EE 443/CS 543 Optical Fiber Communications
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Fall Semester

Lecture 18

http://www.wiretechworld.com/the-future-of-optical-fibres/
Summary of Lecture 17

1. Pulse Code Modulation (PCM) is used to represent analog data as a sequence of binary (1s and 0s) digital signal (a string of bits).
2. A bit is the basic data unit in digital communications and the bit rate is the basic data rate.
3. Symbols are made up of combinations of bits for format signals for transmission.
4. The symbol rate is the number of symbols per second (also called the signal rate, or baud rate).
5. The bit rate $R_b$ is the reciprocal of the bit period $T_b$ ($R_b = 1/T_b$).
6. The symbol rate $R_S$ is the reciprocal of the symbol period $T_S$ ($R_S = 1/T_S$).
7. The bit rate may be written as $R_b = R_S \times \log_2(n)$ where $n$ is the number of bits per symbol.
8. Signal-to-noise ratio (SNR) measures the signal power to noise power ratio.
Summary of Lecture 17 (continued)

9. Energy per bit $E_b$ to noise spectral density $N_0$ is related to the SNR by

$$SNR = \left( \frac{R_b}{B} \right) \left( \frac{E_b}{N_0} \right)$$

where $R_b$ is the bit rate and $B$ is the total bandwidth.

10. $E_b/N_0$ can be thought of as a normalized SNR. ($E_b = P_{signal} \times T_S,$ where $T_S$ is the symbol period).

11. Baseband signaling can be categorized into four categories: Non-Return-to-Zero (NRZ), Return-to-Zero (RZ), Phase-encoded and Multi-level.

12. Desirable properties of a line code include:
   
   a. Self-synchronization 
   b. Low bit error probability 
   c. Suitable power spectral density 
   d. Adequate transmission bandwidth 
   e. Error detection capability
Summary of Lecture 17 (continued)

13. Primary examples of line codes presented were
   a. Unipolar RZ and unipolar NRZ
   b. Polar RZ and polar NRZ
   c. Bipolar NRZ and bipolar RZ \textit{(aka duo-binary)}
   d. Bipolar RZ (3-level) or RZ-AMI
   e. Manchester (bi-phase or split-phase)

14. Manchester is the IEEE 802.3 standard (Ethernet) and has a transition at the center of every bit period (a “one” is \(+A\) in the first-half of the period and is \(–A\) in the second-half; a “zero” is \(–A\) in the first-half of the period and \(+A\) in the second-half.

15. Manchester coding is easy to synchronize, has no DC component but needs twice the bandwidth of NRZ coding.
Summary of Lecture 17 (continued)

16. The spectral density $S(f)$ of signal $s(t)$ is the Fourier transform

$$S(f) = \int_{-\infty}^{\infty} s(t)e^{-j2\pi ft} dt$$

and $s(t)$ can be regained by taking the inverse Fourier transform.

17. The power spectral density (PSD) of the signal describes the power spectral density – it is commonly expressed in watts per hertz (W/Hz).

18. The power spectral density of signal $s(t)$ is equal to $|S(f)|^2$.

19. The power spectral density can be obtained by the taking the Fourier transform of the autocorrelation function of $s(t)$. 
Optical Fiber Connection Methods

**Connection Method**

- **Fusion splice**
  Fusing the tips of fibers to connect one another

- **Mechanical splice**
  Physically connecting the fibers using “V-groove” device

- **Connector**
  Physically connecting the fibers using adapter

https://www.slideshare.net/MrCalvinPham/aq7275-hng-dn-s-dng-my-o-si-cp-quang-yokogawa-otdr
Reflectance or optical return loss (also called "back reflection") of the connector is the amount of light back reflected toward the source due to reflections off the interface of the polished end surface of the connector and air. It is called Fresnel reflection and is caused by the light going through the change in index of refraction at the interface between the fiber (n=1.5) and air (n=1). Reflectance is primarily a problem with connectors but also affects mechanical splices which contain an index matching gel to reduce reflectance.

https://www.thefoa.org/tech/ref/OSP/term.html
Numerical Aperature

In optics, the **numerical aperture (NA)** of an optical system is a dimensionless number that characterizes the range of angles over which the system can accept or emit light.

https://en.wikipedia.org/wiki/Numerical_aperture

[Diagram of numerical aperture]

**mode field diameter (MFD)**

Effective Numerical Aperture $N_{e\theta}$

https://www.sukhamburg.com/effNumAperture.html
Optical Fiber Splicing Techniques

- Optical Fiber Splicing Techniques
  - Fusion Splicing
  - Mechanical Splicing
    - V-grooved Splicing
    - Elastic-tube Splicing

https://circuitglobe.com/splicing-of-optical-fibers.html
One of the Problems Encountered With Fiber Splicing

Lateral Offset

Michaelson Interferometer can be used for characterizing the offset

Optical Fiber Splicing

There are two types of splices, fusion and mechanical. Fusion splicing is most widely used as it provides for the lowest loss and least reflectance, as well as providing the strongest and most reliable joint. Fusion splicing machines are available in two types that splice a single fiber or a ribbon of 12 fibers at one time. Virtually all singlemode splices are fusion. Mechanical splicing is mostly used for temporary restoration and for multimode splicing. Automated splicing machines are available which produce very good and repeatable splices.

https://www.thefoa.org/tech/ref/OSP/term.html
Fusion Splicing

Fusion splices are made by "welding" the two fibers together usually by an electric arc. To be safe, you should not do that in an enclosed space like a manhole or an explosive atmosphere, and the equipment is too bulky for most aerial applications, so fusion splicing is usually done above ground in a truck or trailer set up for the purpose. Splicing on poles is obviously dangerous too. It’s easier to bring extra cable length into a trailer on the ground and work in a clean environment for splicing, placing splices in a closure and testing. The final closure is then placed in location and the extra fiber carefully looped and mounted in an appropriate place.

https://www.thefoa.org/tech/ref/OSP/term.html
Fusion Splicing

Splicing any fiber by making use of the **fusion technique provides a permanent (long-lasting) contact** between the two fibers. In the fusion splicing, the two fibers are thermally joined.
Fusion Splicer – Artech Communications Systems

V-Groove Mechanical Splice of Optical Fiber

Alignment Sleeve Mechanical Splice of Optical Fiber

$9.95 on Amazon.com

Best used with large diameter Plastic optical fiber

https://www.amazon.com/Economic-Mechanical-Splice-Cladding-Multimode/dp/B00FY4ZD5O
Mechanical Splicing of Optical Fibers

Mechanical splices are used to create permanent joints between two fibers by holding the fibers in an alignment fixture and reducing loss and reflectance with a transparent gel or optical adhesive between the fibers that matches the optical properties of the glass. Mechanical splices generally have higher loss and greater reflectance than fusion splices, and because the fibers are crimped to hold them in place, do not have as good fiber retention or pull-out strength. The splice component itself, which includes a precision alignment mechanism, is more expensive than the simple protection sleeve needed by a fusion splice. Mechanical splices are most popular for fast, temporary restoration or for splicing multimode fibers in “on-premises” installation.

https://www.thefoa.org/tech/ref/termination/mechsplice.html
Mechanical Cleaving of Optical Fibers

The most important step in mechanical splicing is cleaving the fiber properly. Most mechanical splicing kits come with an inexpensive cleaver that looks like a stapler.

https://www.thefoa.org/tech/ref/termination/mechsplice.html
How Can We Evaluate the Quality of Optical Splices and Connections?

Techopedia explains *Optical Time Domain Reflectometer (OTDR)*

Fiber communication system maintenance depends on optical time domain reflectometers. An OTDR simply generates a pulse inside a fiber to be tested for faults or defects. Different events within the fiber create a back scatter. Pulses are returned to the OTDR and their strengths are then measured and calculated as a function of time and plotted as a function of fiber stretch. The strength and returned signal tell about the location and intensity of the fault present. Not only maintenance, but also optical line installation services utilize OTDRs.


An excellent tutorial of Optical TDR from Keysight Technologies is at

Optical Time Domain Reflectometer (OTDR)

The OTDR consists of a high-power laser transmitter that sends narrow pulses of light down the fiber. Back-scattered light and reflected light returns to the OTDR through the fiber and is directed into a sensitive receiver via a coupler in the OTDR front end. For each measurement, the OTDR sends out a pulse and measures the light coming back over time. At any point in time, the light the OTDR sees is the light scattered from the pulse passing through a region of the fiber. Think of the OTDR pulse as being a "virtual source" created by the scattering that is testing all the fiber between itself and the OTDR as it moves down the fiber. Since it is possible to calibrate the speed of the pulse as it passes down the fiber from the index of refraction of the glass in the core of the fiber, the OTDR can correlate the backscattered light with an actual location in the fiber. Thus, it can create a display of the amount of backscattered light at any point in the fiber.

https://www.thefoa.org/tech/ref/testing/OTDR/OTDR.html
Optical Time Domain Reflectometry (Backscatter Signal)

From: John M. Senior, Optical Fiber Communications, 3rd ed., 2009; Figure 14.33, p. 954
Box Car Integrator for Signal Recovery

The boxcar integrator (*aka* boxcar averager, boxcar detector, or gated integrator) is a sampling instrument that integrates the applied input signal during a predefined gate-width or aperture width, starting at a predefined trigger, gate, or aperture delay after an applied trigger. Each of these integrated samples of input signal can then be averaged, using either an analog averager or by digitizing each sample and then averaging the resulting digital values.

http://123.physics.ucdavis.edu/week_1_files/Boxcar_Averager.pdf

https://www.zhinst.com/products/uhfli/uhf-box/old-school
Box Car Integrator (continued)

The boxcar performs signal recovery by combining three processes.

(1) The input signal only affects the output during the period in which it is being sampled; at all other times its level is unimportant. The sampling window achieves temporal separation of the signal from the noise.

(2) The signal is integrated during the gate width, unlike common sample and hold circuits that simply take a "snapshot" measurement of the signal level at one point in time. Hence if there is noise or other interference present at the input at frequencies that are much higher than the reciprocal of the gate-width, these will be suppressed.

(3) The measured samples are themselves averaged, ensuring that low frequency fluctuation or noise, which would cause sample-to-sample variation, is also reduced.
Box Car Integrator (continued)

Princeton Applied Research / EG&G Model 162 Boxcar Averager

Box car integrators are used for ultra fast measurements using pulsed lasers

Backscatter Power Plot From a Fiber Under Test

From: John M. Senior, Optical Fiber Communications, 3rd ed., 2009; Figure 14.34, p. 955
Backscattered Optical Power Equation

Backscattered optical power: \( P_R \)

\[
P_R = \frac{1}{2} P_{in} S \gamma_R W_0 v_{gr} \left( \exp(-\gamma v_{gr} t) \right)
\]

- \( P_{in} \) = Optical power launched into fiber
- \( S \) = Fraction of captured optical power
- \( \gamma_R \) = Rayleigh scattering coefficient (loss/length)
- \( W_0 \) = Pulse width
- \( v_{gr} \) = Group velocity
- \( \gamma \) = Attenuation coefficient of optical fiber
- \( t \) = Time

where \( S = \frac{(NA)^2}{4n_1^2} \) (step index)

From: John M. Senior, Optical Fiber Communications, 3rd ed., 2009; Section 14.10.1, p. 952
Display of Optical Time Domain Reflectometer Trace

[Diagram showing OTDR trace]

https://www.thefoa.org/tech/ref/testing/OTDR/OTDR.html
Display of Optical Time Domain Reflectometer Trace

https://www.researchgate.net/figure/Typical-OTDR-trace-7_fig2_221935740
Optical Time Domain Reflectometer Using Sampling Block Diagram

Without the box car integrator

https://www.researchgate.net/figure/OTDR-Block-diagram-6_fig1_221935740
Optical Time Domain Reflectometer – Yokogawa A7270

https://cdn.tmi.yokogawa.com/BUAQ1000-01EN.pdf
Requirements for Optical Fiber Connectors

The optical connectors are generally used to join sources as well as detectors to optical fiber temporarily.

- Some of the principal requirements of a good connector design are as follows:
  - Low losses
  - Interchangeability
  - Ease of assembly
  - Low environmental sensitivity
  - Low-cost and reliable construction
  - Ease of connection

https://pt.slideshare.net/liju_thomas/optical-fiber-connectors/7
Optical Fiber Patch Cables and Panels

Optical fiber optic patch cables are used to cross-connect, connected to fiber optic communication equipment or test the individual fibers in the fiber optic cables.

Fiber optic connectors are unique. Fiber cables transmit pulses of light instead of electrical signals, so the terminations must be much more precise. Instead of merely allowing pins to make metal-to-metal contact, fiber optic connectors must align microscopic glass fibers perfectly in order to allow for communication.

While there are many different types of fiber connectors, they share similar design characteristics.

Simplex vs. duplex: Simplex means 1 connector per end while duplex means 2 connectors per end.

There are three major components of a fiber connector: the ferrule, the connector body, and the coupling mechanism.

https://www.cablestogo.com/learning/connector-guides/fiber-networking#lst
Major Components of a Fiber Optic Connector

There are three major components of a fiber connector: the ferrule, the connector body, and the coupling mechanism.

• **Ferrule**: this is a thin structure (often cylindrical) that holds the glass fiber. It has a hollowed-out center that forms a tight grip on the fiber. Ferrules are usually made from ceramic, metal, or high-quality plastic, and typically will hold one strand of fiber.

• **Connector Body**: this is a plastic or metal structure that holds the ferrule and attaches to the jacket and strengthens members of the fiber cable itself.

• **Coupling Mechanism**: this is a part of the connector body that holds the connector in place when it gets attached to another device (a switch, NIC, bulkhead coupler, etc.). It may be a latch clip, a bayonet-style nut, or similar device.

https://www.cablestogo.com/learning/connector-guides/fiber-networking#1st
Optical Fiber Connectors

http://srisailamsp.blogspot.com/2016/12/fiber-optic-cables.html
Optical Fiber Connectors

The St, SC, FC and the LC optical fiber connectors are the most widely used.

http://www.unitekfiber.com/introduction-to-several-common-fiber-optic-connect.html
Small Form Factor (SFF)

SFF connectors grew from the effort to make fiber connections smaller. In a rack or closet environment, space for several connections is limited, and thus manufacturers sought a way to increase port density. A standard was developed for smaller connectors called SFF (Small Form Factor). There are many different types of SFF connectors, but they are all smaller than normal ST or SC connections.

https://www.cablestogo.com/learning/connector-guides/fiber-networking#!lst
Angled Physical Contact (APC) Optical Fiber Connectors

APC Connector is a type of fiber connector that minimizes back reflection due to a 5° to 15° angle-polish applied to end faces.

FC Optical Fiber Connector

FC stands for Fixed Connection. It is fixed by way of a threaded barrel housing. FC connectors are typical in test environments and for singlemode applications. FC connectors were designed for use in high-vibration environments. The FC Connector is the most popular connector used today. It can be seen in every area of the communications environment, from a telecom's distribution room to a LAN closet, the FC has set the standard for optical Fiber connectors. It's been mostly replaced by SCs and LCs.

FC connectors offer extremely precise positioning of the fiber optic Cable with respect to the transmitter's optical Source Emitter and the receiver's optical detector.

http://www.timbercon.com/FC-Connector.html
The ST connector was one of the first connector types widely implemented in fiber optic networking applications. Originally developed by AT&T, it stands for Straight Tip connector. ST connections use a 2.5mm ferrule with a round plastic or metal body. The connector stays in place with a "twist-on/twist-off" bayonet-style mechanism. Although extremely popular for many years, the ST connector is slowly being supplanted by smaller, denser connections in many installations.

https://www.cablestogo.com/learning/connector-guides/fiber-networking#lst
SC Optical Fiber Connector

SC connectors also use a round 2.5mm ferrule to hold a single fiber. They use a push-on/pull-off mating mechanism which is generally easier to use than the twist-style ST connector when in tight spaces. The connector body of an SC connector is square shaped, and two SC connectors are usually held together with a plastic clip (this is referred to as a duplex connection). The SC connector was developed in Japan by NTT (the Japanese telecommunications company), and is believed to be an abbreviation for Subscriber Connector, or possibly Standard Connector.

https://www.cablestogo.com/learning/connector-guides/fiber-networking#!1st
One popular Small Form Factor (SFF) connector is the LC type. This interface was developed by Lucent Technologies (hence, Lucent Connector). It uses a retaining tab mechanism, similar to a phone or RJ45 connector, and the connector body resembles the squarish shape of SC connector. LC connectors are normally held together in a duplex configuration with a plastic clip. The ferrule of an LC connector is 1.25mm.

https://www.cablestogo.com/learning/connector-guides/fiber-networking#lst
MTP® Optical Fiber Connector

MTP® is a special type of fiber optic connector. Made by US Conec, it is an improvement of the original MPO (Multi-fiber Push-On) connector designed by NTT. The MTP® connector is designed to terminate several fibers—up to 12 strands—in a single ferrule. MTP® connections are held in place by a push-on/pull-off latch, and can also be distinguished by a pair of metal guide pins that protrude from the front of the connector. Because of the high number of fiber strands available in a small connection, MTP® assemblies are used for backbone, cross-connect, and breakout applications.

https://www.cablestogo.com/learning/connector-guides/fiber-networking#1st
MTRJ Optical Fiber Connector

This is another popular SFF connector. Based on a specification by NTT, it was developed by AMP/Tyco and Corning, and stands for Mechanical Transfer-Registered Jack. The MTRJ connector closely resembles an RJ-style modular plug, even getting part of its name from the resemblance. MTRJ connectors are always duplex in that they hold two fibers. The body and ferrule are normally made from plastic or plastic composite, and lock into place with a tab (just like a modular RJ-style plug).

https://www.cablestogo.com/learning/connector-guides/fiber-networking#1st
MU Optical Fiber Connector

MU looks a miniature SC with a 1.25 mm ferrule. It’s more popular in Japan and the far east.

MU is covered in the TIA connector intermateability standard (TIA-604-17).

https://www.thefoa.org/tech/connID.htm

There were few new connectors introduced between 2000 and 2017. But there have been several new connectors that are designed for small size, making the duplex LC in the middle look quite large. The Senko CS on the left is a duplex connector using the LC 1.25mm ferrule. The SN on the right also is a duplex connector using 1.25mm ferrules but it uses a vertical format. The salient feature of these connectors is panel or transceiver density. The CS is horizontal and has about twice the density of a LC.

Similar to the SENKO is the US Conec MDC which appears to have been designed to a similar requirement.

https://www.thefoa.org/tech/connID.htm

CS (L) and SN (R) connectors with a duplex LC

US Conec MDC
RJ-45 Ethernet (Copper Wire) Connector

An 8-position, 8-conductor modular connector that is most often used for data networks such as Ethernet. RJ-45 connectors are physically wider than the RJ-11/12 connectors used for telephone. In network applications, RJ-45 cable assemblies are used to connect from a patch panel to a network switch, and to connect a computer’s Network Interface Card to a data port.

https://www.cablestogo.com/learning/connector-guides/fiber-networking#1st
Infiniband™ (4x) Copper Wire Network Connector

Infiniband™ is a high-bandwidth I/O communication technology that is typically deployed in data centers, server clusters, and HPC (High Performance Computing) applications. Infiniband cables use a connector based on the Micro GigaCN series developed by Fujitsu. The most common type of connector in use is the "4X", named because it supports four aggregated data links. The cable assembly will appear identical to the 10G-CX4 cables; however, the 10G-CX4 cables are tested for a different set of standards. Infiniband cables cannot be used in 10G-CX4 applications.

https://www.cablestogo.com/learning/connector-guides/fiber-networking#1st
10G-CX4 Copper Wire Network Connector

10G-CX4 was the first 10G copper standard published. The connector used is similar to that of the Infiniband connector. The 10G-CX4 specification is designed to work up to a distance of 15 meters. Each of the 4 lanes carries 3.125 G baud of signaling bandwidth. 10G-CX4 gives the advantage of low power, low cost, and low latency.

https://www.cablestogo.com/learning/connector-guides/fiber-networking#lst
### Comparison Chart of Popular Optical Fiber Connectors

<table>
<thead>
<tr>
<th>Name</th>
<th>Mating Cycles</th>
<th>Ferrule Size</th>
<th>Typical Insertion Loss (dB)</th>
<th>IEC Specification</th>
<th>Cost</th>
<th>Ease of Use</th>
<th>Application Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC</td>
<td>1000</td>
<td>Ø 2.5mm Ceramic</td>
<td>0.25 - 0.5</td>
<td>61754-4</td>
<td>$$</td>
<td>•••</td>
<td>Mainstream, Reliable, Fast deployment, Field fit</td>
</tr>
<tr>
<td>LC</td>
<td>500</td>
<td>Ø 1.25mm Ceramic</td>
<td>0.25 - 0.5</td>
<td>61754-20</td>
<td>$$</td>
<td>••••</td>
<td>High density, Cost effective, Field fit</td>
</tr>
<tr>
<td>FC</td>
<td>500</td>
<td>Ø 2.5mm Ceramic</td>
<td>0.25 - 0.5</td>
<td>61754-13</td>
<td>$$$</td>
<td>••••</td>
<td>High precision, Vibration environments, Field fit</td>
</tr>
<tr>
<td>ST</td>
<td>500</td>
<td>Ø 2.5mm Ceramic</td>
<td>0.25 - 0.5</td>
<td>61754-2</td>
<td>$$$</td>
<td>••••</td>
<td>Military (legacy), Field fit</td>
</tr>
<tr>
<td>MPO/MTP</td>
<td>1000</td>
<td>6.4 x 2.5mm molded</td>
<td>0.25 – 0.75</td>
<td>61754-7</td>
<td>$*</td>
<td>••••</td>
<td>High Density, Aggregate Networking, Fast deployment</td>
</tr>
</tbody>
</table>

IEC is International Electrotechnical Commission (part of ITU)

[https://www.ppc-online.com/blog/fiber-connectors-whats-the-difference](https://www.ppc-online.com/blog/fiber-connectors-whats-the-difference)
Questions?

Cross-sectional view of bulkhead connector

http://www.fiber-optic-components.com/tag/fiber-optic-connector