Optical Networks
Enabling Technologies, Building Blocks

29 August 2012, Belem, Para, Brazil

Dr. Cicek Cavdar, cavdar@kth.se

Optical Networks Lab (ONLab)
Royal Institute of Technology,
Stockholm, Sweden

Special thanks to Biswanath Mukherjee from UC-Davis and Aysegul Yayimli from ITU for the class material.
Outline

- WDM networks enabling technologies.
  - optical fiber
  - optical transmitter (see previous class notes)
  - optical receiver (see previous class notes)
  - MEMs optical switching architecture (see p. c. n.)
  - optical couplers
  - optical switches

- Optical Impairments
  - Linear impairments
  - Non-linear impairments
Optical Fiber

- Excellent physical medium for high-speed networking
- Two low-attenuation windows:
  - Centered approx. 1310 nm, a window of 200 nm
  - Centered approx. 1550 nm, a window of 200 nm
- Combined, they provide a theoretical upper bound of 50 THz.
Optical Fiber

- The attenuation of glass optical fiber is caused by two factors: absorption and scattering.
  - Absorption occurs in several specific wavelengths called water bands due to the absorption by minute amounts of water vapor in the glass.
  - Scattering is caused by light bouncing off atoms or molecules in the glass. It is strongly a function of wavelength, with longer wavelengths we have lower scattering.

- Longer wavelengths in the infrared for lower loss in the glass fiber and at wavelengths which are between the absorption bands.

- If the attenuation is lower, why don’t we use even longer Ws? Noise
# DWDM Band Wavelength Range

<table>
<thead>
<tr>
<th>Band Name</th>
<th>Wavelengths</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-band</td>
<td>1260 – 1360 nm</td>
<td>Original band, PON upstream</td>
</tr>
<tr>
<td>E-band</td>
<td>1360 – 1460 nm</td>
<td>Water peak band</td>
</tr>
<tr>
<td>S-band</td>
<td>1460 – 1530 nm</td>
<td>PON downstream</td>
</tr>
<tr>
<td>C-band</td>
<td>1530 – 1565 nm</td>
<td>Lowest attenuation, original DWDM band, compatible with fiber amplifiers, CATV</td>
</tr>
<tr>
<td>L-band</td>
<td>1565 – 1625 nm</td>
<td>Low attenuation, expanded DWDM band</td>
</tr>
<tr>
<td>U-band</td>
<td>1625 – 1675 nm</td>
<td></td>
</tr>
</tbody>
</table>
Full-spectrum Fiber

- Besides the traditional fibers above, full-spectrum fiber is also attracted in the industry
  - Permanently reduced water peak, as well as additional enhanced specifications in the L-band.
  - Involve simultaneous (WDM) transmission in multiple operating windows (1270 to 1610 nm) over a single fiber.
  - Provide more useable wavelengths than standard single-mode fiber and therefore more bandwidth per fiber.
Use low-attenuation windows for data transmission: Thus, the signal loss can be made very small. This reduces the number of amplifiers needed. 1550 nm window is preferred for long-haul (wide-area) networks. Standards set for industry: ITU\(^1\) grid. Optical signals have been sent over 80 km without amplification. Low error rates: Typically operate at BERs of less than 10\({}^{-11}\). Fiber is also, flexible, light, reliable in corrosive environment. Immune to electromagnetic interference, and does not cause interference.

\(^1\)ITU: International Telecommunication Union
Attenuation

- Attenuation in optical fiber leads to a reduction of the signal power as the signal propagates over some distance.
- When determining the maximum distance that a signal can propagate for a given transmitter power and receiver sensitivity, one must consider attenuation.
- Receiver sensitivity is the minimum power required by a receiver to detect the signal.
- Let $P(L)$ be the power of the optical pulse at distance $L$ km from the transmitter, and
- $A$ be the attenuation constant of the fiber (in dB/km).
- Attenuation is characterized by:

\[ P(L) = 10^{-A \cdot L / 10} P(0) \]

where $P(0)$ is the power at the transmitter.
ASE Noise

- One of the major impairments that an optical signal encounters is accumulated noise.
- Principal source of this noise is spontaneous emissions of optical amplifiers, which are amplified throughout the signal as they propagate through the network.
Dispersion

Dispersion is the widening of a pulse duration as it travels through a fiber.

As a pulse widens, it can broaden enough to interfere with neighboring pulses (bits) on the fiber, leading to inter-symbol interference.

Dispersion thus limits the bit spacing and the maximum transmission rate on a fiber-optic channel.

Several kinds:
- intermodal dispersion
- chromatic dispersion
- material, waveguide, profile dispersions
- polarization mode dispersion
Signal distortion due to chromatic dispersion*

- Spectrum broadening
- Difference in group velocity
- Pulse broadening (Waveform distortion)

Optical spectrum

Original signal

Transmitter output

Optical fiber

Receiver input

Regenerated signal

Optical Networks, Enabling Technologies, Çiçek Çavdar

(*) Kazuo Yamane, Fujitsu
Chromatic Dispersion

- Light within a medium travels at a slower speed than in vacuum. The speed at which light travels is determined by the medium’s refractive index.
- In an ideal situation, the refractive index would not depend on the wavelength of the light. Since this is not the case, different wavelengths travel at different speeds within an optical fiber.
- Laser sources are spectrally thin, but not monochromatic. This means that the input pulse contains several wavelength components, traveling at different speeds, causing the pulse to spread.
- The detrimental effects of chromatic dispersion result in the slower wavelengths of one pulse intermixing with the faster wavelengths of an adjacent pulse.
Chromatic Dispersion

- The Chromatic Dispersion of a fiber is expressed in ps/(nm*km), representing the differential delay, or time spreading (in ps), for a source with a spectral width of 1 nm traveling on 1 km of the fiber.

- For DWDM systems using DFB lasers, the maximum length of a link before being affected by chromatic dispersion is commonly calculated with the following equation:

\[
L = \frac{104,000}{CD \times B^2}
\]

*L is the link distance in km, CD is the chromatic dispersion in ps/(nm * km), and B is the bit rate in Gbps.*
Chromatic Dispersion Compensation

- CD is quite stable, predictable, and controllable. Dispersion Compensation Fiber (DCF), with its large negative CD coefficient, can be inserted into the link at regular intervals to minimize its global chromatic dispersion.

- While each spool of DCF adequately solves chromatic dispersion for one channel, this is not usually the case for all channels on a DWDM link. At the extreme wavelengths of a band, dispersion still accumulates and can be a significant problem. In this case, a tunable compensation module may be necessary at the receiver. (*)

(*) Gildas Chauvel, Anritsu Corporation
Dispersion compensation example (*)

Transmission fiber
- Positive dispersion (Negative dispersion)
  - Longer wavelength → Slow (Fast)
  - Shorter wavelength → Fast (Slow)

Dispersion compensating fiber (DCF)
- Negative dispersion (Positive dispersion)
  - Longer wavelength → Fast (Slow)
  - Shorter wavelength → Slow (Fast)

40 Gb/s optical signal
- 25 ps
  - Transmitter output
  - After fiber transmission
  - After dispersion comp.

Optical Networks, Enabling Technologies, Çiçek Çavdar

(*) Kazuo Yamane, Fujitsu
DC allocations and dispersion maps*

Optical Networks, Enabling Technologies, Çiçek Çavdar

(*) Kazuo Yamane, Fujitsu
Polarization Mode Dispersion (PMD)

- Well defined, frequency independent eigenstates
- Deterministic, frequency independent Differential Group Delay (DGD)
- DGD scales linearity with fiber length

$\Delta \tau$: Differential Group Delay (DGD)

(*) Kazuo Yamane, Fujitsu
Higher-order PMD*

Mode-coupling at random locations with random strength

- Frequency dependence of DGD
- Statistically varying due to environmental fluctuations
- Fiber PMD unit: $\text{ps}/\sqrt{\text{km}}$

Maxwellian distribution of the instantaneous DGD

Frequency of occurrence

Prob.($\text{DGD}>3\times\text{PMD}$) = $4\times10^{-5} = 21$ min/year

Prob.($\text{DGD}>3.5\times\text{PMD}$) = $10^{-6} = 32$ sec/year

Optical Networks, Enabling Technologies, Çiçek Çavdar

(*) Kazuo Yamane, Fujitsu
It is hard to compensate since PMD varies as a function of time. New fiber types have less PMD now. PMD characteristic changes slowly due to “normal” environmental fluctuations (e.g. temperature).

But, fast change due to e.g. fiber touching.

High-speed PMD compensation device & Intelligent control algorithm

PMD compensation is required especially for 40Gbit/s or higher bit rate long-haul systems.

(*) Kazuo Yamane, Fujitsu
Adjacent Channel Crosstalk

- Adjacent channel X-talk is common in all forms of communication systems.
- In a dense WDM optical communication system the adjacent channel X-talk is very significant and limits the minimum separation of two adjacent channels with an acceptable penalty.
- For narrow channel spacing, there is a partial overlap of channels in frequency domain. The effect depends on large number of parameters such as channel spacing and filtering characteristics of multiplexers and demultiplexers.
Nonlinearities in Fiber

- Nonlinear effects in fiber may potentially have a significant impact on the performance of WDM optical communication systems.

- Nonlinearities in fiber may lead to attenuation, distortion, and cross-channel interference.

- In a WDM system, these effects place constraints on the spacing between adjacent wavelength channels, limit the maximum power on any channel, and may also limit the maximum bit rate.

- Types:
  - Nonlinear refraction
  - Stimulated Raman scattering
  - Stimulated Brillouin Scattering
  - Four-wave mixing
Nonlinearities in Fiber

- It is shown that, in a WDM system using channels spaced 10 GHz apart and a transmitter power of 0.1 mW per channel, a maximum of about 100 channels can be obtained in the 1550-nm low-attenuation region.
- The details of optical nonlinearities are very complex, and beyond our scope.
- However, it is important to understand that they are a major limiting factor in the available number of channels in a WDM system, especially those operating over distances greater than 30 km.
- The existence of these nonlinearities suggests that WDM protocols which limit the number of nodes to the number of channels do not scale well.
Non-linear Impairments

- Self Phase Modulation: Intensity of the light causes the phase of optical signal to vary in time
- Cross Phase Modulation: Interaction of two signals when they are closely packed
- Four-wave mixing: Interference of stray signals with close frequencies

Mitigation:
- Self Phase Modulation, Cross Phase Modulation … these nonlinear effects can be avoided by maintaining the signal power low enough.
- Small amount of residual system dispersion can be effective reducing the non-linear effects.
Optical Fiber Couplers

- Coupler is a general term that covers all devices that combine light into or split light out of a fiber.
- It can be either active or passive device.

- The *splitting ratio*, $\alpha$, is the amount of power that goes to each output.
- For a two-port splitter, the most common splitting ratio is 50:50, though splitters with any ratio can be manufactured.
- Combiners are the reverse of splitters, and when turned around, a combiner can be used as a splitter.
- A $2 \times 2$ coupler is a $2 \times 1$ combiner followed immediately by a $1 \times 2$ splitter.
A 16 x 16 Passive Star Coupler

- The passive-star coupler (PSC) is a multi-port device in which light coming into any input port is broadcast to every output port.
- The PSC is attractive because the optical power that each output receives $P_{out}$ equals:

$$P_{out} = \frac{P_{in}}{N}$$

where $P_{in}$ is the optical power introduced into the star by one node.
Wavelength Routing Devices

- A wavelength-routing device can route signals arriving at different input fibers (ports) of the device to different output fibers (ports) based on the wavelengths of the signals.

- Wavelength routing is accomplished by:
  - demultiplexing the different wavelengths from each input port,
  - switching each wavelength separately,
  - and then multiplexing signals at each output port.

- The device can be either:
  - non-reconfigurable, in which case there is no switching stage between the demultiplexers and the multiplexers, and the routes for different signals arriving at any input port are fixed (referred to as routers),
  - or reconfigurable, in which case the routing function of the switch can be controlled electronically.
Non-reconfigurable Wavelength Router
Wavelength Routing Switch

- The WRS has $P$ incoming fibers and $P$ outgoing fibers.
- On each incoming fiber, there are $M$ wavelength channels.
- Similar to the nonreconfigurable router, the wavelengths on each incoming fiber are separated using a grating demultiplexer.
- The outputs of the demultiplexers are directed to an array of $M \times P \times P$ optical switches between the demultiplexer and the multiplexer stages.
- All signals on a given wavelength are directed to the same switch.
- The switched signals are then directed to multiplexers associated with the output ports.
- Finally, information streams from multiple WDM channels are multiplexed before launching them back onto an output fiber.
PxP WRS
Wavelength Conversion

Consider the following network.
Wavelength Conversion

- Four lightpaths have been set up:
  - A to F on wavelength $\lambda_1$,
  - B to F on $\lambda_1$,
  - B to E on $\lambda_2$, and
  - F to A on $\lambda_2$.

- To establish a lightpath, we require that the same wavelength be allocated on all the links in the path.

- This requirement is known as the *wavelength-continuity constraint*.

- Can we establish a lightpath from C to E?
Wavelength Conversion

Consider the following network.
Wavelength Conversion

- It is easy to eliminate the wavelength-continuity constraint, if we are able to:
  - convert the data arriving on one wavelength along a link, into another wavelength at an intermediate node and
  - forward it along the next link.

- Such a technique is referred to as: \textit{wavelength conversion}.

- A single lightpath in such a \textit{wavelength-convertible} network can use a different wavelength along each of the links in its path.
Wavelength Converter

The function of a wavelength converter is to convert data on an input wavelength onto a different output wavelength among the \( N \) wavelengths.

\[
\lambda_s \xrightarrow{Wavelength Converter} \lambda_p \rightarrow \lambda_c
\]

\[
s = 1, 2, \ldots, N \\
c = 1, 2, \ldots, N
\]
An ideal wavelength converter should possess the following characteristics:

- transparency to bit rates and signal formats
- fast setup time of output wavelength
- conversion to both shorter and longer wavelengths
- moderate input power levels
- possibility for same input and output wavelengths (no conversion)
- insensitivity to input signal polarization
- large signal-to-noise ratio, and
- simple implementation.
Wavelength Converting Switch
For questions, please send e-mail: cavdar@kth.se

Note: In the presentation, most material are cited from related sources. Since some material cited here may be confidential, or not be allowed to be circulated, please directly contact their own sources if you will use them.