# Payload Length and Rate Adaptation for Throughput Optimization in Wireless LANs

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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 transmitted bit rates. Furthermore, if there is even a single bit error in the packet, the entire packet is discarded and the packet is retransmitted. This causes the effective throughput to be a function of the packet payload length. We provide a theoretical framework to optimize single-user throughput by selecting the transmitted bit rate and payload size as a function of channel conditions for both additive white Gaussian noise (AWGN) and Nakagami-m fading channels. Numerical results reveal that careful payload adaptation significantly improves the throughput performance at low signal to noise ratios (SNRs) while at higher SNRs, rate adaptation with higher payload lengths provides better performance. We compare the range of SNRs over which payload length adaptation is crucial for AWGN and different fading channels based on the m-parameter of Nakagami fading realization. We then specify SNR values for switching between transmitted bit rates and payload lengths such that the effective throughput is maximized.**

## I. INTRODUCTION

Wireless local area networks (WLANs) are rapidly becoming part of our network infrastructure.The 802.11 WLAN physical layer (PHY) supports multiple data rates by using different modulation and channel coding schemes. For instance, the 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.

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. We consider both AWGN and block fading Nakagami-m channels in this paper.

An early investigation of the effect of payload size on throughput was conducted in [2]. Rate adaptation using a theoretical framework to evaluate the throughput has been investigated in [3]. A link adaptation strategy for IEEE 802.11b was provided in [4]. Frame lengths were classified into 3 broad classes: 0-100 bytes, 100-1000 bytes and 1000-2400 bytes. We extend the above results by presenting a novel algorithm which takes into account the tight coupling between payload length and data rate to maximize the single-user throughput based on the channel conditions. Our theoretical formulation allows payload length to be varied continuously over a wide range and we provide a mathematical framework to dynamically adapt the payload length to maximize the throughput for AWGN and different fading channels. Our results indicate that both the payload length as well as the data rate is dependent on the channel under consideration. The algorithm does not require any changes in the current MAC operations and the data rates and payload lengths can be varied with received signal strength measurement as in [4].

The paper is outlined as follows. In the next section, we provide a theoretical model to evaluate single-user throughput in 802.11a systems and use it to plot the payload lengths versus transmission rate under different channel conditions. Section III contains numerical results for our rate and payload length adaptation scheme, and provides the transmission rate/packet length combinations that maximize effective throughput as a function of average symbol SNR for AWGN and Nakagami-m fading channels. Section IV states conclusions and future research directions.

## II. THROUGHPUT ANALYSIS IN IEEE 802.11A WIRELESS NETWORKS

In this section we present a mathematical framework for single user throughput optimization by varying the payload length. We provide an integrated framework for link adaptation by considering various physical and MAC layer adaptation

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parameters. In particular, we have developed an adaptive frame length transmission algorithm using adaptive modulation as supported by IEEE 802.11a and adaptive framing in the MAC layer.

We define *throughput* as the number of payload bits per second received correctly. For simplicity of analysis, we consider the effects of payload variation in additive white Gaussian noise (AWGN) channels and assume that the acknowledgements from the receiver are error-free. We also assume a linear mapping between received signal strength (RSS) and SNR as in [4]. Thus based on the RSS of the ACK frames from the access points, the mobile station can estimate the SNR at the receiver. Throughput corresponding to PHY mode $m$ is given by:

$$T(m) = \frac{L}{L + C_m} * R_m * P_s^m(\gamma_s, L) \tag{1}$$

where,
$L$: payload length in bits,
$C_m$: header and DCF overhead corresponding to rate '$m$' in bits,
$R_m$: data rate corresponding to PHY mode $m$,
$P_s^m()$: packet success rate (PSR) defined as the probability of receiving a packet correctly corresponding to PHY mode $m$
$\gamma_s$: SNR per symbol.

$C_m$ encapsulates both header overheads and CSMA/CA interframe spacing. The time delay is converted to bytes for the purpose of optimization by the following expression :

$$C_m = R_m * T_{ho} \tag{2}$$

where $R_m$ is transmission rate corresponding to PHY mode '$m$' and $T_{ho}$ is the total protocol overhead and can be evalauted as in [3].

We have assumed hard-decision Viterbi decoding at the receiver. For a $L$ bits long packet, the probability of packet error can be bound by [5]:

$$P_e^m(L, \gamma_s) \leq 1 - (1 - P_u^m(\gamma_s))^L \tag{3}$$

where $P_u^m(\gamma)$ is the union bound of the first-event error probability corresponding to PHY mode $m$ [6] and is given by:

$$P_u^m(\gamma_s) = \sum_{d=d_{free}}^{\infty} a_d \cdot P_d(\gamma_s) \tag{4}$$

with $d_{free}$ being the free distance of the convolutional code selected in PHY mode $m$, $a_d$ is the total number of error events of weight $d$ which can be obtained from [6]. For hard-decision decoding with probability of bit error $\rho$, $P_d(\gamma_s)$ is given by

$$P_d(\gamma_s) = \begin{cases} \sum_{k=(d+1)/2}^{d} \binom{d}{k} \cdot \rho^k \cdot (1-\rho)^{d-k} & \text{if d is odd} \\ \frac{1}{2} \cdot \binom{d}{d/2} \cdot \rho^{d/2} \cdot (1-\rho)^{d/2} & \\ + \sum_{k=d/2+1}^{d} \binom{d}{k} \cdot \rho^k \cdot (1-\rho)^{d-k} & \text{if d is even} \end{cases} \tag{5}$$

The bit error probability $\rho$ computation for AWGN for the various PHY modes in IEEE 802.11a is described in [3]. In order to compute the packet error rate in fading environments, we employ average bit error probability expressions for BPSK, and M-ary QAM in Nakagami-m fading [7]. The Nakagami-m fading model is used to describe a wide range of fading models and includes the Rayleigh distribution (m = 1) as a special case. The fade is assumed constant for the entire packet duration over all subcarriers. The average bit error for BPSK over a Nakagami fading channel with for integer $m$ and average SNR per symbol $\gamma_s$ is given by [7]:

$$P_b = \frac{1}{2}\left[1 - \mu \sum_{k=0}^{m-1} \binom{2k}{k} \left(\frac{1-\mu^2}{4}\right)^k\right] \tag{6}$$

where,

$$\mu = \sqrt{\frac{\bar{\gamma}_s}{m + \bar{\gamma}_s}}$$

The bit error probability for M-ary QAM in Nakagami-m fading can be derived from [7] as:

$$P_b \cong 4\left(\frac{\sqrt{M}-1}{\sqrt{M}}\right)\left(\frac{1}{\log_2 M}\right) \sum_{i=1}^{\sqrt{M}/2} \frac{1}{2}\Bigg[1 - \mu \sum_{k=0}^{m-1} \binom{2k}{k} \left(\frac{1-\mu^2}{4}\right)^k\Bigg] \tag{7}$$

where,

$$\mu = \sqrt{\frac{1.5(2i-1)^2\bar{\gamma}_s}{m(M-1) + 1.5(2i-1)^2\bar{\gamma}_s}}$$

The packet success rate (PSR) is given as :

$$P_s^m(\gamma_s, L) = 1 - P_e^m(L, \gamma_s) \tag{8}$$

where $L$ is the packet length including the various overheads in bits.

In order to find the optimal payload length $L^*$, we assume the payload length $L$ varies continuously. Differentiating Eq. (1) with respect to $L$ and setting it to zero with packet success rate given by Eq.(8), the optimal payload length at a given SNR is:

$$L^* = -\frac{C_m}{2} + \frac{1}{2}\sqrt{C_m^2 - \frac{4 * C_m}{\log(1 - P_u^m(\gamma_s))}} \tag{9}$$

Some key assumptions in our model are single transmission, no losses due to collisions, i.e. packet losses are caused only by bit errors in AWGN and fading environments, and transmission of acknowledgments are error free.

## III. NUMERICAL RESULTS

### A. *Impact of payload length on effective throughput*

The variation of throughput with payload lengths at different SNRs, for all the PHY modes supported in IEEE 802.11a, over an AWGN and Rayleigh fading channel are shown in Figs. 1 and 2, respectively. We varied the payload lengths from 1-2264 bytes and added 40 bytes of RTP/UDP/IP header used for multimedia traffic. The maximum allowable MPDU frame body length is 2304 bytes without fragmentation [8]. The plots show that there is an optimal payload length

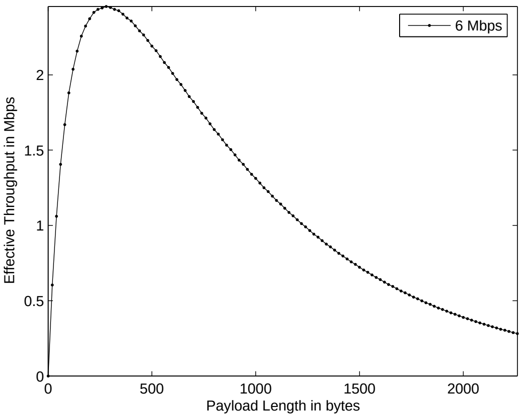


Fig. 1. Throughput versus payload length at an SNR of 2 dB in AWGN channel

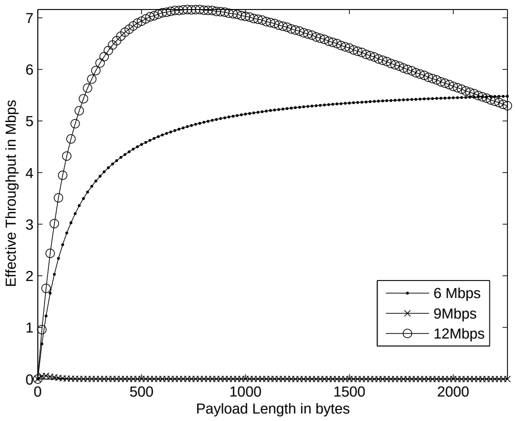


Fig. 2. Throughput versus payload length at an average SNR of 12 dB in Rayleigh fading channel

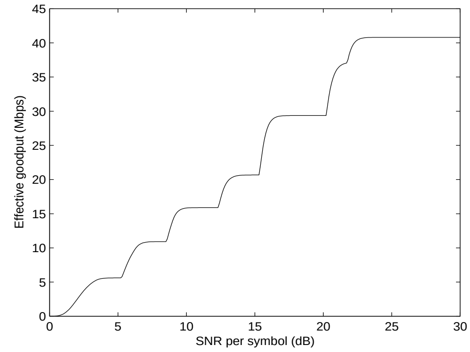
and rate corresponding to the received SNR for throughput maximization. This is quite intuitive since at a given SNR, increasing the data rate, i.e. bits per constellation or payload length, would initially cause an increase in throughput but it reaches an optimum value beyond which higher packet error rate (Eq. (3)) leads to a decrease in throughput. As shown in Fig. 1, at an SNR of 2 dB, only PHY mode 1 corresponding to 6 Mbps is used. The higher data rates are not evident in the plot since the packet error rates at these higher rates drastically reduce the effective throughput. The optimal payload length at an SNR of 2 dB is around 280 bytes corresponding to an effective throughput of 2.45 Mbps. Thus there is a significant reduction in the effective throughput from the supported data rate of 6 Mbps and reducing the payload length or increasing it does not increase throughput at such low SNRs. For instance, the effective throughput achieved at an SNR of 2 dB in AWGN with a 20 byte payload is 0.6 Mbps and with a 2000 byte payload, it is around 0.4 Mbps.

We also observe a similar behaviour for fading channels. In particular, we plot the throughput curves for an average SNR of 12 dB for a Nakagami-m fading channel with m set equal to one (which corresponds to Rayleigh fading) in Fig. 2. As seen from Fig.2, the optimal payload length is around 740 bytes with an effective throughput of 7.2 Mbps. A 2000 byte payload length would correspond to a throughput of 5.7 Mbps and a 20 byte payload length would decrease the effective throughput to 0.9 Mbps. It is interesting to observe from this plot that PHY mode 2 corresponding to 9 Mbps is not used since the packet error rate at this mode for an average SNR of 12 dB in Rayleigh fading, is intolerable. Instead PHY mode 3 corresponding to 12 Mbps that although has a larger constellation size (QPSK as compared to BPSK in PHY mode 2), has a significantly lower bit error rate which reduces its packet error rate. This has been widely described in literature and is attributed to the poor performance of the rate 3/4 punctured convolutional codes for PHY mode 2 compared to a rate 1/2 convolutional code for PHY mode 3 [3]. This results in the effective throughput for PHY mode 3 to be significantly higher compared to PHY mode 2.

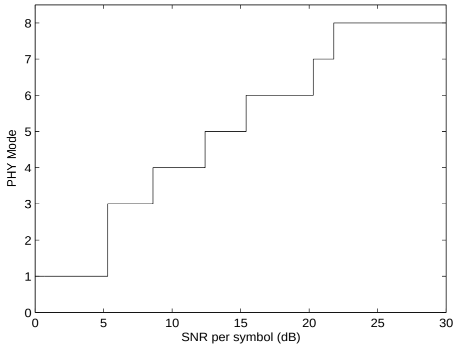
Selecting the proper data rate along with payload size is crucial for maximizing spectral efficiency. Selecting the lowest rate always, say BPSK, is too conservative an approach, wasting system resources, while selecting a much higher data rate can cause a severe degradation in overall throughput. Another interesting observation from the above plots, is that there are relatively sharp peaks in the throughput plots for lower SNRs while a more gradual transition is observed for higher SNRs i.e for the 2 dB case there is a small range of payload lengths around 280 bytes which can be selected for optimal performance whereas for the 12 dB case, there is a much broader range of payload lengths around 740 bytes. This suggests that the payload length adaptation is more crucial at lower SNRs. We discuss this in greater detail in the following section.

### *B. Optimal Payload Length and Rate adaptation*

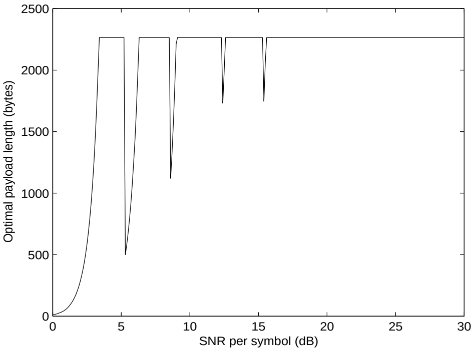
In this section, we present the optimal payload length and rate adaptation for AWGN and Rayleigh fading channels. In Fig. 3(a), we plot the effective throughput as a function of SNR obtained by a joint adaptation of payload lengths and data rate based on our theoretical framework in an AWGN channel. The resulting transmitted data rates are shown in Fig. 3(b) and the corresponding payload lengths are shown in Fig. 3(c). The optimal payload length and rate adaptation for a slowly fading Rayleigh channel is shown in Fig. 4. The effective throughput is plotted against average symbol SNR in Fig. 4(a) while Figs. 4(b) and 4(c) indicate the optimal data rate and payload size. It is observed from Figs. 3(c) and 4(c) that payload variation is more significant at the lower SNR regions while at higher SNRs, a larger payload length can be used with careful data rate adaptation. Moreover, the range of SNRs over which payload length adaptation is critical, is wider for Rayleigh fading compared to AWGN. It is also interesting to note the dependence of rate selection on fading environments. In particular, as evident from Fig. 4(b), the



(a) Effective throughput obtained by rate and payload length adaptation in AWGN

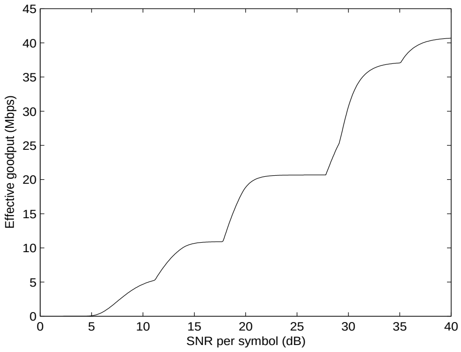


(b) Optimal rate adaptation

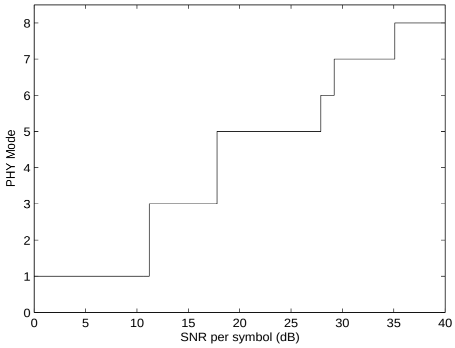


(c) Optimal payload length adaptation

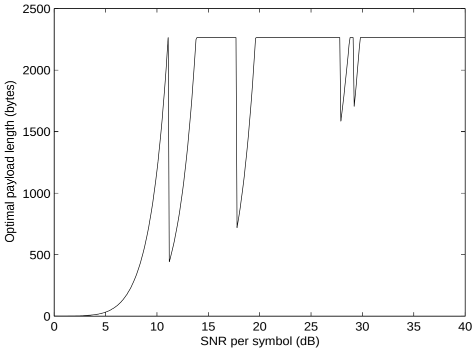
Fig. 3. Optimal rate and payload length adaptation in AWGN



(a) Effective throughput obtained by rate and payload length adaptation in Rayleigh fading



(b) Optimal rate adaptation



(c) Optimal payload length adaptation

Fig. 4. Optimal rate and payload length adaptation in Rayleigh fading

mandatory rates of 6, 12 and 24 Mbps are used over a much wider range of SNRs compared to an AWGN environment.

### *C. Rate adaptation with fixed payload size*

In this section we show the difference in rate adaptation and SNR thresholds for different channel conditions for a fixed payload size of 1500 bytes. In Fig. 5(a), we plot the effective throughput against SNR for all IEEE 802.11a PHY mode rates in an AWGN channel for a fixed payload size of 1500 bytes. In Fig. 5(b), we plot the effective throughput against average symbol SNR for a Rayleigh fading channel. It is interesting to observe the difference in SNR thresholds and data rates used in these two cases. In the AWGN case, all PHY modes apart from PHY mode 2 (9 Mbps) is used with the highest mode (54 Mbps) used at SNRs above 25 dB. However, in the Rayleigh fading case, neither modes 2 nor 4 corresponding to 9 Mbps and 18 Mbps respectively are used. Moreover, PHY mode 6 corresponding to 36 Mbps is used for an extremely narrow SNR range. This suggests that the rate 3/4 punctured convolutional codes with a lower constellation size are always outperformed by the higher constellation sizes with rate 1/2 convolutional code in Rayleigh fading for the IEEE 802.11a PHY data rates. We also plot the effective throughput against SNR for a 1500 payload size in Nakagami-m fading with $m =$

$4$ in Fig. 5(c). We observe that as the fading decreases and approaches the AWGN case ($m \rightarrow \infty$), PHY rates 4 and 6 are used over a wider range of SNRs. The above results again indicate a tight dependence of data rate used with the fading channel model.

## IV. CONCLUSIONS AND FUTURE WORK

We have presented a theoretical framework for achieving higher throughputs by careful adaptation of payload length and data rates with varying channel conditions under the assumption of AWGN and slowly varying flat fading Nakagami-m channels. The packet headers and protocol overheads reduce the effective throughput drastically, motivating the need for link adaptation with varying channel conditions. We present plots for payload length and rate selection for maximizing the single user throughput over a wireless link based on the average received SNR per symbol or an equivalent packet error rate. We also show the strong dependence of payload and rate adaptation on the wireless channel condition. The algorithm does not involve any changes in the current MAC as the data rate and payload length can be adapted based on the received signal strength measurement. Although we discuss the link adaptation scheme for IEEE 802.11a wireless networks, the approach is also applicable to IEEE 802.11b and g networks. Future research involves analyzing the effects of retransmissions on overall packet loss rate and latency as well as including the effect of collisions in a multiuser scenario. We are performing similar studies on frequency selective multipath fading channels.

## REFERENCES

[1] "IEEE 802.11a, Part11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High-Speed Physical Layer in the 5GHz Band," *supplement to IEEE 802.11 Standard*, 1999.

[2] P. Lettieri and M. B. Srivastava, "Adaptive Frame Length Control for Improving Wireless Link Throughput, Range and Energy Efficiency," in *INFOCOM (2)*, pp. 564–571, 1998.

[3] D. Qiao, S. Choi, and K. G. Shin, "Goodput Analysis and Link Adaptation for IEEE 802.11a Wireless LANs," *IEEE Trans. on Mobile Computing (TMC)*, vol. 1, no. 4, 2002.

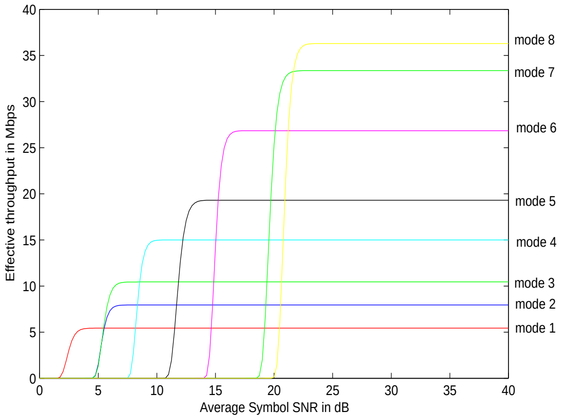
[4] J. P. Pavon and S. Choi, "Link Adaptation Strategy for IEEE 802.11 WLAN via Recieved Signal Strength Measurement," in *Proc. IEEE ICC '03*, pp. 1108–1113, May 2003.

[5] M. B. Pursley and D. J. Taipale, "Error Probabilities for Spread-Spectrum Packet Radio with Convolutional Codes and Viterbi Decoding," in *IEEE Transactions on Communications*, vol. COM-35, pp. 1–12, Jan. 1987.

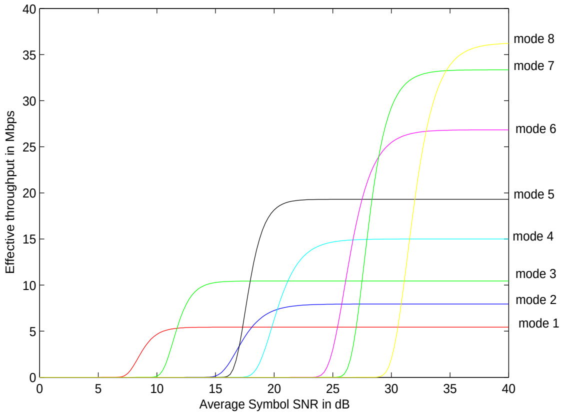
[6] C. Lee and L. H. C. Lee, *Convolutional Coding: Fundamentals and Applications*. Artech House Publishers, 1997.

[7] M. K. Simon and M.-S. Alouini, *Digital Communication over Fading Channels*. Wiley-IEEE Press, 2nd ed., November 2004.

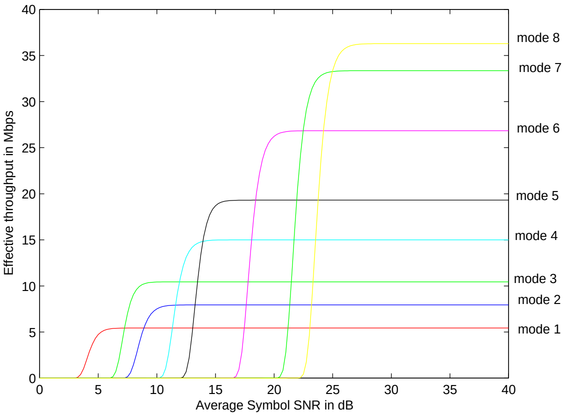
[8] "IEEE 802.11 Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification," *Standard, IEEE*, Aug. 1999.



(a) Rate adaptation for 1500 byte payload length in AWGN



(b) Rate adaptation for 1500 byte payload length in Rayleigh fading



(c) Rate adaptation for 1500 byte payload length in Nakagami-m fading with m = 4

Fig. 5. Optimal rate adaptation for fixed payload lengths of 1500 bytes in different channel conditions