On the Performance Behavior of IEEE 802.11 Distributed Coordination Function

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Abstract- **The basis of the Medium Access Control (MAC), proposed in IEEE 802.11 standard for wireless local area networks, is the Distributed Coordination Function (DCF). DCF uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to resolve contention between wireless stations and to verify successful transmissions. In this work we present an analytical model of the IEEE 802.11 MAC protocol validated by simulation results for the DCF throughput, for both packet transmission schemes employed by DCF, the basic access and the RTS/CTS access mechanism. Moreover, we depict the saturation throughput and the average packet delay for 1, 5.5 and 11 Mbps in order to highlight the effect of the bit rate on network performance for both mechanisms.**

Keywords: CSMA/CA, Distributed Coordination Function, IEEE 802.11b.

I. INTRODUCTION

During the past few years an increased need for extension of applications of wireless networks is observed, that corresponds in the rendering of effective performance services in higher data rates. Although IEEE 802.11b [1] provides a means for allocating a part of the channel bandwidth to some stations (PCF - Point Coordination Function), the commonly available access method (DCF - Distributed Coordination Function) uses the CSMA/CA protocol to allow contended access to the wireless medium under binary exponential backoff rules [2]. In CSMA/CA a scheme called *listen before talk* is implemented, where stations wishing to take control of the the medium have to sense if the channel is idle, which means no other stations are transmitting at this time. In addition, an acknowledgment frame (ACK) is used to verify a successful transmission and in the absence of it retransmission is scheduled.

The performance of IEEE 802.11 standard [2] has been highly investigated by several studies, through the presentation of simulation and analytical results. Bianchi in [3] uses a Markov process to demonstrate a simple and accurate analytical model for the saturation throughput of the network under ideal channel conditions. That is, the channel is assumed to be error-free. However, in [3] Bianchi does not take into consideration the backoff suspension, nor the finite number of retry attempts that the IEEE 802.11 standard [2] specifies. That is, a packet is being transmitted continuously until its successful reception. In [4], Wu et al. improve Bianchi's model by considering finite packet retry limits, but still ignoring the backoff suspension issue. In [5] Ziouva et al. confronted the backoff suspension case by adding a new probability p_b that denotes when the channel is busy, meaning that there is currently an ongoing transmission. However, they neglect the fact that after each successful transmission a new backoff procedure must commence according to the standard [1]. The key contribution of this paper is that not only do we adopt the use of probability p_b, as in [5], but also we give emphasis on the fact that after each successful transmission a new backoff procedure must commence. Moreover as in [4] we do consider finite retry limits which when reached the packet is discarded.

The goal of this paper is to combine together all the above features and produce a more accurate analytical model for saturation throughput. This model is compared with Wu's model [4] and validated via numerous simulations, with the aid of the famous simulator NS-2 [6]. The comparison proves that the analytical model leads to satisfactory results, as it is closer to the simulation results than Wu's model, even if when the number of stations increases and the channel bit rate varies.

The rest of this paper is organized as follows: Section II gives a brief overview of the DCF access method, while section III presents the proposed enhanced mathematical model. In section IV we proceed firstly into a throughput analysis and later on, we verify the throughput analytical results via detailed simulations. In Section V the valuable performance metric of the average end-to-end packet delay is measured. Finally, section VI concludes the paper.

II. OVERVIEW OF DCF

This section briefly describes the DCF operation, and the two access schemes that it uses the Basic access mode and the RTS/CTS access scheme as defined in the IEEE 802.11 standard [2].

A station wishing to transmit a new packet monitors the channel to determine if another station is transmitting. If the medium is sensed to be idle the station transmits its packet. Otherwise the station defers its transmission until the medium gets free for a time interval greater than DIFS (Distributed Inter Frame Space). After the DIFS time has elapsed, the station defers its transmission for an additional time which is randomly selected. When this time expires then stations are allowed to transmit. However, when stations attempt to transmit simultaneously a collision will occur. Therefore, with this scheme, collision probability is minimized, as stations who wish to transmit, are likely to wait for different time intervals before their transmissions commence and hence their packets are less likely to collide. The receiver station responds back to the source station with an ACK (acknowledgement) packet, a SIFS (Short InterFrame Space) time interval after the reception of the data packet. This way the successful transmission of the data packet is being verified. If an ACK packet is not detected by the source station then a retransmission is scheduled.

Each station maintains a counter, which for the Basic Access scheme is called short retry count (SSRC) and has an initial value of zero. The SSRC counts the number of times a packet is being retransmitted and when it exceeds a specific value m the packet is discarded. The backoff interval that a station has to wait before commence transmission is defined by the value of the backoff timer. This value is uniformly chosen in the range (0,w-1),where w-1 is known as Contention Window (CW). The CW is an integer chosen in the range (CWmin, CWmax), where CWmin, CWmax are determined by the characteristics of the PHY layer. At the first transmission attempt CW=CWmin and after each unsuccessful transmission w is doubled up to a maximum value $2^{m'}W$, where m' is the maximum number of backoff stages. The reader should note that W= (CW_{min}+1) and $2^{m'}W$ = (CW_{max}+1). Therefore, we have:

$$\begin{cases} W_i = 2^i W & i \le m' \\ W_i = 2^{m'} W & i > m' \end{cases} \quad (1)$$

where i is the backoff stage. We should note here that $i \in [0, m]$, where m represents the station's retry count. The 802.11b standard [1] specifies that m could be larger or smaller than m′ depending on the employed access scheme. For Basic access scheme we have m=7 and m′=5. Therefore for the Direct Sequence Spread Spectrum (DSSS), CW_{min} and CW_{max} are equal to 31 and 1023 respectively.

After the backoff timer value has been selected, it keeps decreasing as long as the wireless medium remains idle. If the medium is sensed to be busy, then the backoff timer is frozen to its current value (backoff suspension) and resumes, if the medium is sensed to be idle again for time more than DIFS. The station initiates its packet transmission when the backoff timer value reaches zero.

Furthermore, DCF provides an optional way for packet transmission the so called RTS/CTS access mode. The main goal of this access scheme is not only to tackle the hidden terminal problem, but also to reduce the time wasted on collisions. The sender transmits a short Request To Send (RTS) packet prior to the transmission of the data packet. After a SIFS interval from the reception of the RTS packet the receiver station responds with a Clear To Send (CTS) packet. If the CTS packet is not detected by the sender then the station enters backoff stage 0 and a new RTS packet is being sent. The transmission of the data packets begins only after the successful reception by the sender of the CTS frame.

III. MATHEMATICAL MODEL

The core of the analytical model follows the same assumptions as in [3]. The network consists of n stations and each one has always a packet in its transmission queue, available for transmission (saturated stations). Moreover, the key assumption of this paper is the same as in [3],[4] and [5].That is, at each transmission attempt regardless of the number of retransmissions suffered, each packet collides with a constant and independent probability p. Furthermore, as in [5] we assume that p_b, stands for the probability that the channel is busy and is independent of the backoff procedure. Note also that the time slot is equal to the system time slot σ, only if there is no medium activity on the channel. Otherwise, time slot is the time demanded, either to complete a successful transmission, or the time to perform a failed transmission.

Let {s(t),b(t)} be a bi-dimensional, discrete time Markov chain, which is shown in Fig 1.Here s(t) is the stochastic process which represents the backoff stage at different CW levels and b(t) is the stochastic process which represents the backoff counter for a given station at slot time t.

The state transition diagram of the Markov chain model shown in Fig.1 has the following one-step transmission probabilities:

1. The backoff counter decrements when the station senses the channel idle:
$$P\{i,k \mid i,k+1\} = 1 - p_b,\ k \in [0, W_i - 2],\ \ i \in [0, m]$$
2. The backoff counter freezes when the channel is busy:
$$P\{i,k \mid i,k\} = p_b, k \in [1, W_i - 1],\ \ i \in [0, m]$$
3. The station enters backoff stage 0, if it detects a successful transmission of its current frame:
$$P\{0,k \mid i,0\} = \frac{(1-p)}{W_0}, k \in [0, W_0 - 1],\ \ i \in [0, m-1]$$
4. The station enters into the next backoff stage and chooses a new value for the backoff counter after an unsuccessful transmission:
$$P\{i,k \mid i-1,0\} = \frac{p}{W_i}, k \in [0, W_i - 1],\ \ i \in [1, m]$$
5. The station reaches the last backoff stage and returns to the initial backoff stage after a successful or unsuccessful transmission:
$$P\{0,k \mid m,0\} = \frac{1}{W_0}, k \in [0, W_0 - 1]$$

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

$$b_{i-1,0} \cdot p = b_{i,0} \Leftrightarrow b_{i,0} = p^i \cdot b_{0,0}, \quad i \in [0,m] \quad (2)$$

$$b_{i,k} = \begin{cases} \frac{W_i - k}{W_i} \cdot \left[(1-p) \cdot \sum_{j=0}^{m-1} b_{j,0} + b_{m,0} \right] & i = 0 \\ \frac{W_i - k}{W_i} \cdot \frac{1}{1-p_b} \cdot b_{i,0} & 0 < i \le m \end{cases} \quad (3)$$

The normalization condition for the stationary distribution is

$$1 = \sum_{i=0}^{m} \sum_{k=0}^{W_i - 1} b_{i,k} \quad (4)$$

Thus, using equations (1), (3) and (4) we can express the value $b_{0,0}$ as a function of the probabilities p and p_b, as shown in equation (5).

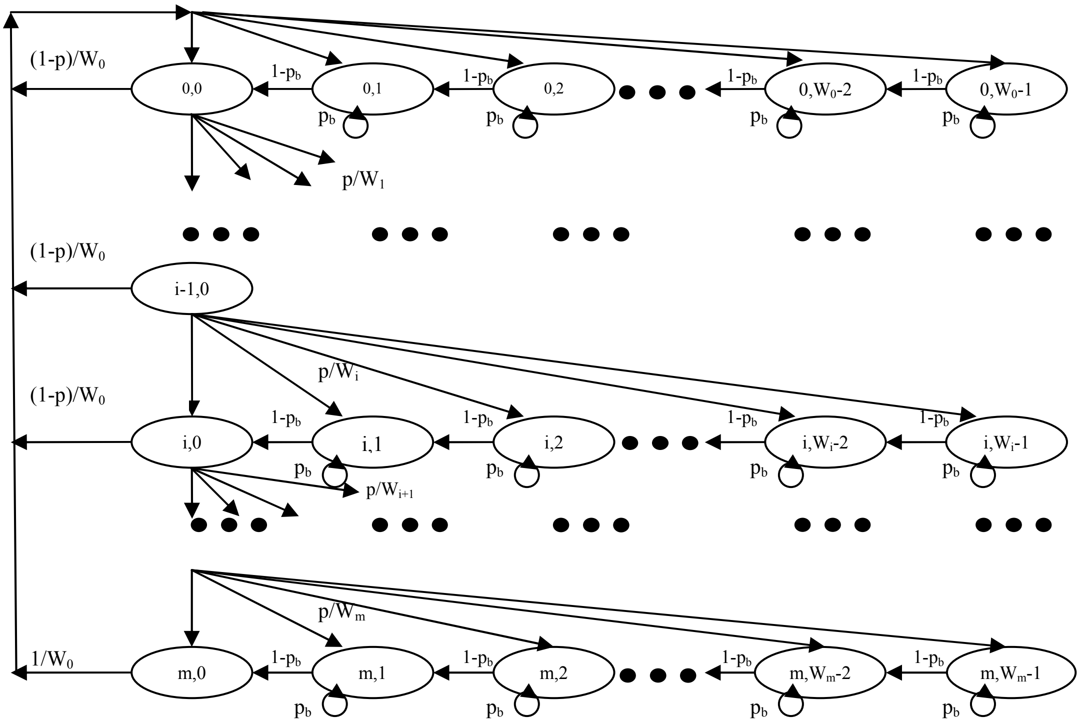

Figure 1. The state transition diagram for the Markov chain model.

$$b_{0,0} = \begin{cases} \dfrac{2(1-p_b)(1-2p)(1-2p)}{(1-p_b)(1-p)(1-2p)(W+1)(1-p^{m+1}) + 2pW(1-p)[1-(2p^{m'})] + (1-2p)p[1-p^{m} + (2p)^{m'} W(1-p^{m-m'})]} & m > m' \\ \dfrac{2(1-p_b)(1-p)(1-2p)}{(1-p_b)(1-p)(1-2p)(W+1)(1-p^{m+1}) + 2pW(1-p)[1-(2p^{m})] + (1-2p)p(1-p^{m})} & m \le m' \end{cases} \quad (5)$$

Now we can calculate the probability τ that a station transmits in a randomly chosen slot time. Therefore we have the following equation (6):

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{1-p^{m+1}}{1-p} b_{0,0} \quad (6)$$

Equations (5) and (6) show that the calculation of the probability τ depends on the conditional collision probability p and the probability p_b that the channel is busy. The probability that in a time slot at least one of n-1 remaining stations transmit is

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

Furthermore, the channel is detected busy when at least one station transmits during a slot time. Note also that a station remains with probability p_b at state (i,k) , k≥1 when at least one of n-1 remaining stations transmit, therefore:

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

Equations (6), (7) and (8) represent a nonlinear system with three unknowns, τ, p and p_b, and it can be solved using a numerical method.

IV. Throughput Analysis And Results

Let P_s be the probability that an occurring packet transmission is successful and P_{tr} the probability that there is at least one transmission in a randomly selected slot time. Therefore,

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \quad (9)$$

$$P_{tr} = 1-(1-\tau)^n \quad (10)$$

Using the same symbols as those in [3], the normalized system throughput can be expressed as the ratio

$$S = \frac{\text{E[Payload Information in a slot time]}}{\text{E[Length of a slot time]}} = \frac{P_s P_{tr} E[P]}{(1-P_{tr})\sigma + P_s P_{tr} T_s + (1-P_s) P_{tr} T_c} \quad (11)$$

where E[P] is the average packet length, σ the duration of an empty slot time and, T_s , T_c are the average time the channel is sensed busy due to a successful transmission and collision respectively. The values of T_s and T_c depend on the access mechanism and considering the ACK and CTS timeout effect [7] we have:

$$\begin{cases} T_s^{bas} = DIFS + H + T_D + SIFS + T_{ACK} + 2\cdot\delta \\ T_C^{bas} = DIFS + H + T_D + SIFS + T_{ACK} + 2\cdot\delta \end{cases} \tag{12}$$

$$\begin{cases} T_s^{rts} = DIFS + T_{RTS} + H + T_{CTS} + T_D + \\ 3\cdot SIFS + T_{ACK} + 4\cdot\delta \\ T_C^{rts} = DIFS + T_{RTS} + SIFS + T_{CTS} + 2\cdot\delta \end{cases}$$

where T_D, T_{ACK}, T_{RTS} and T_{CTS} is the time required to transmit the E[P], ACK, RTS and CTS respectively, δ is the propagation delay and $H=MAC_{hdr}+PHY_{hdr}$ is the packet header.

All the parameters used in simulation and the analytical model are summarized in Table 1 and follow the DSSS parameters in paper [8]. Note that the analytical model is independent of the parameters, so it can be implemented for different PHY layers.

Packet Payload	8224 bits
Channel Bit Rate	1,5.5,11 Mbps
MAC Header	224 bits[1]
PHY Header	192 bits
Propagation Delay	1 µs
Slot Time	20 µs
DIFS	50 µs
SIFS	10 µs
ACK	112 bits + PHY Header
CTS	112 bits + PHY Header
RTS	160 bits + PHY Header

Table 1. Parameters for MAC and DSSS PHY Layer

To validate our analytical model we used the NS-2 from Lawrence Berkeley National Laboratory [6]. The network topology consists of an area of 100m x 100m, and an Access Point (AP) is placed in the centre of the simulation area. Around the AP there are several stations, forming a circle of radius R=50m. Each station sends Constant Bit Rate (CBR) traffic at the AP using UDP connections, at such a rate that ensures that the transmission queues of the stations are always nonempty. In order to avoid intermediate hops and therefore throughput degradation, no routing protocol is used. All stations have Line Of Sight, so all can hear about each other and have no mobility at all. Therefore the hidden terminal problem and the capture effect can be ignored.

The IEEE 802.11b standard [1] specifies various channel bit rates, thus we proceed in an extensive investigation into how throughput is affected by the medium data rate via numerous simulations. All results have been obtained with five replications each time with different random seed with a 95% confidence interval, lower than 1% and the average value is used in the patterns.

First we see the results for saturation throughput obtained for 1 Mbps bit rate for both basic and RTS/CTS access mechanisms, shown in Fig.2. The solid lines represent the average throughput obtained from our simulation and the dashed lines the basic and RTS/CTS schemes from Wu's model [4]. We see that the new analytical model is closer to our simulation results than Wu's model, especially when the size of the network is increasing. In a densely populated network, stations will have to suspend their backoff counter more often and therefore, such a mechanism benefits saturation throughput. Note also that our analytical curve is very close to the simulation results for both access modes. Moreover, we can see that the RTS/CTS mode gives a greater throughput than the basic mode for all number of active (saturated) stations. This is because in RTS/CTS mode collisions only involve RTS packets, which are relatively small in size. Hence the bandwidth wasted on collisions is much less severe compared to the wasted bandwidth of basic mode.

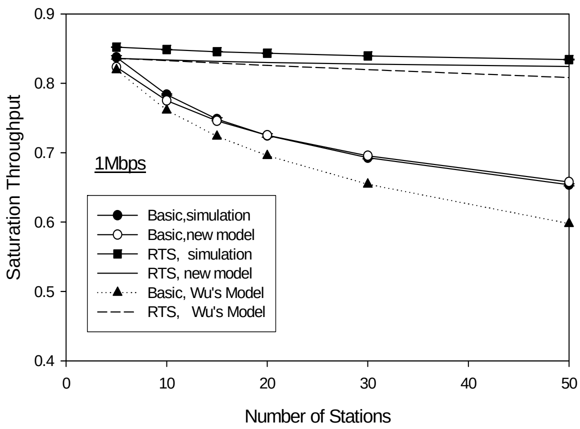

Figure 2. Simulation versus analysis at 1 Mbps bit rate for both access mechanisms

The same simulation scenario is used for measuring the saturation throughput for 5.5 and 11 Mbps, shown in Figs. 3 and 4 respectively. In both cases, analysis and simulation are in satisfactory agreement. When data rate increases then Basic mode is preferable as the RTS/CTS throughput degrades severely, due to enormous low-speed overhead that the RTS/CTS mode introduces. Note that RTS and CTS control packets are traveling across the network at the low rate of 1Mbps. Throughput efficiency also decreases as the data rate increases. That is happening, because, as data rate increases, the time spent for packet transmission is decreased, but the backoff delay and the DIFS and SIFS intervals do remain unchanged.

V. AVERAGE DELAY MEASUREMENTS

The simulation scenario for the average end-to-end packet delay holds the same topology as the one we used for throughput. Fig. 5 depicts the average packet delay for both access mechanisms at 1, 5.5 and 11 Mbps. The crucial point here is, that as the size of the network is increasing, and so does the average packet delay for both access schemes, irrespective of the channel data rate employed. However, as the channel bit rate increases, delay for both access schemes decreases. This is due to the fact that time needed for data transmission is in this case significantly shorter. However, note that SIFS, DIFS and slot time do remain constant.

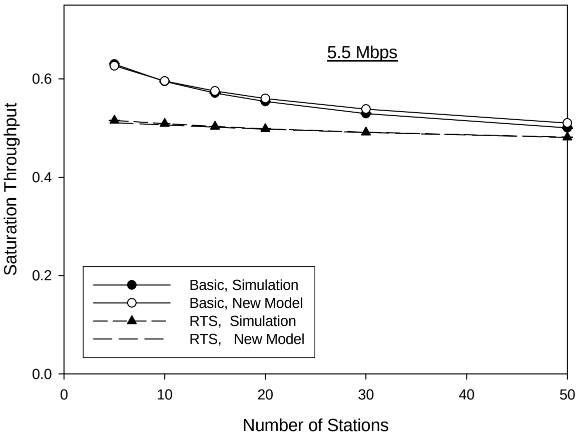

Figure 3. Simulation versus analysis at 5.5 Mbps bit rate for both access mechanisms

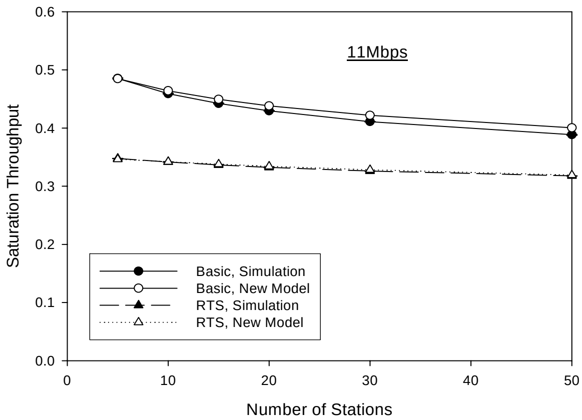

Figure 4. Simulation versus analysis at 11 Mbps bit rate for both access mechanisms

Another extremely interesting point is that the delay observed on the RTS/CTS mode is lower than the delay of basic access mode only for 1Mbps channel rate. This is against common expectation as on RTS/CTS mode collisions can occur only on the short RTS frames, thus collision duration is significantly decreased and RTS delay is expected to be lower than basic delay, as the number of active stations in the network increases. Note that the packet payload used for all simulations is 1000 bytes, so in basic access we encounter larger collision durations, which certainly lead to higher delay values.

However, for 5.5 and 11 Mbps, RTS/CTS delay is getting slightly larger than the basic delay as the network grows. This is justified, as RTS/CTS mode introduces additional overhead (because of the transmission of RTS and CTS control packets). These control packets are transmitted at 1 Mbps at all data rates. This might not have an influence on 1 Mbps data rate, but does make a difference at higher data rates. Therefore, we could say that it is rather deficient to use the RTS/CTS scheme for high data rates, a conclusion derived from the interpretation of Fig.5.

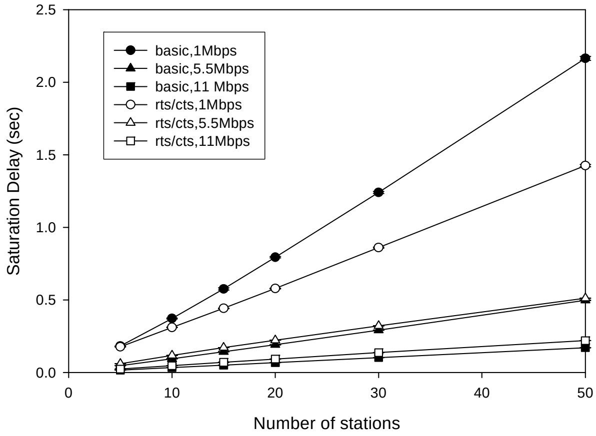

Figure 5. Average packet delay for both access mechanisms.

VI. CONCLUSIONS

In this paper a bi-dimensional discrete time Markov chain was used to obtain a new analytical model for the saturation throughput performance of the 802.11b Distributed Coordination Function. Comparisons with the model presented in [4] and simulation results show that the new model provides greater saturation throughput. Satisfactory results were observed for both access mechanisms and for various channel bit rates. We also studied through simulation, the effect of the bit rate and the access method on average packet delay. The superiority of RTS/CTS access mechanism in 1 Mbps descends as the data rate increases, and overall delay is significantly reduced.

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