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

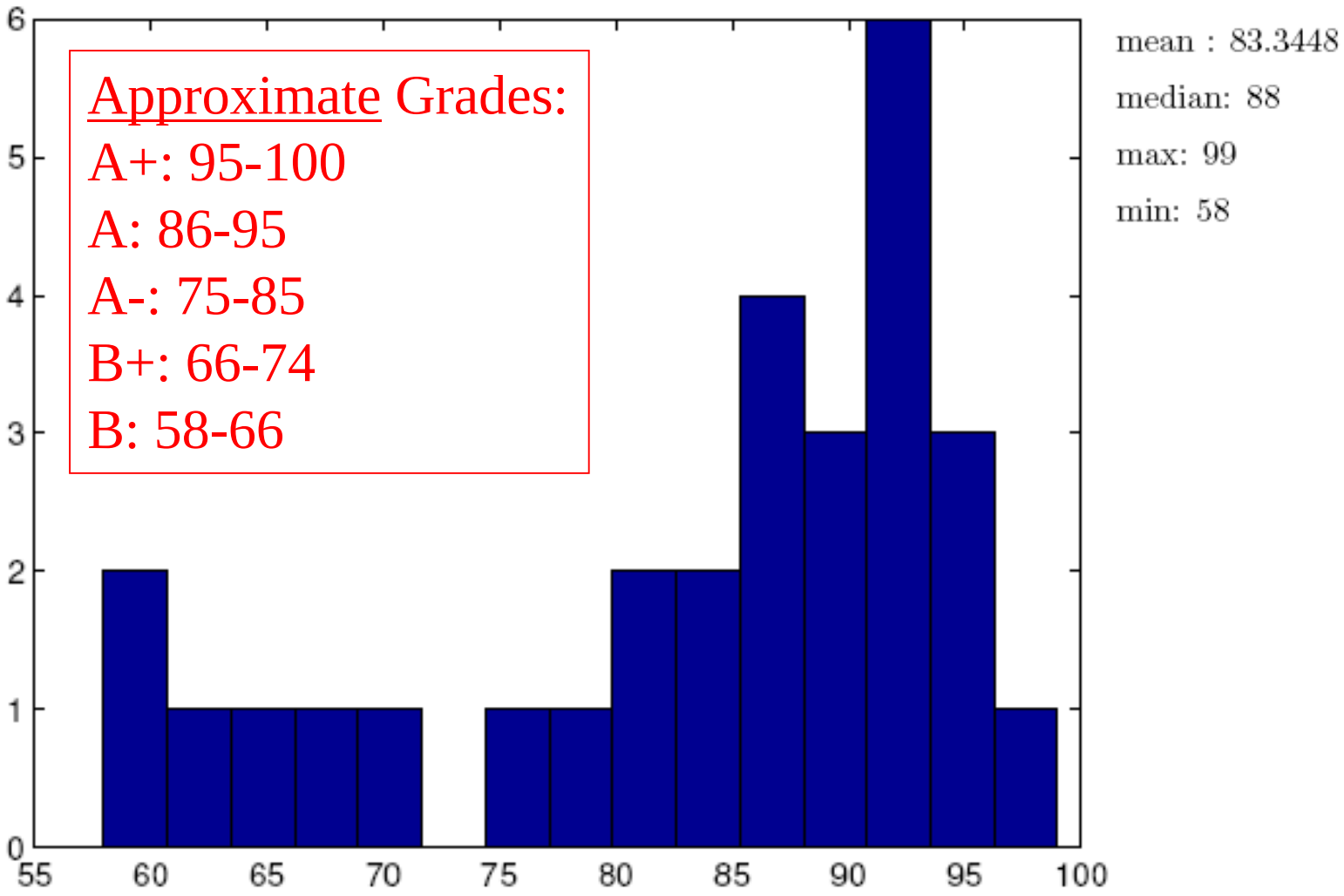
Midterm Postmortem

- 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)

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

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

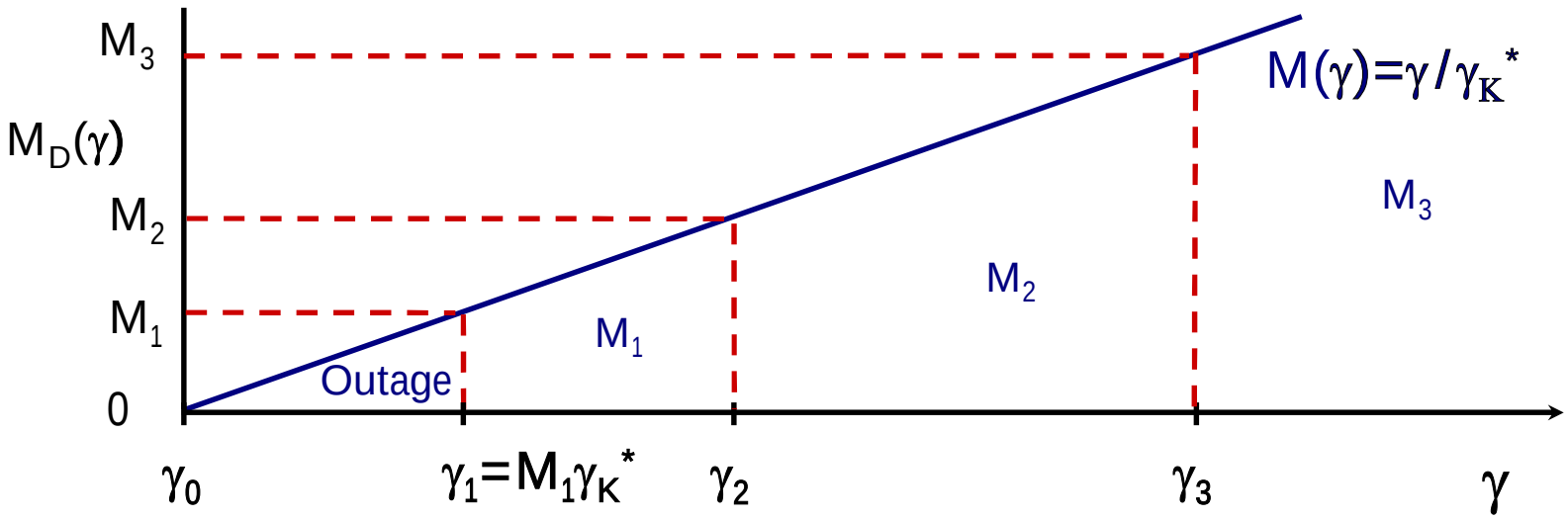
Midterm Grade Distribution



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



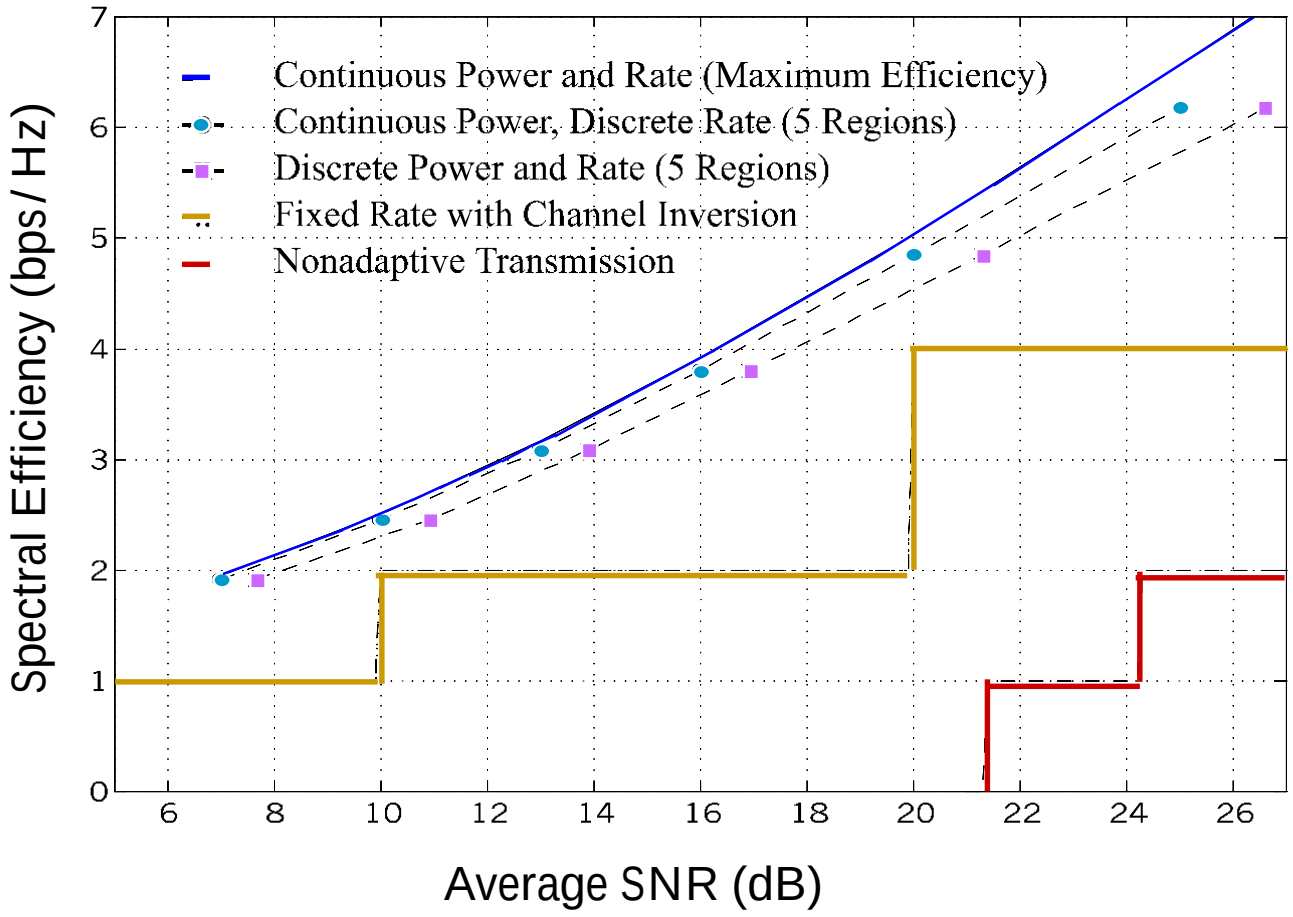
- Power adaptation:

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

- 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

$$\overline{\tau_j} = \frac{\pi_j}{N_{j+1} + N_j} > T >> T_M$$

$\overline{\tau_j}$ = 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 ($\hat{\gamma} \neq \gamma$)

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

  - Joint distribution $p(\hat{\gamma},\gamma)$ depends on estimation: hard to obtain. For PSAM the envelope is bi-variate Rayleigh

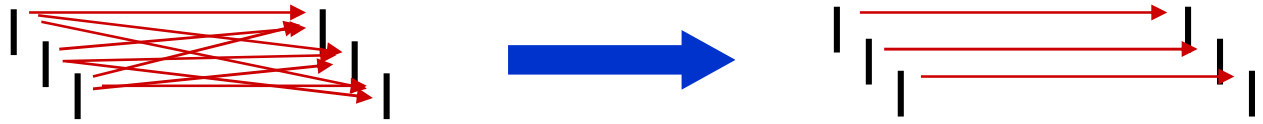
- Error floor from delay: let $\xi = \gamma[i]/\gamma[i-i_d]$.

$$\overline{P_b} = \int_0^{\infty} \int_0^{\infty} .2[5BER_{\text{target}}]^{\xi} \, p(\xi \mid \gamma) \, p(\gamma) d\xi d\gamma$$

  - $p(\xi|\gamma)$ 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