Received <day> <Month>, <year>; | Revised <day> <Month>, <year>; | Accepted <day> <Month>, <year>

DOI: xxx/xxxx

ARTICLE TYPE

Enhanced Collision Resolution and Throughput Analysis for the 802.11 Distributed Coordination Function

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Abstract

The IEEE 802 standards rely on the distributed coordination function (DCF) as the fundamental medium access control method. DCF uses the binary exponential backoff (BEB) algorithm to regulate channel access. The backoff time determined by BEB depends on a contention window (CW) whose size is doubled if a station suffers a collision and reset to its minimum value after a successful transmission. Doubling the size of CW reduces channel access time, which decreases the throughput. Resetting it to its minimum value harms fairness since the station will have a better chance of accessing the channel compared to stations that suffered a collision. We propose an algorithm that addresses collisions without instantly increasing the CW size. Our algorithm aims to reduce the collision probability without affecting the channel access time and delay. We present extensive simulations for fixed and mobile scenarios. The results show that, on average, our algorithm outperforms BEB in terms of throughput and fairness. Compared to exponential increase exponential decrease (EIED), our algorithm improves, on average, throughput and delay performance. We also propose analytical models for BEB, EIED, and our algorithm. Our models extend Bianchi's popular Markov chain-based model by using a collision probability that is dependent on the station transmission history. Our models provide a better estimation of the probability that a station transmits in a random slot time, which allows a more accurate throughput analysis. Using our models, we show that both the saturation throughput and maximum throughput of our algorithm are higher than those of BEB and EIED.

KEYWORDS:
Distributed coordination function, IEEE 802.11, medium access control, collision resolution, delay, throughput, fairness, binary exponential backoff.

1 | INTRODUCTION

The distributed coordination function (DCF) is a carrier sense multiple access with collision avoidance (CSMA/CA) protocol [1]. DCF uses a slotted binary exponential backoff where stations can only transmit at the beginning of each slot. The protocol operates as follows: a station wishing to transmit must first sense the channel. If the channel is sensed free, the station waits a specified time called DCF inter-frame space (DIFS) and transmits a frame if the channel remained free during that time. If the channel is sensed busy, the station waits for the DIFS duration plus a random period of time called backoff time (BO) before transmitting. The backoff time is adjusted using the binary exponential backoff (BEB) algorithm[1].

The backoff process in BEB is simple and can be summarised as increasing the contention window size upon a collision and reducing it upon successful transmission. Each station initially sets its backoff time to $r \cdot \sigma$, where r is a random integer in the range $(0, CW]$, CW is the contention window (CW) size, and σ is the slot time. Then, the station senses whether the channel is idle for the given slot time. If the channel is idle, then the station reduces its backoff time by one slot time. Otherwise, the station pauses its backoff time (the station will resume it once the channel is idle again). Once the backoff time reaches zero, the station is allowed to transmit.

If two or more stations have the same initial value for the backoff time, a collision will occur. In this case, to reduce the collision probability in retransmission, the colliding stations double their CW size, and the backoff time is updated using the new CW size. The exponential increment of CW continues until the transmission is successful or the packet transmission retry limit is reached (the retry limit is 4 for short packets and 7 for long packets)[1]. The value of CW is doubled until it reaches a maximum value ($CW_{\max}$). Upon a successful transmission, BEB resets CW to its minimum value ($CW_{\min}$). In IEEE 802.11, the default values for $CW_{\min}$ and $CW_{\max}$ are 31 and 1023, respectively[1,2].

Doubling CW upon collision reduces channel access time, which decreases the throughput. Moreover, doubling CW to reduce the collision probability becomes less efficient as the number of active stations increases. For example, increasing CW from 31 to 63 reduces the collision probability by 47% for five active stations, while it reduces the collision probability by 3% only for twenty active stations. On the other hand, resetting CW to its minimum value upon successful transmission harms fairness as the station will have a smaller CW and therefore a better chance of accessing the channel compared to stations that suffered a collision.

To improve the performance of DCF, we propose a collision resolution method that reduces the collision probability without instantly doubling CW. Our method resolves collisions once they occur without harming channel access time by keeping CW relatively small compared to BEB. This is achieved by doubling CW only if collisions reoccur in a retransmission.

We implement our enhanced collision resolution algorithm (ECRA) using exponential increment, exponential decrement (EIED) to adjust CW. We opted for an exponential decrease rather than a CW reset to maintain fairness among competing stations. Since our algorithm does not increase CW instantly upon collisions and keeps CW small, the exponential decrease does not affect channel access time significantly. Our collision resolution method is generic and can operate over different increment/decrement mechanisms.

Our algorithm does not involve any complex calculations or estimations. We use three new variables to calculate CW for each station: (1) CW_T, a variable used to store a temporary value picked from the range $(0, CW_{\max}]$, (2) Retransmission Factor RF, with an initial value equal to $CW_{\min}$, and (3) Retransmission Timer RT, which is used to differentiate a collision resolution state (RT is odd) from a normal state (RT is even). Each station picks a value to update its CW by dividing CW_T by RF. If a collision occurs, the station reduces the collision probability by updating CW as the remainder of the division of CW_T by RF rather than instantly doubling CW, as in BEB. Our method guarantees that a collision reoccurs only if two or more stations pick the same value from the range $(0, CW_{\max}]$ to update their CW_T. If a collision reoccurs in retransmission, then CW is increased. Moreover, ECRA works well irrespective of the reason for the failure as it does not try to predict failures or estimate channel conditions. Like BEB, it treats all failed transmissions as collisions, irrespective of whether the failure was due to noise, a weak signal, or collisions.

Due to the extensive use of DCF in almost every wireless network[3] and the effectiveness of its CSMA/CA mechanism, several works[4,5,6,7,8,9] have proposed theoretical models to analyze its performance. These models are based on Markov chains and assume saturated conditions, ideal network conditions (i.e., no hidden stations), and decoupling[10]. The decoupling assumption implies that the backoff processes at different nodes are independent[10] and leads to a collision probability that is independent of the station transmission history. This yields an inaccurate estimation of the probability that a station transmits in a random slot time and results in an inaccurate throughput analysis. To address this limitation, we extend these models by using a collision probability that is dependent on the station transmission history.

This paper is based on the first author's PhD thesis[11]. In Section 2, we review related work, covering both backoff algorithms and analytical models. In Section 3, we present our first contribution, a new collision resolution algorithm called ECRA. In Section 4, we compare the throughput, fairness, and delay performance of ECRA to those of BEB and EIED for both static and mobile environments. In Section 5, we present our second contribution, analytical models for BEB, EIED, and ECRA. We derive for each algorithm the probability that a station transmits in a random slot time and use this probability to compare the theoretical saturation throughout and maximum throughput of the three algorithms. Section 6 summarizes our main conclusions.

2 | RELATED WORK

Several algorithms were proposed to enhance the performance of BEB. These algorithms can be split into two main categories. The first one follows the BEB process in using fixed parameters while changing the method to increment or decrement CW. The second category tries to determine an adaptive CW size based on different parameters, such as the number of active stations, the channel status, and the transmission history, along with other parameters. Algorithm 1 and Fig.1 describe the BEB process in detail.

Algorithm 1. BEB[1]

Input	$CW_{max}, CW_{min}, \sigma$
Initialize	$CW = CW_{min}$
Step 1	$BO = rand(1, CW) * \sigma$
Step 2	**while** ($BO \neq 0$ and channel is $idle$) **do**
	$BO = BO - \sigma$
	end while
Step 3	$Transmit$
	if $successful\ transmission$ **then**
	$BO = 0$
	$CW = CW_{min}$
	else
	$CW = \min((CW + 1) * 2 - 1, CW_{max})$
	$go\ to\ step$ 1
	end if

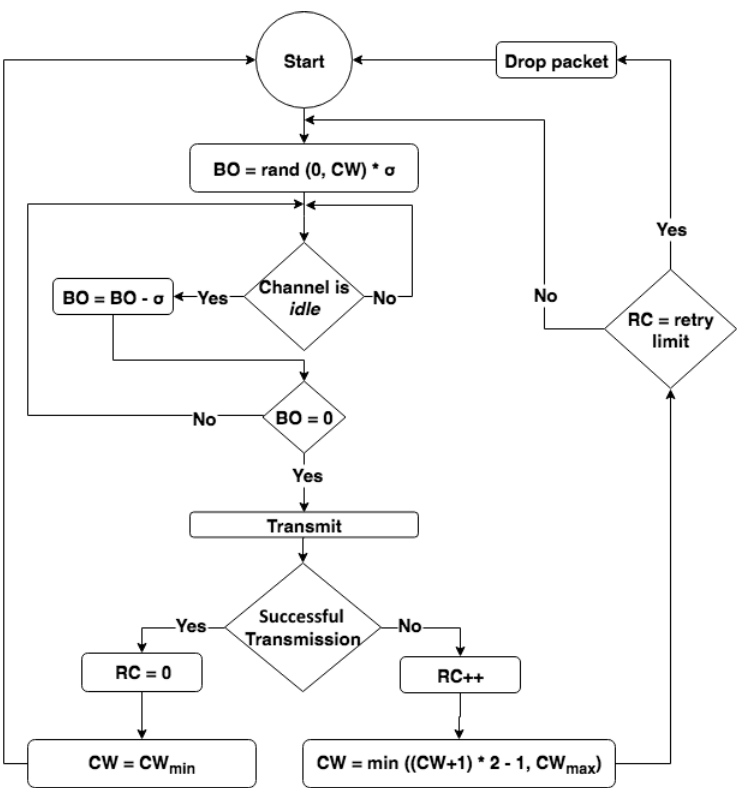

Figure 1 BEB flowchart[1]

Early ideas in the first category focused on replacing the exponential increase in BEB with a less aggressive increase to maintain fairness, and replacing the sudden reset of CW with a gradual decrease. Such methods include multiple increase linear decrease (MILD)[12], EIED[13], exponential increase linear decrease (EILD)[14], and gradual DCF (GDCF)[15,16].

Though the previously discussed methods propose slight changes to the standard and require no complex computations, replacing the exponential increase with a less aggressive one increases the collision probability. Furthermore, a gradual decrease reduces channel usage time since colliding stations will require consecutive successful transmissions to decrease CW.

The backoff algorithms in the second category focus on collecting feedback from the network to adjust CW. Based on the collected feedback, stations calculate and estimate several parameters, including the channel busyness ratio and the number of active stations. The collected feedback will later be used to find an optimal CW size that reflects the network status. Based on their main operation, the methods in this category can be further classified into different approaches: channel status observation, slot time reservation, collision detection and elimination, and estimation of the number of active stations.

An optimal CW size based on the channel status is the highlight of the backoff algorithms presented in[17,18,19,20,21,22,23,24,25,26,27,28,29,30,31]. The main idea in these algorithms is that stations will continue monitoring the channel to collect information about the slot time lengths, successful transmissions, failed transmissions, and other factors. Though these algorithms provide a useful method to calculate CW based on channel status, they require stations to continue collecting data from the network. Continually sensing the channel will consume the station energy, especially if the station is not interested in transmission. Furthermore, these algorithms assume that all collected data are accurate, ignoring the possibility of packet errors and the effects of hidden stations. Another shortcoming of these methods is the nature of wireless ad hoc networks (WANETs), which may change dramatically in seconds, meaning that the collected data reflect the previous channel status rather than the current one.

To improve fairness and throughput, the algorithms presented in[32,33,34,35,36,37,38] use slot reservation and announcement to create a collision-free environment. In this approach, the main idea is to distribute channel access fairly among competing stations. The main limitation of the previously discussed algorithms is the assumption that the number of stations is fixed in the long run, and therefore, it is possible to distribute the channel fairly among competing stations. This assumption contradicts the very nature of WANETS, in which stations can join and leave on the fly. Another problem with the previously discussed algorithms is that the assumption that all stations are constantly active is incorrect; therefore, inactive stations will obtain a channel share, and they require complex computations, which can affect the energy consumption, especially in sensor networks.

Focusing on an effective and collision-free method to distribute channel access among stations, the work in[39,40] follows an approach similar to token networks. The same concept is used in[41,42,43,44,45,46]. The works presented in[47,48,49,50,51,52,53] follow an approach similar to the collision detection technique used in Ethernet. Finally, in[54] stations are divided into subsets, with multiple contention rounds for each subset. The main setback of this approach is the delay caused by the extra elimination rounds that each station must go through.

Several methods have focused on the relation between the number of active stations and the CW size[55,56,57,58,59,60,61,62,63,64]. These methods assume that an optimal CW size must take into account the number of active stations in a channel. Since the nature of WANETS makes it very difficult to determine the number of active stations[21], these methods use feedback from the network to estimate the number of active stations.

In[65], the authors propose two algorithms: fast collision resolution (FCR) and real-time FCR (RT-FCR). FCR incorporates several enhancements to the standard algorithm, as it sets $CW_{\min}$ to a significantly lower value and sets $CW_{\max}$ to a significantly higher value compared to BEB. FCR updates CW for competing stations by monitoring their transmission history. RT-FCR is an updated FCR algorithm to improve fairness and QoS for real-time applications. RT-FCR modifies FCR by using the distributed self-clocked fair queueing (DSFQ) technique presented in[66,67], in addition to the service differentiation introduced in[68,69].

In the sensing backoff algorithm (SBA)[70], upon successful transmission, the sender and receiver decrease their CW size, their neighbours decrease their CW values by a lesser amount, and colliding stations increase their CW. The CW increment and decrement are updated using a factor derived from the number of active stations. This algorithm assumes that all stations are within range of each other. The Successful Transmission Priority (STP)[71] follows a similar concept but focuses on prioritizing stations with successful transmission. STP may improve throughput when the number of stations is low but it will harm fairness as colliding stations will have less chance of accessing the channel.

The work in[72] uses a Kalman filter to estimate the number of active stations based on the collision probability. The estimated number of active stations is then used to calculate an optimal CW. Following the same principle, the dynamic optimisation protocol (DOP) in[73] uses the Bayesian estimator presented in[74] instead of the Kalman filter. The Bayesian estimator is based on the sequential Monte Carlo methodology presented in[75].

In[76], the authors propose CW size optimisation based on geometric densities. Stations have different backoff intervals based on their neighbours and their transmission history. The quadratic backoff algorithm[77] adjusts CW using a polynomial function. The growth rate of the polynomial function is based on the channel conditions and the network size. The renewal access protocol (RAP) algorithm[78,79] uses a fixed-size CW for all stations, and the backoff time is decreased by one slot time upon successful transmission only. The main shortcoming of this method is that it assumes a fixed number of stations. Oh et al.[80] address this limitation by introducing an adaptive RAP algorithm.

Considering the nature of WANETs and the fact that in such networks the number of stations is continuously changing, the work in[81] estimates the number of active stations at every time instant. Finally, in the adaptive contention window control algorithm[82], each station updates its CW by calculating the collision probability based on the number of active stations.

The main limitation in estimating the number of active stations is that it is practically unforeseeable in WANETs, especially at runtime[65,74,54,61,17]. Moreover, the possibility of estimation errors will result in inaccurate CW adjustments. Another limitation of this approach is that stations must estimate the number of active stations at every time instant since in WANETs that number changes continuously. Furthermore, the assumption that active stations remain active is invalid since in WANETs, stations change their status regularly.

In[83,84], it is noted that an unsuccessful transmission may be due to factors other than collisions, and BEB is enhanced with a capability to differentiate between different types of unsuccessful transmissions.

Unlike previous work, our algorithm does not instantly increase the CW size when a collision occurs. Furthermore, our algorithm does not try to estimate the number of active stations or the channel status as accurate estimations are very challenging in wireless networks due to their dynamic nature.

Several analytical models to analyse the performance of DCF have been proposed. Most of the models adopt the same framework as Bianchi's model due to its applicability and predictive accuracy[6]. These models extended Bianchi's framework to address different network conditions and various CSMA/CA schemes[8,7].

The models in[85,86,87,88,89,90,91,92,93,94,95,96] follow the same framework as Bianchi's to analyse the performance of IEEE 802.11 DCF under saturated conditions. The model presented in[85] extends Bianchi's model by setting a fixed retry limit in retransmissions similar to the retry limit in the IEEE 802.11 standard[1]. Alshanyour and Agarwal[94] use a three-dimensional Markov chain and differentiate between short and long packet retry limits.

The effect of the previous backoff stage on the current one is the main idea in[87,88], where the authors suggest taking into account the current backoff stage and the current backoff counter when calculating the transition probability. The model in[93] extends Bianchi's model by introducing the effect of backoff freezes in the DCF analysis. The same concept is proposed in[89,90], where the authors present an analytical model to analyse the throughput and packet delivery ratio.

The main shortcoming of the previous models is that focusing on backoff freezes under saturated conditions will not provide an accurate throughput analysis. Since the next slot time after a successful transmission can only be accessed by the station that successfully transmitted, and the next slot time after a collision cannot be accessed by any station[1,97], backoff freezes become insignificant for throughput analysis.

The model presented in[95] extends Bianchi's model by adjusting multiple collisions probabilities for multiple consecutive transmissions in a one-dimensional Markov chain. The problem with this model is that these collision probabilities do not take into account the number of active stations in the network. The work in[91,92] extends Bianchi's model by using variable data rates rather than a constant one.

Vishnevsky and Lyakhov[98] extend Bianchi's model by considering the seizing effect. The idea is to split the stations into two main categories: privileged stations (stations that have successfully transmitted and thus have a better chance of accessing the channel) and ordinary stations (the remaining stations). The authors show how taking the seizing effect into consideration allows to improve the estimation of the saturation throughput under ideal conditions.

The models presented in[99,100,101,102] focus on unsaturated conditions, suggesting that saturated conditions are rarely applicable in WANETs. In[103], the authors extended Bianchi's model by considering the hidden station effect. The models presented in[104,105,106] extend Bianchi's model by assuming non-ideal network conditions.

The analytical model presented in[107,108] extends Bianchi's model by considering the effects of dropped packets due to retransmission limits on the average delay. Following the same concept, the models in[109,110,111] include throughput and delay analysis. A four-dimensional Markov chain model is introduced in[112], in which the authors integrate a retransmission limit, data load and finite buffer capacity in the model.

Focusing on QoS, the works in[113,114,9] extend Bianchi's model to analyse throughput under saturated conditions in IEEE 802.11e. The work in[115,116,117,118] extends Bianchi's model to analyse throughput under unsaturated conditions in 802.11e.

Xiao [119,120] extends Bianchi's model by introducing a priority scheme in 802.11 and 802.11e, assuming unsaturated conditions. The model proposed in [121] aims to improve the accuracy of Bianchi's model, especially when the CW is low. This is done by taking into account sender priority and packet loss rate.

Compared to this previous work, our model allows a more accurate calculation of the collision probability in each backoff stage by taking into account the number of stations and the collision probability in the previous backoff stages.

3 | ENHANCED COLLISION RESOLUTION ALGORITHM (ECRA)

The main idea of ECRA is using a collision resolution method to replace the instant increase of the CW size. The collision resolution method is used to reduce the collision probability without negatively affecting channel access time. We aim to improve throughput and fairness without significantly affecting delay.

ECRA does not involve any complicated calculations. In ECRA, we introduce three extra variables: CW_T, which holds a temporary CW value between 0 and $CW_{\max}$; RF, which is used to calculate the initial value of the backoff time; and RT, which is used to differentiate a collision resolution state (RT is odd) from a normal state (RT is even).

ECRA applies the collision resolution method when RT indicates a collision resolution state (RT is odd). If RT indicates a normal state, then ECRA uses the exponential increment/decrement. The initial value of RT is 0, and RF is set to its maximum value, which is equal to $CW_{\min}$.

In ECRA, if a station wishes to transmit, it must update its CW_T using eq. (1).

$$CW_T = rand(1, CW_{\max}) \tag{1}$$

where $rand(a, b)$ is a function that generates a random integer in $[a, b]$. The station then updates its CW using eq. (2) if RT is even and eq. (3) if RT is odd.

$$CW = \lfloor \frac{CW_T}{RF + 1} \rfloor \tag{2}$$

$$CW = CW_T \mod \lfloor \frac{CW_{\max} + 1}{RF + 1} \rfloor \tag{3}$$

Upon collision, the station increases RT to enter a collision resolution state while maintaining the same CW size. ECRA reduces the collision probability by using eqs. (2) and (3); thus, it will guarantee that for a collision to reoccur in re-transmission, two or more stations must pick the same value for CW_T from $(0, CW_{\max}]$.

To illustrate the process, let us consider an example with five active stations. A collision will occur if two or more stations picked the same value from (0,31] ($CW_{\min}$=31). To reduce the collision probability in re-transmission, BEB doubles the CW size to 63. Similarly, a collision will reoccur if two or more stations picked the same value from (0,63]. In ECRA, for a collision to reoccur in re-transmission, two or more stations must select the same value from (0,1023] ($CW_{\max}$=1023). The example shows that the collision resolution method in ECRA is more effective at reducing the collision probability compared to the immediate increase of the CW size that BEB uses upon collisions.

If a collision still occurs, then RT is increased further, entering a normal state (RT is even). In this case, ECRA increases the CW size by reducing RF. Each time that RT is even and the station suffers a collision, ECRA increases the CW size exponentially by reducing RF until it reaches its minimum value of two. ECRA increases the CW size if and only if the collision resolution method was not successful.Upon successful transmission, ECRA decreases the CW size exponentially by increasing RF until it reaches its maximum value, which is equal to $CW_{\min}$. In the meantime, ECRA resets the value of RT to zero, indicating a successful transmission.

However, during the collision resolution state, interference may occur due to new transmissions by other stations. For this reason, we update eq. (3) by adding the current CW size (eq. (4)). ECRA resolves collisions by calculating the remainder value between colliding stations. This guarantees a collision will only occur if the colliding stations picked the same value from the range $(0, CW_{\max}]$. To prevent any collision with other stations that did not participate in the previous collision, ECRA adds the current CW size to the updated CW of the colliding stations.

$$CW = \lfloor \frac{CW_{\max} + 1}{RF + 1} \rfloor - 1 + CW_T \mod \lfloor \frac{CW_{\max} + 1}{RF + 1} \rfloor \tag{4}$$

Using eq. (4), we reduce the collision probability for colliding stations without instantly increasing the CW size.

The ECRA process and collision resolution method are detailed in Algorithm 1 and Fig.2.

Algorithm 2. ECRA

Input	$CW_{\max}, CW_{\min}, \sigma$
Initialise	$RF = CW_{\min}, RT = 0, CW = CW_{\max}$
Step 1	**if** $RT\ is\ even$ **then**
	$CW_T = rand(1, CW_{\max})$
	$CW = \lfloor \frac{CW_T}{RF+1} \rfloor$
	else
	$CW = \lfloor \frac{CW_{\max}+1}{RF+1} \rfloor - 1 + CW_T \mod \lfloor \frac{CW_{\max}+1}{RF+1} \rfloor$
	end if
	$BO = CW * \sigma$
Step 2	**while** ($BO \neq 0$ and channel is $idle$) **do**
	$BO = BO - \sigma$
	end while
Step 3	$Transmit$
	if $successful\ transmission$ **then**
	$RF = \min(\lfloor (RF + 1) * 2 - 1 \rfloor, CW_{\min})$
	$RT = 0$
	else
	if $RT\ is\ even$ **then**
	$RT + +$
	$go\ to\ Step\ 1$
	else
	$RF = \max(\lfloor \frac{RF+1}{2} \rfloor - 1, 2)$
	$RT = 0$
	$go\ to\ Step\ 1$
	end if
	end if

4 | ECRA PERFORMANCE ANALYSIS

This section presents the benchmark algorithms, the simulation settings, and the simulation results in both fixed and mobile scenarios.

4.1 | Benchmark Algorithms

We chose EIED[13] and BEB as our benchmark algorithms. We chose EIED because like BEB and our algorithm, it does not require any feedback from the network, and it does not rely on estimations. Note that, EIED is a common benchmark scheme and was used as a benchmark algorithm in many previous papers[82,122,123,77,124,125,126,127].

Moreover, since our algorithm exploits an exponential increment/exponential decrement technique, similar to the one used in EIED, it is important to compare its performance to that of EIED to show the added value from our contribution. We implemented EIED as described in Algorithm 2 and Fig.3.

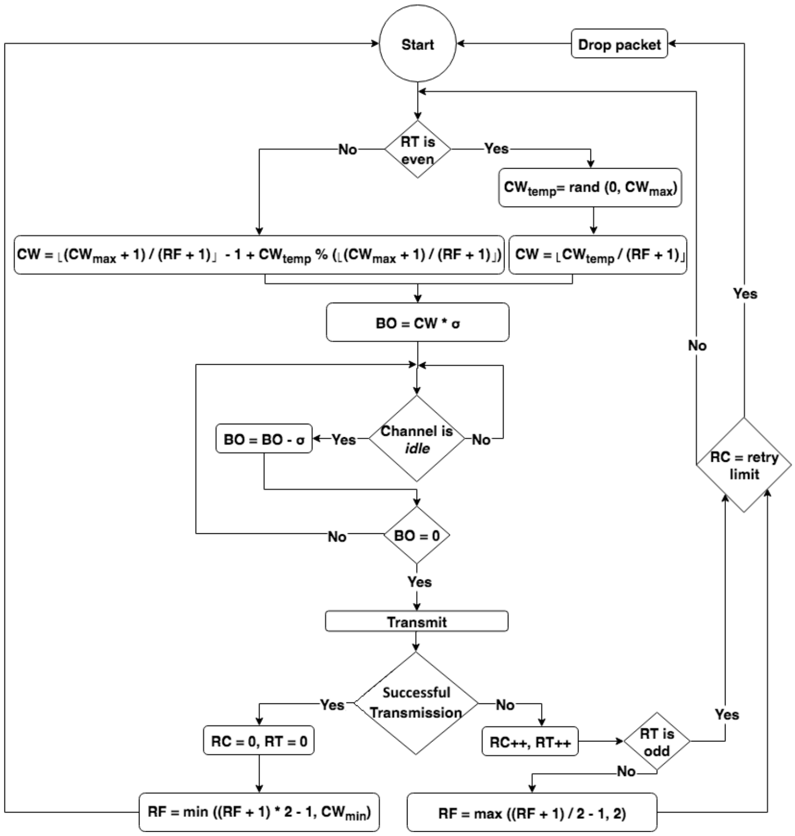

Figure 2 ECRA flowchart

Algorithm 2. EIED[13]

Input	$CW_{\max}, CW_{\min}, \sigma$
Initialize	$CW = CW_{\min}$
Step 1	$BO = rand(1, CW) * \sigma$
Step 2	**while** ($BO \neq 0$ and channel is $idle$) **do**
	$BO = BO - \sigma$
	end while
Step 3	$Transmit$
	if $successful\ transmission$ **then**
	$BO = 0$
	$CW = \max((CW + 1)/2, CW_{\min})$
	else
	$CW = \min(((CW + 1) * 2) - 1, CW_{\max})$
	$go\ to\ Step$ 1
	end if

4.2 | Simulation Settings

We compared the performance of our algorithm to that of BEB and EIED using different simulation scenarios that reflect real-time applications. We used QualNet Simulator 7.4[128], which contains the default BEB algorithm. We used 802.11b parameters for the PHY layer and 802.11 for the MAC layer with a retry limit adjusted to 7 for short packets and 4 for long packets[1]. The simulation parameters are reported in Table 1.

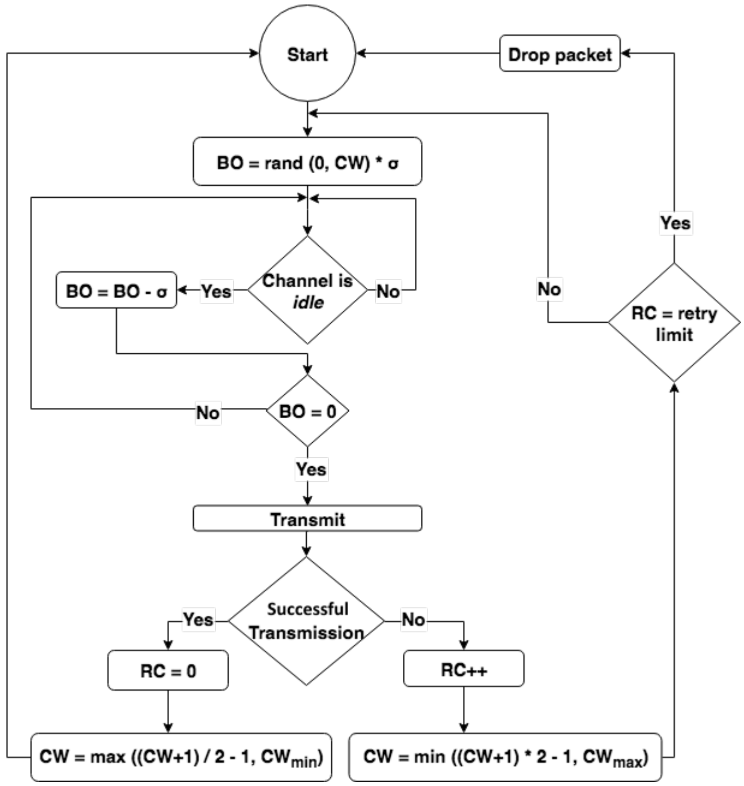

Figure 3 EIED flowchart

We considered different numbers of competing stations varying from 10 to 50 with an increment of 10. A simulation time of 300 s was chosen after trying several simulation times in experiments and concluding that 300 s is sufficient for the scenario to stabilise. The simulation area is selected based on the station's transmission range to test multiple scenario conditions where stations are close to each other or away from each other. Additionally, the area allows stations to move freely in the mobile scenarios.

For performance evaluation purposes, we grouped our simulations into five categories according to the number of stations (10, 20, 30, 40, and 50). For each category, we created 18 scenarios in static environments, where stations retain their starting positions until the end of the simulation. We also created 18 scenarios in mobile environments, where stations are allowed to move randomly as specified in Table 1. In each category, $n/2$ CBR flows were set up, where n is the number of stations in that category. In each category, we created scenarios using different topologies: random, grid, and linear.

We also used different sending procedures between stations, namely, single-hop and multi-hop. The transmission time was also adjusted. Some stations transmitted at the same time in some scenarios and at random times in other scenarios. In the single-hop scenario, stations were in the range of each other and could sense each other. In the multi-hop scenario, stations were not in range of each other and used other stations to send their packets.

We created scenarios in which stations send and receive in pairs (half the stations are senders, and the other half are receivers). In other scenarios, we adjusted different stations to send to a single station. The latter scenario will increase the collision probability among stations, which will help in studying the performance under heavily loaded conditions.

Finally, we considered two scenarios regarding sending time. In the first scenario, all stations transmit at the same time, whereas in the second scenario, stations transmit at random times. We ran each scenario 30 times using different seeds to validate the results obtained. A complete set of our simulation scenarios and the data that supports the findings of this study can be accessed using our Mendeley Dataset V1 [129].

4.3 | Static Environment

In the static environment, stations kept their starting positions until the end of the simulation.

Table 1 Simulation parameters in Qualnet. RTS is the request to send. CTS is the confirm to send. ACK is the acknowledgement. SIFS is the short interframe space.

Parameter	Value
Simulation area	1000 m X 1000 m
Simulation time	300 s
Number of stations (n)	10, 20, 30, 40 and 50
PHY layer	802.11b
Protocol	MAC 802.11
Channel access	CSMA/CA
RTS / CTS	Enabled
ACK	Enabled
Propagation delay	1 μs
SIFS	10 μs
DIFS	50 μs
slot time length	20 μs
$CW_{\max}$	1023
$CW_{\min}$	31
Traffic type	Constant bit rate CBR
CBR connections	$n/2$
Packet size	512 Bytes
Packets to send	100
Inter-departure time	100 μs
Mobility type	Random way point
Minimum speed	1 m/s
Maximum speed	10 m/s
Pause time	0 s

4.3.1 | Throughput

Fig. 4 shows that the throughput decreased as the number of stations increased. This increase is due to the increase in collisions, which leads to an increase in the number of packets lost due to the re-transmission limit. Table 2 reports the throughput improvement percentages of ECRA and EIED compared to that of BEB.

Table 2 Throughput improvement compared to BEB in static environments

	10	20	30	40	50	Average
EIED	-6.6%	-3.9%	-1.8%	1.3%	10.3%	-0.1%
ECRA	-0.4%	-1.0%	0.2%	4.0%	15.4%	3.6%

The results show that BEB performs very well when the number of stations is small. The results also highlight one of BEB's main shortcomings with regard to its performance degradation when the number of stations increases, as in dense WANETs. This limitation is mainly due to BEB's sudden reset of CW upon successful transmission. Although the sudden CW reset increases the channel access time, it increases the number of collisions because it reduces the CW size and increases the collision probability.

Results also highlight another main shortcoming of BEB, that is relying solely on CW increase to reduce the collision probability. Though the CW increase can effectively decrease the collision probability when the number of stations is small, it does not have the same effect when the number of stations is large.

The results also show that ECRA outperforms BEB and EIED as the number of stations increases. It hits a performance peak at 50 stations, with an improvement percentage of 15% relative to BEB and 5% relative to EIED. ECRA also performs

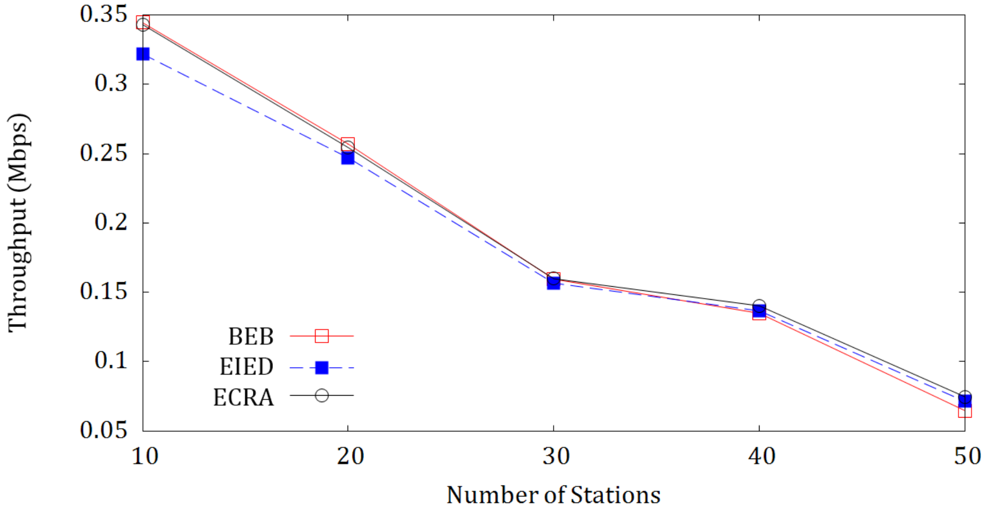

Figure 4 Average throughput per receiver in static environments.

well compared with EIED when the number of stations is low. Based on these results, we project that ECRA will continue to outperform BEB and EIED in dense networks in which the number of stations exceeds 100.

The throughput results of ECRA and EIED show that our collisions resolution method makes ECRA more effective than EIED though both algorithms use the same increment/decrement mechanism. The fact that ECRA outperforms EIED highlights that our collision resolution method enhanced the performance of our algorithm and improved throughput by increasing channel access time while reducing the collision probability.

4.3.2 | Fairness

A backoff algorithm must guarantee fair channel access among competing stations. We evaluated fairness using the Jain fairness index [130]

$$F_{Jain}(s_1, s_2, \ldots, s_n) = \frac{(\sum_{i=1}^{n} s_i)^2}{n \sum_{i=1}^{n} s_i^2} \tag{5}$$

where n is the number of active stations and s_i is the throughput of station i.

Fig. 5 shows that fairness decreased as the number of stations was increased. This is due to the increase in the number of collisions, which leads to an increase in the CW size variation among competing stations, which in turn affects the channel access chances. The improvements in fairness of ECRA and EIED relative to BEB are reported in Table 3. ECRA achieved better fairness than BEB due to its ability to increase channel access time, which allowed more stations to transmit. It also decreases CW gradually rather than suddenly resetting to its minimum value like BEB. EIED performs better than ECRA because it increases the CW size for all stations. Though this leads to a very high CW size, it maintains the CW values of most competing stations within a small range, thus allowing fair channel access.

Table 3 Fairness improvement compared to BEB in fixed environments

	10	20	30	40	50	Average
EIED	-2.9%	0.1%	4.0%	9.4%	14.0%	4.9%
ECRA	-0.5%	0.1%	2.7%	2.8%	6.4%	2.3%

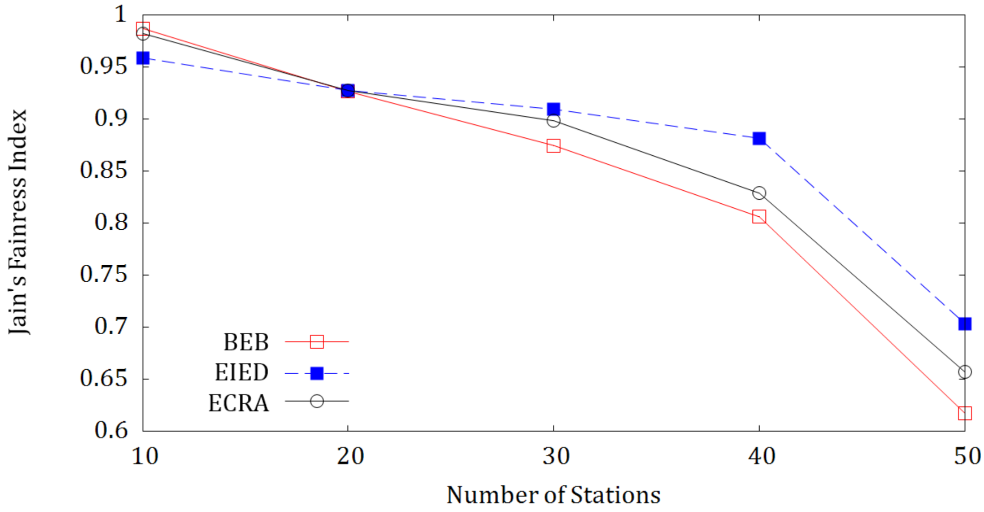

Figure 5 Average fairness per receiver in fixed environments

4.3.3 | Delay

The delay results are shown in Fig. 6, and the improvement percentages of ECRA and EIED relative to BEB are reported in Table 4. The results make clear that the delay increases as the number of stations increases; this is due to the increase in the number of collisions. The results also show that ECRA outperforms EIED in all scenarios. Considering that both ECRA and EIED use the same CW increment/decrement mechanism, the results prove that the ECRA collision resolution method is the main factor affecting the performance. BEB outperforms ECRA and EIED in terms of delay; this is due to the CW reset used in BEB, which allows successfully transmitting stations more channel access with low CW size. Although the CW reset increases the collision probability, it will allow stations to use lower CW values and thus reduce the delay.

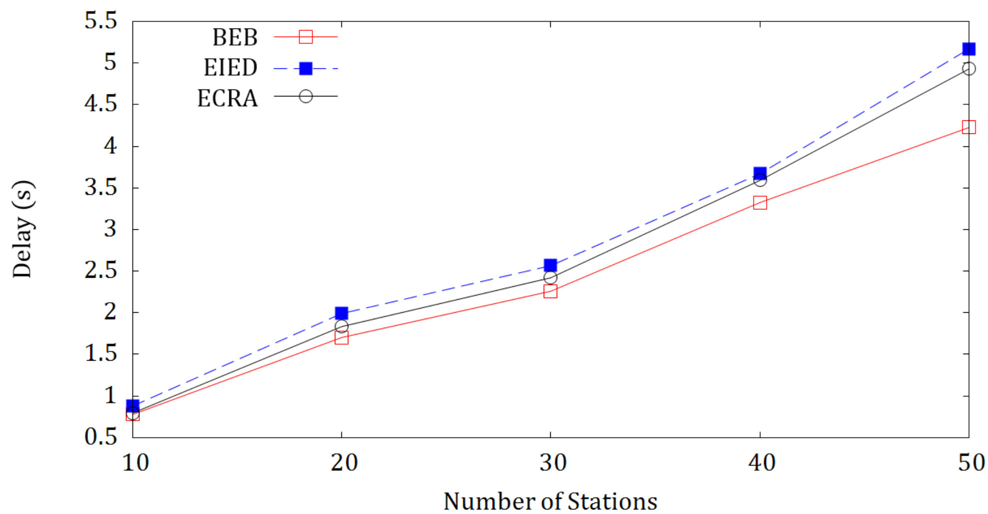

Figure 6 Average delay per receiver in fixed environments

Table 4 Delay improvement compared to BEB in fixed environments

	10	20	30	40	50	Average
EIED	-13.1%	-16.9%	-13.6%	-10.4%	-22.4%	-15.3%
ECRA	-2.2%	-7.7%	-7.2%	-8.0%	-16.7%	-8.4%

4.4 | Mobile Environment

In this environment, stations moved at various speeds, from 1 m/s to 10 m/s, with the pause time between movements adjusted to 0 s. The various speeds reflect the speed range of a walking human to a slowly moving vehicle.

4.4.1 | Throughput

In mobile stations, the throughput results are affected by the constant movement of stations, which results in some stations being out of communication range. This outcome will cause many frames to be dropped and therefore affect the throughput.

Fig. 7 shows the throughput results. The throughput improvement percentages of ECRA and EIED relative to BEB are reported in Table 5. The results show that BEB outperform ECRA and EIED when the number of stations is low; this is due to the CW reset in BEB, which is effective in lightly loaded networks. ECRA outperform both BEB and EIED as the number of stations increases due to its effective collision resolution method operation. The results also make clear that the performance of ECRA is not affected by increasing the number of stations, as its performance is improved compared to that of BEB and EIED.

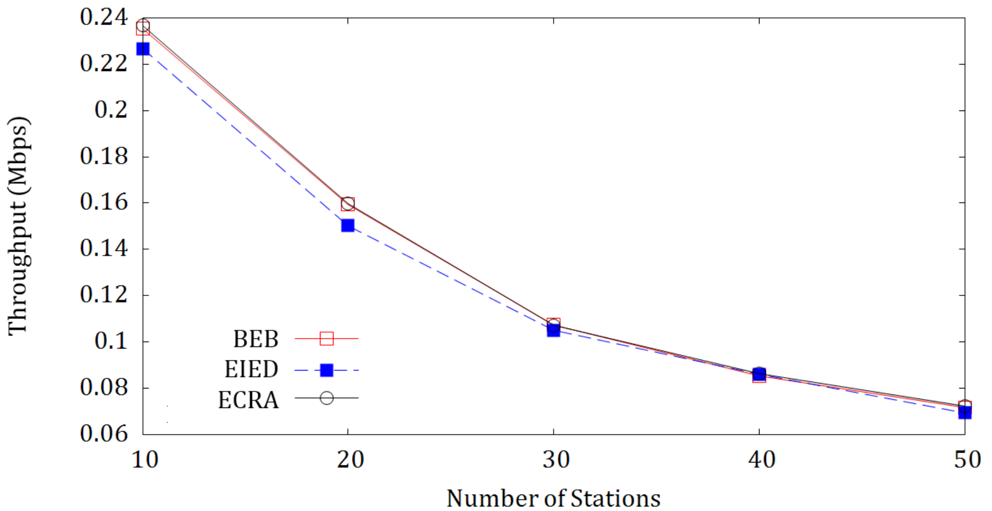

Figure 7 Average throughput per receiver in mobile environments

Table 5 Throughput improvement compared to BEB in mobile environments

	10	20	30	40	50	Average
EIED	-3.6%	-5.7%	-2.1%	0.8%	-3.3%	-2.8%
ECRA	0.6%	0.3%	-0.1%	1.2%	0.9%	0.6%

4.4.2 | Fairness

The fairness results are presented in Fig. 8, and the improvement percentages of ECRA and EIED relative to BEB are reported in Table 6.

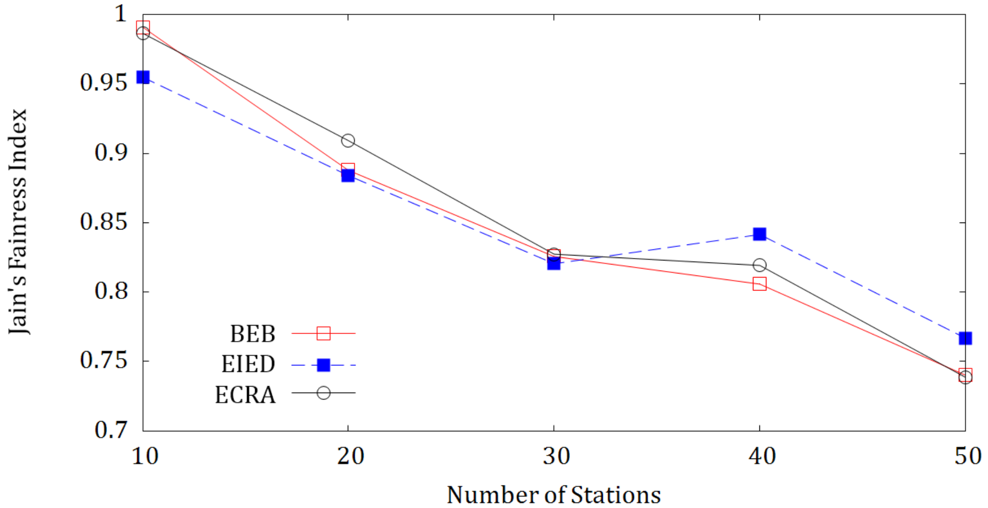

Figure 8 Average fairness per receiver in mobile environments

Table 6 Fairness improvement compared to BEB in mobile environments

	10	20	30	40	50	Average
EIED	-3.6%	-0.4%	-0.6%	4.4%	3.6%	0.7%
ECRA	-0.4%	2.4%	0.2%	1.7%	-0.2%	0.7%

Station mobility results in some stations being out of range, especially in scenarios with a small number of active stations. This will affect the throughput and therefore the fairness results as many packets will be lost due to receivers being out of range. As the number of stations increases (to 40 and 50), the likelihood of having out of range stations is reduced due to the high number of stations available. ECRA outperforms EIED when the number of stations is low, but its performance degrades as the number of stations increases. The performance of EIED is partially due to the high CW values assigned to the stations. The fairness results also highlight the behaviour of EIED, which focuses more on reducing the collision probability than on increasing channel access time, thus reducing the number of packets lost due to retransmission limits. On average, ECRA performs similarly to EIED, and both algorithms outperform BEB. The main factor affecting fairness in BEB is the immediate reset of CW to its minimum value upon successful transmission. The performance of ECRA suffers as the number of stations increases since it prefers to maintain a low CW size and focus more on increasing channel access time.

4.4.3 | Delay

The delay results are shown in Fig. 9, and the improvement percentages of EIED and the proposed algorithm relative to BEB are reported in Table 7. The delay results in the mobile scenario show that BEB achieved the lowest delay due to its CW reset mechanism. ECRA outperformed EIED in all cases except when the number of stations was 50 where the performance was comparable. On average, ECRA outperformed EIED, which shows that the collisions resolution method is effective since both algorithms use the same increment/decrement mechanism.

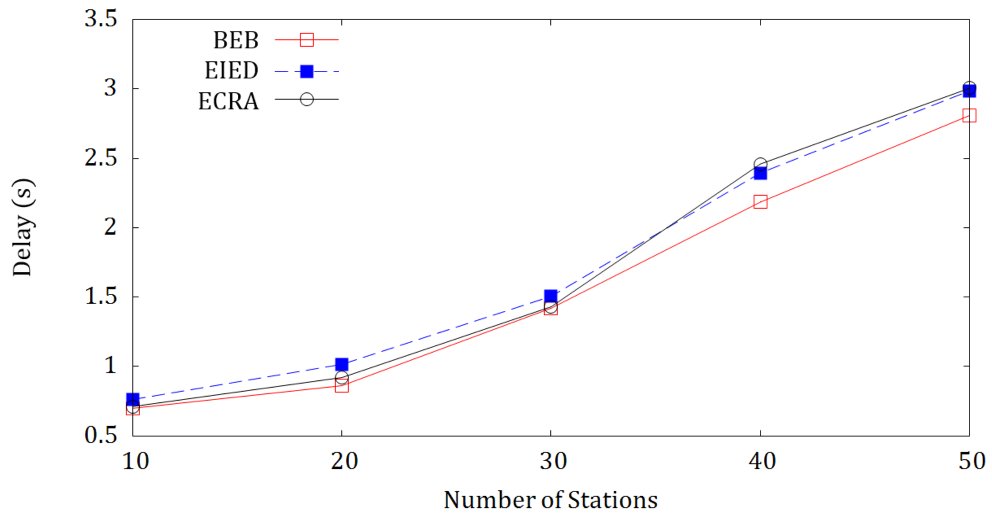

Figure 9 Average delay per receiver in mobile environments

Table 7 Delay improvement compared to BEB in mobile environments

	10	20	30	40	50	Average
EIED	-9.1%	-17.8%	-6.0%	-9.6%	-6.3%	-9.8%
ECRA	-1.9%	-6.8%	-0.7%	-12.6%	-7.0%	-5.8%

5 | PROPOSED ANALYTICAL MODEL

In this section, we propose analytical models for BEB, EIED, and ECRA. Using our models, we calculate the probability τ that a station transmits in a random slot time. Then, we compare the performance of ECRA to that of BEB and EIED with regard to saturation throughput and maximum throughput.

Like Bianchi's model, our model assumes ideal network conditions (no hidden stations) and saturated conditions (each station always has a packet to transmit). However, unlike Bianchi's model, our model assumes that a backoff time initial value of zero is not acceptable, and therefore state (0,0), for example, is only accessible from state (0,1).

Bianchi's model[4,5] also assumes that the collision probability is independent of the station transmission history. This results in an inaccurate estimation of the probability τ, which leads to an inaccurate throughput analysis. For example, in a scenario where a station suffered no previous collisions, the station collision probability will be high compared to its collision probability if it suffered previous collisions. This result is due to the effect of the station's transmission history on its current CW size and therefore its collision probability. We lift this constraint by using a collision probability that depends on the backoff stage. In our model, the probability P_i that in backoff stage i at least two stations select the same value to update their CW is

$$P_i = 1 - \frac{CW_i!}{(CW_i - n)!CW_i^n} \tag{6}$$

where $i \in \{0, 1, 2, \dots, m\}$, $CW_i = 2^i(CW_{\min} + 1) - 1$, $CW_{\min} = 31$, m is the last backoff stage, and n is the number of stations.

5.1 | BEB Model

Fig. 10 shows the state transition diagram for the proposed Markov chain model for BEB. In a state (i, k), $i \in \{0, 1, \dots, m\}$ is the backoff stage and $k \in \{0, \dots, CW_i\}$ is the backoff time corresponding to stage i. The edges between states represent the transition probabilities from one state to another, and P_i denotes the collision probability in backoff stage i. In our model, BEB has six stages ($m = 5$) since $CW_{\min} = 31$, and $CW_{\max} = 1023$.

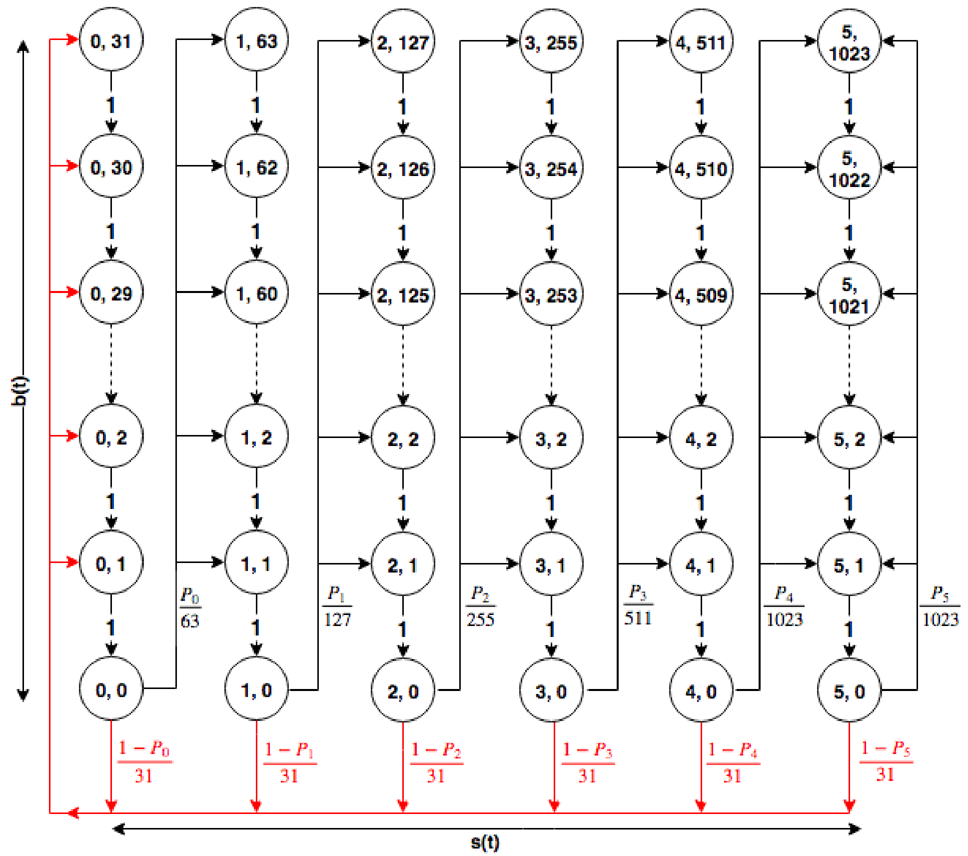

Figure 10 Proposed analytical model for BEB. The states $(s(t), b(t))$ are such that $s(t)$ is the stochastic process representing the backoff stage of the station at time t and $b(t)$ is the stochastic process representing the backoff time for the station at time t.

To illustrate the process, let the probability that a station is in state (i, k) be $b_{i,k}$. Assuming that a station is in state (i, k), $k > 0$, at each slot time, the station reduces k by one to move to the next state $(i, k - 1)$. The station continues reducing k at each slot time until it reaches state $(i, 0)$, where it can access the channel and attempt to transmit. If a collision occurs, the station moves to a random state in the next backoff stage, and if the transmission is successful, the station moves to any random state in the first backoff stage.

In case of a collision, the transition probability from state $(i, 0)$ to any random state in the next backoff stage $(i + 1, k)$, $k > 0$, is equal to $\frac{P_i}{CW_{i+1}}$. If the transmission is successful, the transition probability from state $(i, 0)$ to any random state in the first backoff stage $(0, k)$, $k > 0$, is equal to $\frac{1-P_i}{CW_0}$.

From Fig. 10, we find that state $(0, CW_{\min})$ can be accessed from state $(0, 0)$ conditional on the probability $1/CW_{\min}$ at the beginning of the backoff process. It can also be accessed from all states (where $i = 0$) conditional on their respective probabilities. Therefore,

$$b_{0,CW_{\min}} = \frac{1}{CW_{\min}} \sum_{j=1}^{m} (1 - P_j) b_{j,0} \tag{7}$$

The next state $(0, CW_{\min} - 1)$ and all the states in the first backoff stage (where $i = 0$) can be accessed similarly to state $(0, CW_{\min})$. Moreover, since $(0, CW_{\min} - 1)$ can also be accessed from $(0, CW_{\min})$,

$$b_{0,CW_{\min-1}} = \frac{2}{CW_{\min}} \sum_{j=1}^{m} (1 - P_j) b_{j,0} \tag{8}$$

Based on (7) and (8), we extend our solution to include the remaining states, and we conclude that the transition probability $b_{i,k}$ for any given state (i, k) is

$$b_{i,k} = \frac{CW_i - k}{CW_i} \begin{cases} \sum_{j=0}^{m}(1 - P_j)b_{j,0} & i = 0 \\ P_{i-1}b_{i-1,0} & 0 < i < m \\ P_{i-1}b_{i-1,0} + P_i b_{i,0} & i = m \end{cases} \tag{9}$$

Since stations are allowed to transmit only in states where k equals zero ($BO = 0$), the probability τ that a station transmits in a random slot time is

$$\tau = \sum_{i=0}^{m} b_{i,0} \tag{10}$$

We now show how to compute τ. For $i = 0, \dots, m-2$, we define

$$X_i = \prod_{j=0}^{i} P_j \tag{11}$$

Since all states where $k = 0$ can only be accessed from their respective states where $k = 1$, then using (9) for any state $(i, 0)$ where $i = 1, \dots, m-1$, we have

$$b_{i,0} = b_{i,1} = X_{i-1}b_{0,0} \tag{12}$$

Similarly, for state $(i, 0)$ where $i = m$, we have

$$b_{m,0} = b_{m,1} = P_{m-1}b_{m-1,0} + P_m b_{m,0} \tag{13}$$

Using (13) and (12), we get

$$b_{m,0} = \frac{P_{m-1}X_{m-2}}{1 - P_m} b_{0,0} = X_{m-1}b_{0,0} \tag{14}$$

where

$$X_{m-1} = \frac{P_{m-1}X_{m-2}}{1 - P_m}. \tag{15}$$

Thus, using (10), (12), and (14), we get

$$\tau = \sum_{i=0}^{m} b_{i,0} = b_{0,0} + \sum_{j=0}^{m-1} X_j b_{0,0} = X_m b_{0,0} \tag{16}$$

where

$$X_m = 1 + \sum_{i=0}^{m-1} X_i \tag{17}$$

Since the sum of all state transition probabilities equals one, we obtain

$$1 = \sum_{i=0}^{m} b_{i,0} + \sum_{j=0}^{m} \sum_{k=1}^{2^j(CW_{min}+1)-1} b_{j,k} \tag{18}$$

Using (9), when $i = 0$ we get

$$\sum_{k=1}^{CW_{\min}} b_{0,k} = \frac{(CW_{\min} + 1)}{2} b_{0,0} \tag{19}$$

For $i = 1, \dots, m$ we get

$$\sum_{k=1}^{2^i(CW_{\min}+1)-1} b_{i,k} = \frac{2^i(CW_{\min} + 1)}{2} X_{i-1}b_{0,0} \tag{20}$$

Then, using (18) to (20), we find

$$b_{0,0} = \frac{1}{\frac{(CW_{\min}+1)}{2} + X_m + \sum_{i=0}^{m-1} 2^i(CW_{\min} + 1)X_i} \tag{21}$$

Finally, by finding X_m using (17) and $b_{0,0}$ using (21), we calculate τ using (16).

5.2 EIED Model

The Markov chain model we propose for EIED is similar to the one we used for BEB except that in EIED, there is no sudden reset and CW is decreased gradually. Fig. 11 shows the state transition diagram for the states (i, k), where $i \in \{0,1,\ldots,m\}$ is the backoff stage and $k \in \{0,\ldots,CW_i\}$ corresponds to the backoff time. In EIED, $m = 5$ since $CW_{\min} = 31$ and $CW_{\max} = 1023$. The solid black arrows represent the probability of collision for each backoff stage. The red arrows represent the probability of successful transmission as we gradually decrease the CW size after a successful transmission.

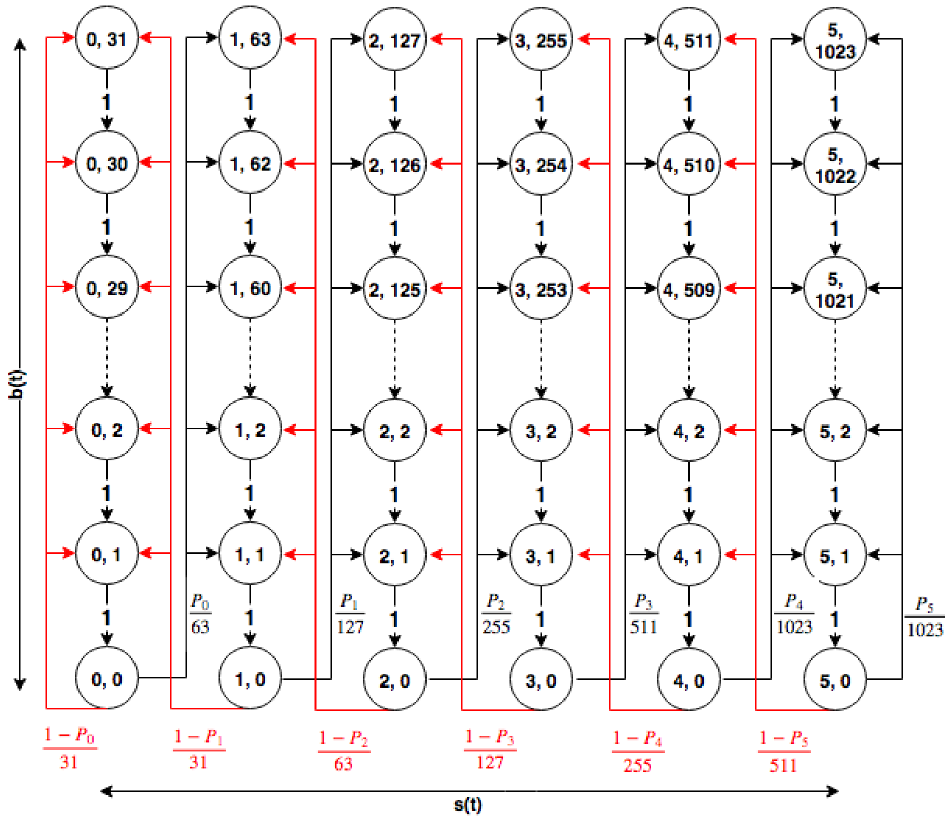

Figure 11 Proposed analytical model for EIED

Following the method we used for BEB, the state transition probability for any given state (i, k) is

$$b_{i,k} = \frac{CW_i - k}{CW_i - 1}\begin{cases}(1-P_i)b_{i,0} + (1-P_{i+1})b_{i+1,0} & i = 0\\ P_{i-1}b_{i-1,0} + (1-P_{i+1})b_{i+1,0} & 0 < i < m\\ P_{i-1}b_{i-1,0} + P_i b_{i,0} & i = m\end{cases} \tag{22}$$

Since all states where $k = 0$ can only be accessed from their respective states where $k = 1$, using (22), for any state $(i, 0)$ if $i = m$ then

$$b_{m,0} = P_{m-1}b_{m-1,0} + P_m b_{m,0} = \frac{P_{m-1}}{1-P_m}b_{m-1,0} \tag{23}$$

If $0 < i < m$, then

$$b_{i,0} = P_{i-1}b_{i-1,0} + (1-P_{i+1})b_{i+1,0} = \frac{P_{i-1}}{1-P_i}b_{i-1,0} \tag{24}$$

For $i = 0, , \ldots, m-1$, we define

$$Y_i = \prod_{j=0}^{i}\frac{P_j}{1-P_{j+1}} \tag{25}$$

Using (25), for any state $(i, 0)$, if $0 < i < m$, then

$$b_{i,0} = Y_{i-1} b_{0,0} \tag{26}$$

Thus, using (10) and (22) to (26), we have

$$\tau = \sum_{i=0}^{m} b_{i,0} = b_{0,0} + \sum_{i=0}^{m-1} Y_i b_{0,0} = Y_m b_{0,0} \tag{27}$$

and

$$Y_m = 1 + \sum_{i=0}^{m-1} Y_i \tag{28}$$

Since the sum of all state transition probabilities equals one (18), and using (22) to (28), when $i = 0$ we get

$$\sum_{k=1}^{CW_{\min}} b_{0,k} = \frac{(CW_{\min} + 1)}{2} b_{0,0} \tag{29}$$

For $i = 1, \dots, m$ we get

$$\sum_{k=1}^{2^i(CW_{\min}+1)-1} b_{i,k} = \frac{2^i(CW_{\min} + 1)}{2} Y_{i-1} b_{0,0} \tag{30}$$

Then, using (25) to (30), we find

$$b_{0,0} = \frac{1}{\frac{CW_{\min}+1}{2} + Y_m + \sum_{i=0}^{m-1} 2^i(CW_{\min} + 1)Y_i} \tag{31}$$

Finally, by finding Y_m using (28) and $b_{0,0}$ using (31) we calculate τ using (27).

5.3 | ECRA Model

Fig. 12 shows the state transition diagram for the proposed ECRA model. For each state (i, k), we have $i \in \{0, 1, \dots, m\}$ and $k \in \{0, \dots, CW_i\}$. Since each backoff stage consists of two stages (one for a normal backoff and one for collision resolution), and CW must be between $CW_{\min} = 31$ and $CW_{\max} = 1023$, the number of backoff stages is equal to nine ($m = 9$). The solid black arrows represent the collision probability in each backoff stage. The red arrows represent the probability of successful transmission as we gradually decrease the CW size. Finally, the blue and green arrows represent the probability of a successful collision resolution and the gradual decrease of the CW size.

The proposed analytical model for ECRA contains two sets of backoff stages: five normal backoff stages (white) and five collision resolution stages (grey). The collision resolution stages are the stages in which the collision resolution method is used.

For the states in the normal backoff stages (where i is even and $0 \le i < m$), we calculate the state probability for any given state (i, k) as

$$b_{i,k} = \frac{CW_i + 1 - k}{CW_i} \begin{cases} \sum_{j=0}^{3}(1 - P_j)b_{j,0} & i = 0 \\ (1 - P_{i+2})b_{i+2,0} + (1 - P_{i+3})b_{i+3,0} + P_{i-1}b_{i-1,0} & 0 < i < m - 1 \\ P_{i-1}b_{i-1,0} + P_{i+1}b_{i+1,0} & i = m - 1 \end{cases} \tag{32}$$

For the states in the collision resolution backoff stages (where i is odd and $0 < i \le m$), we calculate the state probability for any given state (i, k) as

$$b_{i,k} = \begin{cases} \frac{2CW_{i-1}-k+1}{CW_{i-1}} P_{i-1} b_{i-1,0} & k > CW_{i-1} \\ b_{i,k+1} & k \le CW_{i-1} \end{cases} \tag{33}$$

Since all states with $k = 0$ can be accessed from their respective states where $k = 1$, for the states in the normal backoff stages and $i = m - 1$ (32) gives

$$b_{m-1,0} = b_{m-1,1} = P_m b_{m,0} + P_{m-2} b_{m-2,0} \tag{34}$$

Using (32), we rewrite (34) as

$$b_{m-1,0} = P_{m-1} P_m b_{m-1,0} + P_{m-2} b_{m-2,0} \tag{35}$$

For the collision resolution stages, using (33), we get

$$b_{i,0} = b_{i,1} = P_{i-1} b_{i-1,0} \tag{36}$$

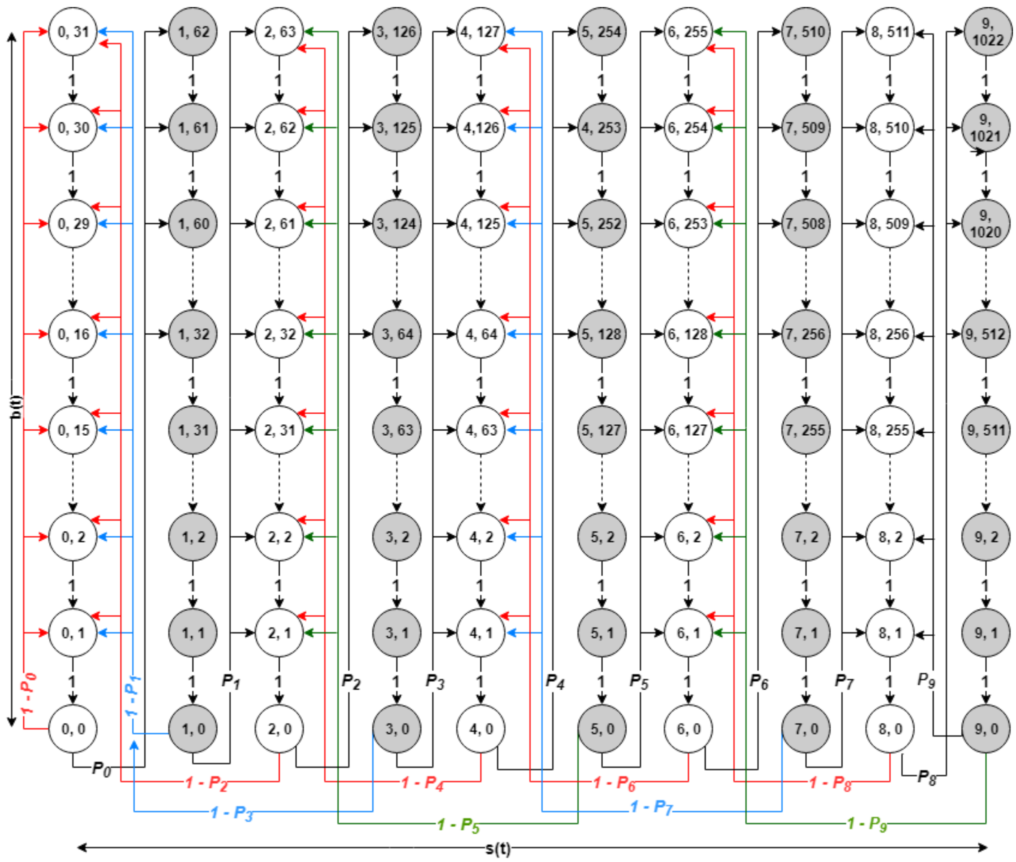

Figure 12 Proposed analytical model for ECRA

We start by finding $b_{m,0}$. Since m is odd, using (36) we get

$$b_{m,0} = b_{m,1} = P_{m-1} b_{m-1,0} \tag{37}$$

Then using (35) we find $b_{m-1,0}$ as

$$b_{m-1,0} = P_{m-1} P_m b_{m-1,0} + P_{m-2} b_{m-2,0} \tag{38}$$

We rewrite (38) as

$$b_{m-1,0} = \frac{P_{m-2}}{1 - P_{m-1} P_m} b_{m-2,0} \tag{39}$$

We define Z_i for $i = 0, \dots, \lfloor m/2 \rfloor - 1$

$$Z_i = \begin{cases} \frac{P_{m-2}}{1-P_{m-1}Pm} & i = 0 \\ \frac{P_{m-2i-2}}{1-Z_{i-1}P_{m-2i-1}[(1-P_{m+1-2i})-(1-P_{m+2-2i})P_{m+1-2i}]} & 0 < i < \lfloor \frac{m}{2} \rfloor \end{cases} \tag{40}$$

We rewrite (38) as

$$b_{m-1,0} = \frac{P_{m-2}}{1 - P_{m-1} P_m} b_{m-2,0} = Z_0 b_{m-2,0} \tag{41}$$

$$b_{m-2,0} = b_{m-2,1} = P_{m-3} b_{m-3,0} \tag{42}$$

$$b_{m-3,0} = b_{m-3,1} = (1 - P_{m-1}) b_{m-1,0} + (1 - P_m) b_{m,0} + P_{m-4} b_{m-4,0} \tag{43}$$

Using (35) and (40), we obtain

$$b_{m-3,0} = \frac{P_m - 4}{1 - (1 - P_{m-1}) P_{m-3} Z_0 - (1 - P_m) P_{m-3} P_{m-1} Z_0} b_{m-4,0} \tag{44}$$

We rewrite (44) as:

$$b_{m-3,0} = \frac{P_m - 4}{1 - Z_0 P_{m-3}[(1 - P_{m-1}) - (1 - P_m)P_{m-1}]} b_{m-4,0} = Z_1 b_{m-4,0} \tag{45}$$

We continue similarly for the remaining states until we reach $i = 1$ which we get using:

$$b_{1,0} = P_0 b_{0,0} \tag{46}$$

Thus, for any given state $(i, 0)$ if $(1 < i < m)$ in the normal backoff stages (i is even), we obtain

$$b_{i,0} = \prod_{j=0}^{\lfloor i/2 \rfloor - 1} P_{2j} \prod_{k=\lfloor (m-1-i)/2 \rfloor}^{\lfloor m/2 \rfloor - 1} Z_k b_{0,0} = L_i b_{0,0} \tag{47}$$

For any given state $(i, 0)$ if $(1 < i \leq m)$ in the collision resolution backoff stages (i is odd), we obtain

$$b_{i,0} = \prod_{j=0}^{\lfloor (i+1)/2 \rfloor - 1} P_{2j} \prod_{k=\lfloor (m-i)/2 \rfloor}^{\lfloor m/2 \rfloor - 1} Z_k b_{0,0} = L_i b_{0,0} \tag{48}$$

Using (46) to (48), we have

$$\tau = \sum_{i=0}^{m} b_{i,0} = b_{0,0}\big[1 + P_0 + \sum_{i=2}^{m} L_i\big] = L_{m+1} b_{0,0} \tag{49}$$

where

$$L_{m+1} = 1 + P_0 + \sum_{i=2}^{m} L_i \tag{50}$$

Since the sum of all state transition probabilities equals one, using (32), (33), and (46) to (48), when $i = 0$ we get

$$\sum_{k=1}^{CW_{\min}} b_{0,k} = \frac{(CW_{\min} + 1)}{2} b_{0,0} \tag{51}$$

When $i = 1$, we obtain

$$\sum_{k=1}^{2CW_{\min}-2} b_{1,k} = 1.5((CW_{\min} + 1) - 1)P_0 b_{0,0} \tag{52}$$

For the remaining states (i, k) in the normal backoff stages where $1 < i < m$ and i is even, we use

$$\sum_{k=1}^{2^i(CW_{\min}+1)-1} b_{i,k} = \frac{2^i(CW_{\min} + 1)}{2} L_i b_{0,0} = R_i b_{0,0} \tag{53}$$

For the remaining states (i, k) in the collision resolution backoff stages where $2 < i \leq m$ and i is odd, we use

$$\sum_{k=1}^{2^i(CW_{\min}+1)-2} b_{i,k} = (1.5(2^i(CW_{\min} + 1)) - 1)L_i b_{0,0} = R_i b_{0,0} \tag{54}$$

Thus, using (51) to (54), we obtain

$$b_{0,0} = \frac{1}{\frac{CW_{\min}+1}{2} + (1.5(CW_{\min} + 1) - 1)P_0 + \sum_{i=2}^{m} R_i + L_{m+1}} \tag{55}$$

Finally, by finding L_{m+1} using (50) and $b_{0,0}$ using (55) we calculate τ using (49).

5.4 | Comparison of Bianchi's model and the proposed model for BEB

In this section, we use our model and Bianchi's model to compute the saturation throughput of BEB and compare the results. The saturation throughput S is the fraction of time the channel is used to successfully transmit the payload bits[5]. That is,

$$S = \frac{\mathbb{E}(\textit{Payload transmitted in slot time})}{\mathbb{E}(\textit{Length of slot time})} \tag{56}$$

where $\mathbb{E}$ is the expectation operator.

We follow a framework similar to Bianchi's[4,5] to analyse the different events that can occur in a random slot time and the different slot time lengths based on such events. The channel is idle if there is no transmission in a slot time. Since each station can transmit in a slot time with probability τ, the probability that the channel is idle is

$$P_d = (1-\tau)^n \tag{57}$$

where n is the number of stations. Therefore, the probability P_t that there is at least one transmission in a slot time is

$$P_t = 1 - P_d \tag{58}$$

The probability P_s of having exactly one transmission in a random slot time given there is at least one transmission in a slot time is

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_t} \tag{59}$$

Since a collision will occur if there is more than one transmission in a slot time, the probability of collision P_c is the probability of more than one transmission in a slot time given that there is at least one transmission in a slot time. Thus,

$$P_c = P_t(1 - P_s) \tag{60}$$

Let T_s be the average time the channel is sensed by a station with successful transmission (Fig. 13). Let T_c be the average time the channel is sensed by a station suffering a collision. Then

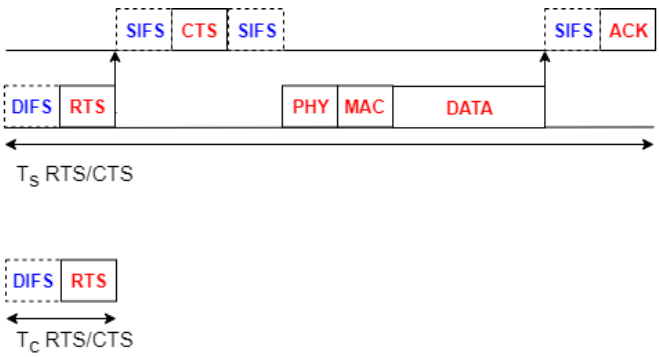

Figure 13 Duration of T_s and T_c using RTS/CTS.[5]

$$T_s = DIFS + T_{RTS} + T_{CTS} + PHY_{PH} + T_{MAC} + T_{DATA} + 3SIFS + T_{ACK} \tag{61}$$

and

$$T_c = T_{RTS} + DIFS \tag{62}$$

where

- T_{DATA}: Time to send payload packet (μs)
- PHY_{PH}: Time to send $PHY_{Preamble} + PHY_{Header}$
- T_{MAC}: Time to send MAC_{Header} (μs)
- T_{RTS}: Time to send RTS (μs)
- T_{CTS}: Time to send CTS (μs)
- T_{ACK}: Time to send ACK (μs)

Since packets are successfully transmitted if there is exactly one transmission in a slot time, a slot time will be empty if there are no transmissions, and a collision will occur if there is more than one transmission in a slot time. Using (56), the saturation throughput is calculated as[5]

$$S = \frac{P_t P_s \mathbb{E}_p}{P_d \sigma + P_t P_s T_s + P_c T_c} \tag{63}$$

where $\mathbb{E}_p$ is the average packet payload size. Maximum throughput can be achieved when every transmission is successful ($P_s = 1$ and $P_c = 0$).

Thus, the maximum throughput is

$$S_{\max} = \frac{P_t \mathbb{E}_p}{P_d \sigma + P_t T_s} \tag{64}$$

To compare the saturation throughput results of BEB using our model to those of BEB using Bianchi's model, we use the same system parameters as in[5] which are given in (Table 8).

Table 8 System parameters used in[5]

Parameter	Value
$ChannelRate$	1 Mbps
PHY_{Header}	128 bits
MAC_{Header}	272 bits
ACK	112 bits + PHY_{Header}
RTS	160 bits+ PHY_{Header}
CTS	112 bits+ PHY_{Header}
$SIFS$	28 μs
$DIFS$	128 μs
σ	50 μs
$MSDU$	1023 bytes

We start the evaluation by calculating the collision probability for BEB with both models. With our model, this probability depends on the backoff stage i and is calculated using (6). With Bianchi's model, the collision probability is calculated as[5]

$$P = 1 - (1 - \tau)^{n-1} \tag{65}$$

where

$$\tau = \frac{\sqrt{\frac{n+2(n-1)(T_c^*-1)}{n}} - 1}{(n-1)(T_c^* - 1)} \approx \frac{1}{n\sqrt{T_c^*/2}} \tag{66}$$

where $T_c^* = \frac{T_c}{\sigma}$ and $T_c = 417\ \mu s$[5].

Table 9 shows the results. The decoupling assumption in Bianchi's model ignores the effect of CW on the state transition probability, which leads to an inaccurate throughput analysis. For example, if the number of stations n is equal to 50 and CW = 31, then a collision will be certain since $n > CW$. This is reflected in our model, where the collision probability decreases from 1 to 0.704 as CW increases. In contrast, Bianchi's model gives a constant collision probability of 0.383. The table also shows that increasing the number of stations has little effect on the collision probability when computed with Bianchi's model.

Fig. 14 shows that with both models, τ decreases as the number of stations increases. This is mainly due to the increased number of collisions as more stations are trying to access the channel.

Several studies[131,5,132,133,134] reported that the throughput of BEB rapidly decreases as the number of active stations increases. Fig. 15 shows that unlike our model, Bianchi's model does not reflect this behaviour.

Table 9 Collision probability for BEB

	Our model						Bianchi
Number of stations	P_0	P_1	P_2	P_3	P_4	P_5	P
10	0.804	0.529	0.305	0.164	0.085	0.043	0.364
20	1.000	0.966	0.794	0.535	0.314	0.170	0.376
30	1.000	1.000	0.976	0.831	0.580	0.349	0.380
40	1.000	1.000	0.999	0.960	0.791	0.538	0.381
50	1.000	1.000	1.000	0.994	0.916	0.704	0.383

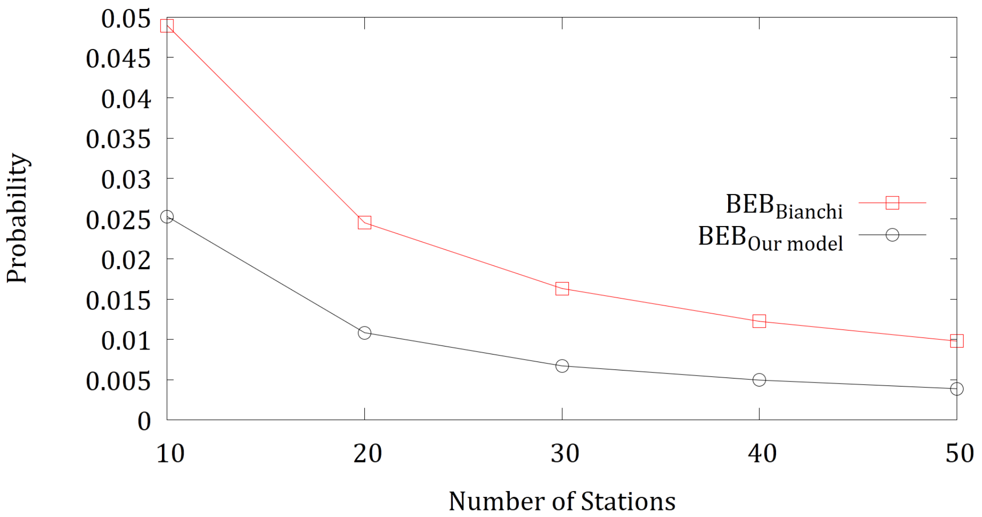

Figure 14 Probability τ that a station transmits in a random slot time as a function of the number of active stations

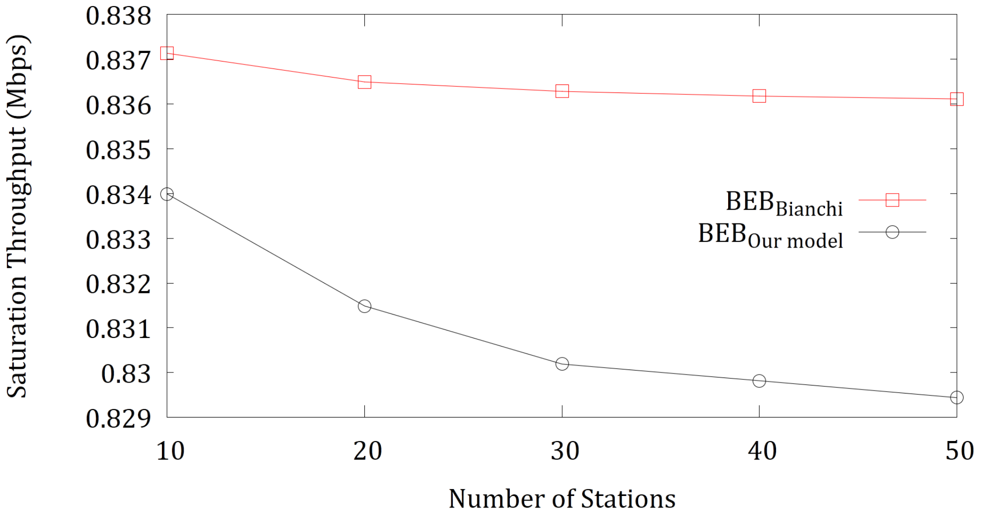

Figure 15 Saturation throughput as a function of the number of active stations

5.5 | Comparison of BEB, EIED and ECRA using the proposed model

In this section, we use our analytical model to compare the saturation and maximum throughput results of ECRA to those of BEB and EIED. To analyse the throughput performance of ECRA, BEB, and EIED using our analytical model, we use the standard values for SIFS and DIFS, as well as for RTS, CTS and ACK frames [1]. We assume that all packets have the 802.11 MAC service data unit (MSDU) size with a channel bit rate of 11 Mbps (Table 10).

Table 10 Theoretical analysis parameters

Parameter	Value
$Channel Rate$	11 Mbps
PHY_{PH}	192 μs
MAC_{Header}	34 octets
ACK	14 octets + PHY_{PH}
RTS	20 octets + PHY_{PH}
CTS	14 octets + PHY_{PH}
$SIFS$	10 μs
$DIFS$	50 μs
σ	20 μs
$MSDU$	2304 bytes

Following Bianchi's procedure [5], we start our analysis by finding the the probability τ. Fig. 16 shows that ECRA increases τ compared to BEB and EIED. This is due to the collision resolution method used in ECRA and the fact that it does not immediately increase the CW size upon collisions. Using the collision method in ECRA increases the channel access time by maintaining lower CW values compared to BEB and EIED. To reduce the collision probability, BEB and EIED instantly increase the CW size upon collision. The instant increase of the CW size reduces the channel access time since stations will spend more time sensing the channel rather than accessing it.

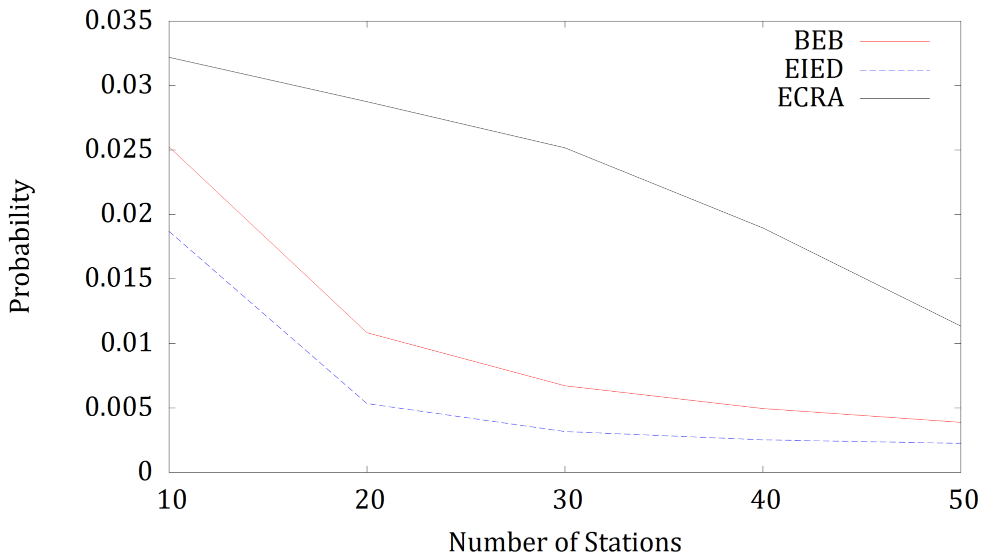

Figure 16 Probability τ that a station transmits in a random slot time as a function of the number of active stations

To prove the effectiveness of our collision resolution method at reducing the average CW size, we calculate the average CW size for a station using the probability that a station is in a backoff stage and the average CW size in that stage. Then, we calculate the average CW size in all the backoff stages. The average CW size results in Fig. 17 show that ECRA maintains a very low average CW size compared to those of BEB and EIED.

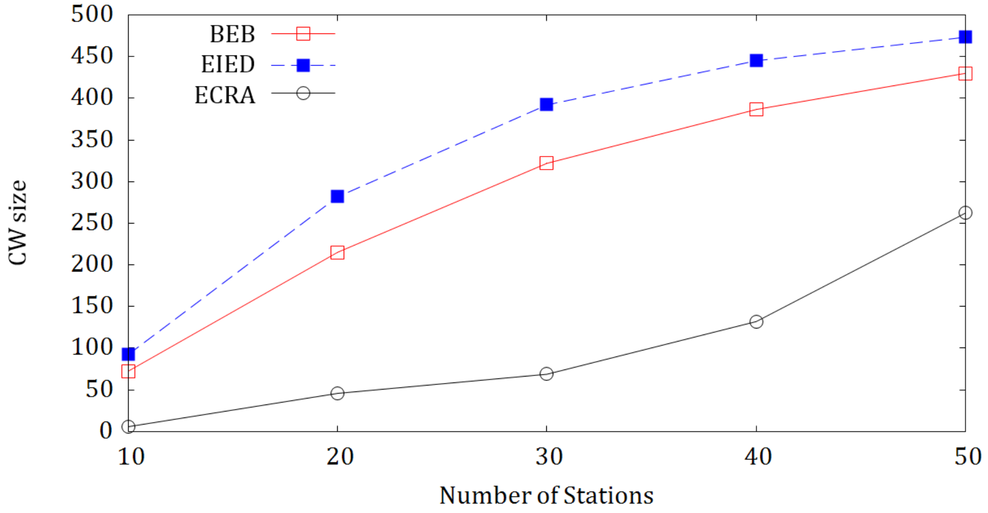

Figure 17 Average CW size

By increasing channel access time, increasing the number of successful transmissions, and reducing the average CW size for each station, ECRA outperforms BEB and EIED in terms of saturation and maximum throughput. Fig. 18 shows that ECRA achieves higher saturation throughput compared to BEB and EIED. The results also show that the collision resolution method in ECRA is effective because it maintains its performance despite the increased number of stations. The results prove that ECRA is more suitable to operate under dense conditions than BEB and EIED.

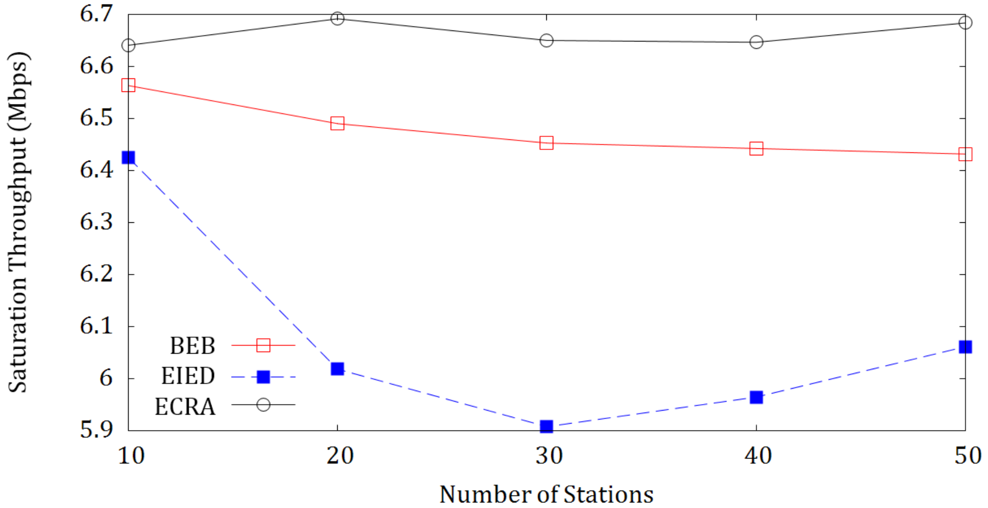

Figure 18 Saturation throughput as a function of the number of active stations

The difference in throughput performance between simulations and theory is due to the environment settings. In the theoretical analysis, we calculate the throughput assuming saturated conditions and ideal channel conditions. This is unlike the simulations, which correspond to a variety of scenarios that cover different network conditions.

Fig. 19 shows that ECRA outperforms BEB and EIED in terms of maximum throughput. In particular, ECRA maintains its performance as the number of active stations increases. The results also show that BEB outperforms EIED. This is mainly due to the ability of BEB to increase the channel access time compared to EIED.

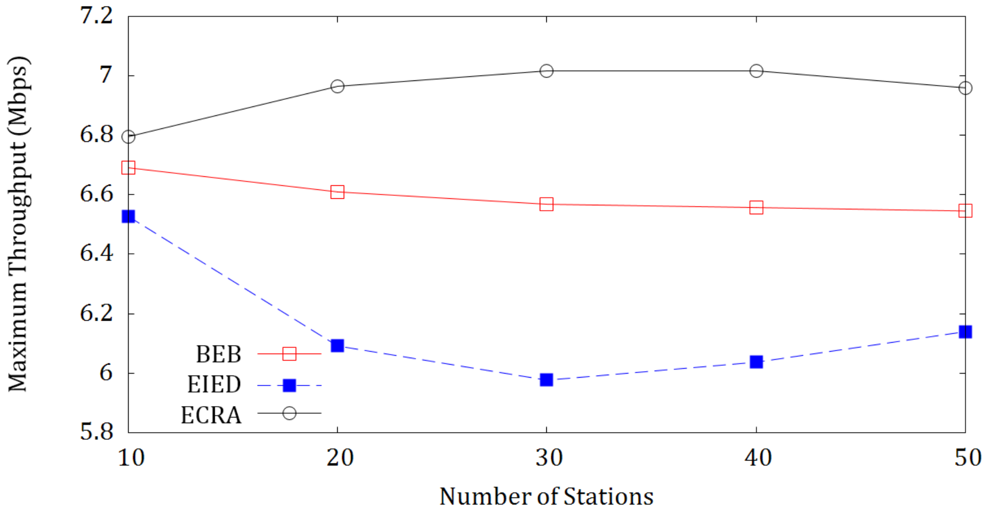

Figure 19 Maximum throughput as a function of the number of active stations

6 | CONCLUSION

We proposed a backoff algorithm (ECRA) that uses a collision resolution method to solve collisions rather than instantly increasing the CW size as in BEB. Simulation results showed that, on average, ECRA outperforms BEB in terms of throughput and fairness. ECRA increases the throughput by reducing the collision probability without affecting channel access time. At the same time, it improves fairness by applying a gradual decrease of the CW size. Compared to EIED, on average, ECRA performed better in terms of throughput and delay and worse in terms of fairness. The main limitation of our algorithm is the increased delay compared to BEB. This is due to the process of separating the colliding stations by adding the current CW size to their backoff time. We also proposed Markov chain models to analyze the theoretical performance of the three algorithms. Our models extend existing models by using a collision probability that depends on the station transmission history. We showed that the analysis of BEB using our model is more accurate and reflects its behaviour in WANETs. Our theoretical results showed that ECRA increases the saturation and maximum throughput compared to BEB and EIED. Our collision resolution algorithm is particularly suitable for vehicle-to-vehicle communication [135,136]. In this application, a large number of stations will be competing for channel access, and improving throughput and fairness, while ensuring an acceptable delay is crucial.As future work, we plan to extend our analytical models to unsaturated conditions.

Appendix

Abbreviation	Meaning
DCF	Distributed Coordination Function
BEB	Binary Exponential Backoff
CW	Contention Window
EIED	Exponential Increase Exponential Decrease
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DIFS	DCF Inter-Frame Space
BO	Backoff Time
CW_{max}	Maximum CW value
CW_{min}	Minimum CW value
ECRA	Enhanced Collision Resolution Algorithm
CW_T	Temporary CW value
RF	Re-transmission Factor
RT	Re-transmission Timer
MILD	Multiple Increment Linear Decrement
EILD	Exponential Increment Linear Decrement
WANETs	Wireless Ad-hoc Networks
FCR	Fast Collision Resolution
RT-FCR	Real Time Fast Collision Resolution
DSFQ	Distributed Self-clocked Fair Queuing
SBA	Sensing Backoff Algorithm
STP	Successful Transmission Priority
DOP	Dynamic Optimisation Protocol
RAP	Renewal Access Protocol
SIFS	Short Inter-Frame Space
RTS	Request To Send
CTS	Clear To Send
ACK	Acknowledgment
CBR	Constant Bit Rate

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