IEEE Information Theory Workshop, Bergen, Norway, 2007.

Joint Optimization of Adaptive Modulation and Coding, Power Control and Packet Retransmission over Block Fading Channels

Jalil S. Harsini
Electrical and Computer Engineering Dept.
University of Tehran & Guilan, Iran
j.harsini@ece.ut.ac.ir

Farshad Lahouti
Electrical and Computer Engineering Dept.
University of Tehran, Iran
lahouti@ut.ac.ir

Abstract—**Adaptive modulation and coding (AMC) and automatic repeat request (ARQ) protocol are powerful techniques for improving the spectral efficiency (SE) or the error performance in wireless packet networks over fading channels. In this paper, we first consider a discrete-rate M-QAM based AMC scheme and propose a variable power transmission scheme for transmission of packets over block-fading wireless channels. Considering the error-correcting capability of the truncated-ARQ, which depends on the maximum number of retransmissions (N_r), we then optimize the AMC and power control schemes that guarantee the required packet loss rate (PLR) performance while satisfying an average transmit power constraint. Numerical results reveal that in wireless packet systems with limited packet length, the proposed link adaptation algorithm improves the system performance in terms of the SE and the PLR. However, this improvement depends on the target PLR and N_r. When the target PLR is sufficiently small, this improvement will be observed in terms of the SE for small N_r, however, in the larger target PLR, the improvement will only be observed in terms of the achievable PLR.**

I. INTRODUCTION

The demand for high data rate and quality of service (QoS) based services is increasing in 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 the 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 can be achieved considering both power and rate adaptation [5]. However, an AMC scheme yields high reliability at the price of reducing the transmission rate using either small size constellations, or, powerful but low-rate forward error correction (FEC) codes. An alternative way to achieve reliability is to use the automatic repeat request (ARQ) protocol at the data link layer, which requests retransmissions for erroneously received packets. Since retransmissions are requested only when a packet is received in error, ARQ helps increasing the system throughput in comparison to the use of FEC codes at the physical layer alone [6]. In [7], a scheme is suggested that combines a constant-power discrete-rate AMC with the truncated-ARQ protocol, in order to enhance spectral efficiency, while satisfying a target packet loss rate (PLR) and delay constraint. While the work of [7] is focused on cross layer analysis of a system that utilizes a constant-power AMC scheme at the physical layer, no attempt has been made to develop efficient algorithms for improving the system performance by optimally adapting the system parameters. This paper focuses on developing an optimization framework for cross-layer link adaptation, aiming at improvement of system performance for QoS-based packet communications. We first construct an AMC scheme providing a fixed number of modulation and coding modes. We then optimize power adaptation and AMC scheme in the physical layer in conjunction with truncated-ARQ at the data link layer that guarantee the required packet loss rate (PLR) performance, while satisfying an average transmit power constraint. The results demonstrate that in wireless packet systems with limited packet length, the proposed cross-layer adaptation algorithms improve the system performance in terms of the spectral efficiency and the PLR. In fact, this improvement depends on the AMC scheme, target PLR and the number of retransmission in ARQ protocol, N_r. More interestingly, when the target PLR is sufficiently small, use of ARQ improves spectral efficiency; and for larger target PLR,

1-4244-1200-5/07/$25.00 ©2007 IEEE.

the system performance improvement will only be observed in terms of the achievable PLR. The rest of this paper is organized as follows. Section II presents the system model. We drive the optimal solutions for power adaptation and optimum AMC mode switching levels that maximize system spectral efficiency under prescribed target packet error rate (PER) and average transmit power constraints in Section III. The joint effects of truncated-ARQ and AMC scheme are investigated in Section IV. Numerical results are provided in Section V.

II. System Model

A. System Description

As shown in Fig. 1, we consider a point-to-point wireless packet communication link between a single-antenna transmitter and a single-antenna receiver. It consists of an AMC and power control module at the physical layer, and an ARQ module at the data link layer. Input packets, arrived from higher layers of stack, are queued at an infinite buffer, divided into frames and transmitted over a wireless channel. At the transmitter, AMC provides multiple transmission modes, where each mode is specified by a modulation and a FEC code pair as in IEEE 802.11a and 802.16 standards [1], [2]. The transmitter selects an AMC mode for transmission and adapts transmit power on a frame-by-frame basis based on the channel state information (CSI) feedback from the receiver. We assume perfect channel estimates at the receiver and perfect CSI (here channel SNR) at the transmitter. We also assume coherent demodulation and maximum-likelihood decoding at the receiver. The decoded bit streams are converted to packet structure and then are pushed towards the upper layers of stack. Another module in Fig. 1 is a selective repeat ARQ protocol implemented in the data link layer. At the receiver, when an erroneous packet is detected, ARQ protocol generates a retransmission request. Following the approach in [7], 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.

B. Channel Model and AMC Modes

We assume a wireless channel with stationary and ergodic time-varying real gain h with unit average channel power gain, 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 [8]. We denote the average transmit signal power by $\bar{S}$. Transmitting with constant power $\bar{S}$, the instantaneous pre-adaptation received signal to noise ratio (SNR) in transmitting kth frame is $\gamma(k)=\bar{S}(h(k))^2/\sigma^2$. 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 $\gamma(k)S(\gamma(k))/\bar{S}$. 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 shows the transmission modes of AMC scheme.

C. PER Approximation for AWGN Channel

In order to maximize the spectral efficiency of the system depicted 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 the PER. In order to approximate the PER of coded discrete-rate M-QAM scheme over AWGN channel, the fitting expression $\min(1, a\exp(-g\gamma))$ is suggested by [7]; 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 [7]; therefore we select the transmission modes and the set of corresponding fitting parameters $\{a_n, g_n, \Gamma_n\}$ similar to [7], as shown in Table I. According to such AMC modes, we can compare our results with that reported in [7]. 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 [7]

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.

III. Optimal Power and Rate Adaptation in the Presence of Truncated-ARQ

In this section, we consider the problem of maximizing spectral efficiency of the system under consideration for a prescribed PLR constraint. First, without considering ARQ protocol, we illustrate the derivation of optimal power adaptation and optimum AMC mode switching levels that maximize spectral efficiency under a target PER and an average transmit power constraint. Then, we investigate the effect of truncated-ARQ on our system model.

A. Power Adaptation and AMC Analysis

Without considering ARQ protocol, 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 each of the $N+1$ regions, weighted by the probability that γ falls in the nth region [3]

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

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

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

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 instantaneous PER constraint, so that $PER_n(\gamma) \le P_t$, $\gamma_n \le \gamma \le \gamma_{n+1}$; $\forall n = 1,...,N$, where P_t denote the target PER. Using (1), we find the following expression for power adaptation in mode n

$$\frac{S_n(\gamma)}{\overline{S}} = \frac{1}{g_n \gamma} \ln\left(\frac{a_n}{IPER}\right), \; \gamma_n \le \gamma \le \gamma_{n+1}, \gamma \ge \Gamma_n \; , \tag{4}$$

where $IPER$ denotes the instantaneous PER. Under the above power adaptation strategy, the desired optimization problem can be formulated as follows

$$\begin{aligned}
&\underset{\{\gamma_n\}_{n=1}^{N},\, IPER}{Maximize} \quad \sum_{n=1}^{N} R_n \int_{\gamma_n}^{\gamma_{n+1}} p_\gamma(\gamma) d\gamma \quad \text{subject to} \\
&C_1 : \sum_{n=1}^{N} \frac{1}{g_n} \ln\left(\frac{a_n}{IPER}\right). \int_{\gamma_n}^{\gamma_{n+1}} \frac{1}{\gamma} p_\gamma(\gamma) d\gamma = 1 \\
&C_2 : \; IPER \le P_t \\
&C_{3:(N+2)} : \gamma_n \ge \Gamma_n \; , \; n = 1,2,...,N
\end{aligned} \tag{5}$$

where C_1 and C_2 conditions show the average transmit power and the instantaneous PER constraints, respectively, and the last N conditions ensure that for each mode n, the power is allocated based on (4). In order to solve (5), we first assume equality in C_2, and search for an optimal solution of (5). If there is not such solution, we reduce the $IPER$ value by a step size and again search for optimal solution of (5). As we will show in the followings, assuming a fixed $IPER$ value that satisfies the C_2 condition, there exit a numerically efficient solution for (5). In this case, we use the Karush-Kuhn-Tucker (KKT) conditions [9] to determine the optimal solution of (5). For this, we first construct the Lagrangian of the optimization problem as below

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

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

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

$$\begin{aligned}
&\sum_{n=1}^{N} \frac{1}{g_n} \ln\left(\frac{a_n}{IPER}\right). \int_{\gamma_n^*}^{\gamma_{n+1}^*} \frac{1}{\gamma} p_\gamma(\gamma) d\gamma = 1 \\
&\gamma_n^* \ge \Gamma_n \; , \; n = 1,2,...,N \\
&\beta_n^* \ge 0 \, , \; n = 1,2,...,N \\
&\beta_n^* (\gamma_n^* - \Gamma_n) = 0, \; n = 1,2,...,N
\end{aligned} \tag{7}$$

With (6) we have

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

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

(8)

Using (7), if $\gamma_n^* > \Gamma_n$, then $\beta_n^* = 0$. Following (8), if $\gamma_n^* > \Gamma_n$ the followings hold

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

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

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

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

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

where the constant λ can be found numerically such that the AMC mode switching levels in (9) satisfy the constraint C_1 in (5).

B. Analysis of Power Adaptation and AMC in the Presence of Truncated-ARQ Protocol

We state some key assumptions that are used in system performance analysis. It is assumed that there are always sufficient packets available at the transmitter queue to be transmitted. Since practical applications tolerate only finite delay and finite buffers at both ends of the communication link are used, we assume that the maximum number of ARQ retransmissions per packet is bounded and equal to N_r. If a packet is received incorrectly after N_r retransmissions, it will be dropped from the receiver buffer, and packet loss will occur. We refer to the percentage of packets dropped due to the imposed retransmission limit as the PLR. We also consider a target PLR at the data link layer denoted by P_{loss}. In order to simplify the truncated-ARQ analysis, we consider an i.i.d. channel error process on the transmissions of one packet due to ARQ as in [10]. Under such assumption, if we denote the target instantaneous PER in the physical layer by P_t, it can be related to P_{loss} by

$$P_{loss} = P_t^{N_r+1} \tag{10}$$

Considering a N_r – truncated ARQ at the data link layer, if we optimize the power adaptation strategy and AMC scheme in Fig. 1 to satisfy a target PER P_t, that is related to P_{loss} through (10), then the PLR performance requirements will be satisfied. Therefore, the optimization procedures proposed in section IV-A can be used to optimize a system combining the truncated-ARQ protocol in the data link layer and an AMC scheme with power control in the physical layer. In order to evaluate the effect of N_r –truncated ARQ protocol over the spectral efficiency, we compute the average number of transmissions per packet, needed for a packet to be either correctly received or dropped due to the truncated ARQ protocol, as (similar to [11, eq. (2)])

$$\overline{N}(IPER, N_r) = 1 + IPER + IPER^2 + \dots + IPER^{N_r} = \frac{1 - IPER^{N_r+1}}{1 - IPER} \tag{11}$$

Thus, the overall average spectral efficiency of the system can be obtained as

$$\eta_W(N_r) = \frac{\eta_W}{\overline{N}(IPER, N_r)} \tag{12}$$

It is evident that $\eta_W(0) = \eta_W$, which corresponds to no retransmission at the packet level.

IV. Numerical Results

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 $PER \approx 1 - (1 - BER)^{N_b}$ (if each bit inside the packet has the same BER and bit-errors are uncorrelated, this equation is exact), for packet length of 1080 bits, this translates to a PER requirement of about 0.0009 to 0.0094. In our experiments, we select the target PLR, P_{loss}=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.

Fig. 2 depicts the average spectral efficiency of the system due to proposed solutions for several values of N_r. In this figure, the performance of joint AMC-ARQ scheme of [7] for N_r = 2, corresponding to the best reported results, is also depicted. It is observed that using the truncated ARQ protocol helps increasing the system spectral efficiency (N_r = 2 vs. N_r = 0). In particular, from Fig. 2, we observe that the proposed optimized AMC scheme for N_r = 1, leads to about 0.42 b/s/Hz spectral efficiency gain in comparison to the simple constant power scheme suggested in [7]. This gain 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 Mb/s increase in transmission rate. Note, however, that the gain in terms of increasing the spectral efficiency vanishes, when allowing more than one retransmission (N_r > 1). Fig. 2 Also indicates that the proposed optimized AMC scheme (N_r = 0), shows higher spectral efficiency in comparison to the best scenario of joint ARQ-AMC scheme suggested in [7] (N_r = 2).

Fig. 3 depicts the actual packet loss probability at the data link layer, corresponding to different cases depicted in Fig. 2. Because the PLR of joint AMC-ARQ scheme in [7] is not fixed over the range of SNR within one transmission mode, an average PLR is plotted in Fig. 3. This figure shows that increasing N_r, the PER adaptation ability of the proposed optimized AMC scheme is decreased. In particular, with N_r = 2 (corresponding to P_t=0.1 at the physical layer), we observe that the actual PLR of our system is much lower than that of the target PLR, which explains the diminishing return in Fig. 2, for $N_r > 1$. In fact, in this scenario increasing N_r improves the system performance in terms of the PLR instead of the spectral efficiency. Also, note that on the two end of each curve for N_r = 1, 2 in Fig. 3, the optimal solution does not fulfill the PLR constraint with equality, and therefore, results in a lower PLR than that required, which in turn leads to a reduced spectral efficiency in Fig. 2. Finally, it is necessary to note that for the scenario under consideration, the desired range of P_{loss} is about (0.001-0.01), and therefore, our results indicate that N_r=1 captures the spectral efficiency gain and no more retransmissions is required. However, our experiments indicate that, using an AMC scheme, guaranteeing a smaller P_{loss} requires a larger number of retransmissions to maximize the spectral efficiency (N_r=2 for P_{loss} =10^{-4}).

ACKNOWLEDGMENT

This work is supported by Iran Telecommunications Research Center (ITRC).

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] E. Malkamaki and H. Leib, “Performance of truncated type-II hybrid ARQ schemes with noisy feedback over block fading channels,” *IEEE Trans. Commun.*, vol. 48, no. 9, pp. 1477–1487, Sept. 2000.

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

[8] 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.

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

[10] Z. Rosberg and M. Sidi, “Selective-repeat ARQ: the joint distribution of the transmitter and the receiver resequencing buffer occupancies,” *IEEE Trans. Commun.*, vol. 38, no. 9, pp. 1430–1438, 1990.

[11] J. G. Kim and M. M. Krunz, “Fluid analysis of delay and packet discard performance for QoS support in wireless networks,” *IEEE Journal on Selected Areas in Communications*, Vol. 19, No. 2, pp. 384-395, Feb 2001.

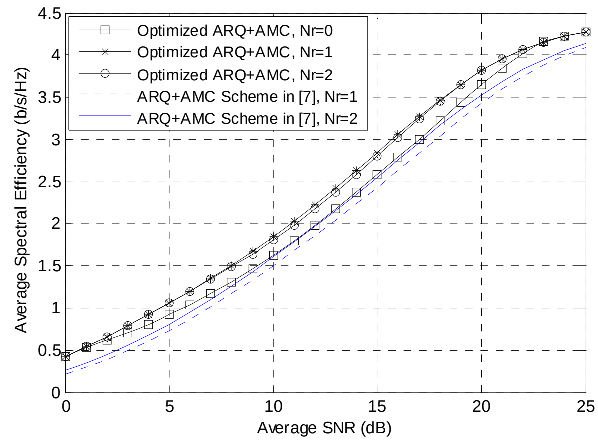

Fig. 2 Spectral efficiency for optimized ARQ-AMC scheme.

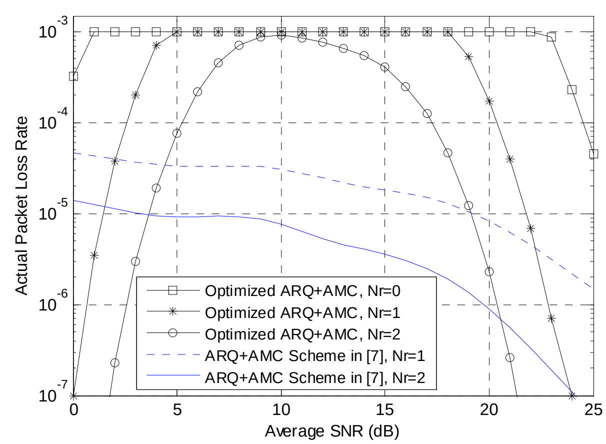

Fig. 3 Actual packet loss rate for optimized ARQ-AMC scheme.

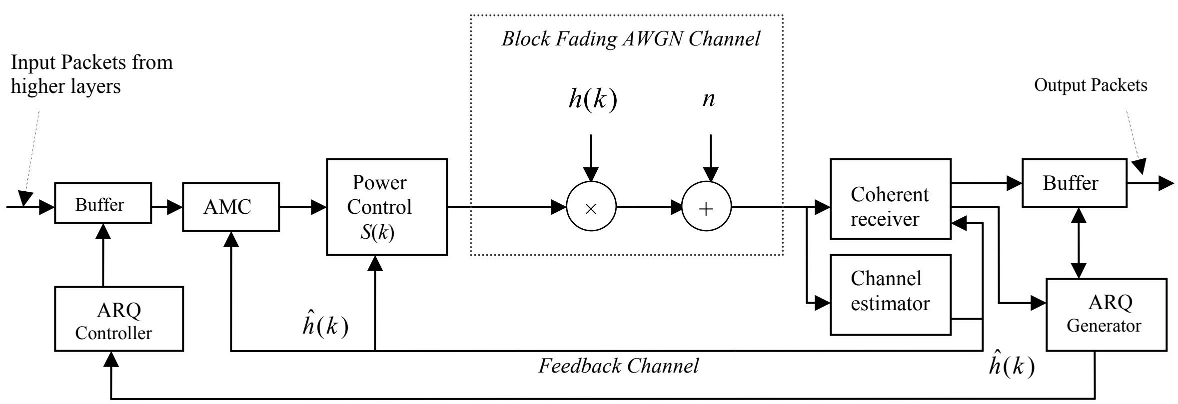

Fig. 1 System model