Joint PHY/MAC Based Link Adaptation for Wireless LANs with Multipath Fading

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***Abstract*— Wireless local area networks offer a range of transmitted data rates that are to be selected according to estimated channel conditions. However, due to packet overheads and contention times introduced by the CSMA/CA multiple access protocol, effective throughput is much less than the nominal data rates. Most multimedia applications use small payload sizes in order to ensure reliable, low latency transmission. This results in a further loss in effective throughput thereby reducing network capacity drastically. Thus, a cross-layer based design approach along with link adaptation is required to improve the network performance under different channel conditions. We investigate the effect of payload size variations on single-user throughput for both non-fading and multipath fading environments. We explore the difference in link adaptation thresholds for different payload sizes with varying channel characteristics. A link adaptation scheme to maximize the throughput with a packet error constraint is presented.**

I. Introduction

Wireless local area networks (WLANs) are rapidly becoming part of our network infrastructure. The IEEE 802.11 WLAN physical layer (PHY) supports multiple data rates by using different modulation and channel coding schemes. For instance, the IEEE 802.11a networks have 8 different modes with varying data rates from 6 to 54 Mbps [1]. However, due to the packet headers from higher layers, as well as the various overheads in the medium access control (MAC) scheme, there is a significant reduction in effective throughput, where effective throughput (or goodput) is defined as the ratio of the expected delivered data payload to the expected transmission time [2]. Moreover, most voice and video applications tend to use very small payload sizes to ensure reliable, low delay delivery. This results in significant loss in effective throughput. A cross-layer based design approach is presented in this paper whereby a joint adaptation of the PHY and MAC layer parameters show a significant performance improvement.

The effective throughput is affected by a number of parameters, including transmission rate, payload and header size, constellation size, transmitted power, and received noise characteristics. When the channel is time varying in nature, the transmission parameters should be adapted according to channel conditions to improve link performance. The mechanism to select one of the multiple available transmission rates is referred to as *link adaptation*. The current link adaptation schemes used in IEEE 802.11a wireless cards are proprietary (mostly based on received signal strength and packet error rates) and in many cases can lead to inefficient bandwidth utilization and unnecessary rate adaptation. In this paper, we analyze the improvement in single-user effective throughput provided by link adaptation by varying the data rate and packet length as a function of channel conditions.

The cross-layer design approach is based on a joint PHY-MAC based link adaptation scheme where the parameters adapted are payload size of the transmitted packet and the PHY data rate based on current channel conditions. A critical component of any link adaptation scheme is the identification of signal to noise ratio (SNR) thresholds at which to alter the link adaptation parameters [3]. We conduct exhaustive simulations to identify the SNR thresholds for 3 different payload sizes of 20 bytes, 200 bytes and 2000 bytes, respectively. These payload sizes cover a wide range of applications from various voice codecs to H.264 video conferencing applications along with various data applications like web browsing, ftp, etc. The wireless channel models considered include both non-fading as well as multipath fading environments. Most results published on link adaptation have focused on path loss and shadowing effects only. We observe that the SNR thresholds using the multipath fading channel is considerably different from the additive white Gaussian noise (AWGN) channel. Link adaptation schemes that only consider the effects of path loss and shadowing have a significant performance loss in frequency-selective multipath fading channels.

An early investigation of the effect of payload size on throughput was conducted in [4]. We extend their work by taking into account various packet header and protocol overheads in the context of IEEE 802.11a wireless LANs, which have a tremendous impact on the effective throughput. Rate adaptation using a theoretical framework to evaluate the throughput has been investigated in [2]. However, the effect of multipath fading was not considered there. As we show in this paper, this can result in significantly different thresholds, thereby causing inefficient switching of data rates. In [5], the impact of frequency selectivity on link adaptation algorithms were considered. However, in Hiperlan/2 the payload size

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does not impact the link adaptation algorithm, which is quite different from the IEEE 802.11 MAC where payload size has a tremendous effect on the throughput [6]. A major contribution of this paper is to provide realistic estimates of throughput and packet error rates for various payload sizes covering a broad range of applications that can be used as a reference by various application designers.

In this paper, we investigate the effect of frequency selectivity and payload length variation on single-user throughput. We also show the limitations of link adaptation schemes which just consider the path-loss and shadowing effects of the wireless channel and neglect the multipath fading effects. The paper is outlined as follows. In the next section, we provide a brief description of our simulation scenario and a description of the multipath fading channel model used in our simulation. In Section III, the effect of payload variation on single-user throughput is considered for non-fading AWGN channels. In Section IV, we investigate the effect of multipath fading on link adaptation thresholds for the different payload lengths. The last section presents conclusions and future research directions.

II. Simulation environment

In order to estimate the packet error rate under different channel conditions, we modified a readily available OFDM simulator for the IEEE 802.11a PHY [7]. The scenario we consider is of a single-user communicating with an access point or with another node in an ad-hoc or mesh network. Non-fading channels as well as multipath fading channels are considered. Noise is modeled as AWGN in both scenarios. The decoding at the receiver is based on soft decision Viterbi decoding. We also assume perfect synchronization and channel estimation.

The payload length used for our simulation purposes were 20, 200 and 2000 bytes. These values cover a wide range of voice and video applications. For the non-fading scenario, we used 1000 packets to estimate the packet error rate. The packet error rate for the fading realization was obtained by averaging over 500 fading realizations with 1000 fixed size packets per realization. This was done for the 20 and 200 bytes payload sizes. The 2000 bytes payload length was averaged over 250 fading realizations due to the computation time at higher payload lengths. The wireless channel model used for the multipath fading case is the Nafteli Chayat model [8] which is a standard indoor wireless channel model with an exponentially decaying Rayleigh faded path delay profile. The channel coefficients are normalized so as to ensure same average power. The rms delay spread used was 50 nanoseconds which is typical for home and office environments.

We define *throughput* as the number of payload bits per second received correctly as in [9]. We consider the contention-based Distributed Coordination Function (DCF) for evaluating the throughput. The MAC header and FCS consists of 28 bytes and the ACK is 14 bytes long. The RTP and UDP overhead for multimedia traffic is 12 and 8 bytes, respectively, and another 20 bytes is added for the IP header. For simplicity of analysis, we assume that the acknowledgments from the receiver are error-free. We also did not consider the backoff interval since we are calculate the effective throughput of a single packet transmission without considering retransmissions and collisions.

Throughput corresponding to PHY mode m and payload length L bytes is given by:

$$T(m) = \frac{L}{T_x} * R_m * (1 - PER^m(\gamma_s, L)) \qquad (1)$$

where,
L: payload length in bits,
T_x: Transmit time of packet including MAC and PHY headers and DCF protocol overheads,
R_m: data rate corresponding to PHY mode m,
$PER^m()$: packet error rate (PER) corresponding to PHY mode m
γ_s: Average SNR per symbol.

The packet error rate is assumed to be caused only by bit errors in the data packet in the wireless channel.

III. Effect of payload variation on single-user throughput in non-fading AWGN channels

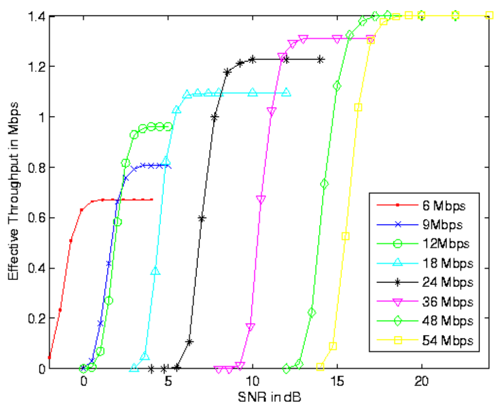
In this section, we explore the effect of payload length variation on single-user throughput. We tabulate the SNR thresholds based on throughput maximization at different payload lengths. However, a throughput based link-adaptation scheme can select a data rate and payload size with high packet error rates. This can cause significant retransmissions and thereby make the latency intolerable. This motivates a throughput maximization scheme with a packet error rate constraint. We tabulate the SNR thresholds for such a scheme with a maximum packet error rate of 5%, which is acceptable for many multimedia applications.

Case a) 20 bytes payload length

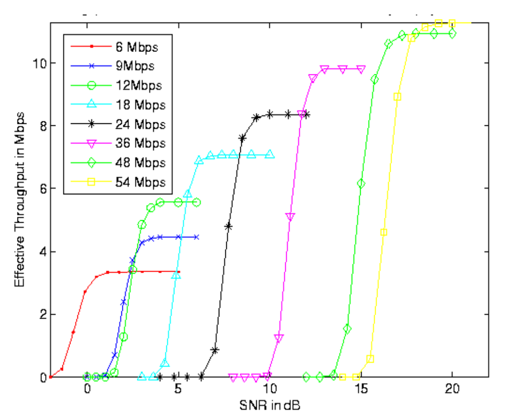
The throughput and packet error rates for a 20 byte payload length in AWGN only channels are shown in Figs. 1(a) and 1(b), respectively. The packet error rate plot in Fig. 1(b) also indicates a line corresponding to 5% packet error rate. A 20 byte payload length is used for 20 ms G.729 speech packets. The link adaptation thresholds with and without packet error rate constraints are tabulated in Tables I and II, respectively. It is interesting to note that 9 Mbps and 54 Mbps data rates are not used in either scenario. It is also interesting to observe that the packet error rate for 54 Mbps is lower than 5% at SNRs above 17 dB. However, the throughput using both 48 Mbps and 54 Mbps are nearly the same and thus we use the 48 Mbps data rate for all SNRs above 16 dB in order to reduce unnecessary data rate switching.

Case b) 200 bytes payload length

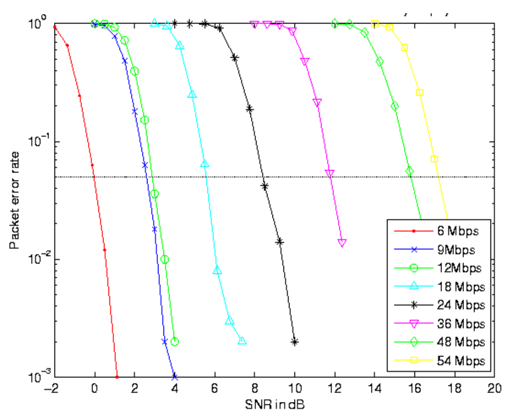
The throughput and packet error rates for a 200 byte payload length are shown in Figs. 2(a) and 2(b), respectively. A 200 byte payload length can be used for 25ms G.711 speech packets. We observe a significant improvement in throughput from



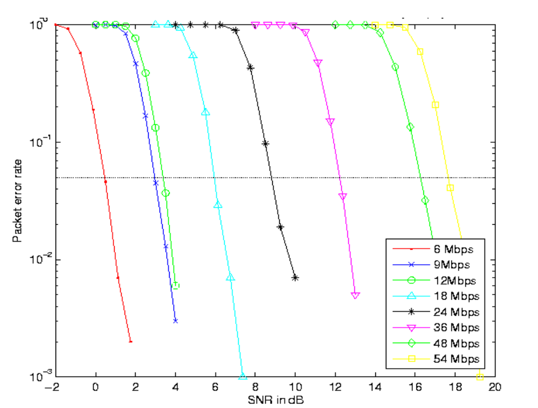
(a) Effective Throughput vs SNR for various data rates with 20 bytes payload in non-fading AWGN channels



(a) Effective Throughput vs SNR for various data rates with 200 bytes payload in non-fading AWGN channels



(b) Packet error rates vs SNR for various data rates with 20 bytes payload



(b) Packet error rates vs SNR for various data rates with 200 bytes payload

Fig. 1. Effective Throughput and packet error rates vs SNR for 20 bytes payload in non-fading AWGN channels

Fig. 2. Effective Throughput and packet error rates vs SNR for 200 bytes payload in non-fading AWGN channels

TABLE I

LINK ADAPTATION THRESHOLDS USING 20 BYTES PAYLOAD WITH MAXIMUM PACKET ERROR RATE CONSTRAINT OF 5% IN A NON-FADING ENVIRONMENT

Data Rate(Mbps)	6	12	18	24	36	48
SNR range(dB)	0-3	3-6	6-9	9-12	12-16	> 16

TABLE II

LINK ADAPTATION THRESHOLDS USING 20 BYTES PAYLOAD WITHOUT PACKET ERROR RATE CONSTRAINT IN A NON-FADING ENVIRONMENT

Data Rate (Mbps)	6	12	18	24	36	48
SNR range (dB)	-2-2	2-5	5-8	8-12	12-16	> 16

TABLE III

LINK ADAPTATION THRESHOLDS USING 200 BYTES PAYLOAD WITH MAXIMUM PACKET ERROR RATE CONSTRAINT OF 5% IN A NON-FADING ENVIRONMENT

Data Rate(Mbps)	6	12	18	24	36	48	54
SNR range(dB)	1-4	4-6	6-9	9-12	12-16	16-18	>18

TABLE IV

LINK ADAPTATION THRESHOLDS USING 200 BYTES PAYLOAD WITHOUT PACKET ERROR RATE CONSTRAINT IN A NON-FADING ENVIRONMENT

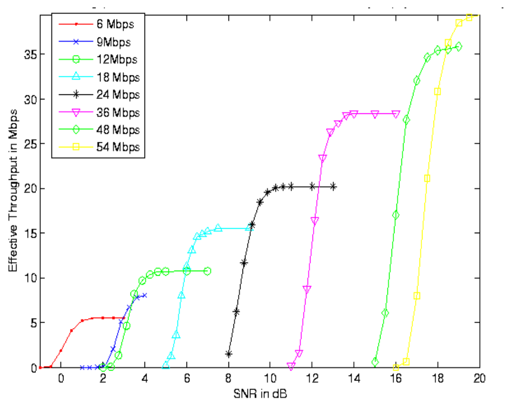
Data Rate (Mbps)	6	12	18	24	36	48	54
SNR range (dB)	-2-3	3-6	6-9	9-12	12-16	16-18	> 18

the 20 byte case but still it is much lower than the nominal rates. The link adaptation thresholds with and without packet error rate constraints are in Tables III and IV, respectively.

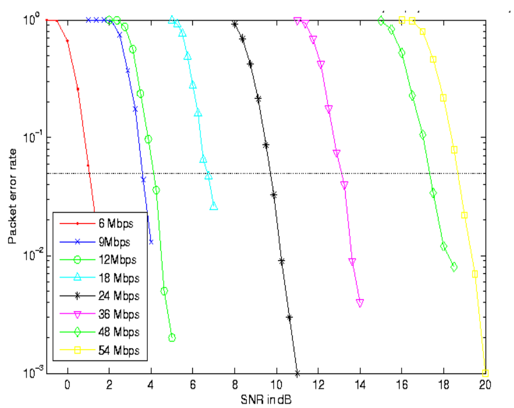
It is interesting to observe that the highest data rate in IEEE 802.11a PHY of 54 Mbps is used at SNRs above 18 dB in both the link adaptation scenarios (with and without maximum packet error rate constraint) unlike the 20 bytes payload case.

Case c) 2000 bytes payload length

The throughput and packet error rates for a 2000 byte payload length are shown in Figs. 3(a) and 3(b), respectively. 2000 bytes payload length can be used for moderate to high



(a) Effective Throughput vs SNR for various data rates with 2000 bytes payload in non-fading AWGN channels



(b) Packet error rates vs SNR for various data rates with 2000 bytes payload in non-fading AWGN channels

Fig. 3. Effective Throughput and packet error rates vs SNR for 2000 bytes payload in non-fading AWGN channels

bitrate H.264 video frames. We observe a significant gain in single-user throughput at higher payload length. This suggests that for throughput constrained applications, it is important to select data rates based on channel conditions and also to operate at higher payload lengths in order to make maximum use of network resources. The link adaptation thresholds with and without packet error rate constraints are in Tables V and VI, respectively.

TABLE V

LINK ADAPTATION THRESHOLDS USING 2000 BYTES PAYLOAD WITH MAXIMUM PACKET ERROR RATE CONSTRAINT OF 5% IN A NON-FADING ENVIRONMENT

Data Rate(Mbps)	6	12	18	24	36	48	54
SNR range (dB)	1-4	4-7	7-10	10-13	13-17	17-19	> 19

A comparison of the above tables indicate that link adaptation algorithms need to adapt to the payload size. For instance, as indicated above, 54 Mbps does not play any role in the 20 bytes payload case while it is used both with 200 bytes and

TABLE VI

LINK ADAPTATION THRESHOLDS USING 2000 BYTES PAYLOAD WITHOUT PACKET ERROR RATE CONSTRAINT IN A NON-FADING ENVIRONMENT

Data Rate (Mbps)	6	12	18	24	36	48	54
SNR range (dB)	1-3	3-6	6-9	9-12	12-16	16-18	> 18

2000 bytes payload sizes.

IV. EFFECT OF PAYLOAD VARIATION ON SINGLE-USER THROUGHPUT IN FADING CHANNELS

In this section, we explore the effect of payload length variation on single-user throughput by incorporating the multipath fading effects. We observe that the link adaptation thresholds and data rates used are significantly different from the non-fading scenario, and there is a significant degradation in performance for link adaptation schemes which fail to consider multipath fading.

Case a) 20 bytes payload length

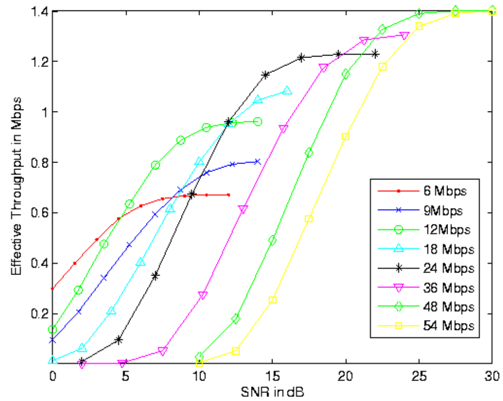
The effective throughput and packet error rates vs SNR for a 20 bytes payload in a multipath fading environment are shown in Figs. 4(a) and 4(b), respectively. The throughput obtained is again significantly lower than the nominal data rate. We also tabulate the SNR thresholds for link adaptation with and without a packet error rate constraint of 5% in Tables VII and VIII, respectively. As can be seen from the tables, there is a substantial shift in the SNR thresholds for optimal adaptation from the AWGN case. In AWGN, for a 20 byte payload size, PHY mode 1 can be used from -2 to 2 dB whereas in a multipath fading scenario, the SNR range varies from 0-5 dB. Similarly, mode 7 is used at SNRs above 16 dB in a non-fading environment whereas it can be used only at SNRs greater than 22 dB in the multipath fading scenario. This indicates that any link adaptation scheme which can adapt the SNR thresholds based on a fading or non-fading realization will outperform schemes which use the same precomputed thresholds in both environments. It is also interesting to observe that the 9 Mbps data rate is not used over the various SNR ranges in both the link adaptation scenarios . This is also observed at the higher payload cases as well. This has been widely described in the literature [2] and has been attributed to the poor frequency selectivity characteristics of the punctured convolutional codes.

TABLE VII

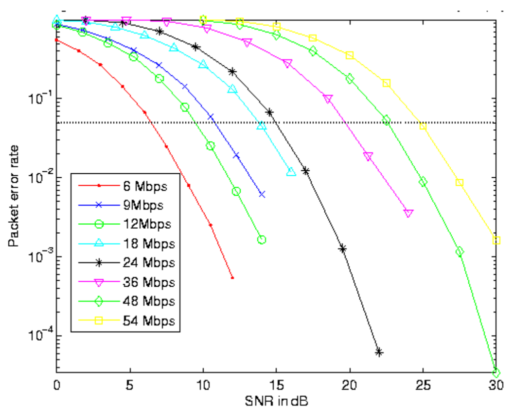
LINK ADAPTATION THRESHOLDS USING 20 BYTES PAYLOAD WITH MAXIMUM PACKET ERROR RATE CONSTRAINT OF 5% IN A NORMALIZED MULTIPATH FADING ENVIRONMENT

Data Rate(Mbps)	6	12	18	24	36	48
SNR range(dB)	7-10	10-14	14-15	15-20	20-23	> 23

Note that though mode 4 (18 Mbps PHY rate) is not used when the packet error rate constraint is neglected, it does play a role from 14-15 dB when a PER of 5% is considered.



(a) Effective Throughput vs SNR for various data rates with 20 bytes payload



(b) Packet error rates vs SNR for various data rates with 20 bytes payload

Fig. 4. Effective Throughput and packet error rates vs SNR for 20 bytes payload in normalized multipath fading

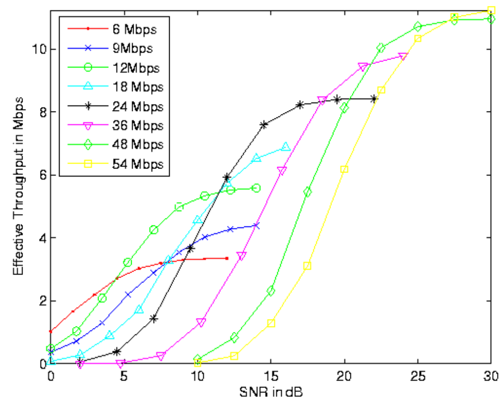
TABLE VIII
LINK ADAPTATION THRESHOLDS USING 20 BYTES PAYLOAD WITHOUT PACKET ERROR RATE CONSTRAINT IN A NORMALIZED MULTIPATH FADING ENVIRONMENT

Data Rate (Mbps)	6	12	24	36	48
SNR range (dB)	0-5	5-12	12-20	20-22	> 22

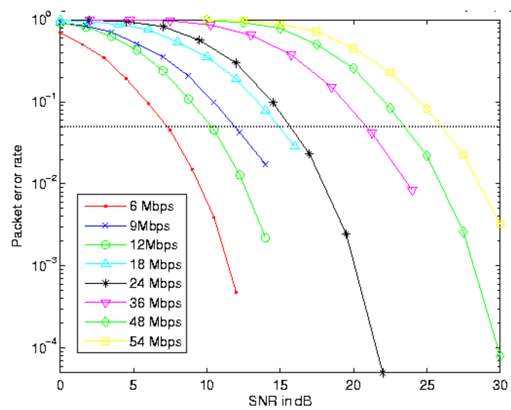
Furthermore, mode 8 corresponding to 54 Mbps is not used in either case though the PER using this data rate is < 5 % at SNRs greater than 24.75 dB.

Case b) 200 bytes payload length

The effective throughput and packet error rates vs SNR for 200 bytes payload in multipath fading environment are shown in Figs. 5(a) and 5(b), respectively. The SNR thresholds for optimal rate adaptation with and without packet error rate constraint are tabulated in Tables IX and X, respectively. A similar observation as in the non-fading case is made regarding the use of mode 8 (54 Mbps). Mode 8 is not used for the 20 bytes payload size but it plays an important role at SNRs above



(a) Effective Throughput vs SNR for various data rates with 200 bytes payload



(b) Packet error rates vs SNR for various data rates with 200 bytes payload

Fig. 5. Effective Throughput and packet error rates vs SNR for 200 bytes payload in normalized multipath fading

27 dB with 200 bytes payload size.

TABLE IX
LINK ADAPTATION THRESHOLDS USING 200 BYTES PAYLOAD WITH MAXIMUM PACKET ERROR RATE CONSTRAINT OF 5% IN A NORMALIZED MULTIPATH FADING ENVIRONMENT

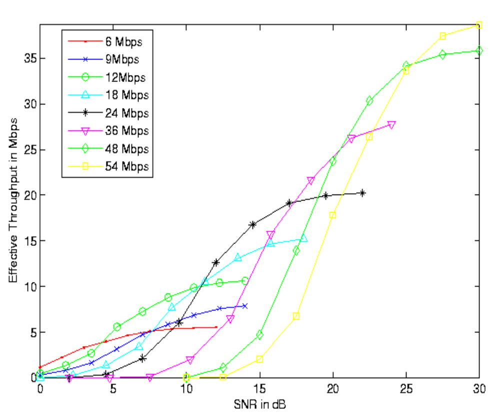
Data Rate(Mbps)	6	12	18	24	36	48	54
SNR range(dB)	7-10	10-15	15-16	16-21	21-24	24-26	>26

TABLE X
LINK ADAPTATION THRESHOLDS USING 200 BYTES PAYLOAD WITHOUT PACKET ERROR RATE CONSTRAINT IN A NORMALIZED MULTIPATH FADING ENVIRONMENT

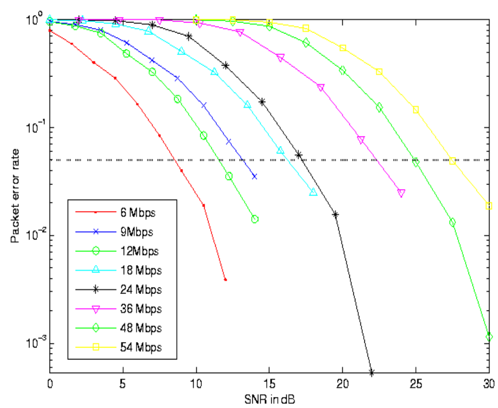
Data Rate(Mbps)	6	12	24	36	48	54
SNR range(dB)	0-5	5-12	12-19	19-22	22-27	>27

Case c) 2000 bytes payload length

The effective throughput and packet error rates vs SNR



(a) Effective Throughput vs SNR for various data rates with 200 bytes payload



(b) Packet error rates vs SNR for various data rates with 200 bytes payload

Fig. 6. Effective Throughput and packet error rates vs SNR for 2000 bytes payload in normalized multipath fading

for 2000 bytes payload in multipath fading environment are shown in Figs. 6(a) and 6(b), respectively. As in the non-fading scenario, a significant gain in throughput is observed. The SNR thresholds for optimal rate adaptation with and without packet error rate constraint are tabulated in Tables XI and XII, respectively.

TABLE XI

LINK ADAPTATION THRESHOLDS USING 2000 BYTES PAYLOAD WITH MAXIMUM PACKET ERROR RATE CONSTRAINT OF 5% IN A NORMALIZED MULTIPATH FADING ENVIRONMENT

Data Rate(Mbps)	6	12	18	24	36	48	54
SNR range(dB)	9-12	12-16	16-17	17-22	22-25	25-27	>27

It is observed from the above link adaptation tables that with increasing payload sizes, the SNRs required for using the various data rates is higher when a maximum packet error rate constraint of 5% is applied. However, when there is no packet error rate constraint, this does not necessarily hold. For instance, PHY mode 8 can be used at SNRs above 27 dB with a payload size of 200 bytes but with a 2000 byte payload size, it can be used at SNRs above 25 dB. This is quite counterintuitive since packet error rate increases with increasing packet sizes. However, the fact that payload length is considerably higher causes the overall throughput to increase as can be seen from Eq. (1).

TABLE XII

LINK ADAPTATION THRESHOLDS USING 2000 BYTES PAYLOAD WITHOUT PACKET ERROR RATE CONSTRAINT IN A NORMALIZED MULTIPATH FADING ENVIRONMENT

Data Rate(Mbps)	6	12	24	36	48	54
SNR range(dB)	0-4	4-11	11-17	17-20	20-25	>25

V. CONCLUSIONS

We investigate the effect of payload size and multipath fading on the link adaptation performance of IEEE 802.11 wireless LANs. We observe that the link adaptation thresholds are dependent on the payload size as well as the fading environment. Any link adaptation scheme that dynamically adjusts the thresholds based on the existing fading realization will outperform schemes which using precomputed thresholds. Moreover, link adaptation schemes which consider only path loss and shadowing will perform significantly worse in the presence of multipath fading. We also observed that link adaptation thresholds are quite sensitive to received SNR estimates - hence accurate SNR estimation and low delay feedback of SNR estimates to the transmitter needs to be considered.

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