource Allocation in Future Wi-Fi

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Abstract: Wireless local area networks (WLANs), known as Wi-Fi, are widely deployed to meet the enhanced needs of data-centric internet applications, such as wireless docking, unified communications, cloud computing, interactive multimedia gaming, progressive streaming, support of wearable devices, up-link broadcasts and cellular offloading. Wi-Fi networks typically adopt the Distributed Coordination Function (DCF)-based Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), which uses the Binary Exponential Back-off (BEB) algorithm at the MAC layer mechanism to access channel resources. Currently deployed Wi-Fi networks face huge challenges towards efficient channel access for denser environments due to the blind exponential increase/decrease of a contention window (*CW*) procedure that is inefficient for a higher number of contending stations. Several modifications and amendments have been proposed to improve the performance of the MAC layer channel access based on a fixed or variable *CW* size. However, a more realistic network density-based channel resource allocation solution is still missing. An efficient channel resource allocation is one of the most critical challenges for future highly dense WLANs, such as High-Efficiency WLAN (HEW). In this paper, we propose a Channel Collision-based Window Scaled Back-off (CWSB) mechanism for channel resource allocation in HEW. In our proposed CWSB, all contending stations select an optimized *CW* size for each back-off stage for collided or successfully transmitted data frames. We affirm the performance of the proposed CWSB mechanism with the help of an Iterative Discrete Time Markov Chain (I-DTMC) model. This paper evaluates the performance of our proposed CWSB mechanism in HEW Wi-Fi networks using an NS3 simulator in terms of the normalized throughput and channel access delay compared to the state-of-the-art BEB and a recently proposed mechanism.

Keywords: future Wi-Fi network; IEEE 802.11ax; channel access in HEW

MSC: 60K05; 68M20

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1. Introduction

Technology evolution, user needs and the impact of COVID-19 have significantly enhanced global data requirements because of work-from-home [1], online education, smart cities, security surveillance [2], online health services [3], vehicular networks and e-business approaches. Cisco Visual Networking Index (Cisco VNI) 2017–2022 [4] reported that global mobile data traffic will increase by seven fold by 2022.

Future Wi-Fi services demand support for both high data rate and dense user support [5] with scenarios, such as sports stadium, airport, train station, exhibition hall, dense wireless office, dense apartment building, dense urban street and pico-cell street deployment. The need for an efficient PHY and MAC layer protocols becomes most important for future Wi-Fi networks to meet with the aforementioned future services. The Institute for Electrical and Electronics Engineers (IEEE) defines 802.11a, 11b, 11g, 11n, 11ac and 802.11ax as Wi-Fi standards for wireless local area network (WLAN) communications.

In 2014 [6], an IEEE 802.11 working group (WG) approved the development of a new WLAN standard, IEEE 802.11ax, also known as 6th Generation (6G) Wi-Fi network. The IEEE 802.11ax task group (TG ax) intends to improve the efficiency for dense user scenarios along with high data rates and termed it as a High-Efficiency WLAN (HEW) network. In Wi-Fi 6, the contending devices, also called stations use Enhanced Distributed Channel Access with Best Effort (EDCA-BE) for medium access. The EDCA-BE MAC protocol is similar to DCF based on carrier sense multiple access with a collision avoidance (CSMA/CA) mechanism, which adopts a traditional Binary Exponential Back-off (BEB) algorithm for the medium contention.

The BEB follows a blind exponential increase and decrease of back-off window and that is inefficient for highly dense HEW networks [7] due to a limited size of contention window (CW) size. In EDCA-BE MAC protocol, each contending station selects a random back-off value from the initial CW (CW_{min}), and its value is doubled (exponentially increased) after each unsuccessful transmission until it reaches a given maximum value CW_{max}.

Each contending station may experience a maximum number of consecutive collisions that shows the maximum number of transmission stages (m). Therefore, at the maximum value of m, the back-off window size no longer doubles, stays at its maximum value and is given by $CW_{max} = CW_{min} \times 2^m$. The CW size reverts to its initial minimum value CW_{min} after every successful transmission or after the maximum number of re-transmissions is reached (data packet is dropped at this level).

In the case of a dense network, the process of resetting CW size to its minimum value CW_{min} after each successful data-transmission may encounter more collisions due to the small CW size for large numbers of contending stations, which directly impacts the overall network performance. Similarly, in a small network, exponentially increasing the value of CW for avoiding collisions causes unnecessarily long delays. Hence, the performance of BEB mainly depends on the CW adjustment and back-off strategy [8], which is not designed for HEW requirements.

Several BEB modifications have been proposed to calculate the optimal CW size to improve the network performance in terms of higher throughput and lower access delay. These modifications are mainly categorized as fixed or adaptive CW adjustment schemes. Fixed CW schemes use different predefined incremental factors to adjust the CW size to improve the network performance, for example, Exponential Increase Exponential Decrease (EIED) [8,9], Exponential Increase Linear Decrease (EILD) [10], Multiplicative Increase Multiplicative Decrease (MIMD) and Smart Exponential Threshold Linear (SETL) [11], whereas the adaptive CW adjustment schemes dynamically adjust the CW size in accordance with the network conditions, such as the total number of active stations.

However, such schemes require that an active station must collect the channel-state information using various methods and coordinate with neighboring stations to reduce the transmission collisions and enhance the network throughput.

To the best of our knowledge, the Channel Observation-based Scaled Back-off mechanism (COSB) was the first effort to scale the back-off window for HEW dense networks [12]. The COSB mechanism observes the channel conditions to measure the collision probability that helps to control the CW size following a CSMA/CA-based EDCA-BE MAC protocol for dense users. An analytical modeling also presented using Recursive Discrete Time Markov Chain (R-DTMC) model to satisfy the validity of COSB in terms of the throughput and access delay. COSB gives a detailed picture of HEW and improves the network efficiency in terms of higher throughout and lower access delay with reference to BEB.

However, in COSB, the recently collided stations are forced to stay at a higher back-off stage (larger CW size) without knowing the number of contending stations or network density. This results in low throughput and higher delay values.

In this paper, we deduced that the last transmissions are the main causes of reduced network throughput, and they also increase the channel collision probability towards a denser network. In this paper, we propose a channel collision-based window-scaled back-off (CWSB) mechanism to optimize the CW considering the last transmission. In CWSB, each contending station for its ith transmission perceives the medium for the total back-off

period to calculate the channel condition collision probability p_{cc}. Furthermore, the CWSB quantizes the slot times into σ, where the value of p_{cc} is based on the perceived slot times between two consecutive back off stages. In addition, while considering CWSB, the current back-off stage b_i does not come to zero or one step reversed (meaning its earlier or previous back-off stage) after a successful transmission compared to BEB and COSB, respectively.

The remaining of the paper is organized as follows: the next section describes the working principals of the MAC protocol. Section 3 discusses the literature review, Section 4 explains our proposed model, and Section 5 presents our results and discussions of this paper. Finally, Section 6 concludes our proposed mechanism.

2. DCF-Based Channel-Access Mechanism in Current WLANs

The IEEE 802.11 defines DCF as a mandatory and point coordination function (PCF) as an optional MAC protocol for Wi-Fi networks. In addition, the PCF belongs to a centralized access scheme that offers contention-free channel access. However, PCF has limitations due to its complexity for dense user applications. In a WLAN network, a MAC protocol ensures high efficient multi user operation. For a multi-user MAC protocol (MU-MAC) technology, both the access point (AP) and stations obey certain rules to transmit data concurrently from AP to/from stations. Mostly, the available network resources for MAC protocol are accessed via the time domain, space domain or frequency domain.

Conventionally, IEEE 802.11 adopts the CSMA/CA mechanism of the DCF procedure as its MAC protocol to access the shared medium [13]. Before each transmission, a clear channel access assessment (CCA) procedure determines the channel condition if it is in ideal state or busy. In addition, DCF minimizes the collision probability for data being transmitted from other stations by using the BEB algorithm and several control frame or sub frames, such as Distributed Inter-Frame Space (DIFS), Request to Send (RTS), Short Inter-Frame Space (SIFS), Clear to Send (CTS) and acknowledgment (ACK).

Figure 1 shows how a DCF adopts CSMS/CA with BEB algorithm for two-way handshaking (basic access mechanism) and four-way handshaking (RTS/CTS access mechanism) to deal with hidden terminal problems. In the RTS/CTS DCF mechanism, the contending stations send an RTS frame and wait to receive a CTS frame prior to each data frame transmission as shown in Figure 1b.

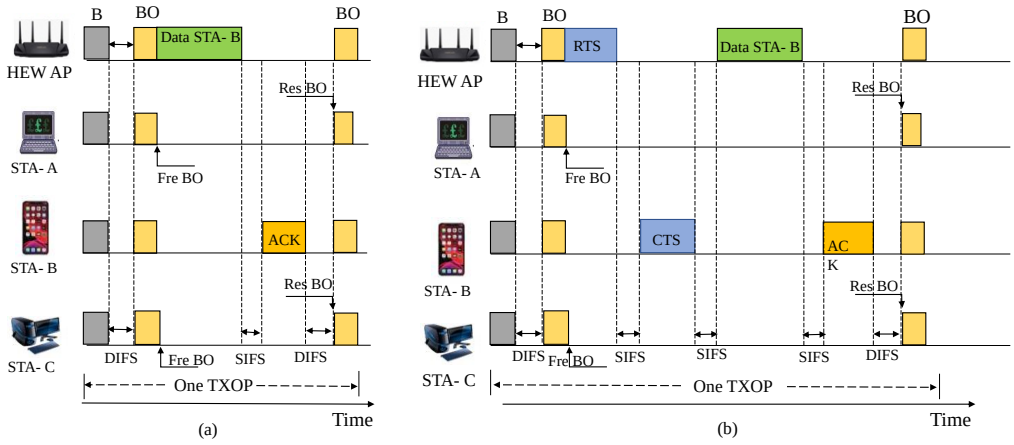


Figure 1. DCF channel-access-mechanism for the IEEE 802.11 (**a**) DCF Basic and (**b**) DCF RTS/CTS transmission procedure.

In a DCF, each contending station employs BEB and a deferral mechanism that helps to distinguish each transmission time to reduce the collision probabilities. In addition, the contending stations choose randomly discrete back-off slots in the range of $(0,\ CW-1)$ before accessing the channel. The DCF enables the BEB algorithm if the channel is sensed idle for a period of DIFS, while the remaining stations set network allocation vector (NAV) to avoid the collisions.

During the exponential back-off rules, each contending station decrements one from the back-off counter if the channel is sensed idle, freezes back-off counter when it detects a transmission on the channel and reactivates the back-off counter process when the channel is sensed idle again for a period of DIFS. Finally, the contending station proceeds the transmission when the back-off counter reaches zero, and the receiver sends back an ACK frame immediately (with a difference of short period SIFS) after the successful reception of the data.

Further, if assumed to have the perfect channel sensing mechanism by each contending station, the transmission may collide if two (or more) stations proceed (data or RTS) transmission within the same slot time as shown in Figure 2a,b, respectively.

In addition, DCF employs three types of frames with the name of control frame, management frame and data/QoS data frame. These physical frames need inter–frame space time interval to obtain the medium access without collision. Normally, control frames follow the previous frame after SIFS whereas data/management frames wait for DIFS/AIFS (including QoS) before they back off in *CW*.

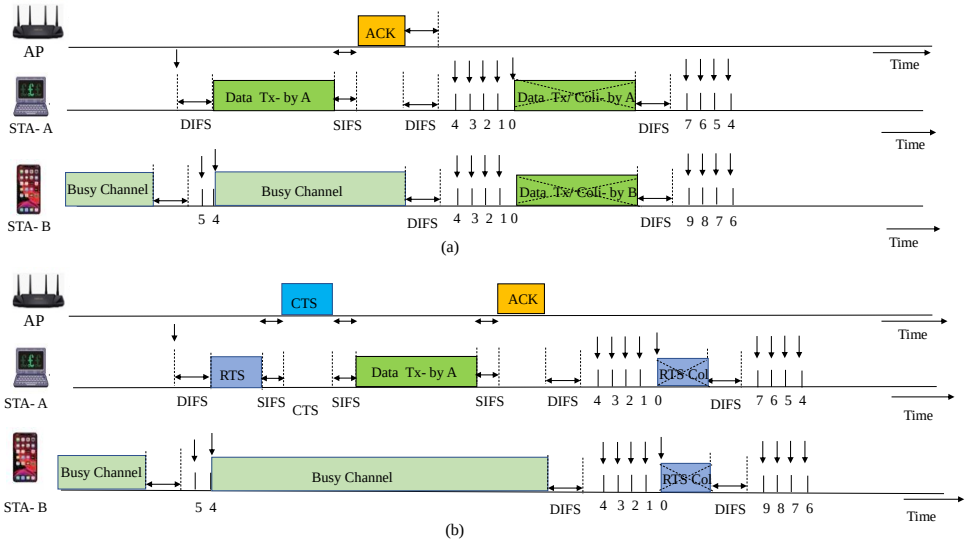


Figure 2. Successful and collided transmissions in the IEEE 802.11 (**a**) DCF Basic and (**b**) DCF RTS/CTS Channel-Access Mechanism.

3. Related Research Work

The resource (spectrum) management or channel access always persist the most challenging issue in IEEE 802.11-based WLAN networks. In this section, we categorize related research work into three sub sections; DCF limitations, fixed *CW* adjustment schemes and adaptive *CW* adjustment schemes.

(1) DCF limitations: Bianchi [7], presents a simple, yet precise analytical model to calculate saturated throughput for the DCF mechanism using BEB algorithm. According to Bianchi, considering the BEB algorithm, a data frame transmission (successful or collided) majorly depends upon the values: (i) *CW* size (*W*), (ii) collision probability p, (iii) transmission probability τ and (iv) number of n contending stations [14]. Below, Equation (1) indicates the value of probability τ that a contending station transmits a data frame specific to a randomly chosen slot time. However, normally, τ depends on W and p, which is still unknown, and thus we have the following major equations.

$$\tau = \sum_{i=0}^{m} bi, 0 = \frac{b_{0,0}}{1-p} = \frac{2(1-2p)(1-p)}{(1-2p)(W+1) + pW(1-(2p)^m)} \quad (1)$$

For Equation (2), to obtain the value of p regarding a contending station, it is sufficient to account for the probability of a transmission collided in a slot time for at least one of the

remaining $(n-1)$ stations. Moreover, each contending station transmits a data frame with probability p for a steady state. This is shown in Equation (2).

$$p = 1 - (1-\tau)^{n-1} \tag{2}$$

Further, Equations (1) and (2) belong to a nonlinear system for two unknown τ and p values that can be calculated using mathematical techniques. In fact, for the calculation of τ, we invert Equation (2) to obtain Equation (3).

$$\tau^*(p) = 1 - (1-p)^{1/(n-1)} \tag{3}$$

In order to prove that the system holds a unique solution due to continuous and monotonic values, we can rewrite the two equations as follows $\tau(p)$, generally,

$$\tau(\rho) = \frac{2}{(1 + W + \rho W \sum_i^{m-1} (2\rho)^i)} \tag{4}$$

For continuous and monotonic decreasing: consider $\tau(0)$ and place in the above equation the $\tau\ (0) = \frac{2}{(1+W)}$ and reduce up to $\tau\ (1) = \frac{2}{(1+2^m W))}$ for continuous and monotonic increasing on the interval [0, 1]. Further, place $\tau^*(0) = 0$ and $\tau^*(1) = 1$ from the above equation, which prove the uniqueness of the solutions $\tau(0) > \tau^*(0)$ and $\tau(1) < \tau^*(1)$.

The above equations help us to compute the collision probability for various number of contending stations following the BEB algorithm. The BEB shows poor network performance in terms of high collisions and low throughput—particularly for a high number of contending stations. Eventually, due to the blind increase and decrease in *CW* for collision avoidance result in higher collisions and unnecessary delays for data transmissions, respectively.

Thus, currently BEB-based deployed Wi-Fi MAC protocol could not support better efficiency for dense environments. To address this issue, a series of modification has been conducted to BEB-based on CSMA/CA to improve the MAC layer performance considering fixed or variable adaptive *CW* size. Based on *CW* adjustments schemes in WLANS, the related works are further classified into two major categories.

(2) Fixed *CW* Adjustment Schemes: First, we discuss several well-known proposed algorithms towards fixed *CW* adjustment schemes, such as EIED, EILD, MILD, ECA and ECA-H as summarized in Table 1. The CSMA/CA based *CW* optimization work comes with the name of the EIED back-off algorithm that exponentially increases or decreases *CW* size by back-off factor $r_I = 2$ and $r_D = \sqrt{2}$ after each collision or successful transmission, respectively [15].

In EIED, r_I and r_D are fractional powers of 2, adopted to achieve improved network performance; however, the constant values of r_I and r_D make the EIED algorithm inefficient for dense networks. The MILD applies two different and constant factors to adjust the *CW* size—for instance, *CW* is multiplied by 1.5 in the case of transmission failure (or collided) and is decreased by one in the case of successful transmissions.

In addition, the enhanced collision avoidance (ECA) modified the standard BEB algorithm in terms of resetting the *CW* value to its CW_{min} after each successful data frame transmission [16,17]. In [16], ECA uses a deterministic back-off value ($V = 16$) after a successful transmission to enhance the throughput in an ad hoc network. In addition, the [17] adopts the same principal to maximize the fairness efficiency.

Similarly, such approaches can be deployed for radio resource management in wireless networks [18]. The aforementioned approaches are easy to implement and support collision-free transmission up to deterministic values. However, the performance gain was observed to be limited with a number of contenders larger than the value of V. Furthermore, the ECA-H (hysteresis) is a modified version of CSMA/ECA that increases the network throughput for a large number of contending stations [19].

Consequently, the ECA-H mechanism enhanced network performance with efficient utilization of available bandwidth [20]. The ECA-H comes at the cost of complex implementation and reduction in long-term fairness. In summary, fixed *CW* adjustment algorithms use constant multiplying factors for both transmissions (successful or failed), the network performance degraded for dense networks due to increased collision probability and reduced aggregated throughput.

(3) Adaptive *CW* Adjustment Schemes: Secondly, we studied the adaptive *CW* algorithms that adjust the *CW* dynamically according to the number of active contenders or traffic load. The idle sense optimal access method improves the network throughput and fairness [21], an Adaptive Back-off Algorithm for Contention Window (ABA-CW) enhances the system performance [22], and in [23], the authors proposed a QoS-based adaptive *CW* back-off algorithm for performance improvements.

However, these methods need to account for the active number station for *CW* adjustment that limits the performance of the DCF mechanism. Further, Ref. [24] proposed a global-view-based adaptive contention window (GV-ACW) MAC protocol to reduce latency and improve alternative energy harvesting for a sensor network The GV-ACW scheme optimizes the *CW* size relaying on near and far sink areas while data forwarding.

In [25], a cognitive back-off (CB) mechanism was proposed that optimized *CW* size only for successful transmissions. The CB provides an analytical improved saturation throughput analysis. In [26], they proposed an AP-based window synchronization where AP shares the optimal *CW* size with active and passive probe scanning by the stations. Hence, Table 1 gives brief details on related work for the *CW* optimization for conventional and future dense IEEE 802.11 WLAN networks.

To the best of our knowledge, COSB was the first effort to scale the back-off window size towards HEW dense networks [12]. The proposed COSB mechanism observes the channel condition to measure the collision probability that helps to scale the back-off *CW* size following CSMA/CA based EDCA(BE) MAC protocol. An analytical model also presented used the R-DTMC model to satisfy the validity of COSB in terms of the throughput and access delay.

COSB gives a detailed picture of HEW and improves the network efficiency in terms of higher throughout and lower access delay with reference to BEB. On the other hand, more specifically, the stations that have recently failed to transmit the data frame or access the channel due to consecutive re-transmission attempts are forced to stay at a higher back-off stage without knowing the number of contending stations or the network density. Since HEW networks are rapidly growing towards denser application, such schemes need more proficient modification to enhance the network efficiency in terms of higher throughput, lower access delay and good fairness metrics.

Table 1. Summary of related work.

Ref	MAC Protocol	Associated Work (Scheme)	Used Formulas (in Case of)		Contributions
[7]	CSMA/CA	BEB	**1. Transmission Collided.** $CW = \min((2^i (CW_{min}+1)) - 1,\ CW_{max})$.	**2. Transmission Succeeded** $CW = CW_{min}$.	Low Collision for sparse network and degraded throughput for dense network
[16,17,19,20]	CSMA/ECA/ECA-H	Deterministic back-off mechanism.	$CW = \min((2^i(CW_{min}+1)) - 1, CW_{max})$.	$k = \frac{[CW_{min}]}{2} + 1$	High throughput and low channel fairness for dense users
[15]	EIED	EIED back-off algorithm.	$CW = \min((r_I(CW_{min}+1)) - 1, CW_{max})$	$CW = \min(((CW_{min}+1)/r_D) - 1, CW_{min})$	Reduced delay but constant parameters
[25]	CB	CB algorithm.	$CW = \min((2^i(CW_{min}+1)^{(\rho ck+1)} - 1), CW_{max})$	CW_{min}	Throughput improved use constant multiplying factor
[26]	AP-based CW	Active and passive probe scanning.	$CW^* = \frac{(CW)}{2} \times n - 1$	$CW^* = \frac{(CW)}{2} \times n - 1$	Good fairness reduced performance due to fixed multiplying rule
[12]	COSB	CW optimization according to p_{obs}.	$CW = \min[2^{b^{i+1}} \times W_{min} \times \omega^{\rho obs}, W_{max}]$	$CW = \min[2^{b^{i+1}} \times W_{min} \times \omega^{\rho obs}, \ W_{min}]$	Higher throughput and low fairness for dense users
This work	CWSB	CW optimization according to p_{cc}.	$CW = [(2^{\ bi+1} \times \lambda^{(1+p_{cc})}, W_{max})]$	$CW = [(2^{\ bi+1} \times \lambda^{(1+p_{cc})}, W_{min})]$	Higher throughput and low channel access delay for dense users.

4. Collision-Based Window-Scaled Back-Off Mechanism—(CWSB)

In this paper, we propose a channel collision-based window-scaled back-off (CWSB) mechanism that mainly enhance network performance in terms of throughput and delay for dense users. The CWSB improves the network efficiency in terms of high throughput and lower delay by observing channel collisions during the channel access mechanism specific to saturated environments. An analytical model named as Iterative Discrete Time Markove Chain (I-DTMC) testifies the performance evaluation of the CWSB mechanism.

In proposed CWSB, each contending station continuously senses the medium after the medium sensed as idle for a distributed inter-frame space (DIFS), all the contending stations start to the back-off procedure by selecting a random back-off value d as shown in Figure 3. For each contending station, immediately following an idle DIFS, the total back-off time is slotted into observed slot times μ. During the back-off procedure, the slot time size is set equal to the time needed at any contending station n to detect the transmission of a data frame from any other $n-1$ stations.

Further, the duration of μ is either a constant slot time σ for an idle period or it could be a variable slot time for a busy (successful or collided) transmission period. During the back-off procedure as the channel is sensed idle during σ, the d is decremented by one. Similarly, the back-off process is frozen while the channel is sensed as busy, and the station continuously senses the channel to access the medium. If the channel is again sensed for a DIFS period, d is resumed.

Eventually, the contending station transmits a data frame after d approaches zero. Moreover, successful or collided transmission depends upon reception of the ACK frame. The case of the ACK frame not receiving the transmission is considered as collided or failed.

Each contending station individual computes the channel conditional collision probability p_{cc}, which is defined as the probability that a transmission by a contending station collided. Furthermore, the CWSB quantizes the slot times into σ, where the value of p_{cc} is based on the perceived slot times between two consecutive back off stages.

A contending station upgrades p_{cc} from D number of perceived slot times $(Dpst)$ of the back-off stage b_i at the ith transmission as

$$p_{cc} = \left(\frac{N_b + N_c + N_s}{Dpst} \right) * N_c \tag{5}$$

where $Dpst = N_i + N_b + N_c + N_s$ where N_i means the ideal slot time, N_b is the busy slot time, N_c is the slot time for collided transmission, and N_s is the slot time for successful transmission.

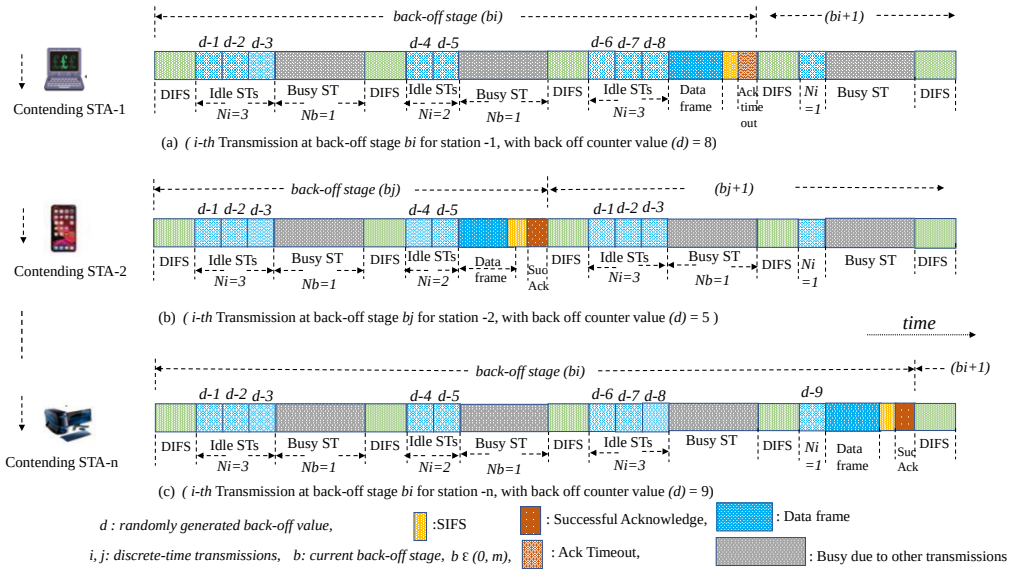


Figure 3. CWSB mechanism during the back-off procedure.

For example, in Figure 3, station-1 randomly chooses back-off counter value d = 8 for its ith transmission at b_i stage. Since station-1 perceived eight idle slot times (N_i), two busy periods (N_b) and one collision period (N_c). Thus, $Dpst = 8 + 2 + 1$ = 11 and $p_{cc} = \left(\frac{2+1}{11}\right) * 1 = 0.27$ for the next stage b_{i+1}, while, in the case of a successful transmission, N_c = 0 and N_s = 1.

Furthermore, when a transmitted data frame experiences collision, the value of current contention window W_{bi} of back-off stage b_i at the ith transmission is actively optimised (stepped up) according to the p_{cc} values and when a data frame is successfully transmitted, the current contention window W_{bi} of back-off stage b_i at the ith transmission is also actively optimised (stepped down).

For BEB, b_i describes the number of back-off stages, where $i \in (0,\ m)$ owns an integer value (from 0 up to 5) for the increase or decrease process. However, in the case of CWSB, the current back-off stage b_i does not come to zero or one step reversed after a successful transmission compared to BEB and COSB as shown in Figure 4, respectively. . Moreover, the back-off stage b_i in CWSB at the ith transmission adopts the below property towards increasing or decreasing for the next stage b_{i+1}, and thus:

$$b_{i+1} = \begin{cases} min(b_i + 1,\ up\ to\ m), & ith\ Txn\ collided\ at\ b_i\ stage \\ min(b_i - 2,\ up\ to\ 0), & ith\ Txn\ successful\ at\ b_i\ stage \end{cases} \quad (6)$$

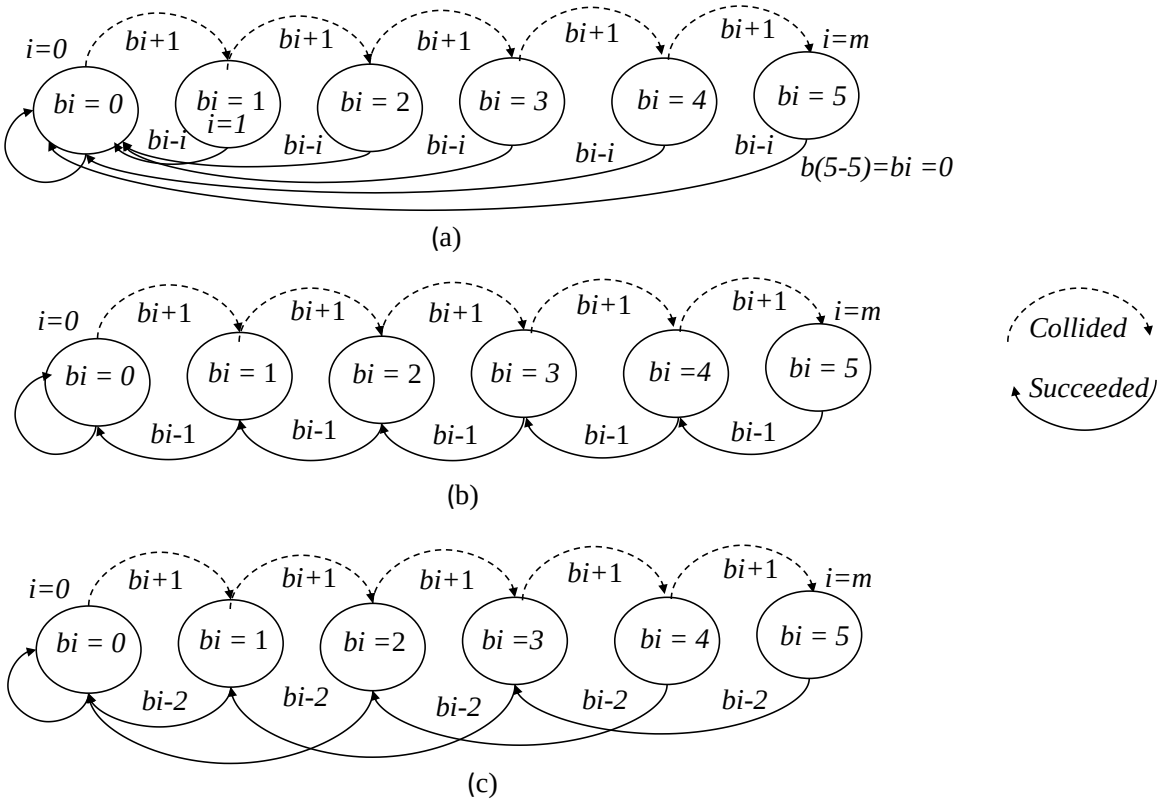


Figure 4. Back-off stage mechanism after collision/successful transmission; (**a**) back-off stage increment/reset in BEB; (**b**) back-off stage increment/reset in COSB; and (**c**) back-off stage increment/reset in the proposed mechanism CWSB.

Figure 4 reveals that the current back-off stage b_i does not come $(i - i)$ to zero or one step reversed after a successful transmission as per BEB and COSB, respectively. Since the current back-off stage for each contending station shows the count of collided or successful data transmissions, it helps to optimize the size of CW more efficiently. The

back-off stage b_i after, increment or decrement results in optimize (stepped up or stepped down) of the current CW_i, respectively. The optimization of CW operates as follows for a contending station.

$$W_{bi+1} = \begin{cases} (2^{bi+1} \times \lambda^{(1+p_{cc})}, W_{max}), \ ith\ Txn\ collided\ at\ b_i\ stage \\ (2^{bi+1} \times \lambda^{(1+p_{cc})}, W_{min}), \ \ ith\ Txn\ successful\ at\ b_i\ stage \end{cases} \quad (7)$$

where λ acts as a constant value to optimise the CW size and is assigned a value as $\lambda = W_{min}$.

Furthermore, Figure 5 describes the major functional comparison of BEB, COSB and CWSB. The working principal of the proposed algorithm is explained in the left highlighted blocks.

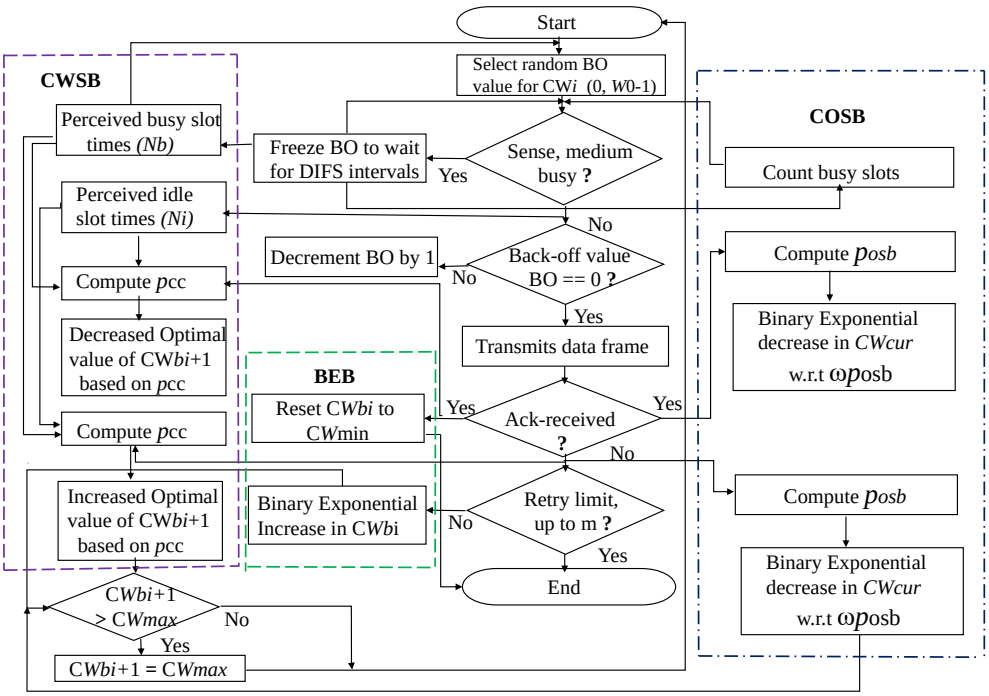


Figure 5. Flow chart comparison of BEB, COSB and the proposed CWSB algorithm.

As shown in left blocks of Figure 5, first, in our proposed CWSB, all contending stations for each ith transmission perceived the medium for the total back-off period to calculate the channel condition collision probability (p_{cc}). Secondly, the next back-off stage ($b_i + 1$) value is obtained based on last collided or successful data transmission. Lastly, the optimized window size is computed for next back-off stage based on pcc and $b_i + 1$ values.

5. Mathematical Modelling of Proposed Algorithm

This section describes a detailed analytical analysis to validate CWSB, the proposed mechanism significantly improves HEW network performances in terms of higher throughput and lower access delay.

Further, the following assumptions are assumed [7], (i) the network has fixed number of contending stations with nonempty queue for data frame transmissions for each calculation, (ii) no hidden stations impacted, (iii) no capture effect, (iv) channel condition is perfect and packet drop is only due to collision during channel contending and data frame transmissions. The analysis of proposed mechanism has been explained in three parts in order to optimize the window size for next back-off stage.

First, CWSB computes channel collision conditional probability (pcc) for each contending station, individually. Secondly, the next back-off stage $bi + 1$ value is obtained based on collided or successful data transmissions. Similarly, the optimized window size (W_{opt}) is computed for next back-off stage based on (pcc) and $bi + 1$ values.

Further, the Iterative Discrete Time Markov Chain (I-DTMC) model implies probability functions along stochastic process to explains the behaviour of each contending station for back-off stages and back-off counter [27], respectively. In addition, the transmission probability τ is derived for each station while receiving the acknowledgement frame.

Hence, normalized throughput is observed as a function of successful transmission in a specific slot time. Finally, the access delay and fairness depend upon the transmission probability τ and the selection of W_{opt}, respectively.

Iterative Discrete Time Markov Chain (I-DTMC) Model

In the I-DTMC model, the transition probabilities are expressed as follows.

1. During the channel contending process, the contending station freezes its back-off counter (c) when a contending station senses that the channel or medium is busy,

$$P\{(b,c)|(b,c)\} = p_b, b \in [0,m], c \in [1, W_i - 1]. \tag{8}$$

2. During the channel contending process, the contending station decrements its back-off counter, when the station senses that the channel is idle,

$$P\{(b,c)|(b,c+1)\} = 1, b \in [0,m], c \in [0, W_b - 2]. \tag{9}$$

3. In the case of a successful data frame transmission at stage 0, station remains at stage 0,

$$P\{(0,c)|(0,0)\} = \frac{1 - pcc}{W_0}, c \in [0, W_0 - 1]. \tag{10}$$

4. In the case of failed transmission at b_i stage , the contending station increments the current CW size and moves towards the next back-off stage from $b-1$ to b, as in Equation (11).

$$P\{(b,c)|(b-1,0)\} = \frac{p_{cc}}{W_b}, b \in [0,m], c \in [0, W_b - 1] \tag{11}$$

5. In the case of successful data frame transmission, the contending station steps down the current CW and decrements its back-off stage from b to $b-1$ for the next transmission attempt, as Equation (12).

$$P\{(b-1,c)|(b,0)\} = \frac{1 - p_{cc}}{Wb - 1}, b \in [0,m], c \in [0, W_b - 1] \tag{12}$$

6. In the case of unsuccessful transmission at $m-1$ stage, the contending station moves to the maximum stage m with probability,

$$P\{(m,c)|(m-1,0)\} = \frac{p_{cc}}{W_m}, b \in [0,m], c \in [0, W_m - 1] \tag{13}$$

7. In the case of unsuccessful data frame transmission at the maximum stage m, the contending station remains at the mth stage.

$$P\{(m,c)|(m,0)\} = \frac{p_{cc}}{W_m}, \;\; b \in [0,m], \;\; c \in [0, W_m - 1] \tag{14}$$

Further, let us assume that, $S_{b,c} = \lim_{t \to \infty} P\{\alpha(t) = b, \beta((t) = c)\}$ is the stationary distribution of the I-DTMC model. Figure 6 shows that it is easy to determine a solution in terms of the transition probability for each state. First, note that:

$$s_{1,0} = \gamma \times s_{0,0} \tag{15}$$

where $\gamma = \frac{p_{cc}}{(1-p_{cc})}$; therefore, the aforementioned equation can be written as, $s_{b,0} = \gamma \times s_{b-1,0}$, similarly $s_{b-1,0} = \gamma \times s_{b-2,0}$ up to $s_{1,0} = \gamma \times s_{0,0}$. Therefore, we can extract as

$$s_{b,0} = \gamma^b \times s_{0,0} \qquad (0 < b < m) \tag{16}$$

for the $m-1$ stage

$$s_{m-1,0} = \gamma^{m-1} \times s_{m,0} \tag{17}$$

and thus by the relations for the m stage, we can write

$$s_{m,0} = \gamma^m \times s_{m,0} \tag{18}$$

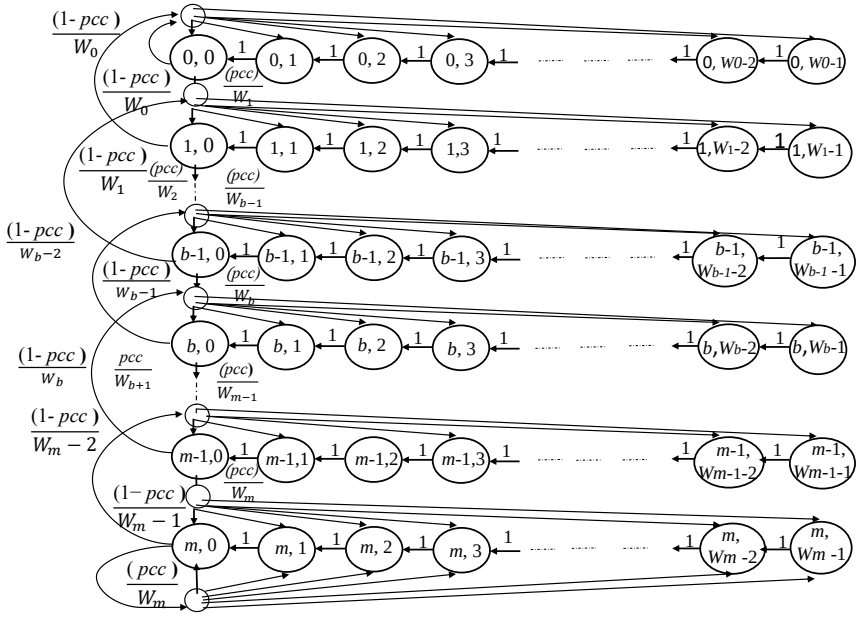


Figure 6. Iterative discrete time Markov chain (I-DTMC) model for the channel collision-based window-scaled back-off (CWSB) mechanism.

Further, a general normalization equation is as follows.

$$\sum_{b=0}^{m} \times \sum_{c=0}^{Wb-1} s_{b,c} = 1 \tag{19}$$

The above equation follows the chain regularities,

$$s_{b,c} = \frac{W_b - 1}{W_c} \times \left\{ \begin{array}{cc} (1-p_{cc}) \times s_{b+1,0} & if\ b = 0 \\ (1-p_{cc}) \times s_{b+1,0} + p_{cc} \times s_{b-1,0} & if\ 0 < b < m \\ p_{cc} \times (s_{m-1,0}) + p_{cc} \times (s_{m,0}) & if\ b = m \end{array} \right\} \tag{20}$$

The iterative characteristic of state transitions probabilities can be written as

$$\sum_{b=0}^{m-1} \times \gamma_b \times\ s_{b,0} + m \times s_{m,0} = \frac{s_{0,\,0}(1 - \gamma^m - m\gamma^m(1-\gamma))}{(1-\gamma)^2} \tag{21}$$

where $\gamma_b = \frac{1-\gamma^m}{1-\gamma}$, $s_{b,0} = \frac{s_{0,0}}{1-\gamma}$, $s_{m,0} = \frac{\gamma^m \times s_{0,0}}{1-\gamma}$, we will find Equation (22), after simplifying the above Equations from (15), (16) and (20), (21)

$$s_{b,\,c} = (\frac{W_b - c)(b+1)}{W_b} \times s_{b,\,0}, \ \ b \in [0, m], \ \ c \in [0, W_b - 1] \tag{22}$$

By solving Equations (15)–(22), where all the values of $s_{b,c}$ in I-DTMC model are presented as dependencies of $s_{0,0}$ and p_{cc}. Similarly, the value of $s_{0,0}$ was finally calculated by normalizing the states of I-DTMC as follows.

$$\sum_{b=0}^{m-1}(b+1)\times s_{b,c}\sum_{c=0}^{Wb-1}\frac{W_b-c}{W_b}+\frac{m\times(W_m-c)}{W_m}s_{m,0}=1 \tag{23}$$

$$\frac{s_{0,0}}{2}\left\{W^{opt}\frac{(1-(2\gamma)^m-m(2\gamma)^m(1-2\gamma))}{(1-2\gamma)^2}\quad+\frac{(1-\gamma^m-m\gamma^m(1-\gamma))}{(1-\gamma)^2}\right\}=1 \tag{24}$$

In order to normalize Equation (24), we assume $W^{opt}=\lambda^{(1+p_{cc})}$, where λ is equal to W_{min}; thus, after taking mathematical steps we have

$$s_{0,0}=\left\{\frac{2(1-\gamma^2)(1-\gamma^m)}{(1-\gamma^m-m\gamma^m(1-\gamma))}\quad\times\frac{1}{((1-2\gamma)(1-\gamma^m)(W^{opt}+1)+\gamma W^{opt}(1-\gamma)(1-(2\gamma)^m))}\right\} \tag{25}$$

Hence, a transmission occurs only when d reaches zero regardless the number of back-off stages. The probability τ that a contending station transmits a data frame in a random chosen slot time is represented as in Equation (26),

$$\tau=\frac{s_{0,\,0}(1-\gamma^m-m\gamma^m(1-\gamma))}{(1-\gamma)^2} \tag{26}$$

Further, in adding the value of $s_{0,0}$ to the above equation, we obtain the final τ for CWSB.

$$\tau=\frac{2}{[1+W^{opt}+(W^{opt}\times\gamma\times\sum_{b=0}^{m-1}(2\gamma)^b)]} \tag{27}$$

The two non-linear equations can be determined together using numerical techniques to find the values of τ and p. In addition, ρ and p_{cc} are replaceable for practical calculations, and the value lies between 0 and a maximum of 1.

However, in general, τ depends upon the value of p_{cc}, which is always unknown until the contending station perceived channel slots during contending process. Due to the steady state, each contending station transmits a data frame with probability τ and p_{cc}, and subsequently, the probabilities p and pb are expressed as follows,

$$p_{cc}=1-(1-\tau)^{n-1} \tag{28}$$

$$p_b=1-(1-\tau)^n \tag{29}$$

where p_b means the collision probability for a busy slot time.

6. Normalized Throughput Analysis

This section describes a detailed analysis towards a major research goal, the calculation of the network throughput. We assume that Φ defines the normalized throughput of the network and can be calculated as the fraction of time the accessed channel is used to successfully transmit mean payload bits by contending station, a general equation is

$$\Phi=\frac{E[mean\ payload\ transmitted\ in\ a\ slot\ time]}{E[total\ length\ of\ a\ slot\ time]} \tag{30}$$

To compute Φ, let τ_{tp} have the probability when at least a (data/control) frame transmission occurs during the examined slot time. Moreover, as the network has n number of contending stations for contending the medium or channel and as each station transmits a data frame with transmission probability τ, the transmission probability τ_{tp} can be defined as.

$$\tau_{tp}=1-(1-\tau)^n \tag{31}$$

Similarly, if τ_{suc} defines the probability for a particular contending station that transmits a data frame in the considered slot time with a successful transmission probability, then τ_{suc} can be computed as

$$\tau_{suc} = \frac{n\tau - (1-\tau)^{n-1}}{\tau_{tp}} \tag{32}$$

Moreover, to compute the value of Φ in terms of a real deployed network can be found as follows,

$$\Phi = \frac{(E[P] \times \tau_{tp} \times \tau_{suc})}{T_{suc} \times \tau_{tp}\tau_{suc} + (1-\tau_{tp})\sigma \ + \tau_{tp}(1-\tau_{suc})T_c} \tag{33}$$

where we assume that all stations have the average identical data frame payload as $E[P]$, and then $E[P] \times \tau_{tp} \times \tau_{suc}$ is the slot time to transmit average data payload successfully, since $\tau_{tp} \times \tau_{suc}$ shows the probability for a successful data frame transmission in a given slot time.

Moreover, the lower part of the above equation is related to the average length of a particular slot time , where (i) $(1-\tau_{tp})\sigma$ means that transmission has not occurred in a slot time, (ii) $(\tau_{tp} \times \tau_{suc})$ belongs to a successfully transmitted data frame, and (iii) τ_{tp} $(1-\tau_{suc})$ shows the collision for a transmitted data frame.

In addition, T_{suc} and T_c shows the average time when the communication channel is sensed as busy due to successful and collided transmissions. To evaluate the analytical approach, the values of $E[P]$, T_{suc}, T_c and idle slot time σ adopt the same time unit. Similarly, $(DF)_{hdr} = PHY_{hdr} + MAC_{hdr}$ defines the time a station takes in transmitting the header of a data frame, and δ represents the propagation delay, whereas $SIFS$ stands for short interframe space, and ACK is the time when an acknowledgment is received after a successful data frame transmission. Thus, the value of T_{suc} and T_c can be obtained for the basic DCF mechanism as shown in Figure 7.

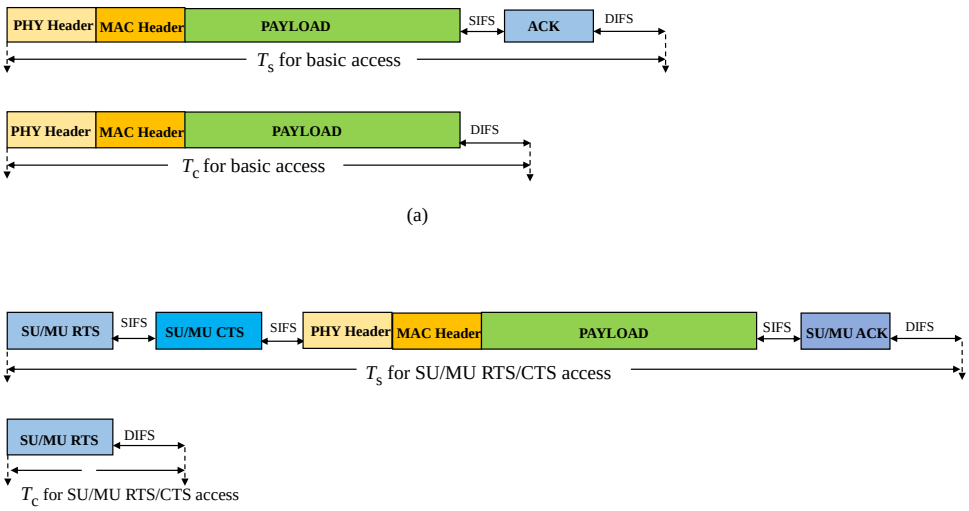


Figure 7. T_s and T_c calculations for the (**a**) basic and (**b**) SU/MU RTS/CTS access mechanism.

$$T_{suc} = DF_{hdr} + E[P] + SIFS + 2\delta + ACK + DIFS \tag{34}$$

$$T_c = DF_{hdr} + E[P] + SIFS + \delta \tag{35}$$

Similarly, DCF with RTS/CTS can be written as follows, where collision can appear in the RTS frame.

$$T_{suc}^{RTS/CTS} = RTS + CTS + DF_{hdr} + E[P] + 3SIFS + 4\delta + ACK + DIFS \tag{36}$$

$$T_c^{RTS/CTS} = RTS + \delta + DIFS \tag{37}$$

More specifically, the exact values of T_{suc} and T_c depend upon the IEEE 802.11 standard.

Further, the authors in [28,29] emphasized considering the impact of hidden nodes for up-link and down-link throughput calculation in the case of a dense network. A fake collision algorithm proposed in [29] allowed a source node more transmission opportunities in the case of more hidden nodes than in the BEB algorithm. Bianchi [7] recommended adopting the RTS/CTS mode in the presence of hidden nodes. Hence, the CWSB mechanism also follows the BEB algorithm to reduce the impact of hidden nodes. A detailed analysis is out of scope for this work.

7. Results and Discussions

The proposed CWSB mechanism was simulated using the ns3 simulator (https://www.nsnam.org/releases/ns-3-34/ (accessed on 30 September 2021)), version 3.34. Further, we also assumed that PHY channel conditions were perfect with no impairments, no neighbour capture, and we focused the performances of the MAC layer. Table 2 summarizes the notations and network parameters used in this analysis. Further, a full-buffer traffic model was supposed for the APs and the connected stations, i.e., they always have a data frame for transmissions. A residential indoor scenario was considered for the evaluation defined by [30] IEEE TGax document. Multiple access points were deployed for network connectivity as shown in Figure 8.

Table 2. Revised simulation parameters.

Parameters	Values
MAC Protocol	EDCA-BE (CSMA/CA)-based
Channel BW	20 MHz
Operating Frequency	5 GHz
Contending Stations	5 to 75
Payload size	1472 bytes
CW_{min}	32
CW_{max}	1024
slot time	9 ms
Simulation time	100–400 s
Distance from Access Point	5/15 m
Propagation loss model	LogDistancePropagation

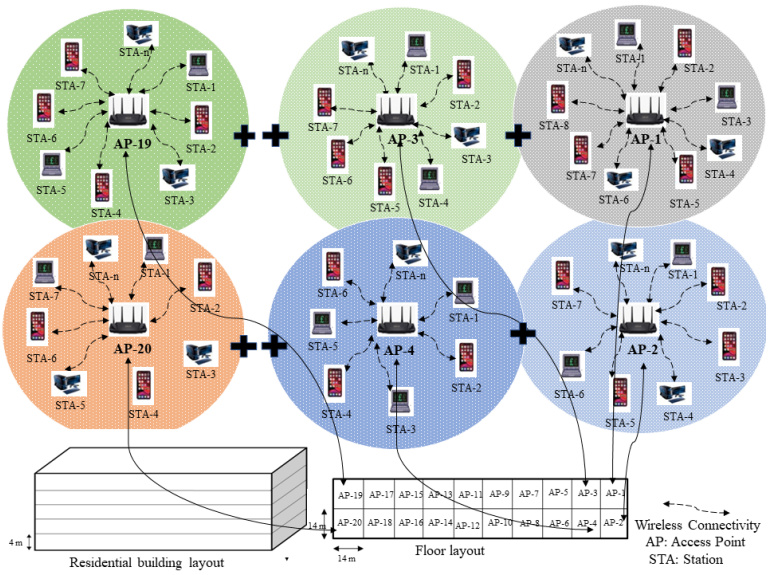


Figure 8. Multiple AP topology for a residential scenario.

Throughput and Delay Analysis

To evaluate the performance of CWSB, the simulation and analytical results are compared with the state-of-the-art BEB and one of the related contention window scaling algorithm term as COSB. Figure 9 describes the performance of BEB in terms of the throughput, which is severely degraded due to its blind increase and decrease of CW size. The COSB scales the contention window by decrementing one after each successful transmission instead of CW to CW_{min} to reduce the channel collision probability, while it takes more time to reach its initial back-off stage. More specifically for dense users, most of the stations remain at a higher contention window and have low accessing rights to access the channel. The performance of COSB is also limited for a higher number of contending stations. CWSB provides increased throughput and a shorter delay for an increased number of contending stations (up to 75 contending stations instead of 50 stations).

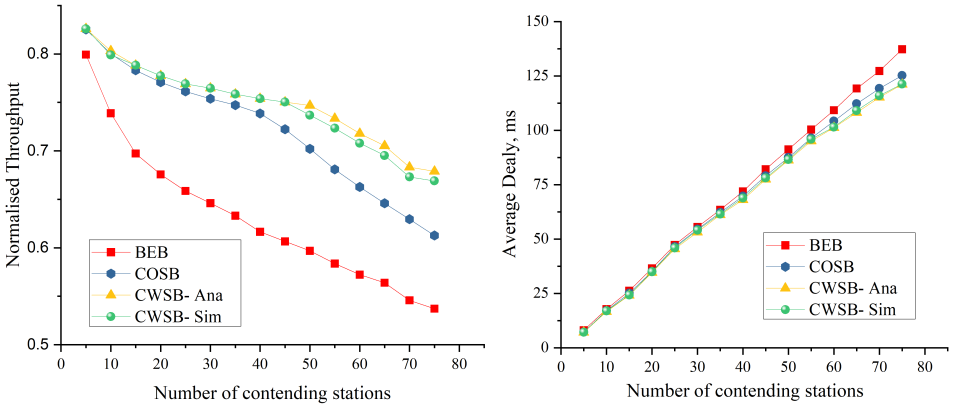


Figure 9. Calculated normalised throughput and average delay under a saturated traffic environment.

Initially, the performance of the proposed mechanism is slightly better than COSB until 40 contending stations, whereas CWSB shows performance enhancement due to an efficient channel collision-based window-scaled back-off mechanism for dense users. Figure 9 illustrates that the CSWB also reduced the average delay for data frame transmissions due to optimal scaling of the contention window size specifically for denser networks.

Furthermore, Figure 9 also represents that the analytical model of CWSB is accurate due to the analytical results (CWSB-Ana) being closely matched with the simulation results (CWSB-Sim) for improved normalised throughput and lower average delay calculations. This minor difference between the analytical analysis and simulation results is due to several reasons, such as (i) the calculation of τ and p_{cc} belonging to a non-linear system. In addition, (ii) T_{suc} also accounts for the value of several parameters (DF_{hdr}, $E[P]$, $SIFS$, 2δ, ACK and $DIFS$) as mentioned in Equation (35).

Further, Figure 10 reveals the normalised throughput and average delay for an unsaturated traffic environment with a varying number of contending stations and varying the offered load (packets/s). Figure 10 also shows that the normalised throughput increases linearly with the traffic arrival rate at first for all mechanisms (BEB, COSB and CWSB) until saturation is obtained for approximately 15 contending stations, whereas the throughput performance starts to decrease badly for BEB and slightly for COSB, while CWSB provides enhanced throughput towards an increased number of contending stations. In addition, Figure 10 also shows a similar behaviour for the reduced average delay towards the considered protocols.

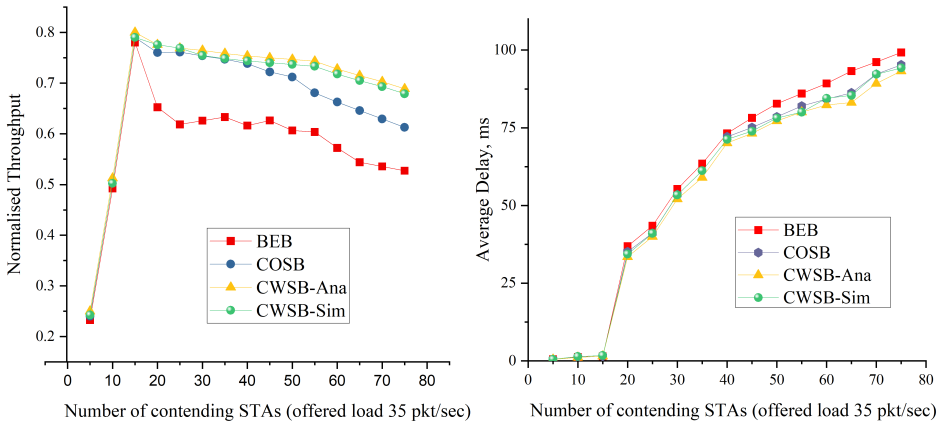


Figure 10. Calculated normalised throughput and average delay under an unsaturated traffic environment.

Figure 11 presents the normalised throughput performance under an unsaturated environment for various offered loads that considered 10 and 30 contending stations. Figure 10 also reveals that the throughput of CWSB depends on the number of contending stations or the saturation of the network. Although, for fewer number of users (i.e., 10 contending stations), the normalised throughput had same results until the offered load increased and more stations transmitted the data. However, Figure 10 also shows the degraded performance of BEB, when the number of contending stations increased up to $n = 30$. In this scenario, the COSB performed better than BEB, whereas CWSB had enhanced throughput even for a higher number of contending stations along with a higher load.

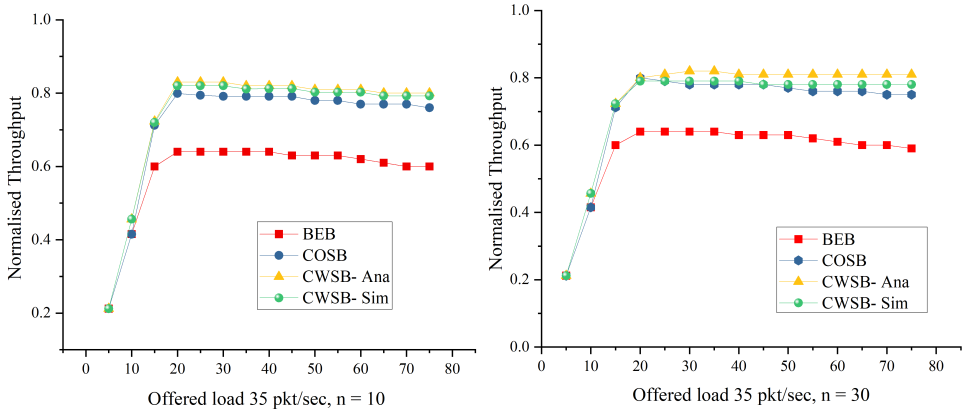


Figure 11. Normalised throughput under an unsaturated traffic environment.

Figure 8 shows an indoor dense scenario building of five floors, where each floor has 20 apartments, and each floor has one AP. Further, it is necessary to consider that all contending stations (from station-1 to station-n) are placed at fixed positions for each AP, and the topology is assumed to be static. In a floor layout, 20 APs are installed, and all contending stations follow the CWSB mechanism for transmission opportunities as shown in Figure 3. Furthermore, Figure 12 shows the performance of CWSB considering the scalability for the increased number of APs (we show the performance of AP-1 to AP-5). Figure 8 reflects a grid topology where corner APs (AP1- and AP-2) show a slightly higher normalized throughput and low average delay (with respect to AP-3, AP-4 and AP-5 where fewer contending stations face a higher probability of collision due to the nodes of the neighbouring APs).

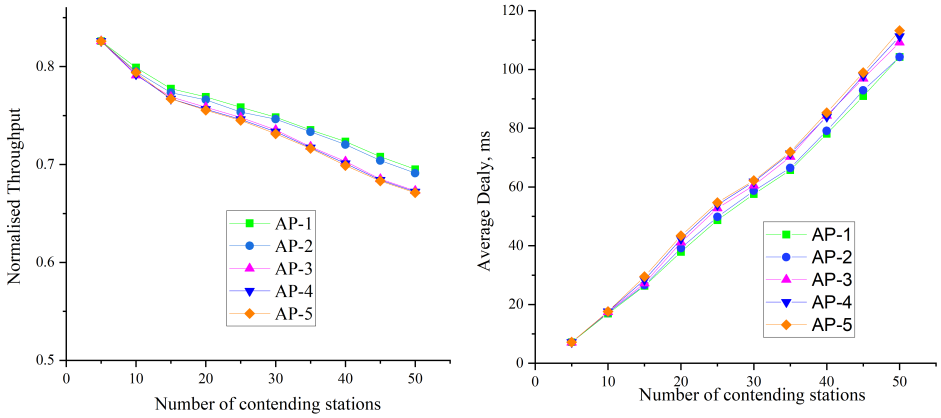


Figure 12. Scalability analysis of the CWSB mechanism for multiple APs.

In COSB, the *CW* size of some contending stations increases and suffers from a fairness issue due to repeatedly operating at higher back-off stages or *CW* size, and a few fortunate contending stations can operate at a lower back-off stage or smaller *CW* size. Further, under COSB, once the contending station reaches a higher back-off stage, it has to deliver several successful data frames to return to the lower back-off stage or smaller *CW* size, which seems challenging due to the high probability in a dense network. The proposed CWSB brings better fairness to the contending stations because every contending station has more opportunities to return to the lower back-off stage or smaller *CW* size.

Figure 13 shows the throughput comparison of BEB, COSB and CWSB for indoor residential dense scenarios. Performance logs reveal that the CWSB mechanism optimizes *CW* to improve the throughput and reduce collision probabilities compared to BEB and COSB, respectively. Further, CWSB provides better channel access opportunities to the contending stations in a dense environment due to the optimized window-scaled back-off mechanism.

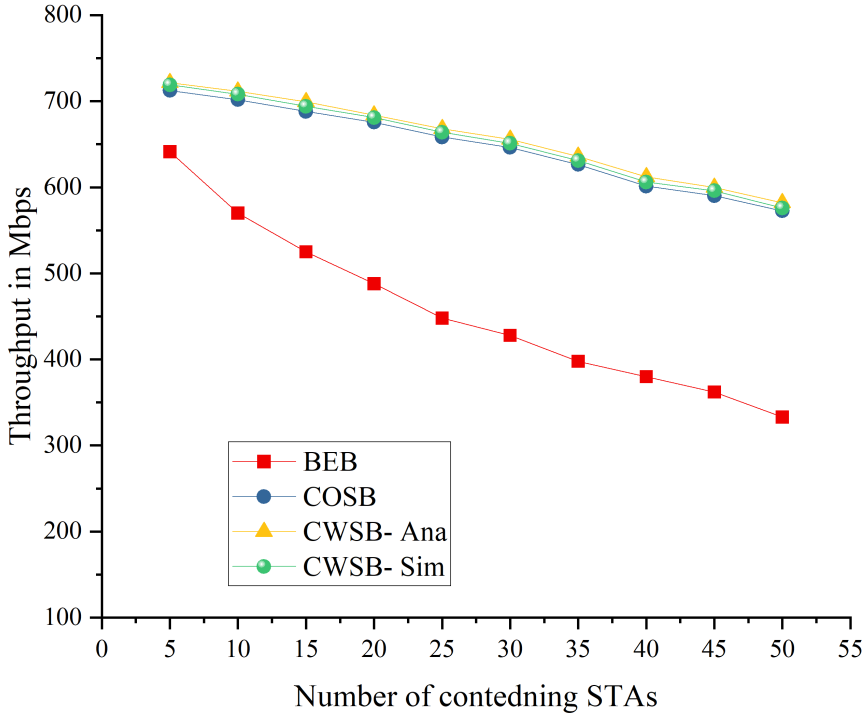


Figure 13. Throughput comparison of BEB, COSB and CWSB for an indoor residential scenario.

Per-station throughput evaluation metrics are suggested by 11ax TG, such as (i) at the 5th percentile (the minimum throughput of stations measured at the cell edge), (ii) at the

50th percentile (average throughput of stations measured in the simulation) and (iii) at the 90th percentile of per-station throughput (top performance throughput of stations at the cell centre of BSS or a deployed HEW network). Per-station performance at the 50th percentile throughput of CWSB is shown in Figure 14 for various numbers of contending stations.

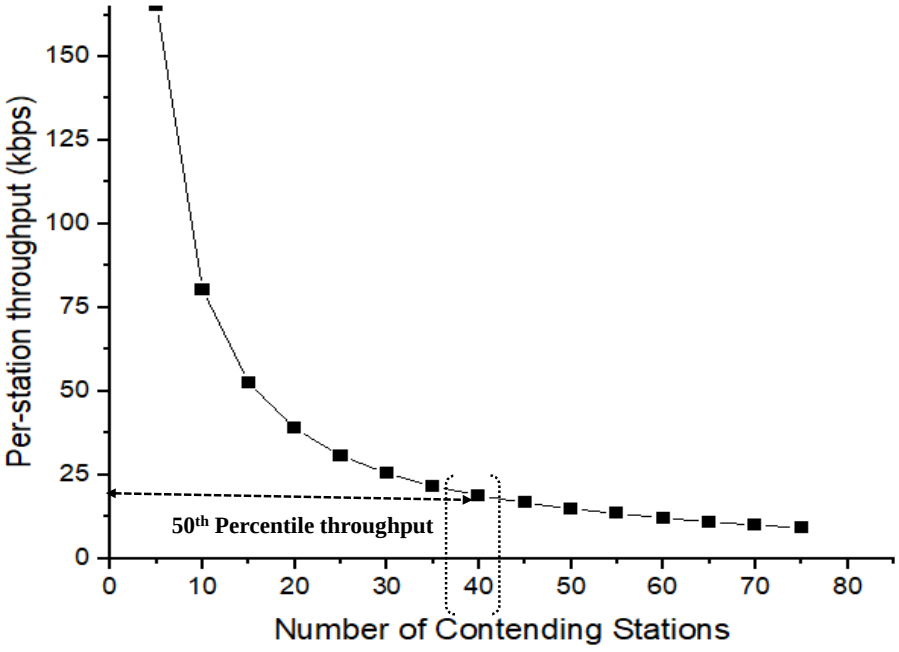


Figure 14. Per-station 50th percentile throughput for CWSB.

8. Conclusions

Wireless local area networks (WLANs), known as Wi-Fi, are widely deployed to meet the enhanced needs of data-centric internet applications, such as wireless docking, unified communications, cloud computing, interactive multimedia gaming, progressive streaming, support of wearable devices, up-link broadcasts and cellular offloading. The Wi-Fi network adopts Distributed Coordination Function (DCF)-based Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), which uses the Binary Exponential Back-off (BEB) algorithm at the MAC layer mechanism to access channel resources.

Currently deployed Wi-Fi networks face huge challenges towards efficient channel access for denser environments due to the blind exponential increase/decrease of a contention window (CW) procedure that is inefficient for a higher number of contending stations. Several modifications and amendments have been proposed to improve the performance of the MAC layer channel access based on a fixed or variable CW size. However, a more realistic network density-based channel resource allocation solution is still missing.

An efficient channel resource allocation is one of the most critical challenges for future highly dense WLANs, such as High-Efficiency WLAN (HEW). In this paper, we proposed a Channel Collision-based Window-Scaled Back-off (CWSB) mechanism for channel resource allocation in HEW. In our proposed CWSB, all contending stations select an optimized CW size for each back-off stage for collided or successfully transmitted data frames.

We affirmed the performance of the proposed CWSB mechanism with the help of an Iterative Discrete Time Markov Chain (I-DTMC) model. This paper evaluated the performance of our proposed CWSB mechanism in HEW Wi-Fi networks using an NS3 simulator in terms of the normalized throughput and channel access delay compared to the state-of-the-art BEB and a recently proposed mechanism. Hence, simulation results show that the CWSB provides improved throughput and shorter delay for an increased number of contending stations (up to 75 contending stations instead of 50 stations) and was improved for denser networks in terms of the throughput and access delay.

The CWSB focused on improvements of the throughput and average access delay for dense networks, and future work should aim the scheduling and resource allocation for dense users to improve the fairness and area throughput as network metrics.

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Abbreviations

The following abbreviations are used in this manuscript:

AP	Access Point
BSS	Base Service Set
BO	Back-Off Counter
BEB	Binary Exponential Back-off
CS	Carrier Sense
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CW	Contention Window
CTS	Clear-to-Send
DIFS	DCF Inter-Frame Space
DCF	Distributed Coordination Function
EDCA	Enhanced Distributed Channel Access
ECA	Enhanced Collision Avoidance
HEW	High-Efficiency WLANs
I-DTMC	Iterative Discrete Markov Chain model
MAC	Medium Access Control
MU-RTS	Multi-User Request-to-Send
MU-CTS	Multi-User Clear-to-Send
NAV	Network Allocation Vector
RTS	Request-to-Send
station	Station
SIFS	Short Inter-Frame Space
TXOP	Transmission Opportunity
TF	Trigger Frame
WLAN	Wireless Local Area Network
p_{cc}	Channel collision probability
τ_{tp}	Transmission probability
W^{opt}	Window optimization
τ_{suc}	Successful transmission probability
δ	Propagation delay

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