ECE5984

Orthogonal Frequency Division Multiplexing and Related Technologies

Fall 2007

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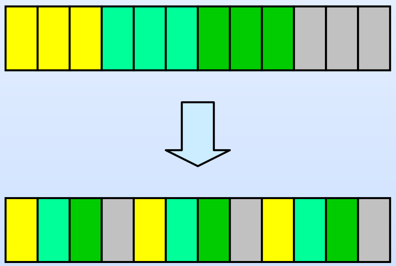
Adaptive Modulation in OFDM

http://www.ccit.aast.edu/public/VT/Term4/

Bit interleaving

Transmitter

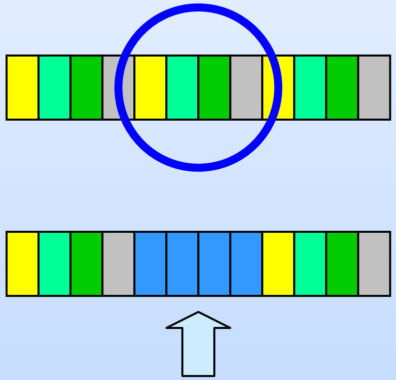
Bits are interleaved ...



... and will be de-interleaved in the receiver

Channel

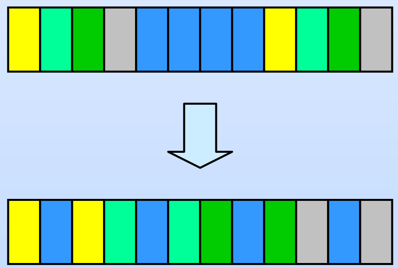
Fading affects many adjacent bits



Bit errors in the receiver

Receiver

After de-interleaving of bits, bit errors are spread!



(better for FEC)

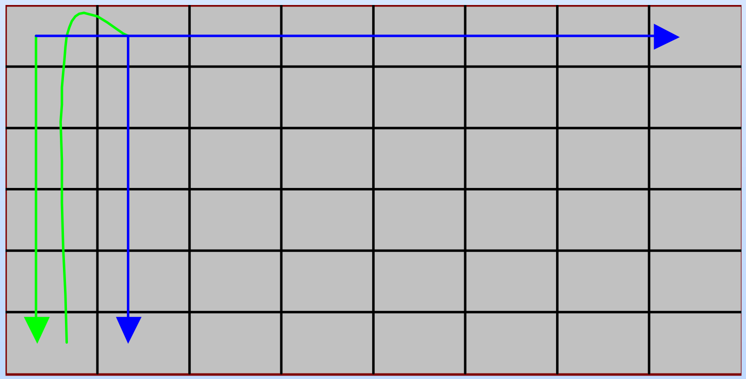
Interleaving

- **Most codes are designed for AWGN channel. Performance rapidly degrades in frequency selective channels with correlated channels.**
- **Scatter error bursts**
- **Can be done in time and in frequency domains**

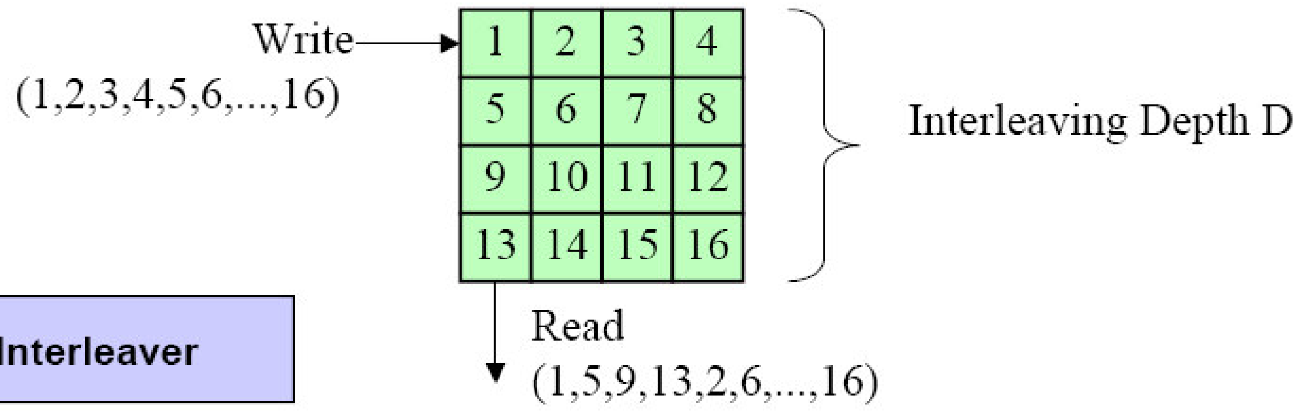
Interleaving basically a matrix which you write data in columns and read in rows

6x8 block interleaver shown

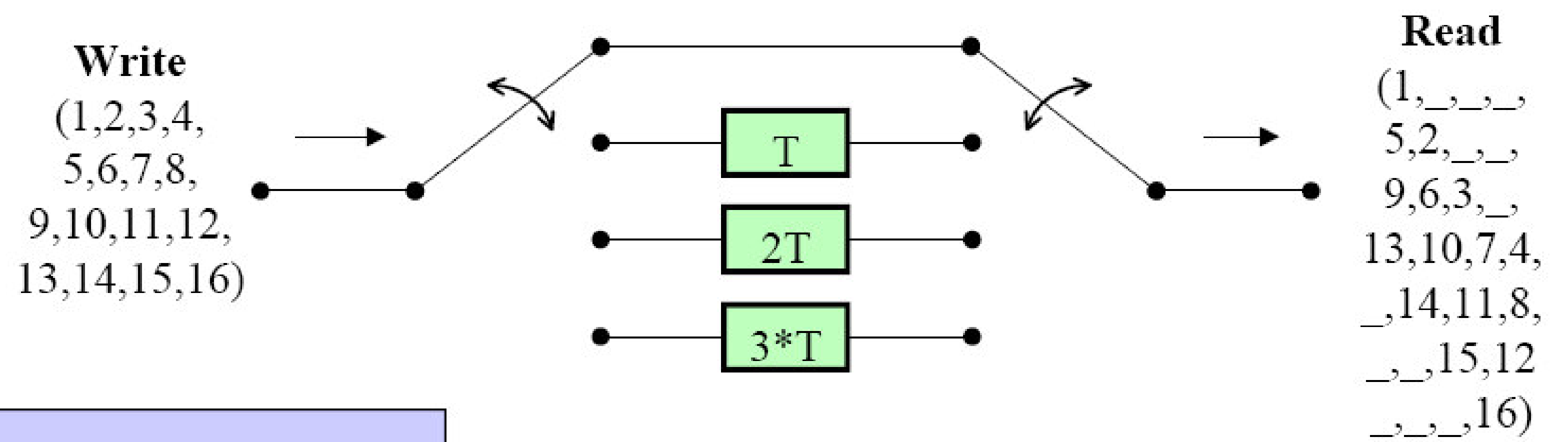
Has interleaving depth 48



Interleaving (1)



Block Interleaver



Convolutional Interleaver

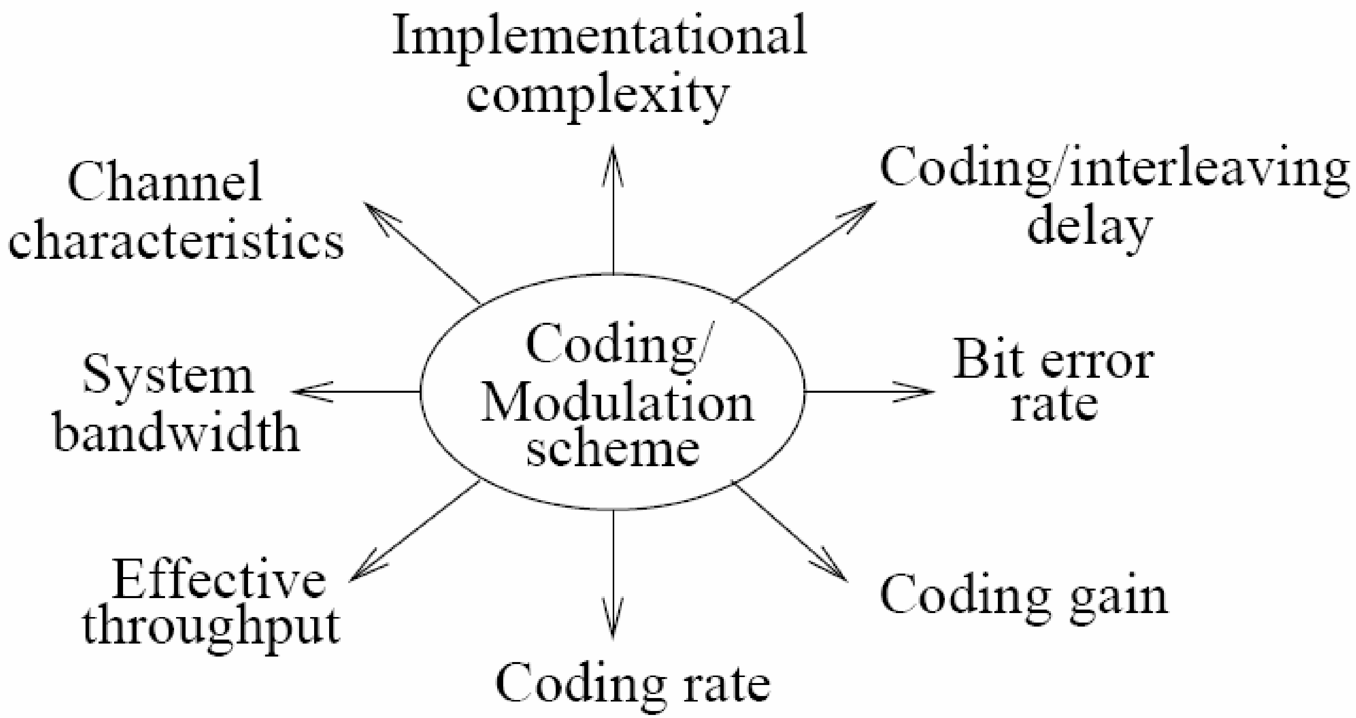
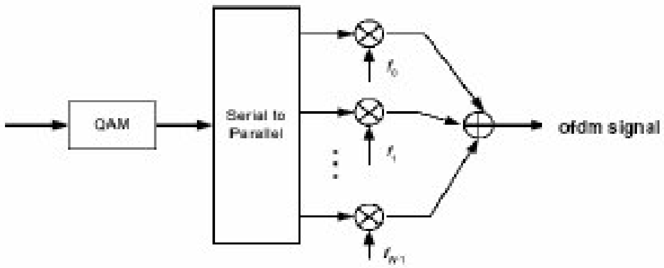


Figure 2: Factors affecting the design of channel coding, modulation and transceiver

Homework

Due date: Tuesday 25-9-2007

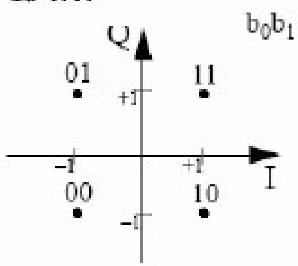
- Derive expression for OFDM-signal
- Use 4 subchannels and 4QAM



OFDM transmitter

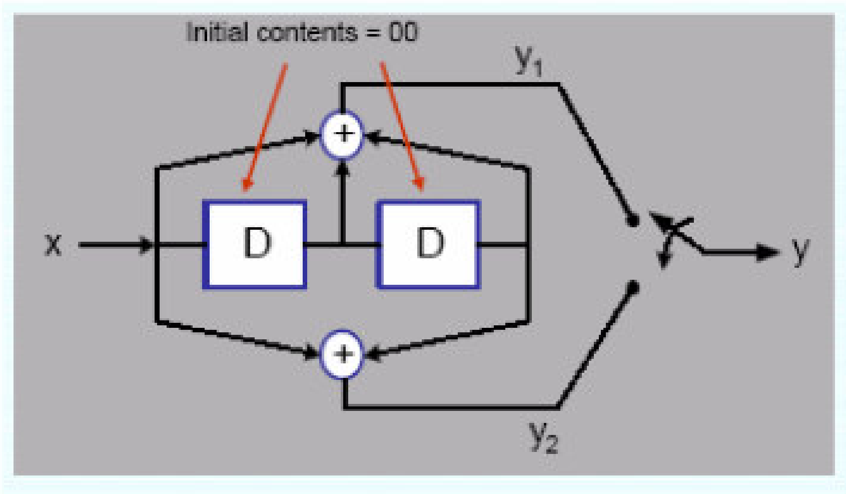
- Input data sequence:
  11 01 00 10
- Subcarrier frequencies are:
  $-2f_c$ $-1f_c$ $1f_c$ $2f_c$

4QAM



- Please use Viterbi algorithm to decode the received sequence:

  Z=[11 10 10 10 01]



Please draw the trellis and state diagram

Syllabus

- **Wireless channels characteristics** (7.5%) **1**
- **OFDM Basics** (10%) **1**
- **Modulation and Coding** (10%) **2**
  - Linear and nonlinear modulation
  - Interleaving and channel coding
  - Adaptive modulation,Optimal bit and power allocation

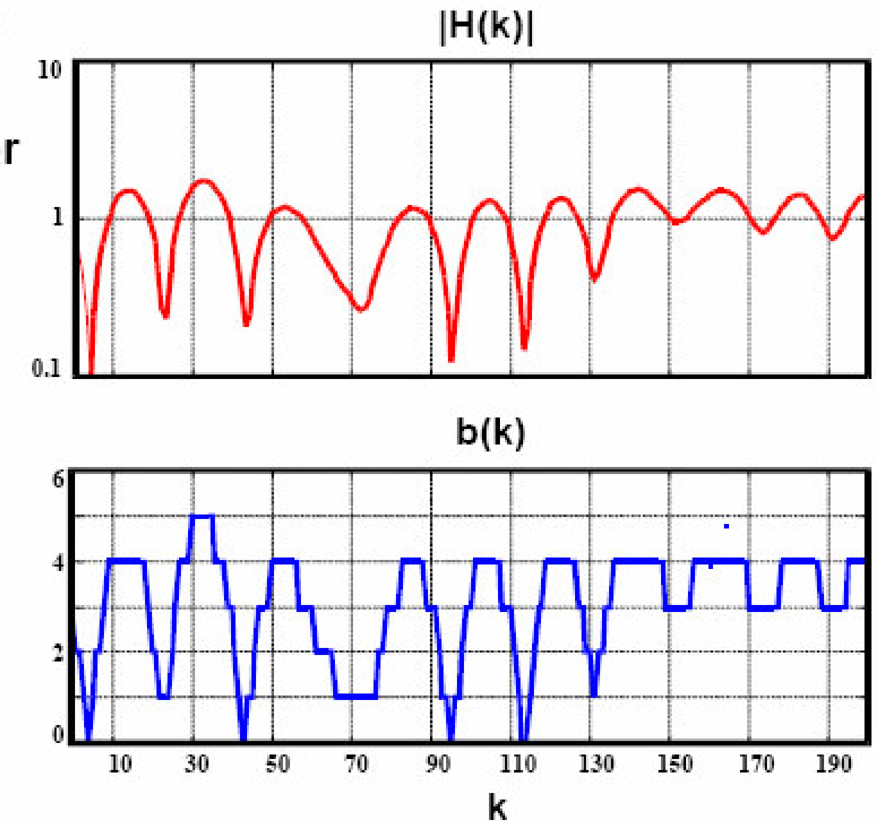
Concept Behind Adaptive Modulation

- **The bit error probability of different OFDM subcarriers in a dispersive channels depends on the frequency domain channel transfer function.**
- **The overall BER can be improved if the deep faded subcarriers are identified and excluded from transmission**
  - Degradation in system throughput
- **This degradation can be avoided using adaptive modulation techniques**
  - Coding rate can also be adapted
- **Adaptation is done based on the transmitter's perception to the changes in the channel conditions in the forthcoming time slot**
  - Channel estimation is needed
  - Doppler problem : fast fading and slowly fading

Adaptive Modulation (Bit Loading)

OFDM gives the opportunity to use:

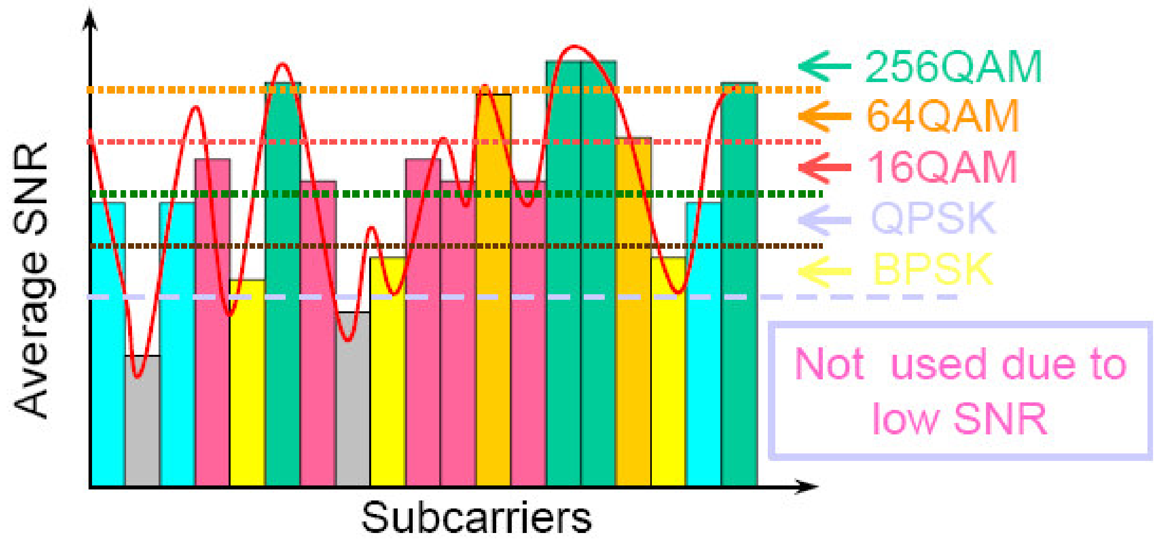
- different modulation schemes for each subchannel
- different power for each subchannel



Adaptive Modulation

Adaptation to the channel transfer function using subchannel specific modulation schemes and power

Adaptive Modulation (Bit Loading)



Algorithms: Chow, Cioffi and Bingham: capacity maximization

Fischer: Error probability minimization

Grünheid: simple blockwise loading algorithm

Hughes-Hartogs: sets target rate R, intensive searching

Steps for Adaptation

- **Step one:**
  - Channel quality estimation. (better in slowly fading)
    - Open loop (reciprocal of the transfer function, eg: TDD)
    - Closed loop (side information, eg: FDD)
- **Step two:**
  - Choice of the appropriate parameters for the next transmission
    - Modulation and coding according to SNR
- **Step three:**
  - Signaling or blind detection of the employed parameters at the receiver side

Goal of Adaptive Modulation

- **The local signal to noise ratio**

$$\gamma_n = |H_n|^2 \cdot \gamma,$$

- **Choose the appropriate modulation mode for transmission in each subcarrier given the local SNR.**
- **Modulation mode is not varied on a subcarrier-by-subcarrier basis to reduce complexity**
  - Subbands and same modulation for each of these subbands

Types of Adaptive Modulation

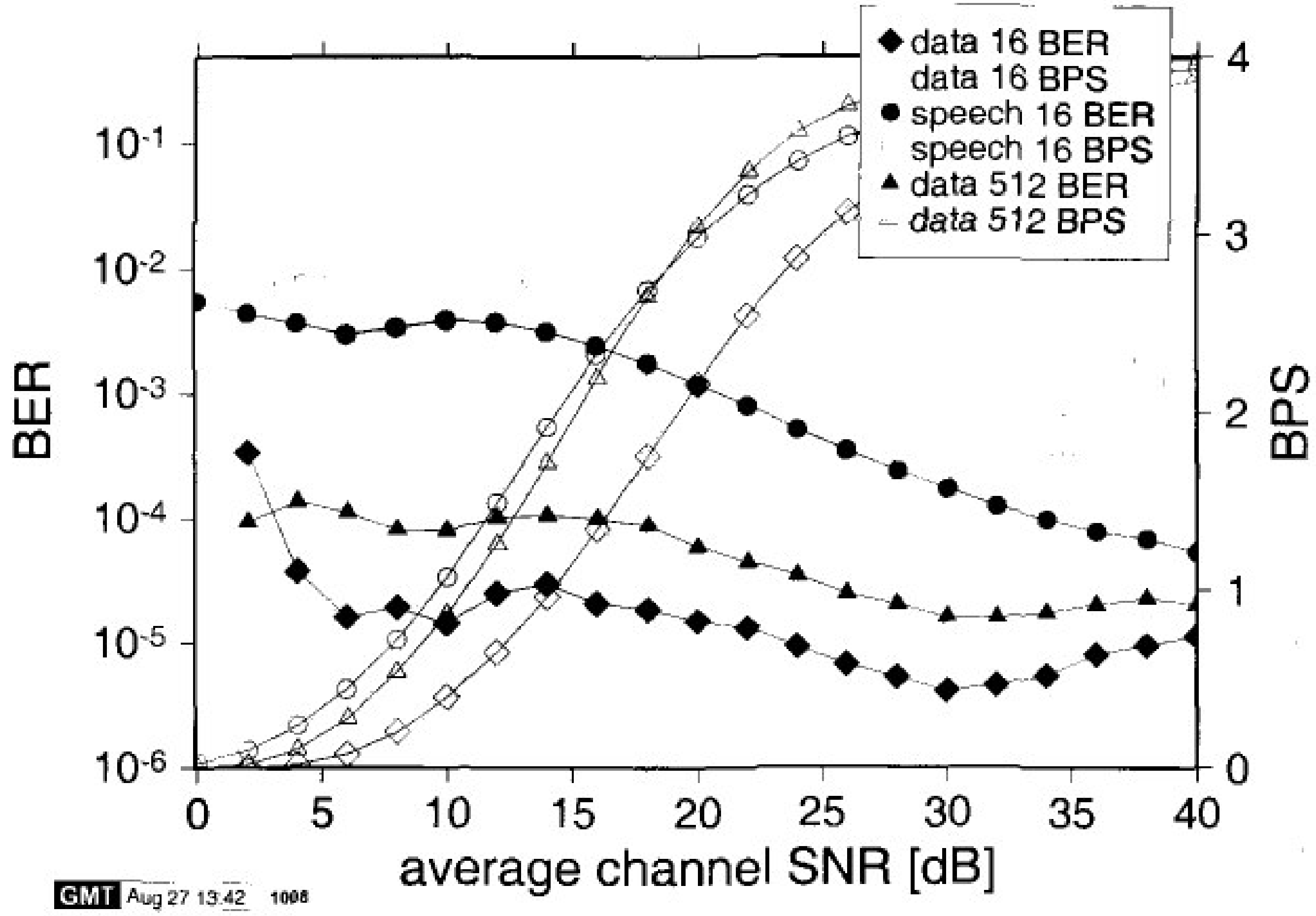
- **Fixed threshold controlled algorithm**
- **Upper bound BER estimator**
- **Fixed throughput adaptation algorithm**

Fixed Threshold Controlled Algorithm

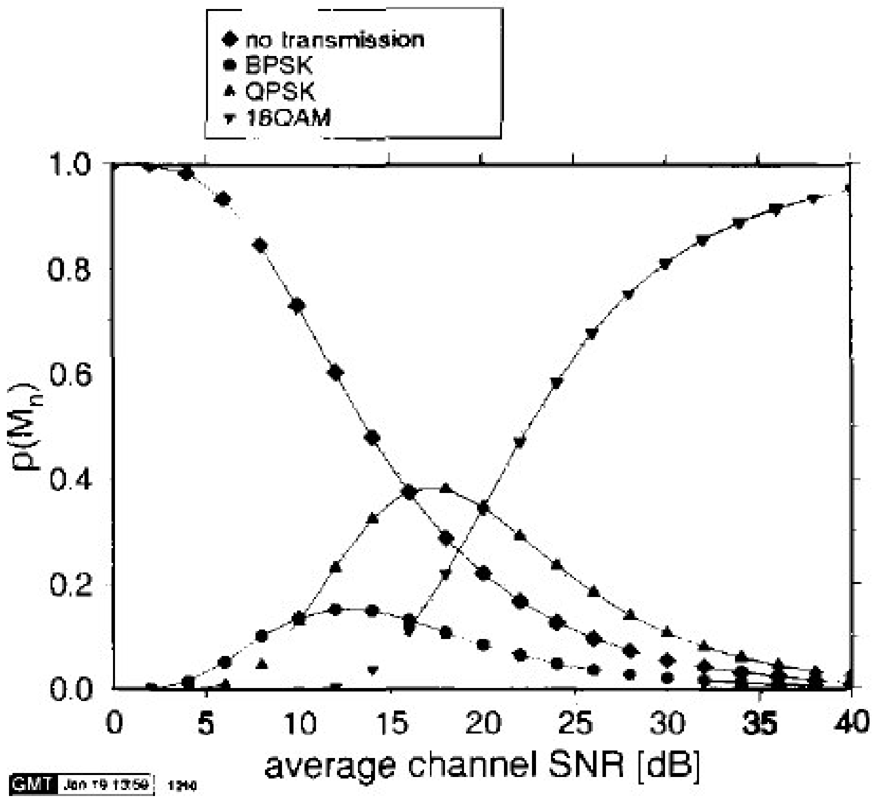
- **The channel quality is assumed to be constant for all symbols in the time slot. → slowly varying channel.**
- **→ all data symbols in the transmit time slot employ the same modulation mode chosen according to the predicted SNR.**
- **The SNR thresholds for a long term BER can be found using optimization procedure.**

	l_0	l_1	l_2	l_4
speech system	$-\infty$	3.31	6.48	11.61
data system	$-\infty$	7.98	10.42	16.76

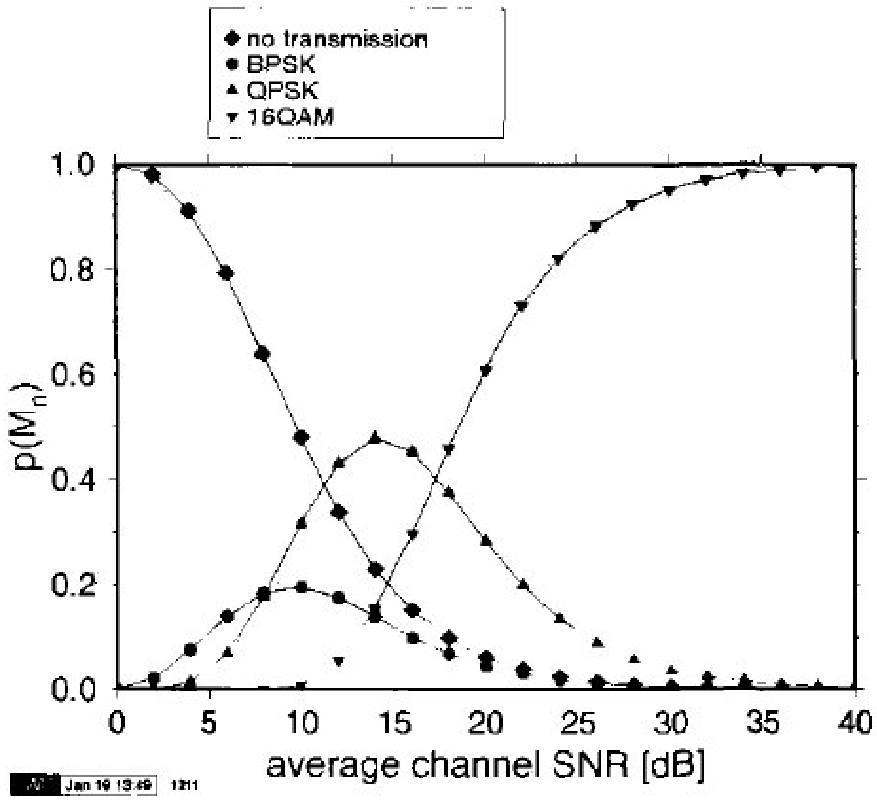
- **OFDM is used in frequency selective channel that have channel quality varying across different subcarriers.**



re 6.4: BER and BPS throughput performance of the 16 sub-band, 512 subcarrier switching level adaptive OFDM modem employing BPSK, QPSK, 16-QAM and "no transmission" over the Rayleigh fading time dispersive channel of Figure 4.3 using the switching thresholds of Table 6.1



(a) 16 sub-bands

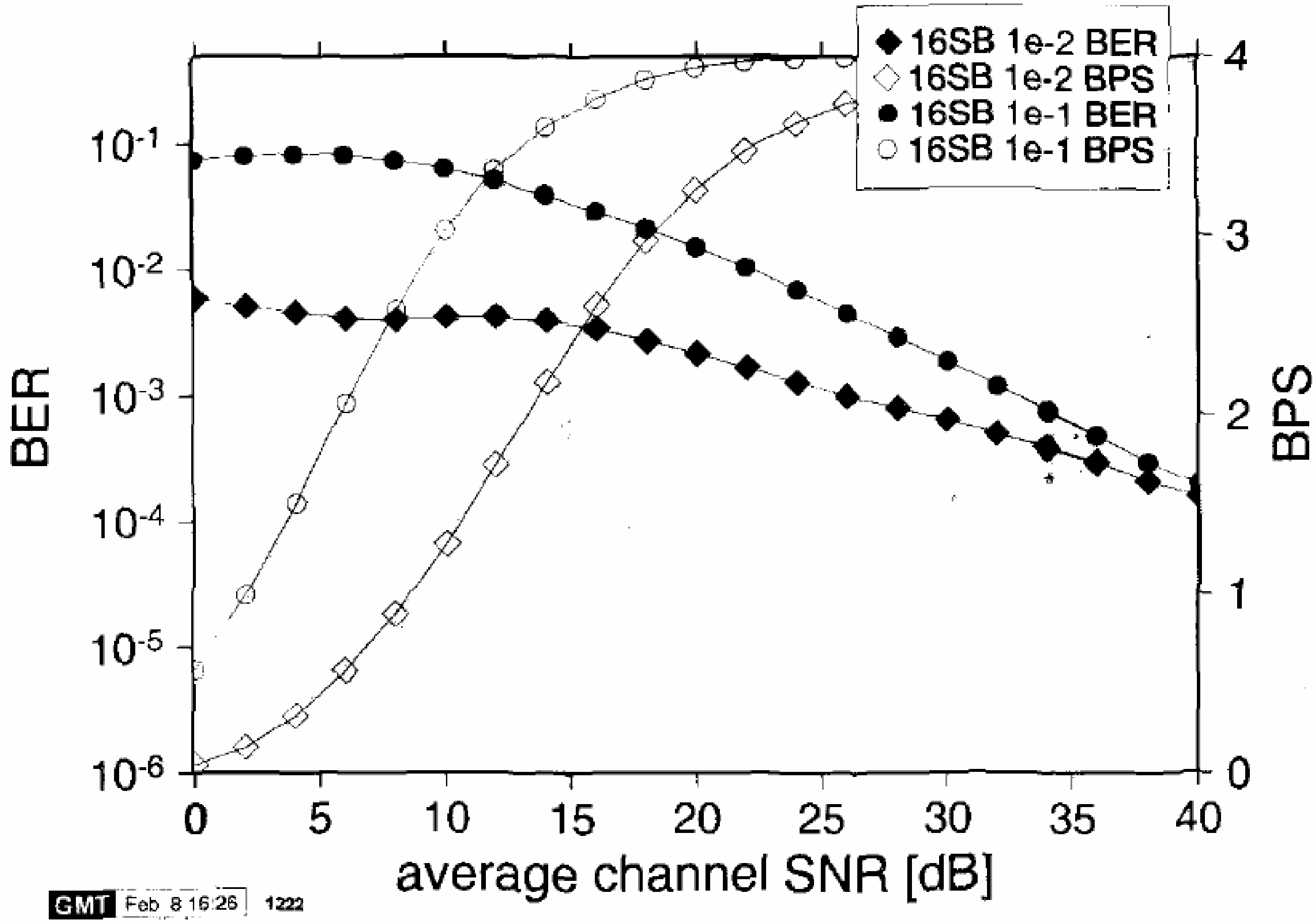


(b) subcarrier-by-subcarrier

Sub-band BER Estimator Adaptation Algorithm

- **The previous method has throughput penalty if used in an adaptive sub-band OFDM and the channel quality is non constant throughout each sub-band.**

- **Sub-band BER estimator adaptation algorithm takes into consideration the non-constant SNR values across the subacarriers in the jth sub-band**
  - Calculating the expected overall P[E] for all available modulation modes in each sub-band $\bar{p}_e(n) = 1/N_s \sum_j p_e(\gamma_j, M_n)$
  - For each sub-band, the modulation mode with the highest throughput and its estimated BER is below a given threshold is choasen.



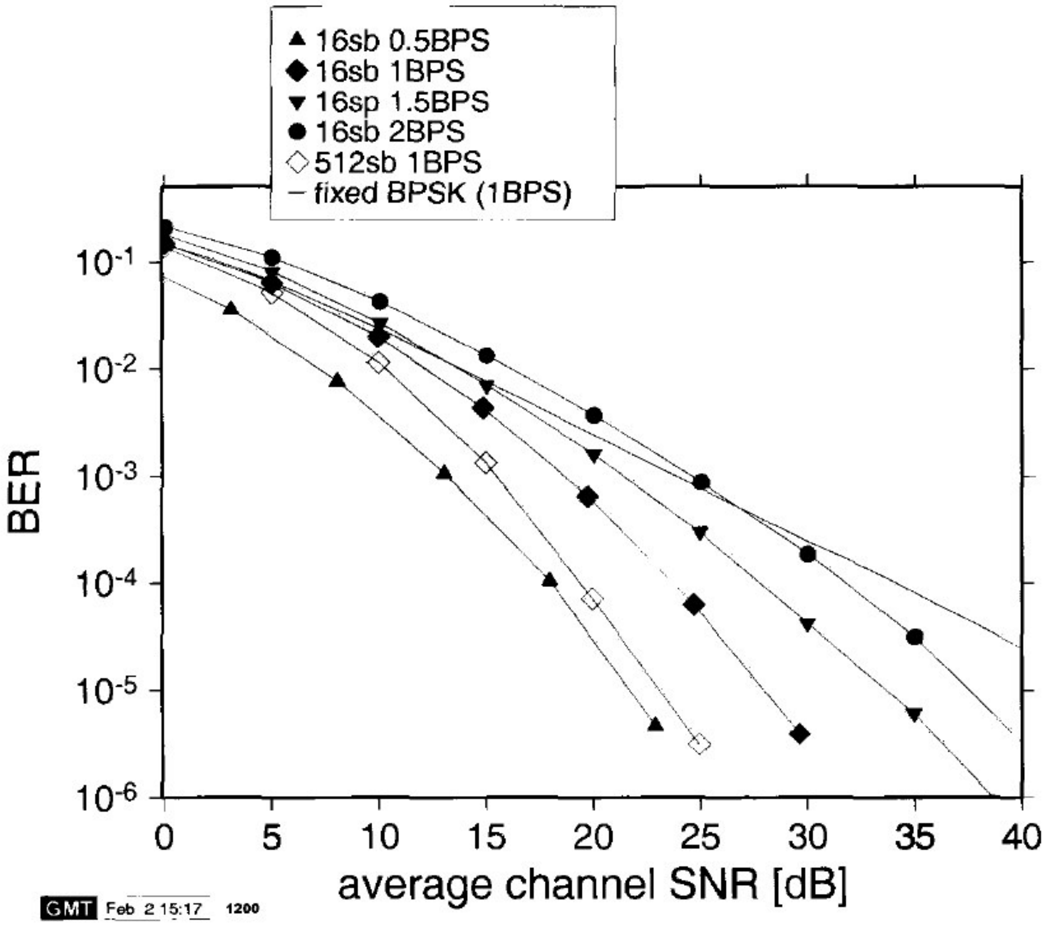
6.6: BER and BPS throughput performance of the 16 sub-band, 512 subcarrier BER estimator adaptive OFDM modem employing BPSK, QPSK, 16-QAM and "no transmission" over the Rayleigh fading time dispersive channel of Figure 4.3

Constant Throughput Adaptive Modulation

- **The previous two methods are difficult to use for situations with variety constant rate applications.**
- **Constant Throughput Adaptive Modulation exploits the frequency selectivity of the channel while offering a constant bit rate.**
- **Sub-band adaptivity is assumed for simplification**
- **The algorithm is based on a cost function**
  - The cost function depends on the expected number of bit errors in each sub-band $e_{n,s}$. n is the sub-band index, s is the modulation index.
  - The cost function is calculated on the basis of the estimated channel transfer function and the number of bits transmitted per sub-bad and per modulation $b_{n,s}$
  - A set of cost functions are calculated for each sub-band and modulation index

$$c_{n,s} = \frac{e_{n,s+1} - e_{n,s}}{b_{n,s+1} - b_{n,s}}$$

- **The modulation mode adaptation is performed by repeatedly searching for the block n having the lowest value of cost and incrementing its state variable.**
- **This is repeated until the total number of bits in the OFDM symbol reaches the target number of bits**



6.7: BER performance versus SNR for the 512 subcarrier, 16 sub-band constant throughput adaptive OFDM modem employing BPSK, QPSK, 16-QAM and "no transmission" in the Rayleigh fading time dispersive channel of Figure 4.3 for 0.5, 1, 1.5 and 2 bits per symbol (BPS) target throughput

Capacity of Fading Channels

- **Three cases**
  - Fading statistics known
  - Fade value known at receiver
  - Fade value known at receiver and transmitter
- **Optimal Adaptation**
  - Vary rate and power relative to channel
  - Optimal power adaptation is water-filling
  - Exceeds AWGN channel capacity at low SNRs
  - Suboptimal techniques come close to capacity

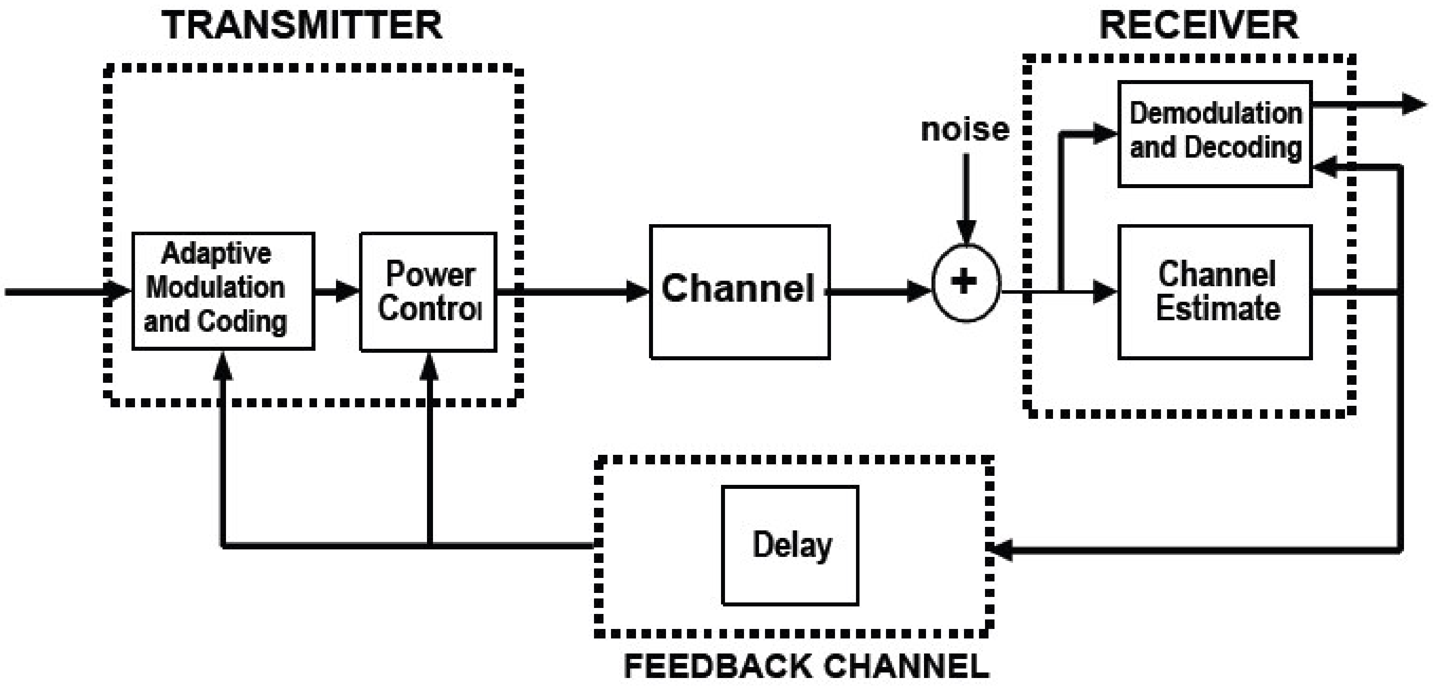
Adaptive Modulation

- Changing modulation relative to fading. Transmitter uses channel fade level to adapt.
- Parameters to adapt:
  - Constellation size
  - Transmit power
  - Instantaneous BER
  - Symbol time
  - Coding rate/scheme

Only 1-2 degrees of freedom needed for good performance

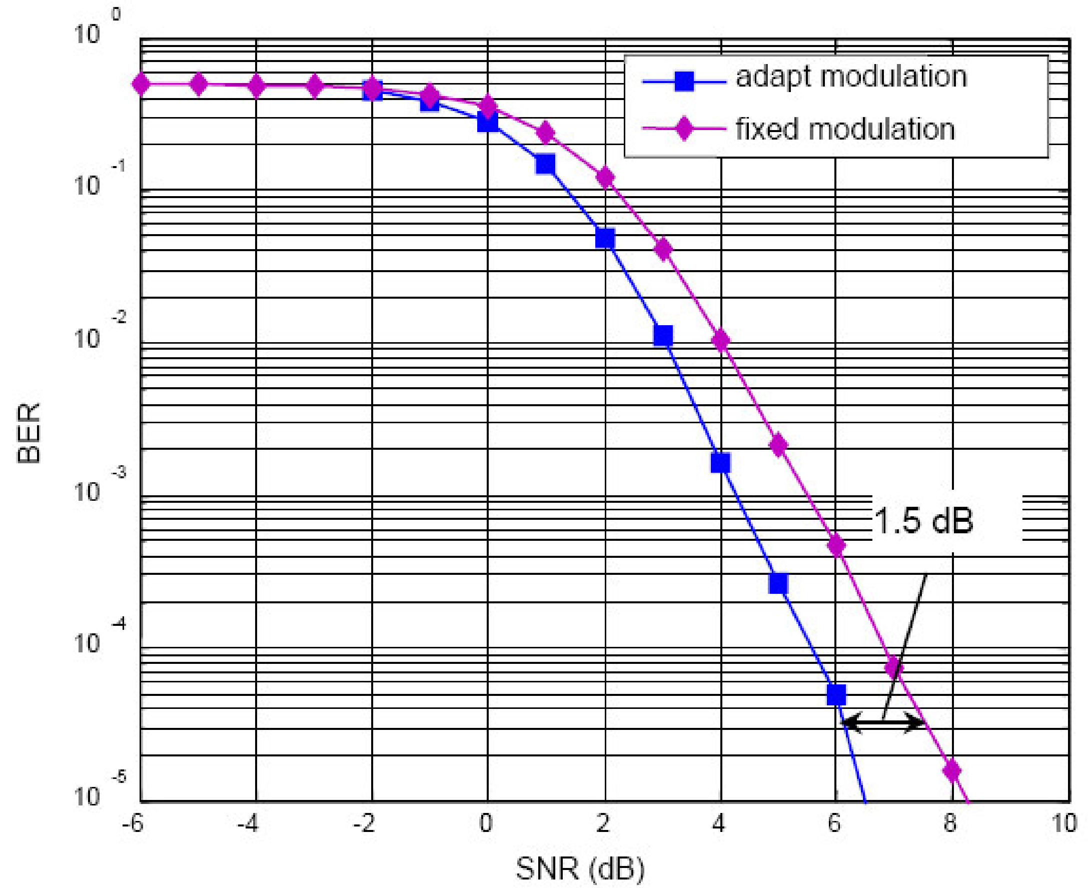
- Optimization criterion:
  - Maximize throughput
  - Minimize average power
  - Minimize average BER

Adaptive Modulation



Requires reliable feedback channel and accurate channel estimation
Increases transmitter and receiver complexity

- **Adaptive modulation (average 2 bits per subcarrier)**



Adaptive Techniques

- Variable-Rate Techniques
  - Data rate $R(\gamma)$ is varied relative to channel gain γ
    - λ Fix symbol rate $R_s = 1/T_s$ and use multiple modulation schemes or increase constellation size
    - λ Fix modulation but change symbol rate (difficult to achieve because of variable bandwidth)
- Variable-Power Techniques
  - Transmit power is changed to compensate for SNR variations due to fading
  - Invert channel to maintain constant received SNR
- Variable-Coding Techniques

Variable-Rate Variable-Power MQAM

M-ary signaling: binary message sequence divided into words of length K bits, sent every T_s seconds

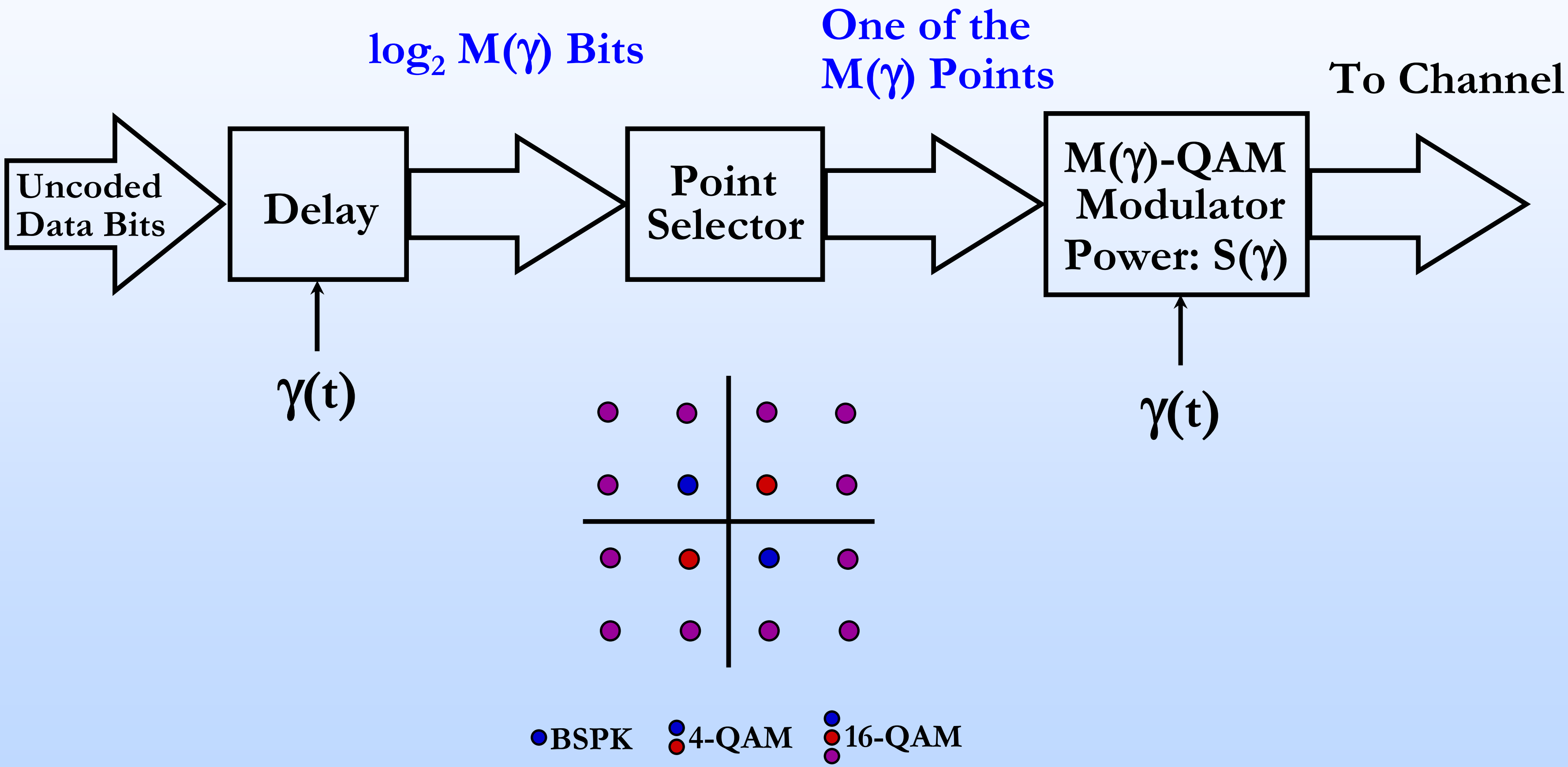
$M = 2^K$, $K = \log_2 M$, $R = K/T_s$ bps

Let $B = 1/T_s$ (Nyquist), $R = B \log_2 M$,

Spectral Efficiency: $R/B = \log_2 M$

Goal: Maximize spectral efficiency subject to a target P_b, using Variable-Rate Variable-Power MQAM

Variable-Rate Variable-Power MQAM



Goal: Optimize $S(\gamma)$ and $M(\gamma)$ to maximize $EM(\gamma)$

Optimization Formulation

BER in non-fading AWGN channel with MQAM modulation, Coherent detection, SNR = γ :

$$P_b \le 0.2e^{-1.5\gamma/(M-1)} \quad M \ge 4 \quad 0 \le \gamma \le 30dB$$

$$P_b(\gamma) \le 0.2\exp\left[\frac{-1.5\gamma}{M-1}\frac{P(\gamma)}{\overline{P}}\right]$$

Adaptive MQAM: Rate for fixed BER

$$M(\gamma) = 1 + \frac{1.5\gamma}{-\ln(5BER)}\frac{P(\gamma)}{\overline{P}} = 1 + K\gamma\frac{P(\gamma)}{\overline{P}} \qquad K = \frac{-1.5}{\ln(5P_b)} < 1$$

Optimization Formulation

Rate and Power Optimization

$M(\gamma)$ is random. Spectral efficiency is maximized by Maximizing $E[\log_2 M(\gamma)]$:

$$\max_{P(\gamma)} E\log_2[M(\gamma)] = \max_{P(\gamma)} E\log_2\left[1 + K\gamma\frac{P(\gamma)}{\overline{P}}\right]$$

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

Subject to average power: $\int_0^\infty P(\gamma)p(\gamma)\,d\gamma = \overline{P}$

Variable-Power Techniques

Maintains constant SNR σ at the receiver by adapting transmitting power. Adaptation is subject to maintaining given average power

$$\int_0^\infty P(\gamma)p(\gamma)d\gamma = \overline{P} \qquad \frac{P(\gamma)}{\overline{P}}\gamma = \sigma$$

$$\int_0^\infty \frac{P(\gamma)}{\overline{P}} p(\gamma)d\gamma = \int_0^\infty \frac{\sigma}{\gamma} p(\gamma)d\gamma = 1 \longrightarrow \sigma = \frac{1}{\mathbf{E}_{\gamma_0}\left[1/\gamma\right]}$$

σ depends on p(γ), which in turn depends on $\overline{\text{P}}$. For a given $\overline{\text{P}}$ if σ > 1/E[1/ γ] target BER can not be met.

Note that for Rayleigh fading where γ is exponentially distributed, $E[1/\gamma] = \infty$, so no target P_b can be met using channel inversion.

Variable-Power Techniques

Fading can be inverted above a given cutoff γ_0

Power adaptation based on truncated channel inversion:

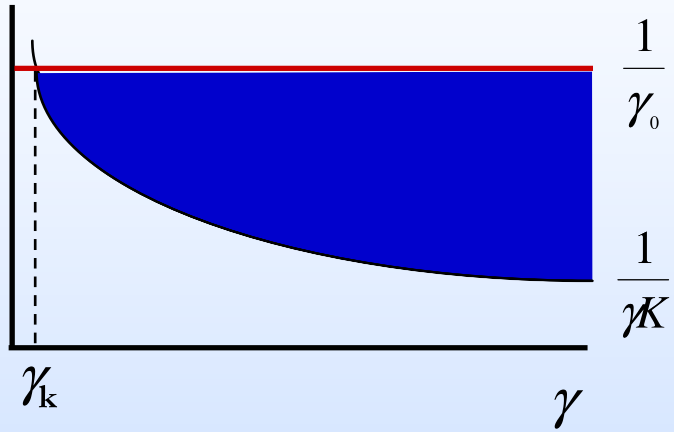
$$\frac{P(\gamma)}{\overline{P}} = \begin{cases} \frac{\sigma}{\gamma} & \gamma \geq \gamma_0 \\ 0 & \gamma \geq \gamma_0 \end{cases} \qquad \mathbf{E}_{\gamma_0}\left[\frac{1}{\gamma}\right] = \int_{\gamma_0}^{\infty} \frac{1}{\gamma} p(\gamma) d\gamma$$

Fading can be inverted above a given cutoff value γ_0 can be Based on a desired outage probability $P_{out} = pr(\gamma < \gamma_0)$

Optimal Adaptive Scheme

- **Power Water-Filling**

$$\frac{P(\gamma)}{\bar{P}} = \begin{cases} \frac{1}{\gamma_0} - \frac{1}{\gamma K} & \gamma \geq \frac{\gamma_0}{K} = \gamma_K \\ 0 & \text{else} \end{cases}$$



instantaneous rate

$$\log_2 M(\gamma) = \log_2(\gamma/\gamma_K)$$

- **Spectral Efficiency**

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

$M = 2^K$, $K = \log_2 M$, $R = K/T_s$ bps

Let $B = 1/T_s$ (Nyquist), $R = B \log_2 M$,

Spectral Efficiency: $R/B = \log_2 M$

Equals Shannon capacity with an effective power loss of K.

Practical Adaptation Constraints

- **Constellation restriction**
- **Constant power restriction**
- **Constellation updates.**
- **Estimation error.**
- **Estimation delay.**
- **Lead to practical adaptive modulation schemes**

Reading assignment

- **Chapter six up to section 6.2.6 from the textbook**
- **Paper: degrees of freedom in adaptive modulation a unified approach**
- **Paper:** Variable-Rate Variable-Power MQAM for Fading Channels
  - Write a report on these papers, due date: Thursday 27-9-2007