Baseband Digital Communications

- Characteristics and Constraints of Wireless Channels
- Baseband Pulse Transmission: Line Signal Codings [NRZ, AMI, Manchester, 2B1Q, ...]
- Pulse Amplitude Modulation [PAM]: Transmitter and Receiver pulse shaping
- Intersymbol Interference [ISI]: Eye Pattern
- The Nyquist Criterion:
  - Raised Cosine Pulses
  - Multipath
  - Performance: Mean-Square Error
  - Probability of Error

Baseband Modulation

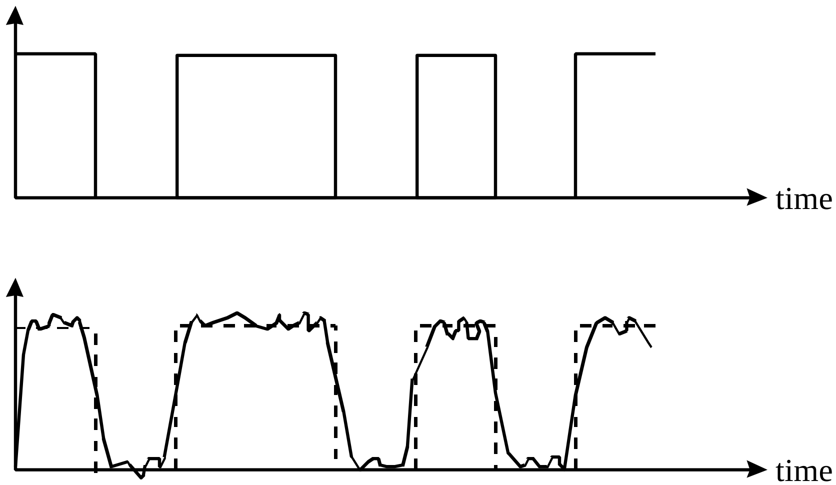
- An information bearing-signal must conform to the limits of its channel
- Generally modulation is a two-step process
  - baseband: shaping the spectrum of input bits to fit in a limited spectrum
  - passband: modulating the baseband signal to the system rf carrier
- Most common baseband modulation is *Pulse Amplitude Modulation* (PAM)
  - data amplitude modulates a sequence of time translates of basic pulse
  - PAM is a linear form of modulation: easy to equalize, BW is pulse BW
  - Typically baseband data will modulate in-phase [cos] and quadrature [sine] data streams to the carrier passband
- Special cases of ***modulated*** PAM include
  - phase shift keying (PSK)
  - quadrature amplitude modulation (QAM)

Need for Baseband Modulation

- An analog signal has a finite bandwidth.

- A digital stream or signal, with sharp transitions, has an infinite bandwidth.

- Due to the limited available system bandwidth, only the major portion of a digital signal spectrum can be transmitted and restored. Even if there is no loss or noise in the communication system, the received signal will have distortion due to the limited channel bandwidth.



To avoid or to reduce this signal distortion, we use ***baseband modulation techniques***

Typical Baseband PAM Signals

a_n represents data (M-ary)

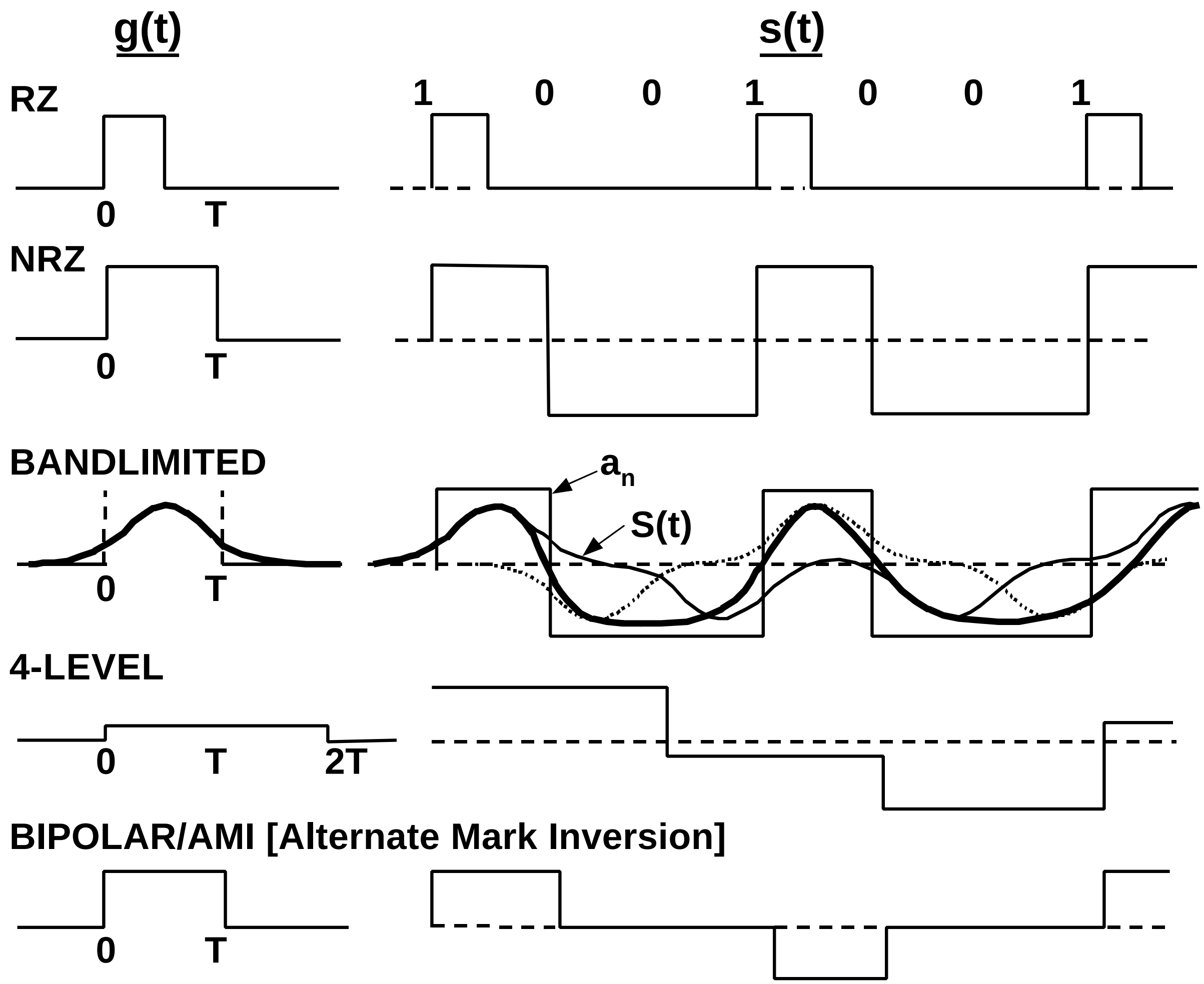
1/T = symbol (baud) rate

Bit rate = $\frac{1}{T} \log_2 M = R$

$$S(t) = \sum_n a_n g(t-nT)$$

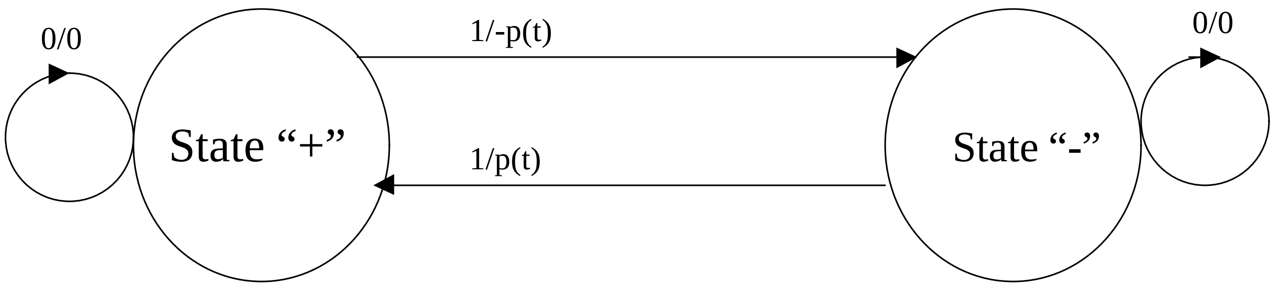
$$= a_0 g(t) + a_1 g(t-T) + \ldots$$

M	a_n
2	0 ® 0 1 ® 1
2	0 ® -1 1 ® 1
2	0 ® -1 1 ® 1
4	00 ® -3 01 ® 1 11 ® 1 10 ® 3
3	0 ® 0 1 ® ±1



Each technique will have different spectrum (at DC and band edge), ease of timing recovery

State Diagram for AMI Signaling



Branch Labels: Input bit (a_n)/output waveform or symbol [$d_n p(t)$]

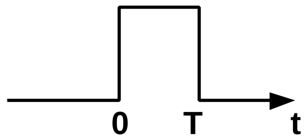
The modulator has two states, labeled "+" and "-". The modulator responds to a source symbol 0 with a zero waveform and to a source symbol 1 with the waveform p(t) or -p(t) depending on whether its state is "-" or "+" respectively.

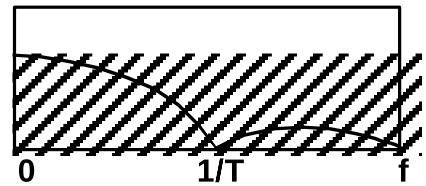
Note that the choice of the states is not obvious. A common mistake is to choose the output levels, 0, 1, and -1 as states. But, if you make this choice, it is hard/impossible(?) to capture the memory of the system.

Examples of Baseband Impulse Responses

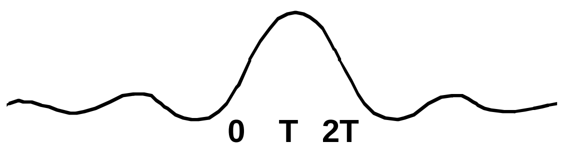
h (t) | **|H(f)|**

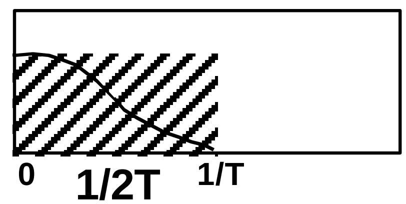
(1) NRZ (non return to zero)





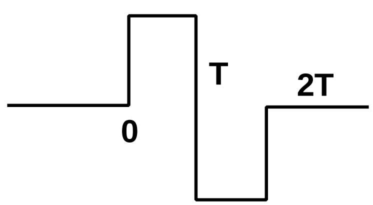
(2) Raised Cosine

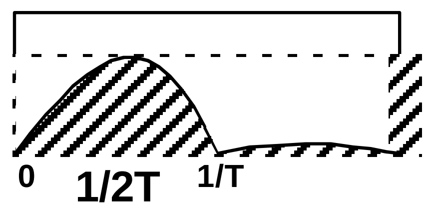




E.g Equalized Voiceband, Cellular or Microwave LOS Modem

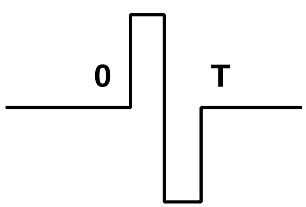
(3) Bipolar (AMI)

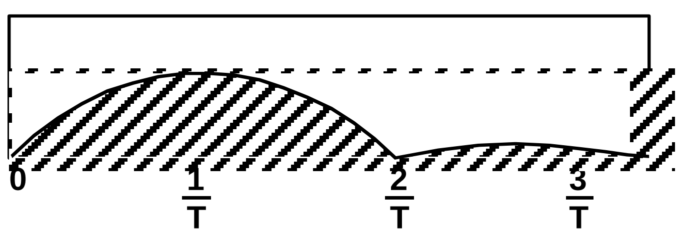




e.g. 1.544/2.048 Mbps T_1 /E_1 Carrier on Twisted-Pair

(4) Manchester



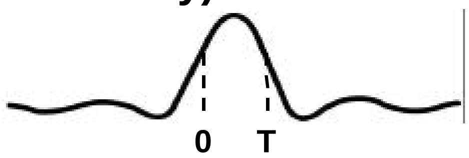


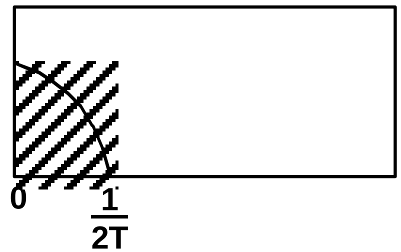
e.g. Ethernet on Coaxial Cable (3-10 Mbps)

Examples of Baseband Impulse Responses (continued)

h (t) | **|H(f)|**

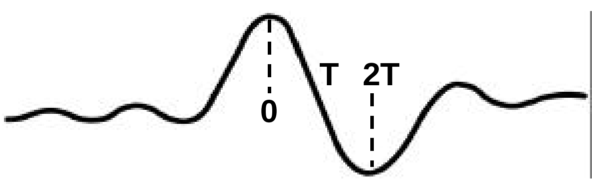
(5) Multipath: Class I Partial Response (Duobinary)

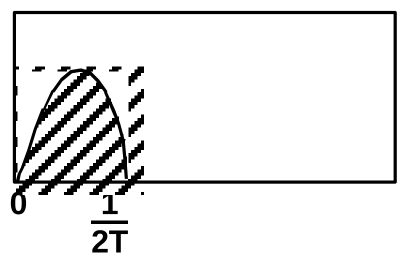




- Multipath (Cellular)
- Need Powerful Equalizer (DFE, VA)

(6) Multipath: Class IV Partial Response

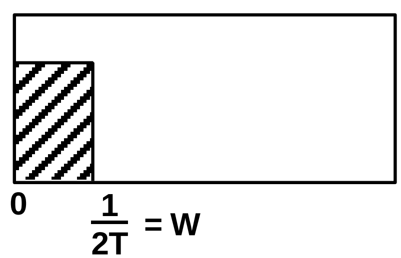




- Multipath Nulls at DC and Nyquist frequency

(7) Minimum - Bandwidth *Nyquist* Pulse

sin2p Wt / 2p WT

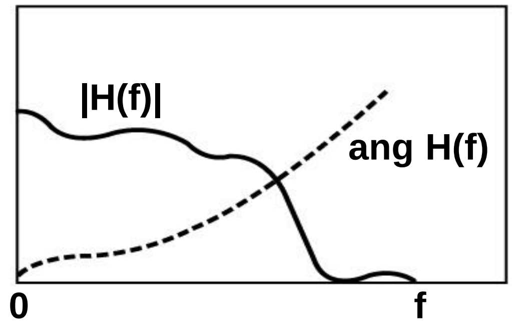


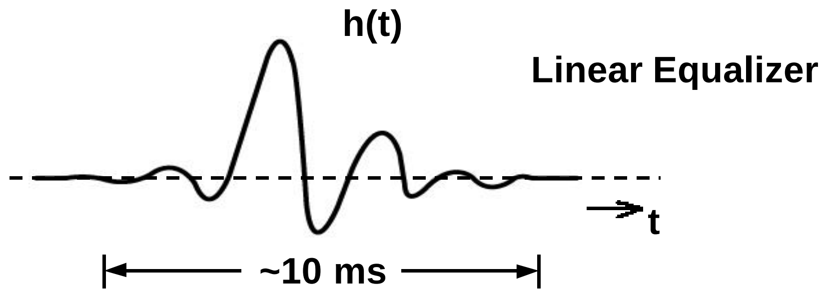
- Regularly spaced zero crossings
- Not Realized in Practice

Typical Linear Channel Characteristics

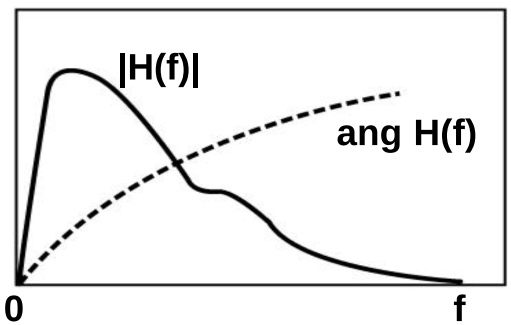
Frequency Response H(f)	Impulse Response h(t)

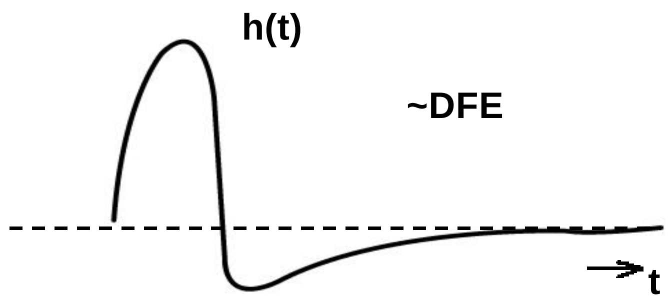
Voiceband Telephone After Demodulation



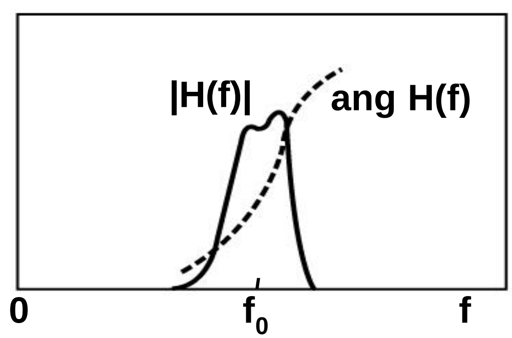


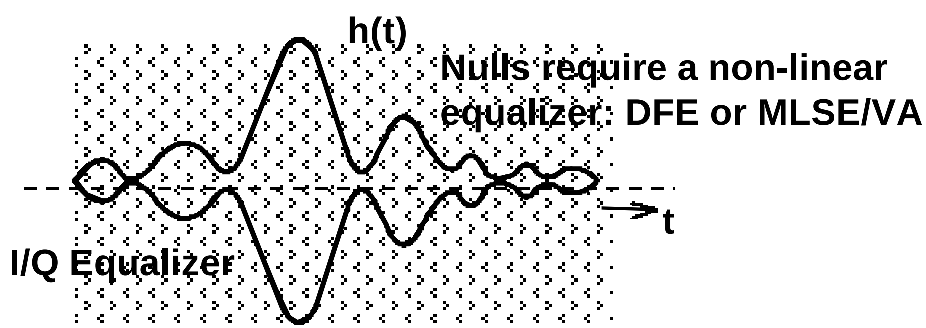
Twisted Copper Pair with Transformers (DSL)



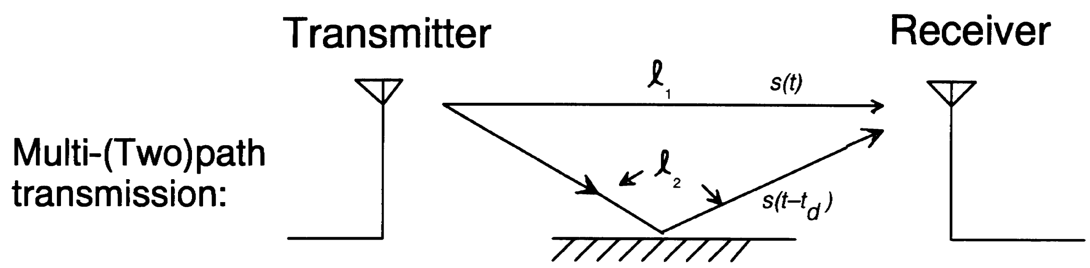


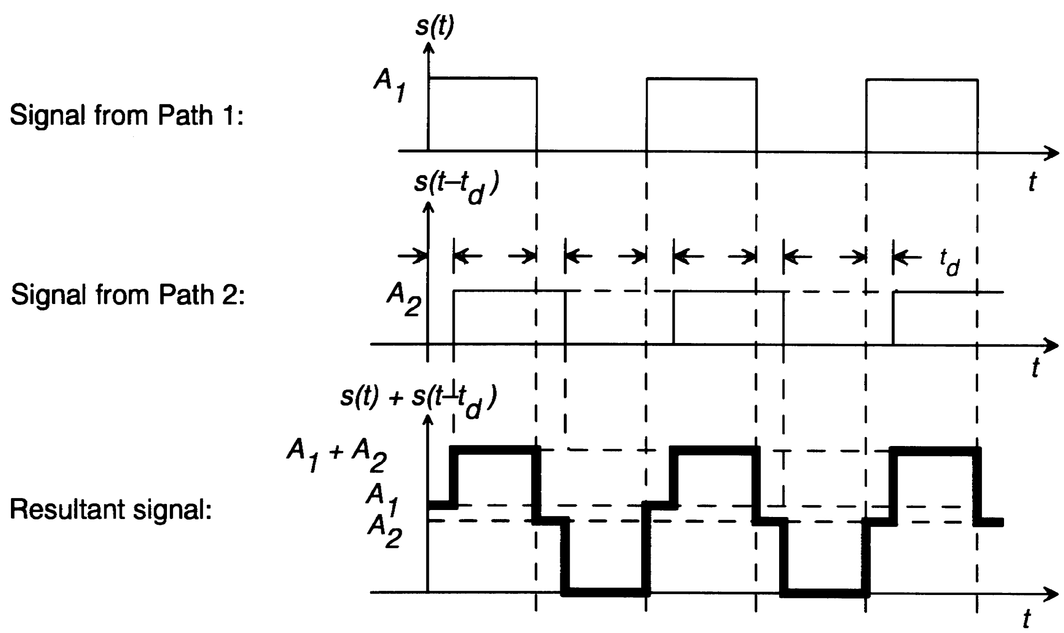
Radio





Pulse Distortion Due to MultiPath

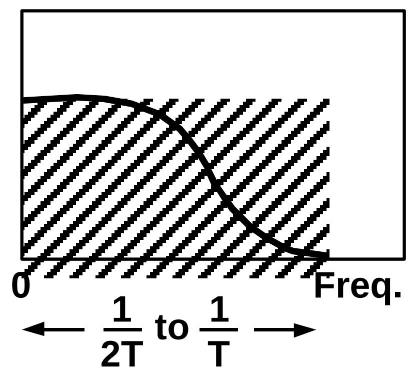




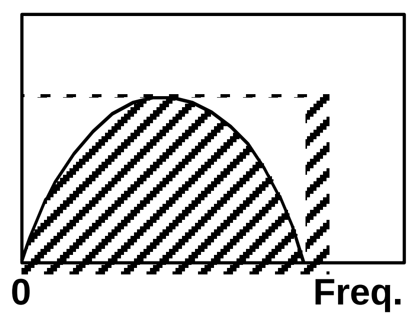
Digital Baseband Modulation Techniques

- **Baseband (PAM): Baseband Channels**
  - NR (Non-Return-to-zero)
  - Bipolar (AMI)
  - Partial response
  - Manchester

Typical Power Spectra:



NRZ



Bipolar, Partial Reponse, or Manchester

Examples: Twisted-Pair and Coaxial Cable Channels

Doubling the Data Rate

- Date Rate = $\frac{1}{T}\log_2 N$

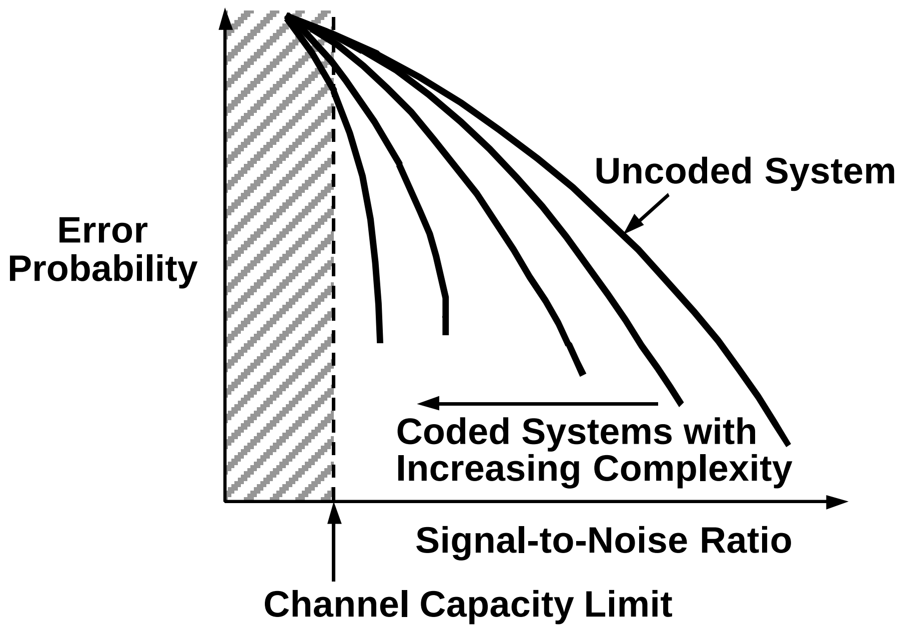
  Recall that 1/T is the symbol rate and N is the number of modulation levels

- If SNR limited ----> double the symbol rate [3 dB SNR penalty]
- If bandwidth limited ----> only choice is to double the number of ***bits/symbol*** by increasing the number of points
  - For example: going from 4-QAM to 16-QAM [from 2 to 4 bits/symbol]
  - This has a ~6-7 dB penalty
- So, assuming that the bandwidth is available it is always better to double the symbol rate
- The above also assumes that the background noise and/or interference is flat with frequency

Coded Baseband Digital Modulation Techniques

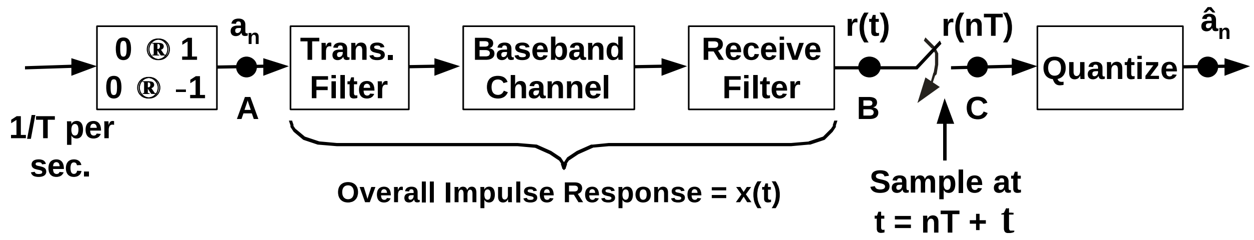
• Coded Systems

- Can be combined with any of the above
- Performance improvement at the cost of increased receiver delay and complexity
- Allows rate to approach <u>channel capacity</u>
- Types: - block coding
  - convolutional or trellis coding

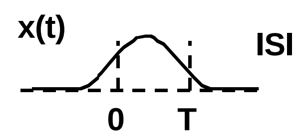


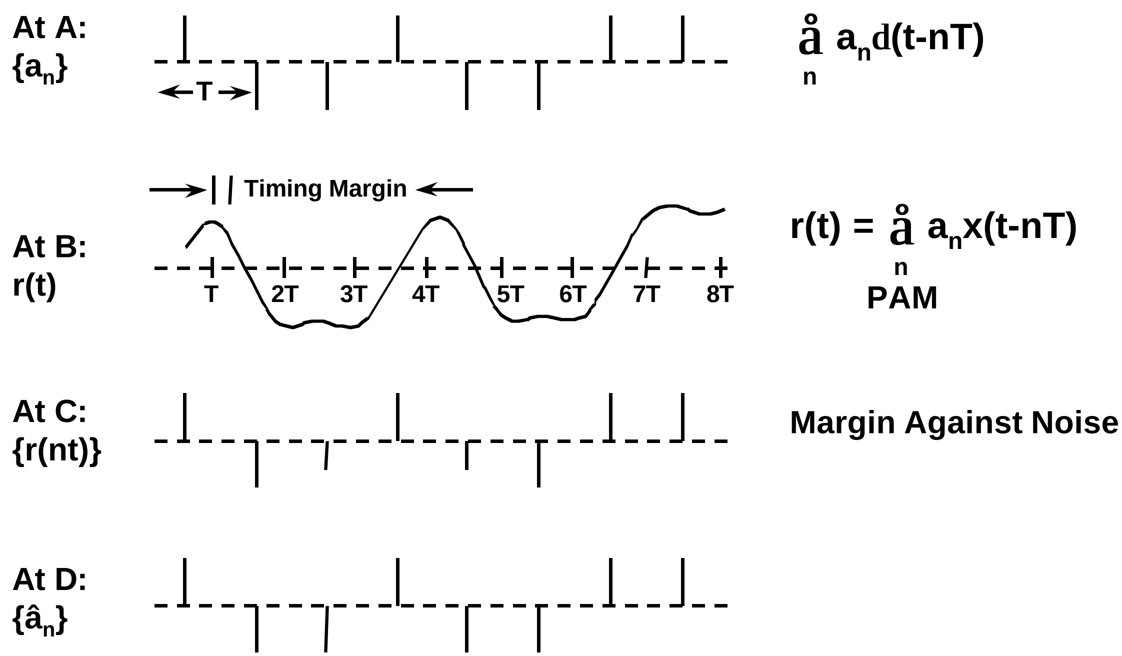
Examples of Application:
- **Cellular Phones**
- **Satellite Channels**
- **High Speed Voiceband Telephone Modems**

Example of a Baseband PAM System



- Baud = Symbols/sec



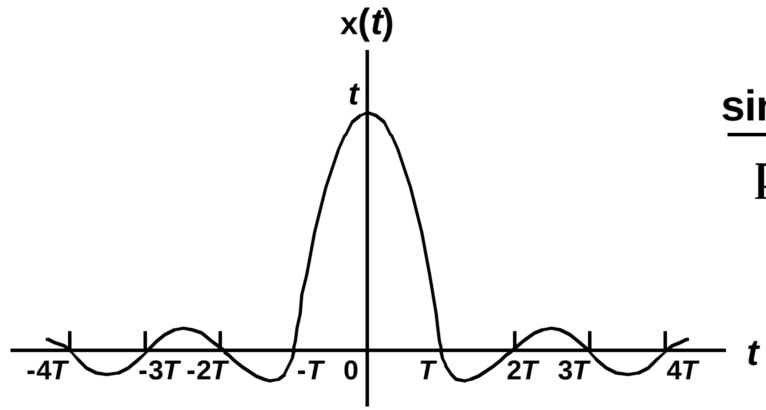


Intersymbol Interference (ISI) Can Cause Errors Without Noise

Band-Limited Signal for No Intersymbol Interference

Don't Need Time Limited Pulses for "0" ISI

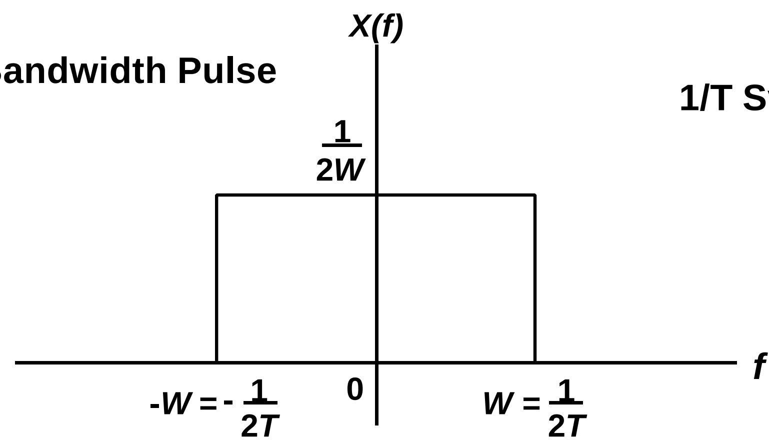
- **Ideal Pulse**



$$\frac{\sin \pi W t}{\pi W t}$$

- **Minimum Bandwidth Pulse**

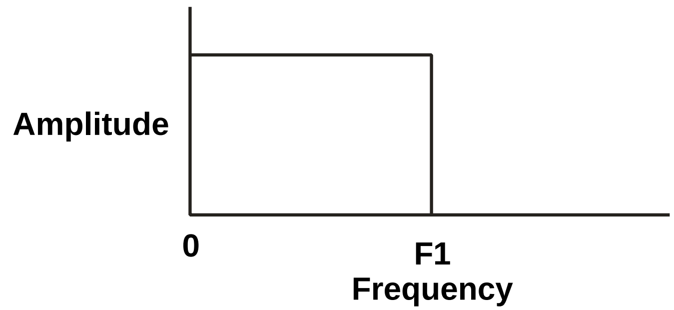
1/T Symbols/sec



Nyquist (1928)

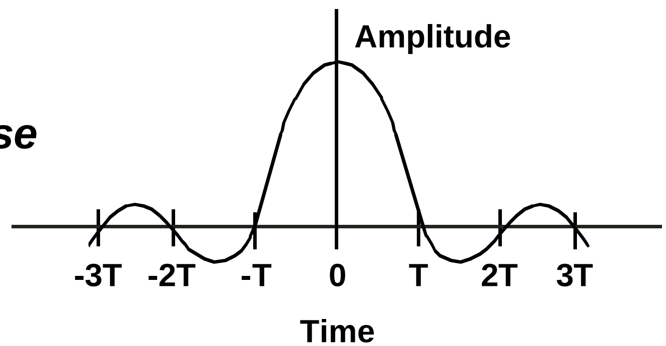
Why Equalization Is Needed

(A)



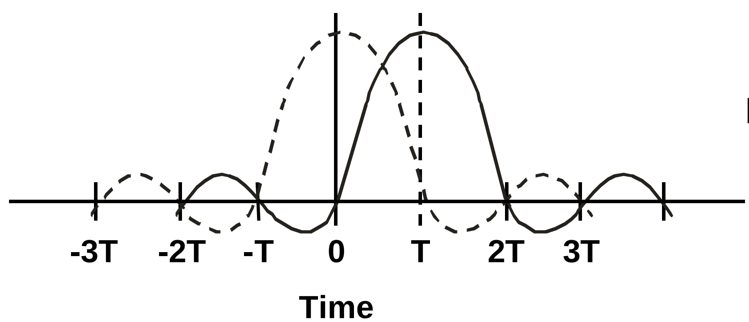
(B)

Transmitted Pulse



P(t)

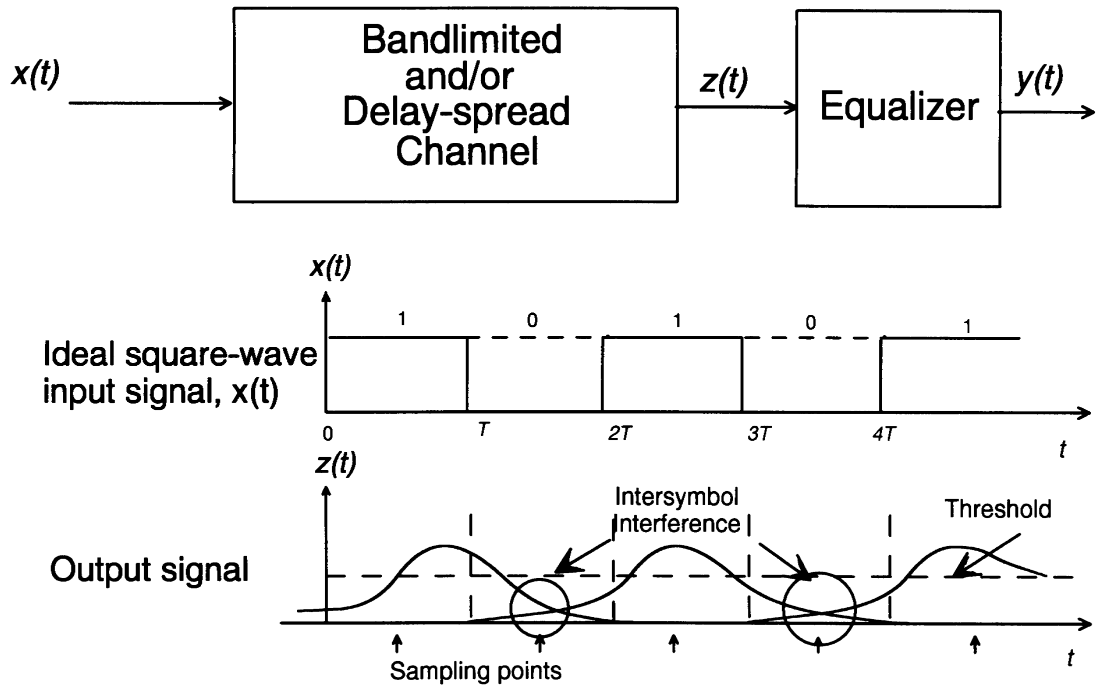
(C)



P(t) + P(t-T)

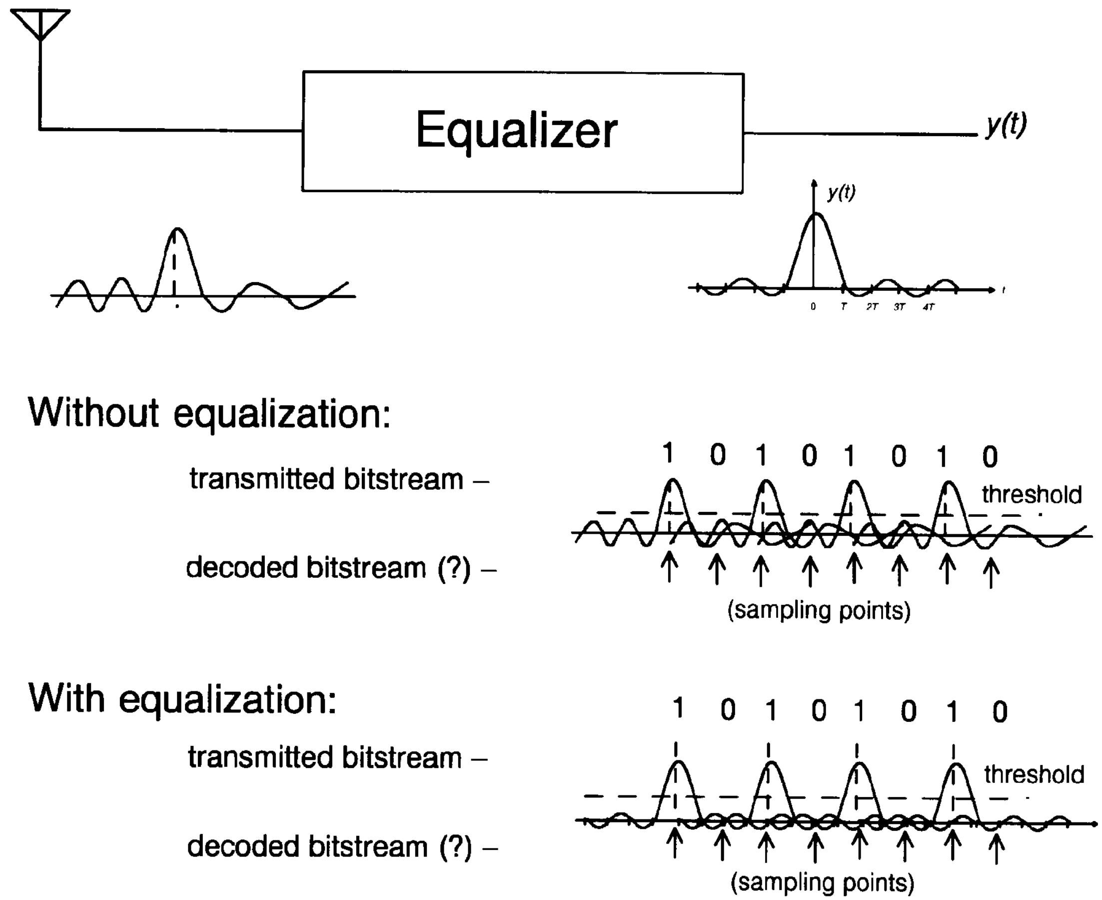
INTERSYMBOL INTERFERENCE: ISI

- Cause of ISI:



- Elimination or reduction of ISI
  - filtering
  - equalization

EQUALIZATION: Pulse Shaping

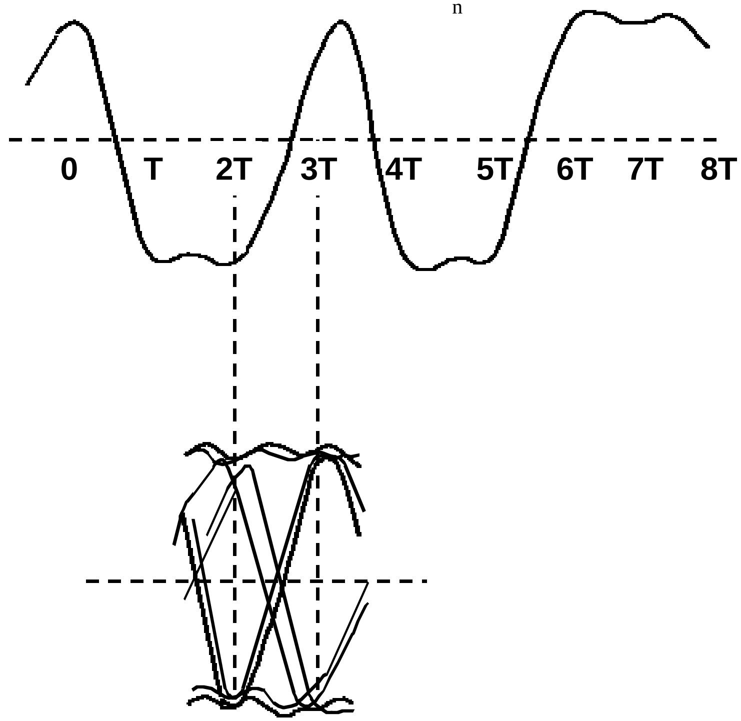


Ideal pulse shaping [to satisfy the ***Nyquist criterion***]:

$$y(t) = 0 \text{ at } t = nT \; [n = 1, 2, 3, \ldots]$$

The Eye Pattern [as a measure of distortion]

$$\text{PAM Waveform}: r(\mathrm{t}) = \sum_{\mathrm{n}} a_{\mathrm{n}}\ x(\mathrm{t}-\mathrm{nT})$$



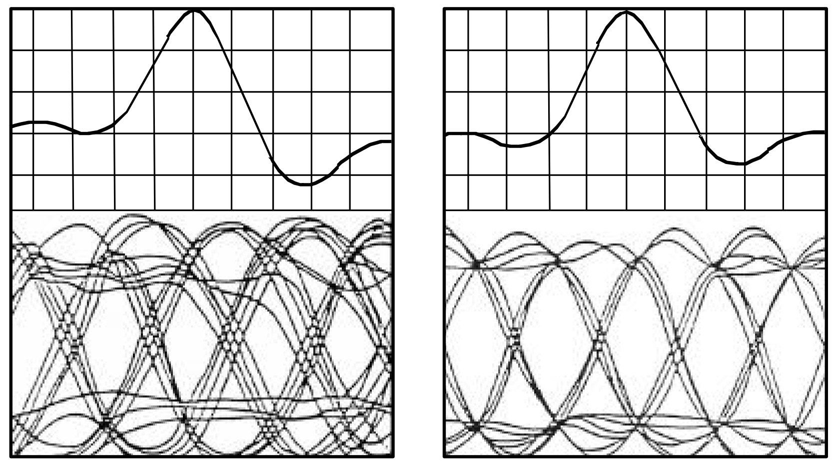
$$r(kT) = \underbrace{a_k x(0)}_{\text{Desired}} + \underbrace{\sum_{\mathrm{m}\neq 0} a_{k-m}\ x_m}_{\text{Intersymbol Interference}}$$

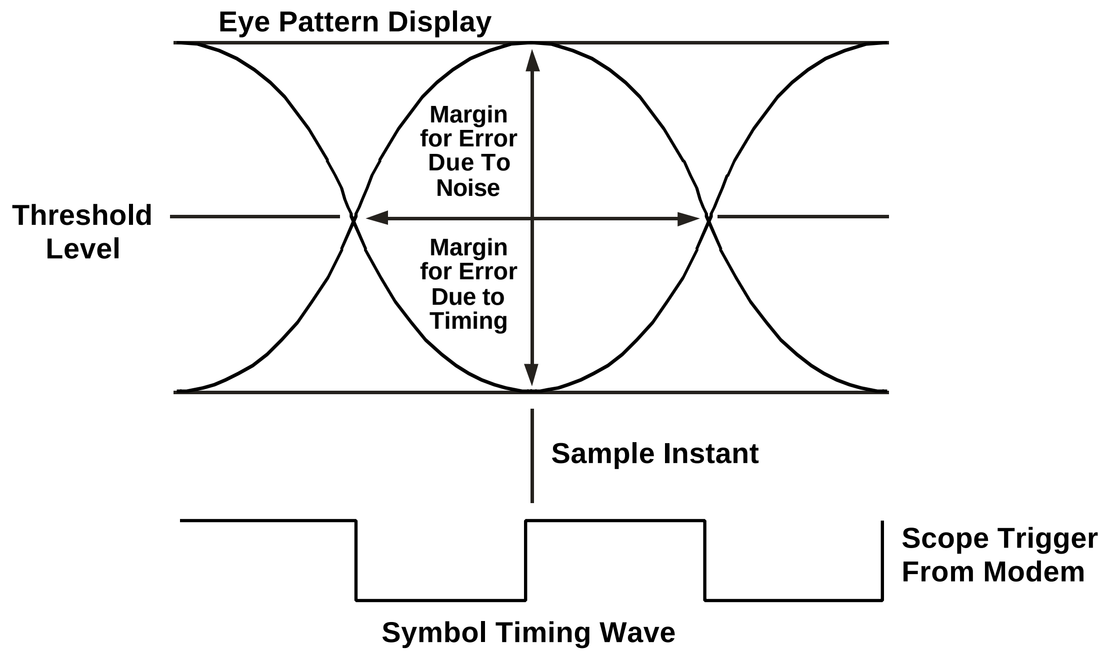
Desired **Intersymbol Interference = is a random variable (pdf is difficult to compute)**

By the Central Limit Theorem the ISI can be approximated by a Gaussian Random Variable of zero mean and variance $\sum_{n\neq 0}^{\infty} x_n^2$

Eye Pattern

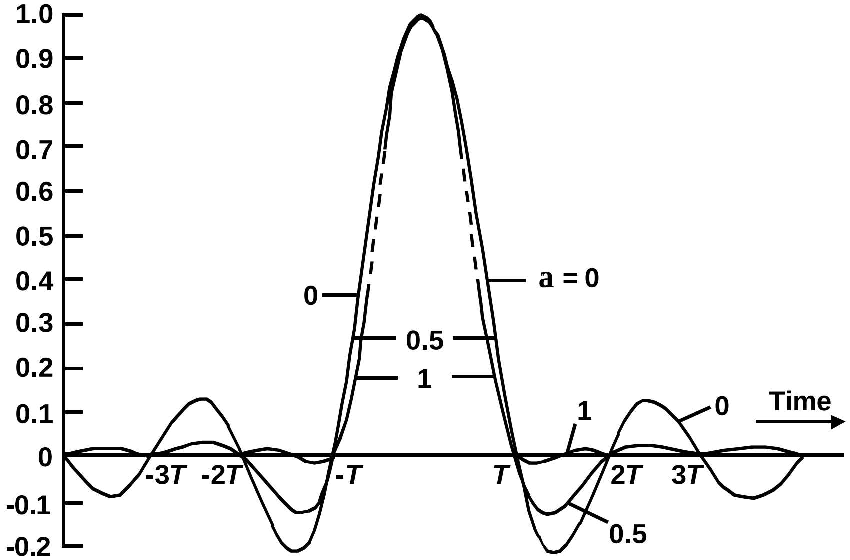
“Bad” - Closed *“Good” - Open*





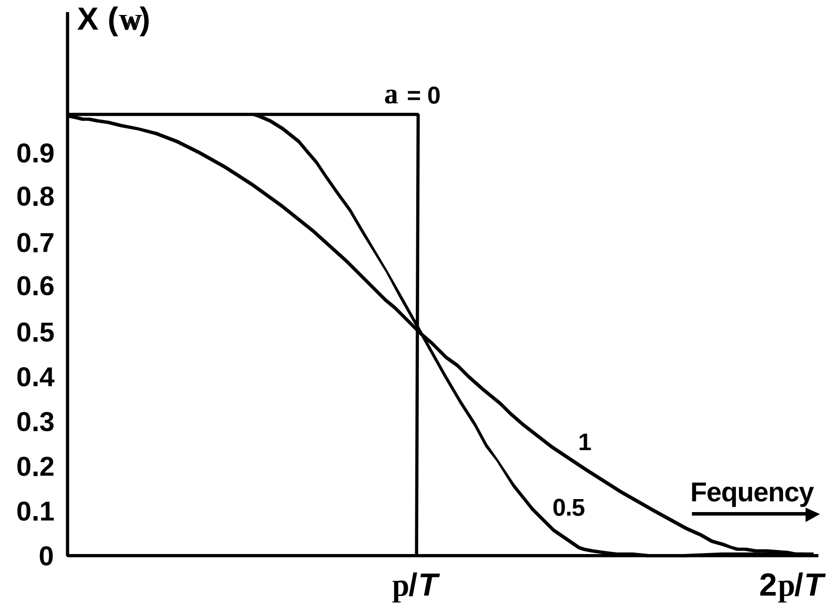
The Raised Cosine Family of Nyquist Pulses

Raised Cosine



(a)

Excess Bandwidth



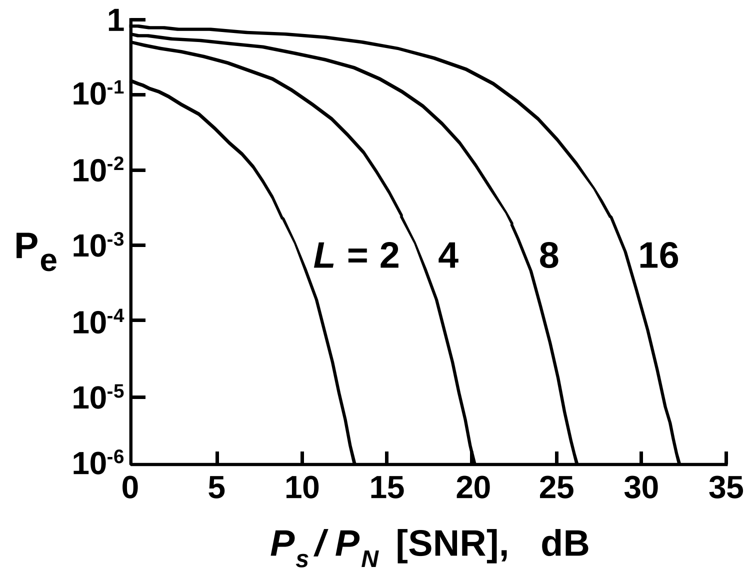
(b)

$$x(t) = \frac{\sin \pi t/T}{\pi t/T} \; \frac{\cos \alpha\pi t/T}{1-4\alpha^2 t^2/T^2}$$

$$X(\omega) = \begin{cases} T, & 0 \le \omega \le \frac{\pi}{T}(1-\alpha) \\ \frac{T}{2}\left\{1-\sin\left[\frac{T}{2\alpha}\left(\omega-\frac{\pi}{T}\right)\right]\right\}, & \frac{\pi}{T}(1-\alpha) \le \omega \le \frac{\pi}{T}(1+\alpha) \end{cases}$$

Raised Cosine Pulse Shaping: (a) Frequency Response, (b) Time Response

Performance of PAM Systems: No ISI/Multipath (Gaussian Noise)



Probability of error P_s for L-level PAM, where P_s / P_N is the signal-to-noise power ratio in the Nyquist bandwidth. Note that *doubling* the bit rate requires about 6-7 dB of SNR

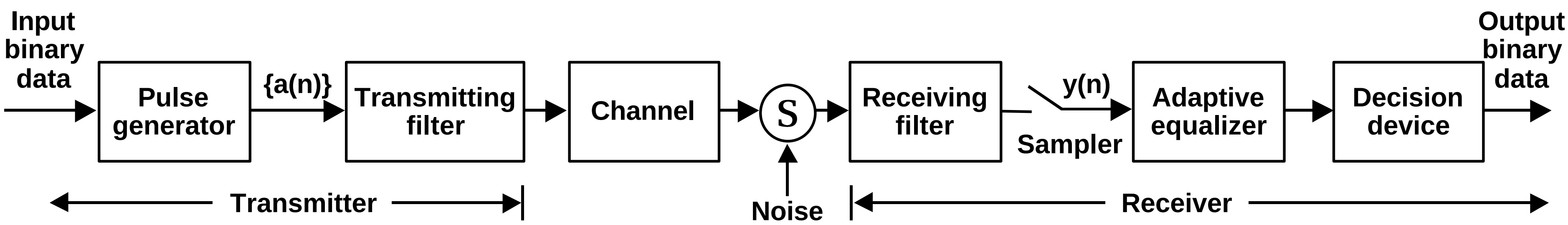
For Nyquist Pulse

$$P_s = \text{XMITT POWER} = \overline{a^2}/T = \frac{2}{LT}\sum_{i=1}^{L/2}[d(2i-1)]^2 = \frac{d^2}{T}\left(\frac{L^2-1}{3}\right)$$

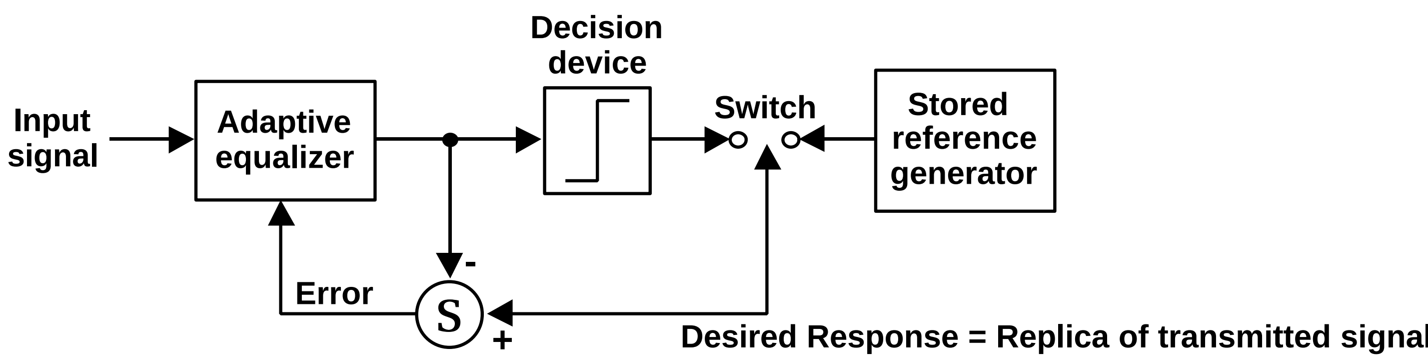
$$P_e = \left(1-\frac{1}{L}\right)\Pr\{|\eta| > d\} = 2\left(1-\frac{1}{L}\right)Q\left[\left(\frac{3}{L^2-1}\frac{P_s}{P_N}\right)^{1/2}\right]$$

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-t^2/2}\,dt$$

Adaptive Equalization



Block diagram of a baseband data transmission system.



Adaptive equalizer with a decision-directed mode of operation.