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 3G wireless 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, channel coding, and diversity techniques 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
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 \( \tilde{E} \) channel quality captured through received SNR \( \gamma \) per frame

General Nakagami-m model

- \( \gamma \) is a random variable having a Gamma pdf:
  \[
  p_\gamma(\gamma) = \frac{m^m \gamma^{m-1}}{\tilde{\gamma}^m \Gamma(m)} \exp\left(-\frac{m\gamma}{\tilde{\gamma}}\right)
  \]
  where \( \tilde{\gamma} := E\{\gamma\} \), \( \Gamma(m) := \int_0^\infty t^{m-1}e^{-t}dt \) and \( m = \text{Nakagami fading parameter} \ (m \geq 1/2) \)

Remark:
- \( m = 1 \) : Rayleigh channel model
- \( m > 1 \) : approximated Ricean channel model
- \( m \to \infty \) : approximated AWGN channel model
Parameters

- **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.

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

### TABLE I  
**Transmission Modes in TM1 With Uncoded $M_n$-QAM Modulation**

<table>
<thead>
<tr>
<th>Modulation Rate(bits/sym.)</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
<th>Mode 5</th>
<th>Mode 6</th>
<th>Mode 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>BPSK</td>
<td>QPSK</td>
<td>8-QAM</td>
<td>16-QAM</td>
<td>32-QAM</td>
<td>64-QAM</td>
<td>128-QAM</td>
</tr>
<tr>
<td>$a_{R_2}$</td>
<td>67.7328</td>
<td>73.8279</td>
<td>58.7332</td>
<td>55.9137</td>
<td>50.0552</td>
<td>42.5594</td>
<td>40.2559</td>
</tr>
<tr>
<td>$g_{R_2}$</td>
<td>0.9819</td>
<td>0.4945</td>
<td>0.1641</td>
<td>0.0989</td>
<td>0.0381</td>
<td>0.0235</td>
<td>0.0094</td>
</tr>
<tr>
<td>$\gamma_{pn}$ (dB)</td>
<td>6.3281</td>
<td>9.3945</td>
<td>13.9470</td>
<td>16.0938</td>
<td>20.1103</td>
<td>22.0340</td>
<td>25.9677</td>
</tr>
</tbody>
</table>

### TABLE II  
**Transmission Modes in TM2 With Convolutionally Coded Modulation**

<table>
<thead>
<tr>
<th>Modulation Coding rate $R_c$ Rate (bits/sym.)</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
<th>Mode 5</th>
<th>Mode 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>BPSK</td>
<td>QPSK</td>
<td>QPSK</td>
<td>16-QAM</td>
<td>16-QAM</td>
<td>64-QAM</td>
</tr>
<tr>
<td>Coding rate $R_c$</td>
<td>1/2</td>
<td>1/2</td>
<td>3/4</td>
<td>9/16</td>
<td>3/4</td>
<td>3/4</td>
</tr>
<tr>
<td>Rate (bits/sym.)</td>
<td>0.50</td>
<td>1.00</td>
<td>1.50</td>
<td>2.25</td>
<td>3.00</td>
<td>4.50</td>
</tr>
<tr>
<td>$a_{R_2}$</td>
<td>274.7229</td>
<td>90.2514</td>
<td>67.6181</td>
<td>50.1222</td>
<td>53.3987</td>
<td>35.3508</td>
</tr>
<tr>
<td>$g_{R_2}$</td>
<td>7.9932</td>
<td>3.4998</td>
<td>1.6883</td>
<td>0.6644</td>
<td>0.3756</td>
<td>0.0900</td>
</tr>
<tr>
<td>$\gamma_{pn}$ (dB)</td>
<td>-1.5331</td>
<td>1.0942</td>
<td>3.9722</td>
<td>7.7021</td>
<td>10.2488</td>
<td>15.9784</td>
</tr>
</tbody>
</table>
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

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 $N_{r \text{ max}}$

  Delay Bound

**Physical Layer**
- Probability of packet loss rate $P_{\text{Loss}}$
  - instantaneous PER $\leq P_0$ for each chosen AMC mode $n$

\[
P_0^{N_{r \text{ max}} + 1} \leq P_{\text{loss}}
\]

\[
P_0 \leq P_{\text{loss}}^{\frac{1}{N_{r \text{ max}} + 1}} := P_{\text{target}}
\]
One of key issues for AMC is how to determine the mode switching thresholds \( \{ \gamma_1, \gamma_2, \ldots, \gamma_N \} \) to optimize the system performance.

\[
\text{Mode} = \begin{cases} 
M_1 & \text{if } \gamma_1 \leq \text{SNR} < \gamma_2 \\
M_2 & \text{if } \gamma_2 \leq \text{SNR} < \gamma_3 \\
\vdots & \\
M_N & \text{if } \gamma_N \leq \text{SNR} < \infty
\end{cases}
\]
Set the region boundary $\gamma_n$ for transmission mode $n$ as the minimum SNR required to achieve $P_{\text{target}}$. 

- $\gamma_0 = 0$, 
- $\gamma_n = \frac{1}{g_n} \ln \left( \frac{a_n}{P_{\text{target}}} \right)$, $n = 1, 2, \ldots, N$, 
- $\gamma_{N+1} = +\infty$
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 $n$:

$$\Pr(n) = \int_{\gamma_n}^{\gamma_{n+1}} p_\gamma(\gamma) d\gamma = \frac{\Gamma(m, m\gamma_n/\bar{\gamma}) - \Gamma(m, m\gamma_n+1/\bar{\gamma})}{\Gamma(m)}$$

Average packet error rate of mode $n$:

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

$$= \frac{1}{\Pr(n)} \int_{\gamma_n}^{\gamma_{n+1}} b_n \exp(-b_n\gamma) p_\gamma(\gamma) d\gamma$$

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

$$b_n := \frac{m}{\bar{\gamma}} + g_n.$$
Performance Analysis

Average PER of AMC: \[ \overline{\text{PER}} = \sum_{n=1}^{N} \Pr(n) \times \overline{\text{PER}}_n \]

Let \[ p := \overline{\text{PER}}. \]

Average no. of transmissions per packet = \[ \overline{N}(p, N_r^{\text{max}}) = 1 + p + p^2 + \cdots + p^{N_r^{\text{max}}} \]
\[ = \frac{1 - p^{N_r^{\text{max}} + 1}}{1 - p}. \]

Actual packet loss probability at data link layer
\[ P_{\text{actual loss}} = p^{N_r^{\text{max}} + 1} \leq P_{\text{target}}^{N_r^{\text{max}} + 1} = P_{\text{loss}} \]

(verify the QoS requirements)
Performance Analysis

\( \text{Spectral efficiency} = \text{bit rate per symbol} \)

\( \text{Spectral efficiency at physical without considering packet retransmission at data link:} \)

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

\( \text{Overall average spectral efficiency considering truncated ARQ:} \)

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

\( \text{Average spectral efficiency for only AMC:} \)

\[
\bar{S}_e(N_r^{\text{max}} = 0) = \sum_{n=1}^{N} R_n \Pr(n).
\]
Performance of Truncated ARQ Only

Transmission mode is fixed (mode $n$):

Average PER at the physical layer:

\[
\overline{\text{PER}}(n) = \int_0^\infty \text{PER}_n(\gamma) \, p_\gamma(\gamma) \, d\gamma = \int_0^{\gamma_{pn}} p_\gamma(\gamma) \, d\gamma + \int_{\gamma_{pn}}^\infty a_n \exp(-g_{n\gamma}) \, p_\gamma(\gamma) \, d\gamma
\]

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

Let $q_n := \frac{\overline{\text{PER}}(n)}{\overline{\text{PER}}(n)}$

Average no. of transmissions per packet:

\[
\overline{N}(q_n, N_{n_{\text{max}}}) = 1 + q_n + q_n^2 + \cdots + q_n^{N_{n_{\text{max}}}} = \frac{1 - q_n^{N_{n_{\text{max}}} + 1}}{1 - q_n}
\]

Average spectral efficiency of mode $n$:

\[
\overline{S}_{e,n}(N_{n_{\text{max}}}) = \frac{R_n}{\overline{N}(q_n, N_{n_{\text{max}}})}
\]
Performance of Truncated ARQ Only

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

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

- This is not guaranteed to be less than $P_{\text{loss}}$.

- There exists a threshold
  - $P_{\text{loss}}$ requirement is satisfied \( \bar{\gamma} \geq \bar{\gamma}_{n,\text{th}} \)
  - $P_{\text{loss}}$ requirement is not satisfied \( \bar{\gamma} < \bar{\gamma}_{n,\text{th}} \)

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

$$\overline{S_{e,n}}(N_r^{\text{max}}) = \begin{cases} 0, & \bar{\gamma} < \bar{\gamma}_{n,\text{th}} \\ \frac{R_n}{N(q_n,N_r^{\text{max}})}, & \bar{\gamma} \geq \bar{\gamma}_{n,\text{th}} \end{cases}$$
Numerical Results:

\[ N_p = 1080 \quad P_{\text{loss}} = 0.01 \quad m = 1 \quad N_{p,\text{max}} \quad \text{varying from 0 - 3} \]

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

$N_p = 1080 \quad P_{loss} = 0.01 \quad m$ varying from 1-4

$N_p^{\text{max}} = 0$

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
Consider Nakagami-m fading channel with \( m = 1 \)
Packet error probability after \( N_r^{\text{max}} \) retransmissions:

\[
P_{n, \text{ARQ}} = q_n^{N_r^{\text{max}} + 1}.
\]

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

- \( P_{\text{loss}} \) requirement is satisfied: \( \bar{\gamma} \geq \bar{\gamma}_{n, \text{th}} \)
- \( P_{\text{loss}} \) requirement is not satisfied: \( \bar{\gamma} < \bar{\gamma}_{n, \text{th}} \)