IEEE 802.11 WLANs: Performance analysis in presence of bit errors

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ABSTRACT – **IEEE 802.11 is worldwide established and the most used protocol for Wireless Local Area Networks (WLANs). As the assumption of an error-free channel is not always true in a realistic environment, we extent a mathematical model previously presented in the literature that calculates IEEE 802.11 DCF performance to take into account transmission errors for the IEEE 802.11a protocol. Our results take into account all the protocol parameters and packet overheads introduced by both the Medium Access Control (MAC) and the physical (PHY) layers as specified in 802.11a. Finally, we explore the effect of transmission errors, data rate and network size on the performance of the basic access and the RTS/CTS schemes, in terms of throughput and packet delay.**

I. Introduction

Continuing advances in wireless communications provide users with a lot of convenience such as mobility, installation speed and simplicity. As a result, wireless technologies and especially the IEEE 802.11 protocol [1][2][3] have gradually become a research focus by many researchers. The IEEE 802.11 Distributed Coordination Function (DCF) medium access control (MAC) method defines two mechanisms to employ packet transmission namely the basic access and the Request-To-Send/Clear-To-Send (RTS/CTS) reservation scheme.

The last few years much research has been done on the performance modeling and analysis of IEEE 802.11 DCF. Bianchi in [4] developed a mathematical model for the 802.11 DCF throughput performance, utilizing a Markov chain model but without considering the impact of bit errors on performance. In [5] and [6], we extended Bianchi's model to calculate average packet delay, under the assumption of ideal channel conditions (no transmission errors) and we produced results for the IEEE 802.11b. Crow in [7] and [8] first studied the effect of errors on performance by means of simulation. Authors in [9] and [10] also considered transmission errors by means of a Markov chain model but investigated only saturation throughput.

The goal of this paper is to derive formulae for the throughput and packet delay of IEEE 802.11 WLANs under an error-prone environment; in a realistic environment, the assumption of an error-free channel is not always true and accurate. We extent the approach in [4] and [6], taking into account transmission errors[1], therefore, a more realistic model is proposed. Our paper uses the same Markov chain with [4] and [6] under the assumption that packet retransmissions are unlimited. The proposed approach is simple and provides an intuitive understanding of the effect of bit errors on DCF performance and has been validated by OPNET simulation results in [6]. Our paper presents throughput and packet delay results for both the basic access and RTS/CTS schemes that illustrate the dependence of performance on transmission errors. Finally, we study what takes place in an average slot time and we derive simple expressions for the time utilized during collisions or transmission errors per successful packet transmission.

The rest of the paper is organized as follows. Section II briefly provides the essential details about the DCF mechanism. Following that, Section III presents the mathematical analysis and modeling. Section IV presents and discusses some of the derived numerical results of DCF performance in an error-prone environment and the paper concludes with Section V.

II. Description of DCF mechanism

We will briefly introduce the basic components of the binary exponential backoff mechanism employed in DCF, in order to understand the mathematical analysis that follows. Readers can refer to [4] [5] [6] or the IEEE 802.11 standards [1][2][3] for further details.

In DCF, a station with a packet to transmit first senses the medium activity to ascertain whether it is in use. If the medium is sensed to be idle for a time interval greater than the Distributed Inter-Frame Space (DIFS), the station initiates a packet transmission (transmits the data packet in basic access or a short RTS packet first in the RTS/CTS scheme). If the medium is sensed busy, the station defers transmission and initialises its random backoff timer[2]. Note that each station is allowed to transmit only when its backoff timer reaches zero and at the beginning of each slot time.

The value of the backoff timer value for each station is uniformly chosen in the interval $[0, W_i - 1]$, where W_i is the current contention window (CW) size, i is the backoff stage, $i \in [0,m]$ and m represents the number of backoff stages. At the first transmission

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[1] Note that bit errors over wireless channels can occur either randomly or in bursts. This paper focuses in random errors.

[2] The backoff timer is decremented when the medium is idle, is frozen when the medium is sensed busy and resumes again only after the medium has been idle for longer than DIFS.

attempt, CW is equal to the minimum backoff window size $W=CW_{min}$. If two or more stations start a packet transmission simultaneously in the same slot, a collision takes place. After each unsuccessful transmission due to a packet collision or error, W_i is doubled until a maximum backoff window size value is reached. After the successful reception of a data packet, the receiver sends back an acknowledgment (ACK) packet after a Short Inter-Frame Space (SIFS) interval. If the source station does not receive an ACK, the data packet is assumed to have been lost and a retransmission is scheduled according to the previous backoff rules.

III. Mathematical modeling and analysis

Our paper utilizes the same discrete-time Markov chain model with [4] and [6] (is not shown due to limited space). We assume that the network consists of n contending stations, each one always having a packet available for transmission. The key assumption is that the collision-error probability of a transmitted packet is constant and independent of the retransmissions that this packet has suffered in the past.

Our analysis[3] considers transmission errors, with p the probability that a transmitted packet encounters a collision or is received in error and is given by:

$$p = 1-(1-\tau)^{n-1}\cdot(1-BER)^{l+H} \tag{1}$$

where BER is the link bit error rate, l is the packet payload size, H is the packet header length and τ is the probability that a station transmits a packet in a randomly chosen slot time. The transmission probability τ is equal to [6]:

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

Equations (1) and (2) form a non-linear system with two unknowns p and τ. Note that $p\in(0,1)$ and $\tau\in(0,1)$. This non-linear system can be solved using numerical methods and has a unique solution.

A. Saturation throughput

Let P_{tr} be the probability that at least one transmission occurs in a randomly chosen slot time, P_s the conditional probability that this transmission is successful and $PER=1-(1-BER)^{l+H}$ the packet error rate, therefore:

$$P_{tr} = 1-(1-\tau)^n \quad , \quad P_s = \frac{n\cdot\tau\cdot(1-\tau)^{n-1}}{1-(1-\tau)^n}\cdot(1-PER) \tag{3}$$

The probability P_c that an occurring transmission collides (due to the fact that two or more stations transmit at the same time) and the probability P_{er} that a packet is received in error are given by:

$$P_C = 1-\frac{n\cdot\tau\cdot(1-\tau)^{n-1}}{1-(1-\tau)^n} \quad , \quad P_{er} = \frac{n\cdot\tau\cdot(1-\tau)^{n-1}}{1-(1-\tau)^n}\cdot PER \tag{4}$$

Consequently, the saturation throughput S can be derived as:

$$S = \frac{P_{tr}\cdot P_S\cdot l}{(1-P_{tr})\cdot\sigma+P_{tr}\cdot P_S\cdot T_S+P_{tr}\cdot P_c\cdot T_C+P_{tr}\cdot P_{er}\cdot T_{er}} \tag{5}$$

where the denominator of equation (5) denotes the average length of a slot time $E[slot]$, σ is the duration of an empty slot time, T_s , T_c *and* T_{er} are the average durations the medium is sensed busy due a successful transmission, a collision and a transmission error, respectively.

The values of T_s and T_c depend on the medium access mechanism and for the basic access scheme are given by:

$$T_S^{bas} = T_C^{bas} = T_{er}^{bas} = DIFS + T_{DATA} + SIFS + T_{ACK} \tag{6}$$

and for the RTS/CTS scheme:

$$\left\langle \begin{array}{l} T_S^{RTS} = T_{er}^{RTS} = DIFS + T_{RTS} + SIFS + T_{CTS} + SIFS + T_{DATA} + SIFS + T_{ACK} \\ T_C^{RTS} = DIFS + T_{RTS} + SIFS + T_{CTS} \end{array} \right. \tag{7}$$

where T_{DATA}, T_{ACK}, T_{RTS} and T_{CTS} is the transmission time for a data, acknowledgement, RTS and CTS packet, respectively. According to the IEEE 802.11a standard [3]:

$$T_{DATA} = 20us + 4us\cdot\left[\frac{294+l}{4\cdot C}\right] \tag{8}$$

$$T_{RTS} = 20us + 4us\cdot\left[\frac{182}{4\cdot C_{con}}\right] \tag{9}$$

$$T_{ACK} = T_{CTS} = 20us + 4us\cdot\left[\frac{134}{4\cdot C_{con}}\right] \tag{10}$$

where C is the data rate at which data packets are transmitted (6, 9, 12, 18, 24, 36, 48, and 54 Mbit/s) and C_{con} is the control rate at which the RTS, CTS and ACK control packets are transmitted (6, 12 or 24 Mbit/s). Note that the data and control rate may not be the same. In order to ensure that the vital information contained in the RTS and CTS packets will be received by all stations in range and to cope with potential hidden stations, control packets are transmitted at a lower data rate which increases reception distance.

B. Average packet delay

Our analysis also calculates the average delay $E[D]$ for a successfully transmitted packet. In fact, packet delay is defined to be the time interval from the time a packet is at the head of its MAC queue ready for transmission, until its successful reception in the destination. $E[D]$ is given by:

$$E[D] = E[X]\cdot E[slot] \tag{11}$$

where $E[X]$ is the average number of slot times for a successful packet transmission and $E[slot]$ is the average length of a slot time. The values of $E[X]$ are

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[3] Note that the derived mathematical analysis for the case of BER=0 has been validated by comparison with simulation results utilizing the OPNET^{TM} simulation package in [6].

independent of the employed access mechanism (basic access or RTS/CTS) and finally can be found as [6]:

$$E[X]=\frac{(1-2p)\cdot(W+1)+pW\cdot(1-(2p)^m)}{2\cdot(1-2p)\cdot(1-p)} \tag{12}$$

IV. Performance evaluation

Unless otherwise specified, the values reported in the following figures have been obtained using the system parameters summarized in table I for the Orthogonal Frequency Division Multiplexing (OFDM) physical layer used in the 802.11a [3].

Parameter	Value
Packet payload size, l	8184 bits
Slot time, σ	9 us
DIFS	34 μs
SIFS	16 μs
Channel data rate	54 Mbit/s
Control bit rate	24 Mbit/s
Minimum CW, CW_{min}	16
Number of backoff stages, m	6

Table I System parameters in IEEE 802.11a

Fig. 1 and 2 study the effect of transmission errors and network size by plotting throughput efficiency and packet delay versus n, for the basic access and the RTS/CTS schemes, respectively, for three BER values ($BER=10^{-4}$, 10^{-5} and 10^{-6}). Both figures 1 and 2 illustrate that as expected when the number of contenting stations increases, throughput drops off and the packet delay increases in both basic access and RTS/CTS schemes as a result of more packet collisions. However, it appears that the throughput performance of RTS/CTS scheme is less sensitive on the network size than the basic access scheme. An interesting observation is that the performance achievable by the basic access is very close (for $BER=10^{-5}$) or higher (for $BER=10^{-4}$) to that achievable by the RTS/CTS scheme. The explanation is twofold; firstly, because a transmission error penalizes performance when the RTS/CTS is utilized compared to the basic access (note T_{er} values in equation (7)) and secondly due to the fact that the overall WLAN performance suffers significantly when the lower rate RTS/CTS exchange reservation scheme is combined with higher transmission data rates. In fact, performance results show that only very large network size values render the RTS/CTS beneficial, for high data rates (54 Mbit/s), unlike common expectation. This result holds true even when the highest control rate (24 Mbit/s) is utilized and is explained due to the exchange of the RTS and CTS reservation packets at a much lower control rate, which results in a significant delay in communication.

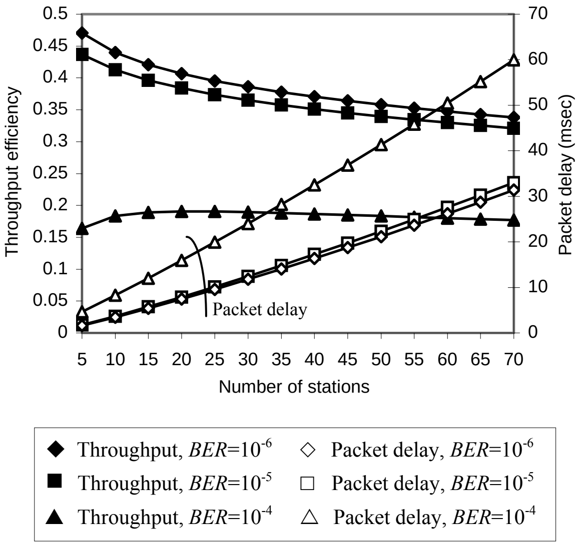

Fig. 1 Effect of BER on the basic access scheme

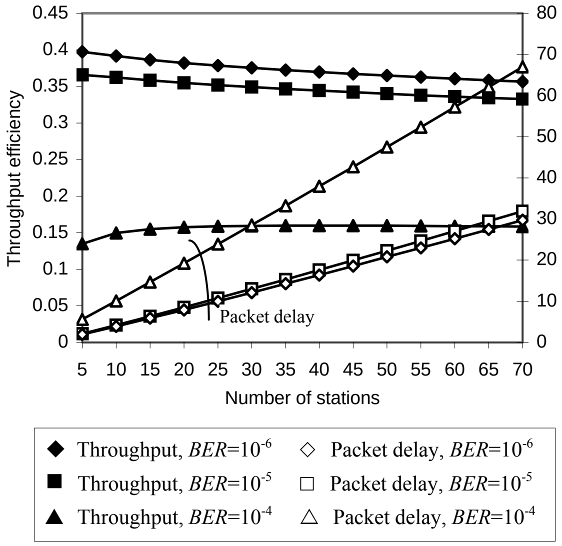

Fig. 2 Effect of BER on the RTS/CTS scheme

In order to better understand the impact of transmission errors on performance, we study what occurs in a randomly selected time slot. Dividing numerator and denominator of equation (5) by $P_{tr}\cdot P_s$, we obtain:

$$S=\frac{l}{\frac{1-P_{tr}}{P_{tr}\cdot P_S}\cdot\sigma+T_S+\frac{P_c}{P_S}\cdot T_C+\frac{P_{er}}{P_S}\cdot T_{er}} \tag{13}$$

The denominator of equation (6) expresses the average time spent on the channel for a successful transmission. This time is further decomposed into four components. It is important to study the third and fourth terms at the denominator of equation (6). The third term represents the time W_{col} wasted due to collisions per successful packet transmission. In fact, P_C/P_S is the average number of collided transmissions per successful transmission, which is multiplied by the average duration T_c that the medium is sensed busy due a collision. Following the same approach, the fourth term at the denominator of equation (6) denotes the time W_{er} wasted due to transmission errors per successful packet transmission.

Figure 3 plots the average amount of time spent in collisions W_{col} and transmission errors W_{er} per successful packet transmission, normalized with respect to the slot time σ. The figure shows that the time wasted due transmission errors is not affected by the network size. This is justified by noting that in equation (13) the term P_{er}/P_s results to be independent of n. When the BER increases, the time wasted due transmission errors increases in both basic access and RTS/CTS schemes. In fact, transmission errors slightly affect W_{er} when $BER=10^{-6}$ but significantly increase W_{er} for higher BER values ($BER=10^{-4}$). We also observe that basic access achieves a significantly lower W_{er} value under high BER values in respect to RTS/CTS; the average duration T_{er} that the medium is sensed busy due a transmission error is considerably larger when RTS/CTS scheme is utilized as it is shown in equation (7). Furthermore, the figure shows the significant dependence of the time spent in collisions both from the number of contenting stations and transmission errors. In fact, the introduction of the RTS/CTS mechanism, the collision duration is reduced drastically since collisions only occur to the RTS packets that are much shorter than the data packets. As a result large network sizes do not have a significant impact on the performance regardless the increased number of collisions. For the same reason, basic access proves to be more sensitive on high values of n that penalize overall performance.

V. Conclusions

In this paper, we have extended an analytical model that calculates throughput and delay performance for IEEE 802.11a WLAN protocol in the presence of transmission errors. In order to better understand the impact of transmission errors on performance, we have studied what occurs in a randomly selected time slot. For this reason, we have derived simple expressions for the time utilized during collisions or transmission errors per successful packet transmission. Analytical results illustrate that transmission errors considerably affect protocol performance. When BER increases, throughput degrades and packet delay increases. Results also indicate that the performance of RTS/CTS scheme is less sensitive on the network size than the basic access scheme but is highly affected by transmission errors. Furthermore, we have found that there is a significant dependence of the time spent in collisions or errors from the number of contenting stations and transmission errors in both the basic access and the RTS/CTS schemes.

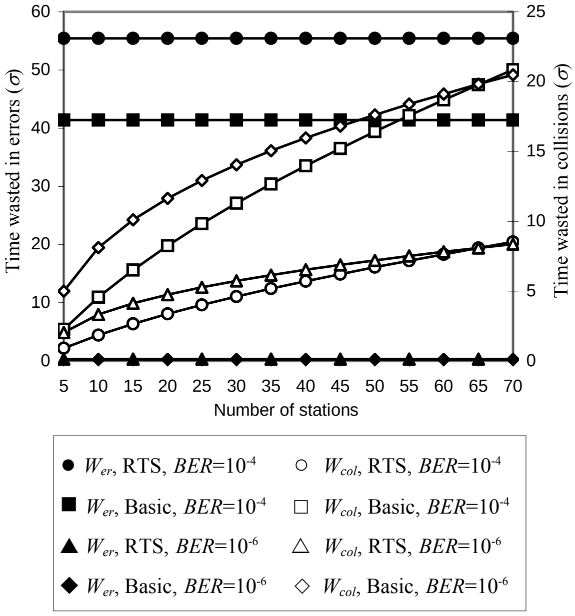

Fig. 3 Average number of slot time units wasted due to errors and packet collisions, per successful transmission

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