

# On the End-to-End Delay Analysis of the IEEE 802.11 Distributed Coordination Function

J.S. Vardakas<sup>1</sup>, I. Papapanagiotou<sup>2</sup>, M.D. Logothetis<sup>1</sup> and S.A. Kotsopoulos<sup>2</sup>

<sup>1</sup>Wire Communications Laboratory

<sup>2</sup>Wireless Telecommunications Laboratory

Department of Electrical & Computer Engineering

University of Patras

265 04 Patras, Greece

Emails: jvardakas@wcl.ee.upatras.gr, ipapapanag@upnet.gr, m-logo@wcl.ee.upatras.gr and kotsop@ece.upatras.gr

**Abstract-** The IEEE 802.11 protocol is the dominant standard for Wireless Local Area Networks (WLANs) and has generated much interests in investigating and improving its performance. The IEEE 802.11 Medium Access Control (MAC) is mainly based on the Distributed Coordination Function (DCF). DCF uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol in order to resolve contention between wireless stations and to verify successful transmissions. In this paper we present an extensive investigation of the performance of the IEEE 802.11b MAC protocol, in respect of end-to-end delay. The end-to-end delay analysis of the IEEE 802.11b has not been completed, because no adequate queuing delay is provided. Our delay analysis is based on Bianchi's model for the DCF, while a more comprehensive model could be used as well. We use z-transform of backoff duration to get mean value, variance and probability distribution of MAC delay. From the mean value and the variance of the MAC delay we determine the mean queuing delay in each station. Our analysis is validated by simulation results for both the Basic and RTS/CTS access mechanisms of the DCF. The accuracy of the analysis found to be quite satisfactory. We assume data rates of 1, 5.5 and 11 Mbps, in order to highlight the effect of the bit rate on delay performance for both access mechanisms.

**Keywords:** IEEE 802.11b, CSMA/CA, MAC Delay, Queuing Delay.

## I. INTRODUCTION

The IEEE 802.11 protocol defines two medium access methods, the widely used Distributed Coordination Function (DCF) and the optional Point Coordination Function (PCF). The DCF uses the CSMA/CA protocol to allow contended access to the wireless medium under binary exponential backoff rules [1]. When using CSMA/CA, each station wishing to take control of the medium has to sense if the channel is idle; if it is not idle, the station defers its transmission to a random time interval. Upon each collision notified by the absence of an acknowledgment (ACK) frame, the bound of random time interval (contention window) is increased in order for a retransmission to be scheduled.

Several studies appear in the literature investigating the performance of the IEEE 802.11 protocol. Bianchi in [2] proposes a Markov process to demonstrate a simple and tractable analytical model for the saturation throughput of the WLAN, under ideal channel conditions (absent of noise, no hidden stations). In [3], Wu et al. extends Bianchi's model to include finite packet retry limits (a packet should be dropped after a certain number of

transmission attempts). In [4], Ziouva proposes a Markov chain model that introduces an additional transition state to the models of Bianchi and Wu, while using a new probability (denoting that the channel is busy), in order to confront the backoff suspension case. However, because of the introduction of the new transition state, the fact that a new backoff procedure must commence after a successful transmission is neglected. More important refinements of the aforementioned models are found in [5] and [6].

The aforementioned studies concentrate mainly on the saturation throughput analysis, whereas the end-to-end delay analysis of the IEEE 802.11b has not been completed (to the best of our knowledge, no queuing delay is provided). In this paper, we aim at analysing the end-to-end delay in IEEE 802.11b WLAN. To this end, we are eventually interested in getting the unconditional probability  $\tau$  that a wireless station transmits in a randomly selected time-slot. This probability results from solving the Markov chain of the above-mentioned models. Especially, we adopt the new Bianchi's model [7], where  $\tau$  is obtained through basic probability theory, while avoiding the Markov chains.

Based on  $\tau$ , we calculate the mean and the variance of the MAC delay. This is done by getting the z-transform of the backoff duration according to [8]. Moreover, we proceed to determine the probability distribution of the MAC delay through the Lattice-Poisson algorithm [9]. The mean and the variance of the delay provide a coarse estimation, while the probability distribution provides a fine estimation of the MAC delay. Having determined the mean and the variance of the MAC delay, we can calculate the mean queuing delay by considering an approximate queuing service model. In the present paper we provide results for the M/G/1 queue [10], because of its simplicity, in order to obtain a first look on the queuing delay. Finally the end-to-end delay is the sum of MAC and queuing delay.

Our analysis is validated by simulation results (through the NS-2 simulator [11]) for both the Basic and RTS/CTS access mechanisms of the IEEE 802.11b DCF; we consider the Bianchi's model [7] with finite packet retry limits. However, a more comprehensive model could be used instead [6]. The accuracy of our analysis found to be quite satisfactory. We assume data rates of 1, 5.5 and 11 Mbps, in order to highlight the effect of the bit rate on delay performance for both access mechanisms.

This paper is organized as follows: Section II gives a brief overview of the DCF access method. Section III presents the proposed mathematical model for the delay analysis. Section IV is the evaluation section. We conclude in section V.

## II. OVERVIEW OF DCF

This section briefly introduces the DCF operation, as defined in the IEEE 802.11 standard [1]. A station is permitted to start a transmission if the medium is sensed free; otherwise the transmission is postponed until the medium is idle for a time interval greater than Distributed Inter-Frame Space (DIFS), followed by an additional randomly selected time interval. At the end of this additional time, the station is permitted to send its packet. The verification of the successful reception is done by the reception of an acknowledgment (ACK) packet from the destination station, a Short Inter-Frame Space (SIFS) time interval from the reception of the data packet. If an ACK packet is not detected by the source station, a retransmission is scheduled.

The randomly selected time interval that a station has to wait before it starts a transmission is known as backoff interval and is defined by a value of the backoff counter. When a backoff procedure is setting up, the backoff counter decrements as long as the medium remains idle; otherwise the counter is frozen to its current value and resumes when the medium is sensed idle for a time greater than DIFS interval.

The value of the backoff counter is uniformly chosen in the range  $(0, w-1)$ , where  $w-1$  is known as Contention Window ( $CW$ ). At the first transmission attempt  $CW$  has an initial value  $W_0 = CW_{\min} + 1$ . After each unsuccessful transmission  $CW$  is doubled up to a maximum value of  $W_{m'} = CW_{\max} + 1 = 2^{m'} W_0$  where  $m'$  is the number of  $CW$  sizes, therefore:

$$\begin{cases} W_i = 2^i W_0 & 0 \leq i \leq m' \\ W_i = 2^{m'} W_0 & m' < i \leq m \end{cases} \quad (1)$$

where  $i \in [0, m]$  is the backoff stage and  $m$  represents the station's retry count.

In the RTS/CTS mode, the sender transmits a short RTS packet prior to the data packet, and the receiver station responds with a CTS packet, after a SIFS time interval. The successful reception of the CTS packet is followed by the initiation of the first backoff stage and by a new RTS packet. The transmission of the data packet is initialized after the reception of the CTS packet by the sender station.

## III. DELAY PERFORMANCE MODEL

In the following analysis we consider that a IEEE 802.11 WLAN consists of  $n$  stations which contend under ideal channel conditions. Each station has always a packet available for transmission in its transmission queue (this is called saturated station). Furthermore, at each transmission attempt, regardless of the number of

retransmissions suffered, each packet collides with probability  $p$ , which is constant and independent of the number of the collisions that the packet has suffered in the past.

### A. Transmission Probability

The performance analysis is verified by supposing simple probabilities than difficult solution of Markov Chains. We can envision the Binary Exponential Backoff (BEB) Algorithm as a function of two coordinates  $(x, y)$ , where  $x \in [0, m]$  represents the backoff stage and  $y \in [0, CW_x - 1]$  represents the value of the backoff counter at the backoff stage  $x$ . In order for a station to be in a specific  $x = i$  position a number of collisions have happened in the previous  $x = i - j$  where  $j \in [0, i - 1]$  and  $x \geq i$ . Thus the event that the station is in position  $x$  is given by the geometric series, which is the number of collision in a geometric progression [7]:

$$P(x) = \frac{(1-p)p^x}{1-p^{m+1}} \quad (2)$$

The probability that a station transmits while being in the backoff stage  $x$  is obtained from the mean value of the uniform distribution that each  $y$  is chosen, plus a time slot that it is needed to leave the specific  $y$  coordinate and go to another  $y$  of a different  $x$ .

$$P(y) = \frac{1}{1+E[D_x]} \quad (3)$$

where  $E[D_x]$  is the average value of the backoff counter at stage  $x$ .

In order to find the transmission probability, the above equations should be divided and summed over a region of  $i \in [0, m]$  [7]:

$$\tau = \frac{1}{\sum_{x=0}^m \frac{P(x)}{P(y)}} \quad (4)$$

### B. Accurate MAC Delay Distribution

To find the accurate MAC delay distribution we need to know the mean value, the variance and the Probability Distribution Function (PDF). The first two can be easily found from the first and second moments of the discrete Z-transform of the Backoff Duration, since the BEB Algorithm is slotted, whereas the third one can be found by the Lattice-Poisson algorithm.

The interruption of the backoff period of the tagged station can occur by two different events and is analyzed as follows. The first one is the collision of two or more stations and the second is the transmission of a single station other than the tagged one. The probability of a slot of the tagged station to be interrupted from the transmission by any other station (one or more) is given by:

$$p = 1 - (1 - \tau)^{n-1} \quad (5)$$

Whereas the probability  $p'$  that the tag station is interrupted by the transmission of a single station (one exactly) is given by:

$$p' = \binom{n-1}{1} \cdot \tau \cdot (1 - \tau)^{n-2} \quad (6)$$

The probabilities that the slot is interrupted by a successful transmission or a collision of another station/s are respectively given by:

$$P(\text{collision} | \text{slot is interrupted}) = p'_c = \frac{p - p'}{p} \quad (7)$$

$$P(\text{successful transmission} | \text{slot is interrupted}) = p'_s = \frac{p'}{p} \quad (8)$$

According to [7] and [12] there is a probability that the station will definitely transmit another packet, after a successful transmission. This occurs when in the second transmission chooses a backoff value equals zero. Hence the Z-transform of the transmission period and the collision period are respectively given by:

$$S(Z) = Z^{T'_s} \quad (9)$$

$$C(Z) = Z^{T'_c} \quad (10)$$

where  $T'_s$  is the average time the channel is sensed busy due to a successful transmission derived from [7], with the modification that the upper limit is set to the finite value  $m$ :

$$T'_s = T_s + \sum_{x=1}^m B_0 \cdot \frac{(1 - B_0^x)}{1 - B_0} T_s + \sigma \quad (11)$$

where  $T_s$  is given in (15) and (16), below, according to the access mechanism,  $\sigma$  is the length of the time slot, and  $B_0$  is the probability that the new backoff counter value equals to zero:

$$B_0 = \frac{1}{1 + CW_{\min}} \quad (12)$$

Similarly, the average time the channel is sensed busy due to an unsuccessful transmission  $T'_c$  and the average packet length  $E[P']$  are respectively given by [7]:

$$T'_c = T_c + \sigma \quad (13)$$

$$E[P'] = E[P] + \sum_{x=1}^m B_0 \cdot \frac{(1 - B_0^x)}{1 - B_0} E[P] \quad (14)$$

The values of  $T_s$  and  $T_c$  depend on the access mechanism, considering the ACK and CTS timeout effect ([13]):

$$\begin{cases} T_s^{BAS} = DIFS + H + T_D + SIFS + T_{ACK} + 2 \cdot \delta \\ T_c^{BAS} = DIFS + H + T_D + SIFS + T_{ACK} + 2 \cdot \delta \end{cases} \quad (15)$$

$$\begin{cases} T_s^{RTS} = DIFS + T_{RTS} + H + T_{CTS} + T_D + 3 \cdot SIFS + T_{ACK} + 4 \cdot \delta \\ T_c^{RTS} = DIFS + T_{RTS} + SIFS + T_{CTS} + 2 \cdot \delta \end{cases} \quad (16)$$

where  $T_D$ ,  $T_{ACK}$ ,  $T_{RTS}$  and  $T_{CTS}$  is the time required to transmit the data packet, ACK, RTS and CTS respectively, while  $\delta$  is the propagation delay and  $H = \text{MAC}_{\text{hdr}} + \text{PHY}_{\text{hdr}}$  is the required time to transmit the packet header.

In order to decrement the backoff process, the channel must not be interrupted and multiplied by the respective time of the idle slot, whereas the probability to stay at the same state is the sum of two multiplications where the station stays at the same state. Thus the Probability Generating Function (PGF) of each state is given by:

$$D_{x,y}(Z) = \frac{(1-p) \cdot Z^\sigma}{1 - p \cdot (p'_s S(Z) + p'_c C(Z))} \quad (17)$$

However, the backoff duration is not doubled after  $m$  times, and stays at the same value for the remaining backoff stages:

$$D_x(Z) = \begin{cases} \sum_{y=0}^{CW_x-1} \frac{D_{x,y}^y(Z)}{CW_x}, & 0 \leq x \leq m' \\ D_{m'}(Z), & m' < x \leq m \end{cases} \quad (18)$$

Thus, for each  $x$  the backoff duration is given by:

$$\begin{aligned} BD(Z) = & (1-p) \cdot S(Z) \cdot \sum_{x=0}^m \left[ (p \cdot C(Z))^x \cdot \prod_{i=0}^x D_i(Z) \right] + \\ & + (p \cdot C(Z))^{m+1} \cdot \prod_{i=0}^m D_i(z) \end{aligned} \quad (19)$$

The first term of the second part of (18) signifies the transmission delay multiplied by the delay encountered in the previous  $x$  and  $y$  stages, whereas the second term is the delay of the dropping packet, which has encountered in all  $x$  collisions.

The mean value  $E[M]$  and the variance  $\text{Var}[M]$  of the MAC delay can be derived by taking the derivative of (18), with respect to  $Z$ :

$$E[M] = BD'(Z) \Big|_{Z=1} \quad (20)$$

$$\text{Var}^2(M) = BD''(Z) \Big|_{Z=1} + BD'(Z) \Big|_{Z=1} - (BD'(Z) \Big|_{z=1}) \quad (21)$$

In order to calculate the PDF of the MAC delay, the Z-transform of the delay can also be expressed as:

$$BD(Z) = \sum_{k=0}^{\infty} d_k Z^k \quad (22)$$

The goal is to calculate  $d_k$ , which expresses the PDF of the backoff duration. A method that gives the inverse Z-transform with a predefined error bound is the Lattice-Poisson Algorithm [9], which is valid for  $|d_k| \leq 1$ . However in the situation of  $BD(Z)$ ,  $d_k$  is a PDF and thus validates the above method. Thus, the PDF is:

$$d_k = \frac{1}{2kr^k} \sum_{j=1}^{2k} (-1)^j \operatorname{Re} \left( BD \left( r e^{i\pi j/k} \right) \right) \quad (23)$$

where  $\operatorname{Re}(BD(Z))$  stands for the real part of the complex  $BD(Z)$ .

Eq. (23) is derived by integration of  $BD(Z)$  over a circle with radius  $r$ , where  $0 < r < 1$ . For practical reasons we suppose that the predefined approximation error is  $r^{2k}$  [9].

### C. End-to-End Packet Delay

The average end-to-end packet delay can be calculated as the sum of the mean MAC delay  $E[M]$  and the queuing delay  $E[Q]$ . The average queuing delay can be obtained by considering a simple queuing system, namely the M/G/1 with infinite queuing size, where the single server is the wireless channel. In the proposed M/G/1 queuing system, the average service time is  $E[M]$ . By applying the corresponding formula for the mean queuing delay,  $E[Q]$ , we obtain [10]:

$$E[Q] = \frac{A \cdot E[M]}{2 \cdot (1 - A)} \cdot \varepsilon \quad (24)$$

where  $A$  is the offered traffic-load and  $\varepsilon$  is the form factor of the holding time distribution, which equals to ([10]):

$$\varepsilon = 1 + \frac{E[M]^2}{\operatorname{var}[M]} \quad (25)$$

Finally, the average end-to-end packet delay  $E[D]$  is given by:

$$E[D] = E[M] + E[Q] \quad (26)$$

## IV. EVALUATION

We consider a WLAN topology consisting of an Access Point (AP), placed in the centre of an area of 100m x 100m, and of  $n$  stations placed on a circle of radius  $R=50m$  around the AP. We assume that all stations send traffic in such a rate that saturated conditions are ensured, and they have line of sight, in order to ignore the hidden terminal problem. The accuracy of the proposed model is assessed by comparing the model with simulation. The simulation results are obtained by NS-2 simulator [11].

The values of the parameters used both in the analysis and simulation comes from the values of the Direct Sequence Spread Spectrum (DSSS) parameters found in [14]; they are summarized in Table 1. All simulation results have been obtained with five replications each time with different random seed and a 95% confidence interval [15], and the average value is used in the figures, since the replication ranges are very small.

The average end-to-end delay versus the number of stations for both the Basic and RTS/CTS access mechanisms is depicted in Fig. 1 for 1 Mbps data rate. In both cases analytical and simulation results are in satisfactory agreement. Moreover, the study of the curves indicates that the total delay increases as the number of the contending stations increases. This behavior can be explained by the fact that in large sized networks packets experience greater number of collisions; therefore stations choose higher backoff stages, which results to longer delays.

The effect of the data rate in the total packet delay can be monitored in Fig. 2 and 3, where the average end-to-end packet delay versus the number of stations is depicted for 5.5 and 11 Mbps respectively. The comparison of the figures reveals that the superiority of the RTS/CTS access mode in terms of the total delay is observed only at 1 Mbps data rate; at higher data rates the use of the Basic access mode results in lower delay. In RTS/CTS mode the control packets are transmitted at 1 Mbps, irrespective of the data rate. This fact introduces an additional overhead, which reflects on the value of the delay.

## V. CONCLUSION

The performance of the IEEE 802.11b standard is extensively investigated in respect of end-to-end delay when the DCF is used. When modelling the DCF, we are ultimately interested in getting the unconditional probability that a wireless station transmits in a randomly selected time-slot. This probability is obtained in a simple way (through basic probability theory) for the Bianchi's model of DCF. Therefore, having considered the Bianchi's model (with finite packet retry limits however), we proceed to calculate the end-to-end delay as follows. From Bianchi's model we get the transmission probability and based on it we calculate the mean, the variance and the probability distribution of the MAC delay, by getting the z-transform of the backoff duration according to [8]. The probability distribution of the MAC delay is determined by the Lattice-Poisson algorithm. From the mean and the variance of the MAC delay, we calculate the mean queuing delay by considering an M/G/1 queue. In our future work, this queuing model will be replaced by an MMPP/G/1/k model, which is more suitable for packet networks. The end-to-end delay is the sum of queuing and MAC delay. Our analysis is validated by simulation results through the NS-2 simulator. Both the Basic and RTS/CTS access mechanisms of the IEEE 802.11b DCF are assumed. Our results show that the accuracy of our analysis is very satisfactory. In the WLAN, we assume data rates of 1, 5.5 and 11 Mbps, in order to highlight the

effect of the bit rate on end-to-end delay performance for both access mechanisms.

Table 1. Parameters for MAC and DSSS PHY Layer

Packet Payload	8224 bits
Channel Bit Rate	1,5,5,11 Mbps
MAC Header	224 bits
PHY Header	192 bits
Propagation Delay	1 $\mu$ s
Slot Time	20 $\mu$ s
DIFS	50 $\mu$ s
SIFS	10 $\mu$ s
ACK	112 bits + PHY Header
CTS	112 bits + PHY Header
RTS	160 bits + PHY Header

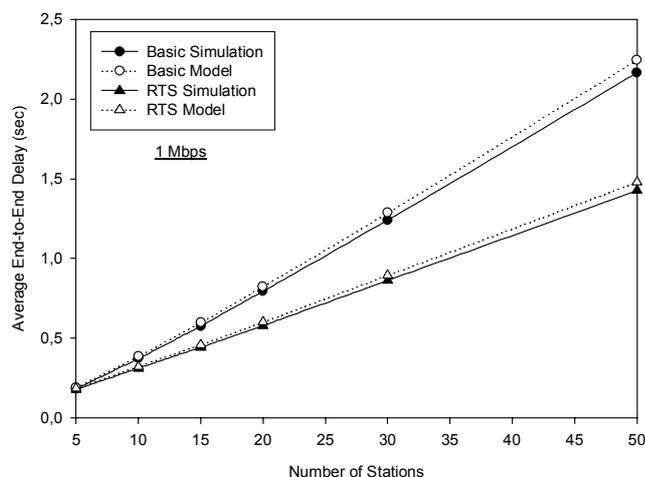


Figure 1. Average end-to-end packet delay versus the number of stations at 1 Mbps data rate.

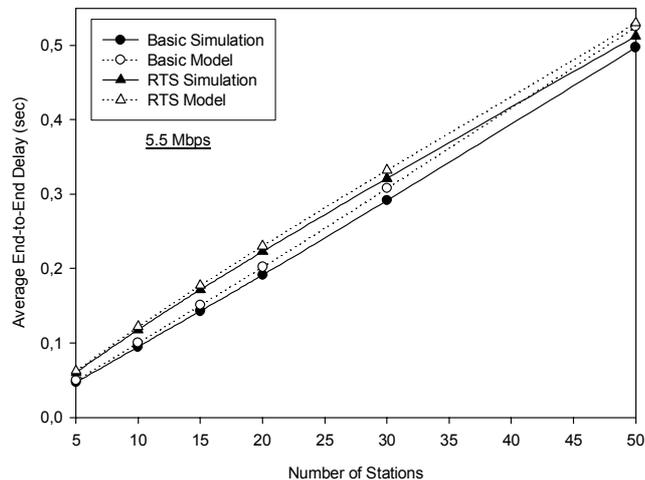


Figure 2. Average end-to-end packet delay versus the number of stations at 5.5 Mbps data rate.

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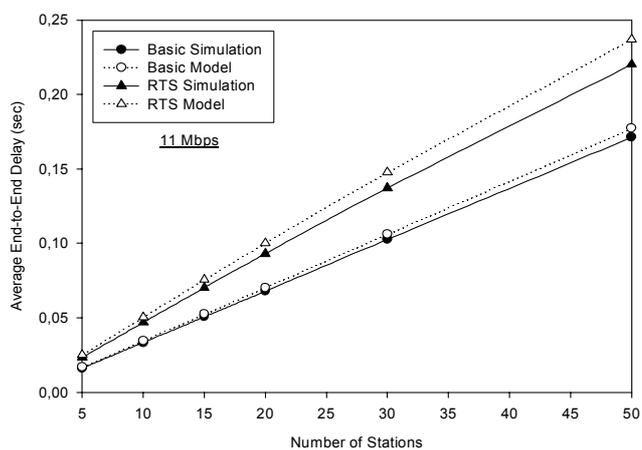


Figure 3. Average end-to-end packet delay versus the number of stations at 11 Mbps data rate.

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