A Cross-Layer Design to Improve Spectral Efficiency in Wireless Networks

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Abstract

A cross-layer design is developed which combines the Adaptive Modulation and Coding (AMC) at the physical layer and truncated Automatic Repeat Request (ARQ) at the data link layer to maximize the spectral efficiency under prescribed error performance constraints. Depending on the error correcting capability of the truncated ARQ, which depends on the maximum allowable number of retransmissions, we design AMC transmission modes, with each mode consisting of a specific modulation and FEC code pair as in IEEE 802.16 standard, that guarantee the required performance. Numerical results reveal that retransmissions at the data link layer relieve stringent error control requirements at the physical layer and thereby enable considerable spectral efficiency gain. This gain is provided by the maximum number of retransmissions per packet which equals the diversity order. The improvement on spectral efficiency decreases when the number of retransmissions increases, suggest that a small number of retransmissions offers a desirable delay-throughput tradeoff, in practice. The performance analysis is done in terms of outage probability also.

Keywords: Adaptive Modulation and Coding (AMC), Automatic Repeat Request (ARQ) protocol, Spectral Efficiency, Outage probability, wireless networks

1. Introduction

QUALITY of Service (QoS) metrics of a connection (flow or session) includes spectral efficiency or data throughput, packet error/loss rate and delay performance. Usually, multimedia applications can be classified in two categories: QoS guaranteed and best effort [1]. The first category includes voice (e.g.,VoIP), video/audio streaming, video/audio telephony and conferencing. Applications like web browsing, email and FTP belong to the second category.

For QoS guarantees in high rate multimedia applications, the scarcity of transmission capacity, multipath fading and Doppler effects are common challenges to most communication networks, military or civilian, when mobile devices communicate a wide range of information over wireless links. The bottleneck common to both networks is the wireless link, not only because wireless resources (bandwidth and power) are more scarce and expensive than their wired counterparts, but also because the overall system performance degrades markedly due to time and frequency dispersive fading effects introduced by the wireless air interface.

In order to enhance spectral efficiency (bandwidth utilization) while adhering to a target error performance over wireless channels, Adaptive Modulation and Coding (AMC) schemes have been widely used to match transmission parameters to time-

varying channel conditions ; see e.g., [2-5], and references therein. However, to achieve high reliability at the physical layer, one has to reduce the transmission rate using either small size constellations or powerful but low-rate error-control codes. In [2], the authors, proposed an AMC scheme to analyze the impact of time-delay on the BER of adaptive M-QAM in terms of spectral efficiency and outage probability.

An alternate way to mitigate channel fading is to rely on the Automatic Repeat Request (ARQ) protocol at the data link layer that requests retransmissions for those packets received in error. Since retransmissions are activated only when necessary, ARQ is quite effective in improving system throughput relative to using only FEC at the physical layer [6].

To minimize delays and buffer requirements in practice truncated ARQ protocols have been widely adopted to limit the maximum number of retransmissions [6]. However, only fixed modulation and coding at the physical layer have been considered in systems with truncated ARQ protocols [6].

Instead of considering AMC at the physical layer and ARQ at the data link layer separately, we adopt a cross-layer design that combines these two layers judiciously to maximize spectral efficiency, or throughput, under prescribed delay and error performance constraints. With ARQ correcting occasional packet errors at the data link layer, the stringent error control requirements is alleviated for the AMC transmissions that guarantee the required performance.

Most existing AMC designs are considered at the physical layer. Their impact and interaction with higher protocol layers remain largely un-explored. A cross-layer combining AMC with truncated ARQ with specifications as in HIPERLAN/2 and IEEE 802.11a standards [7], interaction of AMC with finite length queuing is investigated in [8] and the effects of AMC on TCP protocol is studied in [9]. Results obtained in [7] show better results in terms of spectral efficiency and Pit Error Rate while using a combined approach of AMC with truncated ARQ in IEEE 802.11 a/ Hiperlan standards. Later, the same authors in [10] have introduced the concept of using AMC in the physical layer of IEEE 802.16 standards. This motivated us to explore the idea of making use of combined AMC with truncated ARQ in IEEE 802.16.

In this paper, we study the QoS of an end-to-end connection over a wireless link, where transmitters are equipped with AMC at the physical layer and finite-length buffers at the data link layer. We rely on an appropriate cross-layer model for the wireless link to derive the spectral efficiency and the packet error rate analytically, given the prescribed target error rate with specifications as in IEEE 802.16 standard. Numerical results demonstrate that our joint AMC-ARQ design provides improvement on spectral efficiency with smaller number of retransmissions. Retransmissions ease the strict error-control requirements on modulation and coding, and bring considerable spectral efficiency gain. This gain is found comparable to that offered by diversity, provided that the maximum number of transmissions per packet equals the diversity order.

In this paper, we consider finite length queuing at the Medium Access Control (MAC) sub-layer of the data link layer, where each user employs AMC at the physical layer is discussed under System Model in Section II. We develop a cross-layer design, which combines AMC at the physical layer with truncated ARQ at the data link layer in Section III. We analyze the performance measures in Section IV. Numerical results are presented in Section V. Finally concluding remarks are given in Section VI.

2. System Model

In our proposed system shown in Fig.1, the AMC selector at the receiver determines the modulation-coding pair (mode), which is sent back to the transmitter through a feedback channel based on Channel State Information (CSI) acquired at the receiver. The AMC controller at the transmitter then updates the transmission mode. Coherent demodulation and Maximum Likelihood (ML) decoding are used at the receiver. The decoded bit streams are mapped to packets, which are pushed upwards to the data link layer. The Cross-layer structure shown in Fig.2 consists of a combined adaptive modulation and coding module at the physical layer and ARQ module at the data link layer. The processing unit at the data link layer is a packet, which comprises multiple information bits. On the other hand, the processing unit at the physical layer is a frame, which is a collection of multiple transmitted symbols.

At the physical layer, we assume that multiple transmission modes are available, with each mode consisting of a specific modulation and FEC code pair as in IEEE 802.16 standard [11].
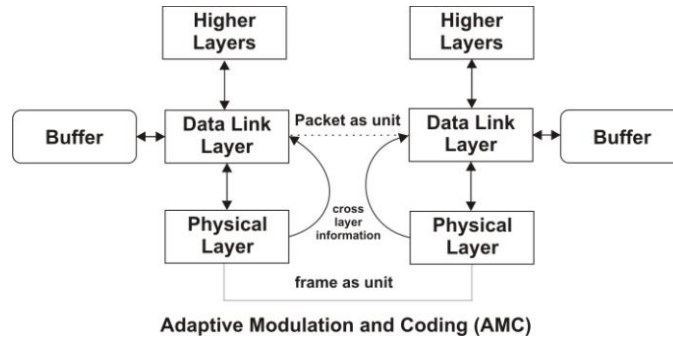

Fig.2. Cross-layer structure combining AMC with truncated ARQ

At the physical layer, we assume that multiple transmission modes are available, with each mode consisting of a specific modulation and FEC code pair as in IEEE 802.16 standard [11]. At the data link layer, the selective repeat ARQ protocol is implemented. If an error is detected in a packet, a retransmission request is generated by the ARQ generator, and is communicated to the ARQ controller at the transmitter via a feedback channel; otherwise, no retransmission request is sent. The ARQ controller arranges retransmission of the requested packet that is stored in the buffer. The feedback for ARQ commands is different from that used for feeding back AMC information, although both ARQ and AMC related parameters are sent back via the same physical feedback channel.

At the physical layer, we consider the Convolutionally coded M_n-ary rectangular or square Quadrature Amplitude Modulation (QAM) modes, adopted from the IEEE 802.16 standard. The transmission modes are listed in Table I, in a rate of ascending order. At the physical layer, we deal with frame by frame transmissions, where each frame contains a fixed number of symbols. Each frame at the physical layer may contain multiple packets from the data link layer. Each packet contains N_p fixed number of bits, which include serial number, payload and Cyclic Redundancy Check (CRC) bits to facilitate error detection. After modulation and coding with mode n of rate R_n b/symbol, each packet is mapped to a symbol-block containing N_p / R_n symbols. Multiple such blocks, together with Nc pilot symbols and control parts, constitute one

frame to be transmitted at the physical layer, as in IEEE 802.16 standard. If mode n is used, it follows that the number of symbols per frame is $N_f = N_c + N_b N_p / R_n$, which implies that Nb (the number of packets per frame) depends on the chosen modulation and coding pair.

The operating assumptions adopted in this paper are given as:

1. The channel is frequency flat, and remains invariant per frame, but is allowed to vary from frame to frame. This corresponds to a block fading channel model, which is suitable for slowly varying fading channels [12]. As a consequence, AMC is adjusted on a frame-by-frame basis.

2. Perfect Channel State Information (CSI) is available at the receiver using training-based channel estimation. The corresponding mode selection is fed back to the transmitter without error and latency, as in [2-4], [13].

    The assumption that the feedback channel is error free and has no latency, could be at least approximately satisfied by using a fast feedback link with powerful error control for feedback information.

3. Error detection based on CRC is perfect, provided that sufficiently reliable error detection CRC codes are used [14]. As in [14], the serial number and the CRC parity bits in each packet are not included in the throughput calculation, because they introduce negligible redundancy relative to the number of payload bits.

For flat fading channels adhering to 1, the channel quality can be captured by a single parameter, namely the received SNR γ. Since the channel varies from frame to frame, we adopt the general Nakagami-*m* model which applies to a large class of fading channels to describe γ statistically [14].

TABLE 1.Transmission Modes as per IEEE 802.16 (d)-2004

Mode n	1	2	3	4	5	6
Modulation	QPSK	QPSK	16QAM	16QAM	64QAM	64QAM
RS Code	(32,24,4)	(40,36,2)	(64,48,8)	(80,72,4)	(108,96,6)	(102,108,6)
CC Code Rate	2/3	5/6	2/3	5/6	3/4	5/6
Coding Rate R_c	1/2	3/4	1/2	3/4	2/3	3/4
R_n(Bits/Symbol)	1.0	1.5	2.0	3.0	4.0	4.5
a_n(dB)	232.9242	140.7922	264.0330	208.5741	216.8218	220.7515
g_n	22.7925	8.2425	6.5750	2.7885	1.0675	0.8125
γ_{pn}(dB)	3.7164	5.9474	9.6598	12.3610	16.6996	17.9629

The received SNR γ per frame is thus a random variable with a Gamma Probability density function:

$$P_r(\gamma) = \frac{m^m \gamma^{m-1}}{\overline{\gamma}\,\Gamma(m)} \exp\left(-\frac{m\gamma}{\overline{\gamma}}\right) \qquad (1)$$

where $\overline{\gamma} := E\{\gamma\}$ is the average received SNR, $\Gamma(m)$ is the Gamma function, and *m* is the Nakagami fading parameter ($m \geq 1/2$). It includes the Rayleigh channel as a special case when *m*=1. A one-to-one mapping between the Ricean factor K and the Nakagami fading parameter *m* allows also Ricean channels to be well approximated by Nakagami-*m* channels [15].

3. Cross-Layer Design

We develop cross-layer design, which combines AMC at the physical layer with truncated ARQ at the data link layer in this section. Since only finite delays and buffer sizes are afforded in practice, the maximum number of ARQ retransmissions has to be bounded. This number can be specified by dividing the maximum allowable system delay over the round trip delay required for each retransmission. Formally, we adopt the following delay constraints.

The maximum number of retransmissions allowed per packet is N_r^{max}. Since only finite retransmissions are allowed, error-free delivery cannot be guaranteed [6]. If a packet is not received correctly after N_r^{max} retransmission, we will drop it, and declare packet loss. This is very reasonable and can be afforded in video/image transmissions for instance, because the underlying bit streams represent highly correlated image contents. On the other hand, the error packets can also be utilized if the receiver decides to do so.

To maintain an acceptable packet stream, the probability of packet loss after N_r^{max} retransmissions is not larger than P_{loss}.

The first constraint dictates that truncated ARQ with up to N_r^{max} retransmissions should be performed at the data link layer. The second constraint is guaranteeing the overall system performance. To satisfy the second constraint, an optimal design at the physical layer is needed to maximize the throughput with the aid of truncated ARQ at the data link layer.

3.1 Performance requirement at the Physical Layer

A packet is dropped if it is received incorrectly after a maximum number of $(N_r^{max}+1)$ transmissions; i.e., after N_r^{max} retransmissions. Let us suppose that the instantaneous packet error rate is guaranteed to be not greater than P_0, packet error rate at mode $n = 0$, for each chosen AMC mode at the physical layer. Then the packet loss probability at the data link layer is not greater than $P_0^{N_r^{max}+1}$. To satisfy the second constraint, we need to impose

$$P_0^{N_r^{max}+1} \leq P_{loss} \tag{2}$$

From (2), we obtain

$$P_0 \leq P_{loss}^{\left(1/(N_r^{max}+1)\right)} = P_{target} \tag{3}$$

Therefore, if we design AMC to satisfy a PER upper-bound as in (3) at the physical layer, and implement a N_r^{max} truncated ARQ at the data link layer, both delay and performance requirements will be satisfied.

3.2. AMC Design at the Physical Layer

Our objective in AMC design is to maximize the data rate, while maintaining the required performance, through AMC at the physical layer. The transmission mode is arranged so that the rate is increasing as the mode index n increases. Let N denote the total number of transmission modes available. As in [2], we assume constant power transmission, and partition the total SNR range into N+ 1 non overlapping consecutive interval, with boundary points denoted as $\{\gamma_n\}_{n=0}^{N+1}$. To avoid deep channel fades, no

payload bits will be sent when $\gamma_0 \leq \gamma \leq \gamma_1$. Since no data is sent when $\gamma < \gamma_0$, the optimal adaptation of rte and power according to the channel conditions suffers a probability of outage P_{out}, equal to the probability of no transmission, given by

$$P_{out} = \int_0^{\gamma_0} P_\gamma(\gamma)d\gamma = 1 - \int_{\gamma_0}^{\infty} P_\gamma(\gamma)d\gamma \qquad (4)$$

Specifically, mode n is chosen, when

$$\gamma \in [\gamma_n, \gamma_{n+1}) \qquad (5)$$

The boundary points $\{\gamma_n\}_{n=0}^{N+1}$ are specified in [2] for a given target BER. Finding the target BER through the required PER, and then specifying the boundaries as in [2], is certainly a possibility to determine the boundary points. For coded transmissions, determining PER from BER is not easy, and also our system uses packets as processing units, we will henceforth specify the boundary points to meet the required PER. To simplify the AMC design, we will rely on the following approximate PER expression:

$$PER_n(\gamma) \approx \begin{cases} 1, & if\ 0 < \gamma < \gamma_{pn}, \\ a_n \exp(-g_n \gamma), & if\ \gamma \geq \gamma_{pn}. \end{cases} \qquad (6)$$

where n is the mode index and γ is the received SNR. Parameters a_n, g_n, and γ_{pn} in (5) are mode-dependent, and are provided in Table I with a packet length of $N_p = 1080$.

We set the region boundary γ_n for the transmission mode n to be the minimum SNR required to achieve P_{target}. In general, the required PER in (3) satisfies $P_{target} < 1$. Inverting the PER expression in (6), we obtain

$$\gamma_0 = 0$$
$$\gamma_n = \frac{1}{g_n} \ln\left(\frac{a_n}{P_{target}}\right), \quad n = 1,2,...,N, \qquad (7)$$
$$\gamma_{n+1} = +\infty.$$

With the γ_n specified by (7), one can verify that the AMC in (5) guarantees (3). Maintaining the target performance, the proposed AMC with (5) and (7) then maximizes the spectral efficiency, with the given finite transmission modes.

On the summary, we design AMC at the physical layer by using the following steps:
1) Given two constraints, determine P_{target} from (3).
2) For the P_{target} found, determine $\{\gamma_n\}_{n=0}^{N+1}$ via (7).
3) Update modes per frame by using AMC as in (5).

Retransmit error packets by N_r^{max} truncated ARQ

4. Performance Analysis

For analytical convenience, we further assume the fading coefficients corresponding to the original and the retransmitted packets are independent and identically distributed random variables. Since the instantaneous PER is upper bounded by P_{target} in our AMC design, the average PER at the physical layer will be lower than $P_{target.}$.

According to the AMC rule in (5), the transmission mode, and thus the instantaneous PER, depend on the received SNR γ. Since $P_{target} < 1$ in general, we have $\gamma_{pn} < \gamma_n$ for the γ_n chosen in (7). Each mode n will be chosen with probability [2],

$$\overline{P}_r(n) = \int_{\gamma_n} P_r(\gamma)d\gamma = \frac{\Gamma\left(m,\frac{m\gamma_n}{\overline{\gamma}}\right)-\Gamma\left(m,\frac{m\gamma_{n+1}}{\overline{\gamma}}\right)}{\Gamma(m)} \tag{8}$$

where $\Gamma(m,x)$ is the complementary incomplete gamma function. Let $\overline{PER}_n$ denote the average packet error rate for mode n (the ratio of incorrectly received packets over those transmitted using mode n). From (1), (6), and (7), we can derive $\overline{PER}_n$ as

$$\overline{PER}_n = \frac{1}{P_r(n)}\int_{\gamma_n}^{\gamma_{n+1}} PER_n(\gamma)P_r(\gamma)d\gamma$$

$$= \frac{1}{P_r(n)}\int_{\gamma_n}^{\gamma_{n+12}} a_n \exp(-g_n\gamma)P_r(\gamma)d\gamma$$

$$\frac{1}{P_r(n)}\frac{a_n}{\Gamma(m)}\left(\frac{m}{\overline{\gamma}}\right)^m x \frac{\Gamma(m,b_n\gamma_n)-\Gamma(m,b_n\gamma_{n+1})}{(b_n)^m} \tag{9}$$

where $b_n := \frac{m}{\overline{\gamma}}+g_n$.

The average PER of AMC can then be computed as the ratio of the average number of incorrectly received packets over the total average number of transmitted packets [2]

$$\overline{PER} = \frac{\sum_{n=1}^{N} R_n P_r(n)\overline{PER}_n}{\sum_{n=1}^{N} R_n P_r(n)} \tag{10}$$

Since truncated ARQ is implemented at the data link layer, the packets in error during the original reception may be retransmitted, up to a maximum of N_r^{max} times. The average number of transmissions per packet can be found as [16]

$$\overline{N}(p,N_r^{max}) = 1 + p + p^2 + \ldots + p^{N_r^{max}}$$

$$= \frac{1-p^{N_r^{max}+1}}{1-p} \tag{11}$$

where $p = \overline{PER}$. With the average PER in (10), the actual packet loss probability at the data link layer with N_r^{max} truncated ARQ is

$$P_{actualloss} = p^{N_r^{max}+1} \le P_{t\arg et}^{N_r^{max}+1} = P_{loss} \tag{12}$$

which verifies the second constraint. When mode n is used, each transmitted symbol will carry $R_n = R_c \log_2(M_n)$ information bits for the mode adhering to a M_n QAM constellation, and a rate R_c FEC code. When truncated ARQ is implemented, each packet and thus each information bit, is equivalently transmitted $N(p,N_r^{max})$ times. Hence, the overall average spectral efficiency as a function of N_r^{max}, is obtained as

$$\overline{S}_e(N_r^{max}) = \frac{\sum_{n=1}^{N} R_n P_r(n)}{\overline{N}(p,N_r^{max})} \tag{13}$$

5. Numerical Results

Test case **(Dependence on the maximum number of retransmissions N_r^{max}):**

Let the performance delay constraint be $P_{loss} = 10^{-3}$ and 10^{-6}. We set the Nakagami fading parameter $m=1$ which corresponds to a Rayleigh fading channel. With N_r^{max} varying from 0 to 3, we show the average spectral efficiencies in Figs 3&4. From Figs.3 and 4, we observe that the spectral efficiency improves with increasing N_r^{max}. However, the increment degrades quickly, and diminishing returns appear. This implies that the maximum number of retransmissions need not be arbitrarily large. Small number of retransmissions can achieve sufficient spectral efficiency gain. They incur small delay-throughput and buffer-size penalties, and thus lead to improved delay-throughput tradeoffs. Due to FEC advantage, this approach has better error performance which results in higher spectral efficiency for low and moderate average   SNR.
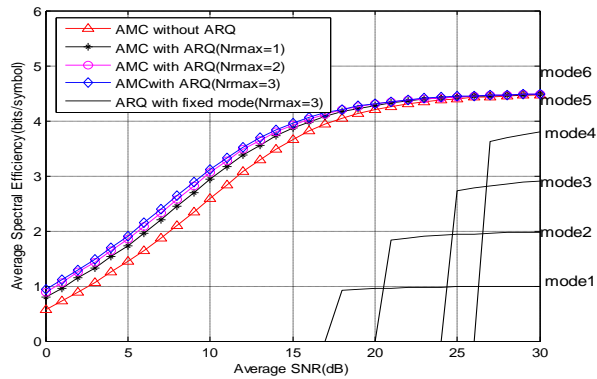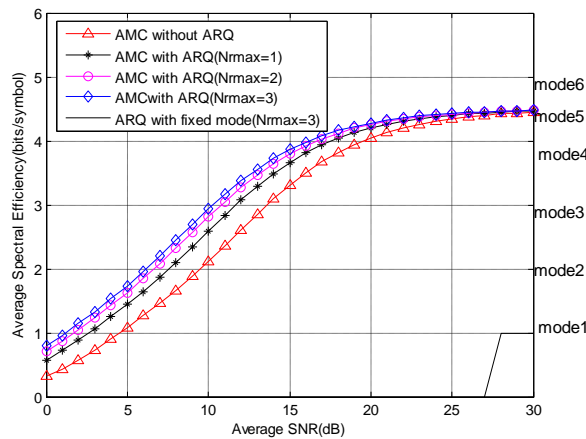

Fig.3 Average Spectral Efficiency versus Average SNR with $P_{loss} = 10^{-3}$

Fig.4 Average Spectral Efficiency versus Average SNR with $P_{loss} = 10^{-6}$

However at high average SNR say 30 dB in Figs 3 and 4, it achieves a higher spectral efficiency of 4.5 bits/symbol. As expected, when the average SNR is very high, say 30 dB in Fig.3, we get the average Spectral Efficiency converges for both cases of AMC with ARQ and without ARQ. At low average SNR, say 10dB in Figs.3 and 4, the average spectral

efficiency gain when combining AMC with truncated ARQ exceeds that of the AMC only scheme by about 0.58bits/symbol and 0.87bits/symbol using three retransmissions for PER of 10^{-3} and 10^{-6} respectively.

In this section, we present numerical results, assuming the packet length $N_p = 1080$, with the PER approximation parameters of (5) listed in Table I.
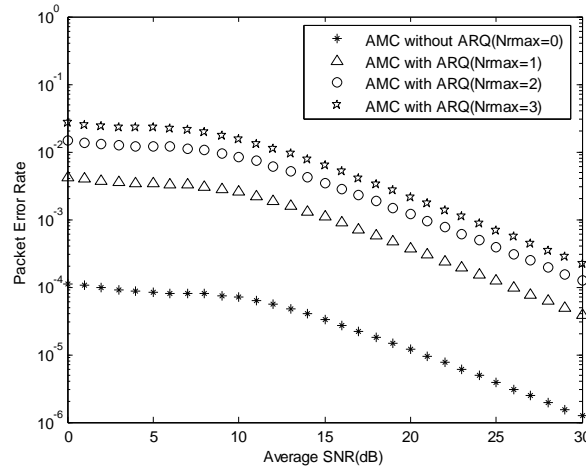

Fig.5 Average Packet Error Rate versus Average SNR with P$_{loss}$ =10^{-3}
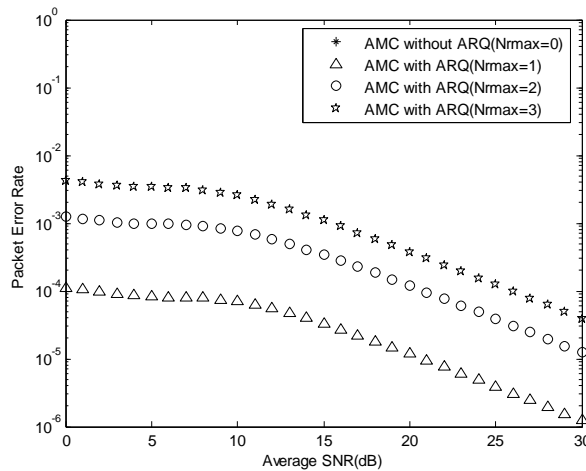

Fig.6 Average Packet Error Rate versus Average SNR with P$_{loss}$ =10^{-6}

The average packet error rate at the physical layer is depicted in Figs.5 and 6. From Figs 5 and 6, we observe that when the average SNR increases, the average packet error rate decreases. As N_r^{max} increases, the error correcting capability of the truncated ARQ increases, which relieves the physical layer from stringent error correction requirements. With a lower performance requirement, transmission rates can be increased at the physical layer, which, in turn leads to the overall spectral efficiency improvement. This gain is introduced by relaxing the system delay requirement in first delay constraint; thus a tradeoff between delay and throughput emerges.
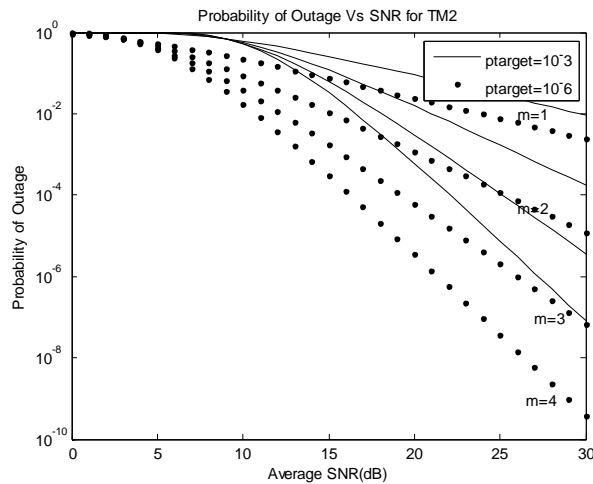
Fig.7 Probability of Outage vs Average SNR for different P$_{target}$

Fig.7 shows the outage probability of values of the various Nakagami fading parameter and target PERs of 10^{-3} nd 10^{-6} respectively.

6. Conclusion

In this paper, we developed a cross-layer design, which combines adaptive modulation and coding at the physical layer with truncated ARQ at the data link layer, in order to enhance system throughput under prescribed delay and performance constraints. We used a closed-form expression of the average spectral efficiency and outage probability for packets transmitted over Nakagami-*m* block fading channels. Numerical results demonstrated the rate improvement of our cross-layer design where retransmissions alleviate stringent error-control requirements on modulation and coding, and bring considerable spectral efficiency gain. Diminishing returns appear on the spectral efficiency improvement as the number of retransmissions increases, which suggests that a small number of retransmissions strike a desirable delay-throughput tradeoff in practice.

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