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The IEEE 802.11 Distributed Coordination Function in Small-Scale Ad-Hoc Wireless LANs

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The IEEE 802.11 standards for wireless local area networks define how the stations of an ad-hoc wireless network coordinate in order to share the medium efficiently. This work investigates the performance of such a network by considering the two different access mechanisms proposed in these standards. The IEEE 802.11 access mechanisms are based on the carrier sense multiple access with collision avoidance (CSMA/CA) protocol using a binary slotted exponential backoff mechanism. The basic CSMA/CA mechanism uses an acknowledgment message at the end of each transmitted packet, whereas the request to send/clear to send (RTS/CTS) CSMA/CA mechanism also uses a RTS/CTS message exchange before transmitting a packet. In this work, we analyze these two access mechanisms in terms of throughput and delay. Extensive numerical results are presented to highlight the characteristics of each access mechanism and to define the dependence of each mechanism on the backoff procedure parameters.

KEY WORDS: IEEE 802.11 Wireless LANs; carrier sense multiple access; collision avoidance; distributed coordination function; performance evaluation.

1. INTRODUCTION

Wireless local area networks (WLANs) become more and more crucial in the proliferation of new services, and they attract the interest of researchers, system integrators, and computer manufacturers. By providing the ability to roam throughout a coverage area while remaining connected to traditional LAN-based services, wireless technology frees the users from the limitations of a wired network. The Institute of Electrical and Electronics Engineers (IEEE) has developed the 802.11 standards, which define the medium access and the physical layer functions of wireless LANs operating in an ISM band [1–3].

The IEEE 802.11 medium access control (MAC) layer specifies the basic access method and various mechanisms to provide contention and contention-free access control on a variety of transmission media. The IEEE 802.11 MAC may operate in one of two different modes. The first mode is based on the distributed coordination function (DCF) and is used for asynchronous data transmission, whereas the second mode uses the centralized point coordination function (PCF) for supporting time-bounded data transmissions. The DCF mode uses the carrier sense multiple access with collision avoidance (CSMA/CA) method, whereas the PCF mode uses a point coordinator to determine which station has the right to transmit during each contention-free period.

Regarding the performance analysis of the IEEE 802.11 protocol, there are some simulation [4] and analytical [5] studies for CSMA/CA protocols. Zahedi [6] provides an approximate model to compute the throughput of an access point (AP), taking into account the hidden terminals and the capture effect. Chhaya [7] calculates the throughput of CSMA/CA with a model that is space

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dependent, whereas Bianchi [8] presents an analysis to compute the saturation throughput of CSMA/CA protocol in the assumption of an ideal channel. Kim [9] considers the CSMA/CA as a hybrid protocol of slotted 1-persistent CSMA and p-persistent CSMA and focuses on the performance of APs in infrastructure networks in Rayleigh and shadow fading channels. In Ref. [10], Bianchi revises and extends Ref. [8], providing a model that accounts for all of the exponential backoff mechanism details in saturation conditions. Finally, Cali [11] suggests a backoff algorithm for p-persistent protocols, where the backoff interval is sampled from a geometric distribution with parameter p.

In ad-hoc wireless LANs, several mobile stations get together in a small area and establish peer-to-peer communications without requiring the coordination of any central station. The CSMA/CA protocol considers that a station with a pending packet transmits with probability p at the end of its backoff delay, whereas in p-persistent CSMA networks, a station transmits with probability p at any idle slot. This consideration differentiates the analysis of Ref. [9] from the analysis of Ref. [12]. The transmission probability p is not related with the backoff procedure in Ref. [9], and Kim varies this parameter to demonstrate its effect on the network throughput. Bianchi's contributions model the backoff mechanism and evaluate the protocol's throughput only at high-traffic conditions [8,10].

In our work, we modify the Markov model presented by Bianchi for calculating the transmission probability p of a station at any offered load. On the basis of the transmission probability p, we use the analytical approaches and assumptions of Refs. [9] and [12] to determine the CSMA/CA protocol throughput. In our analysis, we do not consider the capture effect which presents a better insight to the performance of the access mechanism. For the capture effect, a receiver may capture a frame in the presence of other overlapping or interfering packets. In a small-scale network, a receiver captures a frame only when a single station transmits. In our analysis, this assumption results in a different closed-form equation for the time spent in successful transmissions than that found in Ref. [9], affecting the throughput and delay performance. In addition, we estimate the delay performance of the protocol on the basis of an analysis that strongly depends on the backoff procedure and the modified Bianchi's Markov model and not on the renewal theory used in Ref. [9]. In our work, a thorough theoretical performance analysis of the CSMA/CA protocol is presented that includes closed form solutions for important parameters such as throughput and delay and extensive numerical and simulation results under a wide range of traffic conditions. We assumed that the network consists of a finite number of stations, the channel is error-free, no hidden terminal conditions are met, and all data packets are of constant length. At this point, we note that the assumption of an error-free wireless channel is unrealistic but is justified by the mathematical tractability of the problem. However, an error model is presented in the Appendix, which calculates the probability that a frame is received with errors caused by the wireless channel impairments. As in many performance analysis contributions, the traffic model was selected to obtain exact solutions to the presented mathematical analysis.

Section 2 gives a concise description of the IEEE 802.11 DCF function and presents the station model that is used in sections 3 and 4, where the throughput and delay characteristics of the CSMA/CA protocol are analyzed. Finally, section 5 presents various numerical results and discusses how the protocol's performance is affected by its parameters.

2. THE STATION MODEL

DCF is an operational method of ad-hoc wireless LANs using the IEEE 802.11 protocols. DCF is based on the CSMA/CA access method and a random backoff mechanism following each busy medium condition. According to the CSMA/CA method, a station having a packet to transmit must initially "listen" to the channel if another station is transmitting. If no transmission takes place for a distributed interframe space (DIFS) time interval, which is equal to the minimum duration of inactivity for considering the medium free, the transmission may proceed. If the medium is busy, the station has to wait until the end of the current transmission. It will then wait for an additional DIFS time, and then generate a random delay before transmitting its packet (backoff procedure). This delay is uniformly chosen in the range $(0, w - 1)$, which is called *contention window*. If there is no other transmission before this time period expires, the station transmits its packet. If there are transmissions from other stations during this time period, the station freezes its backoff counter until the end of each transmission and resumes its counting procedure after a DIFS time. The station transmits its packet whenever its counter becomes zero. At the first transmission attempt, $w = W_{min}$, where $W_{min} = W$ is the minimum size of the contention window. After each unsuccessful transmission, w is doubled up to a maximum value $W_{max} = 2^m W$, where m defines the maximum number of contention windows that a station may reach during the backoff procedure. The backoff counter uses as the time unit the duration a station needs to detect the transmission of a packet from any other station. This time interval is called slot time and accounts for the propagation delay, for the time needed to switch from receiving to transmitting state (*Rx_Tx_Turnaround_Time*), and for the time required to signal the MAC layer about the state of the channel (*busy detect time*).

Because collisions cannot be detected in a wireless CSMA/CA system, there are two mechanisms to determine the successful reception of a packet. According to the first mechanism, which is called basic CSMA/CA, the receiving station returns an ACK frame immediately following a successfully received packet. The ACK frame is transmitted after a short interframe space (SIFS), where $t_{SIFS} < t_{DIFS}$. The transmitter reschedules its packet transmission if it does not receive the ACK within a specified *ACK_Timeout*, or if it detects the transmission of a different packet. In the second mechanism, which is called request to send/clear to send (RTS/CTS) CSMA/CA, the station that has a packet to transmit sends a RTS frame and the receiving station responds with a CTS frame after SIFS time. The data packet is transmitted after the successful exchange of the RTS and CTS frames. The RTS frame is retransmitted in case the CTS frame is not received within a predetermined time interval.

To analyze the behavior of the CSMA/CA protocol, initially we have to calculate, under any offered load, the transmission probability of a station given that the station is in the backoff procedure. This transmission probability p is calculated using a Markov model, which is a modified version of the model used by Bianchi [8], [10], and depends on the number of network stations, the offered load, and the parameters (m, W) of the backoff procedure. Then, by adapting the throughput versus total offered load analysis, used for studying the throughput of CSMA protocols for a finite number of stations [12], to the CSMA/CA protocol employed by the IEEE 802.11 standard, we calculate the throughput of both access mechanisms for any offered load. Finally, using the throughput analysis and the station's Markov model, we estimate the mean packet delay.

We assume that the network consists of M contending stations. A station may reside at one of the following states: at an idle state, denoted by I, where the station has no packet to transmit; at a state where it has a packet to transmit but the backoff procedure is disabled, denoted by BD; and at the states where the station has a packet to transmit but the backoff procedure is active. The states of the backoff procedure are denoted by $B(i,k)$, where i takes the values $(0, 1, \ldots, m)$, indicates the backoff stage, and defines the size, W_i, of the current backoff contention window ($W_i = 2^i W_{\min}$), whereas k indicates the state of the backoff counter and its value can be $(0, 1, \ldots, W_i - 1)$ slot times. In our model, which is shown in Fig. 1, the time interval for a state transition can be either a slot time or the duration of a data frame transmission, depending on the current state of the station and the state of the medium. For example, if the station is at $B(0,2)$ state (which means that the backoff stage is 0 and the backoff counter is equal to 2), the station will decrement its backoff counter and will transit to $B(0,1)$ state after a slot time (when the medium is idle) or after a data frame transmission time (when the medium is busy). Furthermore when the station transmits a data packet [which happens at BD, $B(0,0), \ldots B(m,0)$ states], then the next state is reached after the data frame transmission time.

The above-described model is a discrete-time Markov chain under the assumptions that the probability p_c, that a transmitted packet collides is independent of the backoff procedure and that the arrival times at each empty station are independent and identically distributed (in our discrete-time model they follow a geometric distribution). Therefore, an empty station has an arrival with probability g at any time slot, or it has an arrival with probability g_p during a packet transmission time (the relation among g, g_p, and the total offered load G is quoted in section 3). The above-described assumptions become more accurate as W, M, and g become larger. In addition, we assume that there is no limit on re-entering the last backoff stage, as it is done in Refs. [8] and [10]. If the notation $\Pi\{A|B\}$ is used for the probability that a station transits from state B at state A, the transition probabilities of our station model are the following:

- The station remains at the idle state I if there is no packet arrival in any slot time.

$$\Pi\{I|I\} = 1 - g$$

- The station transmits its packet, when it is at the BD state or its backoff counter reaches zero, and enters state I if it detects a successful transmission of its current packet and has no packet arrival during the transmission of its packet.

$$\begin{aligned}\Pi\{I|BD\} &= \Pi\{I|B(0,0)\} \\ &= \Pi\{I|B(1,0)\} \\ &= \ldots \\ &= \Pi\{I|B(m,0)\} \\ &= (1 - p_c)(1 - g_p)\end{aligned}$$

- The station leaves state I when a packet arrives during a slot time, enters state BD and transmits its packet after sensing the channel idle for DIFS time without enabling the backoff procedure.

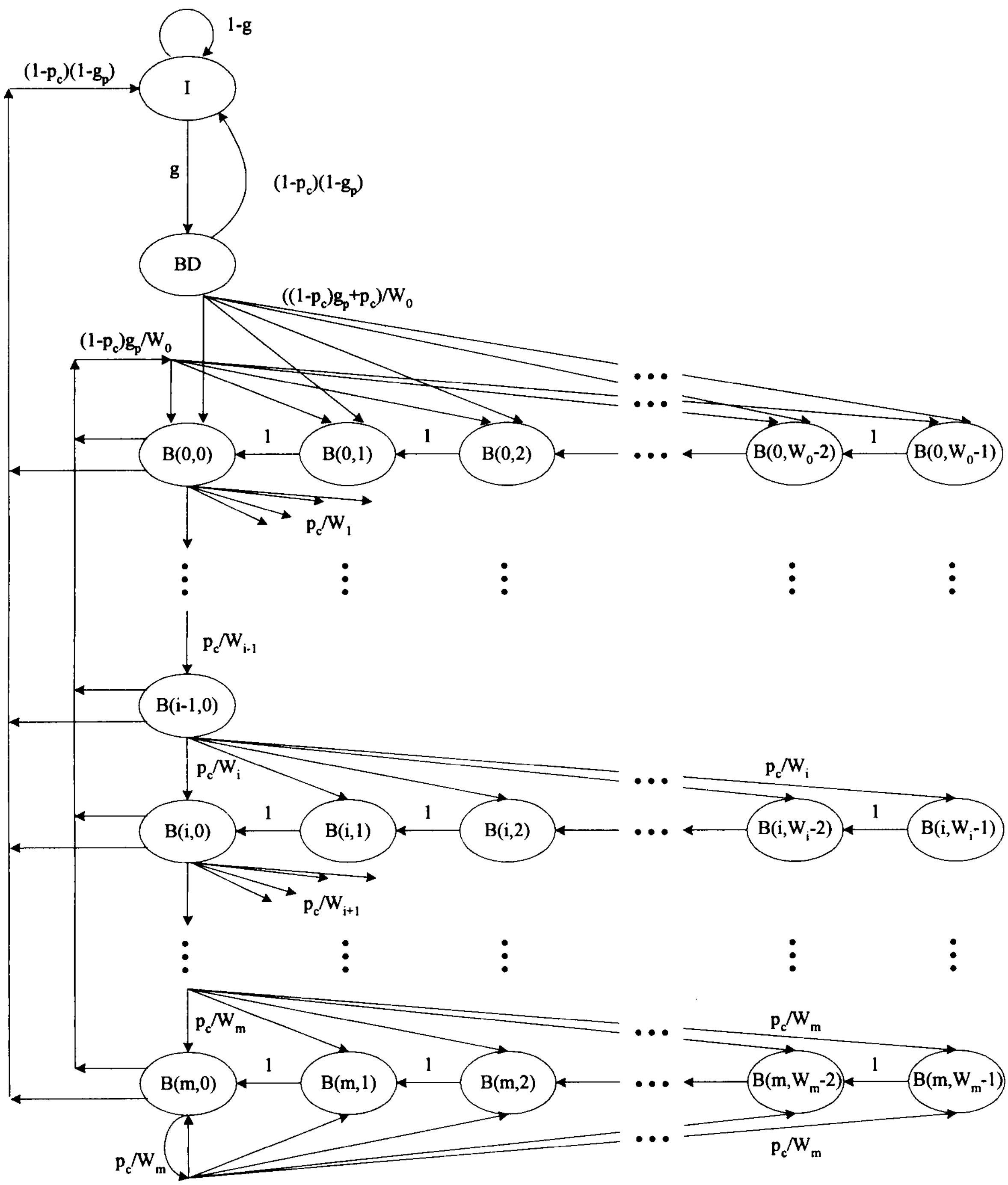


Fig. 1. The Markov model of a station.

$$\Pi\{BD|I\} = g$$

- The station transmits its packet without deferring and transits to any state of backoff stage 0 if its packet was unsuccessfully transmitted or it was successfully transmitted but the station received a new packet during the transmission of the previous one.

$$\Pi\{B(0,k)\,|\,BD\} = \frac{(1 - p_c)\, g_p + p_c}{W_0} \qquad 0 \le k \le W_0 - 1$$

- The backoff counter decrements at the beginning of each slot time.

$$\Pi\{B(i,k)|B(i,k+1)\} = 1 \qquad 0 \le k \le W_i - 2 \qquad 0 \le i \le m$$

- The station choices a backoff delay of stage 0, if its current packet was transmitted successfully and it has a new packet to transmit.

$$\Pi\{B(0,k)|B(i,0)\} = \frac{(1-p_c)g_p}{W_0} \qquad 0 \le k \le W_0 - 1 \qquad 0 \le i \le m$$

- The station choices a backoff delay of stage i after an unsuccessful transmission at stage $i - 1$.

$$\Pi\{B(i,k)|B(i-1,0)\} = \frac{p_c}{W_i} \qquad 0 \le k \le W_i - 1 \qquad 1 \le i \le m$$

- The station has reached the last backoff stage and remains at it after an unsuccessful transmission.

$$\Pi\{B(m,k)|B(m,0)\} = \frac{p_c}{W_m} \qquad 0 \le k \le W_m - 1$$

In steady state, the stationary probability of any state of the Markov chain, denoted by $\Pi\{A\}$, where A is any state, can be calculated by the following relations:

$$\Pi\{B(i,0)\} = p_c^i \Pi\{B(0,0)\} \qquad 0 \le k \le m - 1 \quad (1)$$

$$\Pi\{B(m,0)\} = \frac{p_c^m}{1-p_c}\Pi\{B(0,0)\} \quad (2)$$

$$\Pi\{B(i,k)\} = \frac{W_i - k}{W_i}\Pi\{B(i,0)\} \quad (3)$$

$$0 \le i \le \mathrm{m} \qquad 1 \le k \le W_i - 1$$

$$\Pi\{I\} = \frac{1-g_p}{g[g_p + (1-g_p)p_c]}\Pi\{B(0,0)\} \quad (4)$$

$$\Pi\{BD\} = \frac{1-g_p}{g_p + (1-g_p)p_c}\Pi\{B(0,0)\} \quad (5)$$

The probability conservation relation states that $\Pi\{I\} + \Pi\{BD\} + \sum_{i=0}^{m}\sum_{k=0}^{W_i-1}\Pi\{B(i,k)\} = 1$ and by using Eqs. (1)–(5), we have that

$$\frac{1-g_p}{g[g_p + (1-g_p)p_c]}\Pi\{B(0,0)\} + \frac{1-g_p}{g_p + (1-g_p)P_c}\Pi\{B(0,0)\} + \quad (6)$$

$$\sum_{i=0}^{m-1}\sum_{k=0}^{W_i-1}\frac{W_i - k}{W_i}p_c^i\Pi\{B(0,0) + \sum_{k=0}^{W_m-1}\frac{W_m-k}{W_m}\frac{p_c^m}{1-p_c}\Pi\{B(0,0) = 1$$

From Eq. (6), we calculate $\Pi\{B(0,0)\}$ as

$$\Pi\{B(0,0) = \frac{2g[g_p + (1-g_p)p_c](1-2p_c)(1-p_c)}{2(1-g_p)(1+g)(1-2p_c)(1-p_c) + g[g_p + (1-g_p)p_c]\{(1-2p_c)(W+1)p_cW[1-(2p_c)^m]\}} \quad (7)$$

Substituting Eq. (7) to Eqs. (1)–(5), we can compute the steady-state probabilities of our model, if the values of W, m, g, g_p, and p_c are known. The values of W, m, g, and g_p are known, but the probability p_c must be calculated. Let p_t be the probability that a station transmits during a slot time. A station transmits when its backoff counter is equal to zero; i.e., the station is at any one of the $B(i,0)$ states, or when it is at the BD state. Therefore,

$$p_t = \Pi\{BD\} + \sum_{i=0}^{m}\Pi\{B(i,0)\}$$
$$= \Pi\{BD\} + \sum_{i=0}^{m-1}\Pi\{B(i,0)\} + \Pi\{B(m,0)\}$$

Substituting Eqs. (1), (2), and (5) to the above equation and using Eq. (7), the following equation is derived:

$$p_t = \frac{2g(1-2p_c)}{2(1-g_p)(1+g)(1-2p_c)(1-p_c) + g[g_p + (1-g_p)p_c]\{(1-2p_c)(W+1) + p_cW[1-(2p_c)^m]\}} \quad (8)$$

A transmitted packet collides when two or more stations transmit during a slot time, so the probability p_c that a transmitted packet collides is given by

$$p_c = 1 - (1-p_t)^{M-1} \quad (9)$$

Substituting Eqs. (9) to (8), we obtain one equation with an unknown parameter, the probability p_t. Solving this equation for p_t, we can calculate the probability p_c and then the stationary probability distribution.

To visualize the effect of the total offered load G on the transmission probabilities $\Pi\{B(i,0)\}$ of the various backoff stages and on the transmission probability $\Pi\{BD\}$ of the state at which a station transmits without activating the backoff delay, we show in Fig. 2 the above-mentioned transmission probabilities of a station normalized to the total transmission probability p_t. The results reported in this figure are obtained by implementing the

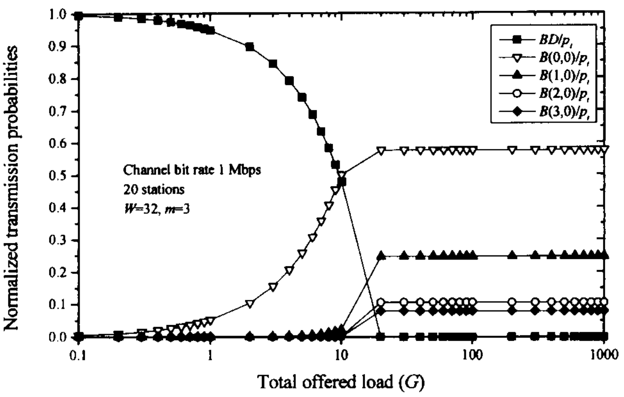


Fig. 2. The normalized transmission probabilities versus the offered load.

above analysis for a network of 20 stations that use a direct sequence spread spectrum DSSS physical medium at 1 Mbps. The parameters employed are summarized in Table I. When the offered load is low, a station transmits its packets immediately after sensing that the medium is idle for DIFS time and thus the transmission probability p_t mainly results from the *BD* state. At higher load conditions, the probability of collisions increases and each station enables the backoff delay, which raises the probability of the backoff states, especially of backoff stage 0, and decreases the *BD* state probability. Finally, at saturation conditions the backoff procedure is always employed and the *BD* state transmission probability becomes zero.

The transmission probability p that a station transmits given that it has activated the backoff procedure can be calculated by finding the probability p_b, that the station employs the backoff procedure and the probability p_{tb}, that the station transmits because its backoff delay expires, under any traffic conditions. The calculation of probability p is essential for the throughput and delay analysis presented in sections 3 and 4. From the above analysis, it is obvious that

$$p_b = \sum_{i=0}^{m} \sum_{k=0}^{W_i - 1} \Pi\{B(i,k)\} = \frac{(1 - 2p_c)(W + 1) + p_c W[1 - (2p_c)^m]}{2(1 - 2p_c)(1 - p_c)} \Pi\{B(0,0)\} \quad (10)$$

$$p_{tb} = \sum_{i=0}^{m} \Pi\{B(i,0)\} = \frac{1}{1 - p_c} \Pi\{B(0,0)\} \quad (11)$$

Because the transmission probability p is a conditional probability, it is valid that $p = p_{tb}/p_b$, and using Eqs. (10) and (11), we find that

$$p = \frac{2(1 - 2p_c)}{(1 - 2p_c)(W + 1) + p_c W[1 - (2p_c)^m]} \quad (12)$$

The dependence of transmission probability p on the total offered load and the number of stations is depicted in Fig. 3. We can see that the transmission probability of a station decreases as the offered load increases. The increase of offered load results in more collisions, thus a station with a collided packet retransmits by choosing a random delay of the next backoff stage. This procedure reduces the transmission probability, because the backoff window has been doubled. In saturation conditions, each station decreases its transmission probability, but ultimately this probability stabilizes to a saturation value. Furthermore, networks with more stations result in lower transmission probabilities.

3. THROUGHPUT ANALYSIS

Performance of CSMA protocols has been investigated in depth in the literature. In most studies an infinite

Table I. Parameters Used in the DSSS Physical Medium

Attribute	Value, channel bit rate 1 Mbps
MAC header	34 octets
Physical (PHY) header	24 octets
Packet payload	1023 octets
ACK, CTS	14 octets + PHY header
RTS	20 octets + PHY header
SIFS	10 μs
DIFS	50 μs
Slot time	20 μs
Propagation delay	1 μs
CW_{min}	32
CW_{max}	1024

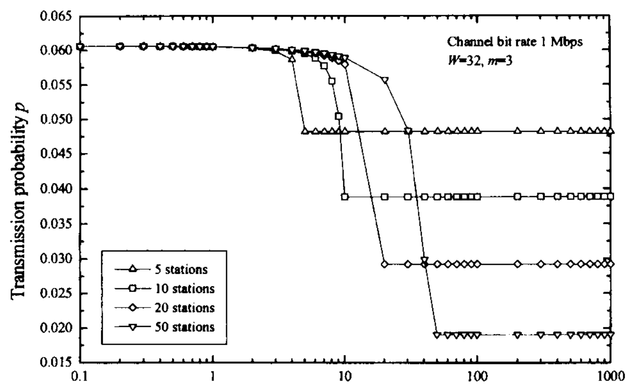


Fig. 3. The transmission probability p of a station with active backoff procedure.

number of stations was considered for forming the collective channel traffic as a Poisson process. This approach is unsuitable for a LAN with a relatively small number of stations. For a finite number of stations another approach is suggested by Ref. [12]. A station is assumed to have idle periods (no packets) that are independent and geometrically distributed (in slotted CSMA protocols). Therefore, superimposing all users' idle periods results to a geometric distribution for the network's idle periods and the channel has the memoryless property [13]. A different assumption is adopted in Refs. [8], [10], and [11], in which the finite number of stations operates in asymptotic conditions (a packet should always be ready for transmission). This article adapts the analytical approach of Ref. [12] and estimates the throughput of the CSMA/CA protocol for various traffic conditions.

We assume that the time is slotted with slot size α, which is the backoff slot time per data frame transmission time. Throughout this analysis, as the unit time is considered the data frame transmission time and all other time intervals are normalized to this time unit. For example, by considering that constant-length packets of 250 octets (payload plus MAC and physical (PHY) headers) are transmitted at 1 Mbps, the unit time corresponds to 2 msec and all other time intervals are normalized according to this value. In this case, the normalized value of the slot size α is equal to 0.01 (20 μsec/2 msec). In dealing with the case of a finite population (e.g., M stations), we assume that the system state alternates between idle periods (I), in which no station has packets to transmit; and busy periods (B), in which at least one station transmits a packet. The idle periods are assumed to be independent and geometrically distributed. Let U be the time spent in useful transmission during a regeneration cycle. If $\overline{X}$ denotes the expectation of a random variable X, then according to Ref. [12], the system throughput S is defined as $S = \overline{U}/(\overline{B} + \overline{I})$. Because the useful transmission time is the time required to transmit a frame's payload, the exact system throughput is given by

$$S = \frac{\xi \overline{U}}{\overline{B} + \overline{I}} \tag{13}$$

where ξ is the ratio of the payload transmission time to the total frame transmission time, which also includes the headers and the frame trailer.

Although the IEEE 802.11 MAC protocol supports the basic CSMA/CA and the RTS/CTS CSMA/CA, we consider another transmission mechanism as a reference to evaluate the other two methods. In the so-called CSMA/CA without acknowledgment, the transmitter sends its data packet and does not wait for acknowledgement. The CSMA/CA without acknowledgment is summarized in Fig. 4. When a station generates a packet during an idle period I or during the backoff time of other stations, the backoff mechanism is not activated and the station transmits its packet. In this case, its transmission probability depends on the probability g to generate a packet during each slot. When a station generates a packet during the busy period B, the backoff procedure is activated and each ready station transmits with probability equal to the transmission probability p that was derived in section 2.

In addition, we consider that all packets that arrive during any ongoing transmission are buffered until the channel detects a new transmission, and then they are rescheduled. Therefore, during a slot a station generates a packet with probability g, which includes new arrivals and rescheduled packets. If G is the offered load of all stations (in units of data packets per data frame transmission time), then $g = \min(1, \alpha G/M)$[12] and the probability g_p that a station has an arrival during a data frame transmission time is given by $g_p = \min(1, G/M)$.

We use the methodology of Refs. [9] and [12] to derive the basic equations. According to Fig. 4, the busy period is divided into several sub-busy periods. Each j sub-busy period is denoted by $B^{(j)}$ and is composed of the time interval DIFS, the transmission delay $D^{(j)}$, which is due to the backoff procedure, and the transmission time $T^{(j)}$, which includes the propagation delay τ. The first sub-busy period $B^{(1)}$ consists of the transmission delay $D^{(1)}$, which is a DIFS delay and the transmission time $T^{(1)}$. For the CSMA/CA without acknowledgment, the transmission time $T^{(j)}$ is equal to $1 + \tau$ in all cases, even if the transmitted packet collides. A busy period continues if there is at least one station with a pending frame during the last transmission period or during the last DIFS time interval. We denote by TP the sum of the last transmission period and the last DIFS, thus $TP = 1 + \tau + f$.

According to Ref. [9], the mean values of the idle period I, the transmission delay $D^{(j)}$ caused by the backoff procedure, and the duration of the busy periods B are given by the following equations:

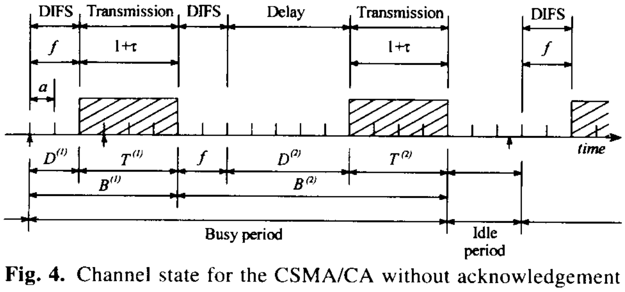


Fig. 4. Channel state for the CSMA/CA without acknowledgement mechanism.

$$\bar{I} = \frac{\alpha}{[1 - (1 - g)^M]} \tag{14}$$

$$\overline{D^{(1)}} = f \tag{15}$$

$$\overline{D^{(j)}} = \frac{\alpha}{1 - (1 - g)^{(TP/\alpha)M}} \left(\sum_{k=1}^{\infty} \{(1 - p)^k - (1 - g)^{TP/\alpha} [(1 - p)^k - (1 - g)^k]\}^M - (1 - g)^{(TP/\alpha)M} \sum_{k=1}^{\infty} (1 - g)^{kM} \right)$$

$$j = 2, 3, \cdots \tag{16}$$

$$\bar{B} = f + 1 + \tau + \frac{1}{(1 - g)^{(TP/\alpha)M}} \{(f + 1 + \tau) [1 - (1 - g)^{(TP/\alpha)M}] + \alpha \sum_{k=1}^{\infty} \{(1 - p)^k - (1 - g)^{(TP/\alpha)}[(1 - p)^k - (1 - g)^k]\}^M - \alpha(1 - g)^{(TP/\alpha)M} \sum_{k=1}^{\infty} (1 - g)^{kM}\} \tag{17}$$

Finally, we calculate the expected value of the useful transmission period U that is different from that found in Ref. [9], because we omit the capture effect:

$$\bar{U} = \frac{1}{1 - (1 - g)^M} Mg(1 - g)^{M-1} + \left[\frac{1}{(1 - g)^{(TP/\alpha)M}} - 1\right] \sum_{n=1}^{M} \Big\{ np(1 - p)^{n-1} + [np(1 - p)^{n-1} + (M - n)g(1 - g)^{M-n-1} - n(M - n)pg(1 - p)^{n-1}(1 - g)^{M-n-1}] \cdot \frac{(1 - p)^n(1 - g)^{M-n}}{1 - (1 - p)^n(1 - g)^{M-n}} \Big\}$$

$$\left\{ \frac{\binom{M}{n}[1 - (1 - g)^{TP/\alpha}]^n(1 - g)^{(TP/\alpha)(M-n)}}{-(1 - g)^{(TP/\alpha)M}} \right\}$$

Substituting Eqs. (17) and (18) into Eq. (13), we get the channel throughput of the unacknowledged CSMA/CA. The calculation of the channel throughput of the Basic and RTS/CTS CSMA/CA protocols is based on the previous analysis. These access mechanisms differ from the CSMA/CA without acknowledgment in the time length of a successful transmission and a nonsuccessful transmission. We define TP_S as the sum of a successful transmission time plus DIFS time, and TP_F as the sum of a nonsuccessful transmission time plus DIFS time. We assume that the jth transmission of the busy period is X slots, so the length of the $(j+1)$th transmission depends on whether the jth transmission was successful or not. Let $B(X)$ be the mean duration of the busy period following the frame accumulation time of X slots, and let $U(X)$ be the mean useful transmission time during the same busy period, then we can calculate $B(X)$ and $U(X)$ by using the following recursive relations [12], when $X = 1$, because for $j \geq 1$ the busy and the useful transmission periods depend on the number of packet arrivals during the last slot of the idle period:

$$B(X) = d(X) + \{TP_S + [1 - (1 - g)^{(TP_S/\alpha)}]B(TP_S/\alpha)\}u(X) + \{TP_F + [1 - (1 - g)^{(TP_F/\alpha)}]B(TP_F/\alpha)\}[1 - u(X)] \tag{19}$$

$$U(X) = \{1 + [1 - (1 - g)^{(TP_S/\alpha)}]U(TP_S/\alpha)\}u(X) + \{[1 - (1 - g)^{(TP_F/\alpha)}]U(TP_F/\alpha)\}[1 - u(X)] \tag{20}$$

where $d(X)$ and $u(X)$ are obtained by Eqs. (16) and (18), respectively. Therefore, the throughput S is given by

$$S = \frac{\xi U(1)}{B(1) + \dfrac{\alpha}{[1 - (1 - g)^M]}} \tag{21}$$

The duration of successful and nonsuccessful transmission plus the DIFS interval of the Basic CSMA/CA and the RTS/CTS CSMA/CA are given respectively by

$$TP_S^{\text{Basic}} = 1 + \beta + \delta + 2\tau + f$$

$$\text{and } TP_F^{\text{Basic}} = 1 + \tau + f$$

$$TP_S^{\text{RTS/CTS}} = 1 + \gamma + \theta + \delta + 3\beta + 4\tau + f$$

$$\text{and } TP_F^{\text{RTS/CTS}} = \gamma + \tau + f$$

where β is the normalized length of SIFS, δ is the normalized length of an ACK frame, γ is the normalized length of an RTS frame, and θ is the normalized length of a CTS frame.

In addition to our mathematical approach, we did some simulations for a system of 20 stations employing the parameters reported in Table I. The results obtained by our mathematical and simulation model are depicted in Fig. 5. As can be seen, our analytical approach is extremely accurate at high offered load, where the graphs of the analytical and simulation results coincide, because the discrete-time Markov chain model used for depicting the backoff procedure followed by each station assumes that the packet of each station collides with the same probability p_c, independently of the backoff procedure. This assumption gives more accurate results at high

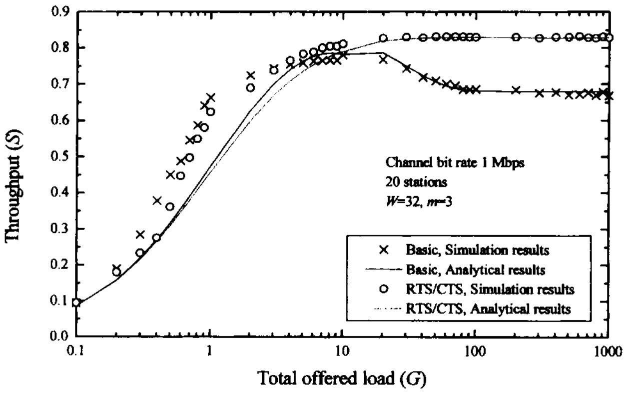


Fig. 5. Throughput of both CSMA/CA access mechanisms.

offered load. In addition, at low-traffic conditions, the Basic CSMA/CA mechanism has slightly better performance than the RTS/CTS. This is because the probability of collision is small when the offered load is low. However, at high-traffic conditions, the RTS/CTS mechanism provides significantly better throughput in comparison to the Basic mechanism. The enhanced performance of the RTS/CTS CSMA/CA at high-load conditions is due to the fact that this access mechanism wastes less bandwidth during a collision (the RTS/CTS packets are much shorter than the data packets).

4. DELAY ANALYSIS

Packet delay is defined as the time elapsed between the generation of a packet and its successful reception. The backoff algorithm and the number of retransmissions mainly affect the average value of normalized packet delay $\overline{L}$. If a packet was received successfully the first time it was transmitted, then the delay depends on the packet transmission time T and the deferral delay, which is defined as the time elapsed from the moment a station starts sensing the medium to the moment the station accesses the medium. The mean value of the deferral delay is denoted by $\overline{R}$.

For calculating the average packet delay for the Basic and the RTS/CTS CSMA/CA, we define T_S as the duration of a successful transmission period and T_F as the duration of a nonsuccessful transmission period. The durations of successful and nonsuccessful transmission for the ACK CSMA/CA and RTS/CTS CSMA/CA are given by

$$T_S^{\text{Basic}} = 1 + \beta + \delta + 2\tau \text{ and } T_F^{\text{Basic}} = 1 + \tau$$

$$T_S^{\text{RTS/CTS}} = 1 + \gamma + \theta + \delta + 3\beta + 4\tau$$

$$\text{and } T_F^{\text{RTS/CTS}} = \gamma + \tau$$

where TP_S is the sum of T_S and DIFS, and TP_F is the sum of T_F and DIFS.

The mean value of the deferral delay is calculated by considering the following conditions:

- A station having a pending packet, while all other stations have no packets to transmit, senses the medium for being idle for DIFS and then transmits its packet. The probability of this event is $\frac{\overline{I}}{\overline{B} + \overline{I}}$.
- A station having a pending packet, while all other nonempty stations have entered the backoff procedure, detects the medium to be idle for DIFS and then transmits its packet. The probability of this event is $\frac{\overline{D}}{\overline{B} + \overline{I}}$.
- A station having a pending packet detects that another station is transmitting and defers its transmission. The station transmits its packet after a random delay according to the backoff procedure. The mean value of this delay, denoted by $\overline{BD}$, depends on the value of the backoff counter and the duration the counter freezes when the station detects transmissions from other stations. The probability of this event is $\frac{\overline{B} - \overline{D}}{\overline{B} + \overline{I}}$.

Thus, the time $\overline{R}$ *is calculated by*

$$\overline{R} = \frac{\overline{I}}{\overline{B} + \overline{I}} f + \frac{\overline{D}}{\overline{B} + \overline{I}} f + \frac{\overline{B} - \overline{D}}{\overline{B} + \overline{I}} \overline{BD} \quad (22)$$

To calculate the $\overline{BD}$ delay, we have to find the probability p_s that a transmission occurring on the channel is successful. Probability p_S is given by

$$p_S = \frac{TP_S}{TP_S + TP_F} u(TP_S) + \frac{TP_F}{TP_S + TP_F} u(TP_F) \quad (23)$$

where $u(X)$ is obtained by Eq. (18). If $\overline{\Psi}$ denotes the mean idle time before a transmission proceeds, then

$$\overline{\Psi} = p_S d(TP_S) + (1 - p_S) d(TP_F) \quad (24)$$

where $d(X)$ is found by Eq. (16). Given that the backoff procedure is active, if the counter of a station is at state $B(i,k)$, an interval of k slot times is needed for the counter to reach state 0, without taking into account the time when the counter is stopped. This time interval is denoted by the random variable C (this variable is measured in number of slots and is multiplied by the normalized slot time duration α to express it with the same time units as the other time intervals) and its average is given by

$$\bar{C} = \frac{\alpha \sum_{i=0}^{m} \sum_{k=1}^{W_i - 1} k\Pi\{B(i,k)\}}{p_b}$$

On the basis of Eqs. (1), (2), (3), and (10), we finally get that

$$\bar{C} = \alpha \frac{1\{W^2[1 - p_c - 3p_c(4p_c)^m] - (1 - 4p_c)\}(1 - 2p_c)}{3(1 - 4p_c)\{(1 - 2p_c)(W + 1) + p_c W[1 - (2p_c)^m]\}} \tag{25}$$

We denote by F the time that the counter of a station freezes. When the counter freezes, it remains stopped for the duration of a frame transmission. This duration depends on the transmission success. Therefore, to calculate the average time $\bar{F}$ that the counter remains stopped, we have to find $\overline{N_{Fr}}$, the average number of times that a station detects transmissions from other stations before its counter reaches state 0, which is given by

$$\overline{N_{Fr}} = \frac{\bar{C}}{\bar{\Psi}} - 1 \tag{26}$$

Therefore, the mean idle time before a transmission proceeds is given by

$$\bar{F} = \overline{N_{Fr}}[p_S T_S + (1 - p_S)T_F] \tag{27}$$

The backoff delay $\overline{BD}$ can be calculated by using the following relationship:

$$\overline{BD} = \bar{C} + \overline{N_{Fr}}[p_S T_S + (1 - p_S)T_F] \tag{28}$$

and Eqs. (25), (26), and (27). Furthermore, delay $\bar{D}$ is equal to $D(1)$, which can be obtained by using the following recursive form:

$$D(X) = f + [1 - (1 - g)^{(TP_S/\alpha)}]D(TP_S)u(X) + [1 - (1 - g)^{(TP_F/\alpha)}]D(TP_F)[1 - u(X)] \tag{29}$$

$D(TP_S)$ and $D(TP_F)$ can be calculated by substituting $X = TP_S$ and $X = TP_F$ in Eq. (29), and therefore, we obtain two equations with two unknowns, $D(TP_S)$ and $D(TP_F)$. Thus, $D(1)$ is calculated by

$$\bar{D} = D(1) = f + [1 - (1 - g)^{(TP_S/\alpha)}] D(TP_S)u(1) + [1 - (1 - g)^{(TP_F/\alpha)}]D(TP_F)[1 - u(1)] \tag{30}$$

Substituting Eqs. (23), (28), and (30) in Eq. (22), the mean value of the medium access time $\bar{R}$ can be obtained. Finally, the mean number $\overline{N_{col}}$ of collisions is

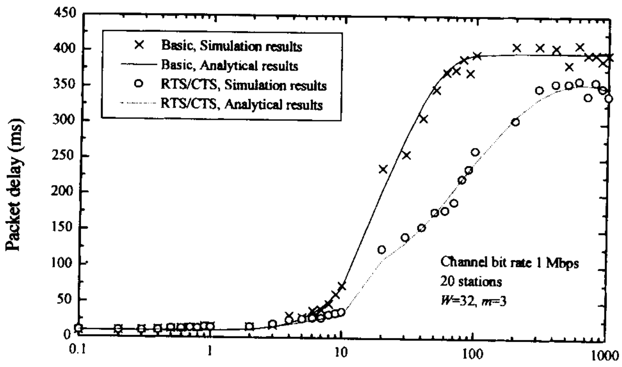


Fig. 6. Packet delay of both CSMA/CA access mechanisms.

calculated by $\overline{N_{col}} = 1/p_S - 1$, and the packet delay [9] is found by

$$\bar{L} = \left(\frac{1}{p_S} - 1\right)(T_F + \bar{Y} + \bar{R}) + (T_S + \bar{R}) \tag{31}$$

where Y is a random variable that represents the time a station waits until a packet collision has been detected and is equals to

$$\bar{Y} = \begin{cases} \text{SIFS + ACK\_timeout,} & \text{Basic CSMA/CA} \\ \text{SIFS + CTS\_timeout,} & \text{RTS/CTS CSMA/CA} \end{cases}$$

The analytical and simulation results derived for the same network are almost identical, as shown in Fig. 6. The RTS/CTS CSMA/CA mechanism provides lower delays than the BasicCSMA/CA at high load. This improved performance is due to the reduced time required for packet retransmission. In addition. Fig. 7 depicts the mean deferral delay $\bar{R}$ of a station, the mean idle time $\bar{\Psi}$ before a transmission proceeds, and the mean wasted time per successful packet transmission caused by collisions (calculated by multiplying the mean number of collisions

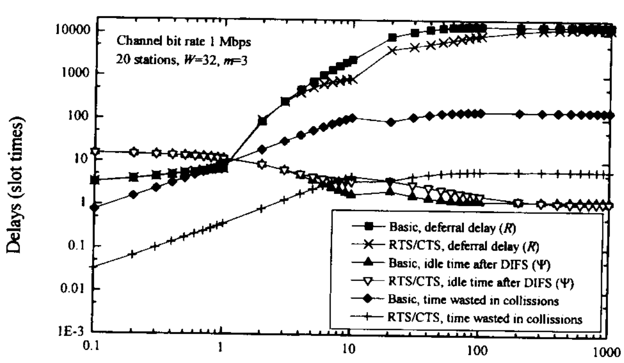


Fig. 7. The packet delay components versus offered load.

N_{col} by the duration of a collision T_F) versus the offered load for both access mechanisms. The deferral delay forms the largest portion of the packet delay, increases rapidly as the load increases, and it is stabilized to a specific value when the offered load saturates the network. As was expected, the deferral delay of the RTS/CTS scheme is lower than the deferral delay of the Basic scheme. The mean idle time before a transmission proceeds is almost equal to the mean initial contention window (about 15 slot times for $W = 32$) in low-load conditions, decreases at higher load, and finally stabilizes at about 1 slot time, because in these conditions there is always a station with its backoff delay expired after DIFS time. The idle time before a transmission proceeds does not differ in the two access mechanisms. Finally, the time wasted on collisions per successful packet transmission is very low at low-traffic conditions, increases as the load increases, and finally it also achieves its maximum value. The Basic CSMA/CA wastes more time in collisions than the RTS/CTS, because a collided packet in the Basic scheme has longer duration than a collided packet in RTS/CTS.

5. PERFORMANCE EVALUATION IN HEAVY-TRAFFIC CONDITIONS

In this section, we study the CSMA/CA behavior in heavy-traffic conditions, which is of interest to the network designers. The following results have been obtained by our analytical approach assuming channel bit rates of 5.5 and 11 Mbps, the high data rate extension of the IEEE 802.11 standard [3]. For IEEE 802.11 networks with DSSS PHY medium at 5.5 and 11 Mbps, the PHY header (24 octets) is transmitted at 1 Mbps, whereas the MAC header and the payload are transmitted at 5.5 and 11 Mbps, respectively. This results in greater overhead and reduces the network throughput. In the IEEE802.11b specification [3], an optional short PHY header (15 octets) has been defined with much shorter transmission duration.

In heavy-traffic conditions, each station always has a pocket available for transmission. Therefore, the probability g_p that a packet is generated during a packet transmission time equals to 1 and Eq. (8) is simplified to

$$p_t = \frac{2(1 - 2p_c)}{(1 - 2p_c)(W + 1) + p_c W[1 - (2p_c)^m]} \quad (32)$$

The above equation is the same with the one found by Bianchi in Refs. [8] and [10]. In Fig. 8, we present the throughput results obtained by our analysis for various

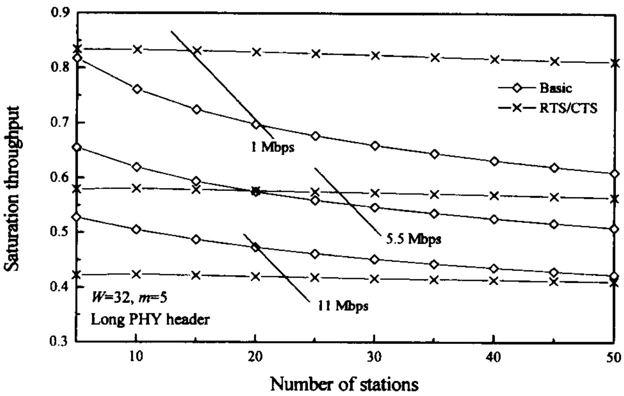


Fig. 8. Comparative saturation throughput results.

channel bit rates. The throughput of the Basic CSMA/CA decreases for a large number of stations, whereas the RTS/CTS mechanism appears more robust because of less bandwidth is occupied by this mechanism during a collision. We can also see how the throughput of the two CSMA/CA mechanisms is affected by the channel bit rate. Note that as the channel bit rate increases, the throughput decreases. This is because the time intervals DIFS, SIFS, and slot time are constant, but the frame transmission time decreases as the channel bit rate increases. Thus, the time spent on DIFS, SIFS, and backoff delay increases in relation to the frame transmission time, causing the throughput degradation. Another important observation is that the Basic access mechanism is more effective than the RTS/CTS as the channel bit rate increases for the constant frame payload of 1023 octets we have considered. This is due to the transmission duration of PHY header (transmitted at 1 Mbps) that is comparable with the transmission duration of MAC header and frame payload (transmitted at 5.5 or 11 Mbps) in the high-rate extension of the IEEE 802.11 standard and the transmission of the RTS and CTS frames involved with the RTS/CTS mechanism. In the assumption of fixed-frame payload size, the frame payload and the number of stations define the threshold where the RTS/CTS scheme becomes more advantageous than the Basic scheme.

The effect of packet size on the throughput of the two access mechanisms for channel bit rates 1, 5.5, and 11 Mbps is illustrated in Fig. 9, where the intersection of the graphs representing the Basic and RTS/CTS mechanisms at the respective channel bit rate defines the threshold at which it is advantageous to switch to the RTS/CTS mechanism. On the other hand, the use of the optional short PHY header, which results in a transmission time that is half of the long PHY header's transmission time,

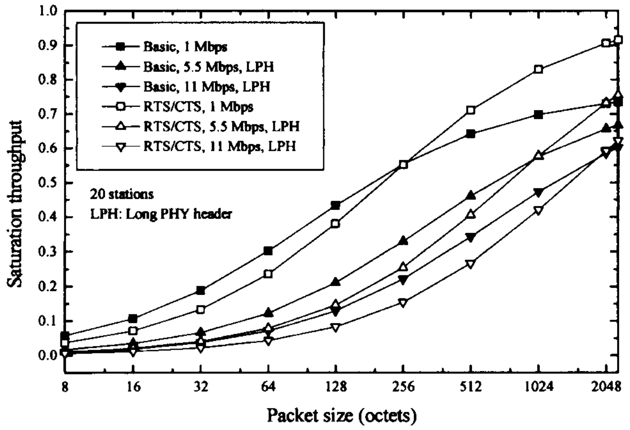


Fig. 9. The effect of packet size on the saturation throughput.

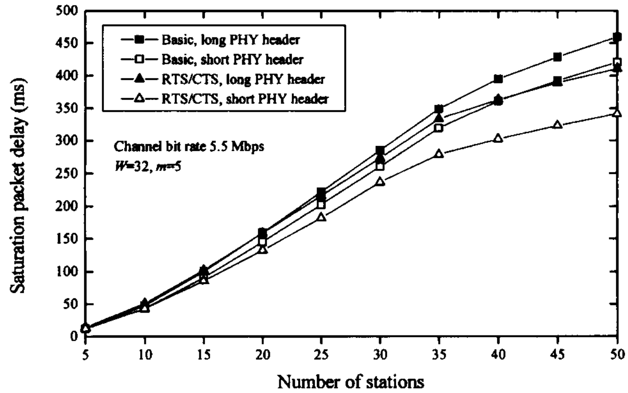


Fig. 11. The effect of the short PHY header on the saturation packet delay.

increases significantly the throughput of the protocol and reduces the packet delay, according to Figs. 10 and 11.

Figure 12 shows that the choice of the suitable initial size of the backoff window in relation to the number of stations, improves the saturation throughput and reduces the packet delay when the Basic CSMA/CA mechanism is used. For example, a high W value increases the throughput of a network with 50 contending stations, but drastically penalizes the throughput in the case of a small number of contending stations. Furthermore, the packet delay decreases as the W value or the number of contending stations increases, because an initial large contention window reduces the probability of collisions. For the same initial contention window value, the packet delay increases when the number of stations becomes smaller, because the probability of collisions also decreases. On the other hand, according to Fig. 13, the throughput of the RTS/CTS CSMA/CA appears to be almost insensitive to the network size for $W \leq 64$, whereas it decreases for $W > 64$ as the network size decreases, and thus the packet delay strongly depends on the initial size of the backoff window and the network size.

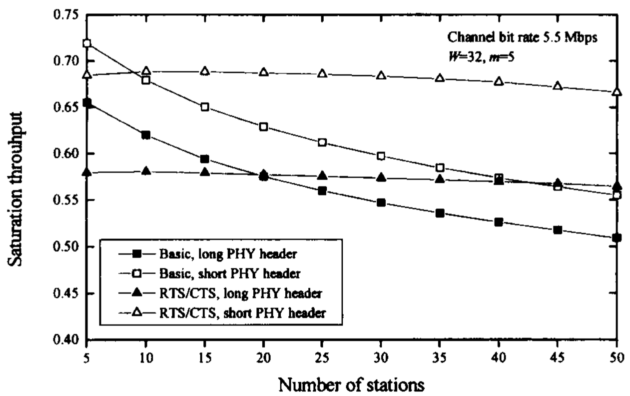


Fig. 10. The effect of the short PHY header on the saturation throughput.

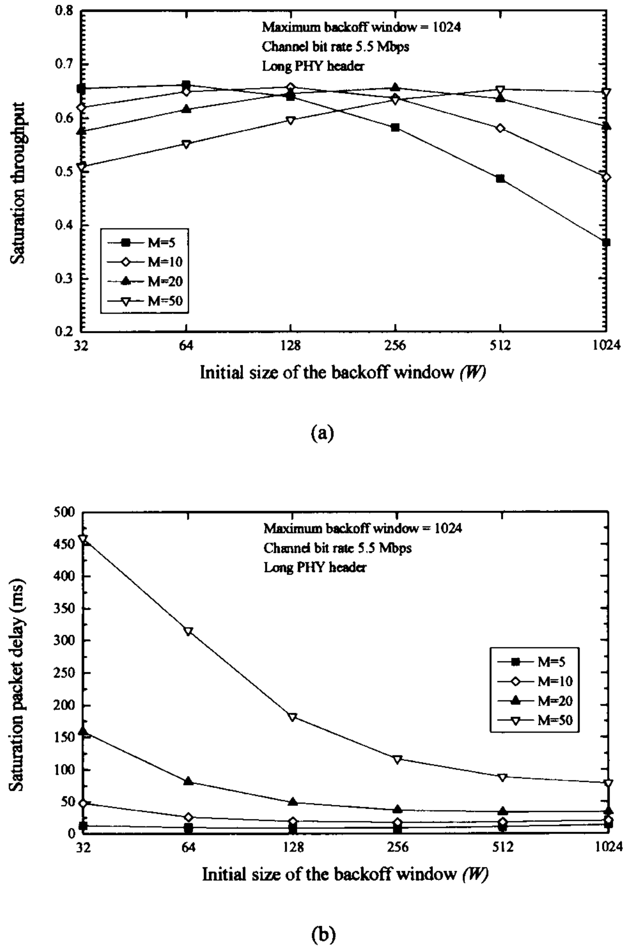
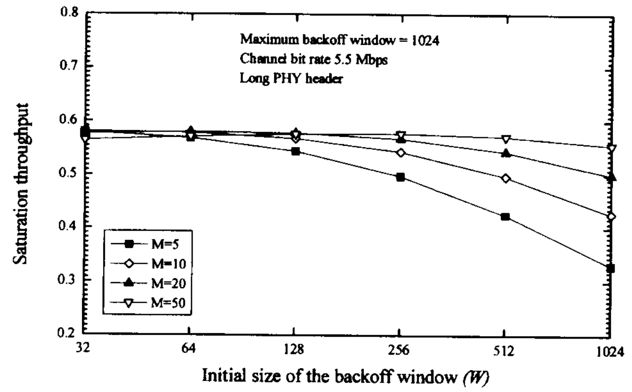
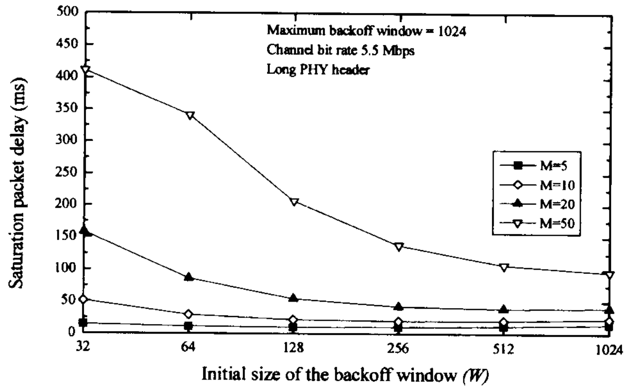


Fig. 12. The effect of the backoff window initial size on the Basic CSMA/CA performance.



(a)



(b)

Fig. 13. The effect of the backoff window initial size on the RTS/CTS CSMA/CA performance.

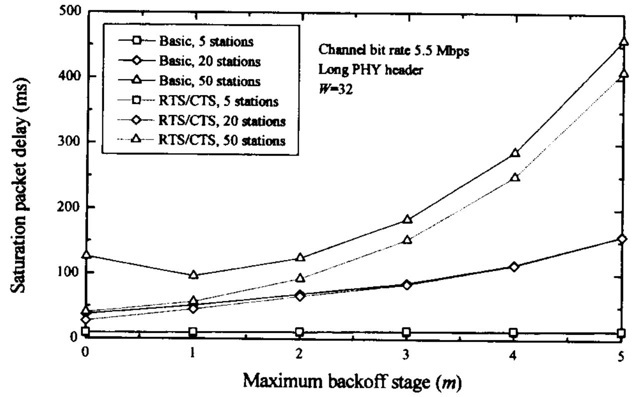


Fig. 15. Packet delay versus the maximum number of backoff stages.

The throughput dependence of both access mechanisms to the maximum number m of the backoff stages is depicted in Fig. 14. We notice that the choice of m does not practically affect the system throughput, as long as $m > 4$, except in the case where the network size is large enough and the Basic mechanism is used.

Figure 15 shows the effect of the maximum number of backoff stages on the packet delay. The packet delay of both access mechanisms increases as the value of m or the number of contending stations increases, since the deferral delay is mainly affected. Finally, Fig. 16 shows the increase of the throughput of the CSMA/CA protocol as the parameter m increases. The average number of transmissions per packet decreases for larger values of m even if the network size is large. The average number of transmissions per packet is obtained by adding its successful transmission to the average number of packet retransmissions, $\overline{N_{col}}$.

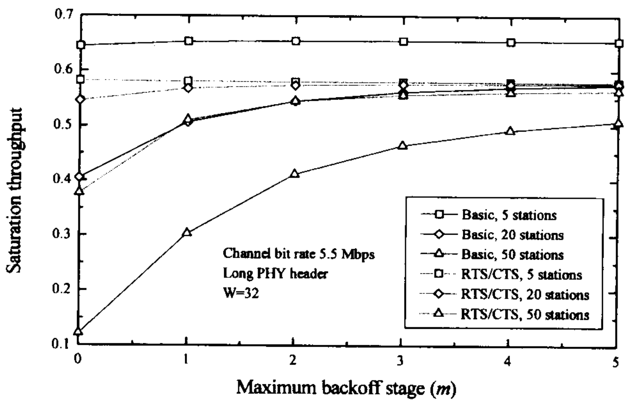


Fig. 14. Throughput versus the maximum number of backoff stages.

6. CONCLUSIONS

In this article, we analyzed and compared the Basic and the RTS/CTS access mechanisms of the CSMA/CA

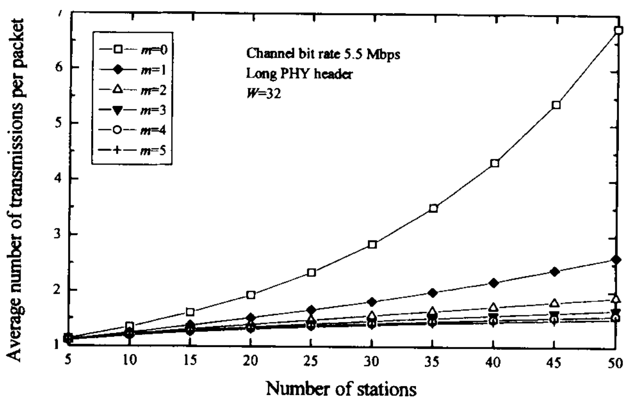


Fig. 16. The average number of transmission attempts per transmitted packet versus the network size and various values of the maximum backoff stage.

protocol considering an error-free channel, a finite number of stations, and constant-length data packets. We obtained closed-form solutions of the throughput and the delay of the CSMA/CA protocol, and we presented extensive numerical results comparing the performance of the two access mechanisms employed by the protocol. The Basic scheme has low throughput and large delays at high load, and depends strongly on the number of stations and the backoff procedure parameters (W, m). Conversely, the RTS/CTS mechanism provides higher throughput and lower delays when the system is highly loaded and the packet size increases, especially at 5.5 and 11 Mbps. Furthermore, the RTS/CTS mechanism is more robust to variations in the number of stations and the backoff procedure parameters. This suggests that the RTS/CTS mechanism should be employed when the traffic is high and the network or the packet size is large enough. The Basic mechanism should be employed when the traffic is low and the number of contending stations or the packet size is small.

APPENDIX

In this appendix, a simple burst error model is introduced to study the frame loss probability caused by the wireless medium impairments. This model represents the fading conditions of the wireless medium and is based on a two-state discrete time Markov chain [14]. The two states are called G (good) and B (bad) and indicate that the medium operates either at a low-bit error rate (denoted by BER_G) or at fading conditions with a higher error rate (denoted by BER_G) or at fading conditions with a higher error rate (denoted by BER_B). State G changes to state B with transition rate x, whereas state B changes to state G with transition rate y. Let p_G and p_B denote the probabilities that the channel is in the G or the B state, respectively. Then,

$$p_G = \frac{y}{x+y} \quad p_B = \frac{x}{x+y} \tag{33}$$

During the frame transmission time T, the channel is in one of the following modes of operation:

Mode 1: Always in G state with probability:

$$P_{\text{Case1}} = p_G P(\text{G} > T) = \frac{y}{x+y} e^{-xT} \tag{34}$$

Mode 2: Always in B state with probability:

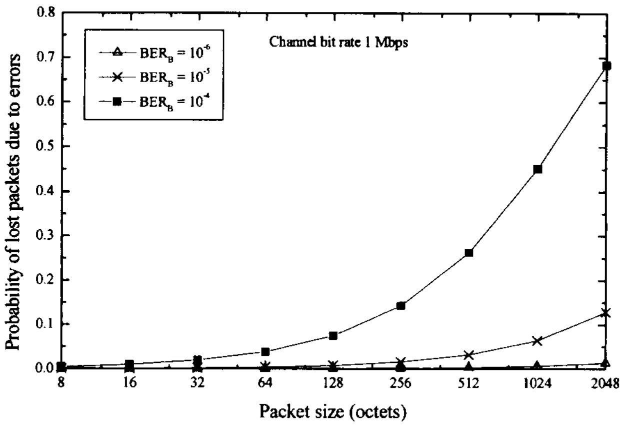


Fig. 17. The effect of wireless medium on the probability of lost packets.

$$P_{\text{Case2}} = p_B P(\text{B} > T) = \frac{y}{x+y} e^{-yT} \tag{35}$$

Mode 3: Undergoes one or more transitions between G and B states with probability:

$$P_{\text{Case3}} = 1 - P_{\text{Case1}} - P_{\text{Case2}} \tag{36}$$

Therefore, the probabilities that a frame of TR_c bits is received with errors are given by

$$P_{\text{err\_Case1}} = 1 - (1 - BER_G)^{TRc} \tag{37}$$

$$P_{\text{err\_Case2}} = 1 - (1 - BER_B)^{TRc} \tag{38}$$

$$P_{\text{err\_Case3}} \leq P_{\text{err\_Case2}} \tag{39}$$

where R_c is the channel bit rate. Using Eqs. (34)–(39), we can approximate the frame error probability using

$$P_{\text{err}} \leq P_{\text{Case1}} P_{\text{err\_Case1}} + P_{\text{Case2}} P_{\text{err\_Case2}} + P_{\text{Case3}} P_{\text{err\_Case2}} \tag{40}$$

Figure 17 shows the packet error probability for different channel conditions and packet lengths. The results were obtained using channel bit rate = 1 Mbps, $BER_G = 10^{-10}$, $BER_B = 10^{-6}$, 10^{-5}, and 10^{-4}, $x = 30$ s^{-1}, and $y = 10$ s^{-1}. The probability of lost packets increases as the payload increases, since the probability the channel enters in state-B during the frame transmission also increases. This model shows that when transmission errors are taken into account, decreased throughput and delay performance will be experienced compared to our theoretical analysis, because this analysis does not take into account the number of retransmissions caused by the hostile wireless medium.

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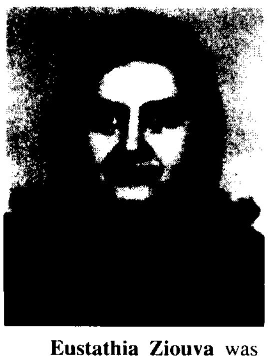

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