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Adaptive Binary Negative-Exponential Backoff Algorithm Based on Contention Window Optimization in IEEE 802.11 WLAN

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Abstract

IEEE 802.11 medium access control (MAC) employs the distributed coordination function (DCF) as the fundamental medium access function. DCF operates with binary exponential backoff (BEB) in order to avoid frame collisions. However it may waste wireless resources because collisions occur when multiple stations are contending for frame transmissions. In order to solve this problem, a binary negative-exponential backoff (BNEB) algorithm has been proposed that uses the maximum contention window size whenever a collision occurs. However, when the number of contending stations is small, the performance of BNEB is degraded due to the unnecessarily long backoff time. In this paper, we propose the adaptive BNEB (A-BNEB) algorithm to maximize the throughput regardless of the number of contending stations. A-BNEB estimates the number of contending stations and uses this value to adjust the maximum contention window size. Simulation results show that A-BNEB significantly improves the performance of IEEE 802.11 DCF and can maintain a high throughput irrespective of the number of contending stations.

Keywords: IEEE 802.11, WLAN, medium access control (MAC), distributed coordination function (DCF), contention window (CW) optimization

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1. Introduction

The IEEE 802.11 standard is currently the most popular protocol used to implement wireless local area networks (WLANs) due to the low-cost chipsets and support for high data rates [1][2]. Medium access control (MAC) is one of the main functions of IEEE 802.11 WLAN that strongly affects the network performance [3]. IEEE 802.11 has employed a distributed coordination function (DCF) as a mandatory contention based MAC protocol [4]. DCF is a random access method based on the carrier sense multiple access with collision avoidance (CSMA/CA) protocol that adopts binary exponential backoff (BEB) to avoid frame collisions.

In DCF, if a station has a frame to transmit, it monitors the wireless channel to determine whether it is idle or not during the DCF interframe space (DIFS). After a channel has been sensed idle during the DIFS, the station waits for a random backoff time slot in the range [0, CW-1], where CW is the current contention window size. The backoff time slot decreases by one for each idle slot time, and the station transmits a frame when the backoff time reaches zero. At the first frame transmission, the station sets the backoff stage to 0 and sets the contention window size to the minimum contention window size ($CW_{\min}$). If the stations do not receive acknowledgements (ACKs), the backoff stage is increased by one and the contention window size is doubled until it reaches the maximum contention window size ($CW_{\max}$). This avoids frame collisions. However, in DCF, if multiple stations are contending for frame transmissions, the wireless resources of the network may be wasted. This is because when it experiences a successful frame transmission the station resets its contention window size to the minimum value without considering the current network status.

In IEEE 802.11 WLAN, frame collisions and backoff delays are important factors determining network performance [5]. If a frame transmission involves multiple collisions, network throughput can deteriorate due to wasted wireless resources. Also, if stations delay their frame transmission too long, the wireless medium remains unused for a long time and network resource utilization decreases. The contention window size affects the collision probability and backoff delay. A large contention window increases the backoff delay and decreases the collision probability and vice versa for a small contention window. In order to improve network performance, the contention window size should be determined by network conditions such as the number of contending stations.

In order to reduce both the collision probability and backoff delay, the binary negative-exponential backoff (BNEB) algorithm sets the contention window size to $CW_{\max}$ when the station experiences a collision, and reduces the contention window size by half when a frame is successfully transmitted without retransmission [6]. The BNEB algorithm performs better than DCF when multiple stations are contending for frame transmissions. However, if the number of contending stations is small, the throughput of BNEB is lower than that of DCF due to the unnecessarily long backoff time [7]. In order to overcome the problem with BNEB, we proposed an adaptive BNEB (A-BNEB) algorithm in [8]. The A-BNEB algorithm estimates the number of contending stations by measuring both the collision and transmission attempt probabilities, and selects an appropriate $CW_{\max}$ from a pre-configured table. In this paper, we improve the A-BNEB algorithm by adapting it to dynamic environments where the number of stations changes according to the packet sizes. Also, we conduct simulations to intensively investigate the performance of the A-BNEB algorithm. The simulation results show that the A-BNEB algorithm achieves the maximum throughput of the IEEE 802.11 network.

The remainder of the paper is organized as follows. Section 2 introduces works related to IEEE 802.11 WLAN. Section 3 briefly illustrates the operation of the BNEB algorithm. In

Section 4, we propose an A-BNEB algorithm and explain the method to estimate the number of contending stations and optimize the maximum contention window size in BNEB. In Section 5, we compare the performance of the A-BNEB algorithm with other algorithms when the number of contending stations changes according to the payload sizes. Finally, we conclude the paper in Section 6.

2. Related Works

Many studies have attempted to model IEEE 802.11 DCF. Bianchi presented an analytical model for obtaining the saturation throughput of IEEE 802.11 DCF using a bi-dimensional Markov chain model, and evaluated the throughput performance of the basic access method and the RTS/CTS mechanism [5][9]. From the results, it was shown that system parameters such as the contention window size strongly affect the performance of the basic access method, but the RTS/CTS mechanism marginally depends on the system parameters. Xiao *et al.* derived the throughput upper limit (TUL) and delay lower limit (DLL) of IEEE 802.11 DCF and showed the existence of TUL and DLL by simply increasing the data rate and maintaining the overhead [10]. In [11] and [12], the performance of DCF in the presence of transmission errors was evaluated using a mathematical model. The analytic results showed that the performance of IEEE 802.11 was severely degraded as the bit error rate (BER) increased. In [13][14][15], the throughput of DCF under the non-saturation condition was analyzed using the Markov chain model.

In order to improve the performance of IEEE 802.11 DCF, fast collision resolution (FCR) was proposed [16]. Each station in FCR uses a smaller contention window size than DCF, and exponentially decreases its backoff counter when $2 \cdot CW_{\min}-1$ consecutive idle slots are detected. Although FCR can resolve collisions faster than DCF and acheive a high throughput, it has to be used with self-clocked fair queueing (SCFQ) scheduling in order to guarantee fairness between stations. The gentle distributed coordination function (GDCF) proposed by Wang *et al.* newly introduced an additional counter to measure the number of consecutive successful frame transmissions [3]. In GDCF, to avoid useless collisions, stations decrease their backoff stages by one when a fixed number of consecutive successful frame transmissions have occurred. The Enhanced GDCF (EGDCF) considered the number of stations, where the maximum permitted number of consecutive successful transmissions varied according to the backoff stage [17]. This enhanced the performance of GDCF for various numbers of contending stations and frame lengths. A scheme for reducing frame collisions by using a disjoint set of transmission time slots was introduced in [18]. In this scheme, each station monitors the wireless link and then chooses an idle slot for its frame transmission. If the station successfully transmits its frame in the slot, it includes this slot in the set of transmission time slots. By using disjoint sets, stations can avoid collisions, especially in the presence of hidden stations.

In [19], an asymptotically optimal backoff (AOB) mechanism was proposed, which dynamically adapts the contention window size to the current network contention level. The AOB mechnism measures the network contention level by checking the slot utilization and the average transmitted frame size. Using both the measured network contention level and the pre-determined optimal slot utilization level, the AOB mechanism achieves near-optimal throughput when the number of contending stations is large. However, the throughput of the AOB mechanism is much lower than the optimal throughput when the number of contending stations is less than 10. In [20], the distributed adaptive contention window scheme (DACWS) was proposed. This scheme dynamically adjusts the contention window size according to the channel status. In order to consider the channel status, DACWS estimates the number of active stations by measuring the transmission failure rate based on an analytical model of the p-persistent CSMA/CA protocol. Although it can provide near-optimal performance for IEEE 802.11 WLAN, its performance may be sensitive to the accuracy of the measured transmission failure rate, because it adjusts the size of $CW_{\min}$.

3. Binary Negative-Exponential Backoff (BNEB) Algorithm

The BNEB algorithm uses three parameters: backoff stage, backoff counter, and contention window. In BNEB, the contention window size is initially set to $CW_{\max}$ in order to reduce the frame collision probability. If a frame is successfully transmitted without retransmission, BNEB halves the contention window size in order to reduce the backoff time delay. However, to reduce the collision probability, BNEB increases the contention window size to $CW_{\max}$ whenever a station experiences a transmission failure. The contention window size of a station at the backoff stage i, W_i, is determined by $CW_{\max}$ and its backoff stage. This is decided as follows:

$$W_i = \begin{cases} CW_{\max}, & 0 < i \le m, \\ 2^i \cdot CW_{\max}, & -L \le i \le 0, \end{cases}$$

where m is the maximum retry limit and L is the parameter for determining $CW_{\min}$ which is equal to $CW_{\max} \cdot 2^{-L}$.

In order to transmit frames using the BNEB algorithm, stations randomly select backoff counters ranging from 0 to $W_i - 1$ and decrease the backoff counters by one whenever the channel has been sensed idle during a slot time. A station transmits its frame when its backoff counter reaches zero. The new backoff stage is decided by the previous backoff stage and the frame transmission result, i.e., success or failure. Let BS_{prev} and BS_{new} be the previous and new backoff stages, respectively. If the previous frame was successfully transmitted, then the new backoff stage is set as follows:

$$BS_{new} = \begin{cases} 0 & \text{if } 0 < BS_{prev} \le m, \\ BS_{prev} - 1 & \text{if } -\mathrm{L} < BS_{prev} \le 0, \\ -L & \text{if } BS_{prev} = -L. \end{cases}$$

If the previous frame transmission failed, then the new backoff stage is set as follows:

$$BS_{new} = \begin{cases} 0 & \text{if } BS_{prev} = m, \\ BS_{prev} + 1 & \text{if } 0 \le BS_{prev} < m, \\ 1 & \text{if } -L \le BS_{prev} < 0. \end{cases}$$

4. Adaptive BNEB (A-BNEB) Algorithm

The normalized saturation throughput of BNEB has been analyzed in a similar manner to Bianchi's Markov chain model [6][7]. The analytic results show that BNEB achieves higher throughput than DCF when multiple stations are contending for frame transmissions. However, if the number of contending stations is small, the performance of BNEB is seriously degraded due to the unnecessarily long backoff time. Therefore, to achieve maximum throughput, it is necessary to adjust the maximum contention window size of BNEB based on the number of contending stations.

Let p be the probability that a transmitted frame experiences a collision. Then, the probability p can be expressed as:

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

where n is the number of contending stations. Let $b_{i,j}$ be the probability that a station is in state (i, j), where i and j represent the backoff stage and backoff counter of the station, respectively. From the mathematical model in [6], $b_{i,j}$ can be calculated as a function of p. Then, using equation (15) in [6], the probability τ that a station transmits a frame in a slot time can be calculated as follows:

$$\tau = \frac{2(1+p)(1-p^{m+1})}{2(1-p)(CW_{\max}p+1)+(1-p)^2\{CW_{\max}(\frac{1-p}{2})^L-1\}+p(1+p)(CW_{\max}+1)(1-p^m)}. \tag{2}$$

Combining (1) and (2), the number of contending stations n can be expressed as

$$n = 1+\frac{\log(1-p)}{\log\left(1-\frac{2(1+p)(1-p^{m+1})}{2(1-p)(CW_{\max}p+1)+(1-p)^2\{CW_{\max}(\frac{1-p}{2})^L-1\}+p(1+p)(CW_{\max}+1)(1-p^m)}\right)}. \tag{3}$$

To estimate the number of contending stations, the collision probability p is required. Let $\hat{p}$ be the packet loss probability. Then it can be measured as follows:

$$\hat{p} = \frac{N_{fail}}{N_{trans}}, \tag{4}$$

where N_{fail} and N_{trans} are the number of transmision failures and total transmission attempts during the estimation interval T, respectively. We assume that there are no channel errors. Then, the packet loss probability $\hat{p}$ can be regarded as the collision probability. Since the backoff parameters m, L, and $CW_{\max}$ are given, we can estimate the number of contending stations $\hat{n}$ in (3) using the measured value $\hat{p}$.

In [5], Bianchi has shown that it is possible to achieve the maximum saturation throughput of IEEE 802.11 using the following approximate solution:

$$\tau_{opt} \approx \frac{1}{n\sqrt{T_c^*/2}}, \tag{5}$$

where τ_{opt} is the optimal τ to achieve maximum throughput, and $T_c^* = T_c/\sigma$ is the duration of frame collision (T_c) measured in unit slot time σ. This means that τ should be adjusted to achieve the maximum network performance based on the number of contending stations n. To calculate τ_{opt}, we use the estimated number of contending stations $\hat{n}$ in (3). If the contention window size is a constant, we can find the relationship between τ and the contention window size [5]. Since the average contention window size of BNEB can be regarded as a constant for the case of a constant p, we can find the optimal average contention window size using τ_{opt}:

$$\overline{W}_{opt} \approx \frac{2}{\tau_{opt}} - 1 . \tag{6}$$

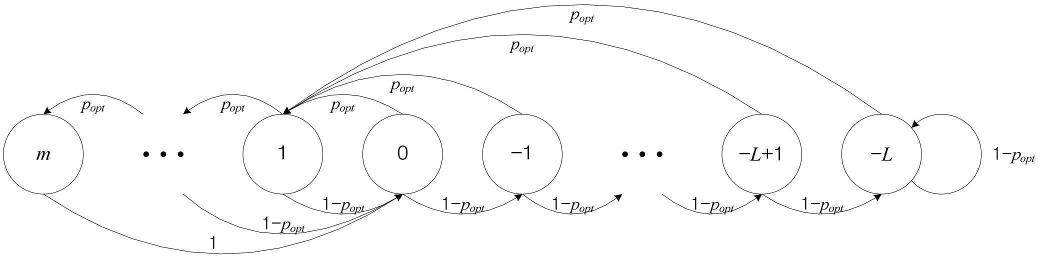


Fig. 1. Markov chain model for the backoff stage

Let $s(t)$ be the random process representing the backoff stage for a station at time t, and $\lim_{t\to\infty} P\{s(t)=i\} = s_i$, $i=-L,-L+1,\cdots,m$. Then, we can model the discrete-time Markov chain for $s(t)$ as shown in **Fig. 1**. Using the chain regularities, s_i can be expressed as follows:

$$s_i = \begin{cases} \frac{(1-p_{opt})^{-i}}{p_{opt}} s_0, & i=-L, \\ (1-p_{opt})^{-i} s_0, & -L+1 \le i \le 0, \\ p_{opt}^{i-1} s_{0,} & 1 \le i \le m. \end{cases} \tag{7}$$

where p_{opt} denotes the optimal collsion probability, given by

$$p_{opt} = 1-(1-\tau_{opt})^{\hat{n}-1} . \tag{8}$$

Since $\sum_{i=-L}^{m} s_i = 1$,

$$\frac{(1-p_{opt})^L}{p_{opt}} s_0 + \sum_{i=-L+1}^{0} (1-p_{opt})^{-i} s_0 + \sum_{i=1}^{m} p_{opt}^{i-1} s_0 = 1. \tag{9}$$

Thus,

$$s_0 = \frac{p_{opt}(1-p_{opt})}{(1-p_{opt}) + p_{opt}(1-p_{opt}^m)} . \tag{10}$$

Let $CW_{\max\_opt}$ be the optimal maximum contention window size of BNEB. $\overline{W}_{opt}$ is calculated using (7) and (10) as follows:

$$\overline{W}_{opt} = \sum_{i=-L}^{m} s_i W_i = \left\{ \left(\frac{1-p_{opt}}{2}\right)^L \frac{1}{p_{opt}} + \sum_{i=-L+1}^{0} \left(\frac{1-p_{opt}}{2}\right)^{-i} + \sum_{i=1}^{m} p_{opt}^{i-1} \right\} CW_{\max\_opt} s_0 . \tag{11}$$

Finally, we can obtain $CW_{\max\_opt}$ from (11) as follows:

$$CW_{\max\_opt} = \frac{(1+p_{opt})\{(1-p_{opt}) + p_{opt}(1-p_{opt}^m)\}}{(1-p_{opt})^2 \left(\frac{1-p_{opt}}{2}\right)^L + 2p_{opt}(1-p_{opt}) + p_{opt}(1+p_{opt})(1-p_{opt}^m)} \overline{W}_{opt} . \tag{12}$$

In the adaptive BNEB (A-BNEB) algorithm, $CW_{\max}$ is adaptively adjusted to achieve the maximum network throughput regardless of the number of contending stations. A-BNEB calculates the optimal $CW_{\max}$, maximizing the network throughput at every estimation interval

T, as shown in **Fig. 2**. The procedure for calculating the optimal $CW_{\max}$ is summarized as follows:

1) An AP measures N_{fail} and N_{trans} during estimation interval T and estimates the collision probability $\hat{p}$ using (4).
2) With the value $\hat{p}$ and the current $CW_{\max}$, the AP estimates the number of contending stations using (3).
3) The AP calculates τ_{opt} using (5), and p_{opt} is obtained from (8).
4) Finally, the optimal $CW_{\max}$ can be calculated using (12).

After calculating the optimal $CW_{\max}$, the AP broadcasts the beacon frame, including the optimal $CW_{\max}$, at the start time of the superframe. Then, all stations receiving the beacon frame use this information to set their maximum contention window size to the optimal value. The updated optimal $CW_{\max}$ is applied to determine the backoff counter after the current transmission attempt.

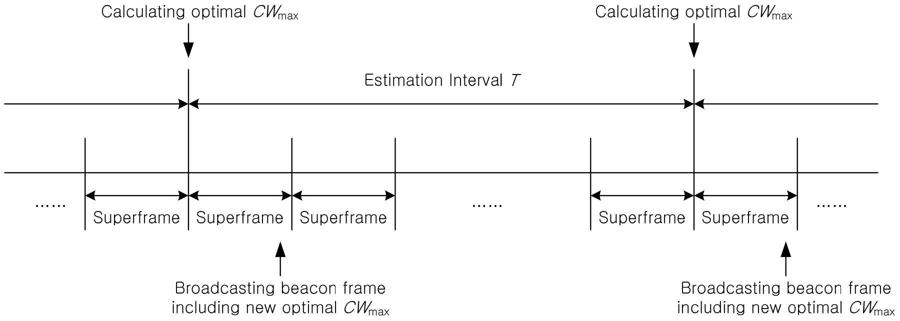


Fig. 2. Time frame to apply A-BNEB algorithm

5. Performance Evaluation

In order To evaluate the performance of DCF, BNEB, DACWS [20], and A-BNEB, we use a Monte Carlo event-driven simulation written in C++. We consider IEEE 802.11a environments, for which the related MAC parameters are given in **Table 1** [4]. In IEEE 802.11a, control packets such as ACK are transmitted with control rate (C_{con}) [21][22]. We assume that all stations exist within the transmission range of the AP. We use the default parameters for DCF and BNEB in IEEE 802.11a, $CW_{\min} = 16$ and $CW_{\max} = 1024$. In A-BNEB and DACWS, the AP estimates the number of contending stations, $\hat{n}$, every second, and uses it to calculate the optimal contention window size. Subsequently, the AP broadcasts the beacon frame including the optimal $CW_{\max}$ and $CW_{\min}$ values for A-BNEB and DACWS, respectively. We assume that the optimal $CW_{\min}$ and $CW_{\max}$ values of DACWS and A-BNEB are greater than 4 and 256 for $L = 6$ and $m = 7$, respectively. In addition, there are 200 associated stations, and the estimated number of active stations for DACWS and A-BNEB does not exceed the number of associated stations.

Fig. 3 compares the normalized throughputs of DCF, BNEB, DACWS, and A-BNEB under the saturation condition as the number of contending stations increases. In the saturation condition, the transmission queues of the stations always have frames to transmit. We consider two different packet payload sizes (100 and 1000 bytes) in order to analyze the impact of payload size on the saturation throughput of the network. In the case where the payload size is 1000 bytes and the number of contending stations is large, the throughput of DCF is seriously deteriorated, because multiple collisions occur as a result of heavy contention for frame transmissions. However, BNEB achieves higher throughput than DCF, because BNEB effectively reduces the probability of frame collisions by increasing the contention window size to $CW_{\max}$. Conversely, when the number of contending stations is small, BNEB performs worse than DCF due to the inefficiency of the long backoff time. A-BNEB and DACWS achieve high throughputs irrespective of the number of contending stations, because they adjust $CW_{\max}$ and $CW_{\min}$ to the optimal values based on the estimated number of contending stations. The throughputs of A-BNEB and DACWS are larger than that of DCF in low contention environments and larger than that of BNEB in high contention environments. However, when the number of contending stations is small, A-BNEB shows higher throughput than DACWS. Even though different m values are used, the throughput of DCF is only influenced by the m value, and the other algorithms show similar throughputs comparable to the case where $m = 7$. In case that the payload size is equal to 100 bytes, both A-BNEB and DACWS also achieve higher throughput than DCF and BNEB. However, the throughputs are degraded, since the overhead ratio (e.g. preamble, PLCP header, MAC header, ACK frame, etc.) per transmission attempt increases.

Table 1. IEEE 802.11a MAC parameters

Parameter	Value
Data rate (C)	54 Mbps
Control rate (C_{con})	24 Mbps
Superframe length	25 msec
MAC header	272 bits
Preamble length	16 μsec
PLCP header length	4 μsec
Transmission time of beacon frame	456 bits / C_{con} + 20 μsec
Transmission time of ACK frame	112 bits / C_{con} + 20 μsec
SIFS	16 μsec
DIFS	34 μsec
Slot time	9 μsec
Propagation delay	1 μsec
Maximum retry limit	7

The mean backoff delays for DCF, BNEB, DACWS, and A-BNEB are shown in **Fig. 4**, where the packet payload size is equal to 1000 bytes. When the number of contending stations is small, the mean backoff delay for BNEB is larger than that of the other algorithms. This is because the waiting time for frame transmission is long due to the large contention window size. As the number of contending stations increases, the backoff delay for DCF increases more rapidly than the other algorithms, because there are multiple frame collisions. A-BNEB and DACWS adjust their contention window sizes to the optimal values in order to ensure that the backoff delay is minimal regardless of the number of contending stations.

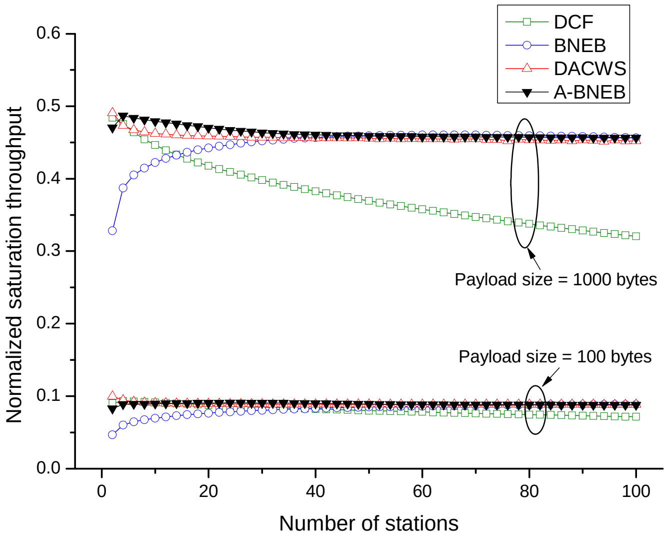


Fig. 3. Normalized saturation throughput of DCF, BNEB, DACWS and A-BNEB

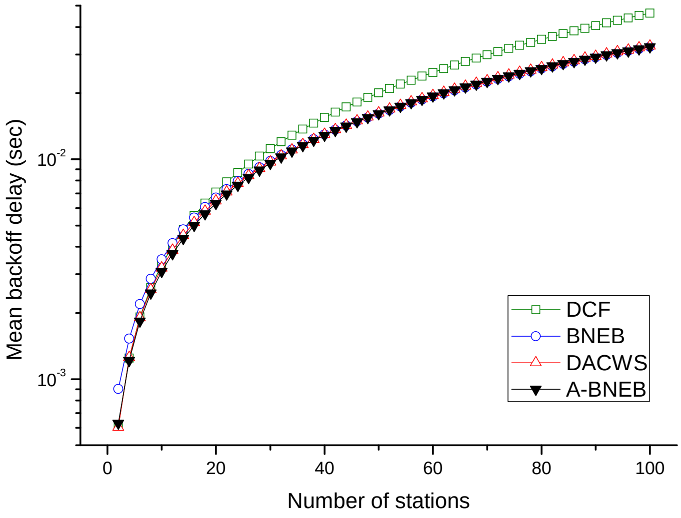


Fig. 4. Mean backoff delay of DCF, BNEB, DACWS and A-BNEB
(packet payload size = 1000 bytes)

The number of active stations is varied as shown in **Fig. 5** in order to evaluate the performance of DCF, BNEB, DACW, and A-BNEB in an environment where the number of contending stations varies over time. **Fig. 6-(a)** shows the normalized throughputs of DCF, BNEB, DACWS, and A-BNEB for a 1000-byte payload for the variation in the number of active stations shown in **Fig. 5**. When $0 < t \le 50$, there are five active stations in the network and the throughputs of DCF, DACWS, and A-BNEB are higher than that of BNEB. In low contention environments, the throughput is greatly influenced by the backoff time because the collision probability is low. Therefore, BNEB achieves a relatively low throughput compared to DCF, DACWS, and A-BNEB, due to the unnecessarily long backoff time. For BNEB and A-BNEB, since the number of transmitted frames per unit time has a high variance due to the large contention window size, the ranges of throughput fluctuation are larger than those of DCF and DACWS. The throughput of DCF decreases stepwise for $50 < t \le 150$ due to the large number of frame collisions, and then increases stepwise for $150 < t \le 200$. The throughput of BNEB is high for $50 < t \le 150$ because BNEB efficiently avoids frame collisions when multiple stations contend for frame transmissions. A-BNEB and DACWS adjust the contention window size to the optimal value according to the estimated number of contending stations based on the measured collision probability $\hat{p}$ **.** Therefore, A-BNEB and DACWS can achieve maximum throughput irrespective of the number of contending stations. However, at the transition points associated with given numbers of stations (i.e. $t = 50$, $t = 100$, and $t = 150$), the throughputs of A-BNEB and DACWS are momentarily decreased. This is because the $CW_{\max}$ and $CW_{\min}$ values of A-BNEB and DACWS, respectively, are not adjusted to the actual number of contending stations. Frame collisions result in less wireless resource wastage when the frame payload size is small, because the transmission time of the collided frames is relatively short. However, the network throughput is significantly affected by the backoff time. Therefore, when the payload is 100 bytes, the normalized throughput of DCF does not significantly decline, as the number of contending stations increases, as shown in **Fig. 6-(b)**. Conversely, the normalized throughput of BNEB is greatly decreased when $0 < t \le 50$, due to the unnecessarily long backoff time. A-BNEB and DACWS achieve high throughputs in all regions, because they can appropriately adjust the contention window size to the optimal value based on the number of contending stations.

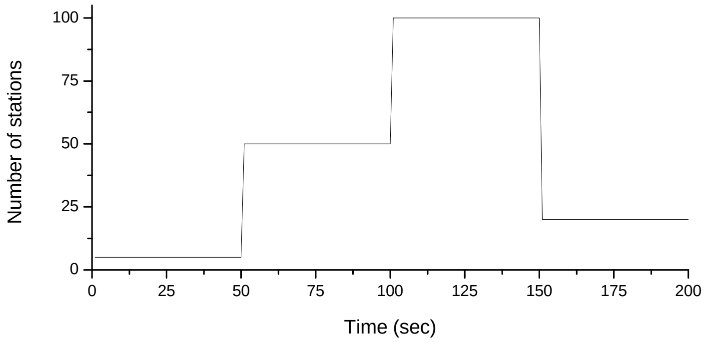
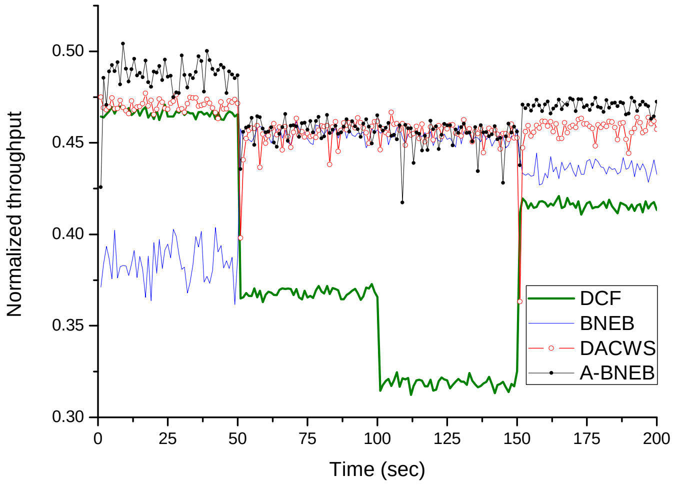
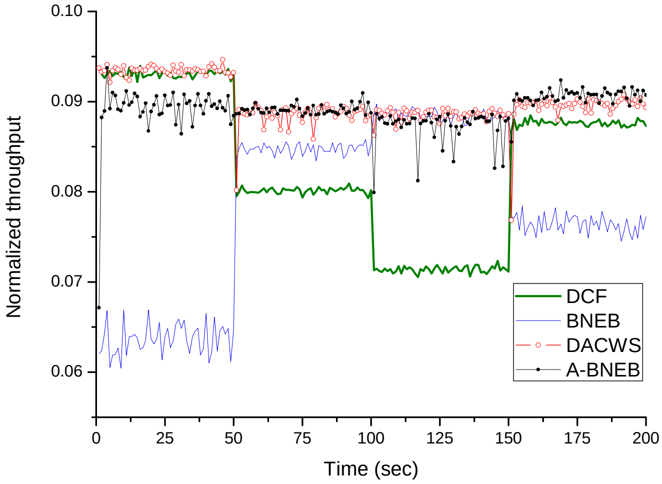


Fig. 5. Simulated variation of the number of active stations

Fig. 7 shows the normalized saturation throughputs of A-BNEB and DACWS when the number of contending stations, *n*, is 25 and 50, respectively. As the estimation interval increases, the accuracy of the estimated number of active stations increases so that the throughputs of A-BNEB and DACWS approach the optimal throughput. On the other hand, if the estimation interval is shortened, the throughputs of A-BNEB and DACWS are degraded, because the accuracy of the estimated number of active stations decreases. The throughput of DACWS is sensitive to the accuracy of optimal contention window estimation, since DACWS starts from $CW_{\min}$. However, the throughput of A-BNEB is less sensitive to the accuracy of optimal contention window estimation since A-BNEB starts from $CW_{\max}$. Therefore, the throughput of DACWS is more seriously degraded than that of A-BNEB as the estimation interval decreases, especially when the number of contending stations is small. As shown in **Figs. 7-(a)** and **7-(b)**, the throughputs of A-BNEB and DACWS are more affected by the estimation interval when the payload size is equal to 1000 bytes.

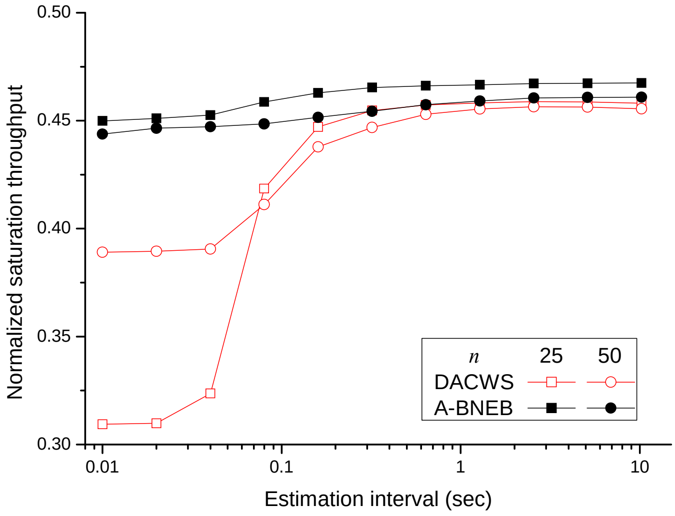


(a) Payload size = 1000 bytes

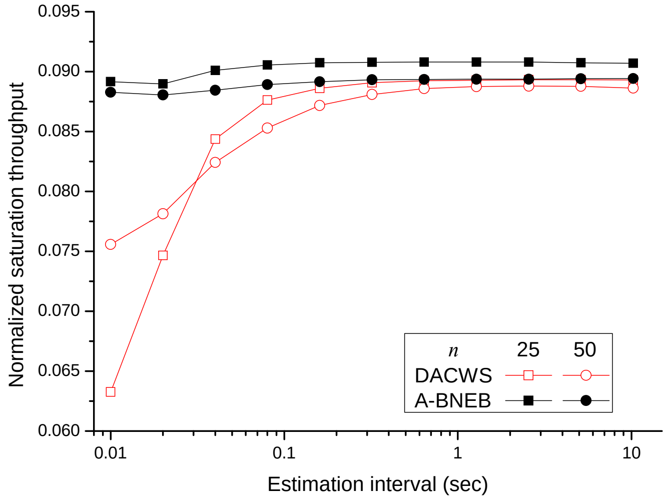


(b) Payload size = 100 bytes

Fig. 6. Comparison of normalized throughput for the variation in the number of active stations shown in **Fig. 5**



(a) Payload size = 1000 bytes



(b) Payload size = 100 bytes

Fig. 7. Comparison of normalized throughput of DACWS and A-BNEB according to estimation interval T

6. Conclusions

In this paper, we proposed the A-BNEB algorithm that enhances the BNEB algorithm in IEEE 802.11 WLAN. In A-BNEB, the AP estimates the number of contending stations by measuring the collision probability. Using the estimated number of contending stations, the AP calculates the optimal $CW_{\max}$ based on mathematical analysis of BNEB, and broadcasts a beacon frame including the optimal $CW_{\max}$ value. Simulation results show that A-BNEB performs better than DCF, BNEB, and DACWS for various packet payload sizes. When the number of contending stations is large, A-BNEB can achieve a high throughput comparable to BNEB. Moreover, when the number of contending stations is small, A-BNEB overcomes the performance problems of BNEB and achieves a high throughput comparable to DCF. The length of the estimation interval for the collision probability can affect the throughput of A-BNEB and DACWS, because this length determines the optimal contention window size. We observe that A-BNEB and DACWS achieve high throughputs regardless of the number of contending stations since their contention window sizes are adaptively changed according to the estimated number of stations. However, simulation results show that the performance of A-BNEB is more robust than DACWS when the estimation interval is short.

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