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Achieving performance enhancement in IEEE 802.11 WLANs by using the DIDD backoff mechanism

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SUMMARY

Wireless local area networks (WLANs) based on the IEEE 802.11 standards have been widely implemented mainly because of their easy deployment and low cost. The IEEE 802.11 collision avoidance procedures utilize the binary exponential backoff (BEB) scheme that reduces the collision probability by doubling the contention window after a packet collision. In this paper, we propose an easy-to-implement and effective contention window-resetting scheme, called double increment double decrement (DIDD), in order to enhance the performance of IEEE 802.11 WLANs. DIDD is simple, fully compatible with IEEE 802.11 and does not require any estimation of the number of contending wireless stations. We develop an alternative mathematical analysis for the proposed DIDD scheme that is based on elementary conditional probability arguments rather than bi-dimensional Markov chains that have been extensively utilized in the literature. We carry out a detailed performance study and we identify the improvement of DIDD comparing to the legacy BEB for both basic access and request-to-send/clear-to-send (RTS/CTS) medium access mechanisms.

KEY WORDS: WLANs; IEEE 802.11; throughput; packet delay; backoff; MAC; DCF; BEB

1. INTRODUCTION

With the rapid growth in popularity of wireless data services and the increasing demand for wireless connectivity, wireless local area networks (WLANs) have become more widespread being almost everywhere including business, office and home deployments. Flexibility, mobility,

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unlicensed frequency band, low cost, connectivity with minimal infrastructure changes are some of the reasons that have made IEEE 802.11 [1] the most widely used WLAN standard.

The IEEE 802.11 specifications are detailed and cover both the medium access control (MAC) and the physical layer (PHY) issues. The IEEE 802.11 MAC provides a shared access to the wireless channel and offers two operating modes; a mandatory contention-based, called distributed co-ordination function (DCF) and an optional centrally controlled channel access function, called point co-ordination function (PCF). The popularity of the IEEE 802.11 WLANs is largely due to the DCF, whereas the PCF is barely implemented in current products due to its complexity and inefficiency for everyday data transmissions.

IEEE 802.11 DCF is based on the carrier sense multiple access with collision avoidance (CSMA/CA) technique and defines two access mechanisms to employ packet transmission, the basic access and the request-to-send/clear-to-send (RTS/CTS). DCF adopts a slotted binary exponential backoff (BEB) scheme to reduce packet collisions due to the case of two or more stations transmitting simultaneously. Under BEB, the contention window (CW) dynamically controls medium access and is doubled every time a station experiences a packet collision. Conversely, if a station successfully transmits its packet, the CW is reset to the minimum value. Although, the random nature of BEB reduces the probability of packet collisions, it cannot completely eliminate collisions and suffers from a low throughput performance under high traffic load. The main reason is that when the number of contending stations is high and a packet is successfully transmitted after a number of collisions, resetting the CW to the minimum value increases the probability of a collision. In order to tackle this inefficiency we propose a slow decrease of the CW by utilizing the DIDD (double increment double decrement) scheme that gently decreases the CW after successful packet transmissions.

The paper is outlined as follows. Section 2 presents the main characteristics of the BEB scheme used in legacy DCF and briefly reviews related work. Section 3 presents the proposed DIDD scheme and focuses in its differences comparing to BEB. Section 4 develops a mathematical analysis based on elementary conditional probability arguments in order to compute DIDD throughput and packet delay performance. Section 5 validates the accuracy of the derived analysis and explores DIDD performance under different network scenarios and parameters. Section 6 concludes the paper and presents future work and extensions.

2. PRELIMINARIES

2.1. Legacy IEEE 802.11 DCF

IEEE 802.11 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. The 802.11 standard also provides an optional way of transmitting data packets, namely the 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.

According to DCF basic access mechanism, a station with a new packet ready for transmission monitors the channel activity. If the channel is idle for a time interval equal to distributed inter-frame space (DIFS), the station transmits. Otherwise, if the channel is sensed busy, the station persists to monitor the channel until it is determined idle for more than DIFS.

The station then initializes 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 all the contending stations reactivate their backoff timers. Upon the successful reception of a packet, the destination station sends back a positive acknowledgement (ACK) after a time interval equal to short inter-frame space (SIFS). Note that in order to avoid channel capture, a station always executes a new backoff process between two consecutive packet transmissions as specified in Reference [1].

Under the RTS/CTS scheme, the station follows the same backoff rules introduced above and issues a small RTS packet, prior to the transmission of the actual data packet. When the destination receives the RTS packet, it will transmit a CTS packet after SIFS interval. The source station is allowed to transmit its data packet if and only if it receives the CTS correctly. If a collision occurs with two or more RTS packets, less bandwidth is wasted comparing with the situation where the larger data packets collide in the basic access mode. Since collisions may occur only on the small RTS packets and are detected by the lack of the CTS responses, the RTS/CTS scheme results in an increase on system performance by reducing the duration of collisions, especially when long data packets are transmitted. After the successful RTS/CTS exchange, the source station transmits the data packet and then the receiver responds with an ACK packet to acknowledge the successful reception of the data packet.

DCF is based on a CSMA/CA technique and employs a contention resolution method, namely BEB, in order to minimize the probability of collisions due to multiple simultaneous transmissions. The backoff counter for every station depends on the collisions that the packets have experienced in the past. The collision avoidance protocol procedures specify that before transmitting, a station uniformly selects a random value for its backoff counter in the interval $[0, W_i - 1]$ where W_i is the current CW size and i is the backoff stage. The value of W_i is equal to $W_i = 2^i W,\ i \in [0, m]$ and depends on the number of failed transmissions of a packet. At the first transmission attempt of a packet, $W_0 = \mathrm{CW}_{\min} = W$ that is the minimum CW size. If a packet collision occurs, W_i is doubled up to a maximum value, $W_m = \mathrm{CW}_{\max} = 2^m W$ where $m = \log_2(\mathrm{CW}_{\max}/\mathrm{CW}_{\min})$ identifies the number of backoff stages. Once W_i reaches $\mathrm{CW}_{\max}$, it will remain at this value until it is reset to $\mathrm{CW}_{\min}$ after a successful packet transmission.

2.2. *Related work*

Numerous research efforts have been conducted on modelling the behaviour of IEEE 802.11 [2–10]. The bi-dimensional Markov chain modelling, first introduced by Bianchi [2], has become the most common method for calculating the saturated performance of the IEEE 802.11 protocol. In References [3, 4], we developed a new performance analysis based on the Markov chain model of Reference [2] and allowed the calculation of the average packet delay and several other performance metrics. Vukovic and Smavatkul [5] extended Bianchi's and our previous work by developing a simple one-dimensional Markov chain model but did not propose any protocol enhancement. Work in References [6, 7] utilized a different modelling approach of IEEE 802.11 DCF by employing elementary conditional probability arguments rather than bi-dimensional Markov chains. Latest work in References [8–10] studies error-prone environments but only focuses in the effect of retry limits on the IEEE 802.11 performance.

A major thread of the research focused on enhancing IEEE 802.11 DCF performance [11–22]. In Reference [11], we have extended the mathematical model of Reference [3] to consider packet bursting, a technique in which a station transmits more than one data packets when it gets hold of the medium and, thus, considerably improves the protocol performance. Work in References [12, 13] has studied the effectiveness of the RTS/CTS reservation scheme in reducing collision duration for high data rates and an all-purpose expression was derived for the optimal use of the RTS/CTS handshake aiming to maximize performance. Aad and Castelluccia [14] suggested three different ways to enhance IEEE 802.11 performance: (a) by scaling the CW based on the priority factor of each station, (b) by giving each priority level with a different value of DIFS, and (c) by using different maximum packet length. In Reference [15], we have studied an appropriate tuning of the backoff algorithm by proposing three sets of parameter values for initial CW size, retry limit and number of backoff stages in order to achieve better performance on particular metrics for specific communication needs. Cali *et al.* [16] proposed to replace the exponential backoff mechanism with an adaptive one but under the assumption that the backoff time is sampled from a geometric distribution. Carvalho and Garcia-Luna-Aceves [17] considered the impact of the minimum CW size and the corresponding capacity improvement that is achieved when CW increases but not combined with any other protocol parameters. Yong *et al.* [18] proposed a new measurement-based algorithm to adaptively calculate and implement the optimal value of initial CW value. However, it needs to compute current channel load status at run time and adjusts the RTS/CTS message structure. In Reference [19] we have proposed an easy-to-implement backoff algorithm named DIDD but we did not carry out a detailed performance analysis. Finally, authors in References [20–22] also suggested certain modifications of the backoff scheme but either their work is based only on simulation [20] or they do not study at all packet delay performance [21, 22].

3. DIDD BACKOFF SCHEME

As it has been discussed earlier, BEB 'forgets' about the collision experience it had and resets the CW to its minimum value after a successful packet transmission regardless of the number of collisions the packet has encountered that depend on the network 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 CW to CW_{min} can lead to significant performance degradation since it increases the collision probability after every successful transmission.

Since the congestion level is not likely to drop rapidly and in order to tackle the above inefficiency, we propose a modified backoff algorithm, namely DIDD, which utilizes a 'smooth' decrease of the CW after a successful packet transmission. More specifically, if a packet collides, DIDD operates exactly as BEB and doubles the CW in order to reduce the probability of a packet collision. However, in the case of a successful packet transmission, DIDD halves the CW (BEB reduces it to CW_{min}) to avoid potential packet collisions. Another characteristic of the proposed DIDD scheme is that packets that reach their maximum number of retransmission attempts are not discarded as under BEB. Figure 1 clearly illustrates the differences between BEB and DIDD schemes in assigning values to CW after packet collisions and successful transmissions.

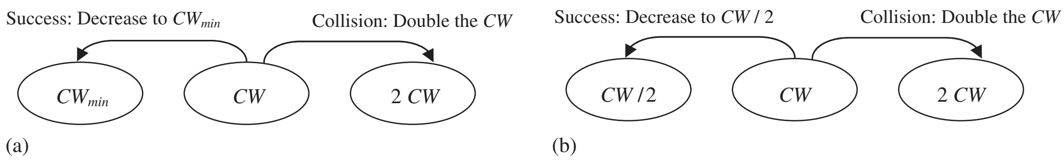


Figure 1. Comparison of the CW process in the BEB and DIDD backoff schemes: (a) legacy binary exponential backoff (BEB) scheme; and (b) double increment double decrement (DIDD) backoff scheme.

4. ANALYTICAL FRAMEWORK

The mathematical modelling of the proposed DIDD scheme can be developed by utilizing three different approaches as shown in Reference [7]. We can either employ a two-dimensional Markov chain model like in References [2, 3, 21], a one-dimensional Markov chain model [5] or elementary conditional probability arguments [6, 7]. This paper employs the latter modelling approach[‖] 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.

4.1. Mathematical modelling and assumptions

The derived mathematical analysis follows closely [2, 3, 7] 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 every station is saturated (i.e. always has a packet waiting to be transmitted). We also assume as in References [2, 3, 7] 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.

If we assume that all stations see the system at steady state and transmit with probability $\tau = P(TX)$ in a randomly chosen slot, the collision probability p is given by

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

Let us denote with (TX) the event that a station is transmitting a packet during a time slot and denote with $P(s = i \mid TX)$ the steady-state probability that a station being transmitting is found in stage i. 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

$$\begin{cases} P(s(k+1) = i+1 \mid s(k) = i) = p & i = 0, \ldots, (m-1) \\ P(s(k+1) = i-1 \mid s(k) = i) = 1 - p & i = 1, \ldots, m \\ P(s(k+1) = i \mid s(k) = i) = 1 - p & i = 0 \\ P(s(k+1) = i \mid s(k) = i) = p & i = m \end{cases}$$

[‖]If we utilize any of the other two modelling approaches, we will reach exactly the same mathematical expressions for DIDD performance.

The first equation accounts for the fact that the CW increases after a packet collision. The second and third equations represent the CW process after a successful packet transmission. Finally, the fourth equation shows that the CW is not further increased after a collision if the maximum backoff stage m is reached.

Since the probability $P(s = i \mid TX)$ is given by the probability that the station, in the previous transmission slot, was found in stage $i-1$ and that the transmission failed (with probability p) or the station was found in stage $i+1$ and the transmission was successful (with probability $1-p$), it follows that $P(s - i \mid TX)$ can be calculated as in Reference [7]:

$$P(s = i \mid TX) = c\left(\frac{p}{1-p}\right)^i = ca^i \tag{2}$$

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.

We also have

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

Substituting Equation (1) into (3), the value of c is found as

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

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 for all i values in $[0, \ldots, m]$:

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

which in turn yields

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

The above equality holds also for the summation

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

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

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

It remains to calculate the conditional probability $P(TX \mid s = i)$. This probability can be calculated by dividing the average number of slots a station spends in the transmission state while in stage i (exactly 1 slot according to the adopted time scale) with the average number of slots spent by the station in the backoff stage i which is equal to $(W_i + 1/2)$ therefore,

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

Therefore, Equation (9) becomes equal to

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

After some algebra, the probability τ is given by**:

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

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 Reference [15]) and has a unique solution.

4.2. Saturation throughput

Following the same reasoning with Reference [2], 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:

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

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

** Note that the above expression for the probability τ is different to the one for the IEEE 802.11 binary exponential backoff algorithm.

†† 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 References [3, 7].

probability τ as

$$S = \frac{n\tau(1-\tau)^{n-1} l}{(1-\tau)^n \sigma + n\tau(1-\tau)^{n-1} T_s + [1-(1-\tau)^n - n\tau(1-\tau)^{n-1}] T_C} \tag{14}$$

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.

4.3. *Average packet delay*

The average delay $E[D]$ for a successfully transmitted packet is defined to be the time elapsed from the instant a packet reaches the head of its MAC transmission queue ready for transmission, until its successful reception is acknowledged by the intended receiver. 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 [6, 7] and is found by[‡‡]:

$$E[D] = \frac{l}{S/n} \tag{15}$$

which by substituting Equation (13) can be rewritten as

$$E[D] = \frac{E[\text{slot}]}{\tau(1-p)} = \frac{E[\text{slot}]}{\tau(1-\tau)^{n-1}} \tag{16}$$

An interesting observation is 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 [7].

5. PERFORMANCE EVALUATION

We first validate the derived analytical model with comparison against OPNET simulation outcome. Then, we study the performance improvement of DIDD compared to the legacy BEB scheme. The standard library of the OPNET 802.11 simulator was appropriately modified in order to model the proposed DIDD scheme and as in Reference [7] to employ saturation conditions, i.e. all stations always have a packet ready for transmission. The simulator closely follows all timer values and packet element transmission times defined by IEEE 802.11 specifications. We consider DSSS as the underlying IEEE 802.11b physical layer and a LAN of n stations operating under an error-free medium and with no hidden stations [23]. The values of the parameters used in both simulation and analytical results can be found in References [3, 7]. Unless otherwise specified, the packet size is fixed as 8184 bits and both the data and control transmission rates are equal to 1 Mbit/s.

Figure 2 shows the throughput and packet delay obtained through the analytical model previously developed and OPNET simulation outcome for the basic access and the RTS/CTS schemes. We observe that analytical results are very consistent with simulation outcome[§§] and

[‡‡]We do not consider any packet loss and, thus, all packets are included in the calculation of the average packet delay (see References [3, 6, 7]).
[§§]Simulations are acquired with a 95% confidence interval lower than 0.002.

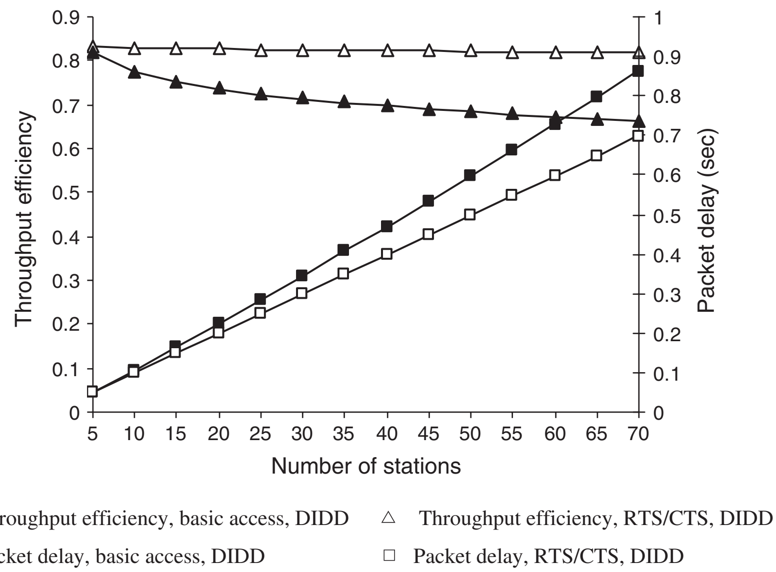


Figure 2. Throughout efficiency and packet delay for basic access and RTS/CTS schemes: analysis (lines) versus OPNET simulation (symbols).

both analysis and simulation always reach the same figures. The figure illustrates that RTS/CTS 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 conditional collision probability p and the transmission probability τ as function of the number of stations for both the cases of legacy BEB and DIDD. As expected, the larger the number of stations, the higher the collision probability for legacy BEB comparing to DIDD. The figure shows that DIDD succeeds in decreasing the probability of a packet collision by utilizing a higher CW after a successful transmission instead of resetting it to CW_{min}. Furthermore, increasing the number of contending stations results in the decrease of the transmission probability.

Figure 4 illustrates the DIDD throughput gain over BEB with and without the use of the RTS/CTS mechanism for two different initial CW values ($W = 16, 32$). The gain without RTS/CTS is much higher than when RTS/CTS is used. This means that the DIDD scheme is more beneficial when the RTS/CTS is not utilized. The reason is that RTS/CTS reduces the collision duration to a small value, which makes the use of DIDD less effective since the collision duration is already small. 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 ($W = 16$) as well as when the number of stations increases, DIDD gives significant improvements over the legacy BEB. For instance, under the basic access scheme, the percentage of improvement for $W = 32$ are 2% ($n = 10$), 8% ($n = 25$), 15% ($n = 50$), and 20% ($n = 70$). In the case of $W = 16$, performance is enhanced even more and the improvements are 6% ($n = 10$), 15% ($n = 25$), 27% ($n = 50$), and 36% ($n = 70$).

Figure 5 depicts packet delay and packet drop probability values for DIDD and legacy BEB schemes. As it is illustrated in Figure 1, an important characteristic of the proposed DIDD backoff scheme (apart from the throughput improvement) is that we do not have any packet drops due to the proposed design of it. Under DIDD, every packet is being retransmitted until

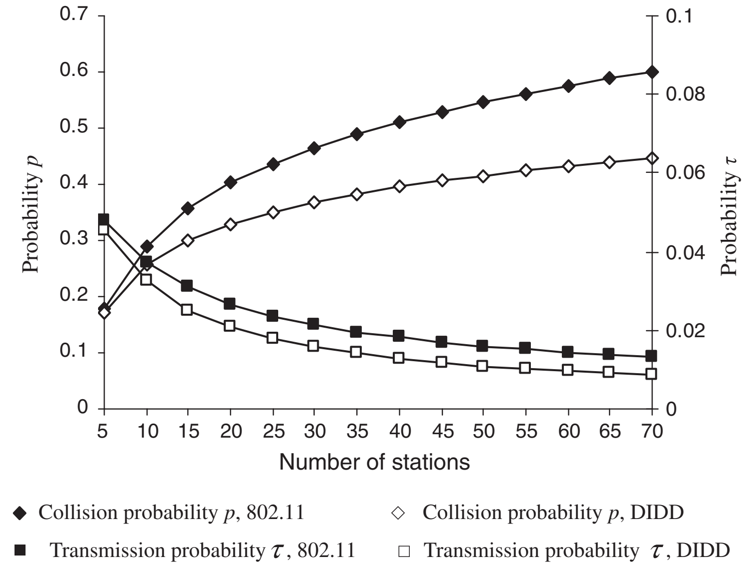


Figure 3. Packet collision and transmission probabilities versus n.

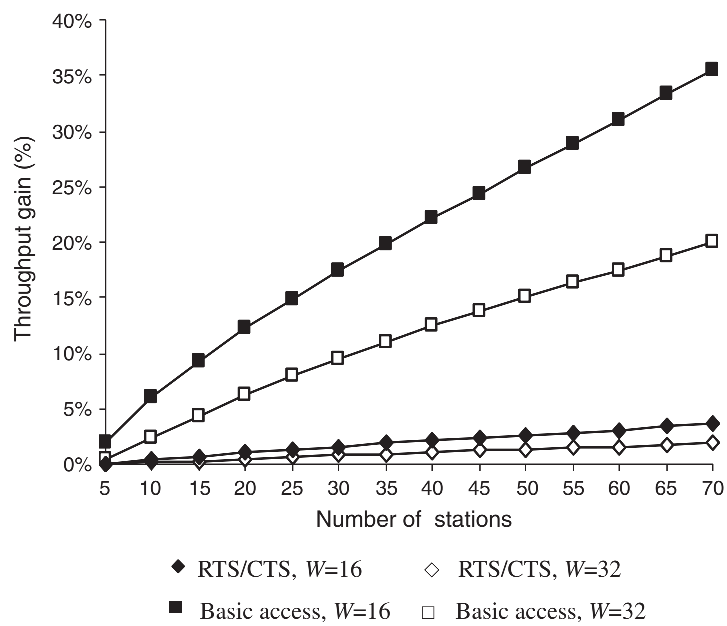


Figure 4. Throughput gain (in %) versus n.

its successful transmission but with a decreased collision probability compared to the legacy BEB (as it has been shown in Figure 3). BEB 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 BEB since it includes the time delay of packets that would have been

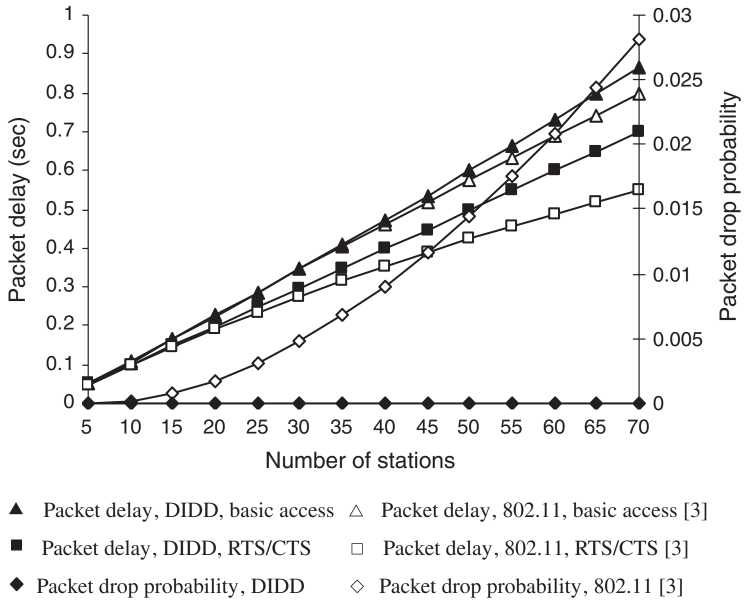


Figure 5. Packet delay and packet drop probability versus n.

discarded using the legacy BEB. This is the small price we pay in order to have higher throughput performance, and not dropped packets at all.

Since the DIDD scheme introduces a different backoff scheme for contention, it is interesting to study how performance is affected by various initial CW sizes. Figure 6 compares the performance of BEB against DIDD that utilizes three different initial CW values ($W = 16$, 32 and 64) and for both medium access schemes. It is not difficult to conclude that in most cases DIDD achieves a higher throughput since it decreases the probability of a packet collision by utilizing a higher CW. Moreover, the increase under the basic access mode is high when we choose a larger initial CW size. For the RTS-CTS access mode, the throughput is less improved even with a large initial CW size (note the different Y-axis scale). This can be explained by the fact that a large CW window size decreases the probability of collisions and the number of retransmissions for the basic access mode. In contrast, as the RTS/CTS access mode avoids long collisions and the associated waste of the bandwidth, the throughput improvement is not significant.

In Figure 7, 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; $(W, m) = (32, 3)$ $(32, 5)$ $(32, 7)$ $(64, 3)$ for DIDD against the standard values (32, 5) for legacy DCF specified in the standard [1]. From the figure it can be seen that: (a) DIDD performs better in throughput than legacy BEB for any pair of (CW, m); (b) the throughput performance gain obtained by DIDD is higher when the number stations is large and under basic access (note the different Y-axis scale); (c) legacy BEB achieves the lowest packet delay values comparing to any combination of backoff parameters in DIDD; (d) DIDD packet delay performance under RTS/CTS will be kept at a certain level (the four delay curves are close); (e) 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 (f) by utilizing

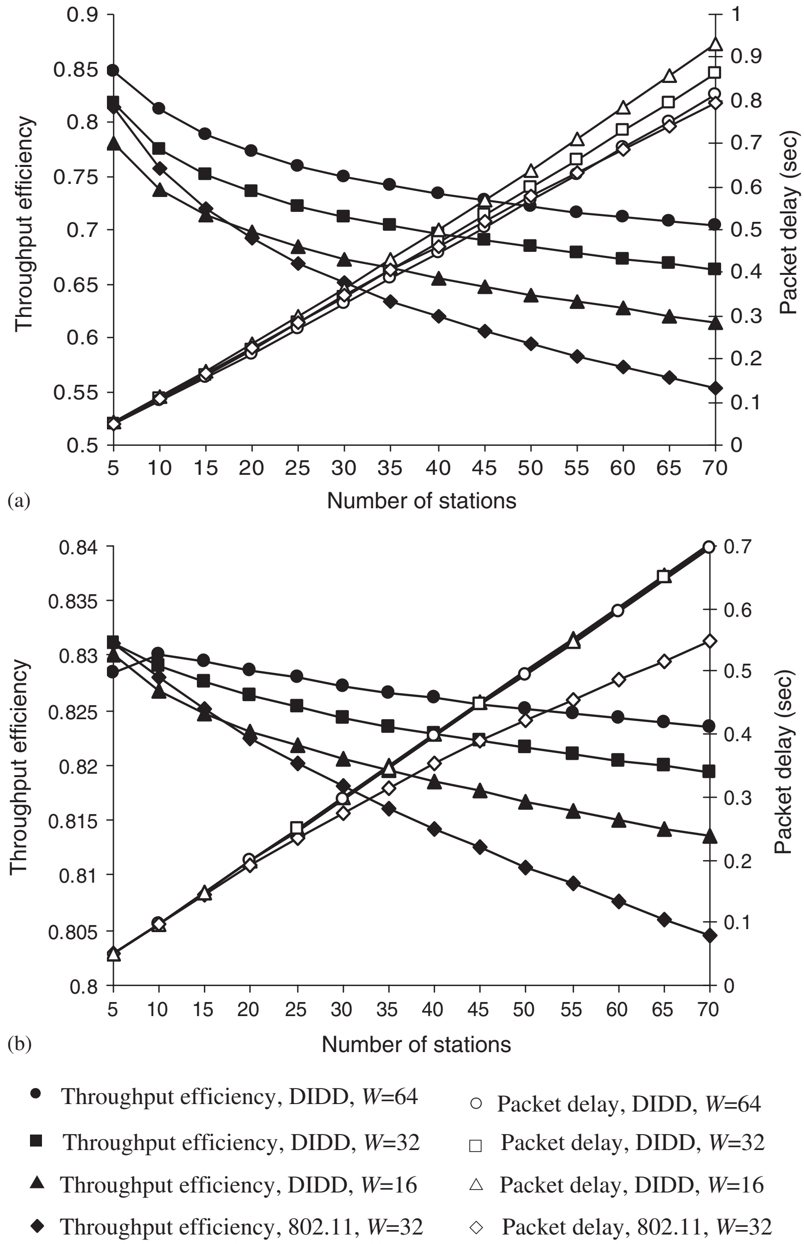


Figure 6. Throughput efficiency and packet delay for various initial CW sizes: (a) basic access; and (b) RTS/CTS.

$W = 32$ 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, $(\mathrm{CW}, m) = (32, 7)$ appears to be the best choice to choose in practical deployment if the number of competing stations cannot be known.

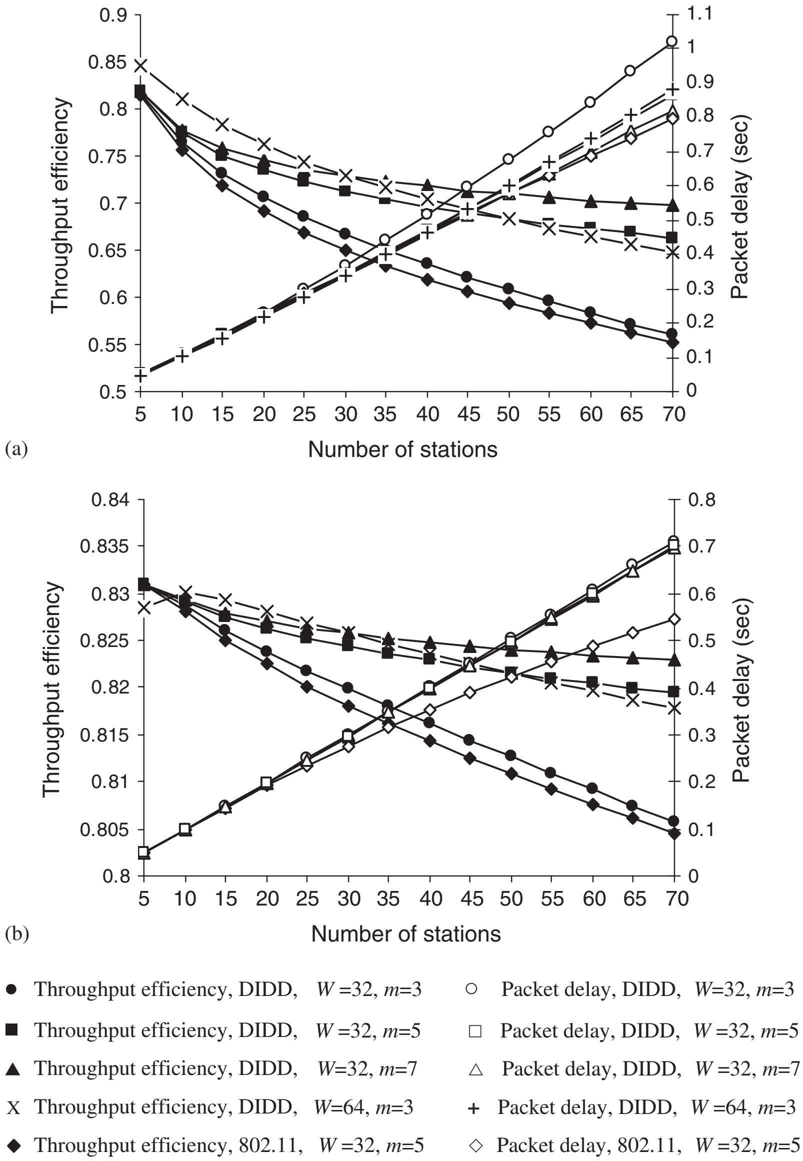


Figure 7. Throughput efficiency and packet delay for various CW sizes and backoff states: (a) basic access; and (b) RTS/CTS.

Figure 8 plots throughput efficiency and packet delay versus network size for three data rates ($C = 2$, 5.5 and 11 Mbit/s) using the short PHY packet overhead (preamble and header) defined in the IEEE 802.11b standard. When data rate increases, throughput efficiency decreases since the transmission time of data packets is reduced but the overhead remains the same. When the basic access scheme is employed, we clearly see that throughput performance considerably decreases when the number of stations increases (more packet collisions) and that DIDD achieves a much higher

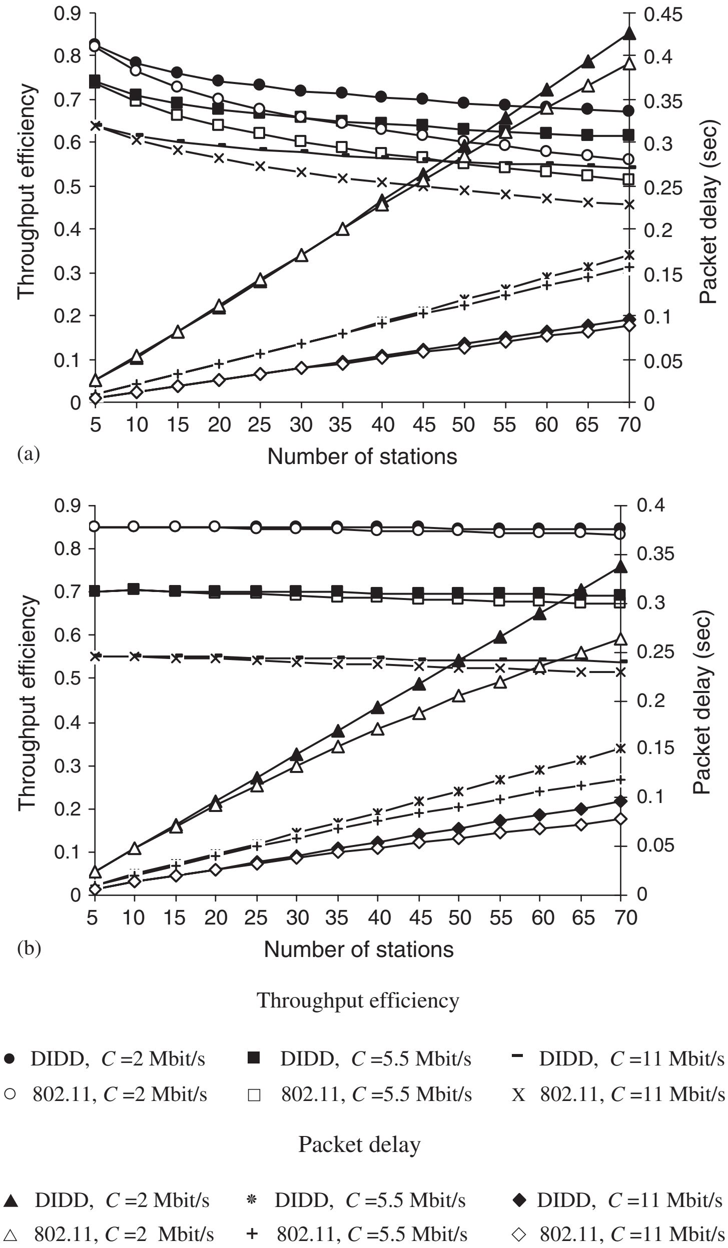
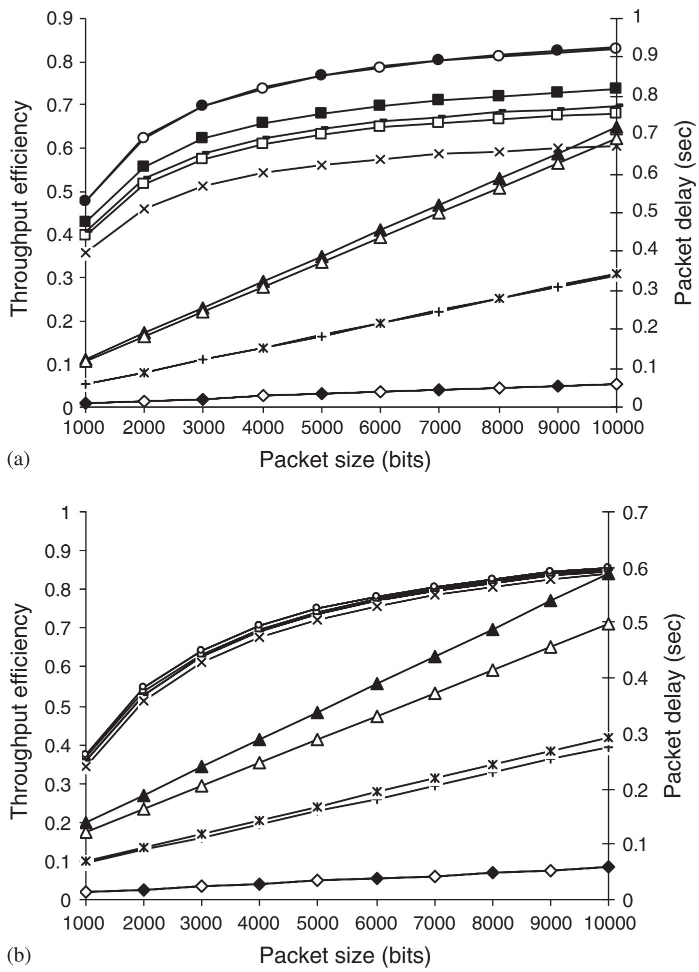


Figure 8. Throughput efficiency and packet delay for different data rates: (a) basic access; and (b) RTS/CTS.

throughput than that of the legacy BEB. For the RTS/CTS mechanism, throughput performance of both the DIDD and legacy BEB schemes is not significantly sensitive to the number of the competing stations for any data rate. At the same time, DIDD achieves slightly higher throughput but considerably higher packet delay than BEB, indicating that DIDD is not the best choice under

RTS/CTS. This can be explained due to the fact that the RTS/CTS scheme reduces collision duration and, thus, the employment of DIDD, which reduces the number of collisions, is not highly beneficial.

In Figure 9, we can be easily observe the influence on throughput and packet delay performance resulted of certain factors; medium access mode, packet length and number of



Throughput efficiency

● DIDD, n=5 ■ DIDD, n=25 – DIDD, n=50
○ 802.11, n=5 □ 802.11, n=25 X 802.11, n=50

Packet delay

◆ DIDD, n=5 ⁎ DIDD, n=25 ▲ DIDD, n=50
◇ 802.11, n=5 + 802.11, n=25 △ 802.11, n=50

Figure 9. Throughput efficiency and packet delay versus packet size: (a) basis access; and (b) RTS/CTS.

stations, in both DIDD and legacy BEB. Firstly, for both DIDD and legacy BEB, the RTS/CTS access mode and/or large packet size will bring higher throughput. DIDD obtains improved throughput performance for both access modes and $n > 5$, but the performance improvement under basic access is much higher as packet length increases. The main reason is the resulting lowered collision probability. On the contrary, under the RTS/CTS scheme, DIDD marginally enhances throughput performance for all packet size values. This is justified since the RTS/CTS reservation scheme avoids long collision duration and the associated cost on performance when a packet collision occurs. Moreover, when the RTS/CTS scheme is utilized, the employment of DIDD, instead of the legacy BEB, causes a considerable increase on packet delay indicating the disadvantage of DIDD under the RTS/CTS case.

6. CONCLUSIONS AND FUTURE WORK

This paper proposes double increment double decrement (DIDD), an easy-to-implement backoff scheme in order to improve the performance of IEEE 802.11 DCF. The main characteristic of the DIDD scheme is its simplicity. An alternative and comprehensive mathematical analysis for the proposed DIDD scheme is developed based on elementary conditional probability arguments rather than bi-dimensional Markov chains. The derived analysis is validated by comparison with OPNET simulation outcome. Detail results show that DIDD outperforms BEB in most cases, especially when the basic access scheme is employed or for highly congested environments. Considering the trade-off between performance decrease under very small network sizes and performance improvement under large network sizes, the combination of $CW_{min} = 32$ and $CW_{max} = 4096$ (for $m = 7$) appears to be the best choice to choose under DIDD in practical deployment if the number of competing stations cannot be known. Thus, the proposed DIDD scheme can be regarded as an option for IEEE 802.11 WLANs and appears to be an ideal solution in highly congested environments and for applications that require no packet loss. However, 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 include support of priority applications or QoS differentiation as well as the development of adaptive CW algorithms that will depend on the congestion load. Another possible direction could be to combine DIDD with other enhancement techniques, i.e. packet bursting to improve IEEE 802.11 services by maximizing the overall protocol performance. Future work could also include the study of throughput and delay performance of DIDD under non-saturated conditions as well as for fading environments by considering either independent or burst transmission errors.

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