EE359 – Lecture 14 Outline

- Announcements
  - Graded MTs ready for pickup
  - Bonus lecture 11/30 5:15-7:15 in 204 Packard
- Midterm Postmortem and Grade Distribution
- Practical Issues in Adaptive MQAM
  - Update rate
  - Estimation error and delay
- Introduction to MIMO
- MIMO channel capacity

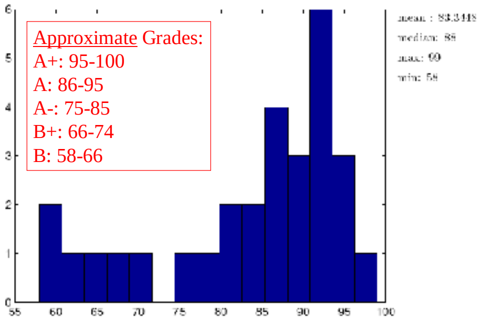
Midterm Postmortem

- Grade distribution typical
- Common Mistakes
  - Prob 1(d): For outage, target SNR must be based on P_b in AWGN and not average P_b in fading
  - Prob 2(a)(ii): Instantaneous rate should not be weighted by state probability
  - 2(c): Transmit power is fixed , so formula same as capacity w/ RX CSI only (not inversion)

$$C=\int_0^\infty B\log_2\left(1+\frac{\gamma P(\gamma)}{\bar{P}}\right)p(\gamma)d\gamma=\int_0^\infty B\log_2(1+\gamma)p(\gamma)d\gamma$$

  - 2(d): Constellation size M for all channel states is not fixed; should adapt M to SNR.

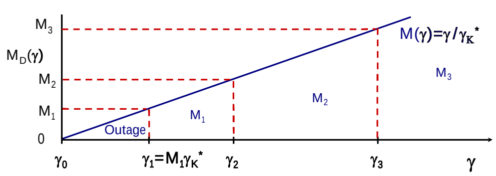
Midterm Grade Distribution



Review of Last Lecture

- Introduction to adaptive modulation
- Variable-rate variable-power MQAM
  - Optimal power adaptation is water-filling
  - Optimal rate adaptation is $R/B=\log(\gamma/\gamma_K)$
- **Finite Constellation Sets**
  - **Use heuristic to assign rates to regions**
  - **Channel inversion power control in each region**

Constellation Restriction



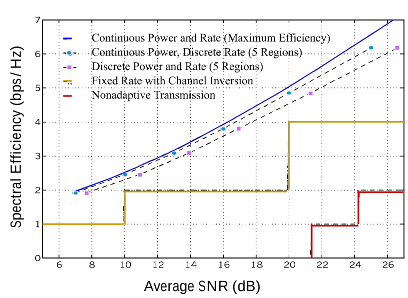
- **Power adaptation:**

$$\frac{P_j(\gamma)}{P}=\begin{cases}(M_j-1)/(\gamma K) & \gamma_j\le\gamma<\gamma_{j+1},\ j>0\\ 0 & \gamma<\gamma_1\end{cases}$$

- **Average rate:**

$$\frac{R}{B}=\sum_{j=1}^{N}\log_2 M_j\, p(\gamma_j\le\gamma<\gamma_{j+1})$$

Efficiency in Rayleigh Fading



Practical Constraints

- Constellation updates: fade region duration

$$\bar{\tau}_j = \frac{\pi_j}{N_{j+1}+N_j} > T >> T_M$$

$\bar{\tau}_j$ = AFRD
T_M = delay spread
N_j = level crossing rate at min fade in region
N_{j+1} = level crossing rate at max fade in region

- Error floor from estimation error
  - Estimation error at RX can cause error in absence of noise (e.g. for MQAM)
  - Estimation error at TX causes mismatch of adaptive power and rate to actual channel
- Error floor from delay: let $\rho(t,\tau)=\gamma(t-\tau)/\gamma(t)$.
  - Feedback delay causes mismatch of adaptive power and rate to actual channel

Detailed Formulas

- Error floor from estimation error ($\hat{\gamma}\neq\gamma$)

$$\bar{P}_b = \int_0^\infty \int_{\gamma_K}^\infty .2[5BER_{\text{target}}]^{\gamma/\hat{\gamma}}\, p(\gamma,\hat{\gamma})\, d\hat{\gamma}\, d\gamma$$

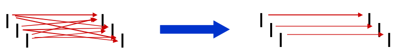
  - Joint distribution $p(\hat{\gamma},\gamma)$ depends on estimation: hard to obtain. For PSAM the envelope is bi-variate Rayleigh
- Error floor from delay: let $\xi=\gamma[i]/\gamma[i-i_d]$.

$$\bar{P}_b = \int_0^\infty \int_0^\infty .2[5BER_{\text{target}}]^{\xi}\, p(\xi\,|\,\gamma)\, p(\gamma)\, d\xi\, d\gamma$$

  - $p(\xi|\gamma)$ known for Nakagami fading

Multiple Input Multiple Output (MIMO)Systems

- MIMO systems have multiple (r) transmit and receiver antennas



- With perfect channel estimates at TX and RX, decomposes into r independent channels
  - R_H-fold capacity increase over SISO system
  - Demodulation complexity reduction
  - Can also use antennas for diversity (beamforming)
  - Leads to capacity versus diversity tradeoff in MIMO

Capacity of MIMO Systems

- Depends on what is known at TX and RX and if channel is static or fading
- For static channel with perfect channel knowledge at TX and RX, waterfilling over space is optimal power allocation:
  - Similar idea in fading, based on short-term or long-term power constraint
- Without channel knowledge, capacity metric is based on an outage probability

Main Points

- Restricting constellation to a finite set has negligible impact on adaptive MQAM
- Adaptive MQAM need not change more than every 10-100 symbol times.
- Estimation error and delay lead to irreducible error floors in adaptive MQAM
- Multiple antennas at both TX and RX greatly enhance capacity and reduce complexity.
  - Alternatively, can be used for diversity gain