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IEEE 802.11 Wireless LANs: Performance Analysis and Protocol Refinement

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The IEEE 802.11 protocol is emerging as a widely used standard and has become the most mature technology for wireless local area networks (WLANs). In this paper, we focus on the tuning of the IEEE 802.11 protocol parameters taking into consideration, in addition to throughput efficiency, performance metrics such as the average packet delay, the probability of a packet being discarded when it reaches the maximum retransmission limit, the average time to drop a packet, and the packet interarrival time. We present an analysis, which has been validated by simulation that is based on a Markov chain model commonly used in the literature. We further study the improvement on these performance metrics by employing suitable protocol parameters according to the specific communication needs of the IEEE 802.11 protocol for both basic access and RTS/CTS access schemes. We show that the use of a higher initial contention window size does not considerably degrade performance in small networks and performs significantly better in any other scenario. Moreover, we conclude that the combination of a lower maximum contention window size and a higher retry limit considerably improves performance. Results indicate that the appropriate adjustment of the protocol parameters enhances performance and improves the services that the IEEE 802.11 protocol provides to various communication applications.

Keywords and phrases: IEEE 802.11, wireless LANs, DCF, packet delay, protocol tuning.

1. INTRODUCTION

During the past few years, the field of wireless local area networks (WLANs) has witnessed a massive development and has become one of the fastest growing areas in telecommunications and networking [1]. Continuing advances in wireless technology and mobile communications have equipped portable devices with wireless capabilities that allow networked communication even while a user is mobile. WLANs have found widespread use and have become an essential tool in many people's professional and personal life. To satisfy the growing needs of wireless data networking, the IEEE working group proposed the 802.11 protocol family [2].

The IEEE 802.11 protocols have become the dominant standard for WLANs and can offer high data rates of 11 Mbit/s [3] and 54 Mbit/s [4]. The IEEE 802.11 standard specifies two different medium access control (MAC) mechanisms for WLANs; the contention-based distributed coordination function (DCF) and the polling-based point coordination function (PCF). The mandatory DCF supports asynchronous data transfer and best suits delay insensitive data whereas the optional PCF provides time bounded services (TBS). DCF employs a carrier sense multiple access with collision avoidance (CSMA/CA) access scheme using binary exponential backoff. Under DCF, data packets are transmitted through two access mechanisms, the basic access

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and the request-to-send/clear-to-send (RTS/CTS) reservation scheme.

Many research efforts have been conducted on modeling the performance of DCF since the standardization of IEEE 802.11 MAC. Bianchi in [5] and Wu et al. in [6] use Markov chain models to analyze the throughput of 802.11 protocol. In particular, Bianchi assumes that packet retransmissions are unlimited and that a packet is being transmitted continuously until its successful reception. Wu in [6] extends Bianchi's analysis to include the finite packet retry limits as defined in the IEEE 802.11 standard [2]. In [7], we provide a new performance analysis of the 802.11 protocol, which is based on the extensively-used-in-the-literature Markov chain model of [6] and allows the calculation of the packet delay, the packet drop probability, and the packet drop time. Ziouva in [8] develops a Markov chain model that introduces an additional transition state to the models of [5, 6, 7] and actually allows stations to transmit consecutive packets without activating the backoff procedure.[1] This feature, which is not specified in any IEEE 802.11 standard, causes an unfair use of the medium since stations are not treated in the same way after a successful transmission. The proposed model in [8] lacks of any validation using simulation results and the calculation of average packet delay utilizes a very complicated approach since it calculates the average number of the collisions of a packet before its successful reception and the average time a station's backoff timer remains stopped.

Several other papers in the literature [9, 10, 11] have attempted to improve IEEE 802.11 performance by either modifying the backoff mechanism or by fine-tuning certain protocol parameters. Carvalho and Garcia-Luna-Aceves in [9] considered the impact of the minimum contention window (CW) size and the corresponding capacity improvement that is achieved when CW increases but not combined with packet retry limits and other protocol parameters. Cali et al. in [10] proposes a method of estimating the number of active stations via the number of empty slots and exploits the estimated value to tune the CW parameter based on a p-persistent version of the IEEE 802.11 protocol. Aad and Castelluccia in [11] suggests three different ways to enhance 802.11 performance; by scaling the CW 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 this paper, we concentrate on the performance enhancement of IEEE 802.11 DCF by simply modifying specific protocol parameter values. In order to adjust the protocol parameters, the mathematical description of the system turns out to be extremely helpful in observing the effect on the considered performance metrics of any parameter changes made. Our work reports and explores several performance metrics such as the average packet delay, the packet drop probability, the average time to drop a packet, the packet interarrival time, and the throughput efficiency. OPNET simulation results validate the accuracy of our performance analysis. Moreover, a performance comparison of (a) the proposed delay analysis in [8], (b) our validated delay analysis, and (c) simulation results, demonstrates that the analysis based on Wu's model, which takes into account packet retry limits, predicts very accurately DCF packet delay performance. We then propose a simple-to-implement appropriate tuning of the backoff algorithm for the basic access scheme (the conclusions are also applicable to the RTS/CTS scheme) depending on the specific communication requirements. The proposed fine-tuning does not depend on the employed access scheme or the packet size and aims to improve the services that the protocol provides to higher layers of the communication protocol stack.

2. DISTRIBUTED COORDINATION FUNCTION

In DCF basic access mode, a station with a packet to transmit monitors the medium activity. If the medium is idle, the station transmits the data packet. If the medium is sensed busy, the station waits until the medium becomes idle for more than a distributed interframe space (DIFS) time interval. The station then defers transmission for a randomly selected interval in order to minimize collisions and transmits the data packet. A station that receives a data packet replies by a positive acknowledgement packet (ACK) after a short interframe space (SIFS) interval. If the source station does not receive an ACK, the data packet is assumed to have been lost and a retransmission is scheduled. Each station maintains a station short retry count (SSRC) that has an initial value of zero for every new packet. The short retry count indicates the maximum number of retransmission attempts of a data packet when the basic access scheme is utilized.

In IEEE 802.11, a station waits a random backoff interval before initiating a packet transmission. The backoff timer value for each station is uniformly chosen in the interval $[0, W_i - 1]$ where W_i is the current CW size and i is the backoff stage. 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. A station initiates a packet transmission when the backoff timer reaches zero. The value of W_i depends on the number of failed transmissions of a packet; at the first transmission attempt, $W_0 = \mathrm{CW}_{\min} = W$. After each retransmission due to a packet collision, W_i is doubled up to a maximum value, $W_{m'} = \mathrm{CW}_{\max} = W2^{m'}$, where m' is the number of backoff stages. Once W_i reaches $\mathrm{CW}_{\max}$, it will remain at this value until it is reset to $\mathrm{CW}_{\min}$ in the following cases: (a) after the successful transmission of a data packet or (b) when SSRC reaches the short retry limit. When the short retry limit is reached, retry attempts will cease and the packet will be discarded. The SSRC is reset to 0 whenever an ACK is received in response to a data packet.

3. MATHEMATICAL MODELING

In this paper, we assume that the network consists of n contending stations and each station always has a packet

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[1] According to the authors of [8], this takes place when a station detects that its previous transmitted packet was successfully received and the channel is idle.

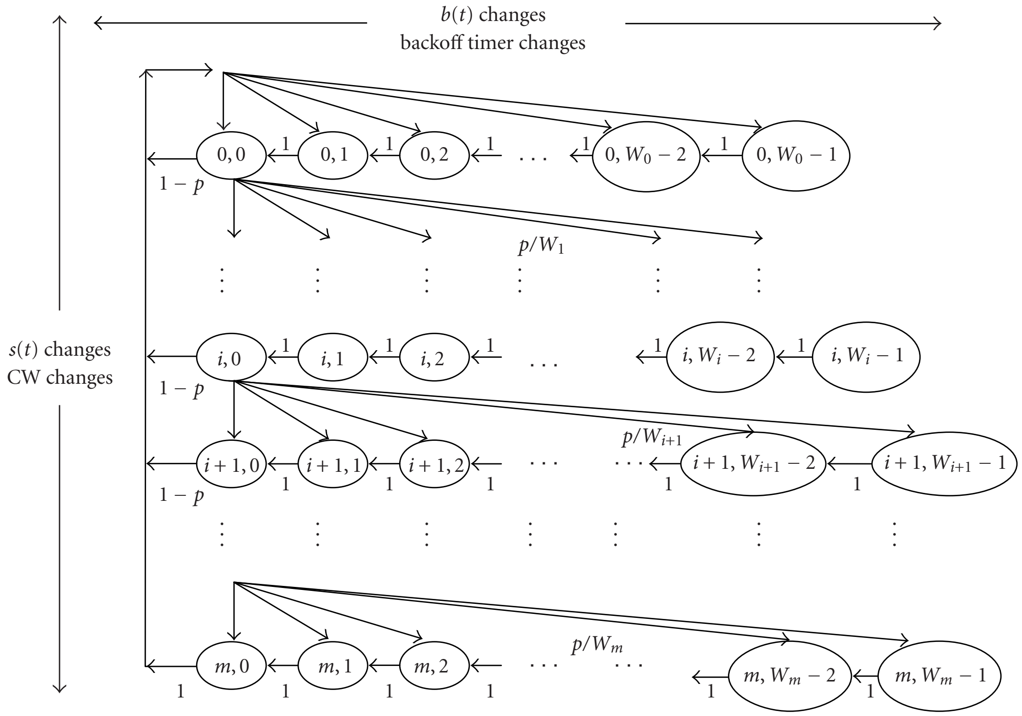

Figure 1: Markov chain model.

available for transmission. The main assumption of our model is that the collision probability of a data packet transmission is constant and independent of the number of collisions the packet has suffered in the past.

Let $b(t)$ and $s(t)$ be the stochastic processes representing the backoff timer and the backoff stage, respectively, for a given station at slot time t. The discrete-time Markov chain illustrated in Figure 1 is employed to model the bidimensional process $\{b(t), s(t)\}$. Let $b_{i,k} = \lim_{t\to\infty} P\{s(t) = i,\ b(t) = k\}$ be the stationary distribution of the Markov chain denoting the probability of a station to be in state (i, k), where $i \in [0, m]$, $k \in [0, W_i - 1]$, and m is the station retry limit. By considering that $b_{i,0} = pb_{i-1,0}$, $i \in (0, m]$, we have the following relation for $b_{i,0}$:

$$b_{i,0} = p^i b_{0,0}, \quad 0 < i \le m. \tag{1}$$

Following the same reasoning with [6, 7] and by means of the above Markov chain model, the probability τ that a station transmits a packet in a randomly chosen slot time is presented by (we consider the case of $m > m'$, which is usually the case)

$$\tau = \frac{2(1-2p)(1-p^{m+1})}{W(1-(2p)^{m'+1})(1-p) + (1-2p)\left[W2^{m'}p^{m'+1}(1-p^{m-m'}) + 1 - p^{m+1}\right]}. \tag{2}$$

The probability p that a transmitted packet encounters a collision is the probability that at least one of the $n - 1$ remaining stations transmits in the same slot time. If all stations transmit with probability τ, the conditional collision probability p is given by

$$p = 1 - (1-\tau)^{n-1}. \tag{3}$$

Equations (2) and (3) form a nonlinear system with two unknowns τ and p. This nonlinear system can be solved utilizing numerical methods and has a unique solution.[2]

4. PERFORMANCE ANALYSIS

Our performance analysis, as already shown in the previous section, includes the effect of packet retry limits and

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[2] The full proof as well as additional details for the derived analysis can be found in the appendix.

considers the following metrics, which are good indicators for the performance of IEEE 802.11 WLANs. We consider throughput efficiency, average packet delay, probability of a packet being discarded when it reaches the maximum retransmission limit, the average time to drop a packet, and packet interarrival time.

4.1. Saturation throughput

Let P_{tr} be the probability that at least one station transmits a packet in a randomly selected slot time and P_s the probability that an occurring packet transmission is successful. For a wireless LAN of n contending stations, the probabilities P_{tr} and P_s are given by

$$\begin{aligned} P_{\mathrm{tr}} &= 1-(1-\tau)^n, \\ P_s &= \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}. \end{aligned} \tag{4}$$

Considering that a random slot is empty with probability $(1-P_{\mathrm{tr}})$ contains a successful transmission with probability $P_{\mathrm{tr}}P_s$ and a collision with probability $P_{\mathrm{tr}}(1-P_s)$, the saturation throughput S is given by

$$S = \frac{P_{\mathrm{tr}}P_s l}{E[\mathrm{slot}]} = \frac{P_{\mathrm{tr}}P_s l}{(1-P_{\mathrm{tr}})\sigma + P_{\mathrm{tr}}P_s T_s + P_{\mathrm{tr}}(1-P_s)T_c}, \tag{5}$$

where $E[\mathrm{slot}]$ is the average length of a slot time, l is the length of the transmitted packet, σ is the duration of an empty slot, T_s and T_c are the average durations the medium is sensed busy due to a successful transmission and a collision, respectively. We have

$$T_s = \mathrm{DIFS} + T_{\mathrm{header}} + T_{\mathrm{DATA}} + \delta + \mathrm{SIFS} + T_{\mathrm{ACK}} + \delta. \tag{6}$$

In order to explicitly specify the value of the time interval T_c, we have to categorize stations in two groups: the listening (noncolliding) and the colliding stations. In the case of the "listening" stations, a packet collision will result in an error reported by the PHY (by utilizing the PHY-RXEND.indication) and the time interval T_c for those stations is equal to an extended interframe space (EIFS) after the packet transmission. For the "colliding" stations the time interval T_c is equal to an ACK_Timeout following the packet transmission. As it is specified in the IEEE 802.11 standard [2], the ACK_Timeout is equal to EIFS (almost equal since the latter is shorter by a slot time). Thus, the values of T_s and T_c, which both depend on the medium access mechanism, in the case of basic access are

$$T_s = T_c = \mathrm{DIFS} + T_{\mathrm{header}} + T_{\mathrm{DATA}} + \delta + \mathrm{SIFS} + T_{\mathrm{ACK}} + \delta, \tag{7}$$

where T_{header} is the time required to transmit the MAC and the physical packet header, $T_{\mathrm{DATA}} = l/C$ is the time required to transmit the packet data payload of l bits, when C is the data rate, $T_{\mathrm{ACK}} = l_{\mathrm{ACK}}/C_{\mathrm{control}}$ is the time required to transmit the ACK packet of l_{ACK} bits, C_{control} is the control (base) rate at which the ACK packet is sent and δ is the propagation delay.

4.2. Packet drop probability

The packet drop probability is defined as the probability that a packet is dropped when the retry limit is reached. A packet is found in the last backoff stage m if it encounters m collisions in the previous stages and it will be discarded if it experiences another collision. Therefore, packet drop probability can be expressed as a function of the last backoff stage (by means of (1)) and the collision probability p as[3]

$$p_{\mathrm{drop}} = \frac{b_{m,0}}{b_{0,0}}p = p^m p = p^{m+1}. \tag{8}$$

4.3. Average packet delay

The delay D for a successfully transmitted packet is defined to be the time interval from the time the packet is at the head of its MAC queue ready for transmission, until an acknowledgement for this packet is received. 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.

The average packet delay $E[D]$ is given by

$$E[D] = E[X]E[\mathrm{slot}], \tag{9}$$

where $E[X]$ is the average number of slot times required for a successful packet transmission and can be found by multiplying the number of slot times d_i the packet is delayed in each backoff stage by the probability q_i for the packet to utilize this backoff stage:

$$E[X] = \sum_{i=0}^{m} d_i q_i. \tag{10}$$

The average number of slot times d_i a station utilizes in the i stage (including the transmission slot) is given by

$$d_i = \frac{W_i + 1}{2}, \quad i \in [0, m]. \tag{11}$$

The probability q_i that a packet reaches the i backoff stage, provided that this packet is not discarded, is given by

$$q_i = \frac{(p^i - p^{m+1})}{1 - p^{m+1}}, \quad i \in [0, m] \tag{12}$$

since packets that are not dropped (with probability $1-p^{m+1}$) arrive at the i stage with probability $(p^i - p^{m+1})$ (we have to deduct the probability p^{m+1} of dropped packets from the probability p^i of the total number of packets arriving at the i stage).

Combining (10), (11), and (12), $E[X]$ is given by

$$E[X] = \sum_{i=0}^{m}\left[\frac{(p^i - p^{m+1})((W_i+1)/2)}{1-p^{m+1}}\right]. \tag{13}$$

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[3] Note that the packet drop probability is independent of the employed access scheme (basic access or RTS/CTS).

4.4. *Average time to drop a packet*

A packet is dropped when it reaches the last backoff stage and experiences another collision. The average time to drop a packet is equal to

$$E[D_{\text{drop}}] = E[X_{\text{drop}}]E[\text{slot}], \tag{14}$$

where $E[X_{\text{drop}}]$ is the average number of slot times required for a packet to experience $m+1$ collisions in the $(0,1,\dots,m)$ stages. Given that the average number of slot times a station defers in the i stage is $(W_i+1)/2$, then $E[X_{\text{drop}}]$ is given by

$$\begin{aligned} E[X_{\text{drop}}] &= \sum_{i=0}^{m} \frac{W_i+1}{2} \\ &= \frac{W(2^{m'+1}-1)+W2^{m'}(m-m')+(m+1)}{2}. \end{aligned} \tag{15}$$

4.5. *Packet interarrival time*

The packet interarrival time is defined as the time interval between two successful packet receptions at the receiver and can be simply obtained from throughput:

$$E[D_{\text{inter}}] = \frac{l}{S/n}. \tag{16}$$

Using the same reasoning with (9), the packet interarrival time $E[D_{\text{inter}}]$ is also given by

$$E[D_{\text{inter}}] = \left(\sum_{j=0}^{\infty} p^{j(m+1)} \sum_{i=0}^{m} p^i \frac{W_i+1}{2}\right) E[\text{slot}], \tag{17}$$

which after some algebra reaches (16).

Intuitively, the average packet delay, interarrival time, and drop time are related by

$$E[D] = E[D_{\text{inter}}] - \frac{p_{\text{drop}}}{1-p_{\text{drop}}} E[D_{\text{drop}}], \tag{18}$$

where $E[D_{\text{inter}}]$ is given by (16) or (17), p_{drop} is given by (8), and $E[D_{\text{drop}}]$ is given by (14). The expression $p_{\text{drop}}/(1-p_{\text{drop}}) = p^{m+1}/(1-p^{m+1})$ represents the average number of dropped packets needed for a successful transmission. The expression in (18) is of key importance since it gives insights of the delay characteristics of the IEEE 802.11 backoff mechanism and relates the average packet delay with the packet interarrival time, the packet drop probability, and the average time to drop a packet.

5. MODEL VALIDATION

The mathematical analysis presented in this paper is validated by comparing analytical with simulation results obtained using our IEEE 802.11 simulator. This IEEE 802.11 simulator is developed using the OPNET modeler communication networks modeling and simulation software package. OPNET modeler is an event-driven simulator and provides a powerful graphical tool to display simulation statistics. In fact, our OPNET 802.11 simulator emulates the real operation of a wireless station as closely as possible, by implementing the collision avoidance procedures and all parameters such as packet transmission times, propagation delays, turnaround times, and so forth. The simulator closely follows all timer values and packet element transmission times defined by IEEE 802.11 specifications. Furthermore, we have suitably modified the model of the IEEE 802.11 wireless station provided in the standard library of OPNET in order to employ saturation conditions, that is, all stations always have a packet ready for transmission.

The Markov chain analysis presented in the previous sections is independent of physical layer parameters and can be applied to all IEEE 802.11 PHY standards. The parameters used in both the analytical model and our simulations follow the parameters in [6, 7] and are summarized in Table 1. The system parameter values are those specified for the direct spread sequence spectrum (DSSS) physical layer utilized in IEEE 802.11b [3].

Figures 2 and 3 confirm the accuracy of the considered assumptions in the mathematical analysis.[4] The figures provide performance results (throughput efficiency, packet delay, packet drop time, and packet drop probability) versus the number of contending stations. Figure 2 depicts an almost exact match observed between analytical results (lines) and simulation outcome (symbols) illustrating that the analytical model that considers retry limits predicts very accurately DCF throughput performance, a conclusion not clearly drawn in [6] which added packet retry limits in the analytical model in [5]. Figure 2 also displays packet delay calculated using our delay analysis as well as Ziouva's model [8] against OPNET simulation results. The performance comparison shows that our packet delay analysis gives results in high agreement with OPNET simulations. We can observe that the model in [8], which is less conformant to the IEEE 802.11 standard than our model, causes a high overestimation of packet delay due to the adoption of the additional transition state and the absence of packet retry limits. Figure 3 also validates our analysis for the other two considered performance metrics: packet drop time and drop probability.

6. TUNING OF PROTOCOL PARAMETERS AND PERFORMANCE RESULTS

There are a variety of performance requirements according to the various communication needs or application desires. For example, time bounded applications that exchange query-like messages, require low packet loss and low delivery delay. Conversely, applications that provide delay insensitive services (i.e., email, ftp) are not concerned much with packet timely deliverance and maximising throughput performance is of prime importance in this case. Additionally, there are many applications that lie somewhere in the middle and may

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[4] Note that simulation results are acquired with a 95% confidence interval lower than 0.002

Table 1: DSSS system parameters in IEEE 802.11b.

Parameter	Value	Parameter	Value
Slot time, σ	20 μs	Packet payload, l	1023 or 1500 bytes
MAC header, l_{MAC}	272 bits	DIFS	50 μs
PHY header, l_{PHY}	192 bits	SIFS	10 μs
Data header time, T_{header}	$(l_{\text{PHY}} + l_{\text{MAC}})/C_{\text{control}}$	Minimum CW, W_0	32
ACK packet, l_{ACK}	112 bits + l_{PHY}	Number of CW sizes, m'	5
Channel bit rate, C	11 Mbit/s	Short retry limit, m	6
Control rate, C_{control}	1 Mbit/s	Propagation delay, δ	1 μs

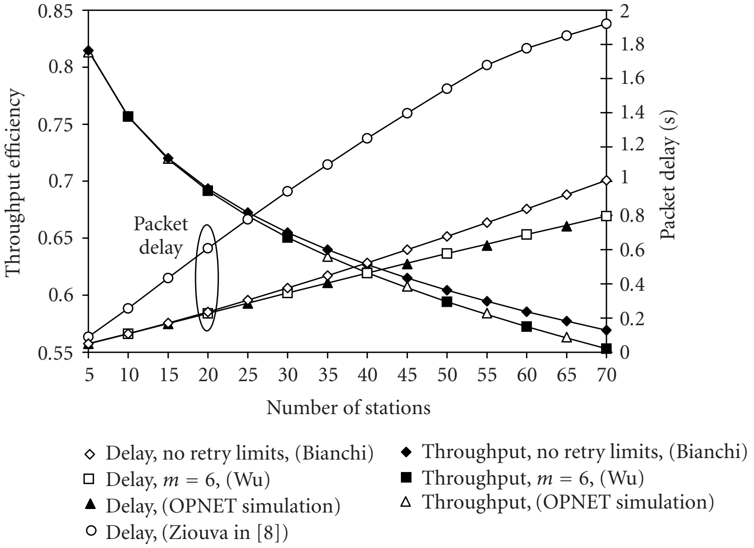

Figure 2: Throughput efficiency and packet delay: analysis versus simulation (l = 1023 bytes).

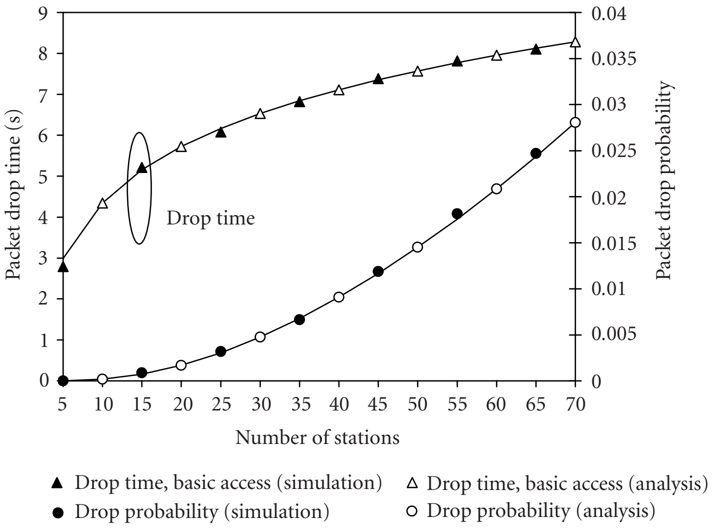

Figure 3: Packet drop time and packet drop probability: analysis versus simulation (l = 1023 bytes).

demand low delivery delay but will not be sensitive to some loss of packets or may demand low loss but not small delay. For example, multimedia applications are not able to tolerate high delay or jitter but may tolerate some packet loss whereas HTTP-like applications can tolerate delay but require minimum data loss.

TABLE 2: Packet delay and throughput efficiency for a small network size ($l = 1500$ bytes).

Number of stations	IEEE 802.11 standard $W = 32, m = 6, m' = 5$		$W = 64, m = 6, m' = 5$	
	Packet delay (s)	Throughput efficiency	Packet delay (s)	Throughput efficiency
$n = 2$	0.003779	0.577334	0.004049	0.538847
$n = 3$	0.005664	0.577849	0.005843	0.560091
$n = 4$	0.007624	0.572318	0.007683	0.567978
$n = 5$	0.009647	0.565203	0.009564	0.570292
$n = 6$	0.011722	0.557878	0.011485	0.569902

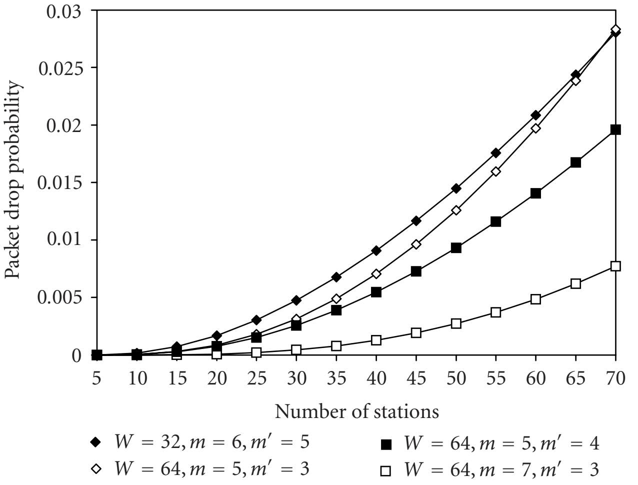

FIGURE 4: Packet drop probability against number of stations ($l = 1500$ bytes).

In order to fulfil specific communication needs, we propose the adjustment of certain protocol parameters to different values than those proposed by the IEEE standard. Three parameters are being examined: the initial contention size (W), the packet retry limit (m), and the number of backoff stages (m'). Our performance analysis examines the following metrics as good indicators for the performance of the IEEE 802.11 protocol, namely, the throughput efficiency, the average packet delay, the packet drop probability as well as the average time to drop a packet.

By employing the analytical model presented previously, various sets of protocol parameter values have been examined and compared with parameter values that the IEEE 802.11 standard proposes in order to identify potential improvements on protocol performance. After an extensive performance study, we have identified three sets of parameter values. Each set of parameter values achieves better performance on some particular metrics and it can be employed according to the specific communication needs. For example, one set of parameter values can significantly improve the throughput efficiency whereas another combination of parameters can considerably reduce the packet drop probability or the packet drop time.

The following three sets of parameter values that are being employed for the basic access scheme, for the case of "long" packets of $l = 1500$ bytes[5] and compared with the values that the IEEE 802.11 protocol proposes ($W = 32$, $m = 6$, $m' = 5$) are

(a) $W = 64, m = 5, m' = 4$,
(b) $W = 64, m = 5, m' = 3$,
(c) $W = 64, m = 7, m' = 3$.

In all considered cases, we increase the value of W to reduce the number of collisions. In the first case, the $\text{CW}_{\max}$ value that the standard proposes ($\text{CW}_{\max} = 1024$) is utilized by decreasing m' to 4; a lower retry limit ($m = 5$) is considered sufficient since increasing W to 64 reduces the collision probability. In the second set, we study the effect of reducing $\text{CW}_{\max}$ to 512 by decreasing m' to 3; this set is expected to improve the average packet delay. Finally, in the last set, the retry limit is increased to the value of 7. As a result, a contending station utilizes two more times the (relatively) small last backoff stage ($\text{CW}_{\max} = 512$) aiming to reduce the packet drop probability while keeping a fairly low packet delay.

At a first glance, it might seem that the choice of a higher value for the initial CW size ($W = 64$) comparing to the value of the standard ($W = 32$) will cause a performance decrease in a small network scenario. A closer study to the case of a small network size ($2 \leq n \leq 6$) was performed and Table 2 presents the packet delay and throughput efficiency for the two different values of the initial contention window W. The table illustrates that the adjustment of W to a higher value does not cause a considerable effect on both the packet delay and throughput efficiency for very small networks; on the contrary performance is improved in networks with five or more contending stations.

The efficiency of each set of parameter values on the packet drop probability is explored in Figure 4 against the number of contending stations. When the standard proposed values are employed, a packet suffers the highest drop probability comparing to the other three cases. The choice of a higher W value improves the drop probability since fewer

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[5] Results for the RTS/CTS scheme and other packet sizes such as "short" VoIP packets of $l = 200$ bytes have reached exactly the same conclusions, denoting that the proposed improvement does not depend on the employed access scheme or the packet payload size.

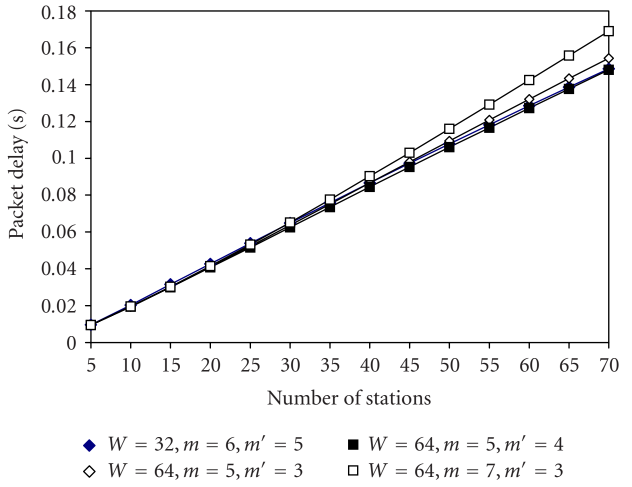

Figure 5: Packet delay against number of stations ($l = 1500$ bytes).

collisions are taking place. When $W = 64$, $m = 5$, $m' = 3$ are employed, the packet drop probability increases rapidly and gradually attains the same value with the standard proposed values in a large network scenario ($n = 70$). This is justified by noting that employing $W = 64$ and $m' = 3$, the maximum value of the CW size will be lower ($\text{CW}_{\text{max}} = 512$) compared to the one that the IEEE standard proposes ($\text{CW}_{\text{max}} = 1024$) resulting in an increased number of collisions when the number of contending stations is high. The lowest packet drop probability is achieved when $W = 64$, $m = 7$, and $m' = 3$ since the packet drop probability is reduced up to 75% compared to the IEEE standard proposed values despite of the decrease of CW_{max}.

Figure 5 depicts that the packet delay increases when the network size grows in all cases due to the higher number of collisions. The figure also shows that the packet delay is not significantly affected by the employment of different parameter values. The only exception is when $W = 64$, $m = 7$, $m' = 3$, the packet delay increases faster than in the other cases when $n > 35$ and a packet experiences an increase on delay of up to 10% in a large network ($n = 70$). However, by means of Figure 4 the situation is easily explained since a larger number of packets are transmitted successfully and not discarded. The small increase of the packet delay is the small price we pay for significantly decreasing the packet drop probability.

Figure 6 plots the average time to drop a packet when it reaches the maximum retransmission limit against the number of contending stations. For all sets of parameter values, the packet drop time increases when the network size increases. The figure shows that the employment of any of the considered sets of parameter values, as compared to the IEEE standard parameters, results in a significant improvement on the packet drop time. The highest packet drop time is attained using the parameter values suggested in the standard, whereas the case of $W = 64$, $m = 5$, $m' = 3$ achieves the lowest packet drop time with a reduction of about 40% for a large network size ($n = 70$).

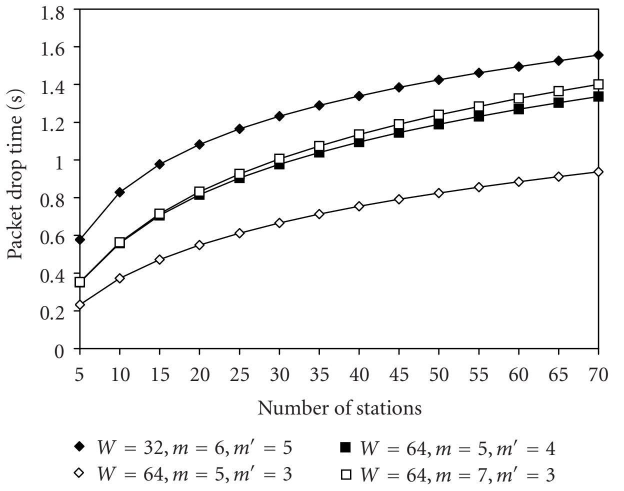

Figure 6: Packet drop time against number of stations ($l = 1500$ bytes).

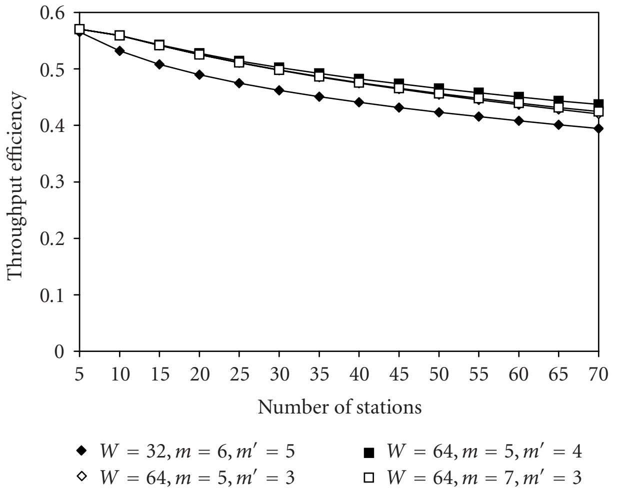

Figure 7: Throughput efficiency against number of stations ($l = 1500$ bytes).

Figure 7 examines the throughput efficiency that each considered set of parameter values achieves with varying the number of contending stations. When any of the proposed value sets is employed, the achievable throughput efficiency is higher compared to the standard parameter values mainly because the larger W value decreases the number of collisions. Especially when $W = 64$, $m = 5$, $m' = 4$, the increase on throughput can be up to 10% compared to the case when the standard parameter values are employed.

Finally, Figure 8 studies packet interarrival time, which is defined as the time interval between two successful packet receptions at the receiver. As expected, packet interarrival time for the standard parameter values is considerably higher than any other case. This can be easily justified by noting that packet interarrival time also includes the time for packets that have been discarded; this time is much greater for the case of $W = 32$, $m = 6$, $m' = 5$ due to the high drop probability values (Figure 4).

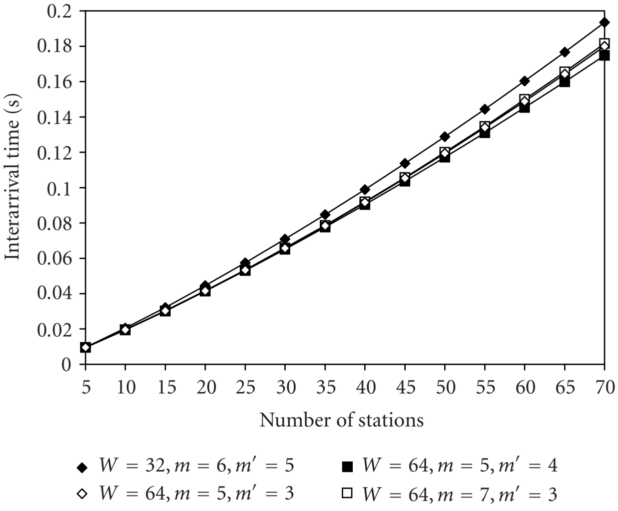

FIGURE 8: Packet interarrival time against number of stations (l = 1500 bytes).

Performance results reported in the previous figures show that when ($W = 64$, $m = 5$, $m' = 4$), lower packet drop probability, packet drop time, packet interarrival time, and better throughput performance are achieved compared to the values proposed by the standard. When the $\mathrm{CW}_{\max}$ is decreased to a lower value ($\mathrm{CW}_{\max} = 512$) for the same retry limit ($m = 5$), we attain the lowest packet drop time compared to any other case but the drop probability increases considerably. On the contrary, the adjustment of the retry limit to a higher value ($W = 64, m = 7, m' = 3$) results in the lowest packet drop probability and a small increase of packet drop time and delay due to the larger number of packets not being discarded and transmitted successfully. Each combination of parameters achieves an improved performance on some specific metrics compared to the standard proposed values and the choice of which set of protocol parameters should be employed depends on the specific communication requirements.

7. CONCLUSIONS

In this paper, we have focused on the performance enhancement of the IEEE 802.11 MAC protocol using several performance metrics such as the average packet delay, the packet drop probability, the average time to drop a packet, the packet interarrival time, and the throughput efficiency. Performance results obtained from our analysis fully agree with OPNET simulations confirming the improvements in accuracy when retry limits are considered. We also compared throughput and delay results for different models presented in the literature. With the infinite retry limit model [5], performance results deviate from simulations as the number of contending stations increases. Moreover, for the model [8] based on a different operational mode of IEEE 802.11 MAC results revealed that it overestimates packet delay performance.

We have also examined the effect of the initial contention window size on performance by employing a higher value ($W = 64$) compared to the standard proposed value ($W = 32$). Results indicate that this adjustment does not considerably degrade performance in very small WLANs but improves performance in networks with five or more contending stations. Based on performance results for the basic access scheme (the same conclusions are derived for the RTS/CTS scheme), we have proposed an appropriate tuning of the backoff algorithm to improve the services that the IEEE 802.11 protocol provides. We have shown that the high value of $\mathrm{CW}_{\max}$ that the IEEE standard has proposed could be safely lowered and when combined with a higher retry limit, then the performance can be improved. Finally, we have proposed three sets of parameter values for initial contention window size, retry limit, and number of backoff stages and we have concluded that each proposed set achieves better performance on particular metrics and it could be employed to match specific communication needs.

APPENDIX

Let $b_{i,k} = \lim_{t\to\infty} P\{s(t) = i,\ b(t) = k\}$ be the stationary distribution of this Markov chain, where $i \in [0, m]$, $k \in [0, W_i - 1]$. Based on the two-dimensional Markov chain illustrated in Figure 1 and by considering that $b_{1,0} = p \cdot b_{0,0}$ and $b_{2,0} = p \cdot b_{1,0} = p^2 \cdot b_{0,0}$, we have the following relation for $b_{i,0}$:

$$b_{i,0} = p b_{i-1,0} = p^i b_{0,0}, \quad 0 < i \le m. \tag{A.1}$$

Owing to chain regularities and by means of equation (A.1), all $b_{i,k}$ values are expressed as a function of $b_{0,0}$ and p as

$$b_{i,k} = \frac{W_i - k}{W_i} \cdot b_{i,0}, \quad 0 \le i \le m,\ 0 \le k \le W_i - 1. \tag{A.2}$$

Applying the normalization condition for this stationary distribution

$$\begin{aligned} 1 &= \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} b_{i,k} = \sum_{i=0}^{m} b_{i,0} \cdot \sum_{k=0}^{W_i-1} \frac{W_i - k}{W_i} \\ &= \sum_{i=0}^{m} b_{i,0} \cdot \frac{W_i + 1}{2} = \sum_{i=0}^{m} p^i \cdot b_{0,0} \cdot \frac{W_i + 1}{2} \\ &= \frac{b_{0,0}}{2} \cdot \left(\sum_{i=0}^{m} p^i \cdot W_i + \sum_{i=0}^{m} p^i \right), \end{aligned} \tag{A.3}$$

from which

$$b_{0,0} = \frac{2}{\left(\sum_{i=0}^{m} p^i \cdot W_i + \sum_{i=0}^{m} p^i \right)}, \tag{A.4}$$

and after some algebra,

$$b_{0,0} = \frac{2(1-2p)(1-p)}{W\left(1-(2p)^{m'+1}\right)(1-p) + (1-2p)\left[W2^{m'}p^{m'+1}\left(1-p^{m-m'}\right)+1-p^{m+1}\right]}. \tag{A.5}$$

By utilizing the Markov chain model, the probability τ that a station transmits a packet in a randomly chosen slot time is equal to

$$\tau = \sum_{i=o}^{m} b_{i,0} = \sum_{i=o}^{m} p^i \cdot b_{0,0} = b_{0,0} \cdot \frac{1-p^{m+1}}{(1-p)} \tag{A.6}$$

and $b_{0,0}$ can be acquired from (A.5). From (A.6), we observe that the transmission probability τ depends on the conditional probability p, which is defined as the probability that a transmitted packet collides and is given by

$$p = 1-(1-\tau)^{n-1}. \tag{A.7}$$

As we stated before, (A.6) and (A.7) represent a nonlinear system with two unknowns τ and p. This nonlinear system, which has a unique solution, can be solved utilizing numerical methods evaluating t and p for a certain W, m, and m' combination. Since the system of the two equations is different from the one in [5], a detailed proof of the uniqueness of this solution is derived next.

Equation (A.7) can be rewritten as

$$\tau^*(p) : \tau = 1-(1-p)^{1/(n-1)}. \tag{A.8}$$

The function $\tau^*(p)$ is a continuous and monotone increasing function in the range $p \in (0,1)$. It increases from $\tau^*(0) = 0$ to $\tau^*(1) = 1$. Function $\tau(p)$ given by (A.6) is also continuous in the same range;[6] continuity in correspondence of the critical value $p = 1/2$ is simply proven by using (A.5) as follows:

$$\begin{aligned}
b_{0,0} &= \frac{2}{\sum_{i=0}^{m}(1/2)^i W_i + \sum_{i=0}^{m}(1/2)^i}, \\
&= \frac{2}{\left(\sum_{i=0}^{m'}(1/2)^i(2^i W) + \sum_{i=m'+1}^{m}(1/2)^i(2^{m'}\cdot W) + \left(1-(1/2)^{m+1}\right)/(1-1/2)\right)} \\
&= \frac{2}{\left(\sum_{i=0}^{m'} W + (2^{m'}\cdot W)\sum_{i=m'+1}^{m}(1/2)^i + \left(1-(1/2)^{m+1}\right)/(1/2)\right)} \\
&= \frac{2}{\left(W(m'+1) + (2^{m'}\cdot W)\left(\left(1-(1/2)^{m-m'}\right)/(1-1/2)\right)(1/2)^{m'+1} + \left(1-(1/2)^{m+1}\right)/(1/2)\right)} \\
&= \frac{2}{\left(W(m'+1) + W\left(\left(\left(2^{m-m'}-1\right)/2^{m-m'}\right)/(1/2)\right)(1/2) + \left(\left(2^{m+1}-1\right)/2^{m+1}\right)/(1/2)\right)} \\
&= \frac{2}{\left(W(m'+1) + W\left(\left(2^{m-m'}-1\right)/2^{m-m'}\right) + \left(2^{m+1}-1\right)/2^m\right)}.
\end{aligned} \tag{A.9}$$

Therefore, when $p = 1/2$, (A.6) becomes

$$\begin{aligned}
\tau\left(\frac{1}{2}\right) &= \sum_{i=o}^{m} b_{i,0} = \sum_{i=o}^{m}\left(\frac{1}{2}\right)^i b_{0,0} = \frac{2^{m+1}-1}{2^m} b_{0,0} \\
&= \frac{2^{m+1}-1}{2^{m-1}\left(W(m'+1) + W\left(\left(2^{m-m'}-1\right)/2^{m-m'}\right) + \left(2^{m+1}-1\right)/2^m\right)}.
\end{aligned} \tag{A.10}$$

Moreover, when $p = 1$ and by means of (A.5), we have

$$\begin{aligned} b_{0,0} &= \frac{2}{\left(\sum_{i=0}^{m} W_i + \sum_{i=0}^{m} 1^i\right)} \\ &= \frac{2}{\left(\sum_{i=0}^{m'} (2^i \cdot W) + \sum_{i=m'+1}^{m} (2^{m'} \cdot W) + (m+1)\right)} \\ &= \frac{2}{\left(\sum_{i=0}^{m'} (2^i \cdot W) + 2^{m'} \cdot W(m-m') + (m+1)\right)} \\ &= \frac{2}{W\left((1-2^{m'+1})/(1-2)\right) + 2^{m'} W(m-m') + (m+1)} \\ &= \frac{2}{W(2^{m'+1}-1) + 2^{m'} W(m-m') + (m+1)}. \end{aligned} \tag{A.11}$$

Therefore, when $p = 1$, (A.6) becomes

$$\begin{aligned} \tau(1) &= \sum_{i=0}^{m} b_{i,0} = \sum_{i=0}^{m} b_{0,0} = (m+1)b_{0,0} \\ &= \frac{2(m+1)}{W(2^{m'+1}-1) + 2^{m'} W(m-m') + (m+1)}. \end{aligned} \tag{A.12}$$

Function $\tau(p)$ is continuous and monotone decreasing in the range $p \in (0,1)$ since it decreases from $\tau(0) = 2/(W+1)$ to $\tau(1)$ given by (A.12). Uniqueness of the solution is proven by considering that $\tau(0) > \tau^*(0)$ and $\tau(1) < \tau^*(1)$.

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[6] Note that if $p = 1$ or $p = 1/2$, the expression for τ in (A.6) cannot be used.

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