ICT Technical Update Module

Optical Networks Part I

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Outline

- Objectives and Additional References
- History of Optical Network
- Overview of Optical Transmission System
- Key Features of Photonics
- Optics Fundamentals
- IP over Optical Network Architecture
- Optical Switching Technology
- Survivability in Optical Networks
- Protection & Restoration Schemes in Optical Networks
Objectives

After studying this course, you are expected to

• Demonstrate understanding of the fundamental problems, tradeoffs, and design issues that arise in optical networking, as well as identify and critically evaluate optical network technologies and solution approaches

• Understand the details of several particular protocols, as example implementations of fundamental principles, and digest descriptions of specific protocols, extracting the salient concepts

• Engage in original work and research in the area of optical networks
Additional References

• Rajiv Ramaswami, Kumar Sivarajan, Optical Networks: A Practical Perspective (Second Edition), 2001
• Wayne D. Grover, Mesh-based survivable networks: Options and strategies for optical, MPLS, SONET, and ATM Networking, 2004
History of Optical Networking

- 1958: Laser discovered
- Mid-60s: Guided wave optics demonstrated
- 1970: Production of low-loss fibers
  - Made long-distance optical transmission possible
- 1970: invention of semiconductor laser diode
  - Made optical transceivers highly refined
- 70s-80s: Use of fiber in telephony: SONET
- Mid-80s: LANs/MANs: broadcast-and-select architectures
- 1988: First trans-Atlantic optical fiber laid
- Late-80s: EDFA (optical amplifier) developed
  - Greatly alleviated distance limitations
- Mid/late-90s: DWDM systems explode
- Late-90s: Intelligent Optical networks
Success of optical communications

Optical fiber advantages
- Huge bandwidth (WDM)
- Long range transmission (EDFA optical amplifiers)
- Strength
- Use flexibility (transparency)
- Low noise
- Low cost
- Interference immunity

Optical components
- Rapid technological evolution
- Increasing reliability
- Decreasing costs

Convergence of services over a unique transport platform
- Success of digital communications
- Data oriented networks
Commercial enabling factors

Demand for bandwidth is a powerful driver
- New bandwidth-demanding services
- “Chicken-and-egg” effect, especially for residential customers

New paradigm in telecom market
- Market opening
- Deregulation (or better anti-trust regulation)
- Competition

Interconnection and access rights/obligations
- World-wide transport services (e.g. GSM)
- Lowering the dominant position of historical operators
- Interoperability
- Horizontal: network-network, system-system
- Vertical: layered protocols
- Fast development of new standards
Overview: Optical Transmission System Pieces
Overview: DWDM Optical components

LD Mod = Laser Diode + Modulator
OA = WDM Optical amplifier
Rx = Receiver
DISP-C = WDM Dispersion compensation
EQUAL. = WDM Equalization
OADM = Optical Add-Drop Multiplexer
What is Light? Theories of Light
What is Light?

- Wave Nature:
  - Reflection, refraction, diffraction, interference, polarization, fading, loss …

- Transverse EM (TEM) wave:
  - Interacts with any charges in nearby space…
  - Characterized by frequency, wavelength, phase and propagation speed
  - Simplified Maxwell’s equations-analysis for monochromatic, planar waves
  - Photometric terms: luminous flux, candle intensity, illuminance, Luminance…

- Particle nature:
  - Number of photons, min energy: $E = hu$
  - “Free” space => no matter OR EM fields
  - Trajectory affected by strong EM fields
Light Attributes

- Dual Nature: EM wave and particle
- Many λs: wide & continuous spectrum
- Polarization: circular, elliptic, linear: affected by fields and matter
- Optical Power: wide range; affected by matter
- Propagation:
  - Straight path in free space
  - In matter it is affected variously (absorbed, scattered, through);
  - In waveguides, it follows bends
- Propagation speed: diff λs travel at diff speeds in matter
- Phase: affected by variations in fields and matter
Geometrical Optics: Fiber Structure

- Fiber Made of Silica: SiO2 (primarily)
- Refractive Index, $n$
- $n_{\text{core}} > n_{\text{cladding}}$

Numerical Aperture:
- Measures light-gathering capability
Geometrical Optics Applied to Fiber

- Light propagates by total internal reflection
- Modal Dispersion: Different path lengths cause energy in narrow pulse to spread out
- $\delta T = \text{time difference between fastest and slowest ray}$
Fiber Anatomy

Cross section (not to scale)

- Plastic
- Kevlar™
- Buffer coating
- Cladding
- Glassy core
Fiber Manufacturing

- Dopants are added to control RI profile of the fiber
- Fiber: stronger than glass
- A fiber route may have several cables
- Each cable may have up to 1000 fibers
- Each fiber may have up to 160 wavelengths
- Each wavelength may operate at 2.5Gbps or 10 Gbps
Single vs. Multimode Fiber

- Silica-Based Fiber Supports 3 Low-Loss “Windows”: 0.8, 1.3, 1.55 µm wavelength
- Multimode Fibers Propagate Multiple Modes of Light
  - core diameters from 50 to 85 µm
  - modal dispersion limitations
- Single-mode Fibers Propagate One Mode Only
  - core diameters from 8 to 10 µm
  - chromatic dispersion limitations
Single Mode Characteristics

- It (almost) eliminates delay spread
- More difficult to splice than multimode due to critical core requirements
- More difficult to couple all photonic energy from a source into it; light propagates both in core and cladding!
- Suitable for transmitting modulated signals at 40 Gb/s and up to 200 km w/o amplification
- Long lengths and bit rates $\geq$ 10 Gbps bring forth a number of issues due to residual nonlinearity/birefringence of the fiber
- Fiber temperature for long lengths and bit rates $> 10$ Gbps becomes significant.
**Metrics and Parameters in Optics**

<table>
<thead>
<tr>
<th>Parameter (Symbol, Unit)</th>
<th>Measuring Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuation ${ A(\lambda), \text{-dB} }$</td>
<td>$A(\lambda) = 10 \log[P_{\text{out}}(\lambda)/P_{\text{in}}(\lambda)]$, $P_{\text{in}} &gt; P_{\text{out}}$</td>
</tr>
<tr>
<td>Attenuation coefficient ${ \alpha(\lambda), \text{dB/km} }$</td>
<td>$\alpha(\lambda) = A(\lambda)/\lambda$</td>
</tr>
<tr>
<td>Insertion Loss, ${ IL_i, \text{-dB} }$ between port $i$ and port $j$</td>
<td>$IL_{ij} = P_j - P_i$, or $IL_{ij} = -10 \log_{10} t_{ij}$, (where $t_{ij} = I/O$ power transfer matrix)</td>
</tr>
<tr>
<td>Amplification gain (g, dB)</td>
<td>$g(\lambda) = 10 \log[P_{\text{out}}(\lambda)/P_{\text{in}}(\lambda)]$, $P_{\text{in}} &lt; P_{\text{out}}$</td>
</tr>
<tr>
<td>Birefringence</td>
<td>$P_O/P_E$; indirectly (BER, X-talk)</td>
</tr>
<tr>
<td>Extinction ratio</td>
<td>$P_B/P_F$; indirectly from IL &amp; $A(\lambda)$</td>
</tr>
<tr>
<td>Pulse spreading (ps)</td>
<td>$\Delta t_{\text{OUT}} - \Delta t_{\text{IN}}$ (indirectly from BER, X-talk, eye diagram)</td>
</tr>
<tr>
<td>Group delay (ps)$^+$</td>
<td>$\tau(\lambda) = \tau_0 + (S_0/2)[\lambda - \lambda_0]^2$ (see G.653)</td>
</tr>
<tr>
<td>Diff. group delay (DGD, ps)</td>
<td>(see ITU-T G.650 for procedure)</td>
</tr>
<tr>
<td>Chromatic disp. coeff. (D, psec/nm-km)</td>
<td>$D(\lambda) = S_0(\lambda - \lambda_0)^{**}$ (see G.653)</td>
</tr>
<tr>
<td>Chromatic disp. slope (S, psec/nm²-km)</td>
<td>it requires laboratory optical setup</td>
</tr>
<tr>
<td>Polarization mode dispersion (PMD, ps)</td>
<td>it requires laboratory optical setup</td>
</tr>
<tr>
<td>Phase shift ($\Delta \phi$, rad)</td>
<td>it requires interferometric setup</td>
</tr>
<tr>
<td>Polarization mode shift ($\Theta$, rad)</td>
<td>it requires laboratory optical setup</td>
</tr>
</tbody>
</table>
Components in Optical Network

- Couplers, Splitters, Isolators, Circulators
- Filters, Gratings, Multiplexers
- Optical Amplifiers, Regenerators
- Light Sources, Tunable Lasers, Detectors
- Modulators
Multiplexing and Switching in optical networks

Multiplexing
• SDM
• WDM
• TDM
• xDM

Switching
• Packet switching
• Circuit switching
Optical transmission system evolution

- 1988 – 2001: capacity has been doubling each year
- Reduction of the lag between laboratory experiment and deployment
A network link
Multiplexing Domain-Space division

Space-division multiplexing

- Each optical cable is a bundle of fibers (up to more than 100)
- High fiber count due to high costs of the right-of-way and labor in laying down cables
- Usually an equal number of fiber is dedicated to each direction, though bidirectional transmission on a single fiber can be done (depending on the amplifiers)
Multiplexing Domain - Wavelength Division Multiplexing - WDM

Main physical characteristics that determine the optical spectrum utilization (allocation and number of the WDM channels)

• Fiber loss gain (transmission window width)
• Optical amplifier gain profile
  - Classical (C) and Long (L) wavelength bands can be used with new EDFAs
• WDM filter transfer function
Wavelength Division Multiplexing (WDM)

- Channels encoded by modulating different wavelengths can be transmitted over the same fiber
Time division multiplexing – TDM

Time-division multiplexing

- A WDM system with 100 GHz spacing is able to support 10 Gbit/s channels
- This huge bandwidth is shared by TDM (in the electronic domain)

Total cable capacity estimation

- 100 fibers x 64 wavelengths x 10 Gbit/s = 64 Tbit/s
Optical transparency

Optical transparency:
- a very interesting and important property of optical networks
- In the strict sense: no optical-electronic conversion needed to switch information

Different levels of transparency in the wide sense
- Full optical transparency
  - Both analogical and digital signals, WDM PON access networks
- Bit-rate optical transparency
  - Only digital streams
  - WDM transport networks
- Payload Optical Transparency
  - All-optical packet switching
  - Photonic ATM networks
- Protocol Transparency
  - Layered approach optical networking
  - WDM transport networks
• Optical line amplifiers (span length $L_s$) compensate propagation and switching loss, but do not regenerate the signal
• Signal degradation limits the maximum transparency length $L$
  – Signal degradation increases the Bit Error Rate (BER)
  – The maximum allowable $L$ is such that a maximum level of BER is guaranteed (usually BER < $10^{-12}$)
WDM regenerated system

- Regeneration is needed to cover long distances
- Optical-electronic conversion is carried out even if it is not needed from a networking point of view
Switching

Circuit vs. packet switching
Circuit vs. packet switching

- **Circuit switching**
  - An amount of network resources is dedicated to each active user (assigned bandwidth)
    - Bandwidth fully available to users who are activated
  - Type of service
    - Call
  - Connections cross the switching nodes
  - Time transparency: constant delay
  - Simple protocols
  - QoS measured in terms of call-blocking probability
  - Low reconfiguration speed

- **Packet switching**
  - Network resources are shared by all the active users (reserved bandwidth or best effort)
    - No guarantees of resource availability during the connection time
  - Type of service
    - Virtual Circuit (VC)
    - Datagram (DG)
  - Packets cross Store & Forward nodes
  - Access flexibility: information units are not carried in a transparent way
  - Complex protocols
  - QoS measured in terms of delay and packet loss probability
  - Packet-by-packet reconfiguration speed
Layers of a circuit-switched network

Features
- Implicitly connection-oriented service
- Node functions: limited to layer 1
- Node crossing without information processing
Circuit switching
Assigned bandwidth

**Assigned-bandwidth mode**

- Only used in circuit switching
- Processing only carried out during call setup and release
- Node crossing function
  - Direct input-output connection
  - No buffering
  - Constant (TDM) or null delay (SDM, WDM)
- Time transparency, the end-points must be compatible (bit rate, control procedure, etc.)
Optical circuit switching

- Connections in WDM network are optical circuits (lightpaths)
- WDM networks are Circuit Switched networks
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Optical Networks Part II
IP over Optical Network Architecture and Survivability in Optical Network
Layered View of the Optical Network

- Layered model- “Everything over WDM”
- Optical networks are developing as transport platforms common to different electronic clients
WDM network systems

The WDM network is a complex system comprising
- Physical transport resources and transmission equipment
- Switching devices (OADMs, OXC)s
- Interfaces to electronic upper layers
- A set of protocols and techniques to control and manage the system
Overview for IP over Optical Network

- Optical networks must be survivable, flexible, and controllable
- Introduce Intelligence in the control plane of optical networks
  - The capability to route optical layer connections in real-time or near real-time, and to provide capabilities that enhance network survivability
- General Consensus
  - The optical network control plane should utilize IP-based protocols for dynamic provisioning and restoration of lightpaths within and across optical sub-networks
- Two Fundamental Issues
  - Adaptation and reuse of IP control plane protocols within the optical network control plane
  - Transport of IP traffic through an optical network
IP Transport over Optical Networks

• Assumptions
  – The IP data plane over optical networks is realized over a virtual topology of optical paths
  – IP routers and OXCs can have a peer relation on the control plane, especially for the routing protocol that allows dynamic discovery of IP endpoints attached to the optical network.
  – The MPLS-based control plane is used

• Coupling of the control planes in IP and optical networks
  – Details of the topology and routing information advertised by the optical network across UNI
  – Level of control on specific connections paths across the optical network
  – Policies regarding the dynamic provisioning of optical paths between routers. This includes access control, accounting and security issues.
IP Transport Model over Optical Networks

• Overlay Model
  – IP/MPLS routing, topology distribution, and signaling protocols are independent of those at the optical layer
    • Conceptually similar to the classical IP over ATM models

• Peer Model
  – IP/MPLS layers act as peers of the optical transport network
  – Single control plane in the OTN and IP/MPLS domains
    • Common IGP such as OSPF or IS-IS with appropriate extensions
  – The optical network elements become IP addressable entities
    • A common address space can be realized by using IP addresses in both IP and optical domains

• Augmented Model
  – Actually separate routing instances in the IP and optical domains, but information from one routing instance is passed through the other routing instance
Optical network design

• Optical network makes available lightpaths to its clients
  - Lightpaths must be accommodated in a physical optical network
  - Overall design must minimize resource usage
• Wavelength routing networks
First-generation optical network

- Example with SONET/SDH OC-48 (STM-16)

ADM=Add-Drop Multiplexer
DCS=Digital Cross-Connect
Wavelength routing networks (1/4)

Adopting WDM links

<table>
<thead>
<tr>
<th>Flow</th>
<th>Wavelength</th>
<th>#OC-48s</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>λ₁</td>
<td>1</td>
</tr>
<tr>
<td>BD</td>
<td>λ₁</td>
<td>1</td>
</tr>
<tr>
<td>AD</td>
<td>λ₁</td>
<td>1</td>
</tr>
<tr>
<td>AC</td>
<td>λ₂</td>
<td>2</td>
</tr>
<tr>
<td>BC</td>
<td>λ₃</td>
<td>1</td>
</tr>
<tr>
<td>BD</td>
<td>λ₃</td>
<td>2</td>
</tr>
<tr>
<td>CD</td>
<td>λ₃</td>
<td>1</td>
</tr>
</tbody>
</table>

Routing with 3 wavelengths
Wavelength routing networks (2/4)

- A logical topology has been built on a physical topology defining optical lightpaths
Wavelength routing networks (3/4)

- Traffic requests changes and protection can be carried out using switches
Wavelength routing networks (4/4)

Nodes

- OXC or WXC

The network makes available lightpaths between nodes

- Wavelength allocation to lightpaths is crucial so as to maximize their space reuse
Wavelength conversion

- Wavelength converters can help in reducing the number of wavelengths needed
Wavelength conversion

(a) No wavelength conversion

(b) Fixed wavelength conversion

(c) Limited wavelength conversion

(d) Full wavelength conversion
Space diversity

![Diagram of space diversity with fiber 1 and fiber 2 connections, showing λ converters and switches.](image)
Wavelength cross-connect

OEO
Wavelength cross-connect

```
\[ \lambda_1 \lambda_2 ... \lambda_W \]
```

```
\[ \text{wavelength demux} \]
```

```
\[ \text{optical switch} \]
```

```
\[ \text{wavelength converters} \]
```

```
\[ \lambda_1 \lambda_2 ... \lambda_W \]
```

```
\[ \text{wavelength mux} \]
```

```
\[ 1 \]
```

```
\[ 2 \]
```

```
\[ M \]
```

```
\[ \text{wavelength demux} \]
```

```
\[ \lambda_1 \lambda_2 ... \lambda_W \]
```

```
\[ \text{optical switch} \]
```

```
\[ \text{wavelength converters} \]
```

```
\[ \lambda_1 \lambda_2 ... \lambda_W \]
```

```
\[ \text{wavelength mux} \]
```

```
\[ 1 \]
```

```
\[ 2 \]
```

```
\[ M \]
```

Wavelength cross-connect
Multi-plane arrangement

\[
\begin{array}{c}
\lambda_1 \lambda_2 \ldots \lambda_W & \lambda_1 & \lambda_1 \lambda_2 \ldots \lambda_W \\
\lambda_1 \lambda_2 \ldots \lambda_W & \lambda_2 & \lambda_1 \lambda_2 \ldots \lambda_W \\
\ldots & \ldots & \ldots \\
\lambda_1 \lambda_2 \ldots \lambda_W & \lambda_W & \lambda_1 \lambda_2 \ldots \lambda_W \\
1 & \text{demux} & 1 \\
2 & \text{switch} & 2 \\
M & \text{mux} & M
\end{array}
\]
## Wavelength cross-connect

<table>
<thead>
<tr>
<th>Technology</th>
<th>Optical WXC</th>
<th>Electronic WXC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transparency</td>
<td>yes</td>
<td>difficult</td>
</tr>
<tr>
<td>Wavelength conversion</td>
<td>difficult</td>
<td>easier</td>
</tr>
<tr>
<td>Bit rate</td>
<td>&gt; 10 Gbit/s</td>
<td>≤ 2.5 Gbits</td>
</tr>
<tr>
<td>WXC size</td>
<td>small</td>
<td>large</td>
</tr>
<tr>
<td>Physical layer design</td>
<td>difficult</td>
<td>easier</td>
</tr>
<tr>
<td>Monitoring</td>
<td>limited</td>
<td>extensive</td>
</tr>
<tr>
<td>Components needed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mux/demux</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>
optical switches                | yes         | no            |
electronic switches             | no          | yes           |
transmitters/receivers          | no          | yes           |
wavelength converters           | maybe       | no            |

**Note:** Electronic switches are cheaper today
Wavelength routing networks
Network types

Wavelength routing networks can be
• Static: less cost, less flexibility
• Reconfigurable: higher costs, higher flexibility

Static networks
• They can be described as a connectivity matrix or through a bipartite graph
• WXC\textsuperscript{s} do not use switches
• Fixed non-dynamic wavelength converters can be used
• There is no change in the network state

Reconfigurable networks
• Set of requested lightpaths can be changed at any time
Static networks-Rings

Unidirectional

Bidirectional
Static WR networks Arbitrary topology

Static WXC

Bipartite graph
Reconfigurable WR networks Problems

- Logical (Virtual) Topology Design (LTD)
  Given a traffic matrix, find the optimal set of lightpaths satisfying the request

- Routing and Wavelength Assignment (RWA)
  Given a physical topology and a set of requested lightpaths, find routing and wavelength assignment for each lightpath on each link minimizing the wavelengths used
Wavelength assignment Graph coloring

- Graph coloring problem: each node must have a color different from its neighbors
  - Minimum number of colors is the graph chromatic number
- Graph coloring problem is NP-complete, even if optimum algorithms exist in particular cases and various heuristics are available
Wavelength assignment Line network

Greedy algorithm

• Number wavelengths from 1 to L
• Start from first lightpath and assign to it wavelength 1
• Go to next lightpath starting from left and assign to the
Routing and Wavelength Assignment
Ring network

Ring
• Simplest network topology with connectivity degree equal to two
• Only two routings available, clockwise and anticlockwise for each lightpath

Theorems
• If the minimum possible load with arbitrary routing is $L_{min}$, shortest path routing yields a load of at most $2L_{min}$
• Given a routing of the requested lightpaths on a ring with load $L$, WA requires $W_{min}=2L-1$ without wavelength conversion
GMPLS-based Control and Signaling
Control Requirements for Optical Networking

- Control Requirements
  - Dynamic Reconfiguration of Optical Network
  - Link Protection and restoration, Capacity Planning, performance monitoring, etc.
  - Rapid service provisioning for negotiated bandwidth and QoS
  - Scalability on bandwidth provisioning
  - Grooming of sub-rate circuits
  - Dynamic Optical VPN for multicast according to SLA
  - Automatic configuration and topology auto-discovery
  - Integrated control of L1, L2 and L3 Switching/Routing
MPLS-based Control for Optical Internet

• IP-based approaches for rapid provisioning
  – Re-use existing signaling framework
  – Less standardization, faster vendor interoperability
  – No addressing concerns arise (use IP addresses)

• Key MPLS features exploited
  – Hierarchical LSP tunneling (label stacking/swapping)
  – Explicit routing capabilities
  – LSP survivability capabilities
  – Constraint-based routing
MPLS-based Control for Optical Internet

- Traffic Engineering in Optical Network
  - Optical network load balancing
  - Performance optimization
  - Resource utilization optimization
- Extensions to MPLS signaling
  - Encompass time-division (e.g. SONET ADMs), wavelength (optical lambdas) and spatial switching (e.g. incoming port or fiber to outgoing port or fiber)
  - Label is encoded as a time slot, wavelength, or a position in the physical space
  - Bandwidth allocation performed in discrete units.
GMPLS Signaling

- **Overview**
  - Extend MPLS to support TDM, lambda and fiber switching.
  - Extend base function to add functionality.
  - The label is encoded as a time slot, wavelength, or a position in the physical space.
  - Bandwidth allocation performed in discrete units.
  - Allows for a label to be suggested
  - Restrict the range of labels
  - Supports the establishment of bi-directional LSPs
Forwarding Interface of GMPLS

- Packet-Switch Capable (PSC)
  - Recognize packet/cell boundaries and forward data based on header.
- Time-Division Multiplex Capable (TDM)
  - Forward data based on the data’s time slot in a repeating cycle.
- Lambda Switch Capable (LSC)
  - Forward data based on the wavelength
- Fiber-Switch Capable (FSC)
  - Forward data based on a position of the data in the real physical spaces.

Allow the system to scale by building a forwarding Hierarchy
Conclusions

• Architectural Evolution for Optical Network
  – Single Control Plane Both for IP domain and Optical Domain
  – IP-centric control mechanisms are being used for optical layer control

• Generalized MPLS Technologies
  – Extends MPLS to encompass time-division, wavelength and spatial switching
  – Adapt IP Traffics to Physical limitations of Optical Technologies
  – Generalized MPLS is used both for Service Model and Architectural Model