1.6. First generation networks and channel multiplexing

In the first generation of optical networks, information is transmitted optically, but handled electronically. The principal component is the point-to-point link, which consists of a transmitter, optical channel, and receiver.

1.6.1. Optical point to point link

- Transmitter

\[
\text{Power (dBm)} = 10 \log_{10} \left( \frac{\text{power}}{1 \text{ mW}} \right)
\]

- Channel
In an optical system, the channel is an optical fiber. Due to propagation loss in the fiber, the relationship between the launched and received power is given by

$$ P_{\text{rec}} = P_{\text{tr}} e^{-\alpha L} = P_{\text{tr}} 10^{-\alpha_f L/10}. $$

In this equation, $\alpha$ is the loss in units of 1/km, while $\alpha_f$ is the loss in dB/km. The latter is used more often.

Given a certain transmitter and needed receive power, and the propagation loss of the line, the maximum length can be solved for

$$ \log_{10} \frac{P_{\text{rec}}}{P_{\text{tr}}} = -\alpha_f L/10 \Rightarrow L = \frac{10}{\alpha_f} \log_{10} \left( \frac{P_{\text{tr}}}{P_{\text{rec}}} \right). $$

An easier way to perform loss calculations (i.e. manage the power budget) is to work in dB units:

$$ 10 \log_{10} P_{\text{rec}} = 10 \log_{10} \left( P_{\text{tr}} 10^{-\alpha_f L/10} \right) = 10 \log_{10} P_{\text{tr}} - \alpha_f L $$

or

$$ P_{\text{rec,dbm}} = P_{\text{tr,dbm}} - \alpha_f L, $$

which makes it easier to include additional loss mechanisms in an additive (or subtractive) fashion.

• Receiver

**BER** - average probability of incorrect bit identification, typically specified as $10^{-12}$ to $10^{-9}$.

**Receiver sensitivity** - $P_{\text{rec}}$, minimum average optical power needed to obtain BER $10^{-9}$, depends on SNR and detector responsivity.

**Photodetection noise** - quantum (or shot) noise, thermal noise (Johnson or Nyquist), amplifier noise (ASE). Determines base SNR. Other effects manifest themselves as a power penalty.

Many developments have concentrated on how to maximize the amount of information sent down the link. Time-division multiplexing (TDM) is used exclusively to inverleave many low-speed electrical channels into a single, high-speed optical channel. Optical time-division multiplexing (OTDM) and wavelength-division multiplexing (WDM) are also used to transmit many optical channels down a single fiber link. Second generation networks will use OTDM and WDM not only to increase link capacity, but to assist in handling information at each central office or switching exchange.
1.6.2. Time-division multiplexing

TDM – (interleaving) is used in telephone networks to generate composite signal at high bit rate. Digitized voice at 64 kb/sec is much less than the capacity of single optical channel. Consider N independent bit streams at bit rate B. The original bit slot time of each stream is $T_B = 1/B$, whereas the new, composite, stream has a bit slot time $T'_B = 1/NB$. This interleaving operation can be performed electronically up to about 10 Gb/s, using a GaAs shift register, for example. Interleaving can also be performed entirely in the optical domain, which is termed OTDM. TDM and OTDM can be done with digital signals only.

![TDM/OTDM Diagram]

Digital hierarchy: DS (signaling designation), T (transmission designation).

- **DS-0**: 1 voice channel 64 kb/sec
- **DS-1**: 24 voice channels 1.544 Mb/sec T1 line
- **DS-2**: 4 DS-1 channels 6.312 Mb/sec T2
- **DS-3**: 4 DS-2 channels 44.736 Mb/sec T3
- **DS-3C**: 2 DS-3 channels 91.053 Mb/sec T3C
- **DS-4**: 6 DS-3 channels 274.175 Mb/sec T4
  
  and so on

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<th>Time</th>
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SONET (synchronous optical network) 1980’s
Defines frame structures (meanings of bits in payload header) for TDM, implemented in hardware and/or software.
1.6.3. WDM – Wavelength division multiplexing

Back to the issue of channel capacity,

\[ C = \Delta f_{ch} \log_2 (1 + S/N) \]

where \( \Delta f_{ch} \) is the channel bandwidth, \( S \) is the average signal power, and \( N \) is the average noise power. Modulation rate \( \Delta f_{ch} \) cannot be increased arbitrarily because of increase in noise. With shot noise, for example, \( N = N_o \Delta f_{ch} \), where \( N_o \) is the spectral density of shot noise. As \( \Delta f_{ch} \to \infty \), \( C \to (S/N_o) \log_2 e \sim S/N_o \), assuming that \( S \) is constant. The solution to this problem is to either increase \( S \) proportionally, or to use multiple channels (i.e. carriers) via WDM.

WDM is sometimes called FDM - frequency division multiplexing. Each channel is carried a different carrier frequency, or wavelength. These channels non-overlapping in the spectral domain and can be combined or separated using spectrally-selective methods such as multiplexers and bandpass filters.

WDM is the emerging technology for second generation networks. Standard channel spacings are 200, 100, and eventually, 50 GHz. Smaller spacings allow for more WDM channels, but place greater demands on component design and fabrication.