lec 1.02: Optical Transmission technology

Optical Fibre uses the phenomenon of total internal reflection

Typical Path loss is 0.2 dB/Km

- Can go over 150 km without requiring amplification

Radiation of copper wires

A static current on a wire produces a static electro-magnetic field

A variable current on a wire produces a varying electromagnetic field i.e it radiates energy.

Copper wires in a circuit give and receive equal radiation thus Antennae are equally as good at giving and receiving signal

Going and returning current cancel each other out as they tend to have an opposite sign

Twisting copper is better than parallel copper in reducing interference. The signs changing mean the stronger signal is negated (look at diagram in notes)

Coaxial copper wiring has less signal loss due to the large conductor and a lower density inner core. Makes use of the Faraday principle

Coaxial Loss:

1. dissipation in the conductor
2. dissipation in the dielectric
3. radiation

Total internal reflection

The idea of total internal reflection is to fire light into a medium who's refractive index, a value which determines the degree of refraction of light entering this medium, is less than the refractive index of the medium which encompasses it.

This is saying that when light travels through the inner medium, there is an angle of entry to the medium at which no refraction of the light will occur as the light hits the outer medium. The entire ray of light is reflected back to the inner medium.

So any rays which enter the medium at an angle less than that of the maximum angle for total internal reflection to occur won't lose any power/signal along the way. This is called the *cone of acceptance*

Refractive index: $n = \frac{c_0}{c}$ where c_0 is the speed of light in a vacuum and c is the speed of light in the medium considered

If the inner mediums refractive index is greater than the outer mediums refractive index than the angle $\theta_2 > \theta_1$ meaning the refracted lights angle from the vertical access is greater than the reflected lights angle from the vertical access at the point of contact between the two mediums.

There is a *cone of acceptance* where all rays less than θ_{max} will propagate via total internal reflection

Path loss in Fibre

The amount of power lost depends on the frequency (or wavelength) used for the transmission

The smallest amount of path loss in fibre occurs at a wavelength of 1.55 μm and is 0.2 dB/Km

Dispersion in Fibre

refractive index is not constant but depends on the frequency

The dispersion coefficient D is measured in $\frac{ps}{nm.km}$

Three types of dispersion:

Modal dispersion:

- different modes propagate at different speeds. Can only happen in multi-mode fibre

Chromatic dispersion:

- Different frequencies propagate at different speeds

Polarization dispersion:

- different spatial polarization can occur at different speeds

Modal dispersion in fibre

Modes are the angles taken by beams of light through a fibre. This angle can affect the distance travelled by a beam.

The mode will cause spreading of the signal. This can lead to Inter Symbol Interference (ISI)

ISI -> Overlapping series of pulses in a channel

Single vs. multi-mode A multi-mode fibre has a larger core, which allows multiple modes to coexists at the frequencies used for optical communication.

A single mode fibre has a smaller core that only allows a single propagation mode.

Use a single mode-fibre to get rid of multi-modal dispersion

Chromatic dispersion in fibre

Optical communication is achieved through pulses. Each pulse has a finite spectral width (it's made up of a number of adjacent frequencies).

Lower frequencies travel slower than higher ones, the pulse spreads, causing transmission errors. They can spread so much that they overlap as well.

Amount of dispersion depends on the data rate and the length of fibre

Modal dispersion has the biggest effect but only in multi-mode fibre. This is why telecoms systems mostly use single mode fibres.

Dispersion is measured in Picoseconds per nanometer of bandwidth per kilometer

Dispersion shifted Fibre

Dispersion in fibre is due to:

- The material (cannot be changed)
- The shape of the waveguide i.e the shape of the fibre cross-section

Can modify the dispersion by changing the distribution of the refractive index

Polarization-mode dispersion

The electric field in a single mode fibre propagates with two orthogonal polarization

Due to imperfect production techniques, the fibre is not completely symmetrical

The two orthogonal components of the electric field have different propagation characteristics, causing slight spreading.

breakdown

Severity of dispersion:

1. Multi-mode/modal dispersion
2. Chromatic dispersion
3. Polarization dispersion

Non-linear effects

Non linearity implies that the transfer function of the fibre depends on the signal being transmitted. Their effects increase with the transmitted power

1. Self-Phase modulation (SPM): since the refractive index depends on the intensity of the traveling light, an amplitude modulated signal sees different values of n, and is subject to a different propagation constant

2. Cross-Phase modulation (CPM): if there are multiple wavelengths in a fiber (WDM), the modulation of other wavelengths produce changes in the refractive index that affects (re-modulate) the signal
3. Four-wave Mixing (FWM): the refractive index nonlinearity also generates new frequencies (e.g. $2w_i - w_j, w_i + w_j - w_k$). This can generate noise in WDM systems. It does not depend on data rate, but it is worse when the wavelength spacing is small

Both SPM and CPM produce a broadening of the pulse, so create additional dispersion and are more problematic at higher rates.

Laser

Light Amplification by Simulated Emission of Radiation (LASER)

All photons are emitted at the same frequency and phase which generates a coherent light

An incoherent light would be something like a light bulb where the photons are emitted at various frequencies and waves

Works by a cascading effect where an initial photon triggers an excited electron attached to a photon and so on until you have a coherent wave. Having two mirrors (one partial) helps to ensure that the most light travels in one direction.

The light who's half wavelength matches the length of the laser is the one that is most reflected.

Don't forget the part where the electrons of an atom are excited and sent to a higher orbit around an atom, as they come back down they emit a photon (light) which is the same phase and frequency. This effect cascades as the photon does the same to the other electrons in high orbit and all the emitted photons are in the same frequency and phase creating coherent light

Modulation

Used to add information to a signal

Lasers used to use on off modulation. Still the most common. The pulses of the laser are gaussian shaped.

Modulation types

- Direct laser modulation: Switching the current on and off
  - Cheap
  - Since the refractive index depends on the current, the pulses generated are *chirped* - the frequency of the carrier varies within the pulse
  - Chirp exacerbates the chromatic dispersion impairment
- External modulation: Intermittently obscuring the light generated by a laser.

Receivers

Photodetectors are the elements used as a receiver.

A photon needs to carry enough energy to allow the electron to jump from valence to conduction band.

Different materials have a different bandgap.

The receiver can cause extra noise to be generated when using Avalanche photodiodes (APD). Variance of the generated current increases, creating additional noise.

Receiver sensitivity is the minimum input optical power required at the receiver to achieve a certain bit error rate (BER)

Meeting the minimum power constraints does not mean that the desired BER will be achieved. Other elements such as SNR must be considered.

Coherent receivers can detect phase as well as amplitude

Coherent receivers have a higher sensitivity when compared against direct detection techniques.

Coherent systems are common in the core network with channels of 100Gb/s and above.

Optical link design

When designing an optical link there is usually a BER requirement that needs to be satisfied.

In order to satisfy a BER the following need to be considered:

1. Power budget: $P_{launch} - Loss(fibre, connectors, ...) - Margin \geq receiversensitivity$. Margin considers unforeseen events
2. OSNR: Must also be satisfied along with Power Budget in order to get a Q-factor good enough to achieve target BER
3. Other Impairments: Such as dispersion (modal, chromatic, polarization) and non-linearities

Noise in Optical Systems

Three main types of noise:

- Amplified Spontaneous Emission (ASE): Amplification also introduces additional noise
- Thermal Noise: Random thermal driver noise of electrons at the receiver.
- Shot Noise: Quantistic nature of optical signals means photons arrive at the receiver at random intervals

BER and OSNR

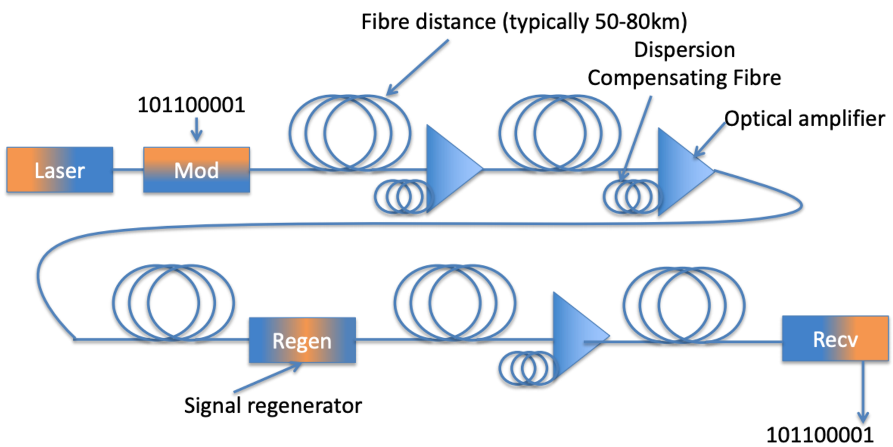
- OSNR, is the relation of the power of the signal and the power of the noise at the receiver

Optical amplifiers effect the power of the noise

Higher OSNR value means its easier to determine whether a receiver bit is 1 or 0

reducing the distance between amplification can reduce ASE in the signal.

Before the OSNR drops below the target bit error rate you should regenerate the signal. Terminate the connection and start anew.



Chain of amplifiers

Over a long distance, multiple optical amplifiers will be used in cascade.

A high gain in the amplifiers increases the ASE noise. Reduce the distance between amplifiers in the system to decrease the amount of ASE in the system.

since each amplifier adds noise, the OSNR deteriorates.

Before the OSNR becomes too low the signal needs to be regenerated

Can catch the phenomenon of Optical Signal to Noise Ratio $OSNR = \frac{P_{signal}}{P_{ASE}}$

The Noise Figure (NF) is a measure of the noise introduced in the system by an amplifier, measured in dB. Average working value is NF=5-6dB

Average spacing for Amplifiers is 80km

reducing this increases the system OSNR.

Calculating OSNR

For a chain of n amplifiers

$OSNR_{recv} = P_{launch[dBm]} - \alpha_{[dB/km]} L_{span[km]} - NF_{ampl[dB]} - 10\log_{10}(n) + 58_{[dB]} - M$

Can also be expressed as

$OSNR_{recv} = P_{launch[dBm]} - NF_{chain[dB]} + 58[dB] - M$

Signal regeneration

Before the OSNR becomes too low

- terminate the signal
- calculate the BER (making sure it is lower than the target BER)
- Re-modulate the signal for the next fibre span
- Calculate a new OSNR

The total BER is the sum of the BERs as each section between regeneration

in WDM if you need to regenerate, you need a regenerator for every wavelength

Dispersion (This was heavily emphasized in tutorial)

The spread of the optical pulse in time ΔT is given by

$\Delta T = D \bullet L \bullet \Delta\lambda$

where D is the dispersion coefficient [ps/Km/nm]

where L is the fibre length

where $\Delta\lambda$ is the signal bandwidth [nm]

Maximum tolerable dispersion:

$D \bullet L = \frac{\Delta T}{\Delta \lambda} []ps/nm] < Limit$

There are two possibilities from the resulting calculations:

1. If $\Delta T < D \bullet L$, don't do anything and accept the impairment due to dispersion.
2. Otherwise, compensate the dispersion to eliminate its effects

Dispersion compensation (for non-coherent systems)

For chromatic dispersion: Another fibre with opposite dispersion characteristics is added. The fibre is called Dispersion Compensating Fibre (DCF)

usually co-located with other optical amplifiers, to reduce non-linear effects

It will introduce loss and this needs to be accounted for in the power budget

In **Coherent systems** electronic equalization can be used at the receiver to compensate for dispersion.

Wavelength division multiplexing

ITU-T has defined grids for WDM

- Coarse WDM
- Dense WDM
- flexgrid systems

Acronyms

- ISI: Inter Symbol Interference
- LASER: Light Amplification by Stimulated Emission of Radiation
- APD: Avalanche Photodiodes
- OSNR: Optical Signal to Noise Ratio
- ASE: Amplified Spontaneous Emission
- DCF: Dispersion compensating fibre
- SPM: Self-Phase Modulation
- CPM: Cross-Phase Modulation
- BER: Bit Error Rate