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A backoff algorithm based on self-adaptive contention window update factor for IEEE 802.11 DCF

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Abstract The binary exponential backoff (BEB) mechanism is applied to the packet retransmission in lots of wireless network protocols including IEEE 802.11 and 802.15.4. In distributed dynamic network environments, the fixed contention window (CW) updating factor of BEB mechanism can't adapt to the variety of network size properly, resulting in serious collisions. To solve this problem, this paper proposes a backoff algorithm based on self-adaptive contention window update factor for IEEE 802.11 DCF. In WLANs, this proposed backoff algorithm can greatly enhance the throughput by setting the optimal CW updating factor according to the theoretical analysis. When the number of active nodes varies, an intelligent scheme can adaptively adjust the CW updating factor to achieve the maximal throughput during run time. As a result, it effectively reduces the number of collisions, improves the channel utilization and retains the advantages of the binary exponential back-off algorithm, such as simplicity and zero cost. In IEEE 802.11 distributed coordination function (DCF) protocol, the numerical analysis of physical layer parameters show that the new backoff algorithm performance is much better than BEB, MIMD and MMS algorithm.

Keywords Back-off algorithm · Contention window · IEEE 802.11 DCF · Normalized system throughput

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1 Introduction

Recently, there has been an increasing demand for towards smart electronic products and mobile workstations with the development of wireless packet computing technology. Wireless networks need to provide more efficient and reliable communications between these mobile terminals [1–6]. If the protocol on the MAC layer is static and can't adjust itself to the changing network environment, it will result in performance degradation.

Prompted by the development and deployment of Wireless Local Area Networks (WLANs), standardization organizations such as IEEE 802.11 look to improve performance. DCF is an important access mechanism in IEEE 802.11 [7] and uses a contention-based algorithm to provide access for all traffic. Studies have shown that the performance of a DCF-based wireless network is mainly affected by binary exponential backoff (BEB) mechanism [8]. A Backoff algorithm is a method for the wireless network MAC layer protocol to resolve a collision when the channel is shared by more than one node. Backoff algorithms should be designed not only to reduce these collisions, but also to avoid long waiting time for high channel utilization [9–12].

The BEB algorithm provides a method using the contention window (CW) for nodes to solve the problem of packet collision. The CW will be doubled for a retry and reset to the minimum after each successful transmission. There have been several algorithms to enhance the BEB system in order to improve performance of IEEE 802.11 DCF. Haitao Wu pioneered a new backoff scheme [13] to reset the CW, namely multiple increase multiple decrease (MIMD) algorithm in which CW will be halved after each successful transmission and doubled when retransmission happens, while Qiang Ni [14] decreases CW to $\frac{1}{\delta}$ times after a successful transmission. Exponential increase exponential decrease (EIED) [15] updates CW with CW/r_D after achieving successful transmission every time. Otherwise, CW is reset to $r_I \cdot CW_{old}$, where, r_I and r_D are CW updating factor.

$$CW_{new} = \begin{cases} \max(CW_{old}/r_D, CW_{min}) & \text{on a success} \\ \min(r_I \cdot CW_{old}, CW_{max}) & \text{on a collision} \end{cases} \tag{1}$$

These mechanisms [13–15] all update CW according to whether the transmission is successful or not once. But such information actually does not reflect network conditions such as the number of competing nodes. These methods will be shown to be ineffective since nodes constantly move and/or frequently switch on or off in a distributed dynamic environment, resulting in a constantly changing number of competing nodes.

In [16], Frederico Cali proposed a persistent DCF, where the access mechanism adaptively adjusts itself to the changing number of competing nodes. It can be seen that network performance declines, as the number of competing stations increases, however, this performance degradation can be improved to a certain extent by the parameter adjustment of the BEB algorithm. Mohammad Shurman [17] improved the selection process of the CW, based on the number of successful and unsuccessful transmissions. In [18], a CW adaptation scheme is proposed in which nodes use information shared by the access point (AP) to optimize CW sizes to improve network utility. In [19], MMS (multi-channel MAC scheme based on 802.11) is proposed, where backoff timer is decremented according to the real-time collision probability and Guo Wang [20] proposed a constrained-send mechanism to limit the transmission of nodes at the end of each back-off procedure. Due to the high density of sensor nodes, a lot of energy has been wasted on medium access competition because of the serious collisions in Wireless Sensor Networks (WSN) [21–24]. Based on 802.11 DCF, in [25], an energy efficient MAC protocol (EEMP) is used to achieve energy efficiency and fast collision resolving for WSN.

From the above papers, it can be seen that the parameters of the backoff algorithm should be adjusted according to the channel condition in order to improve network performance. Nevertheless, these papers did not analyse how to set the CW updating factor by mathematical modeling to make the system throughput achieve an optimal value. In order to improve the performance of DCF, we make some modification to the backoff mechanism and propose a self-adaptive contention window updating factor adjusting backoff algorithm.

The paper is structured as follows. Section 2 introduces 802.11 DCF and conducts an in-depth performance analysis. The new backoff algorithm and its self-adaptive tuning scheme are presented in Sect. 3. Section 4 validates the accuracy of the model by comparing the analytical results with that obtained by means of simulations. Finally, Concluding remarks are given in Sect. 5.

2 Related works

This section will briefly introduce the IEEE 802.11 DCF and present an in-depth performance analysis for the protocol.

2.1 IEEE 802.11 DCF

IEEE 802.11 defines two channel access modes: basic and RTS/CTS-based access mode. The default mode is basic access method in which a positive MAC acknowledgement (ACK) is transmitted by the destination station to signal successful packet transmission. The RTS/CTS-based access mode reserves the channel before data transmission with a four-way handshaking technique, namely request-to-send/clear-to-send (RTS/CTS). In DCF, whenever a backoff procedure occurs, the backoff timer T is selected from a uniform distribution over the interval $[0, CW - 1]$ (namely the contention window). T can be divided into several time slots. The station keeps listening to the channel. If the channel is idle for a slot, the backoff timer will be decreased by one slot. If the channel is busy, the backoff timer will not change, until the channel is sensed to be idle again. When T reaches zero, the station trys to transmit data in basic or RTS/CTS mode. If the transmission fails, CW will be doubled. Otherwise, CW will be reset to the minimum. The updating mode of CW is given by

$$CW_{new} = \begin{cases} CW_{min} & \text{on a success} \\ \min(CW_{max}, 2 \cdot CW_{old}) & \text{on a collision} \end{cases} \tag{2}$$

where, CW_{max} is the maximum value of CW, CW_{min} is the minimum value of CW. In the CW increasing process, let W_i be the size of CW in each backoff stage, such that

$$W_i = \begin{cases} 2^i W, & 0 \le i \le m \\ 2^m W. & i > m \end{cases} \tag{3}$$

where, i denotes the backoff stage, $W = W_0 = CW_{min}$ is the minimum of CW, $2^m W = CW_{max}$ is the maximum of CW and m is the maximum backoff stage.

2.2 Throughput

Consider a fixed number of competing nodes sharing a single-channel under ideal conditions (i.e., no hidden terminals or capture). In saturation conditions, all the nodes immediately have packets available for sending after the completion of each successful transmission.

Let τ be the probability that the station transmits a packet in a randomly chosen slot time. For the n nodes sharing a single channel, the following three events may happen during a given slot time:

(1) No station tries to access the channel, so the probability p_{idl} is

$$p_{idl} = (1-\tau)^n \tag{4}$$

(2) One station accessed the channel successfully, the probability p_{suc} is

$$p_{suc} = \mathrm{C}_n^1 \tau (1-\tau)^{n-1} \tag{5}$$

(3) At least two stations try to access the channel and collision occurs, the probability p_{col} is

$$p_{col} = 1 - p_{suc} - p_{idl} = 1 - \mathrm{C}_n^1 \tau (1-\tau)^{n-1} - (1-\tau)^n \tag{6}$$

The conditional collision probability p_c that a transmitted packet encounters a collision, is the probability that (in a time slot) at least one of the $n-1$ remaining stations transmits. This yields

$$p_c = 1 - (1-\tau)^{n-1} \tag{7}$$

Let S be the normalized throughput, defined as the fraction of time the channel is used to successfully transmit payload bits. S can be expressed using these probabilities,

$$\begin{aligned} S &= \frac{E[\text{ paylod information transmitted in a slot time }]}{E[\text{ length of a slot time }]} \\ &= \frac{p_{suc}E[L]}{p_{suc}T_s + p_{idl}\sigma + p_{col}T_c} \end{aligned} \tag{8}$$

T_s is the average time the channel is sensed busy because of accessing the channel successfully, T_c is the average time the channel is sensed busy by each station during a collision, σ is the duration of an empty slot time. $E[L]$ is the average packet payload size.

Rearranging (8) yields

$$\begin{aligned} S &= \frac{E[L]}{T_s + \frac{p_{idl}}{p_{suc}}\sigma + \frac{p_{col}}{p_{suc}}T_c} = \frac{E[L]}{T_s + \mathrm{g}(\tau)} \\ \mathrm{g}(\tau) &= \frac{(1-\tau)^n\sigma + \left[1-(1-\tau)^n - n\tau(1-\tau)^{n-1}\right]T_c}{n\tau(1-\tau)^{n-1}} \end{aligned} \tag{9}$$

As $E[L]$, T_c, T_s, σ are constants, to maximize the throughput S. Take the derivative of (10) with respect to τ, and set it to 0:

$$\left.\frac{\partial \mathrm{g}(\tau)}{\partial \tau}\right|_{\mathrm{n=constant}} = 0 \tag{10}$$

Thus the optimal transmission probability τ_o [26] that each station should adopt in order to achieve maximum throughput performance within a network scenario of n competing stations is given by:

$$\tau_o = \frac{\sqrt{1 + 2(1-1/n)(T_c^\sigma - 1)} - 1}{(n-1)(T_c^\sigma - 1)} \approx \frac{1}{n\sqrt{T_c^\sigma/2}} \tag{11}$$

where $T_c^\sigma = T_c/\sigma$.

3 Proposed algorithm improvements

3.1 Theoretical models

In this section, we utilize a two-dimensional Markov chain on backoff procedure and adopt the same approximation used in [26] to obtain a new improved algorithm. The key approximation in this model is that, at each transmission attempt, and regardless of the number of retransmissions suffered, each packet collides with constant and independent probability p_c.

Existing backoff algorithms such as BEB and MIMD [13] don't take current network status into account, the CW update method is fixed regardless of how the system network load changes. This results in needless collisions, due to insufficient CW growth factor when the network load is large. Furthermore, when the load is small, the CW diminishment factor is too small to allow for high channel utilization due to large backoff time. In order to maximize the network performance, this improved algorithm modifies the CW updating factor according to the current network status. Taking c as the CW update factor of the improved algorithm, c should be represented with a form that is closely related to the number of competing stations. In this work, this is done with an implicit function.

$$c = \mathcal{F}(n) \tag{12}$$

Here, n is the number of competing stations sharing a single-channel.

The way CW updates is now given by

$$CW_{new} = \begin{cases} \max(\frac{1}{c}CW_{old}, CW_{min}) & \text{on a success} \\ \min(c \cdot CW_{old}, CW_{max}) & \text{on a collision} \end{cases} \tag{13}$$

Let $s(t)$ and $b(t)$ be the stochastic processes representing the backoff stage and the backoff timer. $b_{i,k}$ is the stationary probability for a station with back-off stage i and backoff timer k. The Two-Dimensional process $\{s(t), b(t)\}$ of this proposed scheme can be modeled by the Markov chain illustrated in Fig. 1.

According to the Markov Chains regularities, for each $i \in [0, m]$, $k \in [0, W_i - 1]$, $b_{i,k}$ can be written as

$$b_{i,k} = \begin{cases} q^i b_{0,0}, & k = 0 \\ \dfrac{W_i - k}{W_i} b_{i,0}, 0 \le i \le m & k \in (0, W_i - 1] \end{cases} \tag{14}$$

$$\text{where } q = p_c/(1 - p_c),\ p_c = 1 - (1 - \tau)^{n-1} \tag{15}$$

As the sum of stationary distribution for all states must be equal to 1, then

$$\begin{aligned} \sum_{i=0}^{m} \sum_{k=0}^{W_i - 1} b_{i,k} &= \sum_{i=0}^{m} b_{i,0} \sum_{k=0}^{W_i - 1} \frac{W_i - k}{W_i} \\ &= \frac{1}{2} \sum_{i=0}^{m} (b_{i,0} W_i + b_{i,0}) = 1 \end{aligned} \tag{16}$$

Let W_i be the size of CW of each back-off stage, with

$$W_i = \begin{cases} c^i W, & 0 \le i \le m \\ c^m W. & i > m \end{cases} \tag{17}$$

from the equations (14) to (17), we can get the value of $b_{0,0}$ as:

$$\frac{1}{b_{0,0}} = \frac{W\left[1 - (cq)^{m+1}\right]}{2(1 - cq)} + \frac{1 - q^{m+1}}{2(1 - q)} \tag{18}$$

The probability τ that a node transmits in a randomly chosen slot is the sum of probabilities of all states:

$$\begin{aligned} \tau &= \sum_{i=0}^{m} b_{i,0} \\ &= \frac{2(1 - cq)(1 - q^{m+1})}{W[1 - (cq)^{m+1}](1 - q) + (1 - cq)(1 - q^{m+1})} \end{aligned} \tag{19}$$

3.2 Optimal value of *c*

One outstanding issue in this improved algorithm is how to set the parameter c to achieve the optimal throughput condition. By substituting (11) and (15) in (19), the optimal value of c in different access mode may be obtained, as shown in Table 1. From this, the values of τ and p_c of the improved algorithm can be easily calculated according to

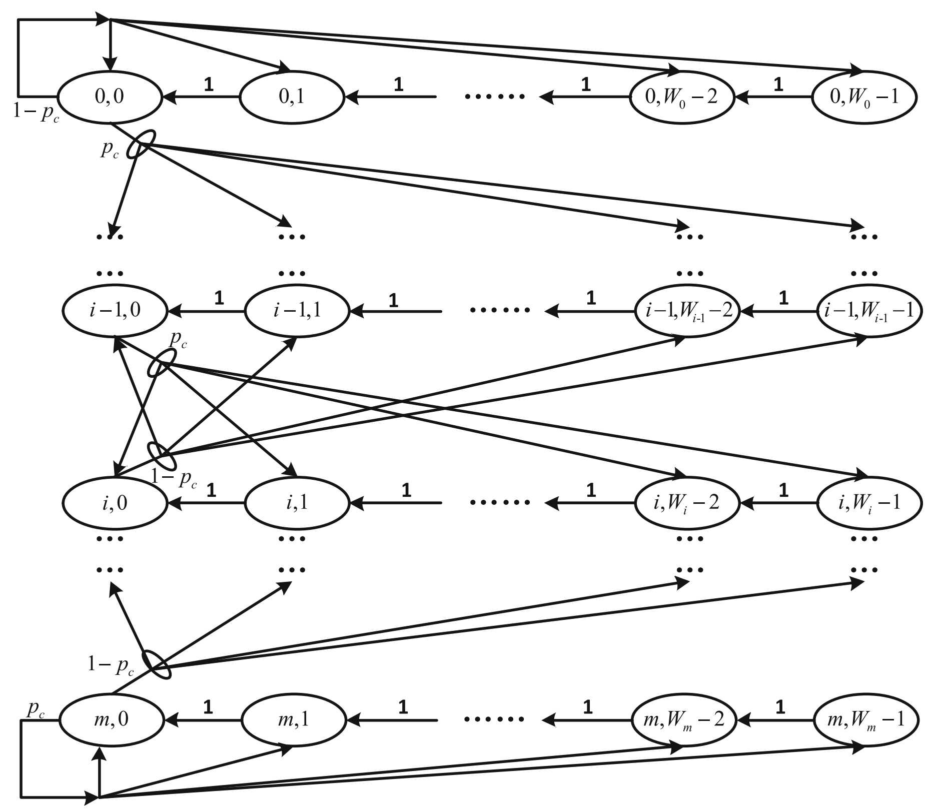

Fig. 1 Markov analytical model of improved algorithm

(15) and (19). In order to contrast with other backoff algorithms, the values of τ and p_c in BEB algorithm and MIMD algorithm were also calculated. Figures 2 and 3 respectively show a station transmission probability τ versus the number of competing stations. It can be seen that in each access mode, transmission probability τ decreases with increasing the network load. We can also see that in the BEB and MIMD algorithms, the transmission probability curves are deviating from the curve of optimal transmission probability (alike in the improved algorithm) as the network load increases in both access modes.

Figure 4 presents the collision probability versus the number of contending stations achieved by BEB, MIMD and the improved algorithm for each access mode. Clearly, in BEB, the curves labeled with Basic mode and RTS/CTS mode overlap, as do the collision probability curves of MIMD algorithm. In each access mode, collision probability increases with increasing the network load. In Basic access mode, the collision probability of the improved algorithm is always lower than that of the other two algorithms irrespective of the number of nodes. In RTS/CTS mode, as the congestion level is low, the collision probabilities of all algorithms are close to each other. However, the collision probability of improved algorithm is consistently lower than that of the other two algorithms as the number of contending nodes increases. Based on the theoretical analysis, it can be concluded that if the number of competing nodes is known in advance, the parameters

Table 1 Optimal value of c

n	Basic	RTS/CTS
5	8.7	0.6
10	11.6	1.7
15	13.2	2.2
20	14.3	2.4
25	15.2	2.7
30	16.0	2.8
35	16.6	3.0
40	17.2	3.1
45	17.8	3.2
50	18.2	3.3
55	18.7	3.4
60	19.0	3.5
65	19.5	3.6
70	19.8	3.7
75	20.1	3.7
80	20.5	3.8
85	20.8	3.9
90	21.0	3.9
95	21.3	4.0
100	21.6	4.0

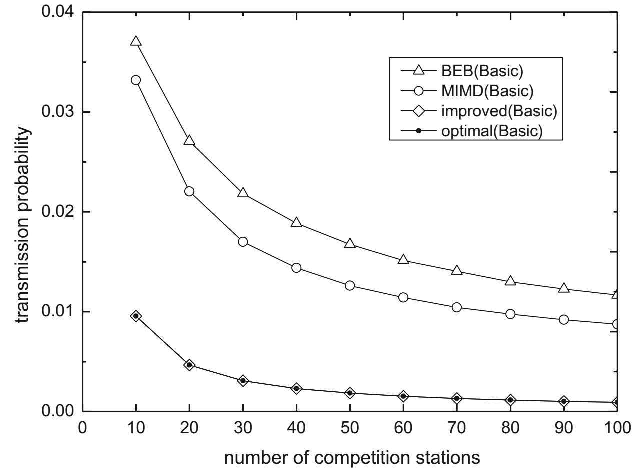

Fig. 2 Transmission probability of basic access scheme

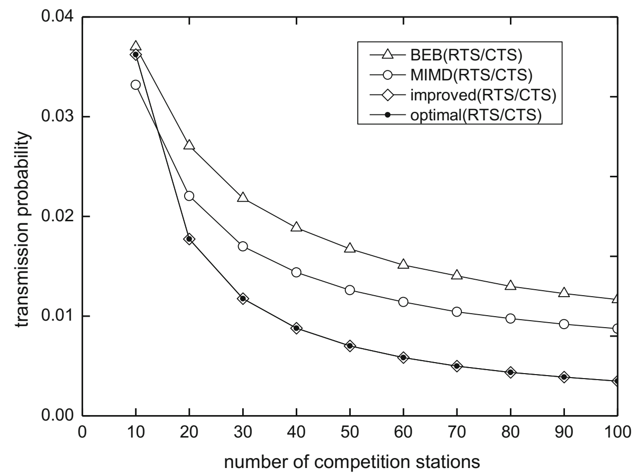

Fig. 3 Transmission probability of RTS/CTS access scheme

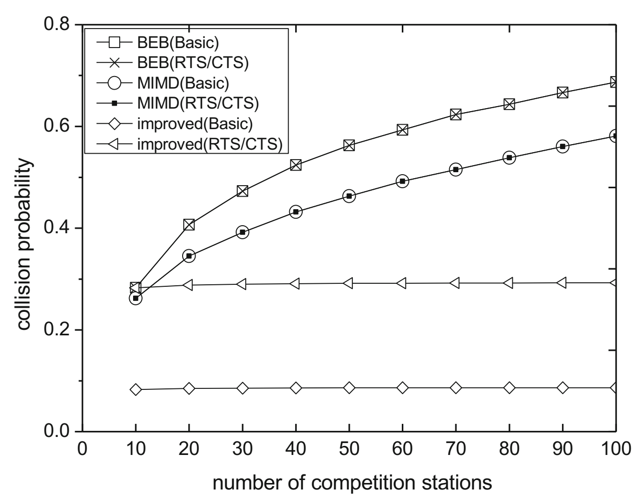

Fig. 4 Conditional collision probability of all access schemes

can be intelligently set to track its optimal value. However, it is usually difficult to determine the number of competing nodes in a WLAN. Thus, in next section, the self-adaptive tuning scheme of our new algorithm is presented without requiring the exact number of competing nodes in the network.

3.3 Self-adaptive tuning scheme

To solve for the presence of the unknown parameter n, consider a simple method that involves zero cost, using the ratio of $t_{collision}$ to t_{idle}, H, to reflect the congestion level of the network. H [25] is given by

$$H = \frac{t_{collision}}{t_{idle}} \tag{20}$$

where $t_{collision}$ is described as the sum of periods of time encountered by a collision during a backoff procedure and t_{idle} is the sum of idle periods of time during a backoff procedure. $t_{collision}$ and t_{idle} are part of the available period which is accounted as the whole period of time a backoff procedure takes to resolve a collision. All of these are available with the legacy MAC. H can be expressed in terms of the probabilities p_{col}, p_{idl} and their corresponding periods of time, T_c and σ by

$$H = \frac{T_c p_{col}}{\sigma p_{idl}} = \frac{T_c^{\sigma}[1-(1-\tau)^n - n\tau(1-\tau)^{n-1}]}{(1-\tau)^n} \tag{21}$$

Combining this with Taylor formula yields:

$$(1-\tau)^n \approx 1 - n\tau + \frac{n(n-1)}{2}\tau^2 \tag{22}$$

(22) can be further simplified as

$$\begin{aligned} H &= \frac{T_c^{\sigma}[1-(1-\tau)^n - n\tau(1-\tau)^{n-1}]}{(1-\tau)^n} \\ &\approx [(1-\tau)^{-n} - 1 - n\tau]T_c^{\sigma} \\ &\approx \frac{n(n+1)\tau^2}{2}T_c^{\sigma} \end{aligned} \tag{23}$$

Replacing τ with τ_o yields the optimal value of H as:

$$H_o \approx \frac{n(n+1)T_c^{\sigma}}{2(n\sqrt{T_c^{\sigma}/2})^2} \approx 1 \tag{24}$$

H_o shows the optimal rate of $t_{collision}$ and t_{idle}, while achieving the maximum throughput. The theoretical optimum of H is approximately constant irrespective of the number of competing nodes. Based on this work, a self-adaptive scheme (as shown in Fig. 5) is introduced to accommodate a variable number of contending nodes. Before running this algorithm, first calculate the optimal values of c for each scale of competing nodes, listed previously in Table 1. At run time, each node measures its $H_{current}$ from (20) and compares it with H_o. In addition, let MAX be the threshold number of observations, and D_H be the threshold floating value of H_o. Each time before transmitting a packet, when $H_{current}$ is larger (less) than $H_o + D_H(H_o - D_H)$, *count* is increased (decreased) by 1. If the value of *count* is higher (lower) than the predefined threshold $MAX(-MAX)$, a larger (smaller) c will be adopted to reflect the increased (decreased) scale of competing nodes realized by a node.

As can be seen, the self-adaptive tuning scheme adapts to current channel state for achieving the optimal system throughput in a WLAN. Embedded at the MAC layer, it has no overheads for the performance of higher-layer applications.

4 Performance evaluation

To test the performance of this algorithm and validate the correctness of theoretical analysis previously derived, simulation experiment have been carried out with Matlab (R2009a). The simulation time is 100 s. The number of nodes is variable, ranging from 10 to 100 with a step size of 10. In addition, each node is uniformly distributed in the single-hop networks. All of the nodes have a data flow rate of 1000 Byte of packets towards their destination node. Both access modes are taken into account for the performance metrics under consideration (throughput and frame delay). With the parameters in Table 2, the results are summarized as follows:

4.1 Throughput

The throughput results are shown in Figs. 6 and 7. In each access mode, the normalized system throughput of the four algorithms show a downward trend, with the increase of competing nodes. The declining trend of the normalized system throughput for the BEB algorithm is the most pronounced. By contrast, the normalized system throughput of the improved algorithm remains approximately steady and only falls slightly as the network load increases. In RTS/CTS access mode, when the number of competition nodes is 10, the improved algorithm has no obvious advantage over the other algorithms of normalized system throughput. This is due to the fact that both the other algorithms are also able to adapt to the network conditions, owing to the low congestion level. However, as the number of competing nodes increase, the normalized system throughput in the improved algorithm gradually outperforms that of the other algorithms. In Basic mode, the normalized system throughput of improved algorithm is

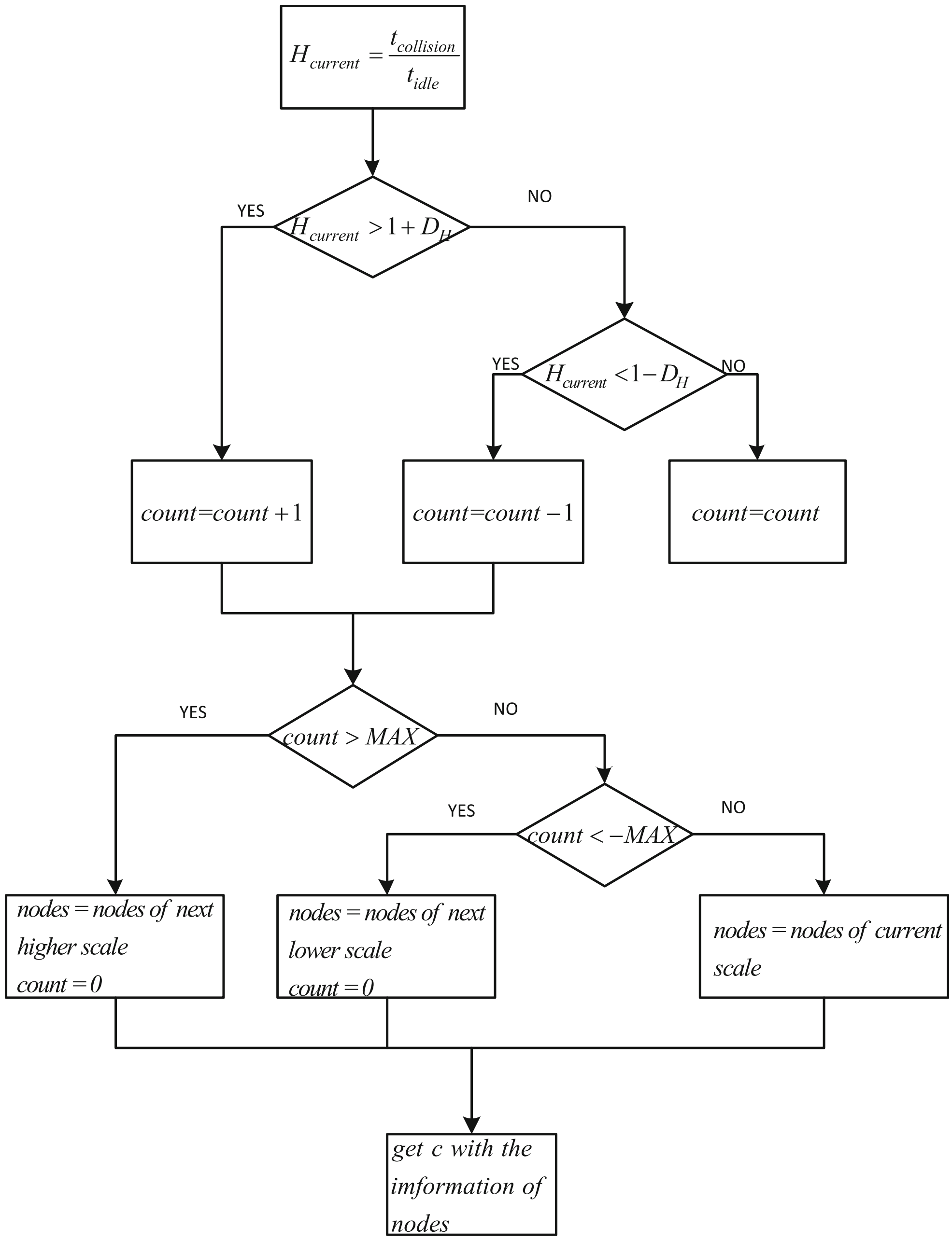

Fig. 5 Algorithm flowchart

always higher than the other algorithms, and this trend emphasized as the number of competition nodes increases.

4.2 Frame delay

In this analysis the frame delay is also considered. Average access delay is defined as the time interval between when a packet is ready for transmission and the time that the packet is received correctly at the MAC destination. Figures 8 and 9 respectively show the curve of average access delay in each access mode. As is evident from the figures, access delay in the algorithms all show an upward trend as the number of competing nodes increases. In both access modes, the average access delay of the improved algorithm is lower than that of the other algorithms despite the various numbers of contending nodes. In the Basic access mode, when the number of competing nodes is 100, the average access delay of BEB is less than half that of the improved algorithm. This indicates that the improved algorithm can effectively reduce the probability of collision, thus improving the efficiency of nodes competing for limited channel resources.

Table 2 Parameters for simulation

Parameters	Values
MAC header/bits	224
PHY header/bits	192
RTS/bits	352
CTS/bits	304
ACK/bits	304
slot time/us	20
SIFS/us	10
DIFS/us	50
propagation/us	1
CW_{min}	32
Channel Bit Rate / Mbit / s	2

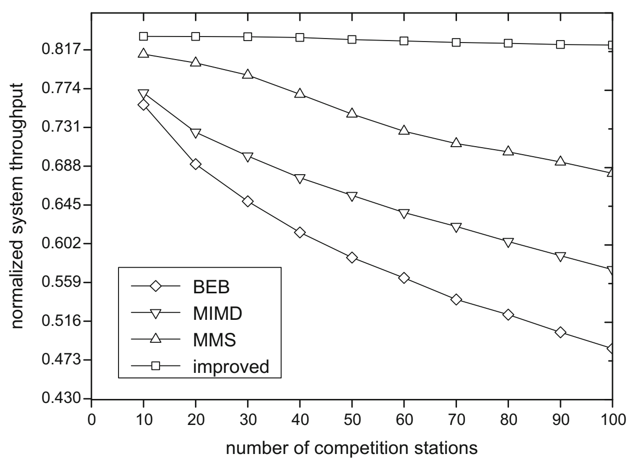

Fig. 6 Normalized system throughput of basic access scheme

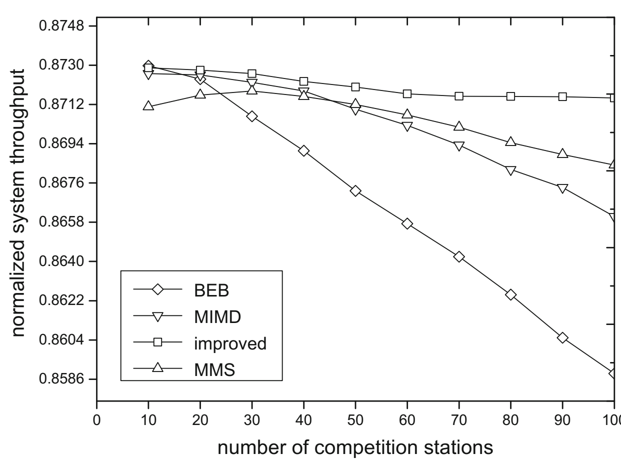

Fig. 7 Normalized system throughput of RTS/CTS access scheme

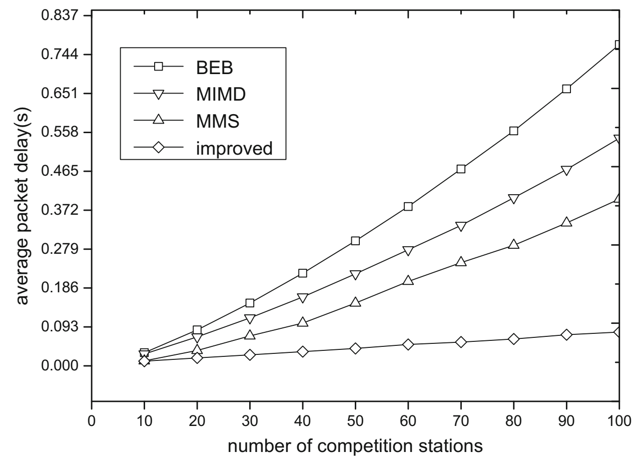

Fig. 8 Average packet delay of basic access scheme

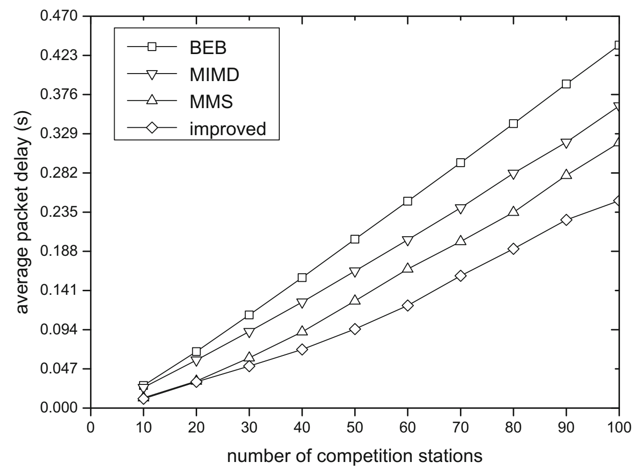

Fig. 9 Average packet delay of RTS/CTS access scheme

5 Conclusion

In this paper, a new back-off algorithm and associated self-adaptive tuning scheme are proposed and extensively evaluated. In addition, the different performance metrics of BEB, MIMD, MMS and this new improved algorithm are compared with each other under saturated conditions. Theoretical analysis results have shown the effectiveness of the new algorithm in improving system throughput and network delay. Experimental results confirm the analysis, showing that the new back-off algorithm can actually improve the performance metrics in each access mode. In particular, this new back-off algorithm is simple, effective and incurs no extra overhead to be distributed among neighboring nodes.

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