Adaptive Modulation and Coding

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Introduction

Adaptive Transmission System
Adaptive Techniques
Variable-rate Variable-power MQAM
General M-ary Modulations
Adaptive Techniques in Combined Fast and Slow Fading
Introduction (1)

Basic principle

- Feed channel estimation information back to the transmitter
  - Transmission scheme can be adapted relative to the channel characteristics
- Take advantage of favorable channel conditions to send at higher data rates or lower power
  - Increase average throughput, reduce required transmit power, or reduce average probability of bit error
- Maximization of average spectral efficiency while maintaining a given average or instantaneous bit error probability
- Field: MIMO channels, frequency-selective fading channels with equalization, OFDM, or CDMA, and cellular system
**Introduction (2)**

**Practical constraints**

*When adaptive modulation should be used?!
*

- Require a feedback path between the transmitter and receiver
- Use other means of mitigating the effects of fading when the channel is changing faster than it can be reliably estimated and fed back to the transmitter
- Hardware complexity
  - How often the transmitter can change its rate and/or power
- The quality of fixed-rate application with hard delay constraints (voice or video) may be significantly compromised.
  - The adaptive modulation should be optimized to minimize outage probability for a fixed data rate
Introduction

**Adaptive Transmission System**

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General M-ary Modulations

Adaptive Techniques in Combined Fast and Slow Fading
Consider the flat-fading channel model

Parameter

- $\sqrt{g[i]}$: stationary and ergodic time-varying channel gain
- $n[i]$: AWGN noise with power spectral density $N_0/2$
- $\bar{S}$: average transmit signal power
- $B = 1/T_S$: received signal bandwidth, where $T_S$ is symbol time
- $\bar{g}$: average channel gain
- $\gamma[i] = \bar{S}g[i]/(N_0B)$, $0 \leq \gamma[i] < \infty$
  - : instantaneous received SNR
- $\gamma = \bar{S}\bar{g}/(N_0B)$: expected value over all time
9.1 Adaptive Transmission System (2)

- Estimation of the power gain or received SNR at time $i$
- Common parameters to adapt
  - Data rate $R[i]$, transmit power $S[i]$, and coding parameter $C[i]$
  - For M-ary modulation
    - Data rate : $R[i] = B \log_2 M[i]$ bps
    - Spectral efficiency : $R[i]/B = \log_2 M[i]$ bps/Hz
  - The SNR estimate as
    - $\hat{\gamma}[i] = \tilde{S}\hat{g}[i]/(N_0 B)$ based on the power gain estimate $\hat{g}[i]$
  - The transmit power, the data rate of the modulation and the coding parameters are adapted relative to $\hat{\gamma}[i]$
    - $S(\hat{\gamma}[i]) = S[i]$
    - $R(\hat{\gamma}[i]) = R[i]$
    - $C(\hat{\gamma}[i]) = C[i]$
9.1 Adaptive Transmission System (3)

**System model**

- The rate of channel variation
  - How often the transmitter must adapt
  - Impact the estimation error

**Assumption:**
Feedback path does not introduce any errors

**Consideration:**
- Estimation error
- Delay
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9.2 Adaptive Techniques (1)

9.2.1 Variable-Rate Techniques

- Fixing the modulation and changing the symbol rate
  - Symbol rate variation is difficult to implement
- *Fixing the symbol rate of the modulation & using multiple modulation schemes or constellation size*
  - GSM system: 8PSK ~ GMSK
  - IS-136 TDMA cellular system: 4 ~ 16PSK
9.2 Adaptive Techniques (2)

9.2.2 Variable-Power Techniques

- The goal: maintain a fixed bit error probability or a constant received SNR
- Compensate for SNR variation due to fading
- Power adaptation for channel inversion

\[
\frac{S(\gamma)}{\bar{S}} = \frac{\sigma}{\gamma} \quad \text{where } \sigma \text{ equals constant received SNR}
\]

- Average power constraint \( \bar{S} \) implies

\[
\int \frac{S(\gamma)}{\bar{S}} p(\gamma) d\gamma = \int \frac{\sigma}{\gamma} p(\gamma) d\gamma = 1
\]

\[
\sigma = 1/E[1/\gamma] \quad \Rightarrow \quad E[1/\gamma] = \infty
\]

- Power adaptation with cutoff value \( \gamma_0 \)

\[
\frac{S(\gamma)}{\bar{S}} = \begin{cases} \frac{\sigma}{\gamma} & \gamma \geq \gamma_0 \\ 0 & \gamma < \gamma_0 \end{cases}
\]

\[
\sigma = 1/E_{\gamma_0}[1/\gamma] \quad \Rightarrow \quad E_{\gamma_0}[1/\gamma] \triangleq \int_{\gamma_0}^{\infty} \frac{1}{\gamma} p(\gamma) d\gamma
\]
9.2 Adaptive Techniques (3)

- **9.2.3 Variable Error Probability**
  - The instantaneous BER can be adapted subject to an average BER constraint
  - Error probability is typically adapted along with some other form of adaptation

- **9.2.4 Variable-Coding Techniques**
  - Provide different amounts of coding gain to the transmitted bits
  - Ex.) Rate-compatible punctured convolutional (RCPC) codes

- **9.2.5 Hybrid Techniques**
  - Joint optimization of the different techniques
  - Rate-power adaptation for maximizing spectral efficiency
  - Adaptive modulation and coding
    - Ex.) EGPRS standard for data transmission in GSM cellular system
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Adaptive Techniques
**Variable-rate Variable-power MQAM**
General M-ary Modulations
Adaptive Techniques in Combined Fast and Slow Fading
9.3 Variable-Rate Variable-Power MQAM (1)

**Concept**
- The rate and power of MQAM is varied to maximize spectral efficiency while meeting a given instantaneous $\bar{P}_b$ target.

**Basic parameter**
- Fixed symbol time: $T_s$
- Given $\bar{S}$, $N_0$, $\gamma = \bar{S}g / N_0B$, and $\bar{\gamma} = \bar{S} / N_0B$

\[
\frac{E_S}{N_0} = \frac{ST_S}{N_0} = \bar{\gamma}
\]

- Spectral efficiency for fixed $M$ (the number of bits per symbol)

\[
\frac{R}{B} = \log_2 M
\]
9.3 Variable-Rate Variable-Power MQAM (2)

9.3.1 Error Probability Bounds

In [20], BER for an AWGN channel with MQAM modulation

\[ P_b \leq 2e^{-1.5\gamma/(M-1)} \]

Tighter bound for \( M \geq 4 \) & \( 0 \leq \gamma \leq 30 \) dB

\[ P_b \leq 2e^{-1.5\gamma/(M-1)} \]

Use these bounds and obtain \( M \) as a function of the target \( P_b \) and the power adaptation policy

Ex.9.3) Find the required average SNR to achieve target BER

Target BER for non-adaptive BPSK modulation Rayleigh fading: \( \overline{P_b} = 10^{-3} \)

Solution)

From pp.185 \( \overline{P_b} = \frac{1}{2} \left[ 1 - \sqrt{\frac{\gamma_b}{1 + \gamma_b}} \right] \approx \frac{1}{4\overline{\gamma}} \Rightarrow \overline{\gamma} = \frac{1}{4\overline{P_b}} = 250 = 24 \text{ dB} \)

Spectral efficiency

\[ R/B = \log_2 2 = 1 \text{ bps/Hz} \]

Adaptive modulation provides a much higher spectral efficiency
9.3 Variable-Rate Variable-Power MQAM (3)

9.3.2 Adaptive Rate and Power Schemes

- $P_b$ bound

\[ P_b(\gamma) \leq 0.2 \exp \left[ -1.5\gamma \frac{S(\gamma)}{M - 1} \right] \]

- Rearrangement

\[ M(\gamma) = 1 + \frac{1.5\gamma}{-\ln(5P_b)} \frac{S(\gamma)}{S} = 1 + \gamma K \frac{S(\gamma)}{S} \]

where \( K = \frac{1.5}{-\ln(5P_b)} < 1 \)

- Maximization of spectral efficiency

\[ E[\log_2 M(\gamma)] = \int \log_2 \left( 1 + \gamma K \frac{S(\gamma)}{S} \right) p(\gamma) d\gamma \]

\[ \frac{S(\gamma)}{S} = \begin{cases} \frac{1}{\gamma_0} - \frac{1}{\gamma K} & \gamma \geq \gamma_0/K \\ 0 & \gamma < \gamma_0/K \end{cases} \]

Fig. 4.5: Optimal Power allocation

Received SNR \( \frac{\gamma S(\gamma)}{S} \)

where \( \frac{\gamma_0}{K} \) is the optimized cutoff fade depth below which the channel is not used.
9.3 Variable-Rate Variable-Power MQAM (4)

- Instantaneous rate
  - Define $\gamma_K = \gamma_0/K$

  \[ \log_2 M(\gamma) = \log_2 \left( \frac{\gamma}{\gamma_K} \right) \]

- Average spectral efficiency

  \[ \frac{R}{B} = \int_{\gamma_K}^{\infty} \log_2 \left( \frac{\gamma}{\gamma_K} \right) p(\gamma) d\gamma \]

- Compared with the power adaptation and average spectral efficient in chapter 4
  - Same the power and rate adaptation
  - Same average spectral efficiency, with an effective power loss of $K$ for adaptive MQAM
9.3 Variable-Rate Variable-Power MQAM (5)

Plot the average spectral efficiency of adaptive MQAM

Figures

Figure 9.2: Average Spectral Efficiency in Log-normal Shadowing ($\sigma = 8$dB)

Figure 9.3: Average Spectral Efficiency in Rayleigh Fading
9.3 Variable-Rate Variable-Power MQAM (6)

9.3.3 Channel Inversion with Fixed Rate

- Transmit a single fixed-rate MQAM modulation that achieves the target BER
- M is obtained by substituting the channel inversion power adaptation (spectral efficiency : \( R/B = M \))

\[
\frac{R}{B} = \log_2 \left( 1 + \frac{-1.5}{\ln(5P_b)E[1/\gamma]} \right)
\]

- \( M < 4, \ln(5P_b) \rightarrow \ln(0.5P_b) \)

- Maximum value relative to the cutoff level

\[
\frac{R}{B} = \max_{\gamma_0} \log_2 \left( 1 + \frac{-1.5}{\ln(5P_b)E[1/\gamma]} \right) p(\gamma > \gamma_0) \]

\text{with truncated channel inversion}
In practice

- Non-integer values of $M$ is possible $\Rightarrow$ complexity $\uparrow$
- It is difficult to continually adapt in fast fading environment.

Consider restricting the constellation size to just a handful of values.

Figure 9.4: Spectral Efficiency with Different Power Adaptation Policies (Rayleigh Fading)
9.3.4 Discrete Rate Adaptation

Continuous-power discrete-rate adaptation scheme

Square constellation size: \( M_j = 2^{2(j-1)}, j = 2, \ldots, N-1 \)

- The choice of constellation depends on the fade level \( \gamma \) over that symbol time.
- Divide the range of \( \gamma \) into \( N \) fading regions: \( R_j = [\gamma_{j-1}, \gamma_j), j = 0, \ldots, N-1 \)
- Suboptimal technique to determine the boundaries
  - Closed-form solution

\[
\log_2 M(\gamma) = \log_2 \left( \frac{\gamma}{\gamma_*} \right) \over M(\gamma) = \frac{\gamma}{\gamma_*} \quad \text{where} \quad \gamma_* > 0 \quad \text{is optimized to maximize spectral efficiency}
\]

- Power adaptation policy

\[
\frac{S(\gamma)}{S} = \begin{cases} 
(M_j - 1) \frac{1}{\gamma K} & M_j < \frac{\gamma}{\gamma_*} \leq M_{j+1} \\
0 & M_j = 0
\end{cases}
\]

\[
\frac{E_S(j)}{N_0} = \frac{\gamma S(\gamma)}{S} = \frac{M_j - 1}{K}
\]
### Table 9.1: Rate and Power Adaptation for 5 Regions

<table>
<thead>
<tr>
<th>Region ((j))</th>
<th>(\gamma) Range</th>
<th>(M_j)</th>
<th>(S_j(\gamma)/\bar{S})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>(0 \leq \gamma/\gamma_k^* &lt; 2)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>(2 \leq \gamma/\gamma_k^* &lt; 4)</td>
<td>2</td>
<td>(\frac{1}{K\gamma})</td>
</tr>
<tr>
<td>2</td>
<td>(4 \leq \gamma/\gamma_k^* &lt; 16)</td>
<td>4</td>
<td>(\frac{3}{K\gamma})</td>
</tr>
<tr>
<td>3</td>
<td>(16 \leq \gamma/\gamma_k^* &lt; 64)</td>
<td>16</td>
<td>(\frac{15}{K\gamma})</td>
</tr>
<tr>
<td>4</td>
<td>(64 \leq \gamma/\gamma_k^* &lt; \infty)</td>
<td>64</td>
<td>(\frac{63}{K\gamma})</td>
</tr>
</tbody>
</table>

#### Spectral efficiency

\[
R = \frac{N-1}{B} \sum_{j=1}^{N-1} \log_2 (M_j) p(M_j \leq \gamma/\gamma_k^* < M_{j+1})
\]

#### Figure 9.6: Discrete-Rate Efficiency in Rayleigh Fading
9.3 Variable-Rate Variable-Power MQAM (10)

- Discrete-Power Discrete-Rate Adaptive MQAM
  - Spectral efficiency
    - With total channel inversion
      
      \[
      \frac{R}{B} = \left[ \log_2 \left( 1 + \frac{-1.5}{\ln(5P_b)[1/\gamma]} \right) \right]_M
      \]
    - Possible constellation set \( M = \{0, \ldots, M_{N-1}\} \)
    - With truncated channel inversion
      
      \[
      \frac{R}{B} = \max_{\gamma_0} \left[ \log_2 \left( 1 + \frac{-1.5}{\ln(5P_b)[1/\gamma]} \right) \right]_M P(\gamma > \gamma_0)
      \]

- Figure 9.8:
  Efficiency in Rayleigh Fading
9.3 Variable-Rate Variable-Power MQAM (11)

9.3.5 Average Fade Region Duration

- The choice of the number of regions
  - Rate of channel variation
  - # of available constellation size

- How long the SNR $\gamma$ remains within a particular fading region $R_j$?

- Parameters
  - $\bar{\tau}_j$ : average time duration (average fade region duration : AFRD)
  - $\{\gamma : A_j \leq \gamma < A_{j+1}\}$ where $A_j = \gamma_k M_j$

- Assumption: fading is approximated as a discrete-time Markov process

\[
\bar{\tau}_j = \frac{T_s}{p_{j,j+1} + p_{j,j-1}} = \frac{\pi_j}{N_{j+1} + N_j}
\]

- $\pi_j = p(A_j \leq \gamma < A_{j+1})$: steady-state distribution

\[
M_j \leq \frac{\gamma}{\gamma_k} < M_{j+1}
\]
9.3 Variable-Rate Variable-Power MQAM (12)

- Transition probability between regions
  \[ p_{j,j+1} = \frac{N_{j+1}T_s}{\pi_j}, \quad p_{j,j-1} = \frac{N_jT_s}{\pi_j}, \quad p_{j,j} = 1 - p_{j,j+1} - p_{j,j-1} \]

- Level crossing rate (in Rayleigh fading)
  \[ N_j = \sqrt{\frac{2\pi A_j}{\bar{\gamma}}} f_D e^{-A_j/\bar{\gamma}} \]
  where \( f_D = c/\lambda \) : Doppler frequency

- Computation corresponding to another Doppler frequency
  \[ \bar{\tau}_j = \frac{f_D}{\hat{f}_D} \bar{\tau}_j \]

**Table 9.2**

<table>
<thead>
<tr>
<th>Region ( (j) )</th>
<th>( \bar{\gamma} = 10\text{dB} )</th>
<th>( \bar{\gamma} = 20\text{dB} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.23ms</td>
<td>.737ms</td>
</tr>
<tr>
<td>1</td>
<td>.830ms</td>
<td>.301ms</td>
</tr>
<tr>
<td>2</td>
<td>3.00ms</td>
<td>1.06ms</td>
</tr>
<tr>
<td>3</td>
<td>2.83ms</td>
<td>2.28ms</td>
</tr>
<tr>
<td>4</td>
<td>1.43ms</td>
<td>3.84ms</td>
</tr>
</tbody>
</table>

Even at high velocities, for symbol rates of the discrete-rate discrete-power will maintain the same constellation and transmit power over tens to hundreds of symbols.
9.3 Variable-Rate Variable-Power MQAM (13)

9.3.6 Exact versus Approximate

More exact analytical expression for the average BER

From (6.24), the BER of MQAM with gray coding

\[ P_b \approx \frac{2(\sqrt{M-1})}{\sqrt{M} \log_2 M} Q\left( \sqrt[3]{\frac{3\gamma}{M-1}} \right) \]

\[ \gamma = \frac{E_s(j)}{N_0} = \frac{M_j - 1}{K} \]

\[ P_b = \sum_{j=1}^{N-1} \frac{2(\sqrt{M_j - 1})}{\sqrt{M_j} \log_2 M_j} Q\left( \sqrt[3]{\frac{3(M_j - 1)}{K(M_j - 1)}} \right) \int_{\gamma_k^{M_j}}^{\gamma_k^{M_{j-1}}} p(\gamma) d\gamma \]

Figure 9.10:
BER for Rayleigh fading
(5 Region)
9.3.7 Channel Estimation Error and Delay

Channel estimation error

BER upper bounds based on the channel estimation

\[ P_b(\gamma, \hat{\gamma}) \leq 0.2 \exp \left[ -1.5 \frac{\gamma}{S(\hat{\gamma})} \right] \left( \frac{S(\hat{\gamma})}{\overline{S}} \right) = 0.2[5P_b]^{\epsilon/\gamma} \]

where \( \epsilon = \hat{\gamma} / \gamma \)

Given the distribution

\[ \overline{P}_b \leq \int_0^\infty 0.2[5P_b]^{\epsilon/\gamma} p(\epsilon) d\epsilon \]

Figure 9.11:

Effect of Estimation Error on BER
9.3 Variable-Rate Variable-Power MQAM (15)

Delay $i_d$ of the estimation and feedback path is nonzero

Delayed version of the channel estimate

$$P_b(\gamma[i], \hat{\gamma}[i]) \leq 0.2 \exp \left[ -1.5 \gamma[i] \frac{S(\hat{\gamma}[i])}{M(\hat{\gamma}[i]) - 1} \frac{1}{S} \right] = 2[5P_b]^{\gamma[i]/\gamma[i-i_d]}$$

Define $\xi[i,i_d] = \gamma[i]/\gamma[i-i_d]$

$$P_b[i_d] = \int_{0}^{\infty} \int_{0}^{\infty} \left[ 2[5P_b]^{\xi} p_{i_d}(\xi, \gamma)d\xi \right] p(\gamma)d\gamma$$

*Figure 9.12:*

**Effect of Normalized Delay on BER**
9.3 Variable-Rate Variable-Power MQAM (16)

9.3.8 Adaptive Coded Modulation

- BER approximation with coding gain $G_c$
  \[ P_b \leq 2e^{-1.57G_c/(M-1)} \]

- Rearrangement
  \[ M(\gamma) = 1 + \frac{1.5\gamma G_c}{-\ln(5P_b)} \frac{S(\gamma)}{S} \]

- Optimal power adaptation policy
  \[ \frac{S(\gamma)}{S} = \begin{cases} 
  \frac{1}{\gamma_0} - \frac{1}{\gamma K_c} & \gamma \geq \gamma_0/K_c \\
  0 & \gamma < \gamma_0/K_c 
\end{cases} \]
  where $K_c = KG_c$

- Adaptive data rate
  \[ M(\gamma) = M(\gamma/K_c) \]

- Spectral efficiency
  \[ \frac{R}{B} = \int_{\gamma_{K_c}}^{\infty} \log_2 \left( \frac{\gamma}{\gamma_{K_c}} \right) p(\gamma) d\gamma \]
  where $\gamma_{K_c} = \gamma_0/K_c$
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9.4 General M-ary Modulations (1)

9.4.1 Continuous Rate Adaptation

Simplified optimization (p.15)

\[ P_b(\gamma) \approx c_1 \exp \left[ -c_2 \frac{S(\gamma)}{\bar{S}} \right] \frac{1}{(2^{c_3 k(\gamma)} - c_4)} \]

where \( c_4 \) : real constant \( c_1, c_2, c_3 \) : positive fixed constant

\[ k(\gamma) = \log_2 M(\gamma) = \begin{cases} \frac{1}{c_3} \log \left[ c_4 - \frac{c_2 \gamma S(\gamma)}{\ln(P_b/c_1)} \right] & S(\gamma) \geq 0, k(\gamma) \geq 0 \\ 0 & \text{else} \end{cases} \]

For maximization of the power and rate adaptation, create the Lagrangian

\[ J(S(\gamma)) = \int_0^\infty k(\gamma)p(\gamma)d\gamma + \lambda \left[ \int_0^\infty S(\gamma)p(\gamma)d\gamma - \bar{S} \right] \]

\[ \frac{\partial J}{\partial S(\gamma)} = 0, \ S(\gamma) \geq 0, \ k(\gamma) \geq 0 \]
Simplified optimal power adaptation

\[
\frac{S(\gamma)}{S} = \left\{ \begin{array}{ll}
\frac{\mu - \frac{1}{\gamma K}}{\gamma K} & S(\gamma) \geq 0, \ k(\gamma) \geq 0 \\
0 & \text{else}
\end{array} \right.
\]

where \( K = -\frac{c_2}{c_4 \ln(P_b/c_1)} \)
\( \mu \) : constant

From (6.18), approximated BER for MPSK

\[
P_b \approx \frac{2}{\log_2 M} Q\left(\sqrt{2\gamma \sin(\pi / M)}\right)
\]
Not easily invertible

Consider the 3 bounds for \( k(\gamma) > 2 \)

- **Bound 1**: \( c_1 = .05, c_2 = 6, c_3 = 1.9, & c_4 = 1 \)
- **Bound 2**: \( c_1 = .2, c_2 = 7, c_3 = 1.9, & c_4 = -1 \)
- **Bound 3**: \( c_1 = .25, c_2 = 8, c_3 = 1.94, & c_4 = 0 \)

**Bound 1**
- For \( P_b > .05, K, \mu, S(\gamma), k(\gamma) \) : positive

**water-filling**
9.4 General M-ary Modulations (3)

- **Bound 2**
  - For $P_b < .2$, $K$: negative & $\mu$, $S(\gamma)$, $k(\gamma)$: positive
  - *inverse water-filling*

- **Bound 3**
  - For $P_b < .25$, $K = \infty$
  - *on-off power transmission*

**Figure 9.15:**

Power Adaptation for MPSK BER Bounds
(Rayleigh fading)

$P_b = 10^{-3}$, $\gamma = 30\text{dB}$
9.4 General M-ary Modulations (4)

9.4.3 Average BER Target

- Adapt the instantaneous $P_b(\gamma)$
- Average probability of error for adaptive modulation

$$\bar{P}_b = \frac{E[\text{number of bits in error per transmission}]}{E[\text{number of bits per transmission}]}$$

- Optimal continuous rate, power, and BER adaptation
  
  Define
  $$f(k(\gamma)) = 2^{c_3k(\gamma)} - c_4$$

  BER adaptation
  $$P_b(\gamma) = \frac{\lambda_2Sf(k(\gamma))}{\lambda_1c_2k(\gamma)}$$

  Power adaptation
  $$\frac{S(\gamma)}{\bar{S}} = \max\left[\frac{f(k(\gamma))}{\partial f(k(\gamma))/\partial k(\gamma)} \lambda_2 \bar{S}(\lambda_1\bar{P}_b - 1) - \frac{f(k(\gamma))^2}{c_2\gamma \partial f(k(\gamma))k(\gamma)/\partial k(\gamma)}, 0\right]$$

  where $\lambda_1$ and $\lambda_2$ must be found through a numerical search such that the average power constraint and average BER constraint are satisfied.
9.4 General M-ary Modulations (5)

Figure 9.16:
Spectral Efficiency for Different Adaptation Constraints
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General M-ary Modulations

Adaptive Techniques in Combined Fast and Slow Fading
9.5 Adaptive Techniques in Combined Fast and Slow Fading

- Composite fading channels consisting of both fast and slow fading
  - Distribution of the instantaneous SNR $\gamma$
    - $P(\gamma/\bar{\gamma})$ where $\bar{\gamma}$: short-term average over the fast fading
  - Short-term average varies slowly due to shadowing
  - Average SNR relative to distribution is $\bar{\gamma}$.
- Transmitter does not adapt to the fast fading
  - Require a target average probability of bit error averaged over the fast fading for a fixed value
- Short term average BER $\Rightarrow$ Tight BER bound $\Rightarrow$ Adaptive rate invert
  - maximize spectral efficiency
- For $c_4 > 0$, *water-filling*: optimal power adaptation in composite fading channel