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)

$1/T = \text{symbol (baud) rate}$

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

\[
S(t) = \sum_n a_n g(t-nT) = a_0 g(t) + a_1 g(t-T) + ...
\]

<table>
<thead>
<tr>
<th>$M$</th>
<th>$a_n$</th>
<th>$g(t)$</th>
<th>$s(t)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$0 \rightarrow 0$</td>
<td>RZ</td>
<td>1 0 0 1 0 0 1 0 0 1</td>
</tr>
<tr>
<td></td>
<td>$1 \rightarrow 1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$0 \rightarrow -1$</td>
<td>NRZ</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$1 \rightarrow 1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$0 \rightarrow -1$</td>
<td>BANDLIMITED</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$1 \rightarrow 1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>$00 \rightarrow -3$</td>
<td>4-LEVEL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$01 \rightarrow 1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$11 \rightarrow 1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10 \rightarrow 3$</td>
<td>BIPOLAR/AMI [Alternate Mark Inversion]</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$0 \rightarrow 0$</td>
<td>3-LIGHT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$1 \rightarrow \pm1$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

(1) NRZ (non return to zero)

(2) Raised Cosine

(3) Bipolar (AMI)

(4) Manchester

E.g. Equalized Voiceband, Cellular or Microwave LOS Modem

e.g. 1.544/2.048 Mbps T1/E1 Carrier on Twisted-Pair

e.g. Ethernet on Coaxial Cable (3-10 Mbps)
Examples of Baseband Impulse Responses (continued)

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

(6) Multipath: Class IV Partial Response

(7) Minimum - Bandwidth Nyquist Pulse

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

- Multipath Nulls at DC and Nyquist frequency

- Regularly spaced zero crossings
- Not Realized in Practice
Typical Linear Channel Characteristics

Frequency Response $H(f)$

- Voiceband Telephone After Demodulation
  - $|H(f)|$ and $\text{ang } H(f)$

- Twisted Copper Pair with Transformers (DSL)
  - $|H(f)|$ and $\text{ang } H(f)$

- Radio
  - $|H(f)|$ and $\text{ang } H(f)$

Impulse Response $h(t)$

- Linear Equalizer
  - $h(t)$
  - $\sim10 \text{ ms}$

- $\sim\text{DFE}$

- Nulls require a non-linear equalizer: DFE or MLSE/VA

I/Q Equalizer

$|H(f)|$ and $\text{ang } H(f)$

$0 \leq f \leq f_0$
Pulse Distortion Due to MultiPath

Multi-(Two)path transmission:

Transmitter

\[ \lambda_1 \]

\[ s(t) \]

\[ \lambda_2 \]

\[ s(t-t_d) \]

Receiver

Signal from Path 1:

\[ s(t) \]

\[ A_1 \]

\[ s(t-t_d) \]

\[ A_2 \]

Signal from Path 2:

Resultant signal:

\[ A_1 + A_2 \]

\[ A_1 \]

\[ A_2 \]
Digital Baseband Modulation Techniques

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

**Typical Power Spectra:**

- Bipolar, Partial Response, 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 channel capacity
  - 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

At A:
\[ \{a_n\} \]

\[ \sum_n a_n \delta(t-nT) \]

At B:
\[ r(t) = \sum_n a_n x(t-nT) \]

At C:
\[ \{r(nt)\} \]

Margin Against Noise

At D:
\[ \{\hat{a}_n\} \]

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
- Minimum Bandwidth Pulse

Nyquist (1928)
Why Equalization Is Needed

(A) Amplitude

Frequency

(B) Transmitted Pulse

P(t)

(C) P(t) + P(t-T)

Time
INTERSYMBOL INTERFERENCE: ISI

• **Cause of ISI:**

```
\[
x(t) \xrightarrow{\text{Bandlimited and/or Delay-spread Channel}} z(t) \xrightarrow{\text{Equalizer}} y(t)
\]
```

- Ideal square-wave input signal, \( x(t) \)

```
\[
\begin{array}{cccccc}
0 & T & 2T & 3T & 4T \\
1 & 0 & 1 & 0 & 1
\end{array}
\]
```

- Output signal

```
\[
\begin{array}{c}
\text{Intersymbol interference} \\
\text{Sampling points}
\end{array}
\]
```

• **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]

PAM Waveform: \( r(t) = \sum_n a_n x(t - nT) \)

\[ r(kT) = a_k x(0) + \sum_{m \neq 0} a_{k-m} x_m \]

Desired \hspace{1cm} 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 \( \sum_{n \neq 0} x_n^2 \)
Eye Pattern

“Bad” - Closed

“Good” - Open

Threshold Level

Eye Pattern Display

Sample Instant

Margin for Error Due To Noise

Margin for Error Due to Timing

Symbol Timing Wave

Scope Trigger From Modem
The Raised Cosine Family of Nyquist Pulses

**Raised Cosine**

\[ x(t) = \frac{\sin \frac{\pi t}{T}}{\frac{\pi t}{T}} \cdot \cos \frac{\alpha \pi t}{T} \cdot \frac{1 - 4\alpha^2 t^2}{T^2} \]

**Excess Bandwidth**

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

Raised Cosine Pulse Shaping: (a) Frequency Response, (b) Time Response
Performance of PAM Systems: No ISI/Multipath (Gaussian Noise)

Probability of error $P_e$ 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

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

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

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{-t^2} dt$$
Adaptive Equalization

Block diagram of a baseband data transmission system.

Adaptive equalizer with a decision-directed mode of operation.