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ON IMPROVING PERFORMANCE FOR IEEE 802.11 WIRELESS LANS UNDER CONGESTED AND ERROR-PRONE ENVIRONMENTS

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ABSTRACT
IEEE 802.11 is worldwide implemented and the most widely deployed protocol for Wireless Local Area Networks (WLANs). This paper proposes a simple and effective contention window-resetting scheme, named Double Increment Double Decrement (DIDD), to improve the performance of IEEE 802.11 Binary Exponential Backoff (BEB) under an error-prone environment. Our work becomes important and meaningful in the sense that it predicts both IEEE 802.11 BEB and DIDD performance very accurately considering transmission errors. We explore the effect of transmission errors, packet size, data rate and network size on the performance of BEB and DIDD, in terms of throughput efficiency, average packet delay, packet drop probability and packet inter-arrival time.

KEY WORDS
Wireless LANs, IEEE 802.11, DIDD, packet delay, backoff

1. Introduction

The widespread use of multimedia applications has created new requirements upon the underlying Wireless LANs (WLANs). To meet these requirements, researchers are seeking solutions mainly in two directions: data rate increase and Quality-of-Service (QoS). Increasing data rate is designed for improving the effective bandwidth that can be shared by the upper layer applications. The Medium Access Control (MAC) layer of WLANs mainly utilizes the IEEE 802.11 [1] Distributed Coordination Function (DCF), which is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. In a CSMA/CA based scheme, MAC and PHY overhead is the main reason for system inefficiency.

Numerous research efforts have been conducted on modelling the behaviour [2]-[6] as well as improving the performance of IEEE 802.11 DCF [7]-[16]. The bi-dimensional Markov chain modeling, first introduced by Bianchi in [2], has become the most common method for calculating the saturated performance of the IEEE 802.11 protocol. In [3], we developed a new performance analysis based on a 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. Work 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.

A 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 packets when it gets hold of the medium and, thus, improves considerably protocol performance. Work in [8] and [9] 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 in [10] suggested three different ways to enhance IEEE 802.11 performance; either by scaling the contention window based on the priority factor of each station or by giving each priority level with a different value of DIFS or different maximum packet length. In [11], we have studied an appropriate tuning of the backoff algorithm by proposing three sets of parameter values for initial contention window size, retry limit and number of backoff stages in order to achieve better performance on particular metrics for specific communication needs. Cali in [12] attempted to approach 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. Carvalho in [13] considered the impact of the minimum Contention Window (*CW*) size but not combined with any other protocol parameters. Authors in [14]-[17] also suggested certain modifications of the backoff scheme but either their work is based only on simulation [14]-[15] or they do not study at all packet delay performance [16]-[17]. Crow in [18] and [19] first studied the effect of errors on performance by means of simulation. Authors in [20] and [21] also considered transmission errors by means of a Markov chain model but investigated only saturation throughput. Latest work in [22]-[24] studies error-prone environments but only focuses in the effect of retry limits on the IEEE 802.11 performance.

Most of research work presented in the literature assumes error-free transmissions in order to study IEEE 802.11 performance. Since the assumption of an error-free channel is not always true in a realistic environment, we extend mathematical models, which were previously presented in the literature, by considering transmission errors for the IEEE 802.11 and DIDD schemes. Our results take into account all the protocol parameters and packet overheads introduced by both the Medium Access Control (MAC) and the physical (PHY) layers as specified in 802.11b. Finally, we explore the effect of transmission errors, data rate, packet size and network size on the performance of IEEE 802.11 BEB and DIDD schemes, in terms of throughput efficiency, average packet delay, packet drop probability and packet inter-arrival time.

2. Overview of IEEE 802.11 BEB and DIDD

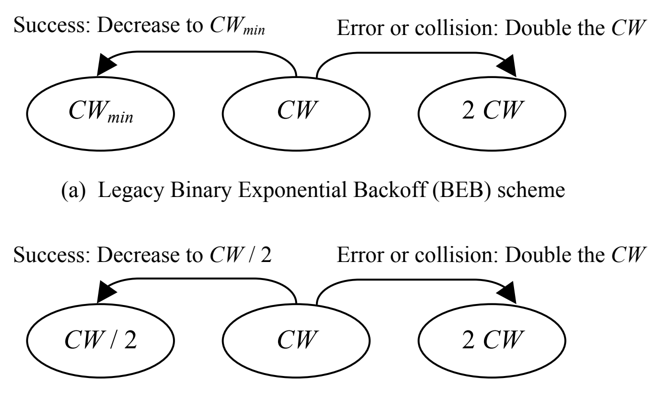
In the legacy DCF, a station with a packet to transmit first senses the medium activity to ascertain whether it is in use. If the medium is sensed to be idle for a time interval greater than the Distributed Inter-Frame Space (DIFS), the station initiates a packet transmission (transmits the data packet in basic access or a short RTS packet first in the RTS/CTS scheme). If the medium is sensed busy, the station defers transmission and initialises its random backoff timer[1]. Note that each station is allowed to transmit only when its backoff timer reaches zero and at the beginning of a time slot.

According to BEB, the value of the backoff timer value for each station is uniformly chosen in the interval [0,W_i - 1], where W_i is the current contention window (*CW*) size, i is the backoff stage, $i \in [0,m]$ and m represents the number of backoff stages. At the first transmission attempt, CW is equal to the minimum backoff window size $W=CW_{min}$. If two or more stations start a packet transmission simultaneously in the same slot, a collision takes place. After each unsuccessful transmission due to a packet collision or error, W_i is doubled until a maximum backoff window size value is reached. The main difference between the legacy BEB and DIDD is that according to DIDD after a successful packet transmission the contention window is halved and not reset to CW_{min} as in BEB (see figure 1). After the successful reception of a data packet, the receiver sends back an acknowledgment (ACK) packet after a Short Inter-Frame Space (SIFS) interval. When the source station receives an ACK, it resets *CW* to CW_{min} and contents again for medium access if a packet is available. If the source station does not receive an ACK, the data packet is assumed to have been lost and a retransmission is scheduled by doubling the *CW*.

Ideally, the *CW* size should be increased only when packet losses are due to collisions in order to decrease congestion, since increasing the *CW* size in the case of transmission errors may degrade the data throughput and may increase the transmission delays. However, a station cannot distinguish collisions from transmission errors at the MAC layer and it handles them in a same way.

We define as a *collision* the event that at least two stations initiate transmission at the same time and, thus, the receivers cannot decode any packets correctly. We define as an *error* the event that there is only one station transmitting but the channel is so noisy (caused by channel fading, path loss, thermal noise, or interferences from other radio sources) that the receiver cannot decode the whole packet successfully. Note that a station cannot distinguish a packet collision from a transmission error. For this reason, the contention window will be increased either due to a packet collision or to an error.

Every station employing the legacy DCF maintains a station short retry count (SSRC) that indicates the number of retransmission attempts of a data packet. If the retry count reaches the specified limit, retry attempts cease and the packet is discarded. Note that in the proposed DIDD scheme we assume unlimited retransmissions.



(a) Legacy Binary Exponential Backoff (BEB) scheme

(b) Double Increment Double Decrement (DIDD) backoff scheme

Figure 1 Comparison of *CW* process of the two backoff schemes

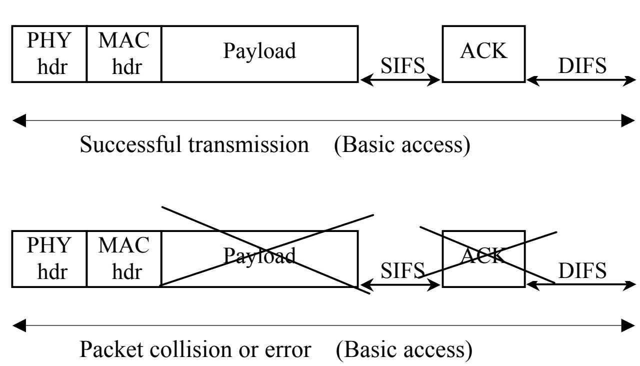


Figure 2 Event durations in an error-prone channel (Basic access)

[1] As defined in [1]. the backoff timer is decremented when the medium is idle, is frozen when the medium is sensed busy and resumes again only after the medium has been idle for longer than DIFS.

3. Mathematical Modelling

A. Analytical Framework and Assumptions

The mathematical modeling of both the legacy BEB and the DIDD backoff schemes can be developed by utilizing three different approaches [6]; we can either employ a 2-dimensional Markov chain model, a 1-dimensional Markov chain model or elementary conditional probability arguments. We follow closely [6] by making use of the same assumptions; the network consists of *n* contending stations, each one always having a packet available for transmission, where all the stations can hear each other (no hidden stations exist).

The main difference between our model and the model that assumes no transmission errors (only packet collisions) is that we denote p_f as the collision-error probability, which is the probability that a transmitted packet encounters a collision (at least one of the *n-1* remaining stations transmit in the same time slot) or is received in error[2] due to channel fading and/or noise. Thus, the equations for calculating the transmission probability as well as throughput will be different from the equations computed for an error-free channel in [3][4] that should be appropriately modified to include transmission errors.

In an error-prone environment, the packet error rate depends on the bit error rate, the packet header and the packet length:

$$PER = 1-(1-BER)^{l+hdr} \qquad (1)$$

where *BER* is the link bit error rate, *l* is the packet payload size and *hdr* is the packet header length.

By utilizing either of the previously mentioned approaches, we can calculate the probability τ that a station transmits a packet in a randomly chosen slot time. The two schemes reach different equations for τ since they employ different contention window adjustment mechanisms used in collision avoidance procedures. For the legacy 802.11 BEB, we have [3]:

$$\tau = \frac{2(1-2p_f)(1-p_f^{\,m+1})}{W(1-(2p_f)^{m+1})(1-p_f)+(1-2p_f)(1-p_f^{\,m+1})} \qquad (2)$$

For the DIDD scheme, we have [6]:

$$\tau = \frac{2(1-2a)(1-a^{m+1})}{(1-(2a)^{m+1})(1-a)W+(1-2a)(1-a^{m+1})} \qquad (3)$$

where $a = p_f / (1-p_f)$, *m* is the number of backoff stages and p_f is the collision-error probability that a transmitted packet encounters a collision (with probability p_{col}) or is received in error (with probability *PER*). To calculate p_f, we assume that at each transmission attempt, regardless of the number of retransmissions, each packet has a constant and independent failure probability given by:

$$p_f = 1-(1-p_{col})(1-PER) = 1-(1-\tau)^{n-1}(1-BER)^{l+hdr} \qquad (4)$$

Equations (2) (4) and (3) (4) respectively form non-linear systems with two unknowns $\tau \in (0,1)$ and $p_f \in (0,1)$ that can be solved using numerical methods having a unique solution (the proof of the uniqueness is similar to the one found in the Appendix of [11]).

B. Saturation Throughput Efficiency

Based on previous work [2], [6] and [16], we will next calculate the saturation throughput efficiency *S* that can be evaluated by dividing the time utilized for transmitting payload information in a slot time by the average duration of a slot time *E*[*slot*].

We first compute *E*[*slot*]. There are four types of events taking place in a random chosen slot. First, if none of the stations transmit any packets, they all wait for duration equal to T_{idle} that corresponds to the idle slot interval. Second, if only one station transmits and its packet transmission is successful. Thus, the channel is sensed busy because of a successful transmission that is equal to T_{suc}. Third, if at least two stations simultaneously initiate transmission then a packet collision occurs and the channel is sensed busy for duration equal to T_{col}. Fourth, only one station transmits but the transmitted packet is corrupted due to the channel errors and, thus, the channel is sensed busy for a duration equal to T_{err}.

Note that the previously mentioned events (T_{idle} , T_{suc}, T_{col}) have been studied before in [2]–[7]. However, the calculation of T_{col} in the literature (i.e., $T_{col} = T_{hdr} + T_{DATA} + DIFS$) does not comply with the IEEE 802.11 standard [1]. Actually, T_{col} should include the EIFS (Extended IFS interval) and be equal to $T_{hdr} + T_{DATA} + EIFS = T_{hdr} + T_{DATA} + SIFS + T_{ACK} + DIFS$ as it has been reported correctly[3] in [3, 6, 9]. Therefore, the duration of the above events that may occur in a randomly chosen slot time is:

$$\begin{cases} T_{idle} = \sigma \\ T_{suc} = T_{DATA} + SIFS + T_{ACK} + DIFS \\ T_{col} = T_{DATA} + SIFS + T_{ACK} + DIFS \\ T_{err} = T_{DATA} + T_{EIFS} \\ T_{suc} = T_{col} = T_{err} \end{cases} \qquad (5)$$

Following the same reasoning with [2][3][6] and by considering the above events, *S* can be derived as:

$$S = \frac{(1-P_{idle})\, P_{suc}\, l/C}{P_{idle}\sigma + (1-P_{idle})P_{suc}T_{suc} + (1-P_{idle})P_{col}T_{col} + (1-P_{idle})P_{err}T_{err}} \qquad (6)$$

where the denominator of equation (6) denotes the average length of a slot time *E*[*slot*], T_{idle} , T_{suc}, T_{col} and T_{err} can be obtained from equation (5), *C* is the data rate

[2] Note that we study independent errors since burst errors are left for future research (the analysis of bursty behaviour is not straightforward but rather complex requiring a careful study).

[3] where T_{hdr} is the time required to transmit the MAC and the physical packet headers, T_{DATA} and T_{ACK} is the time required to transmit the DATA and ACK packets, respectively.

and P_{idle}, P_{suc} , P_{col} , P_{err} are the corresponding probabilities for the above events to happen that we will calculate next.

Let P_{idle} be the probability that no packet transmission occurs in a randomly chosen slot time:

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

The probability P_{suc} that an ongoing transmission is successful is obtained when the transmitted packet does not experience either a collision or an error:

$$P_{suc} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}(1-PER) \tag{8}$$

The probability P_{col} that an occurring transmission collides because two or more stations simultaneously transmit is given by:

$$P_{col} = 1 - \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \tag{9}$$

The probability P_{err} that a packet does not experience a collision but it is corrupted because of transmission errors is:

$$P_{err} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} PER \tag{10}$$

In order to better understand the impact of transmission errors on performance, we study what occurs in a randomly selected time slot. Dividing numerator and denominator of equation (5) by $(1-P_{idle})\cdot P_{suc}$, we obtain:

$$S = \frac{l}{\frac{1-P_{tr}}{P_{tr}\cdot P_S}\cdot\sigma + T_S + \frac{P_c}{P_S}\cdot T_C + \frac{P_{er}}{P_S}\cdot T_{er}} \tag{11}$$

The denominator of equation (11) expresses the average time spent on the channel for a successful transmission. This time is further decomposed into four components. It is important to study the third and fourth terms at the denominator of equation (11). The third term represents the time W_{col} wasted due to collisions per successful packet transmission. In fact, P_{col} /P_{suc} is the average number of collided transmissions per successful transmission, which is multiplied by the average duration T_{col} that the medium is sensed busy due a collision. Similarly, the fourth term at the denominator of equation (11) denotes the time W_{err} wasted due to transmission errors per successful packet transmission.

C. Packet Drop Probability

The packet drop probability p_{drop} is defined as the probability that a packet encountering *m+1* collisions is dropped when the retry limit m is reached:

$$p_{drop} = p^m p = p^{m+1} \tag{12}$$

D. Average Packet Delay

The delay *D* is defined to be the time interval from the time a packet is at the head of its MAC queue ready for transmission, until an acknowledgement for this packet is received. The average packet delay *E*[*D*] for a successfully transmitted packet is given by:

$$E[D] = E[X]E[slot] \tag{13}$$

where *E*[*X*] is the average number of slot times required for a successful packet transmission. For the case of the legacy BEB, *E*[*X*] is calculated as [3]:

$$E[X] = \sum_{i=0}^{m}\left[\frac{W_i+1}{2}\frac{(p^i - p^{m+1})}{1-p^{m+1}}\right] \tag{14}$$

Note that if a packet is dropped because it has reached the specified retry limit, the time delay for this packet will not be included in the calculation of the average packet delay since this packet is not successfully received.

For the case of the DIDD scheme, *E*[*X*] is calculated as:

$$E[X] = \frac{1}{\tau(1-p_f)} = \frac{1}{\tau(1-\tau)^{n-1}} \tag{15}$$

E. Packet Inter-Arrival Time

The packet inter-arrival time $E[D_{inter}]$ is defined as the time interval between two successful packet receptions at the receiver.

For the case of legacy BEB, the packet delay, packet inter-arrival time and packet drop time are intuitively related by:

$$E[D_{inter}] = E[D] + \frac{p_{drop}}{1-p_{drop}}E[D_{drop}] \tag{16}$$

where *E*[*D*] is given by (13), p_{drop} is given by (12) and $E[D_{drop}]$, which is the average time to drop a packet, can be found by:

$$E[D_{drop}] = E[X_{drop}]\, E[slot] \tag{17}$$

where $E[X_{drop}]$ is the average number of slot times required for a packet to experience *m*+1 collisions in the (0,1,…*m*) stages and is given by:

$$E[X_{drop}] = \sum_{i=0}^{m}\frac{W_i+1}{2} = \frac{W(2^{m'+1}-1) + W\,2^{m'}\,(m-m') + (m+1)}{2} \tag{18}$$

For the DIDD scheme, the packet inter-arrival time $E[D_{inter}]$ can be directly obtained from throughput [5][6]:

$$E[D_{inter}] = \frac{l}{S/n} \tag{19}$$

It is easy to understand that when we do not consider any packet loss (see [3][5][6]), the packet inter-arrival time $E[D_{inter}]$, coincides with the average packet delay [6].

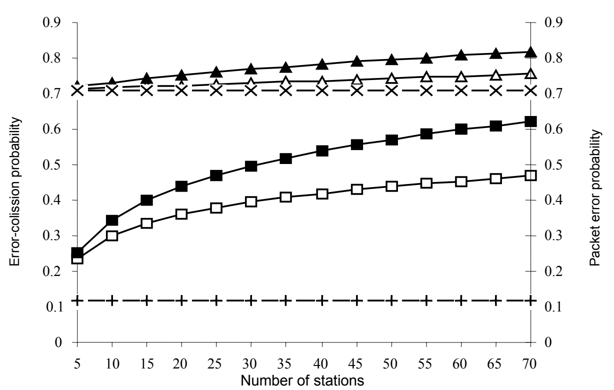
4. Performance Evaluation

The values of the parameters used in the following performance results can be found in Table I. For both IEEE 802.11 BEB and DIDD backoff schemes, we consider IEEE 802.11b [1] as the underlying PHY. Although, the current work considers only the basic access scheme, performance can be easily extended for the RTS/CTS handshaking mechanism.

Figure 3 illustrates the error-collision probability p_f and the probability *PER* a packet is received in error, as a function of the number of stations for the case of legacy BEB and of DIDD. As expected, the larger the number of stations, the higher the error-collision probability for legacy BEB 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}. On the other hand, we can see that *PER* is not affected by the network size. This is easily justified by noting that in equation (13) the term *PER* results to be independent of *n* and only depends on packet size as well as Bit Error Rate (*BER*).

Since the DIDD scheme introduces a different backoff scheme in order to enhance performance, it is interesting to study how succeeds in its aim. Figure 4 plots throughput efficiency and packet delay for legacy BEB and DIDD schemes under an error-prone environment for two different *BER* values ($BER = 10^{-4}, 10^{-5}$). Although, we can clearly see the significant obtained DIDD throughput gain for $BER = 10^{-5}$, this advantage is eliminated by the high error rate for $BER = 10^{-4}$. On the other hand, DIDD attains higher packet delay values than the legacy BEB since it includes the time delay of packets that would have been 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.

Figure 5 illustrates the equivalent performance results for packet inter-arrival time $E[D_{inter}]$ and packet drop probability p_{drop} against network size by employing two different *BER* values ($BER = 10^{-4}, 10^{-5}$). As expected, packet inter-arrival time for legacy 802.11 BEB is considerably higher than DIDD. The main reason for this deficiency in the former case is due to the fact that packet inter-arrival time also includes the time for packets that have been discarded; this time does not apply for DIDD scheme since the scheme achieves no packet drops at all (as it can be seen in the same figure for p_{drop}). Moreover, figure shows that packet drop probability significantly increases when *BER* and network size get higher leading to increased number of retransmissions.

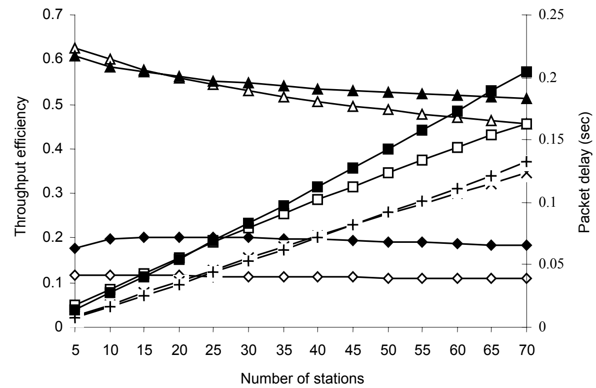


▲ p_f, $BER=10^{-4}$, *802.11* △ p_f, $BER=10^{-4}$, *DIDD*
■ p_f, $BER=10^{-5}$, *802.11* □ p_f, $BER=10^{-5}$, *DIDD*
x *PER*, $BER=10^{-4}$ + *PER*, $BER=10^{-5}$
(both *IEEE 802.11 BEB* & *DIDD*)

Figure 3 Error-collision probability and error probability versus network size for various network sizes under independent errors (Basic access, W=32, m'=5, C= 11Mbit/s, l=1500 bytes)

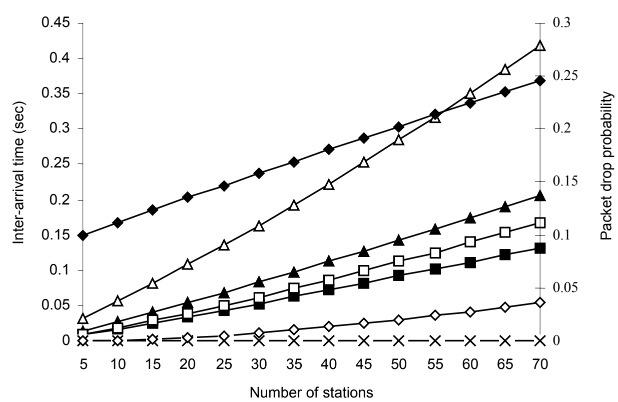
Parameter	802.11 DCF	DIDD
Packet payload, l	1500 bytes	1500 bytes
Data rate, C	11 Mbit/s	11 Mbit/s
Control (base) rate, C_{con}	2 Mbit/s	2 Mbit/s
Minimum CW, W_0	32	32
Number of CW sizes, m'	5	5
Retry limit, m	5	N/A
Bit Error Rate, BER	10^{-4} and 10^{-5}	10^{-4} and 10^{-5}

Table I IEEE 802.11 DCF and DIDD parameter values



◆ S, $BER=10^{-4}$, *DIDD* ◇ S, $BER=10^{-4}$, *802.11*
▲ S, $BER=10^{-5}$, *DIDD* △ S, $BER=10^{-5}$,*802.11*
■ $E[D]$, $BER=10^{-4}$, *DIDD* □ $E[D]$, $BER=10^{-4}$, *802.11*
x $E[D]$, $BER=10^{-5}$, *DIDD* + $E[D]$, $BER=10^{-5}$, *802.11*

Figure 4 Throughput efficiency and packet delay versus network size for 802.11 and DIDD under various *BERs* (Basic access, W=32, m'=5, C= 11Mbit/s, l=1500 bytes)



▲ D_{inter}, $BER=10^{-4}$, *DIDD* △ D_{inter}, $BER=10^{-4}$,*802.11*
■ D_{inter}, $BER=10^{-5}$, *DIDD* □ D_{inter}, $BER=10^{-5}$, *802.11*
◆ P_{drop}, $BER=10^{-4}$, *802.11* ◇ P_{drop}, $BER=10^{-5}$, *802.11*
x P_{drop}, $BER=10^{-4}$ and 10^{-5}, *DIDD*

Figure 5 Packet inter-arrival time and packet drop probability versus network size for 802.11 and DIDD under various *BERs* (Basic access, W=32, m'=5, C= 11Mbit/s, l=1500 bytes)

5. Conclusion and Future Work

In this paper, we introduced a performance analysis, which extends previous work by taking into account transmission errors for the IEEE 802.11 BEB and DIDD backoff schemes. The proposed analysis derived simple expressions that calculate throughput efficiency, average packet delay, packet drop probability and packet inter-arrival time. Analytical results illustrate that transmission errors considerably affect the performance of both schemes. When *BER* increases, throughput degrades, packet delay, packet drop probability and packet inter-arrival time significantly increase. Results also indicate that the proposed DIDD scheme is less sensitive on the network size than the legacy BEB but it attains higher packet delay values since it includes the time delay of packets that otherwise would have been discarded. Thus, DIDD proves to be ideal in high-congested environments or for applications that require no packet loss.

Future work could include the study of throughput and delay performance of both IEEE 802.11 and DIDD under non-saturated conditions. Another possible direction could be to distinguish packet errors from collisions when a packet corruption takes place in order to further improve performance in fading channels.

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