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OPTIMIZED LINK ADAPTATION FOR WIRELESS PACKET COMMUNICATIONS BASED ON DISCRETE-RATE MODULATION AND CODING SCHEMES

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ABSTRACT

Adaptive modulation and coding (AMC) is a powerful technique for improving the spectral efficiency or the error performance in wireless packet networks over fading channels. In this article, using a fixed number of modulation and coding modes we propose a variable power transmission scheme for transmission of packets over block-fading wireless channels. We obtain the general form of optimal power adaptation and optimum AMC mode switching levels that maximize spectral efficiency under prescribed packet error rate (PER) constraint while satisfying an average transmit power constraint. Numerical results reveal that in wireless packet systems with limited packet length, the proposed scheme provides substantial average spectral efficiency gain when compared to the non-adaptive case. The optimization framework presented in this article would be useful for cross-layer optimization of physical layer in packet networks.

Index Terms— Adaptive modulation and coding, block fading channels, optimization, packet communications

1. INTRODUCTION

The demand for high data rate and quality of service (QoS) based services is increasing in modern wireless communication systems. However, wireless links are subject to various physical impairments such as channel fading, which limits the performance of such systems. Link adaptation at the transmitter, in particular adaptive modulation and coding (AMC), is a promising approach towards high throughput and power efficient wireless communications. Today, AMC schemes are already proposed for implementation in wireless systems such as HIPERLAN/2, IEEE 802.11a and IEEE 802.16e standards [1], [2]. In order to optimize the wireless system performance, a link adaptation algorithm selects a suitable channel code and modulation constellation, and sets the transmit power based on the time-varying channel conditions [3]. Goldsmith and Varaiya [4] showed that the Shannon capacity of a flat-fading channel can be achieved by employing both power and rate adaptation. Moreover, in [4] it is shown that adaptation of both these factors leads to a negligibly higher gain in capacity over a scheme with rate adaptation alone. It is noteworthy that to achieve the Shannon capacity, coding schemes have unbounded length and complexity, and no delay constraint is assumed. In contrast, practical systems are delay-limited and must use finite-length codewords. In particular, for a practical system with bounded delay, better throughput is achieved considering both power and rate adaptation in [5]. In the traditional AMC-based link adaptation, system parameters are adapted on a symbol-by-symbol basis, to increase spectral efficiency while satisfying a target bit error rate (BER) performance metric [6][7]. However, in modern wireless packet networks, transmission is performed on a frame by frame basis at the physical layer, where each frame contains a fixed number of symbols and a variable number of packets from the data link layer [2]. On the other hand, packet error rate (PER) is a more relevant physical layer performance measure than BER due to CRC-based ARQ mechanism in data packet transmission [2]. As shown in [8], relating BER and PER is not straight forward especially for coded transmissions. Therefore, the authors in [8] used an approximate expression for PER in order to design the AMC scheme to meet directly the required PER. However, in [8] a simple constant power AMC scheme is considered and the problem of optimal rate adaptation is not addressed. This paper follows the same approach. We derive the optimal link adaptation strategy, on a frame by frame basis, to meet directly the required target PER. We consider joint power and data rate adaptation in the physical layer, aiming at improvement of system spectral efficiency in wireless packet networks subject to a prescribed packet error rate constraint. Towards this end, the optimization algorithm specifies the appropriate AMC mode switching levels and the corresponding power. Numerical results reveal that in wireless packet systems with limited packet length, the proposed scheme provides substantial average spectral efficiency gain, when compared to its non-adaptive counterpart. The remainder of this paper is organized as follows. Section 2 introduces the system model, including an approximate expression for the PER of AMC scheme. We drive the optimal solutions for power adaptation and optimum AMC mode switching levels that maximizes system spectral efficiency under prescribed target PER and average transmit power constraints in Section 3. Numerical

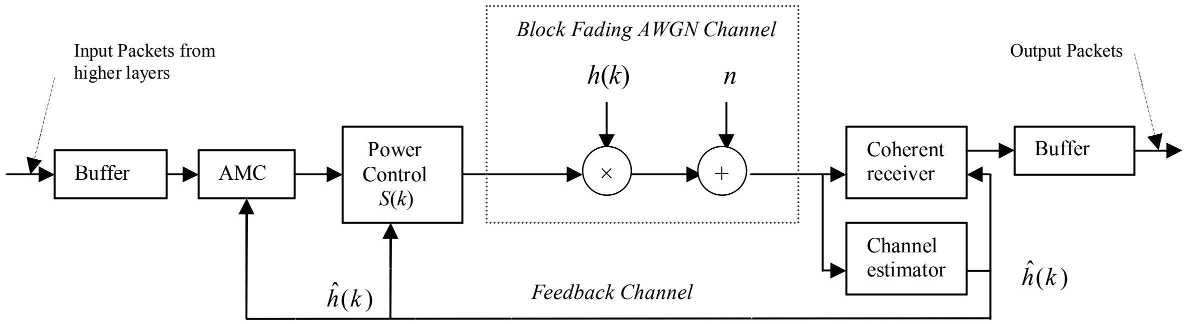

Fig. 1. System and channel model

results are provided in Section 4.

2. SYSTEM MODEL

2.1. System Description

As shown in Fig. 1, we consider a wireless packet communication link between a single-antenna transmitter and a single-antenna receiver. It consists of an AMC and power control module. Input packets, arrived from higher layers of stack, are queued at an infinite buffer, divided into frames and transmitted over the wireless channel. At the transmitter, AMC provides multiple transmission modes, where each mode is specified by a modulation and forward error correction (FEC) code pair. The transmitter selects an AMC mode for transmission and adapts transmit power on a frame-by-frame basis based on the feedback channel state information (CSI) from the receiver. We assume perfect channel estimates at the receiver and perfect CSI at the transmitter. We also assume that coherent demodulation and maximum-likelihood decoding are used at the receiver. The decoded bit streams are converted to packet structure and then are pushed towards the upper layers of stack. Following the approach in [8], at the physical layer frame by frame transmission is considered. Each frame contains a fixed number of symbols (N_s) and a variable number of packets (N_p) from the data link layer. Each packet contains a fixed number of bits (N_b), which include packet header, payload, and cyclic redundancy check (CRC) bits. Applying modulation and coding with rate R_n (bits/symbol) in mode n, N_b bits of a packet are mapped into a block of N_b/R_n symbols. A frame comprises of multiple such symbol-blocks as well as N_c pilot symbols and control parts, as in HIPERLAN/2 and IEEE 802.11a standards [2]. In mode n, the number of symbols per frame is $N_s=N_c+N_pN_b/R_n$, which indicates that N_p depends on the chosen AMC mode. In calculation of spectral efficiency of our system model, we ignore the effect of the header and CRC bits of each packet. We also assume strong CRC code so that packet error detection using CRC bits is perfect.

2.2. Channel Model and AMC Modes

We assume a wireless channel with stationary and ergodic time-varying real gain h with average channel power gain $\overline{h^2}=1$, and additive white Gaussian noise n with zero mean and variance σ^2. The channel is assumed to follow a block fading model, i.e., the gain remains invariant during a frame, but varies from frame to frame. This model is suitable for slowly-varying fading channels [9]. We denote the average transmit signal power by $\overline{S}$. Transmitting with constant power $\overline{S}$, the instantaneous pre-adaptation received signal to noise ratio (SNR) in transmitting kth frame is $\gamma(k)=\overline{S}(h(k))^2/\sigma^2$. We denote the transmit power during transmitting kth frame, which is a function of $\gamma(k)$, by $S(\gamma(k))$. Thus the received post-adaptation SNR when transmitting the kth frame is $\gamma(k)S(\gamma(k))/\overline{S}$. By virtue of stationary assumption of $h(k)$, the distribution of $\gamma(k)$ is independent of k, and we denote this distribution by $p_\gamma(\gamma)$. To simplify the notation we will omit the frame index k relative to γ and $S(\gamma)$. In Fig.1, AMC is performed on a frame-by-frame basis by dividing the range of the channel SNR into N+1 non-overlapping consecutive intervals, denoted by $[\gamma_n, \gamma_{n+1})$, n=0,1,...,N, where $\gamma_0=0, \gamma_{N+1}=\infty$, , and N is the number of AMC modes. Whenever the CSI fed back to the transmitter falls within the interval $[\gamma_n, \gamma_{n+1})$, the mode n is chosen, data is transmitted with rate R_n (bits/symbol) and power $S_n(\gamma)$ (watt). No data is sent when $\gamma\in[\gamma_0,\gamma_1)$ corresponding to deep channel fades or the outage mode with rate R_0 =0 (bits/symbol) and $S_0(\gamma)=0$. In this paper, the transmission modes of AMC scheme are adopted from the HIPERLAN/2 standard [2]. These modes are constructed by convolutionally coded M_n-ary rectangular or square QAM schemes. The encoder consists of a 1/2 rate mother code with generator polynomial g = [133 171] and subsequent puncturing. Table I presents the transmission modes of AMC scheme.

2.3. PER Approximation for AWGN Channel

In order to maximize the spectral efficiency of system model in Fig.1, we need an expression for PER that is invertible and differentiable in terms of the received SNR. To this end, for each mode n, we first obtain the exact PER through Monte Carlo simulations; then we use a fitting expression to approximate PER. In order to approximate the PER of coded discrete-rate M-QAM scheme over AWGN channel, two fitting expressions, $\min(1, a\exp(-g\gamma))$ and $1/(1+(a\gamma)^{g})$ are suggested by [8] and [10], respectively; where, a , g are constants that depend on the channel coding and modulation. In this paper, we use the following expression as a function of post-adaptation received SNR $\gamma(S_n(\gamma)/\bar{S})$ to approximate PER in mode n

$$PER_n(\gamma) = \begin{cases} 1, & 0 \le \gamma < \Gamma_n \\ a_n \exp(-g_n \dfrac{S_n(\gamma)}{\bar{S}}\gamma), & \gamma \ge \Gamma_n \end{cases} \quad (1)$$

where γ is the pre-adaptation received SNR, $S_n(\gamma)$ is the allocated power in mode n, and parameters, $\{a_n, g_n, \Gamma_n\}$ are mode and packet-size dependent constants. These parameters can be obtained by least square fitting the expression of (1) to the exact PER. Under a simple constant power allocation strategy with $S_n(\gamma) = \bar{S}, \quad n = 1,2,...,N,$ the PER expression in (1) reduces to that used in [8]; therefore we select the transmission modes and the set of corresponding fitting parameters $\{a_n, g_n, \Gamma_n\}$ similar to [8], as shown in Table I. According to such AMC modes, we can compare our results with that reported in [8]. It is necessary to note that the fitting parameters in Table I, are also valid under any power allocation strategy that is related to PER through (1).

TABLE I
AMC Transmission Modes and their Corresponding Fitting Parameters [8]

Mode (n)	1	2	3	4	5	6
Modulation	BPSK	QPSK	QPSK	16-QAM	16-QAM	64-QAM
Coding rate	$1/2$	$1/2$	$3/4$	$9/16$	$3/4$	$3/4$
R_n	0.5	1	1.5	2.25	3	4.5
a_n	274.72	90.25	67.62	50.122	53.399	35.351
g_n	7.9932	3.4998	1.6883	0.6644	0.3756	0.0900
Γ_n (dB)	-1.533	1.094	3.972	7.702	10.249	15.978

In this table, the AMC transmission rates, R_n, are specified under assumption that the ideal Nyquist pulses are used for data transmission.

3. POWER ADAPTATION AND AMC ANALYSIS

In this section, we consider our system model in two cases: (1) continuous power and discrete-rate adaptation with an instantaneous PER (IPER) constraint and (2) discrete-rate adaptation using constant power with an IPER constraint. We illustrate the derivation of optimal power adaptation and optimum AMC mode switching levels that maximize spectral efficiency under an average transmit power constraint. Assuming that there are always sufficient packets available at the transmitter buffer to be transmitted, the spectral efficiency of our system model is the average data rate per unit bandwidth R/W, where W [Hz] denotes the received signal bandwidth. The average spectral efficiency of coded discrete-rate M-QAM is the sum of the data rates R_n associated with the individual $N+1$ regions, weighted by the probability that γ falls in the nth region [3]

$$\eta_W = \frac{R}{W} = \sum_{n=1}^{N} R_n \cdot \int_{\gamma_n}^{\gamma_{n+1}} p_\gamma(\gamma) d\gamma \quad \text{bits/sec/Hz} \quad (2)$$

We also assume an average transmit power constraint over AMC modes given by

$$\sum_{n=1}^{N} \int_{\gamma_n}^{\gamma_{n+1}} S_n(\gamma) p_\gamma(\gamma) d\gamma \le \bar{S} \quad (3)$$

3.1. Optimal Power and Rate Adaptation

We now maximize spectral efficiency as presented in equation (2) subject to a target PER and an average power constraint as in equation (3). Consider the case of IPER constraint, so that $PER_n(\gamma) = P_t$, $\gamma_n \le \gamma \le \gamma_{n+1}$; $\forall n = 1,...,N$, where P_t denote the target PER. Using (1), we find the following expression for power adaptation in mode n

$$\frac{S_n(\gamma)}{\bar{S}} = \frac{1}{g_n \gamma} \ln(\frac{a_n}{P_t}), \ \gamma_n \le \gamma \le \gamma_{n+1}, \gamma \ge \Gamma_n \quad (4)$$

Under the above power adaptation strategy, the desired optimization problem can be formulated as follows

$$\underset{\{\gamma_n\}_{n=1}^{N}}{Maximize} \ \sum_{n=1}^{N} R_n \int_{\gamma_n}^{\gamma_{n+1}} p_\gamma(\gamma) d\gamma \quad \text{subject to}$$
$$C_1 : \sum_{n=1}^{N} \frac{1}{g_n} \ln(\frac{a_n}{P_t}) . \int_{\gamma_n}^{\gamma_{n+1}} \frac{1}{\gamma} p_\gamma(\gamma) d\gamma \le 1 \quad (5)$$
$$C_{2:(N+1)} : \gamma_n \ge \Gamma_n \ , \ n = 1,2,...,N$$

where C_1 condition shows the average transmit power constraint and the last N conditions ensures that for each mode n, the power is allocated based on (4). The problem in (5) is a standard constrained optimization problem, which we use the Karush-Kuhn-Tucker (KKT) conditions [11] to determine its optimal solution. In order to do so, we first construct the Lagrangian of (5) as

$$L(\gamma_1,...\gamma_N, \lambda, \beta_1,...,\beta_N) = \sum_{n=1}^{N} R_n \int_{\gamma_n}^{\gamma_{n+1}} p_\gamma(\gamma) d\gamma +$$
$$\lambda \left(\sum_{n=1}^{N} \frac{1}{g_n} \ln(\frac{a_n}{P_t}) . \int_{\gamma_n}^{\gamma_{n+1}} \frac{1}{\gamma} p_\gamma(\gamma) d\gamma - 1 \right) + \sum_{n=1}^{N} \beta_n (\gamma_n - \Gamma_n)$$

where $(\beta_1,...,\beta_N)$, λ are the Lagrangian multipliers. Using KKT conditions, the optimal solution $(\gamma_1^*, \gamma_2^*,...,\gamma_N^*)$ and the corresponding Lagrangian multipliers $(\beta_1^*,...,\beta_N^*)$, λ^* , must satisfy the following conditions

$$\frac{\partial L}{\partial \gamma_n}\left(\gamma_1^*,...,\gamma_N^*,\lambda^*,\beta_1^*,...,\beta_N^*\right)=0\,,\quad n=1,2,...,N \tag{6}$$

$$\sum_{n=1}^{N}\frac{1}{g_n}\ln\left(\frac{a_n}{P_t}\right).\int_{\gamma_n^*}^{\gamma_{n+1}^*}\frac{1}{\gamma}p_\gamma(\gamma)d\gamma \le 1$$

$$\gamma_n^* \ge \Gamma_n\ ,\quad n=1,2,...,N$$

$$\lambda^* \le 0$$

$$\beta_n^* \ge 0\ ,\quad n=1,2,...,N$$

$$\beta_n^*(\gamma_n^*-\Gamma_n)=0,\quad n=1,2,...,N \tag{7}$$

With (6) we have

$$\frac{\partial L}{\partial \gamma_n}\left(\gamma_1^*,\gamma_2^*,...,\gamma_N^*,\lambda^*,\beta_1^*,\beta_2^*,...,\beta_N^*\right)=$$

$$\begin{cases} -R_1 p_\gamma(\gamma_1^*)-\lambda^*\dfrac{\ln(a_1/P_t)}{g_1}\dfrac{p_\gamma(\gamma_1^*)}{\gamma_1^*}+\beta_1^*=0\,, & n=1 \\ R_{n-1}p_\gamma(\gamma_n^*)-R_n p_\gamma(\gamma_n^*)+\lambda^*\dfrac{\ln(a_{n-1}/P_t)}{g_{n-1}}\dfrac{p_\gamma(\gamma_n^*)}{\gamma_n^*}- & \\ \lambda^*\dfrac{\ln(a_n/P_t)}{g_n}\dfrac{p_\gamma(\gamma_n^*)}{\gamma_n^*}+\beta_n^*=0\,, & n\ge 2 \end{cases} \tag{8}$$

Using (7), if $\gamma_n^* > \Gamma_n$, then $\beta_n^*=0$. Following (8), if $\gamma_n^* > \Gamma_n$ then it satisfies the following condition

$$\gamma_1^* = -\frac{\ln(a_1/P_t)}{g_1 R_1}\lambda^*$$

$$\gamma_n^* = \frac{g_n\ln(a_{n-1}/P_t)-g_{n-1}\ln(a_n/P_t)}{g_n g_{n-1}(R_n-R_{n-1})}\lambda^*\ ,\ n=2,...,N$$

As a result, the general form of optimal mode switching levels can be written as

$$\gamma_1 = Max\left(-\frac{\ln(a_1/P_t)}{g_1 R_1}\lambda\ ,\ \Gamma_1\right)$$

$$\gamma_n = Max\left(\frac{g_n\ln(a_{n-1}/P_t)-g_{n-1}\ln(a_n/P_t)}{g_n g_{n-1}(R_n-R_{n-1})}\lambda\ ,\ \Gamma_n\right),\ \ n=2,...,N \tag{9}$$

where the constant λ can be found numerically such that the AMC mode switching levels in (9) satisfy the constraint C_1 in (5), while the maximum average transmit power is used. We refer to this scenario as adaptive power-IPER.

3.2. Constant Power Adaptive Rate AMC Scheme

A simple constant power AMC scheme is used in [8], assuming $S_n(\gamma)=\bar{S}\,,\forall n\in\{1,2,...,N\}$, and satisfying a target IPER constraint, P_t. This means that the instantaneous PER is guaranteed to be no greater than P_t for each chosen AMC mode. Under such assumption, the AMC mode switching levels $\{\gamma_n\}$ are set to the minimum SNR required to achieve P_t, i.e. $\gamma_n = 1/g_n.\ln(a_n/P_t)$. However, all available average power in (3) is not used by this scheme. An improved solution is to set $S_n(\gamma)/\bar{S}=\alpha\,,\forall n\in\{1,2,...,N\}$, and find the constant α such that equality condition in (3) is satisfied. Accordingly, we find

$$\alpha=\frac{1}{\int_{\gamma_1}^{\infty}p_\gamma(\gamma)d\gamma} \tag{10}$$

To satisfy the constraints $PER_n(\gamma)\le P_t\,,\gamma_n\le\gamma\le\gamma_n;\ ,n=1,2,...,N$, it is sufficient to satisfy the PER constraint at each boundary point γ_n. Assuming $\gamma_n \ge \Gamma_n$ and substituting $S_n(\gamma)/\bar{S}=\alpha$, in (1), results in

$$\gamma_n=\frac{1}{g_n.\alpha}\ln\left(\frac{a_n}{P_t}\right),\quad n=1,2,...,N \tag{11}$$

Therefore, γ_1 can be obtained by the following equation

$$\frac{\ln(a_1/P_t)}{g_1}=\frac{\gamma_1}{\int_{\gamma_1}^{\infty}p_\gamma(\gamma)d\gamma} \tag{12}$$

In this scenario, which we refer to as the constant power-IPER, if $(\gamma_1,...,\gamma_n)$ are obtained by the above procedure, the final mode switching levels are selected as $\gamma_n^*=Max(\gamma_n,\Gamma_n),\ n=1,2,...,N$.

4. NUMERICAL RESULTS

In this section, we present numerical results for spectral efficiency, power adaptation and PER using the solutions derived in the previous sections. We use the PER approximation parameters listed in Tables I, obtained for packet length N_b=1080 bits. Varying N_b would yield different numerical results, however similar observations are expected [2]. According to IEEE 802.11a standard, a PER of 1–10 percent indicates a reasonable point of operation for packet services without delay constraint, when packet length is 1500 byte [2]. However, based on approximate equation $PER\approx 1-(1-BER)^{N_p}$ (if each bit inside the packet has the same BER and bit-errors are uncorrelated, this equation is exact), for packet length of about 1000 bits, this translates to a PER requirement of about 0.001 to 0.01. Therefore, in our experiments, we select the target PER, P_t=0.001. Although our derivations are for general fading distributions, for the following numerical results, a Rayleigh fading channel model has been assumed, i.e. $p_\gamma(\gamma)=(1/\bar{\gamma})\exp(-\gamma/\bar{\gamma}),\ \gamma\ge 0$, where $\bar{\gamma}$ denote the average received SNR. Under such assumption, the objective and constraints functions in (5) are convex functions of $\{\gamma_n\}$ variables; however, the problem in (5) is not a convex optimization problem as defined in [12]. Nevertheless, numerical experiments show that the proposed solution always converges to a unique solution resulting in a desired level of performance gain. The average spectral efficiency for AMC scheme is depicted in Fig. 2. This plot shows that the optimal rate and power adaptation has a significant effect on system spectral efficiency. In particular, if we compare power adaptive scheme with the simple constant power scheme used in [8], we observe that employing the proposed power and rate adaptation algorithm leads to at least 0.45 b/s/Hz spectral efficiency gain. This shows a significant rate improvement. For instance, in the HIPERLAN/2 standard, where the symbol rate is 12 Msymbols/s [2], this gain leads to an approximate 5.4 Mb/s increase in transmission rate. Fig. 2 also reveals that, the proposed constant power AMC scheme provides a higher spectral efficiency in comparison with that suggested in [8], especially when the average SNR is low. Fig. 3 demonstrates the actual average PER corresponding to different cases depicted in Fig. 2, respectively. The penalty of spectral efficiency in constant power-IPER scenario is predictable, because the PER adaptation ability of the adaptive power IPER scheme is no longer available. In fact, for constant power-IPER scenario, the average achievable PER is much lower than our target IPER as shown in Fig. 3. From a practical point of view, constant power AMC scheme simplifies the hardware complexity of the system, at the cost of a smaller spectral efficiency. Fig. 4 shows that the allocated transmit power by adaptive power-IPER policy follows the inverse water-filling pattern with respect to instantaneous SNR within each rate region interval.

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5. REFERENCES

[1] Mobile WiMAX – *Part II: A Comparative Analysis*, WiMAX Forum, May, 2006.

[2] A. Doufexi, S. Armour, M. Butler, A. Nix, D. Bull, J. McGeehan, and P. Karlsson, "A comparison of the HIPERLAN/2 and IEEE 802.11a wireless LAN standards," *IEEE Commun. Mag.*, vol. 40, pp. 172–180, May 2002.

[3] M. S. Alouini and A. J. Goldsmith, "Adaptive modulation over Nakagami fading channels," *Kluwer Journal on Wireless Communications,* Vol. 13, No. 1-2, pp. 119-143, May 2000.

[4] A. Goldsmith and P. Varaiya, "Capacity of Fading Channels with Channel Side Information," *IEEE Trans. Infor. Theory*, vol. 43, no. 6, Nov 1997.

[5] N. Ahmed, M.A. Khojestapour and R.G. Baraniuk, "Deley-limited Throughput Maximization for Fading Channels using Rate and Power Control," *IEEE Globecom* 2004.

[6] S. T. Chung and A. J. Goldsmith, "Degrees of freedom in adaptive modulation: A unified view," *IEEE Trans. on Communications*, pp. 1561–1571, Sept 2001.

[7] B.J. Choi and L. Hanzo, "Optimum mode-switching-assisted constant-power single- and multicarrier adaptive modulation," *IEEE Trans. Vehicular Tech.*, vol. 52, no.3, pp. 536-560, 2003.

[8] Q. Liu, S. Zhou, and G. B. Giannakis, "Cross-layer combining of adaptive modulation and coding with truncated ARQ over wireless links," *IEEE Trans. on Wireless Communications*, vol. 3, no. 5, pp. 1746-1755, Sept. 2004.

[9] E. Biglieri, G. Caire, and G. Taricco, "Limiting performance of block fading channels with multiple antennas," *IEEE Trans. Inform. Theory*, vol. 47, pp. 1273–1289, May 2001.

[10] K. B. Song, and S. A. Mujtaba, "On the code-diversity performance of bit-interleaved coded OFDM in frequency-selective fading channels," in *Proceeding of IEEE VTC*, 2003.

[11] J. Nocedal and S. J. Wright, *Numerical Optimization*, Springer-Verlag, New York, 1999.

[12] S. Boyd and L. Vandenberghe, *Convex Optimization,* Cambridge University Press, Cambridge, England, 2004.

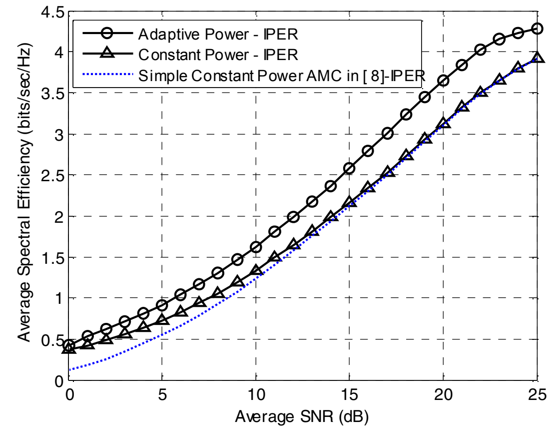

Fig. 2 Spectral efficiency for AMC schemes.

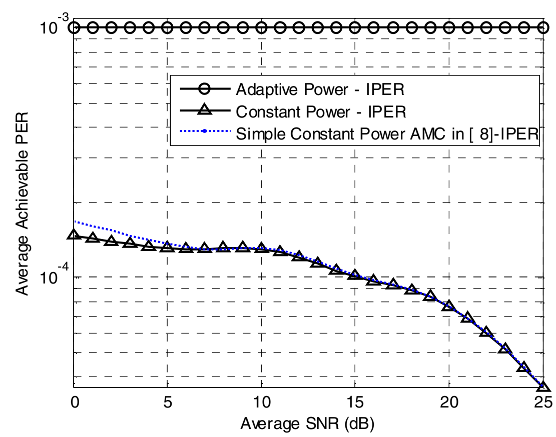

Fig. 3. Actual average PER's for AMC schemes.

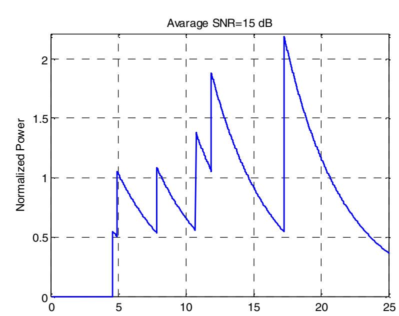

Fig. 4 Optimal $\frac{S(\gamma)}{\bar{S}}$ for adaptive power-IPER AMC Scheme.