Packet Delay Distribution of the IEEE 802.11 Distributed Coordination Function

P. Raptis, V. Vitsas
Dept. of Information Technology
Technological Educational Instituion
Thessaloniki, Greece
{praptis, vitsas}@it.teithe.gr

K. Paparrizos
Dept. of Applied Informatics
University of Macedonia
Thessaloniki, Greece
paparriz@uom.gr

P. Chatzimisios, A.C. Boucouvalas
School Design,Engineering & Computing
Bournemouth University
Fern Barrow, Poole, UK
{pchatzimisios, tboucouv}@bmth.ac.uk

Abstract

This paper studies the packet delay distribution of the IEEE 802.11 Distributed Coordination Function (DCF) protocol. DCF treats packets in an unfair manner. Results indicate that in large networks, most packets have very low time delays, some packets have delays close to the average value and a small number of packets experience extremely high delays. We study the DCF delay distribution by developing a mathematical model that calculates the important properties of the constituent curves of the delay distribution curve, namely the probability that a packet will be successfully transmitted from a particular backoff stage and the average delay of the successfully transmitted packets from this backoff stage. The model is simple, gives an insight view of the internal mechanisms of DCF and applies to both basic and RTS/CTS access mechanisms. The accuracy of the analytical model is verified by simulations. Analytical results are presented that explore the effect of network size and of the initial contention window size on the fairness of DCF regarding the distribution of packet delays.

1. Introduction

Wireless local area networks (WLANs) are gaining great popularity and are getting rapidly deployed all over the world [1]. The WLANs are flexible and easy to implement as no cables are required. The dominating protocol utilized by WLANs is the IEEE 802.11.

IEEE 802.11 defines Medium Access Control (MAC) and Physical Layer (PHY) specifications for WLANs [2]. IEEE 802.11 MAC protocol is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme. The mandatory Distributed Coordination Function (DCF) mechanism describes two techniques to transmit data packets; a two-way handshaking (DATA-ACK) called basic access and an optional four-way handshaking (RTS-CTS-DATA-ACK) called Request-To-Send/Clear-To-Send (RTS/CTS) access method. In the basic access the transmitter sends a data packet (DATA) and the receiver responds with an acknowledgement (ACK) after the successful reception of the data. The RTS/CTS mode requires the exchange of short frames between the transmitter (RTS) and the receiver (CTS), prior to data packet transmission.

A considerable number of researchers worldwide show an increasing interest in modeling the IEEE 802.11 DCF and study performance indicators such as throughput [3][4][5], packet delay [6][7] and packet drop probability [8]. Bianchi [3] proposed a Markov chain model to evaluate the performance of the DCF on a channel with no errors. The key assumption of the model in [3] is that at each transmission and regardless of the number of retransmissions suffered, the packet collides with a constant probability. Wu [4] modified Bianchi's Markov chain to calculate the throughput taking into account the packet's retransmission limit as specified in the standard. Chatzimisios et al. [6][8] employed Wu's Markov chain to develop a mathematical model that calculates additional performance metrics, the average packet delay, the packet drop probability and the packet drop time.

In this paper, we extend the study of packet delay in [8] by examining the packet delay distribution. Results indicate that the time delays of packets are not close to their average value; most packets have very low time delays and a small number of packets experience very high delays. Thus, packet delay distribution is needed in addition to the average packet delay value examined in [8] to efficiently study the performance of DCF using the packet delay metric. As the number of collisions (use of higher backoff stages) is the main factor that increases the packet delay, we utilize Wu's Markov chain to develop a mathematical model that calculates (a) the average packet delay per stage (number of collisions) and (b) the probability that a stage is utilized for a successful packet transmission. The model gives an insight view of internal mechanisms of the DCF that affect packet delay. Using the developed mathematical model, we examine the

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influence of the initial contention window size parameter and of network size on the fairness of the protocol, as expressed by the average delay per stage and the probability per stage. In our analysis we assume that the channel is error free and no hidden terminals and capture effect conditions are present.

The paper is organized as follows. Section 2 briefly describes the Binary Exponential Backoff (BEB) access scheme and the procedures of the DFC of the IEEE 802.11 MAC protocol. Section 3 briefly presents for completeness the Markov chain and the mathematical models for the saturation throughput and average packet delay developed in [4][8]. Section 4 presents simulative delay distribution results and justifies the need for the two additional delay performance metrics that express the fairness of BEB, the average delay per stage and the probability per stage. Section 5 develops a mathematical model that calculates the two new metrics and section 6 validates the developed model by comparing analytical with simulation results. Section 7 presents analytical results that examine the effect of network size and initial contention window size on the fairness of the protocol and, finally, section 8 presents the conclusions.

2. Distributed Coordination Function (DCF)

If a station has a packet to transmit and senses the channel to be idle for a period of Distributed Inter Frame Spacing (DIFS) then the station proceeds with its transmission. If the channel is busy the station defers until an idle DIFS is detected and then generates a random backoff interval before transmitting in order to avoid collisions. The backoff time counter is decreased in terms of slot time as long as the channel is sensed idle. The counter is stopped when the channel is busy and resumed when the channel is sensed idle again for more than DIFS. A station transmits a packet when its backoff timer reaches zero. If the destination station successfully receives the packet, it waits for a short inter-frame space (SIFS) time interval and transmits an acknowledgement (ACK) packet. If the transmitting station does not receive an ACK packet within a specified ACK timeout interval, the data packet is assumed to have been lost and the station schedules a retransmission. Each station holds a retry counter that is increased by one each time a data packet is unsuccessfully transmitted. If the counter reaches the retransmission limit *m* the packet is discarded.

The backoff time counter is chosen uniformly in the range $[0, W_i -1]$, where $i \in [0, m]$ is the backoff stage number and W_i is the current contention window size (*CW*). The contention window at the first transmission of a packet is set equal to $CW_{min}=W_0=W$. After an unsuccessful packet transmission the contention window *CW* is doubled up to a maximum value $CW_{max}=2^{m'}W$ (where *m'* is the number of *CW* sizes). Once *CW* reaches CW_{max} it remains in this value until it is reset. The *CW* is reset to CW_{min} after a successful packet transmission or if the packet's retransmission limit is reached.

The RTS/CTS access scheme follows the same backoff rules as the basic access. The station sends a short RTS packet first instead of the data packet. The receiving station responds with a CTS packet after a SIFS time interval. The sender is allowed to transmit the data packet only if it receives a valid CTS. Upon the successful reception of the data packet the receiver transmit an ACK frame. If the source station does not receive a CTS frame, the retry counter is increased by one.

3. Mathematical Modeling

This study assumes ideal channel conditions (no transmission errors or hidden stations), the contenting stations are of fixed number *n* and each station has always a packet available for transmission of the same fixed size.

3.1. Markov Chain Model

Let *b(t)* and *s(t)* be the stochastic processes representing the backoff time counter and the backoff stage (0,…*m*) respectively for a given station at time *t*.

We utilize the same discrete-time Markov chain with [4][8] in order to model the bi-dimensional process $\{b(t), s(t)\}$. The key approximation in this model is that each packet collides with constant and independent probability *p*. Let $b_{i,k} = \lim_{t \to \infty} P\{s(t) = i, b(t) = k\}$ be the stationary distribution of the Markov chain, where $i \in [0,m]$, $k \in [0, W_i -1]$. The probability τ that a station transmits a packet in a randomly chosen slot time can be expressed as:

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

where $b_{0,0}$ can be obtained from:

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

The probability *p* that a transmitted packet encounters a collision is given by:

$$p = 1-(1-\tau)^{n-1} \qquad (3)$$

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Equations (1) and (2) represent a non-linear system with two unknown τ and p, which can be solved using numerical methods and has a unique solution.

3.2. Saturation Throughput

Let P_{tr} be the probability with that at least one station (out of n) transmits in a considered slot time:

$$P_{tr} = 1-(1-\tau)^n \quad (4)$$

Let P_s be the probability that a transmission occurring on the channel is successful and is given by the probability that only one station transmits and the n-1 remaining stations defer, with the condition that a transmission occurs on the channel. Probability P_s is given by:

$$P_s = \frac{n\cdot\tau\cdot(1-\tau)^{n-1}}{P_{tr}} = \frac{n\cdot\tau\cdot(1-\tau)^{n-1}}{1-(1-\tau)^n} \quad (5)$$

The saturation throughput S is calculated as the ratio of the successfully transmitted payload information in a slot time:

$$S = \frac{P_{tr}\cdot P_s\cdot l}{E[slot]} = \frac{P_{tr}\cdot P_s\cdot l}{(1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c} \quad (6)$$

where $E[slot]$ is the average length of a slot time, σ is the period of an empty slot and l is the packet length. T_s and T_c are the time durations the channel is sensed busy during a successful transmission and a collision, respectively.

The time duration of T_s and T_c depends upon the access method employed. For the basic access method, we have:

$$T_s^{bas} = T_c^{bas} = DIFS+H+l+\delta+SIFS+ACK+\delta$$

and for the RTS/CTS access method:

$$T_s^{RTS} = DIFS+RTS+SIFS+\delta+CTS+SIFS+\delta+H+l+SIFS+\delta+ACK+\delta$$

$$T_c^{RTS} = DIFS+RTS+SIFS+CTS$$

where H is the packet header (equal to the sum of MAC and physical header) and δ is the propagation delay.

3.3. Average Packet Delay

The delay for a successfully transmitted packet is defined as the time interval from the time the packet is at the head of its MAC queue ready to be transmitted, until an acknowledgement for this packet is received. If a packet reaches the specified retry limit then this packet is dropped and its time delay is not included in the calculation of the average packet delay. A simple model was developed in [8] for calculating the average packet delay $E[D]$ for both basic access and RTS/CTS:

$$E[D] = \sum_{i=0}^{m}\frac{W_i+1}{2}\cdot\frac{p^i-p^{m+1}}{1-p^{m+1}}\cdot E[slot] \quad (7)$$

where $(1-p^{m+1})$ is the probability that the packet is not dropped and $(p^i - p^{m+1})/(1-p^{m+1})$ is the probability that a packet that is not dropped reaches the i stage.

4. Delay Distribution

First, we study the packet delay distribution results taken by simulation (the system parameter values used are shown at Table 1). Fig. 1 plots simulative packet delay distribution curves i.e. probability versus time delay, for different W and n values for basic access. The figure shows "unusual" distribution shapes for all the selected W and n values; the time delays of individual packets are not around their average value, as it might have been expected. Very low packet time delays occur with high probability. This probability suddenly drops when time delay exceeds a certain value and local picks are observed at higher time values. This unusual packet delay distribution shape is caused by the Binary Exponential Backoff (BEB) access scheme utilized by DCF. As most packets have very low delays and few packets experience much higher delays than average, BEB treats packet in an unfair manner.

Fig. 2 further examines packet delay distribution by plotting simulative packet delay distribution for W=32 and n=50. In this case, a sudden probability drop is observed at the time delay value of 150 ms. This drop is explained by considering that most packets ((1-p) approximately 46% is this case), are successfully transmitted at their first transmission attempt at stage 0, i.e. without experiencing a collision. Local picks are observed at approximately 300 ms and 650 ms, which correspond to successfully received packets after one and two collisions respectively. Fig. 2 verifies that packet time delays are grouped according to the number of collisions suffered (or the stage at which the successful transmission occurs) by plotting the constituent parts of the delay distribution curve, namely the packet delay distribution at backoff stages. The delay distribution of the kth stage represents the probability that a successfully transmitted packet has a time delay value and is successfully transmitted using the kth stage (i.e. at the kth transmission attempt). Delay distribution per stage curves have a 'nornal' shape and delays of packets of the same stage are around their average value. These results indicate that the "unusual" distribution of the packet time delays caused by the Binary Exponential Backoff scheme utilized by DCF can be efficiently studied by

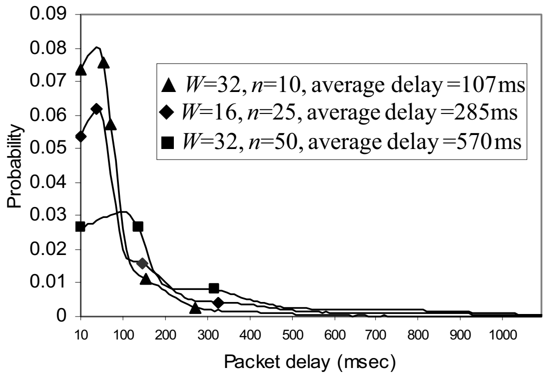

Fig. 1 Delay distribution, m=6, m'=5.

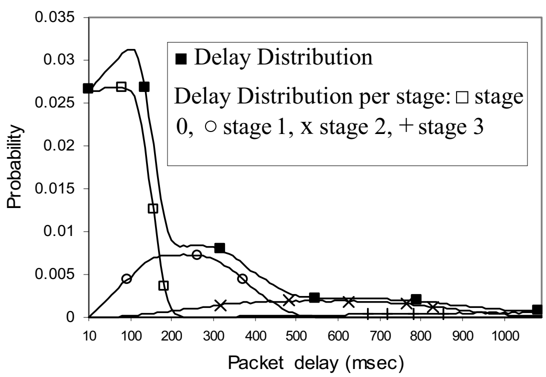

Fig. 2 Delay Distribution and its constituent parts delay distribution per stage for W=32, m=6, m'=5 and n=50

calculating (a) the average packet delay at each stage and (b) the probability that each stage is utilized by successful packet transmissions (i.e. the area under the delay distribution curve of this backoff stage).

Another important observation of the presented results in Fig. 2 is that most of the packets (approximately 80 %) have a lower delay that the average delay of 570 ms. Only 20% of the packets have a higher than the average time delay and these time delay values occur with very low probability. As a result, very high delay values (of successfully transmitted packets utilizing high backoff stages) occur with low probability rendering the BEB an unfair scheme for the packet delay performance metric.

5. Packet Delay Per Stages

Let D_k be the delay of a successfully transmitted packet from the kth backoff stage. The delay D_k is calculated as the summary of the delays that a packet experiences at 0,1,…,k stages. The average delay $E[D_k]$ is given by:

$$E[D_k]=\sum_{i=0}^{k}\left[\frac{W_i-1}{2}\cdot E'[slot]\right]+k\cdot T_c+T_s \quad \text{for } 0\le k\le m \quad (8)$$

where $(W_i-1)/2$ is the average number of slot times that the station defers in the ith stage, kT_c is the time that the packet utilizes in collisions until reaches the k stage, T_s is the time to transmit successfully from the kth stage, $E'[slot]$ is the average length of a slot time when the remaining n-1 stations compete for the channel and is given by:

$$E'[slot]=(1-P'_{tr})\cdot\sigma+P'_{tr}\cdot P'_s\cdot T_s+P'_{tr}\cdot(1-P'_s)\cdot T_c \quad (9)$$

where P'_{tr} is the probability with that at least one station out of n-1 transmits in the considered slot time and is given by:

$$P'_{tr}=1-(1-\tau)^{n-1} \quad (10)$$

and P'_s is the probability that a transmission occurring on the channel is successful and is given by the probability that only one station transmits of the n-1 remaining stations, with the condition that a transmission occurs on the channel:

$$P'_s=\frac{(n-1)\cdot\tau\cdot(1-\tau)^{n-2}}{P'_{tr}}=\frac{(n-1)\cdot\tau\cdot(1-\tau)^{n-2}}{1-(1-\tau)^{n-1}} \quad (11)$$

From equation (8) after some algebra we get:

$$E[D_K]=\begin{cases}\frac{1}{2}\cdot\left[W\cdot(2^{k+1}-1)-(k+1)\right]\cdot E'[slot]+k\cdot T_c+T_s & \text{for } 0\le k\le m' \\ \frac{1}{2}\cdot\left[W\cdot 2^{m'}(k-m'+2)-W-k-1\right]\cdot E'[slot]+k\cdot T_c+T_s & \text{for } m'<k\le m\end{cases} \quad (12)$$

Let q_k be the probability that a successfully transmitted packet is transmitted successfully from the kth stage, so we get:

$$q_k=\frac{p^k}{1-p^{m+1}}\cdot(1-p) \quad \text{for } 0\le k\le m \quad (13)$$

where (1- p) is the probability that a packet is successfully transmitted after the packet reached the k stage with probability p^k, provided that the packet is not dropped $(1-p^{m+1})$.

6. Model Validation

The model is validated by comparing the analytical results with that taken from simulation outcome. The parameter values used for both simulation and analytical results follow the values specified for the Direct Spread Sequence Spectrum (DSSS) employed in the IEEE 802.11b standard and are shown in Table 1.

Table 1 System Parameter Values

Channel bit rate	1 Mbit/s
Packet Payload	8224 bits
MAC header	224 bits
PHY header	192 bits
ACK	112 bits + PHY header
RTS	160 bits + PHY header
CTS	112bits + PHY header
Propagation delay, δ	1 µs
Slot time, σ	20 µs
SIFS	10 µs
DIFS	50 µs
Minimum *CW*, W_0	32
Number of *CW* sizes, m'	5
Short retry limit, m	6

Fig. 3 plots the average packet delay per stage and the probability per stage for networks of n=5 and n=50 stations. The model is accurate as the analytical results (lines) match the simulation results (symbols) in both basic access and RTS/CTS cases. All simulation results are taken with a 95% confidence interval lower than 0.005 for all stages. The figure shows that the probability of use of stages lowers as the backoff stage gets higher because more collisions are needed to reach higher stages and is independent on the access mechanism employed. The collision probability for n=5 is low so the delay per stage is almost the same for both basic access and RTS/CTS access mode. For a network of 50 stations the delay per stage for the RTS/CTS access is lower than the basic access as the collisions for basic access last longer.

7. Analytical Results

Fig. 4 and 5 plot the average packet delay per stage and the probability per stage respectively versus the number of stations for the basic access mode. For comparison, Fig. 4 also plots the average packet delay, which linearly increases as the number of stations increases. The delay at stages highly increases as the number of stations increases due to the higher values of the collision probability. At the same time, the probability of use of higher stages with the high delay values increases for large networks.

Results presented in Fig. 4 and 5 indicate that the binary exponential backoff scheme does not result in a high distribution of packet delay values for small networks because the probability of using higher stages is extremely low for small n and the corresponding delay values are not very high. However, for large networks sizes, Fig. 5 indicates that the probability of using higher stages significantly increases and Fig. 4 indicates that the corresponding packet delay is also considerably increased. As a result, for n=50, the average packet delay is 0.57 sec and a packet is

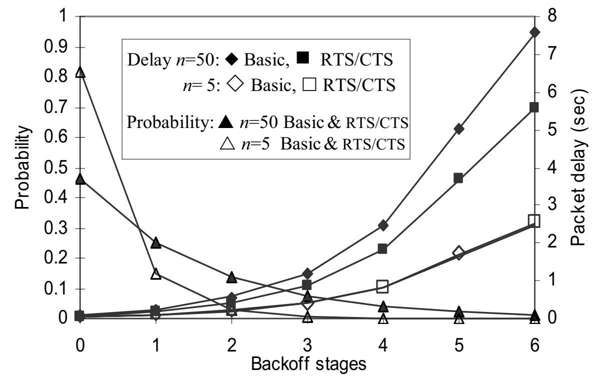

Fig. 3 Packet delay per stage and probability per stage versus backoff stages

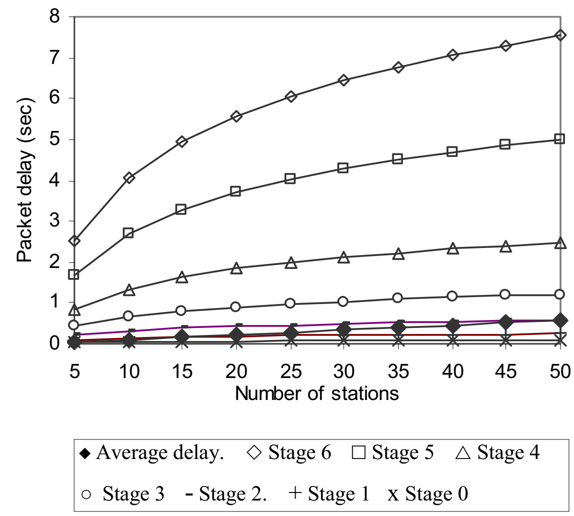

Fig. 4 Average packet delay and delay per stage versus number of stations for basic access

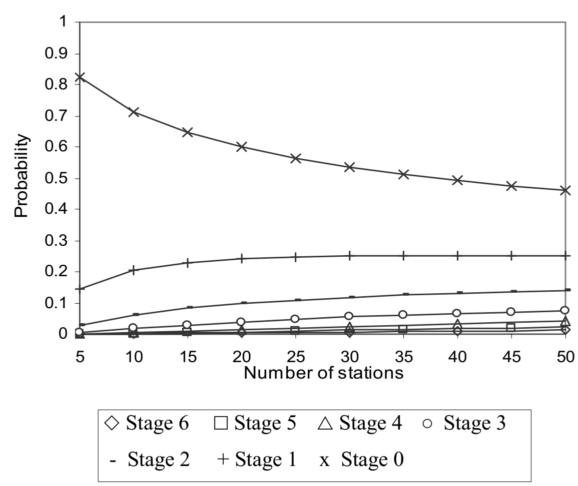

Fig. 5 Probability per stage versus number of stations

successfully transmitted from stage 0 with probability 0.46 with a (much lower than average) delay of 0.085 sec and from stage 6 with probability 0.01 and with extremely high average delay of 7.5 sec.

The delay per stage and the probability per stage for basic access are plotted in Fig. 6 and 7 respectively for different values of initial contention window size and *n*=25. The delay per stage is increasing as the initial contention window size is increasing. At the same time, as the initial contention window size is increasing the probability per stage is increasing only at stages 0 and 1 because the collision probability decreases. Although the probability of using higher stages is getting lower for higher *W*, the BEB scheme does result in a higher distribution of packet delay values for higher *W* as the corresponding delay values are higher at all stages. Thus, for higher *W* the unfairness of BEB scheme is increasing as a small proportion of packets suffer long delays when they transmitted from higher stages. For *W*=8, the BEB seems to be quite fair as the probability of use of stages is divided almost equally and the delay per stage is quite low but collision probability is higher and consequently the packet drop probability higher.

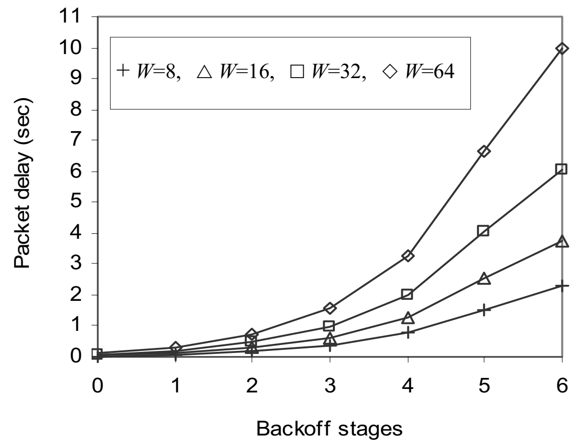

Fig. 6 Packet delay per stage versus backoff stages for *n*=25, *m*=6, *m'*=5 for basic access

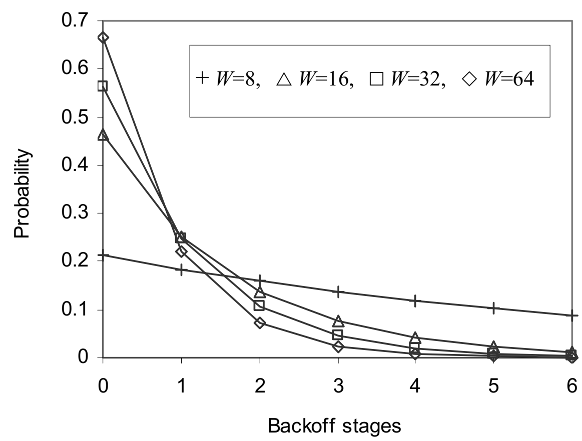

Fig. 7 Probability for use of a stage for successful transmission versus backoff stages for *n*=25, *m*=6, *m'*=5 and for basic access

8. Conclusions

This paper studies the delay distribution of DCF by developing a mathematical model that calculates two new performance metrics, the probability that a packet is successfully transmitted from a specific backoff stage and the corresponding average packet delay. Comparison with simulation results show that the analytical model is accurate in predicting the average delay per stage and the probability per stage. Analytical results indicate that, in large networks, DCF treats individual packets in an unfair manner because most packets are transmitted without collision and have very low time delays where as a few packets are successfully received after colliding several times and have significantly high delay values.

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