EE 443 Optical Fiber Communications
Dr. Donald Estreich
Fall Semester

Lecture 17

http://www.wiretechworld.com/the-future-of-optical-fibres/
Summary of Lecture 16 (on November 7, 2019)

1. The requirements of an OFC link include transmission distance, data rate and bit-error rate (BER).
2. Primary elements of the OFC link include source, fiber transmission link and photodetector (photodiode and amplifier).
3. Our two primary parameters of interest were (1) link power budget and (2) rise-time budget (to be sure we meet the data rate needed).
4. All OFC systems should have a link power margin (typically 6 to 8 dB) to allow for temperature variations, component aging and future component replacement or interchange.
5. The optical power-loss model included the source, fiber flylead connect, connectors, fiber sections (with splices as required), fiber flylead to receiver and photodiode (with amplifier).
6. Slide 15 summarized data on photodiodes receiver sensitivity versus data rate for several commonly used photodiodes (e.g., PIN vs APD).
Summary of Lecture 16 (continued)

7. One way to present a link-loss budget for an OFC link is to plot the power level versus distance of the link; showing source output power, step losses for connectors and splices, sloped loss of fiber itself, system margin and minimum detector sensitivity.

8. Another way to present a link-loss budget is with a spreadsheet table (which summarizes the loss increments on the plot).

9. The rise-time budget includes four rise time components: the transmitter rise time, the group velocity (material) dispersion rise time, the modal dispersion (multimode fiber only) rise time and the receiver (photodiode) rise time.

10. The system rise time is calculated by taking the root-mean-square of the sum of the four rise times.

\[ t_{\text{system}} = \sqrt{\sum_{i=1}^{4} t_i^2}; \quad i = 1, 2, 3, 4 \]
11. The transmitter rise time depends upon the diode’s response time and the drive circuitry around it.

12. The receiver rise time is dominated by the behavior of an RC network with 10%-to-90% rise time $\tau$ (nanoseconds) related to the receiver’s bandwidth $B_{rcvr}$ in MHz by

$$\tau = \frac{350}{B_{rcvr}}$$

13. The group velocity (material) dispersion rise time can be estimated from the dispersion coefficient $D$, the fiber length $L$ and the spectral width $\sigma_\lambda$.

$$t_{mat} = |D|L\sigma_\lambda$$
Summary of Lecture 16 (continued)

14. The modal dispersion rise time is estimated assuming a Gaussian pulse temporal response with a standard deviation (spread) $\sigma$ where the full-width half-maximum rise time is

$$t_{\text{FWHM}} = t_{\text{mod}} = 2\sigma \sqrt{2\log_e(2)} = 2.35\sigma$$

15. Examples of transmission distance versus data rate for both 800 nm and 1550 nm wavelengths were presented to illustrate the attenuation dominated region versus the dispersion dominated region of operation (obviously, at higher data rates).
Pulse Code Modulation

**Pulse-code modulation (PCM)** is a method used to digitally represent sampled analog signals. It is the standard form of digital audio in computers, compact discs, digital telephony and other digital audio applications.

---

**Diagram:**

- **A** represents the analog signal.
- **B** shows pulse amplitude modulation.
- **C** displays pulse width modulation.
- **D** illustrates pulse position modulation.
- **E** depicts pulse code modulation (3-bit coding).

---

*Analog signal*

*Pulse Amplitude Modulation*

*Pulse Width Modulation*

*Pulse Position Modulation*

*Pulse Code Modulation (3-bit coding)*
Digital-to-Digital Conversion

Line coding is the process of converting digital data to digital signals.

That is equivalent to converting bits (data) to symbols (baud). A “bit” is the basic data element in the digital representation and the “bit rate” is the number of bits sent per second (bits/sec). “Symbols” are the way we choose to combine bits into signals for transmission. The “symbol rate” (or signal rate, or modulation rate, or baud rate) is the number of symbols sent per second.

A goal of data communications is to increase the data rate (bit rate) depends upon the bandwidth of the channel.

*Analogy:* People (bits) in cars (symbols) using a highway where we want to avoid traffic jams and delays.
Bit Rate versus Symbol Rate (Baud Rate)

The speed of data is commonly expressed in bits/second or bytes/second. The data rate $R_b$ is related to the bit period $T_b$ (duration of a bit).

$$R_b = \frac{1}{T_b}$$

The bit rate is commonly referred to as the channel capacity.

Communication systems use symbols to convey information. A symbol may be one bit per symbol (called binary), or a group of bits, or a collection of defined voltage levels (multiple level symbols), etc.

The symbol rate $R_s$ is related to the symbol’s period (or duration) $T_s$ by

$$R_s = \frac{1}{T_s}$$

The symbol rate is also called Baud rate. Bit rate $R_b$ can be written as

$$R_b = R_s \times \log_2(\eta) = R_s \times n$$

where $\eta = 2^n$ = number of levels (for $n$ bits per symbol).
Signal-to-Noise Ratio versus Energy/Bit-to-Noise Ratio

In analog and digital communications, signal-to-noise ratio, usually written $S/N$ or $SNR$, is a measure of signal strength relative to background noise strength. The ratio is usually expressed in decibels (dB) and equals $10 \cdot \log_{10}[S/N]$.

Another metric that is often more useful in digital systems is the energy per bit-to-noise power ratio, denoted by $E_b/N_0$.

Define: 
- $R_b = \text{bit rate (in bits per second)}$
- $S = \text{total signal power (watts)}$
- $E_b = \text{energy per bit (in joules/bit)}$
- $N = \text{total noise power (watts encompassing entire bandwidth $B$ in Hz)}$
- $N_0 = \text{noise spectral density (}$N = N_0 \cdot B\text{ where } B = \text{bandwidth in Hz}$)

Then,

$$\frac{S}{R_b} = E_b \quad \text{and} \quad \frac{E_b}{N} = \frac{S}{R_b \cdot N} \quad \text{and} \quad SNR = \frac{R_b E_b}{N_0 B}$$

Increasing the data rate $R_b$ increases the $SNR$. However, in general it also increases the noise in the denominator, which lowers the $SNR$. 
Relationship Between \( E_b/N_0 \) and S/N

\[
E_b = \left( \frac{\text{Signal power}}{\text{Bit rate}} \right) = \frac{S}{R_b} = \left( \frac{E/t}{\text{bits/t}} \right)
\]

\[
N_O = \left( \frac{\text{Noise power}}{\text{Bandwidth}} \right) = \frac{N}{B}
\]

\[
\frac{E_b}{N_O} = \left( \frac{S}{R_b} \right) = \left( \frac{S}{B} \right) \times \left( \frac{B}{N} \right) = \left( \frac{S}{N} \right) \times \left( \frac{B}{R_b} \right)
\]

Signal-to-noise ratio

Processing gain
Relationship Between $E_b/N_0$ and S/N (continued)

In digital communications systems the $E_b/N_0$ ratio can be thought of as a “normalized signal-to-noise ratio. “

We can roughly equate signal power to energy per bit by

$$E_b = P_{\text{signal}} \cdot T_S,$$

where $T_S$ is the symbol period,

and the noise power per hertz, denoted by $N_0$, is the total noise power $N$ divided by bandwidth $B$.

$E_b/N_0$ is commonly used to as the primary variable in establishing the bit error rate for all modulation schemes.
A **line code** is a specific code (with precisely defined parameters) used for transmitting a **digital signal** over a channel. **Line coding** is used in **digital data** transport – patterns and levels of voltage, current or photons used to represent **digital data** on a transmission link.
Four Categories of Baseband Signaling

NRZ (non-return-to-zero)
A non-return-to-zero (NRZ) line code is a binary code in which ones are represented by one significant condition, usually a positive voltage, while zeros are represented by some other significant condition, often a negative voltage (or zero), with no other neutral or rest condition.

RZ (return-to-zero)
Return-to-zero (RZ or RTZ) describes a line code used in telecommunications signals in which the signal drops (returns) to zero between each pulse. This takes place even if a number of consecutive 0s or 1s occur in the signal. The signal is self-clocking.

Phase-encoded ($\phi$-encoded)
In telecommunication and data storage, Manchester code (also known as phase encoding) is a line code in which the encoding of each data bit is either low then high, or high then low, for equal time. It is a self-clocking signal with no DC component.

Multi-level binary
Desirable Properties of a Line Code

- **Self-Synchronization:** There is enough timing information built into the code so that bit synchronizers can extract the timing or clock signal. A long series of binary 1’s or 0’s should not cause a problem in time recovery.

- **Low Probability of Bit Error:** Receivers can be designed that recover the binary data with a low probability of bit error when the input data is corrupted by noise or ISI.

- **A Spectrum that is Suitable for the Channel:** If a channel is AC-coupled, the PSD of the line code signal should be negligible at frequencies near zero Hz. In addition, the signal bandwidth needs to fit the channel bandwidth, so ISI will not be a problem.

- **Transmission Bandwidth:** This should be as small as possible.

- **Error Detection Capability:** It should be possible to implement this feature easily by the addition of channel encoders and decoders, or the feature should be incorporated into the line code.

Unipolar RZ and Unipolar NRZ (*aka* “On-Off Keying”)

Appears as raw binary bits without any coding. Typically binary 1 maps to logic-level high, and binary 0 maps to logic-level low.

### ADVANTAGES
1. Simplicity
2. Doesn’t require a lot of bandwidth

### DISADVANTAGES
1. Presence of a DC level
2. Contains low-frequency components (→ drooping)
3. No clocking component to synchronize to at receiver
4. Long string of zeros causes loss of synchronization
Polar RZ and Polar NRZ

Polar RZ takes twice as much bandwidth as polar NRZ.

State “1” ⇒ Pulse of amplitude +A
State “0” ⇒ Pulse of amplitude -A

**ADVANTAGES**

1. Simplicity
2. Both polar RZ and NRZ have no low-frequency components

**DISADVANTAGES**

1. No error detection
2. No clock is present
3. Polar RZ needs twice the bandwidth as that of polar NRZ
Bipolar NRZ and RZ (aka Duo-Binary)

Uses three levels of signal level (+A, 0, -A) and has “Alternate Mark Inversion” (AMI)

State “1” \( \Rightarrow \) Alternating levels of +A and -A
State “0” \( \Rightarrow \) No pulse

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Period</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RZ</td>
<td>1. Error detection is possible</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td>2. Transmission over AC-coupled lines can be accomplished</td>
<td></td>
</tr>
<tr>
<td>-A</td>
<td></td>
<td>1. Not favorable to clock recovery</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Long strings of 0’s lead to synchronization problems</td>
<td></td>
</tr>
</tbody>
</table>
Bipolar RZ (3 Levels) or RZ-AMI

Uses three levels of signal level (+A, 0, -A) exhibits "Alternate Mark Inversion" – AMI

State “1” ⇒ Alternating levels of +A and -A
State “0” ⇒ No pulse

<table>
<thead>
<tr>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. No DC component</td>
<td>1. Limited error correction capability</td>
</tr>
<tr>
<td>2. Preferred over NRZ</td>
<td></td>
</tr>
<tr>
<td>for synchronization</td>
<td></td>
</tr>
<tr>
<td>between XMTR/RCVR</td>
<td></td>
</tr>
</tbody>
</table>
Manchester (Bi-Phase or Split-Phase) Coding
IEEE 802.3 standard

In telecommunication and data storage, Manchester code (aka phase encoding) is a line code in which the encoding of each data bit is either low then high, or high then low, for equal time. It is a self-clocking signal with no DC component. Manchester coding is a special case of binary phase-shift keying (BPSK), where the data controls the phase of a square wave carrier whose frequency is the data rate. Manchester code ensures frequent transitions directly proportional to the clock rate -- this aids in clock recovery.

http://www.thenetworkencyclopedia.com/entry/manchester-coding/
Manchester (Bi-Phase or Split-Phase) Coding

The duration of a symbol is divided into two halves.

There is a transition at the center of every symbol period.

The diagram shows a waveform with a transition at the center of every symbol period, indicating the Manchester coding scheme.

State “1” ⇒ +A in 1st half of $T_s$ and −A in 2nd half
State “0” ⇒ -A in 1st half of $T_s$ and +A in 2nd half

<table>
<thead>
<tr>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. No DC component</td>
<td></td>
</tr>
<tr>
<td>2. No signal droop problem</td>
<td></td>
</tr>
<tr>
<td>3. Easy to synchronize to the waveform</td>
<td>1. Greater bandwidth required for this waveform</td>
</tr>
<tr>
<td></td>
<td>2. No error correction capability</td>
</tr>
</tbody>
</table>

A

RZ

0

-A

$T_s$

1 0 1 1 0 1 0

1                0               1               1               0                1              0

The duration of a symbol is divided into two halves.

There is a transition at the center of every symbol period.
Manchester (Bi-Phase or Split-Phase) Coding

Two forms of Manchester

Manchester (as per G.E. Thomas) (1949)

Manchester (as per IEEE 802.3)

IEEE 802.3 standard Minimum bandwidth of Manchester is twice that of NRZ

https://en.wikipedia.org/wiki/Manchester_code
Polar Quaternary NRZ (mBnL) Coding

State “00” ⇒ Voltage level at -3A/2
State “01” ⇒ Voltage level at -A/2
State “10” ⇒ Voltage level at +A/2
State “11” ⇒ Voltage level at +3A/2

Also referred to as mBnL coding, where m is the length of the binary pattern, and n is the number of levels (L = B for binary (n = 2), L = T for ternary (n = 3) and L = Q for quaternary (n = 4). Hence, polar quaternary is 2B1Q.

Used in ISDN networks and in HDSL digital subscriber lines.

Integrated Services Digital Network (ISDN) is a set of communication standards for simultaneous digital transmission of voice, video, data, and other network services over the traditional circuits of the public switched telephone network.
Wide Area Networks Sometimes Use 8b/10b Coding

8b/10b is a line code that maps 8-bit words into 10-bit symbols to achieve DC-balance and bounded disparity, and yet provide enough state changes to allow reasonable clock recovery. This means that the difference between the counts of ones and zeros in a string of at least 20 bits is no more than two, and that there are not more than five ones or zeros in a row. This reduces the demand for the lower bandwidth limit of the channel.

Used in transmitting data on enterprise system connections, gigabit Ethernet and over fiber channel.

8b/10b - The Benefits

- The coding provides frequent transitions for easy clock recovery
- Provides a balance between the number of one bits and zero bits transmitted, this is called DC balance
- DC balance insures that the duty cycle of lasers used in optical transmission is maintained at 50% for optimal performance and power dissipation
- DC balance limits the amount of DC offset that accumulates at the receiver which helps setting the level detect thresholds

https://www.youtube.com/watch?v=B6JRJ3ax3mc
### Block Code: 8B/10B Coding

Tables are used to map every 8-Bit input data into encoded 10-Bit data. For Example (all details are omitted here)

<table>
<thead>
<tr>
<th>DATA(0) or CONTROL(1)</th>
<th>8 BIT INPUT DATA</th>
<th>Dx.y / Kx.y</th>
<th>10-BIT OUTPUT DATA (RD-)</th>
<th>10-BIT OUTPUT DATA (RD+)</th>
<th>DISPARITY (RD-)</th>
<th>DISPARITY (RD+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8'b_000_01110</td>
<td>D14.0</td>
<td>10'b_011100_1011</td>
<td>10'b_011100_0100</td>
<td>2</td>
<td>-2</td>
</tr>
<tr>
<td>0</td>
<td>8'b_010_01100</td>
<td>D12.2</td>
<td>10'b_001101_0101</td>
<td>10'b_001101_0101</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>8'b_100_01001</td>
<td>D9.4</td>
<td>10'b_100101_1101</td>
<td>10'b_100101_0010</td>
<td>2</td>
<td>-2</td>
</tr>
<tr>
<td>1</td>
<td>8'b_101_11100</td>
<td>K28.5</td>
<td>10'b_001111_1010</td>
<td>10'b_110000_0101</td>
<td>2</td>
<td>-2</td>
</tr>
<tr>
<td>1</td>
<td>8'b_111_11011</td>
<td>K27.7</td>
<td>10'b_110110_1000</td>
<td>10'b_001001_0111</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>8'b_111_11110</td>
<td>K30.7</td>
<td>10'b_011110_1000</td>
<td>10'b_100001_0111</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Used in transmitting data on enterprise system connections, gigabit Ethernet and over fiber channel.
Signal Power and Power Spectral Density

Power $P_g$ of the signal $g(t)$

$$P_g = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} g(t)g^*(t)dt$$

$$P_g = \lim_{T \to \infty} \frac{E_{g_T}}{T}$$

$G_T(f)$ is the Fourier transform of $g_T(t)$

Power spectral density $S_g(f)$ of the signal $g(t)$

$$S_g(f) = \lim_{T \to \infty} \frac{|G_T(f)|^2}{T}$$

$$P_g = \int_{-\infty}^{\infty} S_g(f)df = 2 \int_{0}^{\infty} S_g(f)df$$

$S_x(f) \rightarrow \boxed{H(f)} \rightarrow S_y(f) = |H(f)|^2 S_x(f)$

https://slideplayer.com/slide/3170129/
Power Spectral Density

Fourier Transform

Signal

Inverse Fourier Transform

Fourier Spectrum

\[ S(f) = \int s(t)e^{-j2\pi ft} dt \]

\[ s(t) = \int S(f)e^{+j2\pi ft} df \]

https://slideplayer.com/slide/4757604/
Two Methods for Estimating the Power Spectral Density

- **Autocorrelation**
  - \( X(t) \)
  - \( R_{XX}(\tau) \) (offset \( \tau = t_2 - t_1 \))

- **Fourier Transform**
  - \( X(f) \)
  - \( |X(f)|^2 \)
  - \( S_{xx}(f) \)

https://slideplayer.com/slide/4757604/
Power Spectral Density of Unipolar NRZ and Polar NRZ Signals

Power Spectral Density of Unipolar RZ, Polar RZ & Manchester Signals

Spectral Densities of PCM Waveforms

Mean = 0 ➔ DC=0
Transition period ↑ B ↓

Bandwidth efficiency

R/B [bps/Hz]

Next up: Section 9.3.2 Receiver capacitance and bandwidth

https://www.skipprichard.com/ask-questions-to-improve-your-leadership/
Autocorrelation Example