University of Arizona
ECE/OPTI 632:
Advanced Optical Communication Systems
Spring 2012, Ivan B. Djordjevic

Introduction
INTRODUCTION

• The “information era” is characterized by the insatiable demands for information capacity and distance independent connectivity.

• Optical communication systems are evolving quickly to adapt to the ever-increasing demands of telecommunication needs, mostly noticeably witnessed by the explosive growth in transmission capacity demands.

• The optical networking technology has become closely related to the Internet technology, and has the same ultimate goal: to satisfy insatiable demands for high bandwidth and distance independent connectivity in an automated and sophisticated manner.

• The channel data rate in modern optical transport networks is migrating from 10 Gb/s to more spectrally efficient 40Gb/s and 100 Gb/s.

• The 100 Gb/s per-channel data rate systems are ready for commercial deployment.

• Transmission technology for 400-Gb/s Ethernet and beyond 400-Gb/s is an active research topic.
Optical networking architecture

- In terms of ownership, networks and transmission systems can belong either to private enterprises or be owned by telecommunication carriers.
- Ownership can be related to networking equipment and infrastructure associated with a specified network topology or to a logical entity, known as the optical virtual private network, within the physical network topology.
- Typical optical networking structure can be represented by three concentric “circles”.

- **Core network**: wide area network (WAN) or interchange carrier (IXC)
- **Edge network**: metropolitan network (MAN) or local exchange carrier (LEC)
- **Access network**: LAN and a distribution network (connects the central office location of a carrier with individual users)
• The **physical networking topologies**:
  – Mesh (in the core and edge networks)
  – Ring (deployed in all portions of a global network)
  – Star (deployed mostly in an access network)

• From the optical transmission engineering perspective, the optical network configuration is just a mean to support an end-to-end connection via the *lightwave path*.

**Lightwave signal path**

• *Lightwave path*: the trace that optical signal passes between the source and destination without experiencing any opto-electrical-opto (O-E-O) conversion.
• In general, the lightwave paths differ in lengths and in the information capacity that is carried along.
• The lightwave path can be considered as bandwidth wrapper for lower speed transmission channels, which form virtual circuit services.

• In such cases the time division multiplexing (TDM) technique is applied to aggregate the bandwidth of virtual circuits before it is wrapped in the lightwave path.

• Multiplexing of virtual circuits:
  – Fixed multiplexing (each circuit receives a guaranteed amount of the bandwidth-a bandwidth pipe)
  – Statistical multiplexing (in packet-switching the data content is divided into data packets, which can be handled independently)

• The fixed multiplexing of virtual circuits is defined by SONET/SDH standards.

• Bit-rates of different bandwidth channels:

<table>
<thead>
<tr>
<th>Synchronous (TDM) channels</th>
<th>Bit rate</th>
<th>Asynchronous (data) channels</th>
<th>Bit rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-1</td>
<td>1.544 Mb/s</td>
<td>10-BaseT Ethernet</td>
<td>10 Mb/s</td>
</tr>
<tr>
<td>E-1</td>
<td>2.048 Mb/s</td>
<td>100-BaseT Ethernet</td>
<td>100 Mb/s</td>
</tr>
<tr>
<td>OC-1</td>
<td>51.84 Mb/s</td>
<td>FDDI</td>
<td>100 Mb/s</td>
</tr>
<tr>
<td>OC-3=STM-1</td>
<td>155.52 Mb/s</td>
<td>ESCON</td>
<td>200 Mb/s</td>
</tr>
<tr>
<td>OC-12=STM-4</td>
<td>602.08 Mb/s</td>
<td>Fiber Channel-I</td>
<td>200 Mb/s</td>
</tr>
<tr>
<td>OC-48=STM-16</td>
<td>2.488 Gb/s</td>
<td>Fiber Channel-II</td>
<td>400 Mb/s</td>
</tr>
<tr>
<td>OC-192=STM-64</td>
<td>9.953 Gb/s</td>
<td>Fiber Channel-III</td>
<td>800 Mb/s</td>
</tr>
<tr>
<td>OC-768=STM-256</td>
<td>39.813 Gb/s</td>
<td>Gb Ethernet</td>
<td>1 Gb/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10Gb Ethernet</td>
<td>10 Gb/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40Gb Ethernet</td>
<td>40 Gb/s</td>
</tr>
</tbody>
</table>
Optical transmission systems

- The simplest optical transmission system is a point-to-point connection that utilizes a single optical wavelength, which propagates through an optical fiber.
- The upgrade of this topology is deployment of the wavelength division multiplexing (WDM) technology, where multiple optical wavelengths are combined to travel over the same physical route.

Classification of optical transmission systems

- **Transmission length**: very short reach (hundreds of meters), short reach (several kilometers), long reach (tens and hundreds of kilometers), ultra-long reach (thousands of kilometers)
- **Bit rate**: low-speeds (tens of Mb/s), medium-speed (hundreds Mb/s), high-speed (Gb/s)
- **Application perspective**: power budget limited (loss limited) and bandwidth (transmission speed) limited
Major parameters related to optical transmission

- The ultimate goal of optical signal transmission is usually defined as achieving the pre-specified bit error rate (BER) between two end users or between two intermediate points.
- Optical transmission system needs to be properly engineered in order to provide stable and reliable operation during its lifetime, which includes the management of key engineering parameters.
Optical fiber bandwidth

- Optical fiber is the central point of an optical signal transmission.
- It offers wider available bandwidth, lower signal attenuation, and smaller signal distortions compared to other wired physical media.
- The total bandwidth is approximately 400 nm, or around 50 THz, if it is related to the wavelength region with fiber attenuation below 0.5 dB/km.
- The usable optical bandwidth is commonly split into several wavelength bands.
- The bands around the minimum attenuation point, usually referred to as C and L bands, are the most suitable for high channel count DWDM transmission.
- The wavelength region around 1300 nm is less favorable for optical signal transmission because signal attenuation is higher than attenuation in S, C, and L bands. On the other hand it is quite usable for CATV signals, and CWDM technique can easily be employed.

<table>
<thead>
<tr>
<th>Wavelength band</th>
<th>Descriptor</th>
<th>Wavelength range (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-band</td>
<td>Original</td>
<td>1260-1360</td>
</tr>
<tr>
<td>E-band</td>
<td>Extended</td>
<td>1360-1460</td>
</tr>
<tr>
<td>S-band</td>
<td>Short</td>
<td>1460-1530</td>
</tr>
<tr>
<td>C-band</td>
<td>Conventional</td>
<td>1530-1565</td>
</tr>
<tr>
<td>L-band</td>
<td>Long</td>
<td>1565-1625</td>
</tr>
<tr>
<td>U-band</td>
<td>Ultra-long</td>
<td>1625-1675</td>
</tr>
</tbody>
</table>

Ref. [3]
KEY OPTICAL COMPONENTS

• Semiconductor Light Sources
  - Light-emitting diodes (LEDs)
  - Semiconductor lasers: Fabry-Perrot, distributed feedback (DFB), distributed Bragg reflector (DBR), vertical cavity surface emitting (VCSEL), tunable lasers (external cavity laser, multilaser chip, three-section tunable)

• Optical Modulators
  - Direct optical modulation
  - External modulation: Mach-Zehnder modulator, Electro-absorption modulator

• Optical Fibers
  - Multimode
  - Single-mode

• Optical Amplifiers
  - SOA, EDFA, Raman amplifiers
  - Applications: boost amplifiers, in-line amplifiers, preamplifiers

• Photodiodes: PIN, APD, MSM photodetectors

• Optical components
  - Optical isolators, optical circulators, and optical filters
  - Optical couplers, optical switches, and optical multiplexers/demultiplexers
Signal Impairments

Fiber loss:
• Material absorption
  - intrinsic (ultraviolet, infrared),
  - extrinsic (water vapor, Fe, Cu, Co, Ni, Mn, Cr, dopants: GeO$_2$, P$_2$O$_5$, B$_2$O$_3$)
• Rayleigh scattering and
• Waveguide imperfections
  (Mie scattering, bending losses, etc.)
Insertion loss

Dispersion:
• Intermodal (multimode)
• Chromatic:
  - material
  - waveguide
• PMD, PDL

Fiber nonlinearities:
• Scattering effects (SBS, SRS)
• Kerr nonlinearities (SPM, XPM, FWM)

Noise
• Transmitter: Laser intensity noise, mode partition noise, laser phase noise
• Optical cable (fiber and splicing): modal noise, reflection-induced noise
• Optical amplifier # 1: spontaneous emission
• Optical amplifier # 2: amplified spontaneous emission (ASE)
• Optical receiver (photodiode): thermal noise, quantum noise
Enabling Technologies

• Related to the components:
  - Better amplifiers,
  - Compensators,
  - I/Q modulators,
  - PBSs/PBCs
  - Balanced detectors,
  - Optical hybrids,…

• Related to the method:
  - Advanced modulation formats (both binary and multilevel)
  - Constrained (modulation or line) coding
  - Advanced detection schemes (MLSD/MLSE, SOVA, BCJR, coherent detection, …)
  - Forward error correction (RS codes, concatenated codes, turbo-product codes, and LDPC codes),
  - Coded-modulation techniques,
  - Turbo equalization, …
Optical Communications Trends

• Migration to 100 Gb/s Ethernet and Beyond
  - Over the past decades the Ethernet (IEEE 802.3) has expanded from original share-medium LAN technology to a reliable standard across all level of the networks.
  - Because the IP backbones have grown so quickly that some large ISPs already reported router-to-router trunk connectivity exceeding 100 Gb/s in 2007; some industry experts believe that the 100 Gb/s Ethernet (10GbE) standard is too late, while 1 Tb/s Ethernet standard should be available by 2012-2013.
  - The migration of the line rate from 10 Gb/s to 100 Gb/s is expected to help in reduction of capital and operational costs. Since the migration to 100 GbE leads to fewer pipes, but of larger bandwidth among the IP routers, it is expected to simplify the traffic management.

• Dynamically Reconfigurable Optical Networks
  - The optical networks must be able dynamically add, drop and route the wavelength channels at individual nodes.
  - This type of wavelength management in optical domain is performed by reconfigurable optical add-drop multiplexer (ROADM)
  - In optically routed networks neighboring DWDM channels carry random traffic patterns in which different lightwave paths experience different penalties due to the deployment of ROADM and wavelength cross-connects (WXC)
Different lightwave paths ($L_1$ and $L_2$) in an optically-routed network:

Optical distribution networks connected by ROADMs:
- **Software-Defined Optical Transmission (SDOT)**
  
  - The SDOT system should be able to:
    
    (i) dynamically set up the physical link without any human intervention,
    
    (ii) assign an optimal line rate according and signal constellation size in accordance with the optical link conditions,
    
    (iii) select between multi-carrier mode and single-carrier mode,
    
    (iv) choose an optimum code rate, and
    
    (v) accurately report various channel parameters (optical SNR, chromatic dispersion, PMD, electrical SNR) so to predict the fault and alarm before it causes the traffic interruption.

- Conceptual diagram of software-defined optical transmission concept:
- **Transmitter configuration:**

- **Receiver configuration:**
• Forward Error Correction

- Recent progress in FEC for optical communication systems:

- Soft dec. limit
  \( (R=0.8, \text{Binary input AWGN channel}) \)

- RS(255,239)
- Block Turbo Code
- Concatenated Codes
- LDPC
- GLDPC
- LDPC-coded turbo equalization
- Multi-level coded LDPC (12.3 dB)
- NB-LDPC over GF(8) (11.17 dB)
- g-8 LDPC, c-5 (10.8 dB)
- g-6 LDPC, c-5 (10.6 dB)
- Multi-level coded LDPC (12.3 dB)
- g-8 LDPC, c-5 (10.8 dB)
- g-6 LDPC, c-5 (10.6 dB)

- 1st gen. (measured)
- 2nd gen. (measured)
- 3rd gen. (measured)
- 4th gen. (calculated)
- Orthogonal Frequency Division Multiplexing (OFDM) and Discrete Multitone (DMT)

- OFDM system with direct detection suitable for transmission over MMF links:

```
Data input

Demultiplexer

Constellation mapper

Inverse FFT

P/S converter and cyclic extension (CE)

D/A converter

Laser diode

Bias

MMF

Estimate of input data

Multiplexer

Constellation demapper

FFT

S/P converter and CE remover

A/D converter

Photodetector
```
• Polarization-Multiplexing and Coded Modulation

- **Tx configuration:**

Source Channels \( x \)

\[
\begin{align*}
\text{LDPC encoder } & \quad \frac{r_j}{n} = \frac{k_j}{n} \\
\text{Interleaver } & \quad m \times n \\
\text{LDPC encoder } & \quad \frac{r_m}{n} = \frac{k_m}{n} \\
\text{Mapper } & \quad m \times n \\
\text{MZM} & \quad m \times n \\
\text{DFB laser} & \\
\text{PBS} & \\
\text{PBC} & \\
\text{To fiber} & \\
\end{align*}
\]

Source Channels \( y \)

\[
\begin{align*}
\text{LDPC encoder } & \quad \frac{r_j}{n} = \frac{k_j}{n} \\
\text{Interleaver } & \quad m \times n \\
\text{LDPC encoder } & \quad \frac{r_m}{n} = \frac{k_m}{n} \\
\text{Mapper } & \quad m \times n \\
\text{MZM} & \quad m \times n \\
\text{From SMF} & \\
\text{From local laser} & \\
\end{align*}
\]

- **Rx configuration:**

\[
\begin{align*}
\text{PBS} & \\
\text{APP Demapper} & \\
\text{LDPC Decoder } m_x & \\
\text{APP Demapper} & \\
\text{LDPC Decoder } m_y & \\
\end{align*}
\]
Course Syllabus

• Noise sources, channel impairments, and optical transmission system design
• Forward error correction (FEC):
  – Linear block codes and cyclic codes,
  – BCH and RS codes,
  – Concatenated codes,
  – Turbo-product codes, and
  – LDPC codes.
• Advanced modulation formats, constrained coding, and coherent detection:
  – Advanced binary modulation schemes (revisited)
  – M-ary PSK/DPSK, and M-ary QAM/differential QAM; M-ary pulse-amplitude modulation formats,
  – Orthogonal frequency-division multiplexing (OFDM),
  – Constrained (line or modulation) coding, and
  – Coherent detection.
• Coded modulation schemes:
  – Multilevel coding,
  – Bit-interleaved coded modulation,
  – Coded-OFDM
• Advanced chromatic dispersion compensation:
  – Signal pre-distortion compensation,
  – Postdetection compensation: feed-forward equalizer (FFE), decision-feedback equalizer (DFE), maximum-likelihood sequence estimation (MLSE) or Viterbi equalizer (VE), turbo equalization (TE);
  – Optical-phase conjugation based on highly-nonlinear fibers (HNLFs) and periodically-poled LiNbO3 (PPLN);
  – Compensation of chromatic dispersion by OFDM.

• PMD compensation:
  – Optical compensation techniques,
  – Electrical compensation techniques (FFE, DFE, VE, TE, ...);
  – OFDM based techniques in PMD compensation.

• Nonlinearity management:
  – Suppression of intrachannel and interchannel nonlinearities,
  – Compensation of nonlinear phase noise,
  – Digital back-propagation method, and
  – Turbo equalization.
• Spatial-domain-based multiplexing and modulation
• Optical channel capacity
  – Channel capacity preliminaries,
  – Calculation of information capacity,
  – Information capacity of systems with direct detection,
  – Information capacity of multilevel systems with coherent detection,
  – Capacity of optical OFDM systems,
  – Channel capacity of optical MIMO MMF systems,
  – Channel capacity of hybrid FSO – RF channels.
• Parametric processes and applications:
  – Parametric amplifiers,
  – All-optical regeneration,
  – Wavelength conversion, and
  – Multibanded switching.
• Soliton, and dispersion-managed soliton transmission (if time allows).
Course Information

- Instructor: Ivan B. Djordjevic
- Email: ivan@email.arizona.edu
- Phone: 626-5119
- Office: ECE 456B
- Website: http://www.ece.arizona.edu/~ivan
- Office Hours: Tuesdays and Thursdays, 4:00 PM – 5:00 PM
- Class website: http://www2.engr.arizona.edu/~ece632/
- Class time and location:
  Wednesdays, 3:00PM-5:30PM; Elec. & Comp. Engr., Rm 258
- Prerequisite: ECE/OPTI 430/530 recommended (or equivalent)
• **Exams, project, and homeworks**
  – One midterm exam (taken during the regular class times) and a final exam scheduled for: Wednesday 5/9/2012; 1:00 pm - 3:00 pm
  – Homework assignments: approximately every 2-3 weeks
  – Term Project

• **Grading Policy**
  – Homework 20%
  – Midterm 20%
  – Final 30%
  – Term Project 30%
• **Project Info**

  – Term project on anything related to advanced optical communications
    
    • Survey is low risk, maximum grade capped at 85% (single-person project only).
    
    • Novel research more risky: start early, discuss with Instructor
    
    • Group projects for MS students (3-4 people, non-survey)
    
    • Group projects for PhD students (2-3 people, non-survey)
  
  – Project proposal presentation: due February 29, 2012
    
    • Power point presentation (10-15 min per group)
    
    • Should include 2-3 references and their relevance
  
  – Final report: May 02, 2012 (5 pages, references not counted; IEEE format)
References