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Article

Improvement for Contention Window Mechanism Using the Transmission State and Random Backoff History in IEEE 802.11 WLANs

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Abstract

In IEEE 802.11 WLAN networks, the Binary Exponential Backoff (BEB) protocol has been used to avoid collisions due to channel errors, but it is less efficient for dense networks with many transmitting nodes. In this work, we propose a new scheme for adapting the contention window based on the transmission state and random backoff history. We propose four transmission states by aggregating the success or failure status of previous and current transmissions. These states are the conditions for selecting the increasing or decreasing contention window for the subsequent transmission time. The ratio between the random backoff value and the contention window partially determines the amount of change for the new contention window. We use NS-3 simulations to evaluate the performance of our scheme. The results show that the scheme can improve the total throughput and average delay and be more efficient with more nodes.

Keywords: network technology; IEEE 802.11; CSMA/CA protocol; BEB algorithm

1. Introduction

During the past decade, the tendency for numerous wireless devices to communicate with each other in a specific area has accelerated the development of wireless network technology. IEEE 802.11 wireless technology is widely deployed in WLANs, and its next generations are rapidly developing to support higher data rates, security enhancement, and an increasing number of users. The Distributed Coordination Function (DCF) method of IEEE 802.11 uses the Carrier Sensing Medium Access with Collision Avoidance (CSMA/CA) protocol to control the process of participating stations entering the channel to transmit their packets [1]. The protocol is also called a time-frame control protocol because it uses a Binary Exponential Backoff algorithm (BEB) to generate a deferring time for each station to avoid collisions, and to wait for an opportunity to transmit its packets. The BEB algorithm works efficiently in a low-load or an unsaturated network, where the BEB algorithm guarantees that participating stations send their packets without any collision [2].

However, the BEB implementation causes more collisions when the network becomes dense and hence makes channel access control for stations more challenging [3]. The problem is that after achieving a successful transmission, it resets the contention window (CW) to the minimum backoff interval, which accidentally increases collision probability. In addition, the network delay may be affected by the exponential expansion of the CW size to support packet retransmission after the station suffers a collision [3,4]. Many proposed schemes have focused on adjusting the CW size in the BEB algorithm to improve the CSMA/CA protocol. Even so, finding an optimal CW size for a dynamic wireless network remains an open problem. Typically, some schemes control the CW size to increase or decrease depending on the result of each transmission or the history of transmission times that performed better than the BEB algorithm [5–10]. Nevertheless, these schemes mostly expand the CW

size after the station, which suffered a collision without considering the status of the network load. Therefore, they are ineffective in some cases of rapid change in network loads, and it was difficult for them to reach a theoretical maximum throughput [10]. In addition, some other schemes collect additional information in the network environment to estimate the density of the stations, then they combine with the result of each transmission to optimize CW size. So, the schemes reduce collisions, obtain high throughput in a saturated network [3,11]. They also outperform the BEB algorithm, but the obtained CW sizes stayed at high values, which might deteriorate network delay[10]. On the other hand, some research focused on investigating the distribution of random variables in the duration of packet transmission to indicate its influence on network delay [4,12–15].

In this study, we proposed a new scheme to control how to change the size of CW based on the combination of Transmission History and Backoff Probability (named THBP). In our mechanism, the transmission history is expressed by the aggregation of the status (successful or unsuccessful transmission) from two sequent transmissions. In addition, the ratio between the random backoff value (BO) and the CW size defines the backoff probability at the current transmission time. In our scheme, the sizes of CW increases or decreases for subsequent transmissions depends on the transmission history, and the backoff probability.

An internal collision occurs when the BO timers of stations expire simultaneously. The collision is partly due to the CW size, but somehow because of the BO. When a station encounters a collision, the CW is extended to give the station one more opportunity to retransmit its packet. However, the CW size was at a large value after several times of retransmission, yet the station continues to collide. There are two reasons for this problem: One reason for the CW size was not large enough, and needed to be expanded more, the other reason is that the uniformly random mechanism of BOs leads stations expire simultaneously. In this study, along with using the packet transmission history, we additionally observe the probability of occurrence of the BO in the range of $[0, CW - 1]$ to support the adjustment of CW size more reasonably.

The remaining part of this paper is organized as follows. Section II summarizes the related work. Section III introduces the new scheme. Section IV presents the simulation results are compared to other schemes to evaluate our scheme. Some conclusions are presented in the last section.

2. Related Work

In the CSMA/CA scheme using the BEB algorithm [1], each station generates a uniformly random backoff value (BO) from $[0, CW - 1]$, where the BO is an integer in units of slot time and CW is the size of the contention window. In this algorithm, the CW size is limited in the range of $[CW_{\min}, CW_{\max}]$, and its initial value could be set to CW_{\min} . The values of CW_{\min} , CW_{\max} , and a slot time value are specified in the IEEE 802.11 standard [1]. BO depends on the channel status, and when the BO counts down to zero, the packet is allowed to be sent. The CW size is updated to a new value according to the indication in the acknowledgment and recovery procedures of the CSMA/CA scheme. In the BEB algorithm, the new CW size for the next transmission is obtained in Eq. 1.

$$CW_{s_{i+1}} = \begin{cases} \min[2^{(s_i+1)} \times CW_{\min}, CW_{\max}] & \text{on a collision,} \\ CW_{\min} & \text{on a success,} \end{cases} \quad (1)$$

where s_i is defined as a backoff stage at the i th transmission time and $s_i \in (0, s_{\max} - 1)$, the parameter s_{\max} is the maximum times of retransmission. The default value of s_{\max} is seven, along with the value of CW corresponding to $[16,32,64,128,256,512,1024]$. Whenever a station suffers a collision, its CW size is exponentially increased for a retransmission until it catches the value of CW_{\max} or the retransmitted time equals s_{\max} [1].

In the case of a saturated network, the BEB algorithm performed inefficiently, so Song *et al.* [5] proposed a scheme (named exponential increase exponential decrease - EIED) in which the CW size was increased the same as the one in the BEB origin after a collision, and the CW size was divided in half after a successful transmission instead of resetting to CW_{\min} like in the BEB algorithm as in Eq. 1. The new value of CW in this scheme was updated in Eq. 2:

$$CW_{s_{i+1}} = \begin{cases} \min[2^{(s_i+1)} \times CW_{\min}, CW_{\max}] & \text{on a collision,} \\ \max[2^{(s_i-1)} \times CW_{\min}, CW_{\min}] & \text{on a success.} \end{cases} \quad (2)$$

In this scheme, after a station achieved a successful transmission, the size of CW was controlled to gradually decrease to prevent the backoff from falling into a tiny interval. The scheme outperformed the BEB origin. However, in this scheme, CW size was maintained at a high value after a successful transmission, which may be sensitive to throughput and average delay [10].

Recently, Ali *et al.* introduced a Channel Observation-based Scaled Backoff scheme (COSB) [3]. In this scheme, they assigned a counter parameter to count the appearance of busy, idle, collision, and success at each slot time in the backoff duration of a station to estimate the channel activities. Then they calculated a collision probability (p_{col}) as a ratio between the counter parameters and used to control the CW size in combination with the result of each transmission for the subsequent transmission. The CW size was updated in the Eq. 3.

$$CW_{s_{i+1}} = \begin{cases} \min[2^{(s_i+1)} \times CW_{\min} \times \rho^{p_{\text{col}}}, CW_{\max}] & \text{on a collision,} \\ \max[2^{(s_i-1)} \times CW_{\min} \times \rho^{p_{\text{col}}}, CW_{\min}] & \text{on a success.} \end{cases} \quad (3)$$

in which ρ was chosen equals to CW_{\min} and p_{col} is the probability of collision [3].

At first sight, the COSB scheme looked like the EIED scheme when it updated the CW size according to the result of each transmission. However, it became prominent when adding more information about the network environment through the factor p_{col} . The scheme performed better than the EIED and BEB algorithms, especially when the network became saturated. However, the scheme also created a variety of CW sizes, and the extraction mechanism of p_{col} was rather complex. In addition, many of the CW sizes were kept at high values to ensure continuously successful transmission, which was a reason for the average delay degradation.

There are many schemes to solve the problem of increasing collisions due to the BEB algorithm, but the majority of them based on the results of packet transmission to control the size of CW for the next transmission. Several schemes extract more information from the network environment [3,11]. In this study, besides using the history of packet transmission, we additionally observe the probability of the BO occurrence during the backoff duration to control the CW size more reasonable for the next transmission. The BO was one of the factors which partly affected the packet transmission result due to its uniform random manner. Our proposal scheme ensures to improve throughput, and solve the deterioration of the average delay in case of different network loads.

3. The Proposal Scheme

In the THBP scheme, we initially estimated the density of a dynamic wireless network based on the results of two consecutive transmission states. We defined T_{pc} to show 'previous' and 'current' transmission states, with p and c notated with terms '0' and '1' respectively. The term '0' specified a successful transmission, and '1' indicated that the station had experienced a collision. There are four states ($T_{00}, T_{01}, T_{10}, T_{11}$), these present the 'previous' and 'current' transmission states which was successful transmission or collision. Furthermore, we calculate the ratio between the BO value and CW in the current transmission and use it to support the adjustment of CW more reasonable in combination with each transmission state. Mathematically, we defined a backoff probability f_i by the ratio

$$f_i = \frac{BO_i}{CW_i} \in [0,1], \quad (4)$$

where the BO_i was a random backoff value and the CW_i size at the i th transmission. We observed the value of f_i in combination with four states to define more suitable CW size for the next transmission.

In the case of a saturated network, a small CW size causes more collisions because it increases the probability of the stations falling to the same backoff values. Likewise, if a large CW size was kept in an unsaturated network, the average delay might be deteriorated [10]. In this scheme, we defined

$s_i = [0, 1, 2 \dots, (s_{\max} - 1)]$ as the backoff stages in which s_{\max} was the maximum number of retransmitted times as in the BEB algorithm. The backoff stage s_i was updated to the backoff stage s_j as below

$$s_{j \leftarrow i} \begin{cases} \min[s_i + \Delta_{pc}, s_{\max}] & \text{if } \Delta_{pc} > 0, \\ \max[0, s_i + \Delta_{pc}] & \text{if } \Delta_{pc} < 0, \end{cases} \quad (5)$$

with $\Delta_{pc} = 0, \pm 1, \pm 2$ was predicted depending on the rules which extracted from the T_{pc} and the f_i aggregation. Then the new contention window CW_j was obtained by:

$$CW_j = CW_{\min} \times 2^{s_j}. \quad (6)$$

We observe the value of f_i to appear in one of three ranges of $[0, 0.25)$, $[0.25, 0.5)$, and $[0.5, 1.0]$. These ranges correspond to BO being small, medium, or large compared to the CW size. Let us discuss the rules for combining T_{pc} with f_i .

In our mechanism, f_i is used to partly support the change of CW in each transmission state. When the transmission state presents two sequent collisions (T_{11}). The CW typically needs to expand to avoid collision for the next transmission. However, if f_i is small, BO can be larger in the next round with the current CW size. It means that the collision can be solved without changing the backoff stage, and the CW remains unchanged. If f_i is medium, the current CW size is necessary to extend a reasonable amount to support the average delay of the network. If f_i is large, it implies that the BO is proportional to the CW size, and we should increase a large amount of the CW size to avoid collision in the subsequent transmission. In the case of the transmission state changes from success to collision (T_{01}), the BEB algorithm increases the CW size by twice to increase the BO value to avoid collision in the next round. However, in our mechanism, if the f_i is small, BO can be larger in the next round with the current CW size, thus its size remains at this backoff stage. If the f_i is medium or large, the CW is doubled, similar to the BEB algorithm, to support a suitable BO value for the next transmission. Likewise, when the transmission state presents two sequent successes (T_{00}). If f_i is large, the CW size is reasonable at this backoff stage and is unchanged. If the f_i is small and medium, the CW size decreases a small amount to avoid an unnecessary delay for the backoff duration. In the case of transmission state changes from collision to success (T_{10}), instead of decreasing to the previous backoff stage, CW size still remains at this backoff stage with any values of f_i to avoid more collisions in the next round.

The factor Δ_{pc} in equation (5) was described by

$$\Delta_{pc} = \begin{cases} \Delta_{pc}^{(s)} & \text{if } f_i < 0.25, \\ \Delta_{pc}^{(m)} & \text{if } 0.25 \leq f_i < 0.5, \\ \Delta_{pc}^{(l)} & \text{if } f_i \geq 0.5. \end{cases} \quad (7)$$

where (s), (m), (l) correspond to small, medium, and large, respectively. The value of factor Δ_{pc} is used to define the next backoff stage. We present the predicted values of Δ_{pc} in Table 1.

Table 1. The predicted values of the factor Δ_{pc} corresponded to each state.

States	f_i		
	Small	Medium	Large
T_{00}	$\Delta_{00}^{(s)} = -1$	$\Delta_{00}^{(m)} = -1$	$\Delta_{00}^{(l)} = 0$
T_{10}	$\Delta_{10}^{(s)} = 0$	$\Delta_{10}^{(m)} = 0$	$\Delta_{10}^{(l)} = 0$
T_{01}	$\Delta_{01}^{(s)} = 0$	$\Delta_{01}^{(m)} = +1$	$\Delta_{01}^{(l)} = +1$

T_{11}	$\Delta_{11}^{(s)} = 0$	$\Delta_{11}^{(m)} = +1$	$\Delta_{11}^{(l)} = +2$
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Table 1 shows that the state T_{00} specifies the transmission state to be successful twice, and the value of $f_i < 0.5$ refers to a small BO value. Therefore, CW should be smaller, and the backoff stage s_i reduces to $s_i - 1$ by the setting $\Delta_{00}^{(s)} = \Delta_{00}^{(m)} = -1$. If $f_i > 0.5$, it implies that the current CW size was large enough and should remain unchanged, as $\Delta_{00}^{(l)} = 0$.

In the state T_{10} , which means that the transmission state changes from collision to a success, then the backoff stage s_i is good enough. So, CW size is kept unchanged with any values of f_i and $\Delta_{10}^{(s)}$, $\Delta_{10}^{(m)}$ and $\Delta_{10}^{(l)}$ are set to zero. Then, the backoff stage s_i can be changed in the next round.

In the state T_{01} , it refers to a success accompanied by a collision. If $f_i < 0.25$, it implies that the collision of the current transmission time was not due to the size of CW, and the backoff stage s_i should remain unchanged, and $\Delta_{01}^{(s)}$ was set to zero. Only if $f_i > 0.25$, the CW size needed to be increased to the CW size at the backoff stage $s_i + 1$, so we set both $\Delta_{01}^{(m)}$ and $\Delta_{01}^{(l)}$ to equal +1.

In the state of T_{11} , which indicates two consecutive collisions. If $f_i > 0.5$, this means that the CW size and the BO value were rather high, but the station has continuously suffered a collision. Therefore, the CW size needed to be expanded a lot, and here the appropriate factor $\Delta_{11}^{(l)}$ should be +2, which referred to the CW size at the backoff stage s_i jumped to the backoff stage $s_i + 2$. If $0.25 \leq f_i < 0.5$, the CW size needed to expand a few, we thus predicted to increase the CW size in the backoff stage s_i to the backoff stage $s_i + 1$ and set the factor $\Delta_{11}^{(m)}$ to be +1. For the case $f_i < 0.25$, we kept the CW size unchanged, and set the factor $\Delta_{11}^{(s)}$ to be zero.

Likewise, we describe the transition of the CW among backoff stages according to the factor Δ_{pc} in the diagram in Figure 1.

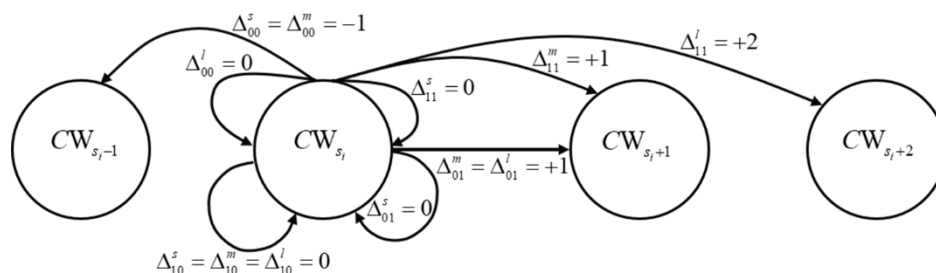


Figure 1. The diagram of the CW size transition following the factor Δ_{pc} among the backoff stages.

In Figure 1, the CW size is at each retransmission time of the BEB algorithm, which was described in Section 2. The CW size is updated in this scheme presented in Equation 8.

$$CW_{s_{j \leftarrow i}} = \begin{cases} \min[CW_{\min} \times 2^{(s_i + \Delta_{pc})}, CW_{\max}] & \text{on a collision,} \\ \max[CW_{\min} \times 2^{(s_i + \Delta_{pc})}, CW_{\min}] & \text{on a success.} \end{cases} \quad (8)$$

The values of $\Delta_{pc} = 0, \pm 1, \pm 2$ specifies the speed change of CW. The proposed THBP scheme guarantees to obtain high throughput, low delay, good fairness, and address the sensitive delay that the EIED and COSB schemes encountered. The scheme contributed to minimizing collisions and improving the network performance for different network loads.

4. Experiment

In this section, we evaluated the efficiency of the THBP scheme through simulations using the NS3 tool, version 3.36.1 [16]. In addition, the simulation results of the THBP scheme were compared

to those of the BEB algorithm and the EIED, COSB schemes by measuring aggregated throughput, average delay, and fairness index in a network with varying load conditions.

In this simulation, we set up topologies of an ad hoc grid and a mobile ad hoc network (MANET) to investigate the efficiency of controlling CW at the MAC layer of IEEE 802.11. Ad-hoc grid and MANET networks, which are wireless networks without infrastructure, are typically designed to accomplish a specific task such as disaster management, military, rescue operations, etc. An ad-hoc grid topology is stable in sharing the resources among nodes, although its nodes are coming and leaving constantly. The nodes in these topologies can be mobile devices, software, and support devices with wireless connectivity. Moreover, the MANET networks with their flexibility and adaptability are applied in environmental monitoring, healthcare, home automation, sensor and vehicular networks, etc.

4.1. Simulation Results on an Ad-Hoc Grid Topology

In this ad-hoc grid topology, we set the five base stations at the center in fixed positions. Then, five to fifty source stations were put in the grid in random positions, with five stations gradually added by each step. The distance between the two stations was about 25 meters in an area of 350×350 m. We assumed that the competing stations (STAs) always had packets to transmit to express saturation conditions. We ran 20 simulation trials with 5 to 50 competing stations and averaged the results. The simulation parameters are shown in Table 2.

Table 2. The simulation parameters.

Parameters	Values	Parameters	Values
Operating Frequency	5 GHz	CW_{\min}	31
Bandwidth	20 MHz	CW_{\max}	1023
Packet size	1024 bytes	Stations	From 5 to 50
aSlottime	9 μ s	PropagationLossModel	LogDistance
Datarate	54Mbps	Distance between stations	From 20 to 25 m
Packet rate	300 kbps	Routing Protocol	OLRS

Initially, we use the simulation parameters in Table 2 to simulate the BEB, the EIED, the COSB, and the THBP scheme on this topology to evaluate our scheme. The simulation results are presented in Figure 2a–c. Figure 2a showed that when the competing stations were less than 15, the THBP performed as well as the BEB algorithm, and their throughput results are nearly the same. However, there is a contrast between them when the competing stations are more than 15. The throughput of the BEB algorithm decreases rapidly, while the throughput of the THBP scheme continues to increase until the number of stations reaches 20. When the number of stations is more than twenty, the THBP's throughput reduces due to more collisions occurring. The BEB algorithm expressed a rapid decrease in throughput from nearly 22 Mbit/s to 18 Mbit/s, which refers to the BEB algorithm facing a rapid increase in collision rate. Besides, Figure 2a also describes the stable implementation of the THBP scheme along with the BEB, where the throughput of the THBP scheme was about 5 Mbit/s better than that of the BEB at each step of increasing the number of transmitting stations. It should be noted that the enhanced schemes typically increased the CW size after a station suffered a collision and decreased the CW size after a station achieved a successful transmission. However, if a station has just achieved a successful transmission at the backoff stage and still has more packets to send but the CW size is controlled in decrease. The decrease may push the station in a collision because the CW size is not large enough for the next transmission. Therefore, the reasonable change of CW size in the THBP scheme is crucial to specify the enough time for stations achieving more times of successful packet transmission instead of experiencing more retransmission. Figure 2a showed that the EIED,

COSB perform more effectively than the BEB algorithm in throughput, but the THBP model achieves the highest throughput of all. The throughput of the THBP scheme was approximately 2 Mbit/s better than that of the EIED scheme and more than 1 Mbit/s better than that of the COSB scheme for 20 or more competing stations.

Furthermore, Figure 2b presents the average delay results of the compared schemes. The THBP scheme outperformed the BEB algorithm in the average delay of the network. Consequently, the THBP scheme has effectively dealt with the increasing collision rate, which the BEB algorithm suffered. Although the throughput of the COSB scheme was superior to that of the EIED and BEB, it experienced a deterioration in the average delay because it mostly kept the sizes of CW at large values due to multiplication during the process of updating the CW size. The average delay result of the THBP scheme was dominant over the results of the EIED and COSB schemes. The appropriate adjustment of the CW size, supported by the f_i values, was a key component in reducing the average delay of the network in this scheme. The THBP scheme expresses a prominent performance in both throughput and average delay, especially in the case of a saturated network. Finally, we investigate the fairness index of each scheme by calculating the fairness index following Jain's fairness [17]. It is an important measure in a wireless network to specify a fair resource allocation for each station, and is an essential element contributing to the efficiency of network performance. Figure 2c shows that the fairness indexes in the compared schemes are approximately the same. In general, the simulated results showed that the reasonable adaptation of the CW size brings the best throughput and average delay while maintaining a good fairness index to the THBP scheme.

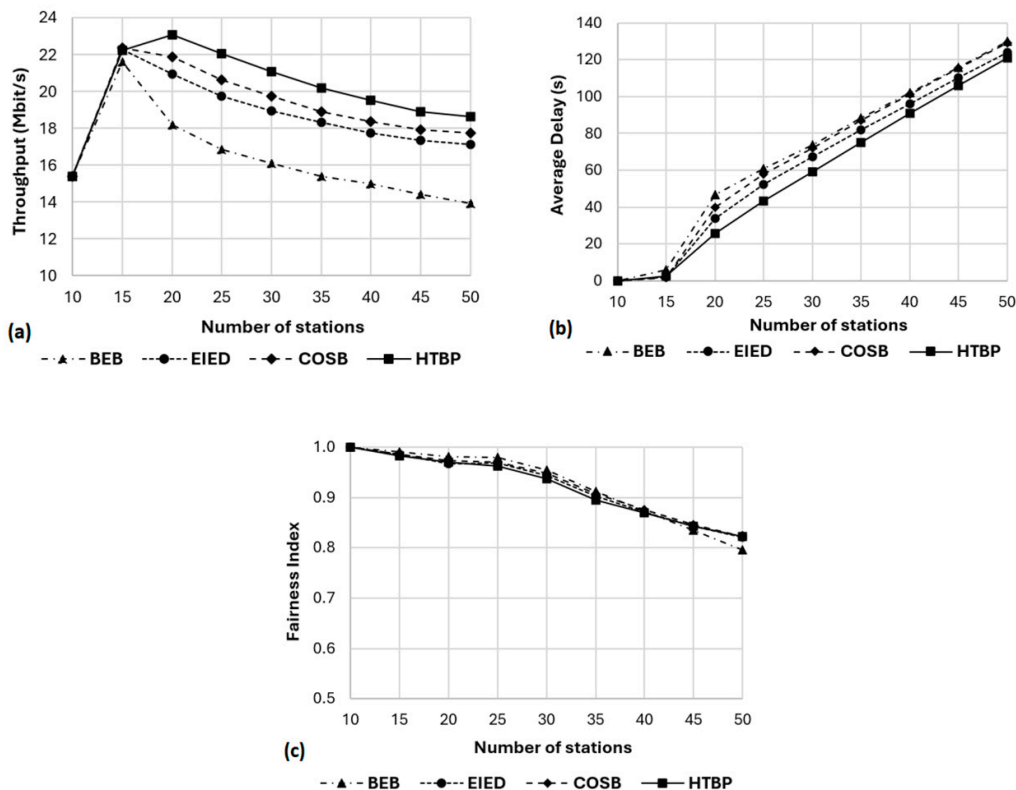


Figure 2. The simulated results of the compared scheme on an ad hoc grid topology.

4.2. Simulation Results on a MANET Topology

In this MANET topology, we use a random waypoint mobility model for station mobility at a speed of 2m/s without pause time, and the other parameters are in Table 2. The transmitting stations (from 5 to 40 stations) are randomly distributed in an area with a constant density based on the total number of stations, and the five sink stations are in fixed positions. The simulated results are presented in Figure 3.

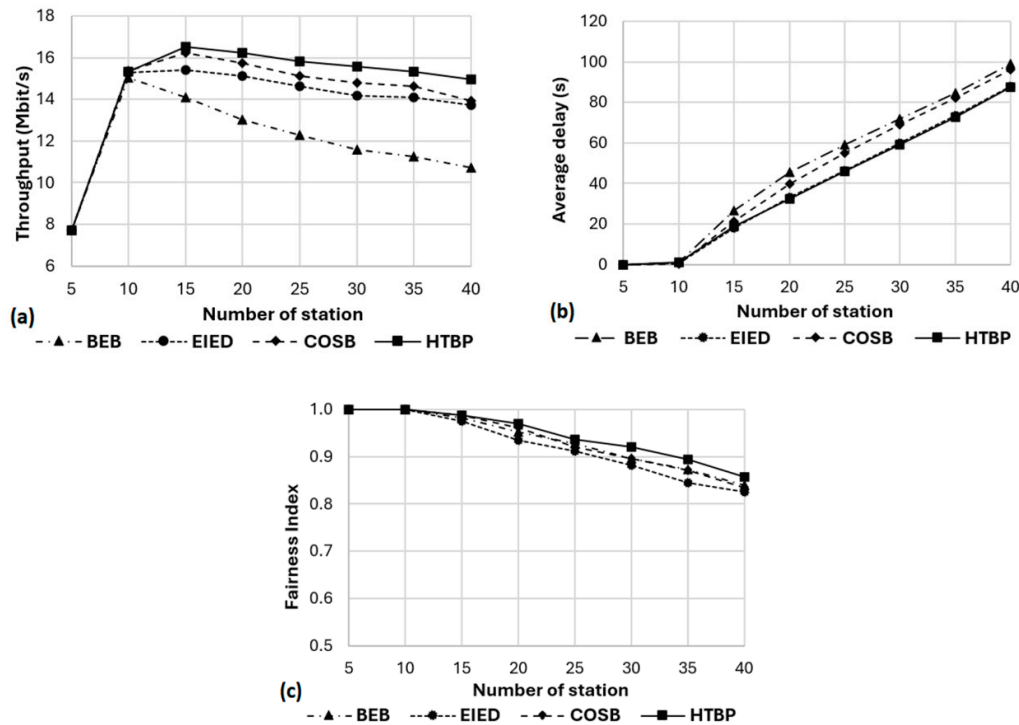


Figure 3. The simulated results of the compared schemes on a MANET topology.

The simulated results in this topology are nearly similar to the results in the ad hoc grid topology. Figure 3a shows that the throughput obtained from the THBP scheme is the best result compared to the BEB, EIED, COSB schemes. Figure 3b presents the average delay of the THBP scheme which is superior to the compared schemes. In addition, the fairness indices of the compared schemes, which are shown in Figure 3c, are approximate to each other in a good performance for the network. Therefore, the THBP scheme performs efficiently on both topologies and indicates a better enhancement to the BEB, EIED, and COSB schemes.

5. Conclusions

In this paper, we proposed a new THBP scheme that adjusts the CW size based on the information available from the consecutive transmission, the BO, and the CW history. The THBP scheme only makes a minor change to the active mechanism of the CSMA/CA protocol. The simulated results in both topologies showed that the THBP scheme specifies a better performance compared to the BEB, EIED, and COSB schemes, and surpasses them in both throughput and average delay, along with its approximate fairness. Moreover, the average delay of the THBP scheme also specifies that the scheme partially solves the issue of delay deterioration that many schemes experienced in the case of different network loads.

In conclusion, the efficiency of a dynamic wireless network in IEEE 802.11 DCF depended on the design of the BEB algorithm, and we continue to pay attention to improving our scheme using other techniques and investigating the scheme in a variety of packet sizes in our future work.

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