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A simple and effective backoff scheme for the IEEE 802.11 MAC protocol

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Abstract

Wireless Local Area Networks (WLANs) based on the IEEE 802.11 have been widely implemented in most commercial products available in the market. This paper proposes a simple and effective contention window-resetting scheme, named Double Increment Double Decrement (DIDD), to improve the performance of the contention based IEEE 802.11 Distributed Coordination Function (DCF). An alternative mathematical analysis for the proposed scheme is developed based on elementary conditional probability arguments rather than bi-dimensional Markov chains. Performance results are presented to identify the improvement of DIDD in terms of throughput and packet drop comparing to the Binary Exponential Backoff (BEB) utilized in the legacy IEEE 802.11 DCF.

1. Introduction

Wireless Local Area Networks (WLANs) are becoming more and more popular attracting the interest of researchers, system integrators and manufacturers of wireless devices. The IEEE 802.11 protocol [1] is the dominant standard for WLANs and is turning into increasingly prevalent for offices, public places, and homes. IEEE 802.11 WLANs are widely deployed in hotspots such as airports, hotels and other areas in which people can have public access to Internet and wireless high-speed data services.

The IEEE 802.11 standard [1] includes detailed specifications for both the Medium Access Control (MAC) and the Physical Layer (PHY). The MAC incorporates two different medium access methods; the compulsory Distributed Coordination Function (DCF) and the optional Point Coordination Function (PCF). The contention-based DCF supports asynchronous data transfer on a best effort basis that best suits delay insensitive data (e.g. email, ftp). On the other hand, the polling-based PCF is built on top of DCF and is utilized for delay sensitive data transmissions (e.g. real-time audio or video). Most of today's IEEE 802.11 devices operate in the DCF mode only, since PCF is barely implemented in current products due its complexity and inefficiency in common data transmissions.

IEEE 802.11 DCF is based on a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) technique and employs a contention resolution method, namely Binary Exponential Backoff (BEB), in order to minimize the probability of collisions due to multiple simultaneous transmissions. DCF defines two access mechanisms to employ packet transmission. The default scheme is called the basic access mechanism, in which stations transmit data packets after deferring when the medium is busy. DCF also provides an optional way of transmitting data packets, namely the Request-To-Send/Clear-To-Send (RTS/CTS) reservation scheme. This scheme uses small RTS/CTS packets to reserve the medium before large packets are transmitted in order to reduce the duration of a collision. Moreover, the RTS/CTS reservation scheme is utilized to combat the hidden station problem.

The paper is outlined as follows. Section 2 presents the main characteristics of the legacy DCF and briefly reviews related work. Section 3 presents the implementation of the proposed Double Increment Double Decrement (DIDD) scheme and focuses in the differences to the BEB utilized in legacy DCF. In section 4, we develop a mathematical analysis based on elementary conditional probability arguments in order to compute DIDD throughput and packet delay performance for both basic access and RTS/CTS mechanisms. Section 5 validates the accuracy of the derived analysis and explores DIDD performance under different scenarios and system parameters. Finally, section 6 concludes the paper and presents future work and extensions.

2. Preliminaries

A. Legacy IEEE 802.11 DCF

According to DCF, each station with a new packet ready for transmission monitors the channel activity until an idle period equal to a Distributed Inter-Frame Space (DIFS) is detected and then the station transmits. Otherwise, if the channel is sensed busy, the station initialises its backoff timer and defers transmission for a randomly selected backoff interval in order to minimize collisions. The backoff timer is decremented when the medium is idle, is frozen when the medium is sensed busy and resumes only after the medium has been idle for longer than DIFS. The station whose backoff timer expires first begins transmission and the other stations freeze their timers and defer transmission. Once the current station completes transmission, the backoff process repeats again and the remaining stations reactivate their backoff timers. Upon the successful reception of a packet, the destination station sends back an immediate positive acknowledgment (ACK) after a time interval equal to Short Inter-Frame Space (SIFS). Note that in order to avoid channel capture, a new backoff process is executed between two consecutive packet transmissions as specified in [1].

Under the RTS/CTS scheme, the station issues a RTS packet, prior to the transmission of the data packet. When the destination receives the RTS packet, it will transmit a CTS packet after SIFS interval immediately following the reception of the RTS packet. The source station is allowed to transmit its packet only if it receives the CTS correctly. If a collision occurs with two or more RTS packets, which is detected by the lack of the CTS response, less time is wasted comparing with the situation where larger data packets collide in the basic access mode. We recall that the RTS/CTS scheme also follows the backoff rules introduced above. Therefore, after the successful RTS/CTS exchange, the source station transmits the data packet and then the receiver responds with an ACK packet to acknowledge a successful reception of the data packet.

The backoff counter for every station depends on the collisions and on the successful packet transmissions experienced by the station in the past. The collision avoidance protocol procedures specify that before transmitting, each station uniformly selects a random value for its backoff counter in the interval $[0,W_i -1]$ where W_i is the current contention window (*CW*) size and i is the number of failed transmissions of this packet. The value of W_i is equal to $W_i = 2^i CW,\ i \in [0,m]$ where $m = \log_2 (CW_{\max} / CW_{\min})$ identifies the number of backoff stages. At the first transmission attempt of a packet, $W_0 = CW_{min} = CW$. If a packet encounters a collision, W_i is doubled up to a maximum value, $W_m = CW_{max} = 2^m CW$. Once W_i reaches CW_{max}, it will remain at this value until it is reset to CW_{min} after a successful packet transmission.

B. Related work

Numerous research efforts have been conducted on modelling the behaviour [2]-[6] as well as improving the performance of IEEE 802.11 DCF [7]-[11]. The bi-dimensional Markov chain modeling, first introduced by Bianchi in [2], has become the most common method for calculating the saturated throughput performance of the IEEE 802.11 protocol. In [3], we developed a new performance analysis based on this Markov chain model that allowed the calculation of the average packet delay and other performance metrics for IEEE 802.11 DCF. Vukovic in [4] extended Bianchi's and our previous work by developing a simpler one-dimensional Markov chain model but does not propose any protocol enhancement. Research in [5] and [6] utilizes a different modelling approach of IEEE 802.11 DCF by employing elementary conditional probability arguments rather than bi-dimensional Markov chains.

Another major thread of the research focused on enhancing IEEE 802.11 DCF performance. In [7], we have extended the mathematical model of [3] to consider packet bursting, a technique in which a station transmits more than one data packet when it gets hold of the medium and, thus, improves considerably protocol performance. Cali in [8] attempted to improve protocol capacity by replacing the exponential backoff mechanism with an adaptive one but under the assumption that the backoff time is sampled from a geometric distribution. Furthermore, authors in [9]-[11] also suggested certain modifications of the backoff scheme. Natkaniec in [9] introduced the DIDD backoff scheme but his work is based only on simulation results and does not derive any analytical model. Wu in [10] and Qiang in [11] developed analytical models for certain proposed modifications of BEB in order to enhance saturation throughput performance. However, their approach has two main disadvantages; it is quite complex and they do not study at all packet delay performance.

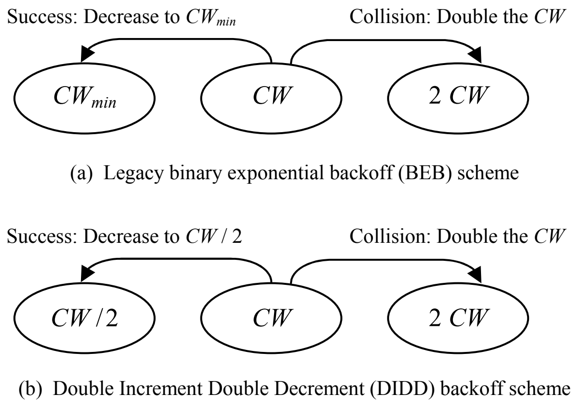

Fig. 1 Comparison of the *CW* process in the two backoff schemes

3. Implementation of the DIDD backoff scheme

As it has been shown earlier, BEB "forgets" about the collision experience it had and resets the contention window after a successful packet transmission regardless of network conditions such as the congestion level. At first glance, BEB tends to work well when there are only a few competing stations. When the number of contending stations increases, the sudden reduction of the contention window can lead to significant performance degradation since it encourages more collisions after every successful transmission.

Since congestion level is not likely to drop rapidly, we propose a "smooth" decrease of the contention window, referred as Double Increment Double Decrement (DIDD). The main concept of DIDD is that *CW* decreases gently and gradually after a successful packet transmission. More specifically, if a packet collides, then similar to the operations of BEB, DIDD will double the contention window in order to reduce the probability of a packet collision (the case of two or more stations transmitting simultaneously). However, in the case of a successful packet transmission, DIDD will halve the *CW* (will not go back to CW_{min}) in order to avoid potential future packet collisions. Figure 1 clearly illustrates the difference between DIDD and BEB schemes in resolving packet collisions and after a successful transmission.

4. Analytical framework

The mathematical modeling and performance analysis of the proposed DIDD backoff scheme can be developed by utilizing three different approaches as shown in [6]. We can either employ a 2-dimensional Markov chain model like in [2][3][10], a 1-dimensional Markov chain model used in [4] or elementary conditional probability arguments as in [5]. This paper employs the latter modeling approach[1] since we believe that it is the most comprehensive and comparing to the other two, it clearly gives insights of both the backoff mechanism and the contention process for medium access.

A. Mathematical modeling and assumptions

The derived mathematical analysis follows closely [2][3][6] by making use of the same assumptions. More specifically, we assume that the network consists of a finite number of *n* contending stations using the same channel access mechanism (basic or RTS/CTS). Moreover, all stations are under heavy traffic conditions, so that at each instant every station is saturated (i.e. always has a packet waiting to be transmitted). We also assume as in [2][3][6] that the collision probability of a transmitted packet is constant and independent of the transmission history of the station. Finally, we ignore the presence of hidden stations as well as the possibility of transmission errors due to noise or fading.

Let us denote with *(TX)* the event that a station is transmitting a packet into a time slot. Moreover, we denote with $P(s=i\,|\,TX)$ the steady state probability that a station being transmitting, in the previous transmission slot, was found in stage $i-1$ and its transmission failed (with probability *p*) or that a station was found in stage $i+1$ and its transmission was successful (with probability 1-*p*). This probability can be formally derived since it is the steady-state distribution of a discrete time Markov chain *s*(*k*), describing the evolution of the backoff stage during the station's transmission instants *k*. The only non-null one-step transition probabilities are:

$$\begin{cases} P\left(s(k+1)=i+1\,|\,s(k)=i\right)=p & i=0,..,(m-1) \\ P\left(s(k+1)=i-1\,|\,s(k)=i\right)=1-p & i=1,..,m \\ P\left(s(k+1)=i\,|\,s(k)=i\right)=1-p & i=0 \\ P\left(s(k+1)=i\,|\,s(k)=i\right)=p & i=m \end{cases}$$

The first equation accounts for the fact that the *CW* increases after a packet collision. The second equation represents the *CW* decrease after a successful packet transmission. Finally, the third equation considers that the *CW* is not further increased after a collision if the maximum backoff stage *m* is reached.

It follows that $P(s=i\,|\,TX)$ can be calculated as in [6]:

$$P(s=i\,|\,TX)=c\left(\frac{p}{1-p}\right)^{i}=c\,a^{i} \tag{1}$$

where *c* is a constant parameter that we will derive next, *p* is the probability that a transmission fails due to a collision, when at least one of the *n-1* remaining stations transmit a packet in the same time slot and $a=p/(1-p)$ is used for convenience in further calculations. If we assume that all stations see the system at steady state and transmit with probability τ, the collision probability *p* is given by:

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

We also have:

$$\sum_{i=0}^{m}P(s=i\,|\,TX)=1 \tag{3}$$

Substituting equation (1) into (3), the value of *c* is found as:

$$c\sum_{i=0}^{m}\left(\frac{p}{1-p}\right)^{i}=1$$

$$c=\frac{1-\dfrac{p}{1-p}}{1-\left(\dfrac{p}{1-p}\right)^{m+1}}=\frac{1-a}{1-a^{m+1}} \tag{4}$$

Using equation (4), equation (1) becomes:

$$P(s=i\,|\,TX)=\frac{1-a}{1-a^{m+1}}a^{i} \tag{5}$$

We are ultimately interested in the unconditional probability $\tau=P(TX)$ that a station transmits a packet in a randomly chosen slot. By utilizing Bayes' theorem:

$$P(s=i\,|\,TX)=\frac{P(TX\,|\,s=i)\,P(s=i)}{P(TX)} \tag{6}$$

which in turn yields, for all *i* values in [0,..*m*]:

$$P(TX)\frac{P(s=i\,|\,TX)}{P(TX\,|\,s=i)}=P(s=i) \tag{7}$$

The above equality holds also for the summation:

$$P(TX)\sum_{i=0}^{m}\frac{P(s=i\,|\,TX)}{P(TX\,|\,s=i)}=\sum_{i=0}^{m}P(s=i)=1 \tag{8}$$

A packet transmission attempt occurs when the backoff counter of the transmitting station becomes equal to zero, regardless of the backoff stage. Thus, the transmission probability τ that a station transmits a packet in a randomly chosen slot time is equal to:

$$\tau=P(TX)=\frac{1}{\displaystyle\sum_{i=0}^{m}\frac{P(s=i\,|\,TX)}{P(TX\,|\,s=i)}} \tag{9}$$

It remains to calculate the conditional probability $P(TX\,|\,s=i)$. This probability can be calculated by dividing the average number of slots spent for transmitting (exactly 1 slot) with the average number of slots spent by the station in the backoff stage *i* which is equal to $\left((W_i+1)/2\right)$, therefore:

$$P(TX\,|\,s=i)=\frac{1}{\dfrac{W_i+1}{2}}=\frac{2}{W_i+1} \tag{10}$$

[1] If we utilize any of the other two modeling approaches, we will reach exactly the same mathematical expressions for DIDD throughput and packet delay performance.

Therefore, equation (9) becomes:

$$\tau = \frac{2}{\frac{1-a}{1-a^{m+1}}\left(\sum_{i=0}^{m}(W_i+1)a^i\right)} \tag{11}$$

After some algebra, the probability τ is given by[2]:

$$\tau = \frac{2(1-2a)(1-a^{m+1})}{(1-(2a)^{m+1})(1-a)W+(1-2a)(1-a^{m+1})} \tag{12}$$

Equations (2) and (12) represent a non-linear system with two unknowns $p\in[0,1]$ and $\tau\in[0,1]$. This system can be solved by utilizing numerical methods (with a similar approach as in [6]) and it has a unique solution.

B. Saturation throughput

Following the same reasoning with [2][3][6], the saturation throughput S can be expressed by dividing the successfully transmitted payload information in a slot time, with the average length of a slot time:

$$S = \frac{P_{tr}P_s l}{E[slot]} = \frac{P_{tr}P_s l}{(1-P_{tr})\sigma + P_{tr}P_s T_s + P_{tr}(1-P_s)T_c} \tag{13}$$

where $P_{tr} = 1-(1-\tau)^n$ is the probability that there is at least one packet transmission in the considered slot time, $P_S = n\tau(1-\tau)^{n-1}/P_{tr}$ is the probability that an occurring packet transmission is successful, $E[slot]$ denotes the average length of a slot time, l is the payload packet length, σ is the duration of the slot time, T_C and T_S are the average durations the medium is sensed busy due to a collision and a successful transmission, respectively[3].

We recall that if the packet size l is normalized by the data rate and instead of bits is expressed in the same time unit as the denominator, S results to be the system throughput efficiency, defined as the fraction of time the channel is used to successfully transmit payload bits.

C. Average packet delay

The average delay $E[D]$ for a successfully transmitted packet is defined to be the time interval from the time a packet is at the head of its MAC queue ready for transmission, until its successful reception. It includes the medium access delay (due to backoff and packet collisions), transmission delay and inter-frame spaces (such as SIFS and DIFS). The average packet delay $E[D]$ can be obtained directly from throughput [5][6] and is found by[4]:

$$E[D] = \frac{l}{S/n} \tag{14}$$

[2] Note that the above expression for the probability τ is different to the one for the IEEE 802.11 exponential backoff algorithm.

[3] Both the values of T_C and T_S depend on the employed medium access scheme (basic access or RTS/CTS) and can be found in [3][6].

[4] We do not consider any packet loss and, thus, all packets are included in the calculation of the average packet delay (see [3][5][6]).

which by substituting equation (13) can be rewritten as:

$$E[D] = \frac{E[slot]}{\tau(1-p)} = \frac{E[slot]}{\tau(1-\tau)^{n-1}} \tag{15}$$

From equation (15) we observe that the average packet delay depends on the average length of a slot time $E[slot]$. It is easy to understand that the packet inter-arrival time, which is defined as the time interval between two successful packet receptions at the receiver, coincides with the packet delay since under DIDD no packets are dropped [6].

5. Performance results

In this section, we first validate the derived analytical model with comparison against OPNET simulation results. Then, we study the performance improvement of DIDD compared to the legacy DCF for different protocol parameters. The values of the parameters used in both simulation and analytical results can be found in [3] and [6]. We consider DSSS as the underlying PHY used in IEEE 802.11b and both the data and control rates are equal to 1 Mbit/s. Unless otherwise specified, the packet size is fixed as 8184 bits.

The OPNET 802.11 simulator developed in [3] was appropriately modified in order to model the proposed DIDD backoff scheme. Once more, we consider a LAN of n stations operating at saturation conditions under an error free medium and no hidden stations. Figure 2 shows the resulting throughput and packet delay obtained from the analytical model developed in the previous section and OPNET simulation outcome. Performance results are given for both the cases of basic access and RTS/CTS schemes. We can observe that analytical results are very consistent with simulation outcome[5] and always coincide with each other. Moreover, the figure illustrates that the RTS/CTS scheme achieves higher throughput and lower packet delay comparing to basic access, for the specific large packet size, due to the shorter collision duration.

Figure 3 illustrates the collision probability p and the transmission probability τ as function of the number of stations for both the cases of legacy DCF and DIDD. As expected, the larger the number of stations, the higher is the collision probability for legacy DCF comparing to DIDD. In fact, DIDD can decrease the chance of a packet collision by utilizing a higher contention window after a successful transmission instead of resetting it to CW_{min}. Furthermore, more contending stations bring about the decrease of the transmission probability; for large network size scenarios, τ attains roughly the same values having a slight decreasing trend.

Figure 4 illustrates the DIDD throughput gain obtained with and without the use of the RTS/CTS mechanism for two different CW values (CW=16, 32). The gain with basic access is much higher than when RTS/CTS is used and it appears that the DIDD scheme is more beneficial when the RTS/CTS is not utilized. The reason is that RTS/CTS reduces the collision time to a small value, which makes the use of DIDD less

[5] Simulation results are acquired with a 95% confidence interval lower than 0.002.

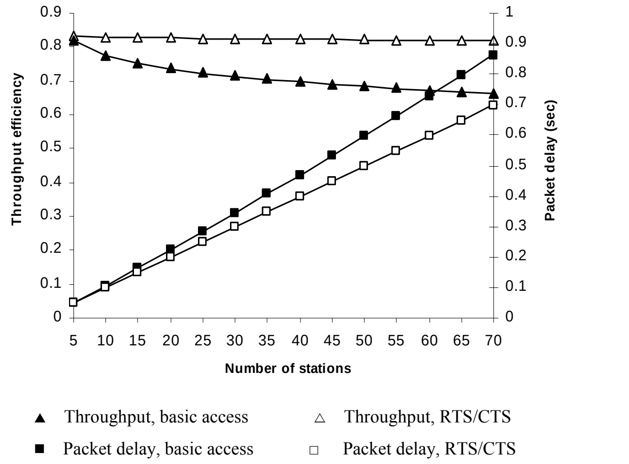

Fig. 2 Throughput efficiency and packet delay for basic access and RTS/CTS: analysis (lines) versus OPNET simulation (symbols)

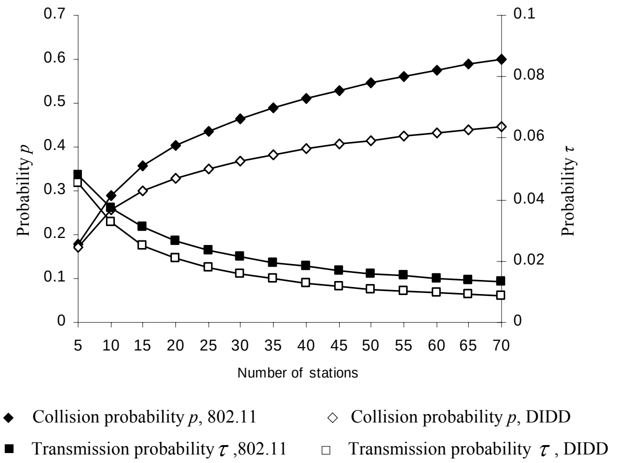

Fig. 3 Collision and transmission probabilities versus n

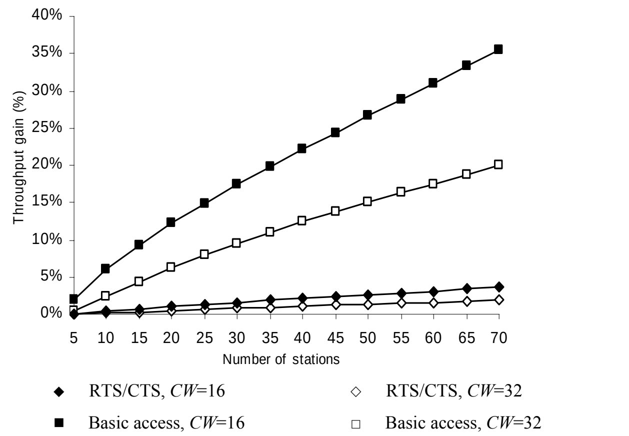

Fig. 4 Throughput gain (in %) versus n

effective since the collision time is already small. Note that DIDD minimises the number of packet collisions whereas the RTS/CTS shortens collision duration. Moreover, we can observe that the initial *CW* size and the number of stations strongly affect the throughput gain of DIDD. In particular, for small initial *CW* sizes (*CW*=16) as well as for large network sizes, DIDD gives significant improvements over the legacy DCF. This is easily explained by considering that small *CW* and large network sizes result in more packet collisions that are eliminated by DIDD. For instance, under the basic access scheme, the percentage of improvement for *CW*=32 are 2% (*n*=10), 8% (*n*=25), 15% (*n*=25), and 20% (*n*=70). In the case of *CW*=16, performance is enhanced even more and the improvements are 6% (*n*=10), 15% (*n*=25), 27% (*n*=25), and 36% (*n*=70).

Figure 5 depicts average packet delay and packet drop probability values for DIDD and legacy DCF schemes. As it is illustrated in figure 1, the main advantage of the proposed DIDD backoff scheme (apart from the throughput improvement) is that we don't have any packet drops due to the proposed design of it. Under DIDD, every packet is being retransmitted until its successful reception but with a decreased collision probability compared to the legacy DCF (as it has been shown in figure 3). DCF causes many packet drops, especially when there are many competing stations. On the other hand, DIDD attains higher packet delay values comparing to the legacy DCF since it includes the time delay of packets that would have been discarded using the legacy DCF. This is the small price we pay in order to have higher throughput performance and not dropped packets at all.

In figure 6, we examine the throughput and packet delay performance of different backoff parameters (*CW* and m') on both basic access and RTS/CTS schemes. Five different combinations are studied; (*CW*, m') = (32, 3) (32, 5) (32, 7) (64, 3) for DIDD and the standard values (32, 5) for legacy DCF. From the figure it can be seen that: 1) DIDD performs better in throughput than legacy DCF for any pair of (*CW*, m'); 2) the throughput performance gain obtained by DIDD is more apparent when the number stations is large and under basic access; 3) legacy DCF achieves the lowest packet delay values comparing to any combination of backoff parameters used in DIDD; 4) DIDD packet delay performance under RTS/CTS will be kept at a certain level (for example, the four curves are nearly overlapped); 5) the worst packet delay performance, especially for large network sizes, is for the case of (32, 3) due to the resulting low *CW* size and high collision probability; and 6) by utilizing *CW*=32 and m'=7, further throughput improvement is obtained when the number of stations is large. Considering the trade-off between performance decrease under very small network sizes and performance improvement under large network sizes, (*CW*, m') = (32, 7) appears to be the best choice to choose in practical deployment if the number of competing stations cannot be known.

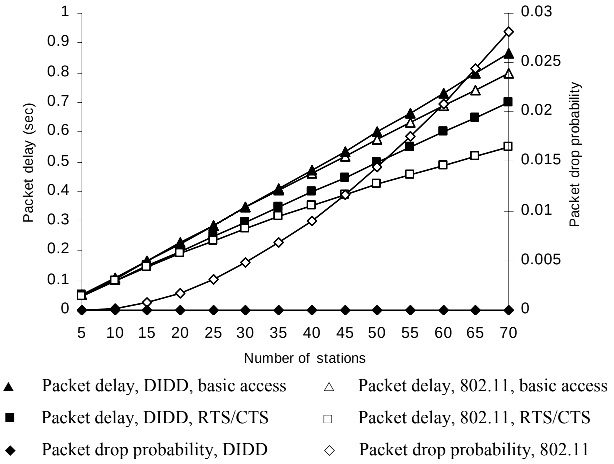

Fig. 5 Packet delay and packet drop probability versus *n*

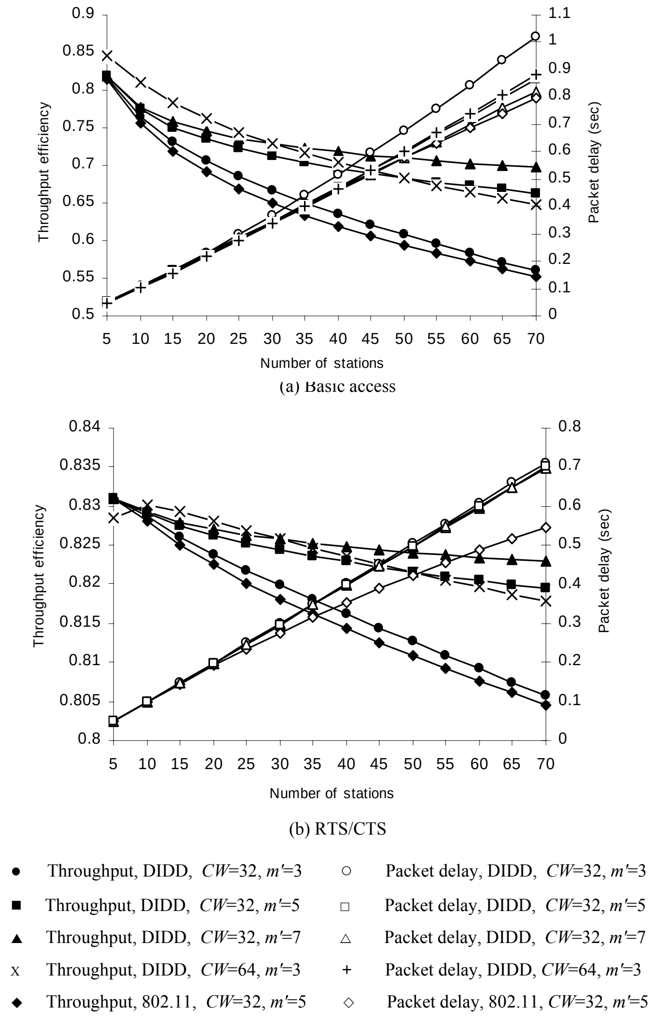

Fig. 6 Throughput efficiency and packet delay for various *CW* sizes and backoff stages

6. Conclusions and future work

This paper proposes DIDD, a simple-to-implement backoff scheme, to improve the performance of IEEE 802.11 DCF. The most important characteristic of the DIDD scheme is its simplicity of implementation in the widely deployed IEEE 802.11 WLANs. Analytical results show that DIDD achieves better performance compared to BEB utilized in the legacy DCF, especially when the basic access scheme is employed, for high congested environments or for applications that require no packet loss. The small price we pay for this performance improvement is that DIDD attains higher packet delay values since it includes the time delay of packets that otherwise would have been discarded.

Possible future extensions of DIDD could include support of priority applications or QoS differentiation through choosing smaller (larger) *CW* values for high-priority (low-priority) applications. DIDD also could be combined with other enhancements techniques i.e. packet bursting to improve IEEE 802.11 services by maximizing protocol performance.

Acknowledgements

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