Optical Communications

Revision notes by Michael Prior-Jones, based on course by Myles Capstick

Optical Transmitters

Simple NRZ transmitters:

- Direct modulation: laser switched on and off by altering bias current. Suffers from *chirp*, which is a frequency distortion of the signal as the bias current changes.
- External modulation: laser runs continuously, and external electro-optic or electro-absorbtion modulator is used to modulate the laser beam. Chirp effects are significantly less than direct modulation.

RZ (pulse) transmitters:

- laser is designed to produce pulses (duty cycle between 5:1 and 10:1)
- external modulator selects whether pulse is transmitted or blocked. Since modulator can be switched during gap between pulses, the modulator does not introduce chirp. However, the pulse laser still produces some chirp effects.

Detectors:

- PIN diode or APD (avalanche photodiode)
- always followed by Nyquist matched filter (typically raised-cosine for NRZ)
- Noise performance of electrical front-end is limiting factor:
- APD gives 10dB electrical gain at expense of bandwidth
- Optical preamp provides gain but introduces wideband noise which must be filtered out.
- Coherent detection improves detection efficiency (analogous to superheterodyne receiver) but is complex to implement: requires optical local oscillator.

Repeaters, Regenerators, Optical Amplifiers:

- Repeater = detector + electrical amp + laser. Does not correct for transmission impairments (eye distortion).
- Regenerator = receiver + resynchronisation + retransmission. Corrects transmission impairments by regenerating signal. Expensive and complex, and restricted to a specific protocol.
- Optical amp = adds gain directly to optical signal. Does not correct transmission impairments but independent of bit rate and protocol. Lower noise than electrical repeater.

Characteristics of optical fibres:

- attenuation
- chromatic dispersion
- both dependent on wavelength
- both limit maximum length of fibre link

Fibre attenuation

Attenuation varies significantly with wavelength. Two wavelengths have good attenuation characteristics: 1300nm and 1550nm. 1550nm is better, but more expensive. Loss is also introduced by fibre splices, and this is slightly higher at 1550nm.

Fibre dispersion

Dispersion is when different wavelengths of light experience different propagation times down the length of the fibre. It is a function of both the material the fibre is made from (*material dispersion*), and the geometry of the fibre (*waveguide dispersion*). It's possible to design fibre so that these two effects cancel out. Standard fibre is designed to minimise dispersion at 1300nm- it's typically around 2ps/nm/km. Using this fibre at 1550nm gives a much higher dispersion of around 16ps/nm/km, and so special dispersion-shifted fibres are available which give low dispersion at 1550nm.

Dispersion introduces eye distortion in transmitted signals. It depends on the laser line width (i.e. the bandwidth of the unmodulated laser) the dispersion of the fibre and the length of the link. Normally the maximum dispersion permissible is equal to 50% of the bit-period. When the dispersion reaches 1 bit-period the eye is completely closed and the transmission is irrecoverably corrupted.

Henry's dispersion rule:

This gives a simple formula for calculating fibre link performance. It's not in SI units…

$$B^2 L_{\max} = \frac{1000c}{2D\lambda^2}$$

This assumes that maximum dispersion is 50% of the bit-period and that the signal bandwidth is the Nyquist bandwidth (i.e. half the bit-rate). It also assumes that you are using a very narrow laser and it has no chirp.

B is the bit-rate in Gbit/s
λ is the free-space wavelength in nm
L_{max} is the maximum link length in km
D is the dispersion in ps/nm/km
c is the speed of light in m/s ($3x10^8$)

This allows you to find the maximum bit-rate for a given distance, or the maximum distance at a given bit-rate.

System Configurations

- unrepeatered: typically 50km at 1300nm or 120km at 1550nm. Some advanced systems can manage 300km @ 2.5Gbit/s using 1550nm.
- repeatered: optical amplifiers (EDFAs) can be used to overcome effects of attnenuation, and give links at up to 1000km (limited by dispersion and amplifier noise). Using optoelectronic regenerators can give as long a link as you want, providing you use a large number of repeaters. Transoceanic links (5000-10000km) use dispersion-shifted fibre and soliton transmission to overcome distance limitations (more later!)

TDM system:

Signals are electrically time-division multiplexed and fed to a high-speed transmitter. They are then electrically demultiplexed at the other end of the link. This uses a high optical bandwidth, and requires all signals to be decoded to recover one element of the multiplex. Commonly used for point-to-point telecomms links.

WDM system:

(wavelength division multiplex)

Equivalent to FDM in RF comms. Each signal has its own transmitter on a particular wavelength. All of these are combined optically onto one fibre and demuxed optically at the receiver. This reduces dispersion problems (lower optical bandwidth for each signal) but the optical system becomes considerably more complex. However, it is possible to demux a single signal in the optical domain, making it more suitable for bus-type systems.

OTDM system:

(optical time division multiplex)
In this situation, a pulse laser drives a bank of optical modulators, one for each signal. An optical multiplexer time-division multiplexes the pulsed signals onto the link. The reverse process occurs at the other end. This is highly complex, but allows soliton transmission to be used to overcome the dispersion limit on very long (transoceanic) links. The system is very dependent on optical amplification to overcome losses in modulation and multiplexing. The pulse laser must also be extremely powerful.

Lasers

Use of Lasers as against LEDs:

LEDs are broadband (30-50nm) and incoherent.
Lasers are narrow(1-3nm or less) and coherent.
LED links only work over very short distances (e.g. linking CD players to minidisk recorders, approx 1m) because effects of dispersion are very heavy.

The Fabry-Perot laser diode

Very simple structure, however, cavity gives rise to multiple modes of oscillation, which results in high linewidth, typically 3nm (250GHz). Not suited to high-speed operation.

The Distributed Feedback laser (DFB)

Typical bandwidth 100MHz. Makes use of diffraction grating on top of active layer to select a specific mode of oscillation.

Laser Modulation

Direct modulation performance

Lasers tend to ring when their bias current is adjusted sharply, giving variations in output power. The output frequency also varies (chirp), and this can give severe dispersion effects in fibre.

External modulators:

Direct modulated DFB lasers have many nice features, but the limitations imposed by chirp mean that external modulation is often necessary on high-speed systems.

Electro-absorbtion modulator:

This is effectively a reverse-biased Fabry-Perot laser diode- altering bias current changes the attenuation of the cavity. They do exhibit some chirp, but they are better than direct-modulated lasers. Because of the similarity of structure it's possible to make EA modulators on the same chip as a laser.

Electro-optic modulator (Mach Zender interferometer)

This uses lithium niobate or a similar material, which changes refractive index when under the influence of an electric field. A length of lithium niobate waveguide can be used to slow down the propagation speed of a wave within it in response to an electric field. The Mach Zender interferometer splits the incoming laser beam into two waveguides: one passes through the "delay line" and the other does not. When they recombine, the relative change of phase can produce constructive or destructive interference to the resultant wave. By altering the delay, the output can be modulated. Using a single delay technique introduces a slight phase modulation to the output. This can be overcome by using a differential modulation: speeding up one wave whilst slowing down another, and this can give perfect modulation with no chirp. However, MZ modulators are relatively long (5mm or more) and require careful matching of electrical and optical phase velocities. They can be used at up to 50GHz with zero chirp.

EO modulators can also be used to produce pulses for OTDM systems, by driving them with a bipolar sine wave.

Optical amplifiers

- Semiconductor Laser Amplifier (SLA) – basically a conventional laser cavity which is used to amplify the signal as it passes through. Typically has a 6dB noise figure.
- Erbium Doped Fibre Amplifier (EDFA) – this uses a pump laser to inject energy into fibre doped with erbium atoms. The energy is then released when stimulated by the incoming signal, providing optical gain. These provide a high bandwidth, too. Can have noise figure close to ideal (3dB)

Optical receivers:

- direct detection: use of photodiode to turn light into electricity.
- coherent detection: incoming signal is mixed down by local oscillator laser to produce either IF or baseband signal (homodyne detection). Very difficult to constructed, because local oscillator must be phase-locked to signal. Rarely used today, as optical amplifiers give better gains and are less complex.

Quantum limit on Rx sensitivity:

$$SNR = \frac{hP_{opt}}{2huB_N}$$

Sensitivity of receiver typically requires SNR of approx 10dB, so can rearrange to find P_{opt} at this level.

In this formula:
SNR is a linear ratio
h is Planck's constant (6.62×10^{34})
η is the quantum efficiency (ranges from 0 to 1)
υ is the frequency of the wave
B_N is the noise bandwidth

Direct detection receivers typically perform 10-15dB worse than the theoretical limit.
Heterodyne receivers can approach the theoretical limit.
Direct detection with an EDFA pre-amp can also approach theoretical limit if very high power levels are incident on the PIN.

Fibre characteristics

Elrefaie's Chromatic Dispersion Index

For Gaussian pulses in single-mode fibre the amount of inter-symbol interference due to dispersion is dependant on the chromatic dispersion index, γ_d

$$\gamma_d = \frac{B^2 L D \lambda^2}{1000 \pi c}$$

B = bit-rate in Gbit/s
D = dispersion in ps/nm/km
L = link length in km
λ = wavelength in nm
c = speed of light in free space (m/s) = $3x10^8$

When $\gamma_d = 0.252$, ISI is contributing 1dB of penalty (i.e. the received power must be increased by 1dB to maintain BER)
For 2dB of penalty, $\gamma_d = 0.321$

Non-linear propagation effects in fibre

At high levels of optical power, the fibre ceases to behave in a linear fashion. The Kerr effect results in changes in refractive index, and the Raman and Brillouin scattering phenomena can also distort signals.

In conventional fibre communications it is desirable to minimise these non-linear phenomena, however, recent research has resulted in techniques which exploit the non-linearities to enhance the transmission of signals along the fibre.

Self Phase Modulation (SPM)

The refractive index of fibre becomes intensity-dependant at high levels of optical power. As the signal power increases, the refractive index increases, and this varies the instantaneous phase of the light pulse.

$n = n_0 + n_2 I$

n is the refractive index of the fibre.
n_0 is the base refractive index, typically 1.5
n_2 is the variation factor: typically 3×10^{-20} m^2/W
I is the optical intensity in W/m^2

Because n_2 is very small, it can be ignored at low optical intensities. However, since the core of an optical fibre has a very small cross-section, the optical intensity (optical power density) is very high, even at fairly modest levels of laser power. In fact, for 1 mW of laser power, the power density in a typical fibre is $18 MW/m^2$ (yes, that is Megawatts!)

This effect changes the pulse shapes in a similar way to laser chirp, although the direction of the distortion is opposite to that introduced by a laser. If the intensity is kept high (by the use of EDFAs), the SPM effect can stop a pulse dispersing.

Cross Phase Modulation

When two signals of different wavelengths travel along a fibre, each will experience SPM. However, they will also experience changes in phase brought about by the intensity of the *other* signal changing the refractive index of the fibre. This effect is known as cross phase modulation (XPM). This distorts pulse shapes as the two signals interact. It's particularly critical in low-dispersion fibres, where the two signals will be travelling at the same speed.

Four Wave Mixing (FWM)

This is analogous to intermodulation in RF: the two waves interact and generate unwanted signals at other frequencies. Again, the effect is maximised in low-dispersion fibres. WDM systems can be badly affected by the effects of FWM, as the "intermodulation products" will add noise to channels in the multiplex.
To minimise FWM, *dispersion control* techniques are introduced: standard fibre (15ps/nm/km) is interspersed with short lengths of negative-dispersion fibre. This is arranged so that the total dispersion over the link is zero, but that the individual fibre segments never have zero dispersion.

Scattering Effects:

The interaction of optical photons with phonons (vibrational states) can generate scattering effects. There are two types of scatter: stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). In both cases, energy is transferred from the signal to a lower energy *Stokes wave* at a different wavelength. This can be used to amplify a signal: a high-energy "pump" beam is introduced into the fibre, and this provides gain at the Stokes frequency.
However, if a signal in an ordinary fibre reaches a sufficiently high power, a Stokes wave will be produced at a different wavelength, which results in power loss at the signal wavelength. Since the Stokes wave generation effect rises exponentially with input power, the output power from a fibre is often "clamped": adding more power at the input just results in more power at the Stokes frequency and no extra benefit results.
In multichannel systems, a shorter wavelength signal may act as a pump for a longer wavelength channel, and cause crosstalk between channels.

The other effect that results from this is *backscatter*: a certain proportion of a high-power incident wave is reflected back by the fibre. This also rises steeply once the launch power reaches a few milliWatts.

Polarisation Effects

- Polarisation Mode Dispersion (PMD): light in a fibre travels in a mixture of two orthogonal polarisations. These two polarisations travel at very slightly different velocities, which gives a dispersion effect. It's a very weak effect and is usually ignored except in high-capactity optically-amplified systems.
- Polarisation Dependent Loss (PDL): optical components behave differently towards different polarisations of wave, and this can introduce loss effects.
- Polarisation Dependent Gain (PDG): EDFAs tend to amplify noise which occurs in orthogonal polarisation to the signal. A linearly-polarised signal will be accompanies by amplified noise on the opposite polarisation, which reduces SNR at the receiver. Using circular polarisation, where the amplitudes of the two orthogonal polarisation states are equal, removes this effect.

System Performance Specification

The received signal at the far end of the link must be of sufficient quality and power level to give the required BER. A performance margin is normally built-in to allow for degradations in system performance over time.

For a system without optical amplification, the performance is best characterised using a power budget, since all the noise is introduced in the receiver.

$$M' = P - L' - S$$

M' is the margin for ageing/degradations, in dB
P is the laser power, in dBm
L' is the link loss in dB (fibre loss per km, plus loss of any splices)
S is the receiver sensitivity in dBm

Dispersion Management

For systems where dispersion is the limiting factor on link performance, it's possible to minimise dispersion by the use of *negative-dispersion fibre*. By splicing a fibre with equal and opposite dispersion characteristics to the main fibre, the overall dispersion of the system is minimised. This fibre can be obtained commercially, and typically has dispersion values of –40 to –80 ps/nm/km.

Alternatively, an optical filter (Fabry Perot etalons or chirped fibre gratings) can be used to provide a more compact solution, although these require active electronic control.

System topologies:

Sub-carrier multiplexing vs wavelength multiplexing

When developing an FDM fibre link, two options are available:

- carry out the FDM in the electrical domain, and use a wide-band optical link to carry the signal.
- modulate individual signals onto different wavelengths of light, and combine optically.

The second option is called wavelength division multiplexing (WDM) and is much more efficient and versatile than the electrical option (known as sub-carrier FDM), although it is more expensive and complex.

Optical networks & routing

Using WDM, all-fibre communication systems can be developed which allow signals to be switched and routed in the optical domain, rather than using optical point-to-point links between electrical routers.

The basis of these systems is the Add/Drop wavelength multiplexer (ADM): this consists of a bank of filters to separate the individual channels according to wavelength, and a combiner to re-combine them. Some channels are hardwired directly through the ADM in the optical domain, whilst others are routed out into the electrical domain for processing and can then be re-inserted. It's possible to build networks of ADMs where different wavelengths carry signals between different nodes.

Using electro-absorbtion techniques (like EA modulators) it's possible to build electrically-controlled optical switches, which can be combined together to make all-optical routers.