(Part 2)
Optical Networks – Some research topics
Topics to be covered

• Fault tolerance
• Impairment aware network design
• OFDM networks
Fault-tolerance in Optical Networks

- **Faults in Optical Networks**
  - **Link failures**
    - the most common type of fault, where the fiber constituting a link between two nodes in the network does not permit data transmission.
  - **Node failures**
  - **Channel failures**
  - **Software failures**
  - Most papers assume *single fault* scenario.
Fault-tolerance in Optical Networks

- Reasons behind faults in optical layer
  - Fiber cut
  - Noise introduced by optical signal regenerators and amplifiers
  - Cable inside a site may get disconnected

- Importance of Fault management in optical networks
  - Large amount of traffic carried by optical channels
  - Each fiber carries many channels, each channel having a capacity of 2.5 to 40 GB/sec
  - Failure may lead to huge data loss
Fault-tolerance in Optical Networks

- Categorization of fault management schemes

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Fault-Management Schemes
  Protection
    Dedicated Backup
      Path Protection
    Shared Backup
      Link Protection
  Restoration
    Path Restoration
      Path Protection
    Link Restoration
      Link Protection
```

Figure 1
Fault-tolerance in Optical Networks

- **Protection scheme**
  - Recovery scheme determined at design time
  - Resources are reserved for each possible failure (link or path).
  - Faster recovery time and guaranteed recovery

- **Restoration scheme**
  - Recovery scheme determined after the occurrence of fault
  - Dynamically search for backup path and available wavelength after failure occurrence.
  - Efficient in utilizing capacity
Fault-tolerance in Optical Networks

- Link protection – backup path reserved around each link

- Primary path: N8 → N4 → N6 → N1
- The faulty edge N4 → N6 is replaced by an alternate route N4 → N7 → N6.
- Backup path: N8 → N4 → N7 → N6 → N1

Figure 2: Link protection scheme
Fault-tolerance in Optical Networks

- Path Protection
  - In the case of a fault, for each primary lightpath using the faulty component, the corresponding backup lightpath will be set up.
  - All data carried by each primary lightpath affected by the fault will be switched over to the corresponding backup lightpath.
  - Primary and backup paths must be *edge-disjoint.*
Fault-tolerance in Optical Networks

- Path Protection – backup path reserved on a end-to-end basis

Figure 3: Path protection scheme
Fault-tolerance in Optical Networks

- Dedicated path protection

  Dedicated Path Protection
  The channel used by a backup lightpath is always reserved for a single primary lightpath.

Figure 4: 1:1 Protection
Fault-tolerance in Optical Networks

- Shared Path Protection (also called backup multiplexing)
  Resources may be shared by two or more backup paths if and only if the corresponding primary paths are edge disjoint.

Figure 5: 1:N Protection
Physical Layer Impairments

- Causes = Attenuation, Distortion & Noise
- As an optical signal propagates:
  - signal loses strength
  - signal becomes distorted, and
  - signal to noise ratio increases

Note: PLI are not defects, but characteristics of the fiber
Physical Layer Impairments (PLI)

• Physical layer impairments are broadly classified into 2 types namely: **Linear & Non-Linear**.

• **Linear Impairments**: Affect a lightpath individually and are not dependant on other lightpaths in the network. **Examples**: Amplified Spontaneous Emission (ASE), Chromatic Dispersion (CD), Polarization Mode Dispersion (PMD).

• **Non-Linear Impairments**: Interference between lightpaths. **Examples**: Cross-Phase Modulation (XPM) and Switch Crosstalk (XT)

• Routing and Wavelength Assignment (RWA) that takes into account the effects of PLI, is termed **Impairment-Aware RWA** (IA-RWA).
Physical Impairments

- Most of the physical impairments are the characteristics of the optical devices used.
- Affects of a few impairments may be improved during RWA.
  - Inter-channel cross talk
  - Intra-channel cross talk

Figure 6: Some non-linear impairments
Physical Layer Impairments

- Signal loses strength and becomes distorted

- Signal to Noise Ratio (SNR) = average signal power/ average noise power

- QoT = Bit Error Rate

- Analytical models vs. Rough estimates
3R-Regeneration

- Optical Reach = distance after which signal QoT becomes unacceptable
- Extending the range of a signal

Retiming

- 3R-Regeneration restores the signal to its original state.
3R-Regeneration

- The optical signal needs to be **regenerated** before the QOT falls below the **acceptable level** (called **threshold**).
- **Optical regenerators** (i.e. regeneration in the optical domain) still in the research phase.
- **3R-Regeneration** (Re-amplification, Re-shaping and Re-timing) - performed in the **electronic domain**. OEO is expensive.

![Figure 7: 3R regeneration](image_url)
Translucent Lightpath & Wavelength Conversion

• 3R regenerators also provide *wavelength conversion* at no extra cost.

Fig 8: Transparent and translucent lightpath
Regenerator Capable Node

Optical Reach = 2000

To regenerate or not to regenerate?

Figure 9: A regeneration-capable node has the option of regenerating signals
Transparent vs. Translucent lightpath

- A lightpath is used for data communication.
- It is characterized by:
  - A route from a source to a destination
  - A channel for each edge on the route

Any lightpath that has to undergo, at least one regeneration, is called a translucent lightpath.

Figure 9: a translucent lightpath
Categories of Optical Networks

- Three categories of optical networks.
  - Fully switched (opaque) network.
    - Each lightpath undergoes Optical-Electronic-Optical (OEO) conversion in every node on its route from its source to destination.
    - Network may be of any size.
    - Costlier and slower.

![Diagram of an opaque network](image)

Figure 10: An opaque network
Categories of Optical Networks

• All-optical (transparent) networks.
  – Lightpaths remain in the optical domain from source to destination.
  – Faster and less costly.
  – Suitable only for networks covering relatively small geographical area.
  – High Bit-Error-Rate when the transmission distance is high.

Figure 11: An all-optical network
Categories of Optical Networks

• Translucent networks.
  – Selected nodes have the capacity to “regenerate” optical signals.
  – Some lightpaths using routes longer than the optical reach, undergo OEO conversion at some regenerating nodes on its route from their respective sources to their destinations.
  – Remaining lightpaths remain in the optical domain from their sources to their destinations.

Figure 12: A translucent network
Translucent networks

• Translucent networks:
  – Provide the advantages of both opaque and transparent networks.
  – Less costly than opaque networks.
  – Sufficiently fast.
  – Low Bit-Error-Rate.
  – Suitable for networks covering large or very large geographical area.
Translucent Lightpaths

- May be considered as a concatenation of two or more transparent lightpaths.
- Each transparent part is called a segment.

Figure 13: Segments in a lightpath
Types of Blocking in translucent networks

- Physical Layer Blocking
- Network Layer Blocking
  - Lack of available resources (e.g. channel) due to the presence of existing lightpaths

Figure 14: A lightpath may be blocked for 2 reasons
Dynamic and static lightpath allocation

- **Dynamic lightpath allocation (DLA)**
  - Traffic requests are not known in advance.
  - Traffic patterns change with time.
  - Lightpaths are established as and when a new traffic request arrives.
  - A lightpath exists only for the duration of data communication.

- **Static lightpath allocation (SLA)**
  - Traffic requests are known in advance.
  - Traffic patterns do not significantly change with time.
  - Lightpaths are established, considering all the traffic requests.
  - Once established, lightpaths exist for a long period of time.
Designing Translucent Networks

• For **dynamic** traffic: Connection requests arrive **randomly** and the **duration** of the connection is **not known** in **advance**. “**Optimal**” regenerator placement is **not possible**.

• A dynamic traffic based, translucent optical network is designed in **2 stages**:
  – 1. Regenerator Placement Problem (**RPP**) &
  – 2. Routing with Regenerators Problem (**RRP**)
Regenerator Placement Problem (RPP)

- Given a network physical topology.
  - Identify the minimum numbers of nodes that should have regenerating capacity, so that, for every ordered node-pair \((s, d)\), \(s\) may establish a valid connection, using a transparent or a translucent lightpath) to \(d\).

Figure 15: A network with sparsely distributed regenerating nodes
Routing with Regenerator Problem (RRP)

• Given
  – a network topology,
  – the location of regenerator nodes, and
  – details about all existing lightpaths,
  – a new request for a lightpath from \(s\) to \(d\),

• Carry out Routing and Wavelength Assignment (RWA) to establish a new lightpath from \(s\) to \(d\), using a minimum number of regenerators.

Figure 16: A translucent network

- Nodes without regenerating capacity
- Nodes with regenerating capacity
- Existing lightpaths
- New lightpath
Loops in translucent lightpaths

Loops - An interesting feature of translucent lightpaths

- Property:
  - If a translucent lightpath has two segments, $S_a$ and $S_b$ sharing common fiber(s), the same channel cannot be used for both $S_a$ and $S_b$.

- This property has not been taken into account in the earlier works on RRP.
The limitations of WDM Technology

- Increasing capacity requirements pertaining to the high data-rate applications like video on demand, cloud computing etc.
- The continuous growth of consumers IP traffic => ever increasing requirements for additional channels.
- The need for flexibility and efficiency in the allocation of spectral resources.
Signal Bandwidth = 10 GHz, Channel Spacing = 100 GHz

- If the user requires only 1 GHz, 90% of the spectrum is wasted.
- Further, if the user requires 12 GHz, the user has to be assigned 2 lightpaths using different frequencies, which may potentially lead to wastage of space and also the overhead cost of splitting and combining of data.

- The fixed granularity of the current wavelength-routed networks.

Figure 18: WDM channels
Optical OFDM Technology

- Orthogonal Frequency Division Multiplexing (OFDM) is a scheme that allows
  - Elastic allocation of spectrum according to connection demands.

Figure 19: A simple way to visualize OFDM vs WDM
Optical OFDM Benefits

- Optical OFDM offers good spectral efficiency by elastically allocating the bandwidth, according to the connection demands.

Figure 20: Elastic bandwidth
Notion of Routing and Spectrum Assignment (RSA)

- Assigning a route and bandwidth/spectrum to lightpath requests.
- In this case, the spectrums of $L_1$ and $L_2$ cannot overlap, as they share a common edge.

$L_1 : 0 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 7$

$L_2 : 2 \rightarrow 4 \rightarrow 5 \rightarrow 6$

Figure 21: Spectrum allocation in OFDM networks
Why the RWA algorithms of WDM don’t work for OFDM

- Currently, wavelength-routed networks require full allocation of a wavelength to a connection b/w end nodes.

- However for OFDM, each connection has to be assigned an appropriate bandwidth to obtain increased spectral efficiency.

- Therefore, the wavelength continuity constraint of traditional WDM networks is transformed to a spectrum continuity constraint.

- To address these issues, new routing and spectrum allocation (RSA) algorithms are developed.
Importance of an efficient path selection

The importance of an efficient routing scheme is shown below using a practical example.

1. Inefficient Path Selection

<table>
<thead>
<tr>
<th>Source → Destination</th>
<th>Traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 → 5</td>
<td>10</td>
</tr>
<tr>
<td>1 → 4</td>
<td>12</td>
</tr>
<tr>
<td>4 → 5</td>
<td>15</td>
</tr>
<tr>
<td>4 → 6</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 22: RSA in OFDM network

Total required spectrum = 37
Importance of an efficient path selection in routing phase

Efficient Path Selection for the same situation

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<td>15</td>
</tr>
<tr>
<td>4 → 6</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 23: Better paths selected

Total required spectrum = 21
Basics of Optical OFDM Technology

- Optical OFDM
  - New technology to send multiple signals over a single optical fiber.
  - Elastic allocation of bandwidth to each signal, according to the connection demands.

Figure 24: Elastic bandwidth allocation
Benefits of OFDM networks

- Good spectral efficiency
- Elastic allocation of bandwidth.
- Overall guard band usage for signals requiring more than 1 channel for communication is less. (compared to WDM)
Routing and Spectrum Assignment (RSA)

• Given:
  - A network topology,
  - Predefined set of requests,
  - The problem is to assign a path and a bandwidth/spectrum to each request, such that the total spectrum need is as small as possible.

Requests to be handled:
L1 : 0 to 7
L2 : 2 to 6

What do we need to do?
1) Solve Routing Sub Problem
2) Assign a bandwidth to each request

Figure 24: static RSA
2. Spectrum Assignment Sub Problem

L1 : 0 → 3 → 4 → 5 → 7
L2 : 2 → 4 → 5 → 6
Spectrum Clash Constraint

- Any two lightpaths which share a common optical fiber, must be
  - assigned non-overlapping bandwidths
  - separated by at least a guard band.
- This is a little different from wavelength clash constraint in WDM.
Spectrum Continuity Constraint

- Spectrum conversion at optical layer not feasible.
- Assigned spectrum must remain the same all along the path.
- This is similar to wavelength continuity constraint