Cross-Layer Combining of Adaptive Modulation and Coding with Truncated ARQ over Wireless Links

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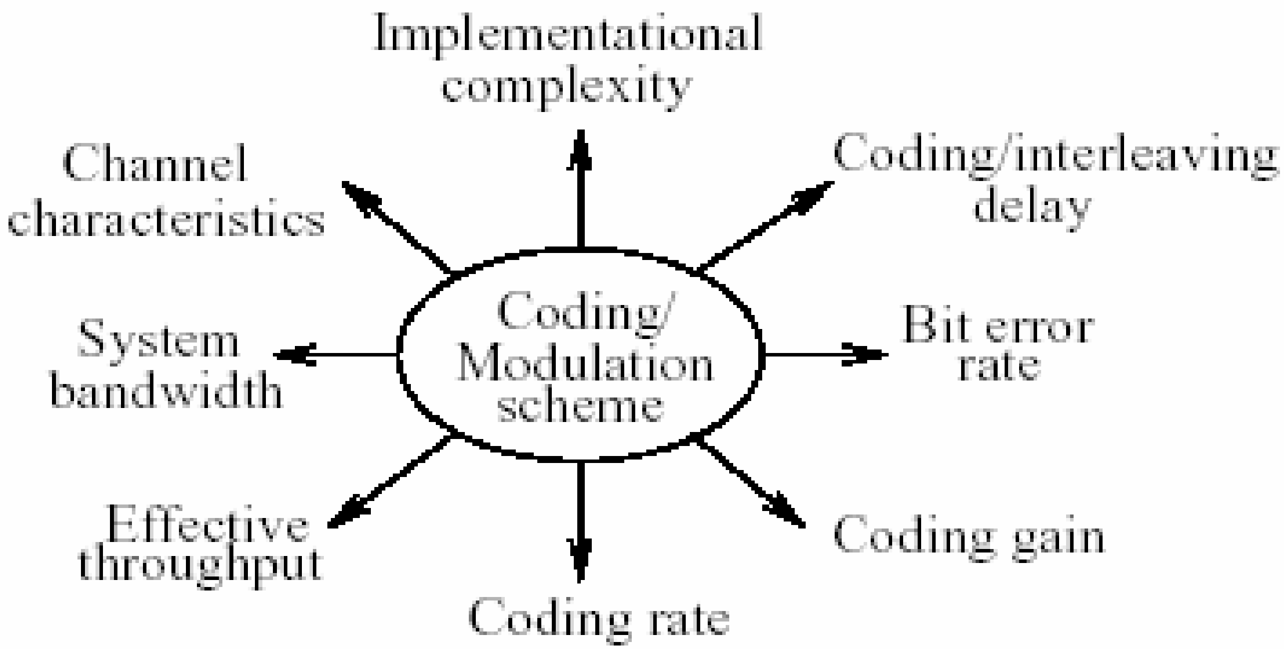
Outline

- Overview
- Motivation
- System & Channel Model
- Truncated ARQ and AMC design
- Performance analysis
- Numerical Results
- Limitations and Future Work

Overview for AMC

- Modulation:
  - Map the digital information to analog symbols to be transmitted over a radio channel
- Channel Coding:
  - Add redundancy to the transmitted data to improve the bit error rate performance of wireless channels
- Adaptive Modulation and Coding:
  - Dynamically change the modulation and coding scheme (AMC) to mitigate the impediments such as time-varying channel fading, interference, and mobility, to maximize the spectral efficiency
  - A key technique used in 3Gwireless systems, WLANs, and WMANs

Main Challenges



Predict the channel state and adjust the modulation scheme accordingly

Classical AMC

- Focus on improving the physical layer performance, i.e., maximize bit rate of per symbols

- Several distinguished professors in this direction
  - Prof. A. J. Goldsmith (Stanford U., USA)
  - Prof. L. Hanzo (U. of Southampton, UK)
  - ......

- Several papers
  - "Adaptive Modulation over Nakagami Fading Channels", M. Alouini and A. J. Goldsmith, Wireless Personal Communications, 2000
  - "Degreees of Freedom in Adaptive Modulation: A Unified View", S. Chung and A. J. Goldsmith, IEEE Trans. On Communications, 2001
  - "Adaptive modulation, channel coding, and diversity tchniques for next-generation wireless systems", L. Hanzo, Nov. 2003

Cross-Layer AMC

- Cross Physical Layer and MAC layer
- Cross Physical Layer and Network Layer
- Cross Physical Layer and Transport Layer
- Cross Physical Layer and Application Layer

- Several Active professors in this direction
  - Prof. G. B. Giannakis (U. of Minnesota, USA)
  - Prof. S. I. Marcus (U. Maryland, USA)
  - Prof. A. J. Goldsmith (Stanford U., USA)
  - Prof. J. W. Modestino (U. of Miami, USA)

- Several papers
  - "Wireless link adaptation policies: QoS for deadline constrained traffic with imperfect channel estimates", T. Holliday, A. J. Goldsmith, and P. Glynn, IEEE ICC 2002
  - "Jointly optimized bit-rate/delay control policy for wireless packet networks with fading channels", J. Razavilar, K. Liu, and S. I. Marcus, IEEE Trans. On Communications, 2002
  - "Queueing with adaptive modulation and coding over wireless links: cross-layer analysis and design", Q. Liu, S. Zhou, and G. B. Giannakis, IEEE Trans. On Wireless Communications, 2005

ARQ

- Enhance reliability by retransmitting packets received in error

- Quite effective in improving system throughput for small transmission error rate

- Real system only implements Truncated ARQ
  - Minimize delays
  - Minimize buffer sizes

Motivation of This Paper

- Goal
  - Maximize spectral efficiency under prescribed delay and error performance constraints

- Main idea
  - Exploit CSI and combine ARQ at data link layer and AMC at physical layer to improve performance

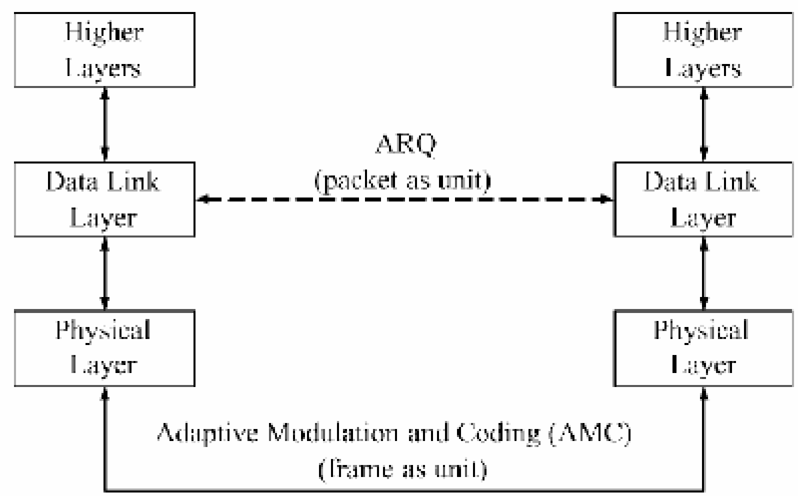
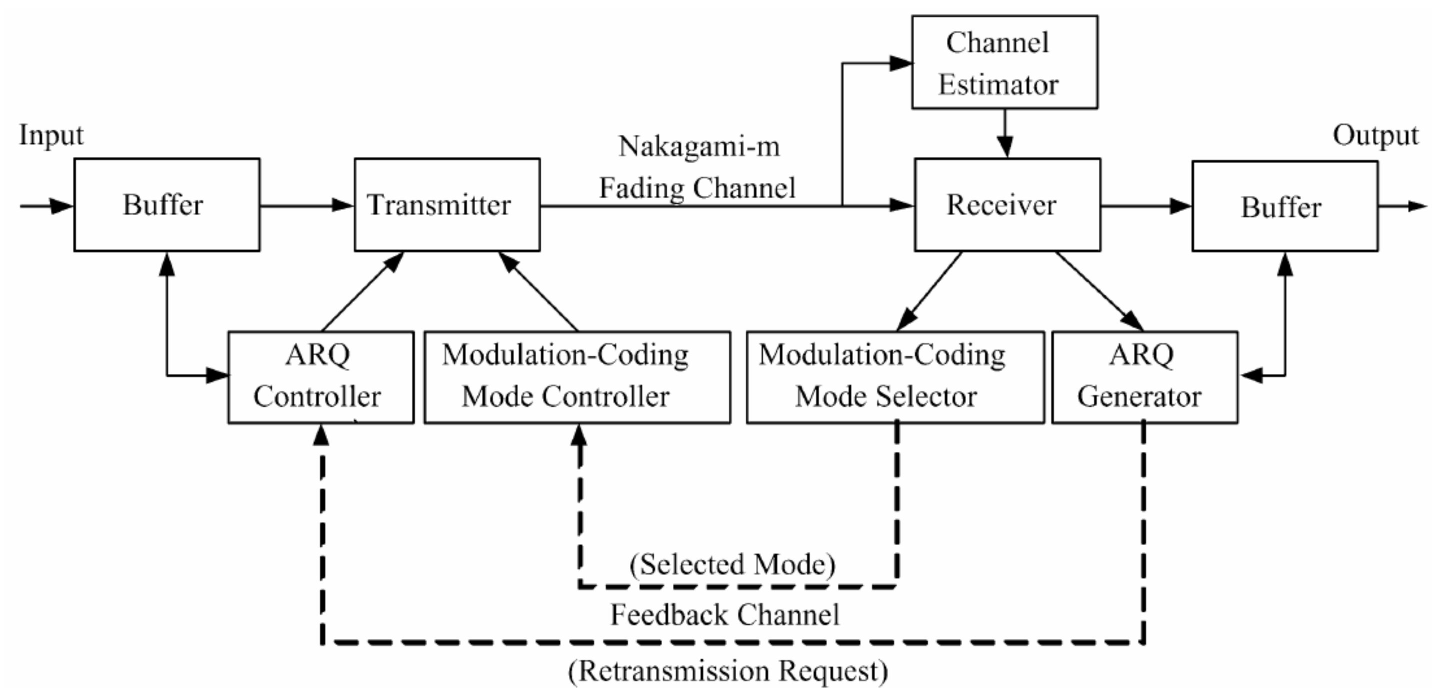


Fig. 2. Cross-layer structure combining AMC with ARQ.

System Model:

- Single-transmit single-receive antenna system
- Multiple transmission modes available at physical layer
- Slow varying fading channels
- Perfect channel state information (CSI)
- Idea feedback channel without error and latency.
- Error detection based on CRC is perfect.



Channel Model

§Slow varying fading channels **è** channel quality captured through received SNR γ per frame

§General Nakagami-m model

- γ is a random variable having a Gamma pdf :

$$p_\gamma(\gamma) = \frac{m^m \gamma^{m-1}}{\bar{\gamma}^m \Gamma(m)} \exp\left(-\frac{m\gamma}{\bar{\gamma}}\right)$$

- where $\bar{\gamma} := E\{\gamma\}$, $\Gamma(m) := \int_0^\infty t^{m-1} e^{-t} dt$ and m = Nakagami fading parameter (m ≥ 1/2)

§Remark:

– m =1 : Rayleigh channel model

– m >1 : approximated Ricean channel model

– m **è** inifinity : approximated AWGN channel model

Parameters

$$\mathrm{PER}_n(\gamma) \approx \begin{cases} 1, & \text{if } 0 < \gamma < \gamma_{pn}, \\ a_n \exp(-g_n \gamma), & \text{if } \gamma \geq \gamma_{pn}, \end{cases}$$

- TM1: Uncoded (without FEC) M_n-ary rectangular or square QAM modes, where $M_n=2^n$, n=1,2,..,7.
- TM2: Convolutionally coded M_n-ary rectangular or square QAM modes, adopted from HIPERLAN/2 or IEEE 802.11a standards.

TABLE I
TRANSMISSION MODES IN TM1 WITH UNCODED M_n-QAM MODULATION

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7
Modulation	BPSK	QPSK	8-QAM	16-QAM	32-QAM	64-QAM	128-QAM
Rate(bits/sym.)	1	2	3	4	5	6	7
a_n	67.7328	73.8279	58.7332	55.9137	50.0552	42.5594	40.2559
g_n	0.9819	0.4945	0.1641	0.0989	0.0381	0.0235	0.0094
γ_{pn}(dB)	6.3281	9.3945	13.9470	16.0938	20.1103	22.0340	25.9677

TABLE II
TRANSMISSION MODES IN TM2 WITH CONVOLUTIONALLY CODED MODULATION

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Modulation	BPSK	QPSK	QPSK	16-QAM	16-QAM	64-QAM
Coding rate R_c	1/2	1/2	3/4	9/16	3/4	3/4
Rate (bits/sym.)	0.50	1.00	1.50	2.25	3.00	4.50
a_n	274.7229	90.2514	67.6181	50.1222	53.3987	35.3508
g_n	7.9932	3.4998	1.6883	0.6644	0.3756	0.0900
γ_{pn}(dB)	-1.5331	1.0942	3.9722	7.7021	10.2488	15.9784

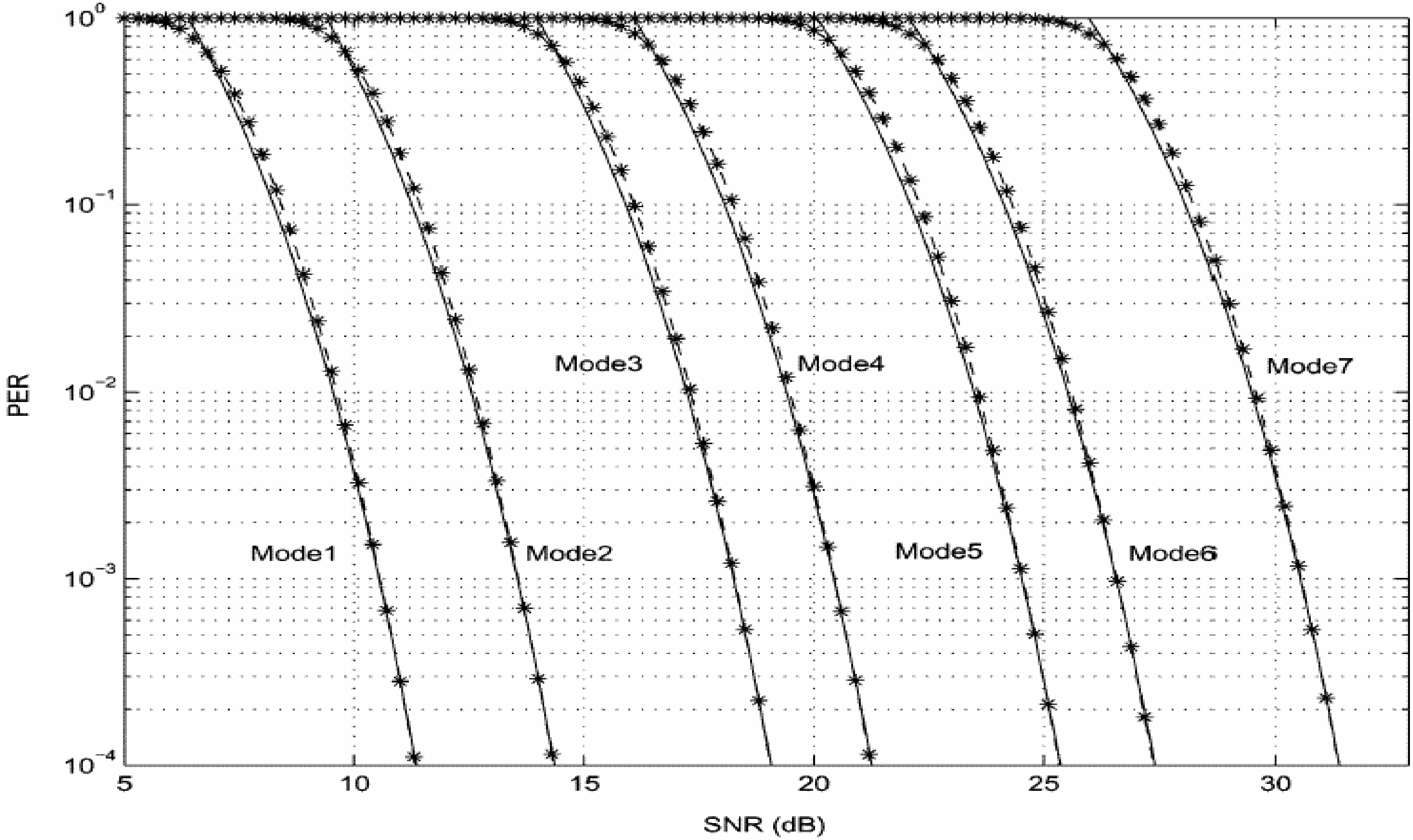


Fig. 9. Packet error rate of the transmission modes in TM1 (stars denote exact PER, solid lines are fitting curves to the exact PER, and dashed lines depict PER based on BER).

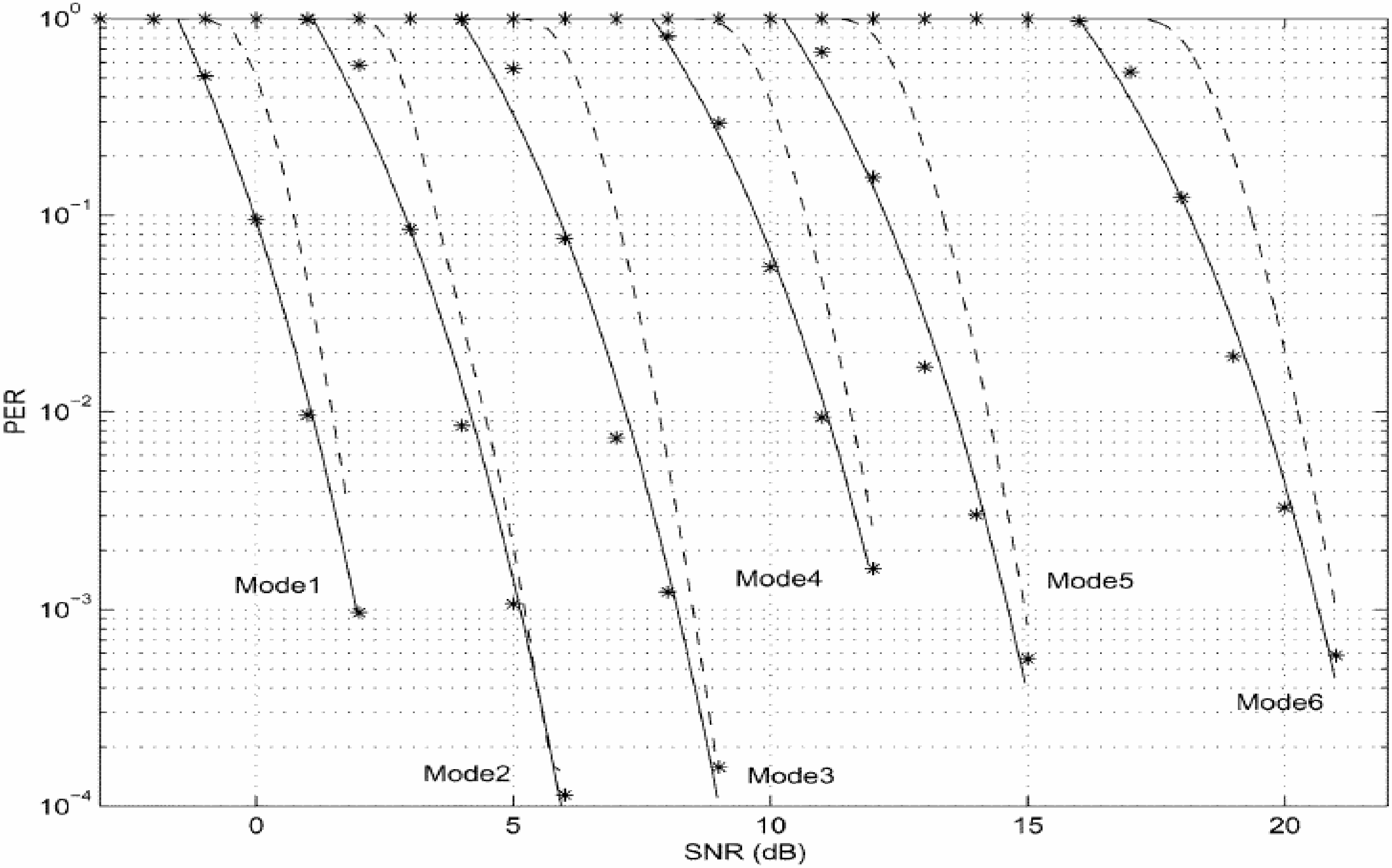


Fig. 10. Packet error rate of the transmission modes in TM2 (stars denote exact PER, solid lines are fitting curves to the exact PER, and dashed lines depict PER based on BER).

Packet and Frame Formats

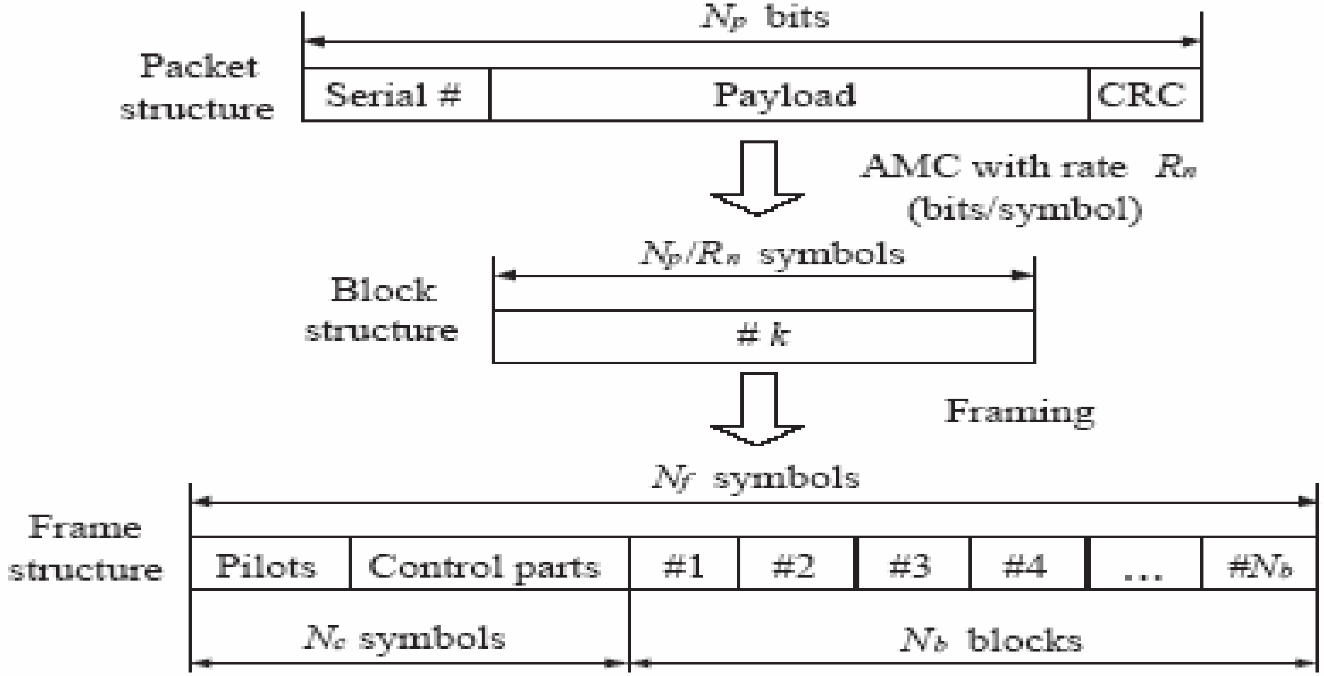


Fig. 3. The packet and frame structures

Packet size N_p bits

Number of symbols per frame $N_f = N_c + N_b N_p / R_n$

Performance Requirements

§ Data Link Layer

- **Maximum number of retransmissions** N_r^{max}
  ç è **Delay Bound**

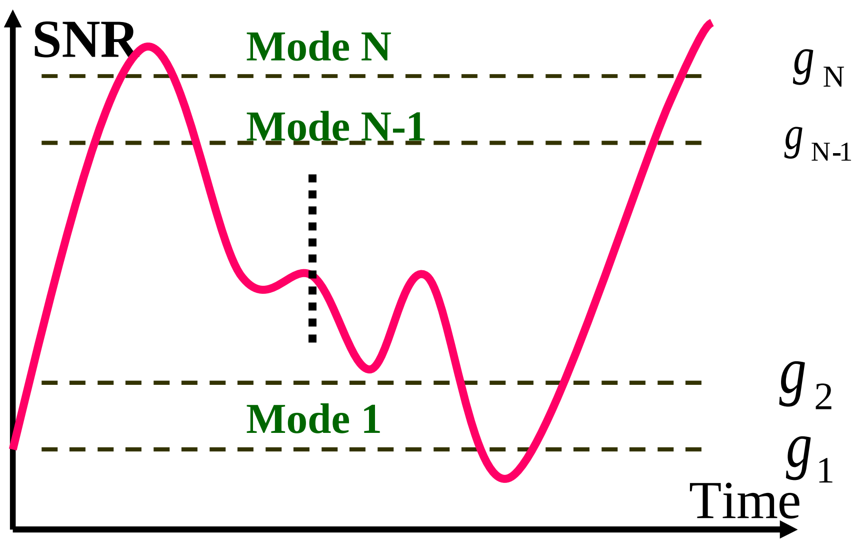
§ Physical Layer

- **Probability of packet loss rate P_{Loss}**
  - **instantaneous PER £ P_0 for each chosen AMC mode n**

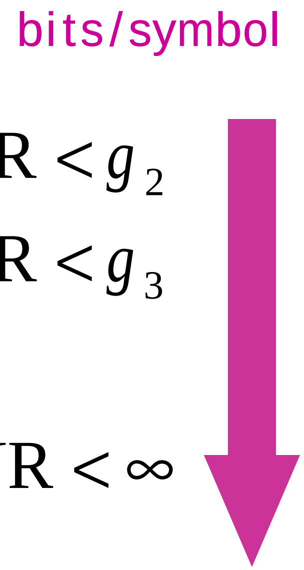
$$P_0^{N_r^{max}+1} \leq P_{loss}$$

$$P_0 \leq P_{loss}^{\frac{1}{N_r^{max}+1}} := P_{target}$$

AMC Design



$$\text{Mode} = \begin{cases} M_1 & \text{if } g_1 \le \text{SNR} < g_2 \\ M_2 & \text{if } g_2 \le \text{SNR} < g_3 \\ & \vdots \\ M_N & \text{if } g_N \le \text{SNR} < \infty \end{cases}$$



- One of key issues for AMC is how to determine the mode switching thresholds $\Sigma = \{g_1, g_2, \cdots, g_N\}$ to optimize the system performance

Details for AMC Design

$$\gamma_0 = 0,$$

$$\gamma_n = \frac{1}{g_n} \ln\left(\frac{a_n}{\mathrm{P}_{\mathrm{target}}}\right), \quad n = 1, 2, \ldots, N,$$

$$\gamma_{N+1} = +\infty$$

Set the region boundary γ_n for transmission mode n = minimum SNR required to achieve P_{target}.

Performance Analysis

§Assumption :

- fading channel coefficients corresponding to original and retransmitted packets are i.i.d. random variables

Combined AMC with truncated ARQ :

Probability of choosing mode n:

$$\Pr(n) = \int_{\gamma_n}^{\gamma_{n+1}} p_\gamma(\gamma) d\gamma = \frac{\Gamma(m, m\gamma_n/\bar{\gamma}) - \Gamma(m, m\gamma_{n+1}/\bar{\gamma})}{\Gamma(m)} \qquad \Gamma(m,x) := \int_x^\infty t^{m-1} e^{-t} dt$$

Average packet error rate of mode n:

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

$$= \frac{1}{\Pr(n)} \int_{\gamma_n}^{\gamma_{n+1}} a_n \exp(-g_n \gamma) p_\gamma(\gamma) d\gamma \qquad b_n := \frac{m}{\bar{\gamma}} + g_n.$$

$$= \frac{1}{\Pr(n)} \frac{a_n}{\Gamma(m)} \left(\frac{m}{\bar{\gamma}}\right)^m \frac{\Gamma(m, b_n\gamma_n) - \Gamma(m, b_n\gamma_{n+1})}{(b_n)^m}$$

Performance Analysis

- **Average PER of AMC:** $\overline{\mathrm{PER}} = \sum_{n=1}^{N} \Pr(n) \times \overline{\mathrm{PER}_n}$

- **Let** $p := \overline{\mathrm{PER}}.$

- **Average no. of transmissions per packet =**

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

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

- **Actual packet loss probability at data link layer**

$$\mathrm{P}_{\text{actual loss}} = p^{N_r^{\max}+1} \le \mathrm{P}_{\text{target}}^{N_r^{\max}+1} = \mathrm{P}_{\text{loss}}$$

(verifies the QoS requirements)

Performance Analysis

- Spectral efficiency = bit rate per symbol

- Spectral efficiency at physical without considering packet retransmission at data link :

$$\overline{S}_{e,\text{physical}} = \sum_{n=1}^{N} R_n \Pr(n).$$

- Overall average spectral efficiency considering truncated ARQ :

$$\overline{S}_e(N_r^{\max}) = \frac{\overline{S}_{e,\text{physical}}}{\overline{N}(p, N_r^{\max})} = \frac{1}{\overline{N}(p, N_r^{\max})} \sum_{n=1}^{N} R_n \Pr(n)$$

- Average spectral efficiency for only AMC :

$$\overline{S}_e(N_r^{\max} = 0) = \sum_{n=1}^{N} R_n \Pr(n).$$

Performance of Truncated ARQ Only

- Transmission mode is fixed (mode n) :

- Average PER at the physical layer :

$$\overline{\mathrm{PER}}(n) = \int_0^{\infty} \mathrm{PER}_n(\gamma)\, p_\gamma(\gamma) d\gamma = \int_0^{\gamma_{pn}} p_\gamma(\gamma) d\gamma + \int_{\gamma_{pn}}^{\infty} a_n \exp(-g_n \gamma)\, p_\gamma(\gamma) d\gamma$$

$$= 1 - \frac{\Gamma(m, m\gamma_{pn}/\bar{\gamma})}{\Gamma(m)} + \frac{a_n}{\Gamma(m)} \left(\frac{m}{\bar{\gamma}}\right)^m \frac{\Gamma(m, b_n \gamma_{pn})}{(b_n)^m}$$

- Let $q_n := \overline{\mathrm{PER}}(n)$

- Average no. of transmissions per packet :

$$\overline{N}(q_n, N_r^{\max}) = 1 + q_n + q_n^2 + \cdots + q_n^{N_r^{\max}} = \frac{1 - q_n^{N_r^{\max}+1}}{1 - q_n}.$$

- Average spectral efficiency of mode n : $\overline{\mathrm{S}}_{\mathrm{e,n}}(N_r^{\max}) = \dfrac{R_n}{\overline{N}(q_n, N_r^{\max})}.$

Performance of Truncated ARQ Only

- Packet loss probability after $N_r^{\max}$ retransmissions :

$$\mathrm{P}_{n,\mathrm{ARQ}} = q_n^{N_r^{\max}+1}.$$

- This is not guaranteed to be less than P_{loss}.
- There exists a threshold $\bar{\gamma}_{n,\mathrm{th}}$
  - P_{loss} requirement is satisfied $\bar{\gamma} \geq \bar{\gamma}_{n,\mathrm{th}}$.
  - P_{loss} requirement is not satisfied $\bar{\gamma} < \bar{\gamma}_{n,\mathrm{th}}$

Average spectral efficiency for truncated ARQ only satisfying the QoS constraints :

$$\overline{\mathrm{S}}_{e,n}(N_r^{\max}) = \begin{cases} 0, & \bar{\gamma} < \bar{\gamma}_{n,\mathrm{th}} \\ \dfrac{R_n}{\overline{N}(q_n, N_r^{\max})}, & \bar{\gamma} \geq \bar{\gamma}_{n,\mathrm{th}} \end{cases}.$$

Numerical Results :

N_p = 1080 P_{loss} = 0.01 m =1 N_r^{max} **varying from 0 - 3**

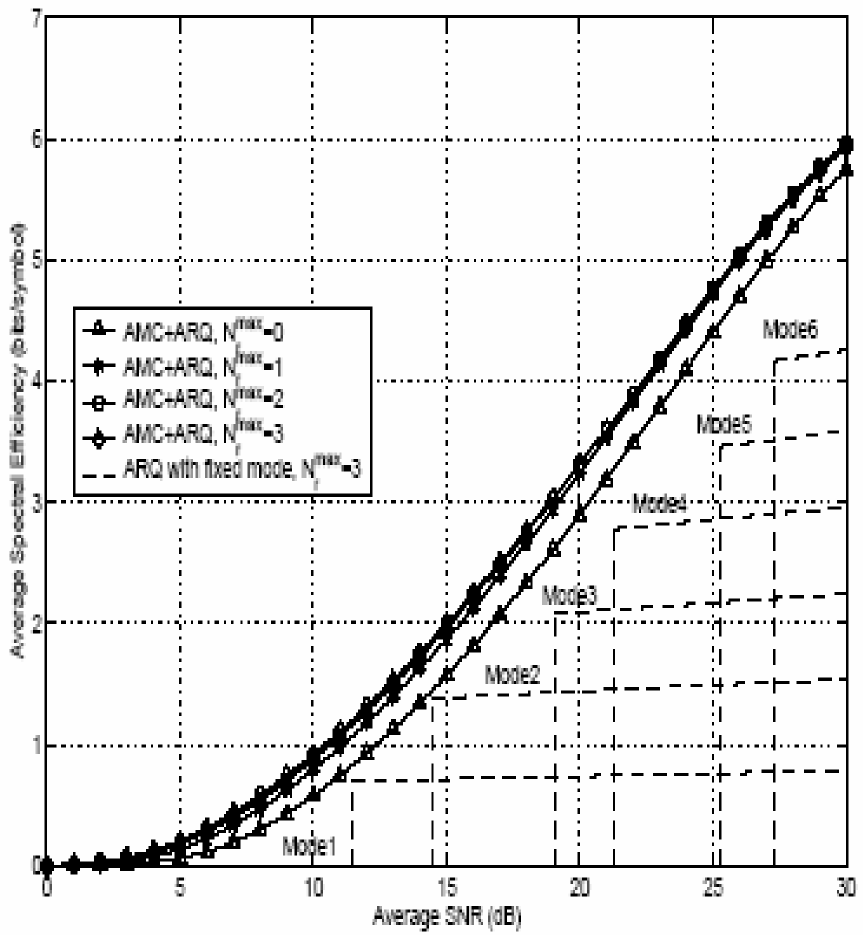


Fig. 4. Average spectral efficiency for TM1 vs. average SNR

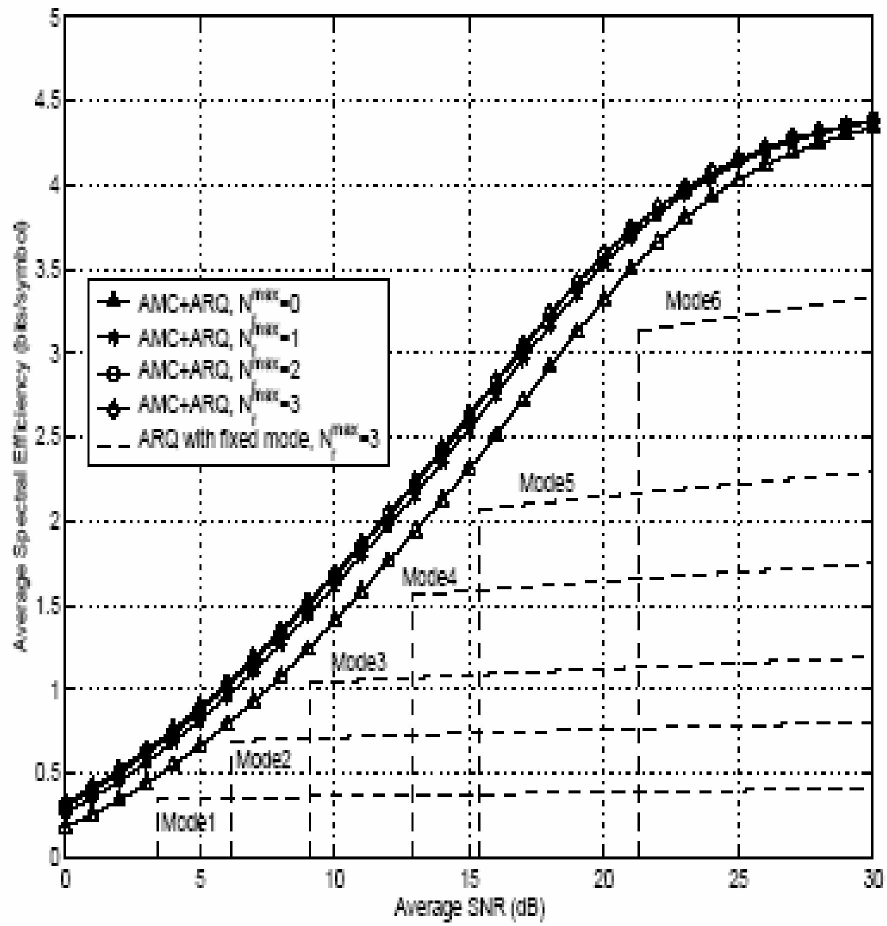


Fig. 5. Average spectral efficiency for TM2 vs. average SNR

Numerical Results

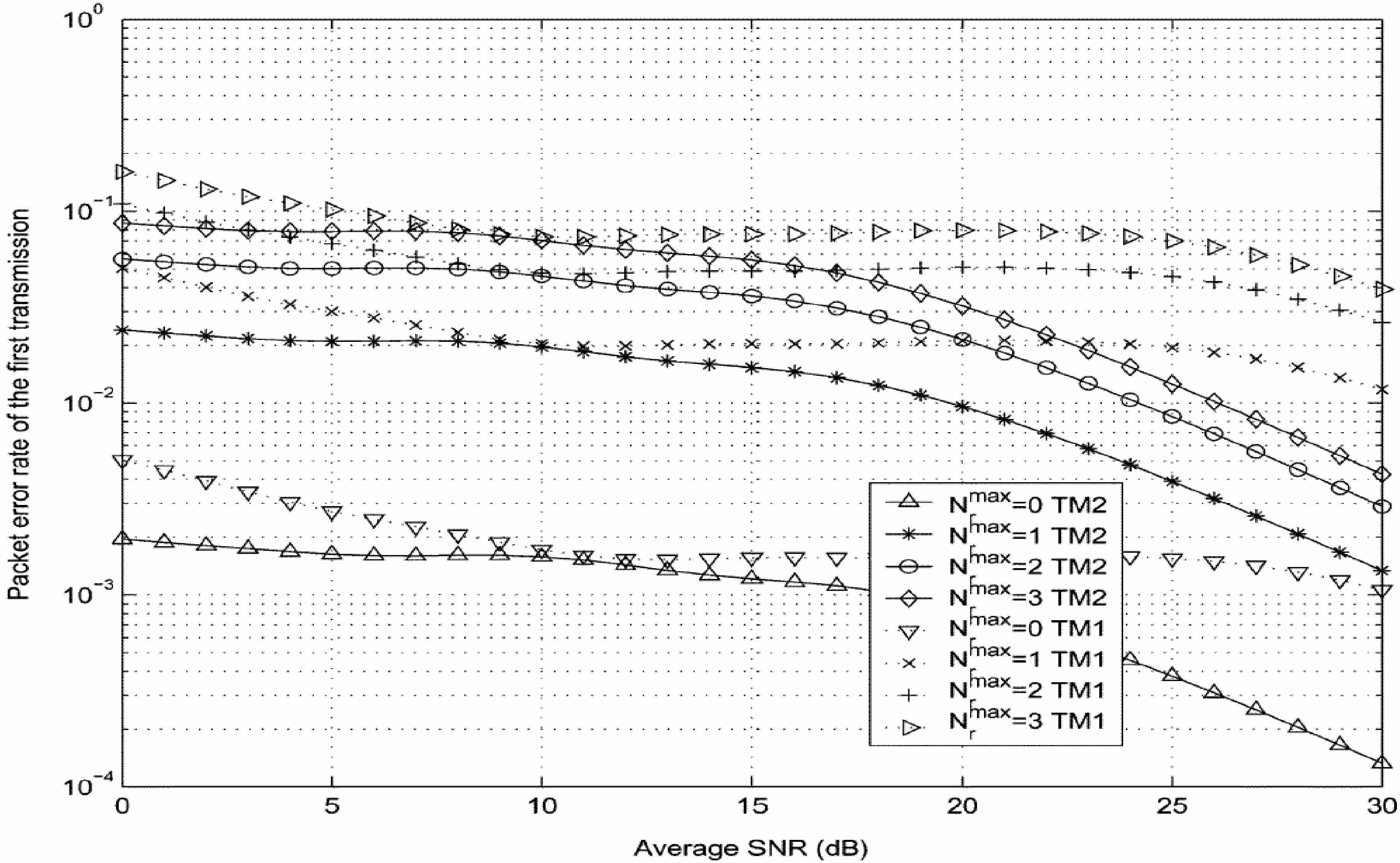


Fig. 6. Packet error rate at the physical layer versus average SNR.

Numerical Results

N_p = 1080 **P_{loss} = 0.01** **m varying from 1-4** N_r^{max} **= 0**

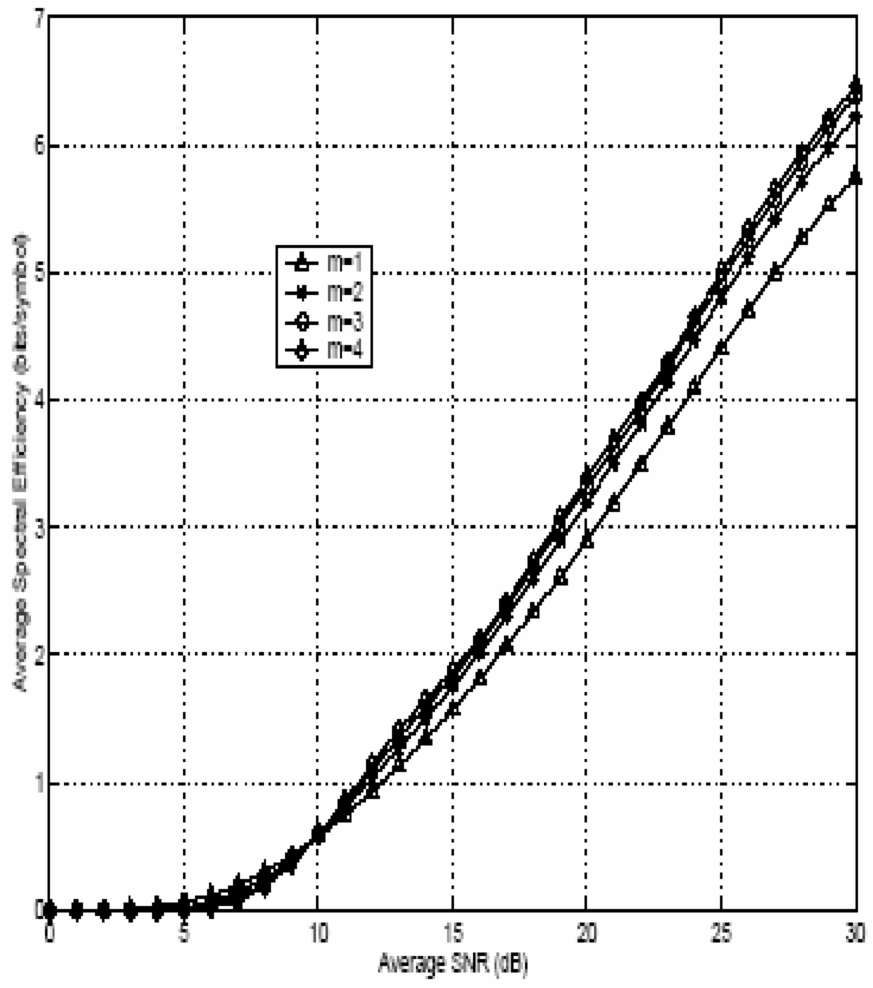


Fig. 7. Average spectral efficiency for TM1 vs. average SNR

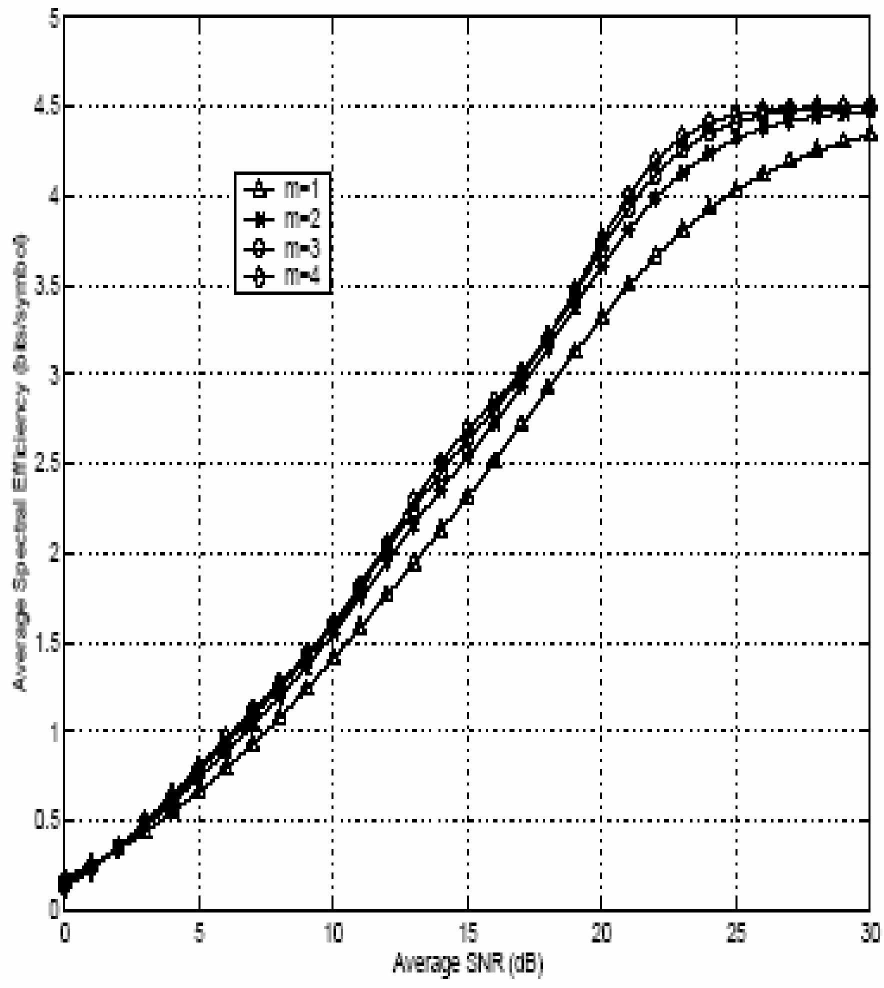


Fig. 8. Average spectral efficiency for TM2 vs. average SNR

Contribution and Limitations

- Contributions
  - A cross layer AMC design for maximizing spectral efficiency under QoS requirements
- Limitations
  - Perfect CSI available
  - Feedback channel has zero delay and is error free
  - Slow varying fading channels
  - Single user link

Homework 3

- Consider Nakagami-m fading channel with m=1

  Packet error probability after $N_r^{\max}$ retransmissions :

$$P_{n,\mathrm{ARQ}} = q_n^{N_r^{\max}+1}.$$

- For the transmission modes defined in Table II and with truncated ARQ (no AMC) with retransmission limit $N_r^{\max}$,find the threshold $\bar{\gamma}_{n,\mathrm{th}}$ for n =1,2,…,6 such that

  - P_{loss} requirement is satisfied $\bar{\gamma} \geq \bar{\gamma}_{n,\mathrm{th}}.$
  - P_{loss} requirement is not satisfied $\bar{\gamma} < \bar{\gamma}_{n,\mathrm{th}}$