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CSMA/CA performance under high traffic conditions: throughput and delay analysis

Eustathia Ziouva, Theodore Antonakopoulos*

Department of Electrical Engineering and Computers Technology, University of Patras, 26500 Rio, Patras, Greece

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Abstract

The IEEE802.11 standard for wireless local area networks is based on the CSMA/CA protocol for supporting asynchronous data transfers. CSMA/CA uses an acknowledgment mechanism for verifying successful transmissions and optionally, a handshaking mechanism for decreasing collisions overhead. In both cases, an exponential backoff mechanism is used. This work investigates the theoretical performance of both mechanisms in terms of throughput and delay under traffic conditions that correspond to the maximum load that the network can support in stable conditions. We present extensive numerical results in order to highlight the effect of the backoff mechanism parameters on network performance for both mechanisms. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Carrier sense multiple access with collision avoidance; Wireless LANs; Distributed coordination function

1. Introduction

Stations of wireless LANs can establish peer-to-peer communications without using a central coordinator by implementing the distributed coordination function (DCF) of the IEEE802.11 standard [1]. DCF is used for asynchronous data transmission, while the so-called point coordination function (PCF) is used for supporting time-bounded data transmissions. DCF shares access to the medium using the carrier sense multiple access with collision avoidance (CSMA/CA) scheme and a random backoff time following a busy medium condition. In wireless LANs, the collision detection mechanism cannot be implemented, and therefore, the robust CSMA/CA has been developed. CSMA/CA implements a *listen before talk scheme*, where a station wishing to transmit must initially sense the radio medium to determine if another station is transmitting. CSMA/CA employs an immediate positive acknowledgment scheme to ascertain the successful reception of a packet. The receiving station initiates the transmission of an acknowledgment frame after a short time interval. If an acknowledgment is not received, the data packet is considered lost, and a retransmission is scheduled.

Concerning the performance analysis of the IEEE802.11 DCF, there are some simulation [2] and some analytical [3] studies. Chhaya [4] calculates the throughput of CSMA/CA with a simple model that is space dependent and evaluates the fairness properties of the protocol, in the possibility of capture and the presence of hidden stations. Bianchi [5] presents a simple analysis to compute the saturation throughput performance of CSMA/CA using the assumption of ideal channel conditions.

In this paper, we modify the model used in Ref. [5] by taking account of the busy medium conditions and how they affect the use of the backoff mechanism [1]. We present a more analytical study of the CSMA/CA throughput when the system handles traffic patterns that correspond to the maximum load the network can support in stable conditions. These traffic patterns are defined as saturation conditions. Our analysis is also extended to the computation of the delay performance of both access mechanisms. The delay analysis presented in our work can also be applied to the analysis of Ref. [5], but since Bianchi does not take account of the busy medium conditions for invoking the backoff procedure, these results will have less accuracy compared to the results presented in Section 4 of this paper. As in Ref. [5], we also assume a finite number of stations and an ideal channel.

Section 2 gives a description of the system model, which is based on a discrete time Markov chain and computes its stationary probability distribution. This model is used in Sections 3 and 4, where the throughput/delay analysis of both mechanisms of the CSMA/CA protocol is performed.

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* Corresponding author. Tel.: +30-61-997-346; fax: +30-61-997-342.
E-mail address: antonako@ee.upatras.gr (T. Antonakopoulos).

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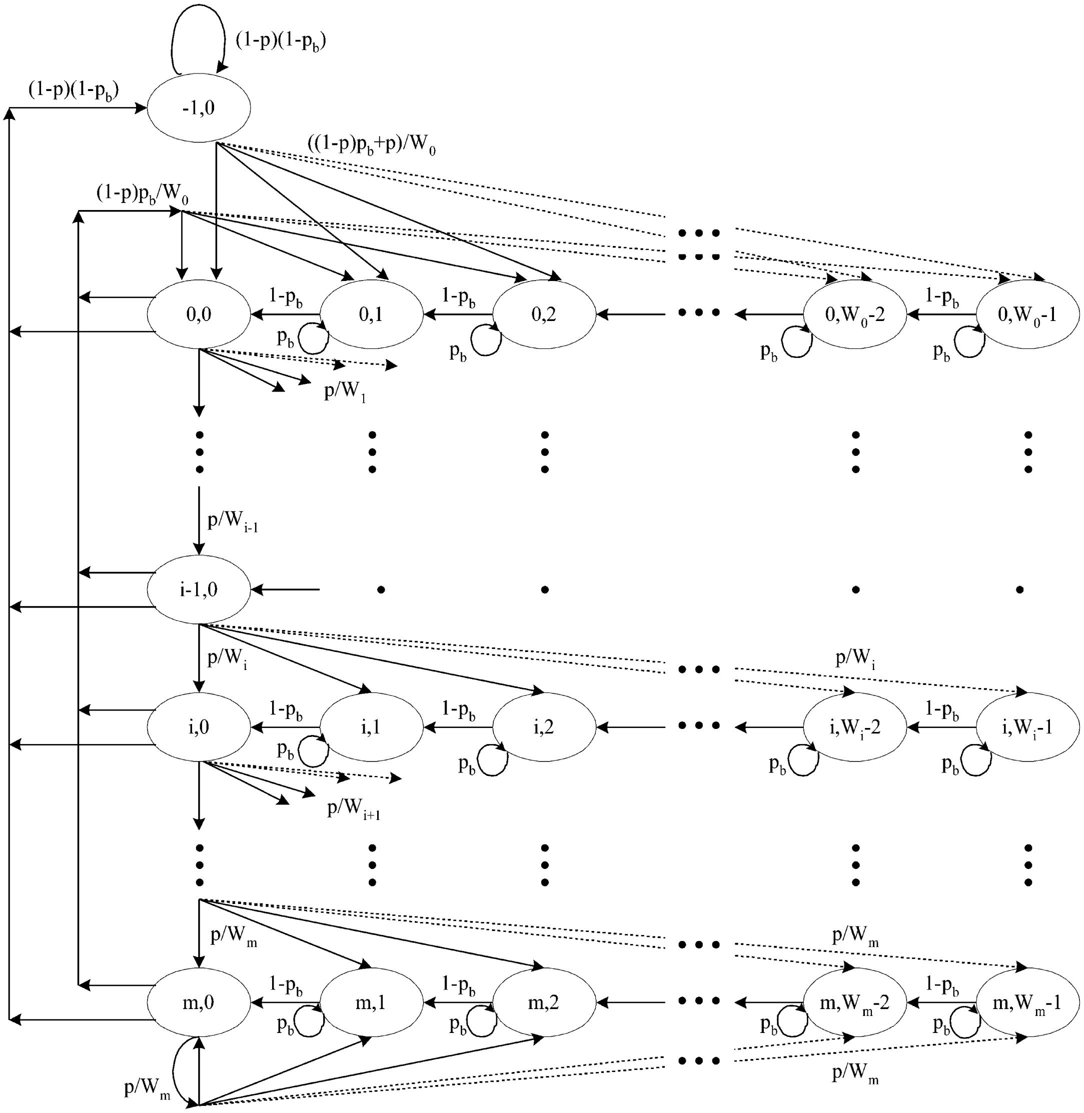

Fig. 1. The state transition diagram for the Markov chain model.

Finally, Section 5 presents extensive numerical results for highlighting the effect of the backoff mechanism parameters on the performance of both mechanisms.

2. The system model

In order to analyze the behavior of the CSMA/CA protocol under traffic patterns that correspond to the maximum load that the network can support in stable conditions, initially we follow the considerations of Ref. [5]. So we assume that the network consists of n contending stations and that each station, after the completion of a successful transmission, immediately has a packet available for transmission.

According to the CSMA/CA protocol, a station having a frame 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, 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 frame (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 will transmit its frame. If there are transmissions from other stations during this time period, the station will freeze its backoff counter until the end of the transmission. Then, the station resumes its counting after DIFS time. 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 $W_{\max} = 2^m W$. The backoff counter uses as time unit the duration a station needs to detect the transmission of a frame from any other station. This time interval is called 'slot time' and accounts for the propagation delay, for the time needed to switch from the receiving to the transmitting state (*Rx_Tx_Turnaround_Time*), and for the time to signal the MAC layer about the state of the channel (*busy detect time*). So, the time immediately following an idle DIFS is considered slotted.

Since collisions cannot be detected in a wireless CSMA/CA system, there are two mechanisms to determine the successful reception of a frame. According to the first mechanism, which is called ACK CSMA/CA, the destination station returns an ACK frame immediately following a successfully received frame. ACK is transmitted after a short interframe space (SIFS), where $t_{\mathrm{SIFS}} < t_{\mathrm{DIFS}}$. The transmitter reschedules its frame transmission if it does not receive the ACK within a specified *ACK_Timeout*, or if it detects the transmission of a different frame. In the second mechanism, which is called RTS/CTS CSMA/CA, the station that has a frame to transmit sends a RTS (request to send) frame and the receiving station responds with a CTS (clear to send) frame after SIFS time. The data frame 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. Although Ref. [1] states that a frame is rejected whenever the station re-enters the last backoff stage a number of times, in order to simplify our analysis, as in Ref. [5], we also assume that there is no limit on re-entering the last backoff stage.

Following the considerations of Ref. [5], $b(t)$ is defined as a stochastic process that represents the value of the backoff counter for a given station at slot time t. We assume that each station has $m+1$ stages of backoff delay and that $s(t)$ is the stochastic process representing the backoff stage i at time t, where $0 \le i \le m$. The value of the backoff counter is uniformly chosen in the range $(0, W_i - 1)$, where $W_i = 2^i W_{\min}$ and depends on the station's backoff stage i. The bi-dimensional process $\{s(t), b(t)\}$ is a discrete-time Markov chain under the assumption that the probability p, that a transmitted frame collides and the probability p_b, that the channel is busy, are independent to the backoff procedure. The above assumptions become more accurate as W and n get larger. So, the state of each station is described by $\{i, k\}$, where i indicates the backoff stage and takes the values $(0, 1, \ldots m)$ and k indicates the backoff delay and takes the values $(0, 1, \ldots, W_i - 1)$ in slot times. In our model, which is shown in Fig. 1, there is another state, denoted by $\{-1, 0\}$. According to Ref. [1], the backoff procedure is invoked whenever a station has a frame to transmit and finds the medium busy or whenever the transmitting station infers a failed transmission. Whenever the backoff counter is equal to zero and the station senses that the channel is idle for DIFS time, then the station transmits without activating the backoff procedure. State $\{-1, 0\}$ models the above condition. As it will be shown at the end of this section, this state is very important for determining the network performance, when the number of stations is less than 25, the usual number of stations in wireless LANs. The state transition diagram of the Markov chain model shown in Fig. 1 has the following transition probabilities:

1. The station transmits its frame without entering the backoff procedure if it detects that its previous transmitted frame was successfully received and the channel is idle.

   $$P\{-1,0|-1,0\} = \{1-p)(1-p_b)$$

2. The station defers the transmission of a new frame and enters stage 0 of the backoff procedure if it detects a successful transmission of its current frame and finds the channel busy or if it detects that a collision occurred to its current not successfully transmitted frame.

   $$P\{0,k|-1,0\} = \frac{(1-p)p_b + p}{W_0} \quad 0 \le k \le W_0 - 1$$

3. The backoff counter freezes when the station senses that the channel is busy.

   $$P(i,k|i,k\} = p_b \qquad 1 \le k \le W_i - 1 \;\; 0 \le i \le m$$

4. The backoff counter decrements when the station senses the channel idle.

   $$P\{i,k|i,k+1\} = 1 - p_b \qquad 0 \le k \le W_i - 2 \;\; 0 \le i \le m$$

5. The station choices a backoff delay of stage 0 if its current frame was transmitted successfully and it senses the channel busy when it tries to transmit a new frame.

   $$P\{0,k|i,0\} = \frac{(1-p)p_b}{W_0} \qquad 0 \le k \le W_0 - 1 \;\; 0 \le i \le m$$

6. The station enters into the $\{-1, 0\}$ state if it verifies a successful transmission and if it senses the channel idle.

   $$P\{-1,0|i,0\} = (1-p)(1-p_b) \;\; 0 \le i \le m$$

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

   $$P\{i,k|i-1,0\} = \frac{p}{W_i} \quad 0 \le k \le W_i - 1 \;\; 1 \le i \le m$$

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

   $$P\{m,k|m,0\} = \frac{p}{W_m} \quad 0 \le k \le W_m - 1$$

At this point, we have to calculate the probability a station

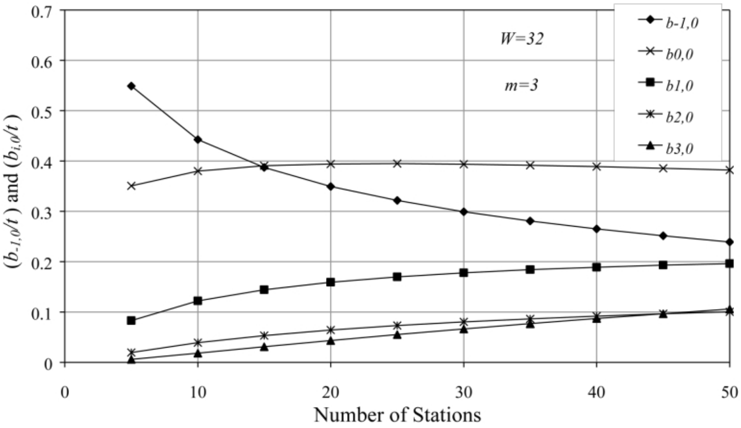

Fig. 2. The normalized backoff probabilities at 0-counter states.

is at state $\{i, k\}$. Let $b_{i,k} = \lim_{t\to\infty} P\{s(t) = i, b(t) = k\}$ be the stationary distribution of the Markov chain, where i, k are integers and $-1 \le i \le m$, $0 \le k \le W_i - 1$. In steady state, the following relations are valid:

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

$$b_{m,0} = \frac{p^m}{1-p} b_{0,0} \tag{2}$$

$$b_{i,k} = \frac{W_i - k}{W_i} \frac{1}{1-p_b} b_{i,0} \qquad 0 \le i \le m \;\; 1 \le k \le W_i - 1 \tag{3}$$

$$b_{0,0} = \frac{p_b + p(1-p_b)}{1-p_b} b_{-1,0} \tag{4}$$

The probability conservation relation states that $\sum_{i=-1}^{m} \sum_{k=0}^{W_i-1} b_{i,k} = 1$ or $b_{-1,0} + \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} b_{i,k} = 1$ and by using Eqs. (1)–(3), we have that

$$b_{-1,0} + \frac{1}{1-p_b} \sum_{i=0}^{m-1} p^i b_{0,0} \sum_{k=0}^{W_i-1} \frac{2^i W - k}{2^i W} + \frac{1}{1-p_b} \frac{p^m}{1-p} b_{0,0} = 1$$

Substituting Eq. (4) into the above equation, we can calculate $b_{-1,0}$ as:

$$b_{-1,0} = \frac{2(1-p_b)^2(1-2p)(1-p)}{2(1-p_b)^2(1-2p)(1-p) + (p_b + p(1-p_b))(1-2p)(W+1) + pW(p_b + p(1-p_b))(1-(2p)^m)} \tag{5}$$

From Eqs. (1)–(5), we can compute the steady state probabilities of our model, if the values of W, m, p and p_b are known. The values of W and m are known, but the probabilities p and p_b must be calculated. Let τ 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 anyone of the $b_{i,0}$ states. Therefore,

$$\tau = \sum_{i=-1}^{m} b_{i,0} = b_{-1,0} + \sum_{i=0}^{m-1} b_{i,0} + b_{m,0}$$

Substituting Eqs. (1) and (2) into the above equation and using Eqs. (4) and (5), the following equation is derived:

$$\tau = \frac{2(1-p_b)(1-2p)}{2(1-p_b)^2(1-2p)(1-p) + (p_b + p(1-p_b)(1-2p)(W+1) + pW(p_b + p(1-p_b))(1-(2p)^m)} \tag{6}$$

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

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

The channel is detected busy when at least one station transmits during a slot time, and thus, the probability p_b that the channel is busy is given by

$$p_b = 1 - (1-\tau)^n \tag{8}$$

Substituting Eqs. (7) and (8) to Eq. (6), we obtain one equation of an unknown parameter, the probability τ. Solving this equation for τ, we can calculate the probabilities p and p_b and then the stationary probability distribution.

Fig. 2 shows how the normalized backoff probabilities depend on the number of stations when the backoff counter equals to 0. States $b_{-1,0}$ and $b_{i,0}$ are important to the CSMA/CA protocol operation because when a station enters one of these states, it then tries to transmit its frame. The normalized backoff probabilities $b_{-1,0}/\tau$ and $b_{i,0}/\tau$ indicate how frequently each state is used in the medium access procedure. From this figure, it is obvious that state $b_{-1,0}$ is very important to the protocol performance analysis and using a model that includes this state produces more accurate throughput and delay results.

3. Throughput analysis

As in Ref. [5], we assume that each transmission, whether it is successful or not, is a renewal process. Thus, it is sufficient to calculate the throughput of the CSMA/CA protocol during a single renewal interval between two consecutive transmissions. In this case, the throughput S is expressed as

$$S = \frac{E[\text{time used for successful transmission in an interval}]}{E[\text{length between two consecutive transmissions}]} = \frac{P_s E[P]}{E[\Psi] + P_s T_s + (1 - P_s) T_c} \tag{9}$$

where $E[P]$ is the average payload length, T_s is the average time that the channel is captured with a successful transmission, T_c is the average time that the channel is captured by stations which collide, P_s is the probability that a transmission is successful and $E[\Psi]$ is the mean value of the random variable Ψ which represents the number of consecutive idle slot times before a transmission takes place, due to the backoff algorithm.

The average payload length $E[P]$ is defined by the pdf of the payload length. Here, we assume that all frames are of the same fixed size, $E[P] = P$ where P can be calculated by the number of bits that the frame payload contains and the channel bit rate. The values of T_s and T_c depend on the channel access method and are defined (according to Ref. [5]) as

$$\left.\begin{aligned} T_s^{\text{ack}} &= H + P + \delta + \text{SIFS} + \text{ACK} + \delta + \text{DIFS} \\ T_c^{\text{ack}} &= H + P + \delta + \text{DIFS} \end{aligned}\right\} \tag{10}$$

ACK CSMA/CA

and as:

$$\left.\begin{aligned} T_s^{\text{rcts}} &= \text{RTS} + \delta + \text{SIFS} + \text{CTS} + \delta + \text{SIFS} + H + P + \delta + \text{SIFS} + \text{ACK} + \delta + \text{DIFS} \\ T_c^{\text{rcts}} &= \text{RTS} + \delta + \text{DIFS} \end{aligned}\right\} \quad \text{RTS/CTS CSMA/CA} \tag{11}$$

where $H = \text{PHY}_{\text{hdr}} + \text{MAC}_{\text{hdr}}$ is the frame header and δ is the propagation delay.

A transmission is assumed to be successful when only one among n stations transmits, given that there is at least one transmission. So the probability P_s that a transmission is successful is given by

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \tag{12}$$

Finally, the mean number $E[\Psi]$ of consecutive idle slot times before a transmission takes place is given by

$$E[\Psi] = \frac{1}{p_b} - 1 \tag{13}$$

Since $E[\Psi]$ is measured in slot times, the values of P, T_s and T_c are also measured in slot times. Using Eqs. (10), (12) and (13) in Eq. (9), we get the throughput of the ACK CSMA/CA mechanism, while using Eqs. (11)–(13) in Eq. (9), we get the throughput of the RTS/CTS CSMA/CA mechanism.

4. Delay analysis

Frame delay is defined as the time elapsed between the generation of a frame and its successful reception. Lets D be the random variable representing the frame delay and $E[D]$ its mean value. The mean frame delay can be found by the following relation:

$$E[D] = E[N_c](E[BD] + T_c + T_O) + (E[BD] + T_s) \tag{14}$$

where $E[N_c]$ number of collisions of a frame until its successful reception, $E[BD]$ is the average backoff delay that a station choices before accessing the channel under busy channel conditions, T_O is the time that a station has to wait when its frame transmission collides, before sensing the channel again. Finally, times T_s and T_c are given by Eqs. (10) and (11), respectively.

The average number of collisions before transmitting a frame can be calculated by using the probability P_s that a transmission is successful. If the probability P_s is known, then the average number of retransmissions is $1/P_s$, thus

$$E[N_c] = \frac{1}{P_s} - 1 \tag{15}$$

The average backoff delay depends on the value of its counter and the duration the counter freezes when the station detects transmissions from other stations. Considering that the counter of a station is at state $b_{i,k}$, then a time interval of k slot times is needed for the counter to reach state 0, without taking into account the time the counter is stopped. This time interval is denoted by the random variable X and its average is given by

$$E[X] = \sum_{i=0}^{m} \sum_{k=1}^{W_i - 1} k b_{i,k}$$

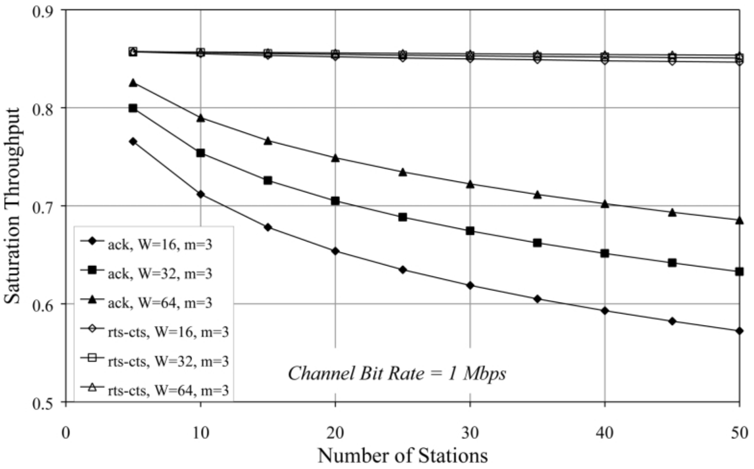

Fig. 3. Saturation throughput for various initial contention window sizes.

Based on Eqs. (1)–(3), we finally get that

$$E[X] = \frac{b_{0,0}}{6(1-p_b)} \frac{W^2(1-p-3p(4p)^m) + 4p - 1}{(1-4p)(1-p)} \tag{16}$$

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 transmission. This duration depends on the transmission success. So, in order to calculate the average time $E[F]$ that the counter remains stopped, we have to find $E[N_{\mathrm{Fr}}]$, the average number of times that a station detects transmissions from other stations before its counter reaches state 0. Based on $E[X]$, the average backoff delay of each station and on $E[\Psi]$, the mean number of consecutive idle slot times before a transmission proceeds, then

$$E[N_{\mathrm{Fr}}] = \frac{E[X]}{\max(E[\Psi], 1)} - 1$$

and

$$E[F] = E[N_{\mathrm{Fr}}](P_s T_s + (1-P_s)T_c) \tag{17}$$

From Eqs. (16) and (17), we have that

$$E[BD] = E[X] + E[N_{\mathrm{Fr}}](P_s T_s + (1-P_s)T_c) \tag{18}$$

Finally, the time T_O depends on the access method and equals

$$T_O = \begin{cases} \text{SIFS} + \text{ACK\_timeout} \\ \text{SIFS} + \text{CTS\_timeout} \end{cases} \tag{19}$$

Substituting Eqs. (15), (18) and (19) into Eq. (14), we can calculate the mean frame delay and we can study how it is affected by various protocol parameters. We must notify that all time intervals in the above relations are measured in slot times.

5. Numerical results

To gain a better understanding on how the CSMA/CA protocol behaves when the network is loaded with traffic conditions that correspond to the maximum load that the network can support in stable conditions and how backoff

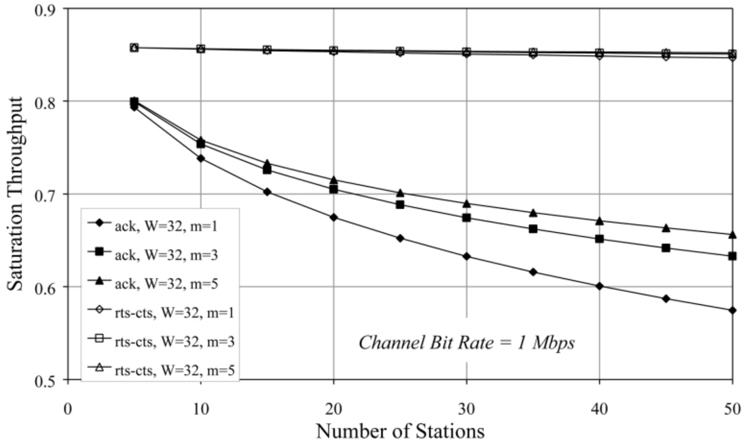

Fig. 4. Saturation throughput for different numbers of backoff stages.

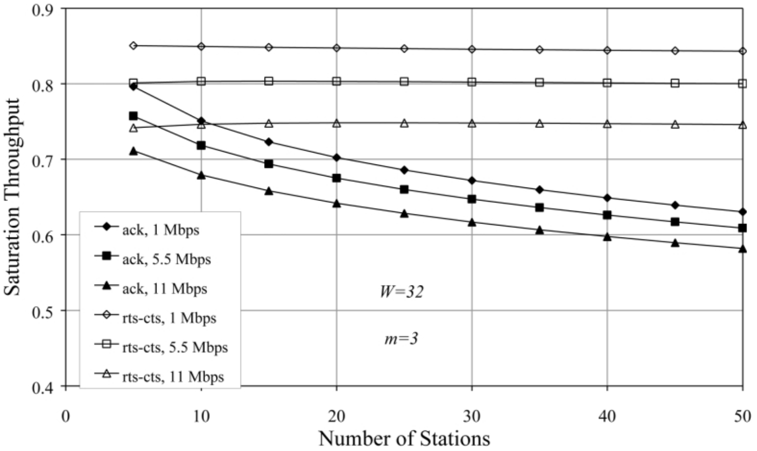

Fig. 5. Saturation throughput for various channel bit rates.

procedure affects the system performance, we present the results of our analysis considering that: Frame payload = 1023 bytes, MAC header = 34 bytes (including the FCS field), PHY header = 16 bytes, ACK = 14 bytes + PHY header, RTS = 20 bytes + PHY header, CTS = 14 bytes + PHY header, SIFS = 10 us, DIFS = 50 us, propagation delay = 1 us, slot time = 20 us and channel bit rate = 1, 5.5 and 11 Mbps.

As it was initially defined, saturation conditions are traffic conditions that correspond to the maximum load that the network can support without loosing its stability. In Fig. 3, we show how the saturation throughput depends on the initial contention window size. The throughput of the ACK CSMA/CA protocol decreases as the number of stations increases, due to the fact that the probability of a collision becomes larger. The RTS/CTS CSMA/CA shows significantly better performance having negligible performance degradation as the number of stations increases. Fig. 3 also depicts the effect of the initial contention window size W on the throughput for both access mechanisms. The ACK CSMA/CA provides higher throughput as a larger initial contention window size is chosen since a larger contention window decreases the probability of collision and the number of retransmissions. The RTS/CTS CSMA/CA shows almost no improvement when the initial contention window increases since this mechanism wastes less bandwidth during a collision in contrast to the ACK CSMA/CA that captures the channel with the entire data frame during retransmissions.

Fig. 4 illustrates the dependence of CSMA/CA throughput upon the number of the backoff stages. The increase in backoff stages aims at the enlargement of the contention window and the reduction of collisions. Due to this behavior, we observe that the ACK CSMA/CA improves its throughput, particularly when a large number of stations are used, while the RTS/CTS CSMA/CA is slightly affected.

Since the CSMA/CA protocol has been recommended for various channel bit rates, it is of interest to study how the protocol throughput is affected by the channel bit rate. Fig. 5 shows that the throughput of both CSMA/CA mechanisms decreases as the channel bit rate increases. The reason is that the duration of DIFS, SIFS and slot time is independent of the channel bit rate, while the frame transmission time decreases as the channel bit rate increases. So the portion

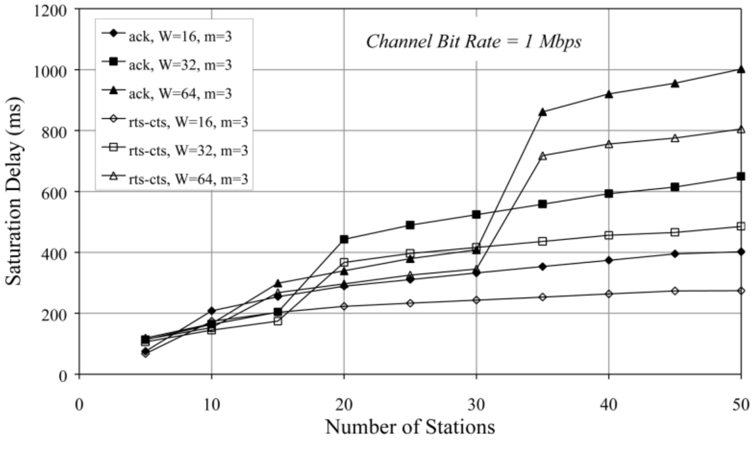

Fig. 6. Saturation delay for various initial contention window sizes.

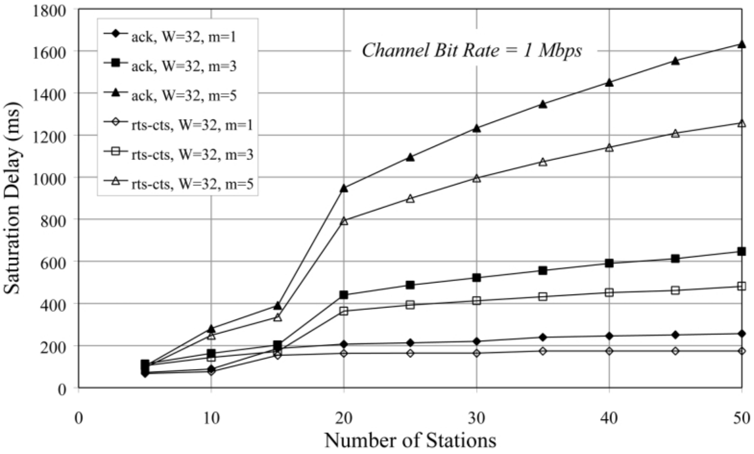

Fig. 7. Saturation delay for various backoff stages.

of time the system spends on DIFS, SIFS and backoff delay during a frame transmission increases as the channel bit rate increases, causing the throughput degradation.

Fig. 6 shows the saturation delay versus the number of stations for various initial contention window sizes. As a larger number of stations attempt to access the medium, more collisions occur, the number of retransmissions increases and the stations suffer longer delays. The RTS/CTS CSMA/CA results in delays lower than that of the ACK CSMA/CA, since lower overhead is involved during retransmissions. At this point, we must discuss the abrupt slopes that occur in the saturation delay curves. When the number of contending stations reaches a specific value, the collision probability increases and that has as a result that the stations choose higher stages of the backoff algorithm. The choice of a higher backoff stage causes longer delays and so these slopes mean that the stations select to use a larger contention window for keeping the network stability.

The CSMA/CA protocol suffers longer delays when the backoff procedure includes more stages *m*, as it is shown in Fig. 7. At this point, we must emphasize that a larger initial contention window size and a larger number of backoff stages improves the ACK CSMA/CA throughput at the expense of higher transfer delays. Finally, Fig. 8 shows the effect of the channel bit rate on the frame delay. The CSMA/CA delay of both access mechanisms decreases as the channel bit rate increases, since the time spent in successful transmissions and collisions diminishes while the DIFS, SIFS and slot time remain constant.

6. Conclusions

In this paper, we analyzed the throughput and delay of the CSMA/CA protocol under maximum load conditions by using a bi-dimensional discrete time Markov chain. According to the results of our analytical approach, the stages of the backoff algorithm and the size of the contention window strongly affect the throughput of ACK CSMA/CA, while RTS/CTS CSMA/CA is more robust to changes on these parameters. On the other hand, the initial size of the contention window and the number of the backoff stages has greater influence on the delay of both access methods. Finally, at high traffic conditions, the RTS/CTS CSMA/

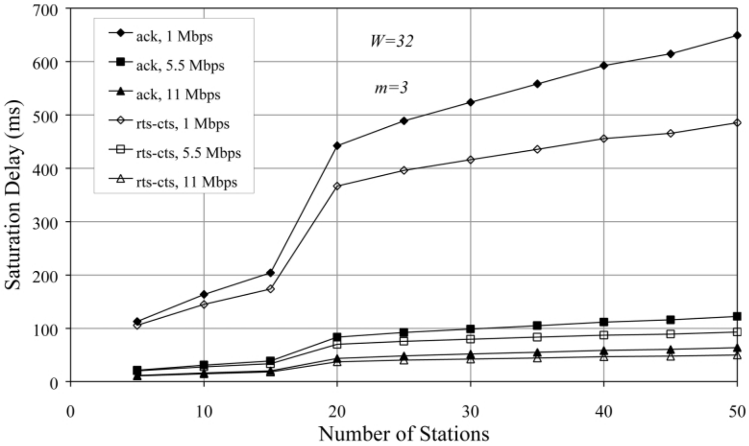

Fig. 8. Saturation delay for various channel bit rates.

CA mechanism presents higher throughput and smaller delays than the ACK CSMA/CA mechanism.

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Eustathia Ziouva *was born in Athens, Greece in 1970. She received the Electrical Engineering Diploma in 1993 from the Department of Electrical Engineering at the University of Patras. In September 1993, she joined the Laboratory of Electromagnetics where she worked in R&D projects of the Greek Government and the European Union for three years as a research member. In September 1999, she started studies for Ph.D. in the field of wireless networks. Her research interests are in the areas of communication networks performance analysis. Ms Ziouva is a member of the Technical Chamber of Greece.*

Theodore Antonakopoulos *was born in Patras, Greece in 1962. He received the Electrical Engineering Diploma degree in 1985, and his Ph.D. degree in 1989 from the Department of Electrical Engineering at the University of Patras, Patras, Greece. In September 1985, he joined the Laboratory of Electromagnetics at the University of Patras participating in various R&D projects for the Greek Government and the European Union, initially as a research staff member and subsequently as the senior researcher of the Communications Group. Since 1991, he has been a faculty of the Electrical Engineering Department at the University of Patras, where he is currently an Assistant Professor. His research interests are in the areas of data communication networks, LANs and wireless networks, with emphasis on performance analysis, efficient hardware implementation and rapid prototyping. He has more than 60 publications in the above areas and is actively participating in several R&D projects of the European Union. Dr Antonakopoulos is a Senior member of the IEEE, serves in the Program Committee of the IEEE International Workshop on Rapid System Prototyping, and is a member of the Technical Chamber of Greece.*