Performance Analysis of IEEE 802.11 DCF in Presence of Transmission Errors

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***Abstract*— IEEE 802.11 is worldwide established and the most used protocol for Wireless Local Area Networks (WLANs). In this paper, we propose an improved analytical model that calculates IEEE 802.11 DCF performance taking into account both packet retry limits and transmission errors for the IEEE 802.11a protocol. Validation of our new performance model analytical results is carried out by comparison with simulation results using the OPNET[TM] simulation package. We explore the effect of transmission errors, packet retry limits, data rate and network size on the performance of the basic access scheme, in terms of throughput, packet delay, packet drop time and drop probability.**

Keywords: IEEE 802.11; WLANs; DCF; errors; packet delay;

I. INTRODUCTION

During the past few years, Wireless Local Area Networks (WLANs) are becoming increasing popular in data telecommunications and networking [1]. The IEEE 802.11 protocol has achieved worldwide acceptance within WLANs and can offer high data rates through 802.11a [2] and 802.11b [3]. IEEE 802.11 Medium Access Control (MAC) incorporates two medium access methods, the compulsory Distributed Coordination Function (DCF) and the optional Point Coordination Function (PCF). DCF is an asynchronous data transmission function which best suits delay insensitive data, whereas the Point Coordination Function (PCF) is used in time-bounded applications. DCF defines two mechanisms for packet transmission; the basic access and the Request-To-Send/Clear-To-Send (RTS/CTS) reservation scheme.

Since the release of the IEEE 802.11 standard, several research efforts have been carried out to model the IEEE 802.11 protocol. Simulation studies of the 802.11 protocol performance are presented in [4] and [5]. Recently, considerable research activity has concentrated on modeling the IEEE 802.11 DCF medium access method. Bianchi in [6] and Wu in [7] used Markov chain models to analyze DCF operation and calculated the saturated throughput of 802.11 protocol. In particular, Bianchi [6] modeled the idealistic assumption of collision only errors, that packet retransmissions are unlimited and a packet is being transmitted continuously until its successful reception. Wu [7] extended Bianchi's analysis to include the finite packet retry limits as defined in the IEEE 802.11 standard. In [8] we calculated the packet delay without considering any packet dropping due to retry limits. Furthermore, in [9] we provided a new performance model of 802.11 DCF by means of the Markov chain model utilized by Wu in [7]. Our work in [9] considered the effect of retry limits and calculated the packet delay, the packet drop probability and the packet drop time.

In this paper, we introduce a mathematical model which extents the approaches in [6], [7], [8] and [9] by taking into account both transmission errors and packet retry limits for the basic access of the IEEE 802.11a protocol. Our new performance model calculates throughput efficiency, average packet delay, packet drop probability and average time to drop a packet for the basic access scheme. Using OPNET simulation results, we validate our mathematical model and we show that the proposed model predicts the DCF performance very accurately. Moreover, we explore the dependency of the protocol performance on bit error rate, packet retry limit, data rate and network size. Due to the simplicity and accuracy of our proposed model, analytical results presented in this paper can give us a benchmark of how each factor affects performance.

II. IEEE 802.11 DISTRIBUTED COORDINATION FUNCTION

IEEE 802.11 DCF is based on a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) access scheme and employs a binary exponential backoff (BEB) technique. Under DCF, before initiating a transmission, each station senses the channel to determine its state (idle or busy). If the medium is sensed to be idle for a time interval greater than the Distributed Inter-Frame Space (DIFS), the station proceeds with the packet transmission. If the medium is sensed busy, the station waits until the ongoing transmission is over. The station then defers for a randomly selected backoff interval, initializing its random backoff timer, which is decremented as long as the channel is sensed idle. The backoff timer is frozen when a transmission is detected and is reactivated when the channel is sensed idle again for more than one DIFS. Moreover, each station is allowed to transmit only when its backoff timer reaches zero and at the beginning of each slot time.

After the successful reception of a packet, the destination station sends back an immediate positive acknowledgment (ACK) after a time interval equal to Short Inter-Frame Space (SIFS). If the source station does not receive an ACK, the data packet is assumed to have been lost and a retransmission is scheduled. Every station maintains a station short retry count (SSRC) that indicates the number of retransmission attempts of a data packet. If the retry count reaches the specified limit, retry attempts cease and the packet is discarded.

Before initiating a packet transmission, 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 size and i is the backoff stage. The value of W_i depends on the number of failed transmissions of the packet; at the first transmission attempt, $W_0=W$. After each retransmission due to a packet collision or error, W_i is doubled up to a maximum value, $W_{m'} = 2^{m'}W$ where m' is the number of backoff stages. Once W_i reaches $W_{m'}$, it will remain at this value until it is reset to W_0 either after the successful transmission of a data packet or when SSRC reaches the short retry limit.

III. MATHEMATICAL MODELLING

Our analysis assumes that the network consists of n contending stations and that each station has always a packet available for transmission. The key assumption of our model is that the collision-error probability p of a transmitted packet is constant and independent of the number of collisions or transmission errors this packet has suffered in the past. Note that a station cannot distinguish a packet collision from a transmission error. For this reason, the contention window will be increased either due to a collision or to an error.

We utilize a discrete-time Markov chain model carrying out a similar analysis with [7] and [9]. Let $b(t)$ and $s(t)$ be the stochastic processes representing the backoff timer and the backoff stage respectively for a given station at slot time t. The Markov chain illustrated in fig. 1 is utilized to model the bi-dimensional process $\{b(t), s(t)\}$. Let $b_{i,k} = \lim_{t\to\infty} P\{s(t)=i, b(t)=k\}$ be the stationary distribution of the Markov chain, where $i \in [0,m]$, $k \in [0, W_i\text{-}1]$ and m is the retry limit.

The main difference with [7] and [9] is that in this paper, p stands for the probability that a transmitted packet encounters a collision or is received in error (since our analysis considers transmission errors). The probability p is given by:

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

where BER is the bit error rate, l is the packet size, H is the packet header and τ the probability that a station transmits a packet in a randomly chosen slot time given by:

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

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.

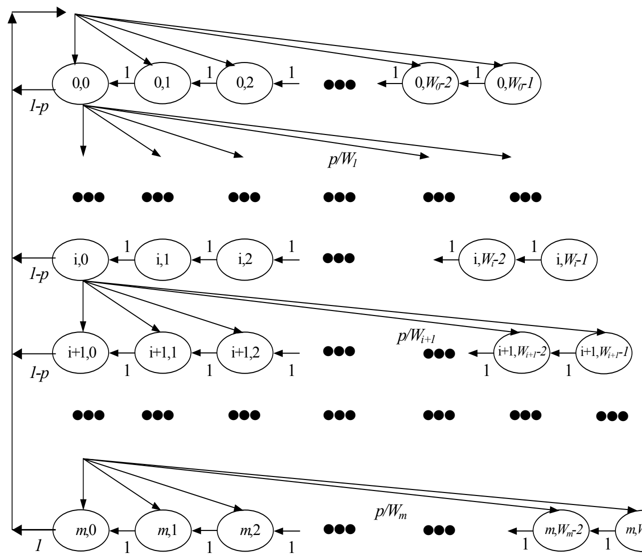

Figure 1. Markov chain model

A. Saturation throughput

Let P_{tr} be the probability that at least one transmission occurs in a randomly chosen slot time:

$$P_{tr} = 1 - (1-\tau)^n . \quad (3)$$

Moreover, let P_S be the probability that an ongoing transmission is successful where PER is the packet error rate:

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}(1-PER) . \quad (4)$$

The probability P_c that an occurring transmission collides because two or more stations simultaneously transmit is:

$$P_C = 1 - \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} . \quad (5)$$

The probability P_{er} that a packet is received in error is:

$$P_{er} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} PER . \quad (6)$$

Therefore, the saturation throughput S can be derived as:

$$S = \frac{P_{tr}P_S l}{E[slot]} = \frac{P_{tr}P_S l}{(1-P_{tr})\sigma + P_{tr}P_S T_S + P_{tr}P_c T_C + P_{tr}P_{er}T_{er}} . \quad (7)$$

where $E[slot]$ is the average length of a slot time, σ is the duration of an empty slot time, T_s, T_c and T_{er} are the average time intervals that the medium is sensed busy due to a successful transmission, a collision or an error respectively. The values of T_s, T_c and T_{er} are equal to:

$$T_S = T_C = T_{er} = DIFS + H + l + SIFS + ACK . \quad (8)$$

B. Packet drop probability

The packet drop probability is defined as the probability that a packet is dropped when the retry limit is reached:

$$p_{drop} = p^{m+1}. \quad (9)$$

C. Packet drop time

A packet is dropped when it reaches the last backoff stage and experiences another collision or an error. Since the average number of slot times a station defers in the *i* stage is $d_i = (W_i + 1)/2$, the average number of slot times $E[T_{drop}]$ required for a packet to experience *m*+1 collisions or errors in the (0,1,…*m*) stages is equal to:

$$E\left[T_{drop}\right] = \sum_{i=0}^{m} \frac{W_i + 1}{2} = \frac{W(2^{m+1} - 1) + (m+1)}{2}. \quad (10)$$

Finally, the average time to drop a packet is given by:

$$E[D_{drop}] = E[T_{drop}]E[slot]. \quad (11)$$

D. Packet delay

The delay *D* is defined to be the time interval from the time a packet is at the head of its MAC queue ready for transmission, until an acknowledgement for this packet is received. If a packet is dropped because it has reached the specified retry limit, the time delay for this packet will not be included in the calculation of the average packet delay. Let *E*[*X*] be the average number of slot times required for a successful packet transmission. *E*[*X*] can be found by multiplying the average number of slot times d_i the packet is delayed in each backoff stage by the probability that a packet that is not dropped reaches the *i* stage. The average packet delay *E*[*D*] for a successfully transmitted packet is given by:

$$E[D] = E[X]E[slot] = \sum_{i=0}^{m} \left[\frac{W_i + 1}{2} \frac{(p^i - p^{m+1})}{1 - p^{m+1}}\right] E[slot]. \quad (12)$$

IV. MODEL VALIDATION

Unless otherwise specified, performance results in the following figures have been obtained using the system parameters in table I for the Orthogonal Frequency Division Multiplexing (OFDM) physical layer utilized in 802.11a [2].

Fig. 2 plots throughput efficiency and packet delay against the number of contenting stations for an error-free channel and data rate of *C*=6 Mbit/s. Results obtained from our analytical model are compared to simulation outcome by means of our IEEE 802.11 simulator developed with the OPNET™ simulation package. The figure validates our analytical model since an almost exact match is observed between analytical results (lines) and simulation outcome (symbols). Moreover, the figure illustrates that analytical modeling that considers retry limits predicts very accurately DCF throughput performance, a conclusion not drawn in [7] which added retry limits in the analytical model in [6].

TABLE I. SYSTEMS PARAMETERS IN 802.11a

Parameter	Value
Packet payload size, *l*	8184 bits
Slot time, σ	9 μs
DIFS	34 μs
SIFS	16 μs
MAC header	272 bits
Channel data (control) rate	6 (6), 54 (24) Mbit/s
Minimum CW, W_0	16
Number of backoff stages, *m'*	6
Short retry limit	6

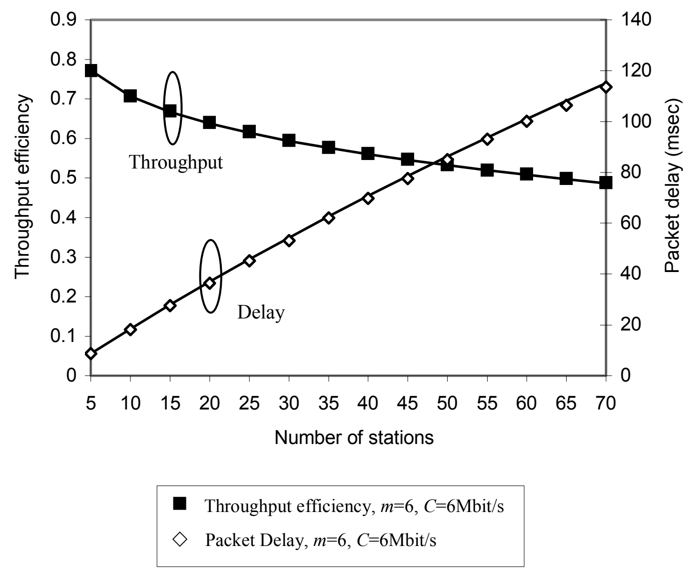

Figure 2. Throughput efficiency and packet delay versus *n* for *BER*=0

V. ANALYSIS RESULTS

Fig. 3 and 4 study the effect of transmission errors by plotting throughput efficiency and packet drop probability versus *BER*, and average packet drop time and average packet delay versus *BER* respectively, for three representative network sizes (*n* = 5, 25 and 50) and data rate of *C*=6 Mbit/s. Fig. 3 illustrates that when *BER* increases, throughput always degrades and gradually drops to 0. We can see that the *n* values affects throughput performance since more contenting stations result in more packet collisions. Fig. 3 also shows that packet drop probability increases when *BER* gets higher due to the increased number of transmissions in error whereas packet drop probability is less sensitive on network size.

Fig. 4 depicts that packet drop time is highly dependent on the number of contenting stations and increases when the network size grows. Increasing *BER* results in packet drop time decrease regardless the number of contenting stations. In fact, the level of decrease grows with *BER* increase but, when packet drop probability increases rapidly (fig. 3), the decrease level is reduced again. Fig. 4 also shows that packet delay gradually increases and finally (for high *BER* values) attains roughly unvarying values. In view of the fact that the packet delay values at high *BER* concern only a small number of successfully received packets due to high drop probability and, therefore, have a very small significance.

Since IEEE 802.11a specifies various data rates, it is motivating to study how performance is affected by the data rate. Fig. 5 and 6 plot throughput efficiency and average packet delay versus network size and average packet drop time and packet drop probability against network size respectively, for $BER=10^{-5}$ and for the lowest mandatory (C=6 Mbit/s) and the highest (C=54 Mbit/s) data rates defined in the IEEE 802.11a [2]. Fig. 5 illustrates that throughput decreases as the number of the stations increases since more collisions take place. Throughput efficiency is also reduced when the data rate increases. This is justified by considering that the time spent for packet transmission is decreased as the data rate increases but the time overhead spent on DIFS, SIFS and the backoff delay remains the same. Moreover, packet delay is sensitive both on network size and data rate. Since *BER* remains the same ($BER=10^{-5}$), the increased number of contenting stations causes collisions, which result in continuous packet retransmissions and generate additional delay.

Fig. 6 shows that for C=6 Mbit/s, packet drop time increases when the network size grows, whereas for C=54 Mbit/s, packet drop time appears to depend less on the number of the contenting stations. In fact, for C=54 Mbit/s the level of increase on the packet drop time is similar with the case of C=6 Mbit/s but the figure misleads the reader because the vertical axis scale cannot depict clearly what takes place. Conversely, the network size has a substantial influence on the packet drop probability due to the increased number of collisions caused from the stations attempt to access the medium. Larger network size means that more stations are trying to transmit resulting in several packet collisions. Since packet drop probability does not depend on the data rate, the results presented in fig. 6 are applicable on both (C=6 Mbit/s and C=54 Mbit/s) data rates.

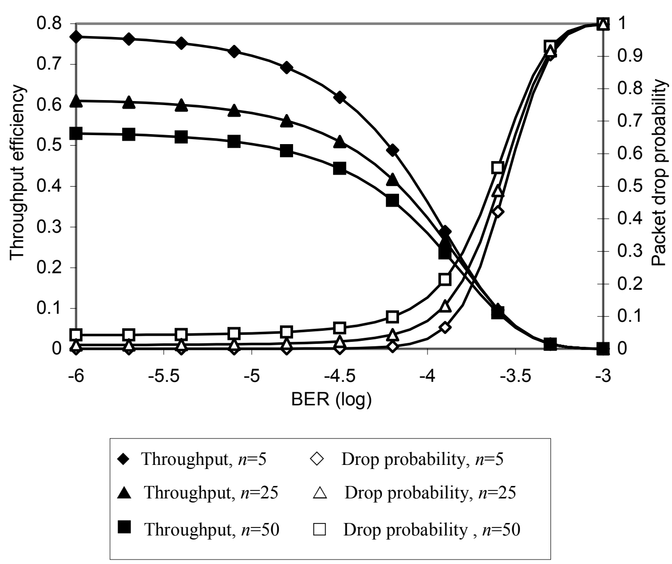

Figure 3. Throughput efficiency and packet drop probability versus *BER* for C=6Mbit/s and m=6

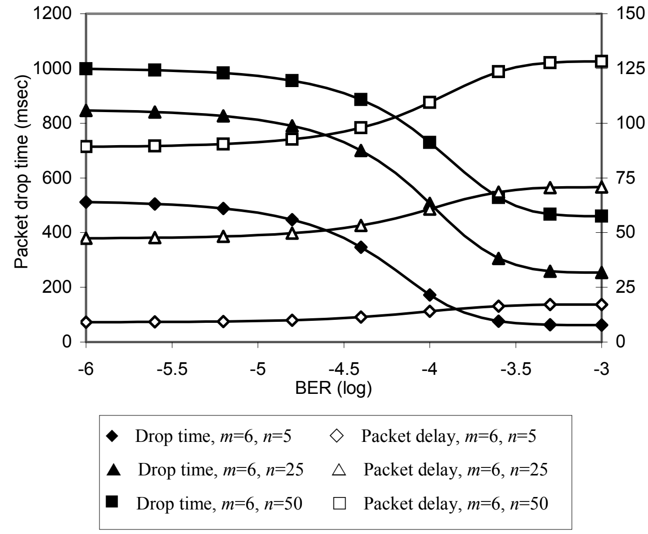

Figure 4. Packet drop time and packet delay versus *BER* for C=6Mbit/s

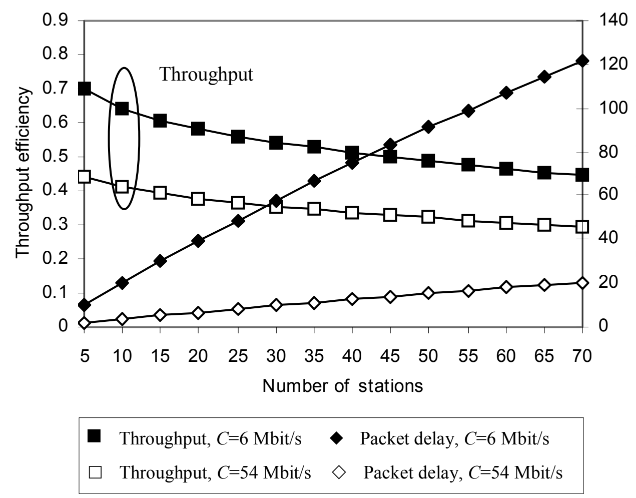

Figure 5. Throughput efficiency and packet delay for $BER=10^{-5}$ and various data rates

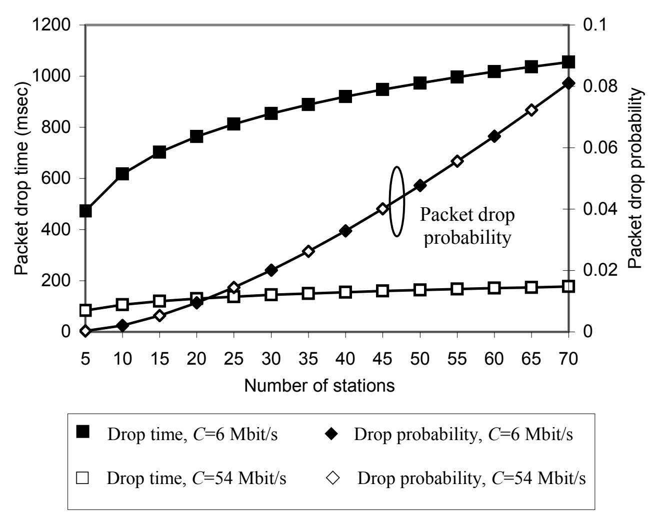

Figure 6. Packet drop time and packet drop probability for $BER=10^{-5}$ and for various data rates

Fig. 7 and 8 present results examining the impact of the retry limit m on protocol performance for three network sizes (n = 5, 25 and 50), C=6 Mbit/s and $BER=10^{-5}$. Fig. 7 illustrates that a small number of contenting stations (n=5) attains the highest throughput and lowest packet delay compared to the other two network sizes due to the reduced number of collisions. Results show that for a small network size, throughput and packet delay only marginally depend on the retry limit. For larger network sizes, the increase of the retry limit results in more successful transmitted packets and consequently the performance is improved. Additionally, packet delay strongly depends on the retry limit and increases with higher m values. The reason for both throughput and packet delay increase is explained due to the fact that more packets are transmitted successfully (clearly depicted in fig. 8).

In fig. 8, when retry limit increases, fewer packets are discarded and packet drop probability decreases rapidly due the fact that there are more opportunities for a packet to be retransmitted and finally received successfully. Fig. 8 also shows that the packet drop time is significantly affected by m values due to the increased number of retransmissions before a packet is discarded. Both fig. 7 and 8 show how higher retry limit values than the standard proposed values affect performance. Results depict that when m>6 (the retry limit value in the 802.11 standard) the performance is not improved significantly. Higher m values result in slightly decreased drop probability but they cause considerably increased packet delay and packet drop time. For this reason, the retry limit value of 6 appears to be a good tradeoff for the basic access scheme.

VI. CONCLUSIONS

This paper introduced a new analytical model using a Markov chain for the IEEE 802.11a protocol performance. The proposed model calculates throughput efficiency, average packet delay, packet drop probability and average time to drop a packet for the basic access scheme. Our work becomes important and meaningful in the sense that it predicts 802.11 protocol performance very accurately considering transmission errors and packet retry limits. Using the mathematical model, we derived analytical results, which illustrate that protocol performance strongly depends on the bit error rate (BER). When BER increases, throughput degrades, packet delay increases and packet drop probability significantly increases. We also show that data rate significantly affects throughput efficiency, packet drop time and packet delay. In particular, we present results indicating that the level of influence highly depends on network size. Finally, performance appears to be sensitive on the retry limit; we show that the retry limit value of 6 appears to be a good tradeoff for the basic access scheme.

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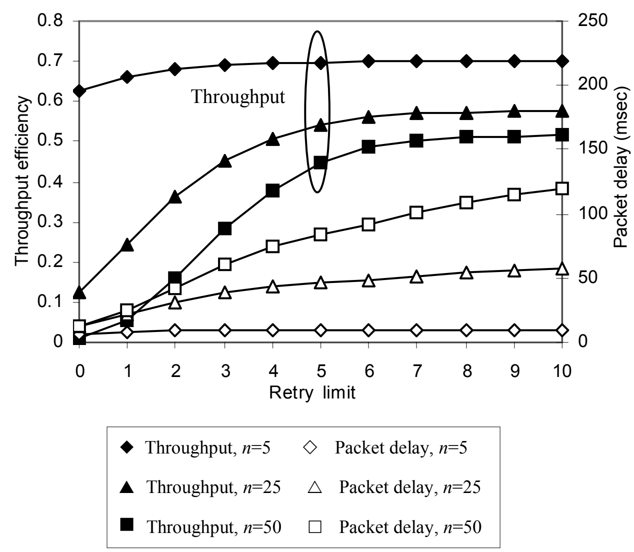

Figure 7. Throughput efficiency and packet delay versus retry limit for $BER=10^{-5}$ and C=6 Mbit/s

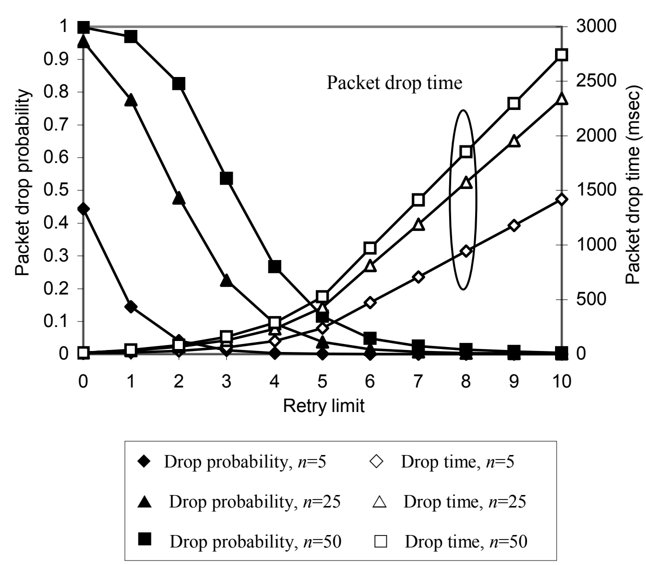

Figure 8. Packet drop probability and packet drop time versus retry limit for $BER=10^{-5}$ and C=6 Mbit/s