Throughput and delay analysis of IEEE 802.11 protocol

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Abstract - **Wireless technologies in the LAN environment are becoming increasingly important. The IEEE 802.11 standard is the most mature technology for Wireless Local Area Networks (WLANs). The performance of the Medium Access Control (MAC) layer, which consists of Distributed Coordination Function (DCF) and Point Coordination Function (PCF), has been examined over the past years. In this paper, we present an analytical model to compute the saturated throughput of 802.11 protocol in the absence of hidden stations and transmission errors. A throughput analysis is carried out in order to study the performance of 802.11 DCF. Using the analytical model, we develop a frame delay analysis under traffic conditions that correspond to the maximum load that the network can support in stable conditions. The behaviour of the exponential backoff algorithm used in 802.11 is also examined.**

I. Introduction

Recent advances in wireless technology have equipped portable devices with wireless capabilities that allow networked communication even while a user is mobile. These devices include palmtop computers, personal digital assistants (PDAs), portable computers, digital cameras and printers.

To deal with this wireless connectivity need, various wireless communication standards have been developed [1]. Two major projects have been involved in standardizing the physical and the medium access control (MAC) layers for wireless LANs, namely IEEE 802.11 [2] and ETSI HiperLAN [3]. This paper focuses on the analysis of the MAC protocol of the IEEE 802.11 protocol which is the most widely used WLAN protocol today.

The IEEE 802.11 standard for wireless networks incorporates two medium access methods. The mandatory Distributed Coordination Function (DCF) method and the optional Point Coordination Function (PCF) which provides Time Bounded Services (TBS). DCF is an asynchronous data transmission function, which best suits delay insensitive data (e.g. email, ftp). It is available in ad-hoc or infrastructure network configurations and can be either used exclusively or combined with PCF in an infrastructure network. PCF, on the other hand, best suits delay sensitive data transmissions (e.g. real-time audio or video) and is only available in infrastructure environments.

A common problem in wireless LAN systems is hidden stations. The presence of hidden stations may result in significant network performance degradation and causes unfairness in accessing the medium because a station's location may result in a larger transmission privilege. The hidden station problem occurs when a station is causing interference due to not been able to detect the existence of a transmission from another station and thus assumes that the medium is free and available to transmit. As an example, lets assume that stations A and B are within communication range of each other and station C is within communication range of station B, but not of A. Therefore, it is possible that both stations A and C could try to transmit to station B at the same time causing a collision. The influence of hidden stations [4] on the performance of an IEEE 802.11 network has been studied in [5].

The performance of CSMA protocols over radio channels was investigated in [6]. The MACAW protocol [7] was designed to improve wireless communication performance based on collision avoidance technique. MACAW is based on the Multiple Access Collision Avoidance (MACA) protocol introduced in [8] and enhances MACA's performance.

Several other papers [9][10][11][12] have studied the efficiency of the IEEE 802.11 protocol by investigating the maximum throughput that can be achieved under various network configurations. Reference [13] analyses the backoff mechanism and proposes alternatives. Also, in [14] the throughput of a CMSA/CA protocol is calculated using a simple model that is space dependent and the fairness problem is considered. Reference [15] investigates the IEEE 802.11 MAC protocol capacity by deriving an accurate analytical estimate of it. Moreover, an extension of the protocol backoff algorithm is proposed.

Bianchi [16] presents a simple analytical model to compute the saturation throughput performance assuming a finite number of stations and ideal channel conditions. In contrast, [17] is based on the same model and assumptions and takes into account the frame retry limit. As a result, the throughput of 802.11 can be predicted more accurately.

In our work a delay analysis of both access mechanisms, basic and RTS/CTS, is developed. This delay analysis is applied to the model initially presented in [17]. Since, the frame retry limit is included, the model is considered to predict the 802.11 frame delay in an accurate way.

The paper is organized as follows: Section II presents in detail the IEEE 802.11 MAC protocol and includes both basic access and RTS/CTS mechanism. Section III reviews the protocol model presented in [17]. Section IV presents the performance evaluation of both DCF access mechanisms. In Section V, a frame delay analysis is developed based on the previous mathematical model. Finally, section VI concludes the paper and presents future work.

II. Distributed Coordination Function (DCF)

The *basic service set* (BSS) is the basic building block of IEEE 802.11 WLANs. The coverage area of a BSS is referred to as the *basic service area* (BSA). A station that is a member of the BSS within the BSA may continue communicating with other members of the BSS. The IEEE 802.11 defines two types of network architecture, the *ad hoc* network and the *infrastructure* network. An ad hoc network deliberates on the grouping of stations into a BSS without the need for any infrastructure implementation. This type of IEEE 802.11 WLAN is often formed for only as long as the WLAN is needed. The infrastructure networks, in contrast to the ad hoc networks, create a range extension and obtain some specific services from other wired or wireless LANs via infrastructure implementations.

The DCF is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. Under DCF, data frames are transferred via two methods. The essential method used in DCF is called Basic Access method and it is shown is Fig. 1. The 802.11 standard also provides an alternative way of transmitting data frames, namely the RTS/CTS method, illustrated in Fig. 2.

Carrier sensing can be performed on both the physical and MAC layers. On the physical layer, physical carrier sensing is done by detecting any channel activity by other stations. In addition to the physical channel sensing, virtual carrier sensing is achieved by using time fields in the frames, which indicate to other stations the duration of the current transmission. All stations that hear the data or the RTS frame, update their Network Allocation Vector (NAV) field based on the value of the duration field in the received frame which includes the SIFS and the ACK frame transmission time following the data frame, before sensing the medium again.

A. The basic access method

Priority access to the wireless medium is controlled by the use of the interframe space (IFS) time period between the transmission of frames. The IFS defines the minimal time that a station has to let pass after the end of a frame, before it may start transmitting a certain type of frame. In 802.11 three different IFS intervals have been specified to provide various priority levels for access to the wireless medium: Short IFS (SIFS), Point Coordination Function IFS (PIFS) and DCF-IFS (DIFS). The SIFS is the smallest followed by PIFS and DIFS. After a SIFS (the shortest interframe space) only acknowledgements, CTS and data frames may be sent. The use of the PIFS and the DIFS is used to separate the PCF and DCF modes, giving a higher priority to the former.

In order to minimize the probability of collisions, a random backoff mechanism is used to randomize moments at which stations are trying to access the wireless medium. This contention resolution technique is called binary exponential backoff (BEB). In particular, the time following an idle DIFS is slotted and a station is allowed to transmit only at the beginning of each slot. A slot time is equal to the time needed by any station to detect the transmission of a frame from any other station. The backoff counter is decremented when the medium is idle and is frozen when the medium is sensed busy. After a busy period the backoff resumes only after the medium has been idle longer than DIFS. A station initiates a frame transmission when the backoff counter reaches zero.

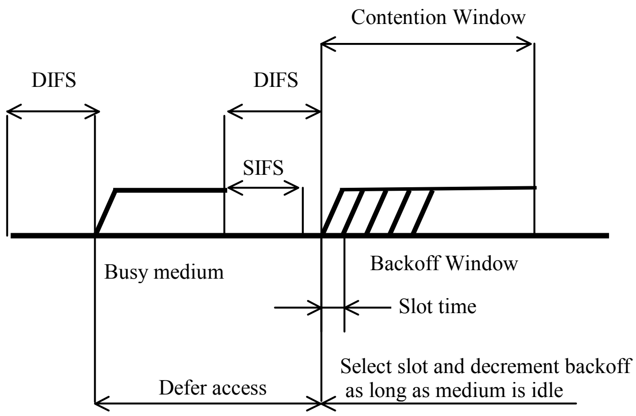

Fig. 1 Basic Access mechanism

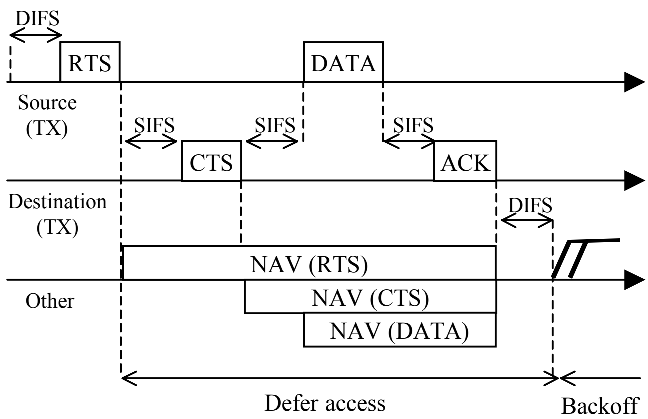

Fig. 2 RTS/CTS mechanism

Every station maintains a station short retry count (SSRC) as well as a station long retry count (SLRC), both of which have an initial value of zero. The short retry count indicates the number of retransmissions of RTS frames or of the data frames when RTS/CTS is not used. The long retry count indicates the number of retransmissions of data frames when RTS/CTS is used.

The contention window (*CW*) is chosen in the interval (0,*CW*-1). The value of *CW* depends on the number of failed transmissions of a frame. At the first transmission attempt, *CW* is set equal to CW_{min} which is called minimum contention window. A collision occurs when two or more stations start transmission simultaneously in the same slot. After each retransmission due a collision, *CW* is doubled up to a maximum value, $CW_{\max} = 2^{m'} \cdot CW_{\min}$ where m' is the number of different contention window sizes . Once the *CW* reaches CW_{max}, it will remain at the value of CW_{max} until it is reset.

The *CW* is reset to CW_{min} in the following cases: (a) after every successful transmission of a data frame, (b) when SSRC reaches the *ShortRetryLimit* and (c) when SLRC reaches the *LongRetryLimit*. When either of these limits is reached, retry attempts shall cease and the frame shall be discarded. The SSRC is reset to 0 whenever a CTS is received in response to a RTS or whenever an ACK is received in response to a data frame. The SLRC is also reset to 0 whenever a ACK is received in response to a data frame when the RTS/CTS is used.

After a successful frame transmission, if the station still has frames buffered for transmission, it must execute a new backoff process. The set of *CW* values are sequentially ascending integer powers of 2 minus 1 and Fig. 3 is illustrates this exponential increase of *CW*.

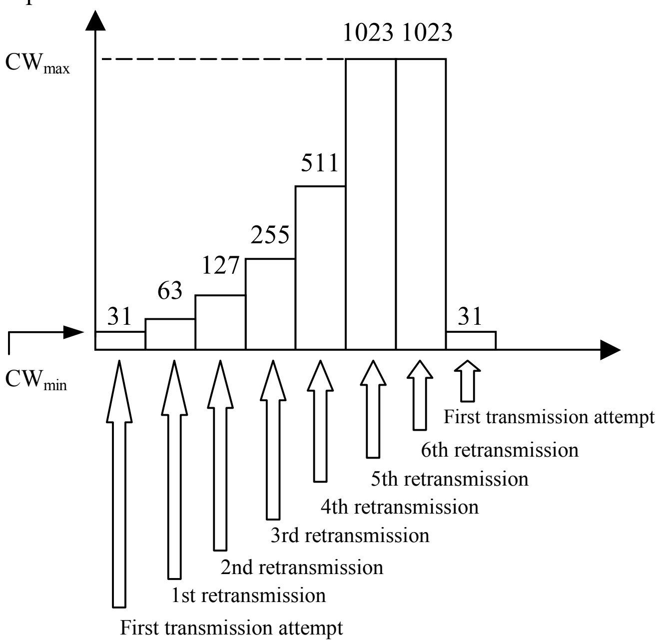

Fig. 3 The exponential increase of CW

After receiving correctly a frame in the destination station, an immediate positive acknowledgment (ACK) is sent to confirm the successful reception of the frame transmission after a time interval equal to SIFS. Since the SIFS interval is shorter than the DIFS interval, the station sending an ACK attempts transmission before stations attempting to send data and hence takes priority. If the source station does not receive an ACK, the data frame is assumed to have been lost and a retransmission is scheduled.

B. The RTS/CTS access method

In 802.11, DCF also defines an optional way of transmitting data frames with transmitting short RTS and CTS frames before the transmission of the actual data frame. The RTS/CTS mechanism is mainly used to minimize the amount of time wasted when a collision occurs and to address the hidden station problem. When the destination receives a RTS frame, it transmits a CTS frame immediately after a SIFS interval. The source station is allowed to transmit its data frame only if it receives the CTS correctly. If the CTS is not received by the source station, it is assumed that a collision occurred and a RTS retransmission is scheduled. After the data frame is received by the destination station, an acknowledgement frame is sent back to the source, verifying successful data reception. The RTS/CTS exchange is shown in Fig.2.

Since all stations are adjusting their NAV based on the duration field value of the RTS from the source station or the CTS from the destination station, the use of RTS/CTS frames helps to minimize the duration of collisions and the collisions caused by hidden stations. More specifically, if a collision occurs with two or more small RTS frames, the time loss is smaller compared to the collision of long data frames. Furthermore, the successful exchange of small messages, RTS and CTS, reserves the area within the range of the receiver and the sender for the intended transmission period guaranteeing undisturbed transmission for the longer data frame. On the other hand, RTS/CTS decreases efficiency since it transmits two additional frames without any payload. For that reason, there is a manageable object *RTS_Threshold* that indicates the data length under which the data frames should be sent without RTS/CTS. The data frame size is the only parameter that is used to decide whether the mechanism is applied. The *RTS_Threshold* parameter is not fixed in the 802.11 standard and has to be set separately by each station.

III. ANALYTICAL MODEL

In this paper, the assumptions necessary for the presented analytical framework are as follows:

1. We ignore the effect of frame errors due to bit errors introduced by channel noise. Therefore frames are received in error only when they encounter collisions due to other simultaneous transmissions.
2. No hidden stations and propagation delays are considered.
3. We assume that the network consists of a finite number of contending stations *n* and that every station always has a packet available for transmission (saturated conditions).
4. The main approximation is that the collision probability of a transmitted frame is constant and independent of the number of retransmissions that this frame has experienced in the past.

Let us consider the following sequence of events in a successful frame transmission using the RTS/CTS access method:

1. t_0 : Station A begins transmitting RTS.
2. $t_1 = t_0$+RTS : RTS finished.
3. $t_2 = t_0$+RTS+SIFS : Station B begins transmitting CTS.
4. $t_3 = t_0$+RTS+SIFS+CTS: CTS finished.
5. $t_4 = t_0$+RTS+SIFS+CTS+SIFS: Station A begins transmitting DATA frame.
6. $t_5 = t_0$+RTS+SIFS+CTS+SIFS+DATA: DATA finished.

7. t_6 = t_0+RTS+SIFS+CTS+SIFS+DATA+SIFS: Station B begins transmitting ACK frame.
8. t_7 = t_0+RTS+SIFS+CTS+SIFS+DATA+SIFS+ACK: ACK finished.
9. t_8 =t_0+RTS+SIFS+CTS+SIFS+DATA+SIFS+ACK+DIFS: Next contention period starts.

From the above sequence of events, the time required for a *successful transmissio*n, i.e., the time interval between the start of a non-colliding transmission and the reception of the ACK frame, can be easily calculated.

A. Transmission Probability

Let *b(t)* be the stochastic process representing the backoff time counter and *s(t)* be the stochastic process representing the backoff stage for a given station at slot time *t*. The bidimensional process {*b(t), s(t)*} can be modelled with a discrete-time Markov chain depicted in Fig. 4. If $b_{i,k} = \lim_{t\to\infty} P\{s(t)=i, b(t)=k\}$, where $i \in [0,m]$ $k \in [0, W_i-1]$ is the stationary distribution of the Markov chain, then we can calculate the probability $b_{i,k}$. We have the following relations :

$$b_{i,0} = p \cdot b_{i-1,0} \ , \qquad 0 < i \le m \tag{1}$$

$$b_{i,0} = p^i \cdot b_{0,0} \ , \qquad 0 \le i \le m \tag{2}$$

$$\begin{cases} W_i = 2^i \cdot W & i \le m' \\ W_i = 2^{m'} \cdot W & i > m' \end{cases} \tag{3}$$

where *m* represents the station short retry count and is equal to 7 according to the standard [2]. Here *m* is also the maximum backoff stage and can have a value larger or smaller than *m'*. For the DSSS physical layer in 802.11b, we have *m'* =5.

As the chain is regular, for each $k \in [0, W_i-1]$ we have:

$$b_{i,k} = \frac{W_i - k}{W_i} \cdot \begin{cases} (1-p)\cdot \sum_{j=0}^{m-1} b_{j,0} + b_{m,0} & , \quad i = 0 \\ p \cdot b_{i-1,0} & , \quad 0 < i \le m \end{cases} \tag{4}$$

Using (2), (4) can be simplified as:

$$b_{i,k} = \frac{W_i - k}{W_i} \cdot b_{i,0} \quad , \quad 0 \le i \le m \tag{5}$$

Equations (2) and (5) express all $b_{i,k}$ values as a function of $b_{0,0}$ and of collision probability *p*. If the normalization condition is imposed, we have:

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

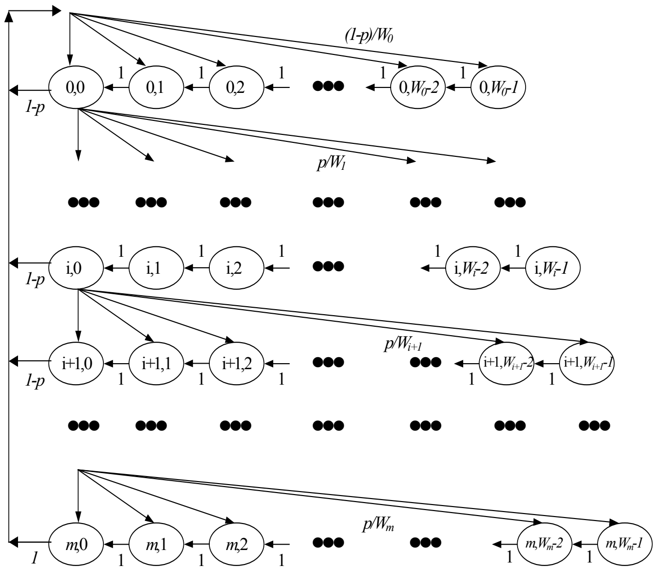

Fig. 4 Markov chain model

By means of (3) and after some algebra, finally $b_{0,0}$ is given by (6).

A station transmits when the backoff counter reaches the value of zero and the transmission probability τ that a station transmits a frame in a randomly chosen slot time can be evaluated as:

$$\tau = \sum_{i=o}^{m} b_{i,0} = \sum_{i=o}^{m} p^i \cdot b_{0,0} = b_{0,0} \cdot \frac{1 - p^{m+1}}{(1-p)} \tag{7}$$

and $b_{0,0}$ values can be acquired from (6).

The transmission probability τ depends on the collision probability *p* which is still unknown and it will be derived next. The probability *p* that a transmitted frame encounters a collision, is the probability that at least one of the *n-1* remaining stations transmit in the same time slot. If we assume that all stations see the system in the steady state and transmit with probability τ, the collision probability *p* is given by:

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

Equations (7) and (8) form a nonlinear system with two unknowns τ and *p*. This nonlinear system can be solved utilizing numerical methods and has a unique solution.

The previous analysis follows closely the performance analysis of IEEE 802.11 in [17].

$$b_{0,0} = \begin{cases} \dfrac{2\cdot(1-2p)\cdot(1-p)}{W\cdot(1-(2p)^{m+1})\cdot(1-p) + (1-2p)\cdot(1-p^{m+1})} & , \ m \le m' \\ \\ \dfrac{2\cdot(1-2p)\cdot(1-p)}{W\cdot(1-(2p)^{m'+1})\cdot(1-p) + (1-2p)\cdot(1-p^{m+1}) + W\cdot 2^{m'}\cdot p^{m'+1}\cdot(1-2p)\cdot(1-p^{m-m'})} & , \ m > m' \end{cases} \tag{6}$$

B. Throughput analysis

The maximum load that the system can carry in stable conditions is defined as the saturation throughput and is the limit that the system throughput reaches as the offered load increases [16]. P_{tr} is defined as the probability that at least one transmission occurs in a given slot time. Since n stations contend to access the medium and each station transmits with probability τ, P_{tr} is given by:

$$P_{tr} = 1 - (1-\tau)^n \quad (9)$$

The probability P_s that an occurring transmission is successful is given by the probability that a station is transmitting and the remaining $n-1$ stations remain silent, conditioned on the fact that at least one station transmits:

$$P_s = \frac{n \cdot \tau \cdot (1-\tau)^{n-1}}{1-(1-\tau)^n} \quad (10)$$

Thus, throughput can be expressed by dividing the time needed to transmit payload information transmitted in a slot time with the average length of a slot time:

$$S = \frac{P_{tr} \cdot P_S \cdot E[P]}{(1-P_{tr}) \cdot \sigma + P_{tr} \cdot P_S \cdot T_S + (1-P_S) \cdot P_{tr} \cdot T_C} \quad (11)$$

where T_s is the average time that the medium is sensed busy due a successful transmission, T_c is the average time that the medium is sensed busy by each station when a collision occurs and σ is the duration of an empty slot.

The values of T_s and T_c depend on the channel access mechanism. Assuming that all stations use the same channel access mechanism, T_s and T_c are defined as follows:

Basic access mechanism:

If $H = MAC_{hdr} + PHY_{hdr}$ is the frame header, the average time delays T_s and T_c for the basic access mechanism are:

$$\begin{cases} T_S^{bas} = DIFS + H + E[P] + SIFS + ACK + \sigma \\ T_C^{bas} = DIFS + H + E[P_C] + \sigma \end{cases}$$

where $E[P_c]$ is the average length of the longest frame payload involved in a collision. Since it is assumed for simplicity that the size of all frames is the same and fixed, therefore, $E[P] = E[P_c] = P$. Furthermore, there is an extra delay equal to a slot time σ because the next slot is empty after a transmission.

RTS/CTS access mechanism:

If the RTS/CTS access mechanism is employed, we have:

$$\begin{cases} T_S^{RTS} = DIFS + RTS + SIFS + CTS + SIFS \\ \qquad + H + E[P] + SIFS + ACK + \sigma \\ T_C^{RTS} = DIFS + RTS + \sigma \end{cases}$$

The above values of T_c represent the period of time during which the channel is sensed busy after a collision by the non-colliding stations. For the two or more colliding stations, there is an extra delay because the colliding stations have to wait for time equal to $ACK_{timeout}$ or $CTS_{timeout}$ before sensing the medium again. This additional delay is neglected and for these colliding stations T_c has a bigger value than the value considered here.

IV. Throughput Analysis Results

This paper uses all the parameters for Direct Spread Sequence Spectrum (DSSS) physical layer used in 802.11b.

Fig. 5 plots throughput versus frame size for both the basic access and RTS/CTS cases for three different network sizes (n=5, 25 and 50) for C=1Mbps. The throughput increases as the frame size increases. However, we see that if the number of the active stations is relatively small, n=5, the throughput of the basic access is higher than the throughput of the RTS/CTS if the frame size is up to 7000 bits. That means that the RTS/CTS mechanism should be employed when the packet size exceeds a specific threshold and in this case the threshold is equal to about 7000 bits. This threshold decreases to about 1900 and 1000 when the network is composed by 25 and 50 stations respectively. Additionally, the figure shows that the RTS/CTS mechanism does not result in significant throughput improvement for small networks However, for large networks, the RTS/CTS mechanism is extremely beneficial for the performance compared to the basic access mechanism.

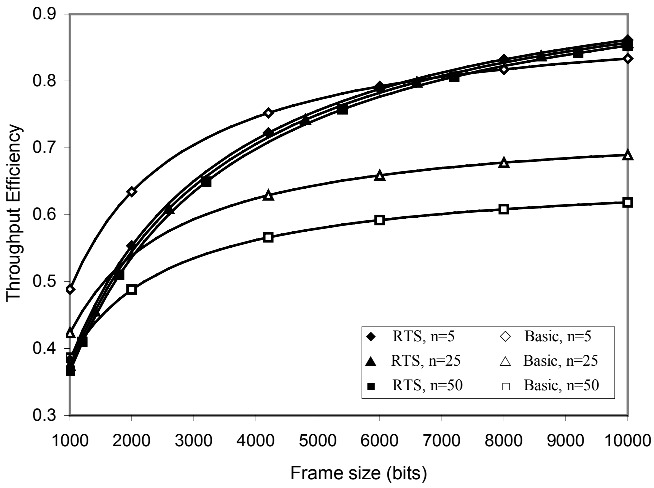

Fig. 5 Throughput versus frame size for C=1Mbps

Since the IEEE 802.11b standard specifies various data rates, it is interesting to study how the throughput is affected by the medium data rate. Fig. 6, plots throughput versus number of stations for three different data rates (C=1, 5.5 and 11 Mbps) for both medium access mechanisms for frame size (l=8224 bits).

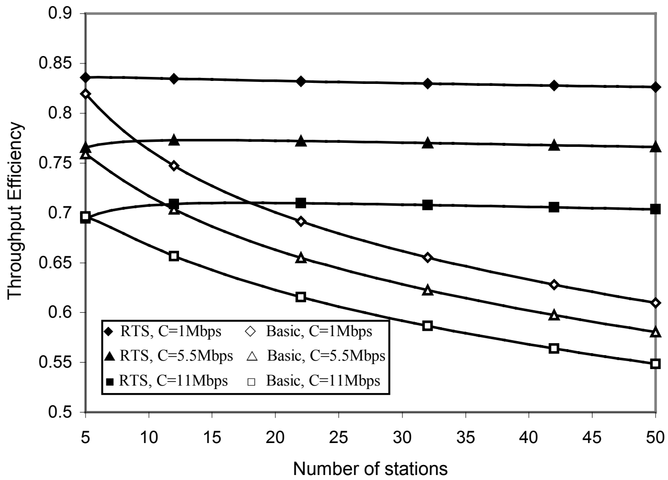

Fig. 6 Throughput versus number of stations

This figure illustrates that the throughput performance weakly depends on the number of the stations for all data rates when RTS/CTS is employed. On the other hand, if basic access is used, the throughput decreases as the number of the stations increases because more collisions take place. Moreover, the throughput efficiency is reduced when the data rate increases. The situation is explained by considering that the time spent for frame transmission is decreased as the data rate increases but the time overhead spent on DIFS, SIFS and the backoff delay remains the same.

V. DELAY ANALYSIS

Since no hidden nodes are considered, collisions take place because two or more contending stations choose the same backoff slot to transmit. The time needed for a frame transmission is considered to start when a frame becomes head of the station's queue and is finalized when an positive acknowledgement is received.

Assuming that the frame drop probability is very low and can be neglected, the average frame delay $E[D]$ is given by:

$$E[D] = E[X] \cdot E[\text{length of a slot time}] \quad (12)$$

where $E[X]$ is the average number of slot times required for successfully transmitting a new frame and E[length of a slot time] is the average length of a slot time.

According to [16], E[length of a slot time] is equal to:

$$E[\text{length of a slot time}] = (1-P_{tr})\cdot\sigma + P_{tr}\cdot P_s\cdot T_s + P_{tr}\cdot(1-P_s)\cdot T_c \quad (13)$$

Moreover, $E[X]$ is equal to:

$$E[X] = \sum_{i=0}^{m-1} \left(p^i \cdot \frac{W_i+1}{2}\right) + \frac{p^m}{1-p}\cdot\frac{W_m+1}{2} \quad (14)$$

After some algebra, (14) reduces to:

$$E[X] = \frac{(1-2p)\cdot(W+1) + pW\cdot(1-(2p)^m)}{2\cdot(1-2p)\cdot(1-p)} \quad (15)$$

Substituting (13) and (15) into (12), the average frame delay can be easily calculated.

VI. CONCLUSIONS AND FUTURE WORK

This paper presents an analytical model using a Markov chain to evaluate the system throughput performance of IEEE 802.11, the most widely accepted standard for Wireless LANs. This model can be used for both access mechanisms of Distributed Coordination Function, in the absence of hidden stations and transmission errors. The effect of the length of transmitted frames, the number of contenting stations in the network and the data rate on the throughput of the system is examined. Furthermore, a frame delay analysis is introduced under traffic conditions that correspond to the maximum load that the network can support in stable conditions.

We have concluded that the throughput performance strongly depends on the number of stations of the wireless network when the basic access method is used. Moreover, if the network is composed of a small number of stations and for small length frames, the basic access method achieves a better throughput performance than the RTS/CTS case. On the contrary, when the RTS/CTS mechanism is employed, the throughput is only slightly influenced regardless of the data rate, the frame size or the number of stations of the network.

Future work can include the throughput and delay analysis including the effect of hidden stations. Another possible area of research is a consideration of an erroneous wireless channel.

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