Performance Analysis of Packet Loss Rate and Packet Time Delay of IEEE 802.11 WLANs

Chiapin Wang
Department of Applied Electronic Technology
National Taiwan Normal University
Taipei, Taiwan
chiapin@ntnu.edu.tw

Yu-Chun Cheng
Department of Applied Electronic Technology
National Taiwan Normal University
Taipei, Taiwan
a0109101415@hotmail.com

***Abstract*—The paper investigates the performance of packet loss rate and packet time delay in IEEE 802.11 wireless local area networks (WLANs) with distributed coordination function (DCF). We derive an analytical model to study these performance metrics in terms of the data payload length, wireless channel condition, adopted medium-access-control (MAC) retry limit and used physical-layer (PHY) modes. From the analysis results, it is shown that the modulation and coding schemes (MCSs) designed in a single-node scenario may not provide expected good performance in multiple-node 802.11 WLANs due to the effect of transmission collision. The developed analytical model can be used to determine appropriate MAC retry limits and PHY date rates according to the specific delay constraint and tolerable packet loss level.**

Keywords-802.11 WLAN; DCF; packet time delay; packet loss rate

I. INTRODUCTION

The IEEE 802.11 [1] technologies offer high data rates for mobile users and become more and more popular nowadays. To provide a reliable transmission quality in error-prone wireless channels, the 802.11 physical layer (PHY) employs different modulation and coding schemes (MCSs) which offer multiple data rates. The IEEE 802.11b PHY employs binary phase shift keying (BPSK), or quadrature phase shift keying (QPSK) modulation to provide 1 or 2 Mbps PHY rate, and complementary code keying (CCK) to provide 5.5 or 11 Mbps PHY rate at the 2.4GHz band. The IEEE 802.11a PHY employ BPSK, QPSK, 16-QAM (quadrature amplitude modulation), and 64-QAM with different coding rate to provide eight PHY modes with data transmission rates ranging from 6 to 54 Mbps at the 5 GHz band. IEEE 802.11g PHY has been developed as an extension to the 802.11b to support higher data rate at 2.4 GHz band. It can provide the data transmission rates ranging from 1Mbps up to 54Mbps by employing the 802.11b modulation schemes and the 802.11a orthogonal frequency division multiplexing (OFDM) schemes. New 802.11 standards such as 802.11n [2] and 802.11ac, provide much higher throughput than legacy 802.11 by using more advanced PHY technologies such as multiple input and multiple output (MIMO) and higher order modulation schemes (up to 256-QAM).

Determining one from multiple available PHY modes with respect to a given channel condition is referred to as link adaptation (LA) and the effectiveness of the implemented LA scheme can significantly affect the system performance [3]. Due to the physical transmission characteristics, there is a tradeoff performed between the robustness and time efficiency of packet deliveries. Thus an optimal MCS is designed to select the PHY mode which can provide best throughput as possible while also maintain an appropriate link quality. Since multimedia applications, e.g. streaming video, voice over WLAN, and net meeting, have specific performance requirements such as the target throughput, constraint delay and tolerable PLR, the performance of throughput, delay and PLR in 802.11 WLANs should be analyzed in order to provide multimedia QoS. In this paper we derive an analytical model to study these performance metrics. From the analysis results, it is shown that the MCS selection scheme for maximizing throughput or minimizing packet error rate derived in a single-node scenario may not provide an expected good performance due to the effect of transmission collision. Furthermore, the default value of retry transmissions may not guarantee a desirable delay constraint. The developed analytical model can be used to design appropriate retry limits and MCS selection schemes according to the specific delay constraint and tolerable PLR.

II. THE ANALYTICAL MODEL

We use an analytical approach to evaluate the packet loss rate and packet time delay in IEEE 802.11 WLANs. We extend a DCF model [4] to develop our analytical model which is capable of providing performance analysis of saturated throughput, packet loss rates, and packet time delays while using different MAC-layer backoff parameters and PHY-layer MCSs under diverse channel conditions.

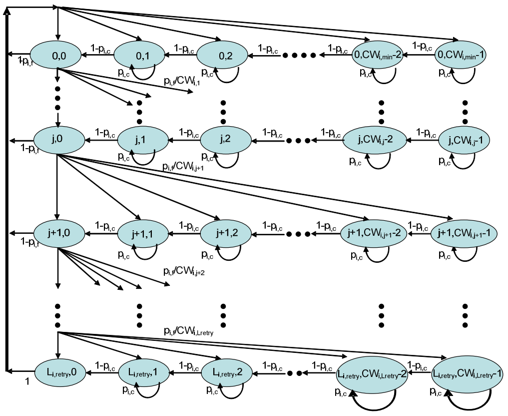

Fig. 1. The state transition diagram

A. Packet Loss Rate (PLR) Analysis

The failure of a packet transmission results from two parts. One is the transmission collision and the other is the packet corruption due to error-prone channels provided that no collision occurs. For the i^{th} node, let $p_{i,c}$ denote the collision probability with other nodes and $p_{i,e}$ denote the packet-error probability. Hence $p_{i,f}$, the transmission-failed probability of the i^{th} node is:

$$p_{i,f} = p_{i,c} + (1 - p_{i,c}) \cdot p_{i,e}. \qquad (1)$$

$p_{i,c}$ can be expressed as:

$$p_{i,c} = 1 - \prod_{h=0, h \neq i}^{K-1} (1 - \tau_h), \qquad (2)$$

where K is the number of 802.11 stations; τ_h is the probability for the h^{th} node to transmit a packet in a slotted time. The packet-error probability $p_{i,e}$ is essentially determined by the signal to noise ratio (SNR), packet length, and used MCS [3]. Consider uncoded modulations and assume that the bit error rate BER_i is identical and uncorrelated within each packet interval, $p_{i,e}$ can be expressed as [5]:

$$p_{i,e} = 1 - (1 - BER_i)^{(PL+HL)*8}, \qquad (3)$$

where PL is packet length and HL is header length in bytes. If the coded modulations are considered such as what are used in the IEEE 802.11a standards, the evaluation in equation (3) may not be always accurate since bit errors are usually correlated when coded transmissions are decoded in the ML (maximum-likelihood) sense [5]. In this case, $p_{i,e}$ would be expressed with an approximate equation [5]:

$$p^{(n)}{}_{i,e} = \begin{cases} 1 & \text{, if } 0 < \gamma < \gamma_p{}^{(n)} \\ a^{(n)} \exp(-g^{(n)}\gamma) & \text{, if } \gamma \geq \gamma_p{}^{(n)} \end{cases}, \qquad (4)$$

where n is the mode index, with each mode representing a MCS. Parameters $a^{(n)}$, $g^{(n)}$ and $\gamma_p{}^{(n)}$ are mode-dependent and can be obtained from [5].

Let $p_{i,l}$ denote the packet-lost probability for the i^{th} node. The probability $P_{i,l}$ can be expressed as:

$$p_{i,l} = p_{i,f}{}^{L_{i,retry}+1}. \qquad (5)$$

In 802.11, a packet transmission needs to wait for a random backoff time. The random backoff timer is uniformly determined from the interval (0, CW-1), where CW is the contention window size. For the i^{th} node, let $CW_{i,min}$ denote the initial window size, $CW_{i,j}$ denote CW in the j^{th} backoff stage, and $L_{i,retry}$ denote the maximum retry limit. After a retransmission due to either corruption or collision, CW is multiplied with an increase factor, σ_i, to a maximum value, $CW_{i,max}$. Once the contention window reaches $CW_{i,max}$, it will remain as $CW_{i,max}$ until it is reset. Hence, the relationships of $CW_{i,j}$, $CW_{i,min}$, $CW_{i,max}$, σ_i, and $L_{i,retry}$ can be expressed as follows:

$$CW_{i,j} = \begin{cases} \sigma_i{}^j CW_{i,\min} & \text{for } j = 0,1,\ldots,m_i\text{-1, if } L_{i,retry} > m_i \\ \sigma_i{}^{m_i} CW_{i,\min} = CW_{i,\max} & \text{for } j = m_i,\ldots,L_{i,retry}\text{, if } L_{i,retry} > m_i \\ \sigma_i{}^j CW_{i,\min} & \text{for } j = 0,1,\ldots,L_{i,retry}\text{, if } L_{i,retry} \leq m_i \end{cases} \qquad (6)$$

$$\text{where} \quad m_i = \log_{\sigma_i}(CW_{i,\max}/CW_{i,\min})$$

For the i^{th} node, let $s(i,t)$ be the stochastic process representing the backoff stage at time t, and $b(i,t)$ be the stochastic process representing the backoff time counter. Let

$$b_{i,j,l} = \lim_{t\to\infty} \Pr\{s(i,t) = j, b(i,t) = l\},\ j \in (0, L_{i,retry}), l \in (0, CW_{i,j} - 1)$$

be the stationary distribution of the Markov chain. With the transition probability as shown in Fig. 1, the following equations can be derived.

$$b_{i,j,0} = p_{i,f} \cdot b_{i,j-1,0}\ ,\ 0 < j \leq L_{i,retry} \qquad (7)$$

$$b_{i,j,0} = p_{i,f}{}^j \cdot b_{i,0,0}\ ,\ 0 \leq j \leq L_{i,retry} \qquad (8)$$

$$b_{i,j,l} = \frac{CW_{i,j} - l}{CW_{i,j}} \cdot \frac{1}{1 - p_{i,c}} \cdot b_{i,j,0}\ ,\ 0 \leq j \leq L_{i,retry},\ 1 \leq l \leq CW_{i,j} - 1 \qquad (9)$$

$$\sum_{j=0}^{L_{i,retry}} \sum_{l=0}^{CW_{i,j}-1} b_{i,j,l} = 1 \qquad (10)$$

Equations (8) and (9) express all $b_{i,j,l}$ values as a function of $b_{i,0,0}$, $p_{i,c}$ and $p_{i,e}$. Finally $b_{i,0,0}$ is given by (11) and depends on the values of $L_{i,retry}$ and m_i.

Since a given node transmits when its backoff timer reaches 0, the probability that the i^{th} node transmits a packet in a randomly chosen slotted time, τ_i, can be derived as:

$$b_{i,0,0} = \begin{cases} \dfrac{2(1-\sigma_i \cdot p_{i,f})(1-p_{i,f})(1-p_{i,c})}{CW_{i,\min} \cdot (1-(\sigma_i \cdot p_{i,f})^{L_{i,retry}+1}) \cdot (1-p_{i,f}) + (1-p_{i,f}{}^{L_{i,retry}+1}) \cdot (1-2p_{i,c} - \sigma_i \cdot p_{i,f} + 2 \cdot \sigma_i \cdot p_{i,c} \cdot p_{i,f})} & , L_{i,retry} \leq m_i \\ \dfrac{2(1-\sigma_i \cdot p_{i,f})(1-p_{i,f})(1-p_{i,c})}{CW_{i,\min} \cdot (1-(\sigma_i \cdot p_{i,f})^{m_i+1}) \cdot (1-p_{i,f}) - (1-\sigma_i \cdot p_{i,f})(1-p_{i,f}{}^{m_i+1}) + (1-\sigma_i \cdot p_{i,f})(CW_{i,\min} \cdot \sigma_i{}^{m_i} - 1)(1-p_{i,f}{}^{L_{i,retry}-m_i}) + 2(1-\sigma_i \cdot p_{i,f})(1-p_{i,f}{}^{L_{i,retry}+1})(1-p_{i,c})} & , L_{i,retry} > m_i \end{cases}. \qquad (11)$$

$$\tau_i = \sum_{j=0}^{L_{i,retry}} b_{i,j,0} = \sum_{j=0}^{L_{i,retry}} p_{i,f}{}^{j} \cdot b_{i,0,0} = b_{i,0,0} \cdot \frac{1 - p_{i,f}{}^{L_{i,retry}+1}}{1 - p_{i,f}} \tag{12}$$

From (12) we can see that τ_i depends on the packet's failed probability $p_{i,f}$, which is determined by the packet-collision probability $p_{i,c}$ and the packet-error probability $p_{i,e}$. From (1) and (6) to (12), we can solve unknown parameters τ_i and $p_{i,f}$ numerically with a given $p_{i,e}$.

B. Packet Delay Analysis

The average number of slots required for a packet waiting for transmission in the j stage is $(CW_{i,j}+1)/2$, where $j \in (0, L_{i,retry})$. Let $E_i[T_{loss}]$ be the average number of slotted time required for a packet to experience $L_{i,retry}+1$ collisions in the $(0,1,\ldots L_{i,retry})$ stages:

$$E_i[T_{loss}] = \sum_{j=0}^{L_{i,retry}} \frac{CW_{i,j}+1}{2} = \begin{cases} \dfrac{CW_{i,\min} \cdot (\sigma_i{}^{L_{i,retry}+1} - 1) + L_{i,retry} + 1}{2} &, L_{i,retry} \le m_i \\ \dfrac{CW_{i,\min} \cdot (\sigma_i{}^{m_i+1} - 1) + CW_{i,\min} \cdot \sigma_i{}^{m_i} \cdot (L_{i,retry} - m_i) + (L_{i,retry}+1)}{2} &, L_{i,retry} > m_i \end{cases} . \tag{13}$$

The average delay for a successfully transmitted packet is defined to be 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 [6]. The average number of slots required for a successfully transmission, $E_i[X]$, is given by:

$$E_i[X] = \sum_{j=0}^{L_{i,retry}} \left[(p_{i,f}{}^{j} - p_{i,f}{}^{L_{i,retry}+1}) \cdot \frac{CW_{i,j}+1}{2} \right] \tag{14}$$

where $(p_{i,f}{}^{j} - p_{i,f}{}^{L_{i,retry}+1})$ is the probability that a packet that is not dropped reaches the j stage.

The average packet delay $E_i[D]$, provided that this packet for the i^{th} node is not discarded, is then derived from equations (15):

$$E_i[D] = E_i[X] \cdot E[slot]. \tag{15}$$

III. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we utilize the developed analytical model in section II to evaluate the performance with respect to various threshold selection schemes. We consider the multiple transmission modes of convolutionally coded M_n-ary rectangular/square QAM, which are adopted from the IEEE 802.11a standards as shown in Table 1 in a rate ascending order. The adopted 802.11 system parameters are shown in Table 2.

TABLE 1. Transmission modes with convolutionally coded modulation [5]

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Modulation	BPSK	QPSK	QPSK	16QAM	64QAM
Coding Rate	1/2	1/2	3/4	3/4	3/4
$a^{(n)}$	274.7229	90.2514	67.6181	53.3987	35.3508
$g^{(n)}$	7.9932	3.4998	1.6883	0.3756	0.09
$\gamma_p{}^{(n)}$ (dB)	-1.5331	1.0942	3.9722	10.2488	15.9784

TABLE 2. Simulation parameters

Parameter	Value
Payload	2304 bytes
Slot time	20 us
Data rate	1, 2, 4, 6Mbps
MAC header	28 bytes
PHY header	24 bytes
ACK	38 bytes
DIFS	50 us
SIFS	10us
Propagation delay	2us
Initial window size	32
Increasing factor	2
Retry limit	5

We investigate two MCS selection schemes indexed as throughput-maximizing scheme and PLR-constraint scheme.

A throughput-maximizing scheme aims at selecting a MCS which provide maximum throughput without the consideration of PLR. A PLR-constraint scheme aims at selecting a MCS which provides maximum throughput under the constraint of a given PLR level. The tolerable packet failure probability $p_{i,f}$ for a PLR-constraint scheme can be obtained from equations (5) and expressed as:

$$p_{i,f} \le p_{i,l}{}^{1/(L_{i,retry}+1)} = p_{i,target}. \tag{16}$$

Fig. 2 shows the throughput with the 5 PHY modes in a single-node WLAN environment. From Fig. 2, it is shown that the SNR thresholds for the throughput-maximizing scheme can be easily obtained (TH_{1_2} = 2.81 dB, TH_{2_3} = 6.36 dB, TH_{3_4} = 12.72 dB, TH_{4_5} = 19.29 dB). Instead of using a throughput-maximizing scheme, alternatively, we can use a PLR-constraint scheme to select a PHY mode with respect to a given SNR. Given a retransmission limit, the packet failure probability to meet the PLR constraint can be obtained from equation (16). For example, if the tolerable PLR is 0.2% and the retransmission limit is 5, $p_{i,target}$ will be 35.495%. If SNR is 5 dB, the selected MCS should be mode 3 (TH_{1_2} = 2 dB, TH_{2_3} = 4.93 dB, TH_{3_4} = 11.25 dB, TH_{4_5} = 17.09 dB).

In a multiple-node WLAN, the thresholds are no longer equal to those in a single-node WLAN. For example in a 20-node WLAN, the throughput-based thresholds are: TH_{1_2} = 2.06 dB, TH_{2_3} = 5.53 dB, TH_{3_4} = 11.77 dB, and TH_{4_5} = 18.32 dB; the PLR-based thresholds are: TH_{1_2} = 3.61 dB, TH_{2_3} = 6.62 dB, TH_{3_4} = 13.01 dB, and TH_{4_5} = 18.97 dB.

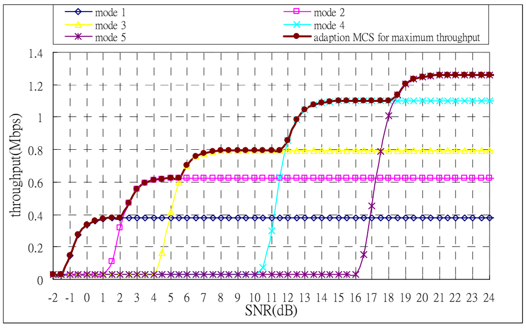

Fig. 2. Throughput of the 5 PHY modes (in case of single node)

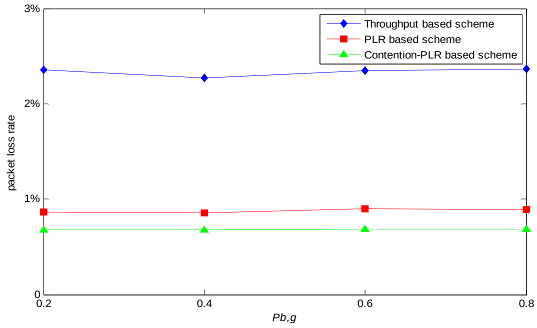

Fig. 3. The packet loss rate with different schemes

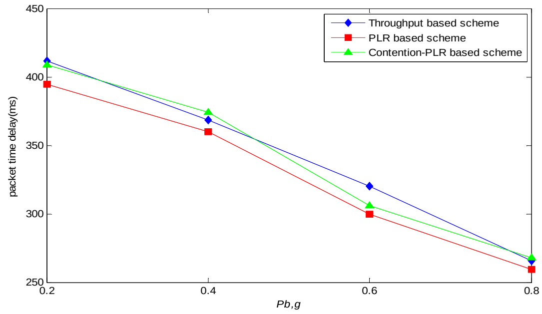

Fig. 4. The packet time delay with different schemes

The reason is that the failure of a packet transmission in contention-based IEEE 802.11 WLANs results from not only the packet corruption due to error-prone channels, but also the transmission collision among nodes. Thus the MCS threshold selection which only considers the effect of packet corruption in a single-node scenario is bias in contention-based WLAN environments and cannot provide expected performance. Instead of that, both packet corruption and transmission collision should be considered for the designs of MCS thresholds.

Next, we establish a simulated environment of IEEE 802.11 networks to compare the performance of three MCS threshold selection schemes which are referred as throughput based scheme, PLR based scheme with PLR threshold 1% and contention-PLR based scheme with PLR threshold 1%. We use a two-state discrete Markov chain to model the SNR distributions. In this model, the channel condition could be either “bad” or “good”. μ_b and μ_g represents the transition rate from “bad” to “good” state and from “good” to “bad” state respectively. If the wireless channel is in the bad state, the SNR value is derived from a uniform distribution in the range of 6 to 18 dB; if the channel is in the good state, the SNR is taken from the range of 18 to 30 dB. The time of the channel staying in the bad (or good) state is exponentially distributed with the average value of $1/\mu_b$ (or $1/\mu_g$). $p_{b,g}$ is $\mu_b/(\mu_g+\mu_b)$ when the state transition probability is from “bad” state to “good” state; $p_{g,b}$ is $\mu_g/(\mu_g+\mu_b)$ when it is from “good” to “bad” state. The values of $p_{b,g}$ and $p_{g,b}$ indicate the statistic of wireless channel conditions. In the simulation set-up, there are total 40 nodes in a WLAN where half the nodes, named good-channel nodes, are of identical channel condition SNR_0 and the other half, named bad-channel nodes, are of identical channel condition SNR_1. SNR_0 is with the parameter $p_{b,g}$ =0.2 where SNR_1 is with the parameter $p_{b,g}$ =0.2, 0.4, 0.6, and 0.8 in each test. In each test, we take 200 examples of SNR and use different MCSs to evaluate the performance of average packet loss rate and delay.

Fig. 3 and Fig. 4 show the packet loss rate and average packet time delay, respectively. From the results we can observe that contention-based PLR scheme can meet the requirement of targeted PLR (1%), while the other two scheme cannot. The throughput based scheme is the worst one to meet the required packet loss rate. In terms of packet time delays, the performances of two PLR-based schemes are worse than that of the throughput based scheme since there is a tradeoff performed between the reliability (PLR) and efficiency (delay) of a transmission. Thus more robust a transmission is, higher the delay. In terms of both packet loss rates and packet time delays, the contention-based PLR scheme performs among all. The developed analytical model can be used to determine appropriate MAC retry limits and PHY date rates according to the specific delay constraint and tolerable packet loss level.

IV. Conclusions

In this paper we investigate the performance of packet loss rate and packet time delay in IEEE DCF-based 802.11 WLANs. We derive an analytical model to study these performance metrics in terms of the data payload length, wireless channel condition, adopted MAC retry limit and used physical-layer PHY modes. From the analysis results, it is shown that the MCS selection scheme designed in a single-node scenario may not provide expected good performance in multiple-node 802.11 WLANs due to the effect of transmission collision. The developed analytical model can be used to determine appropriate MAC retry limits and PHY date rates according to the specific delay constraint and tolerable packet loss level.

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