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(Part 2)
Optical Networks – Some research topics

thinking forward

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

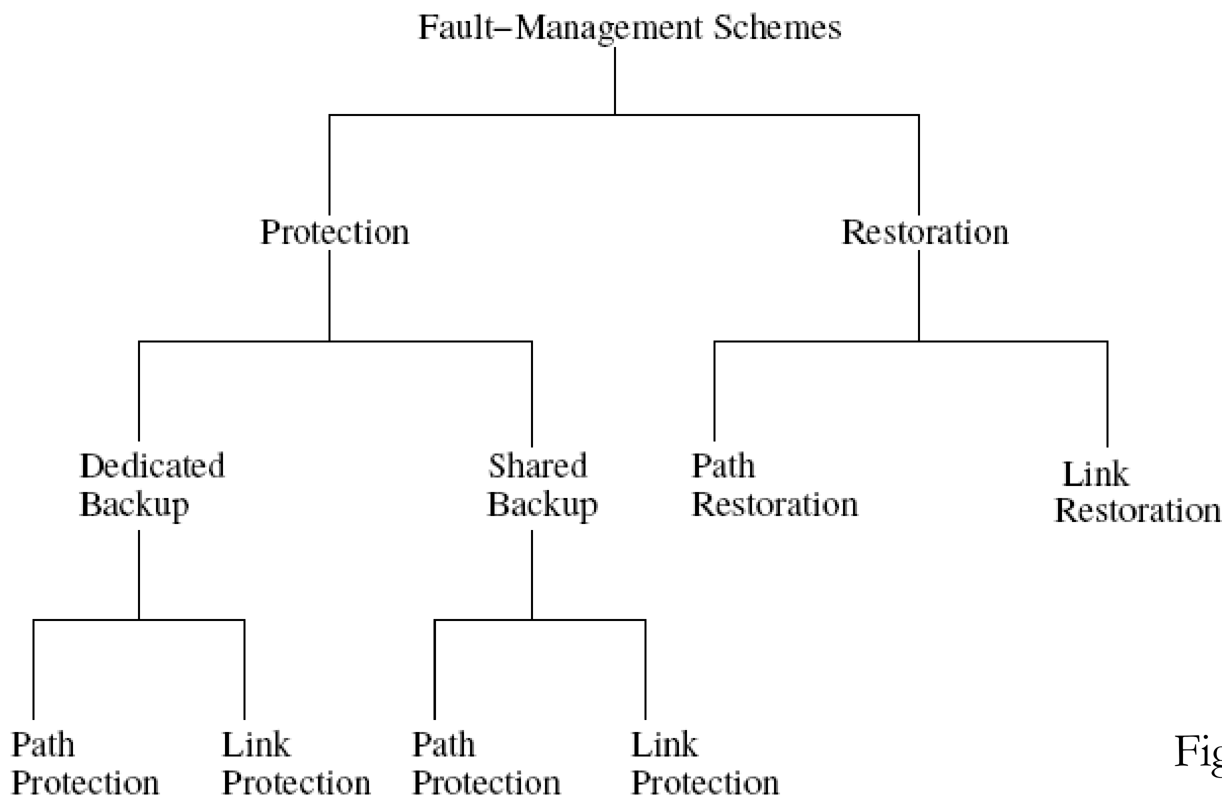


Figure 1

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

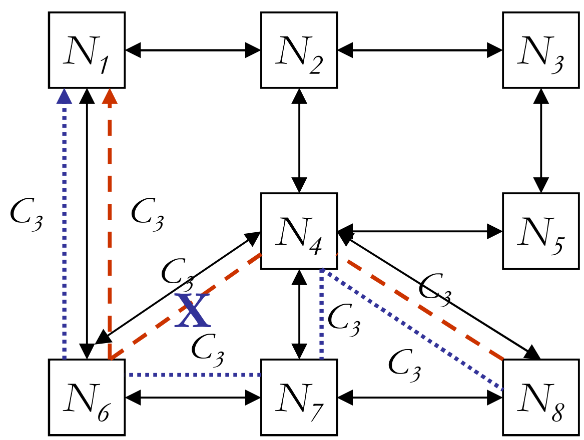
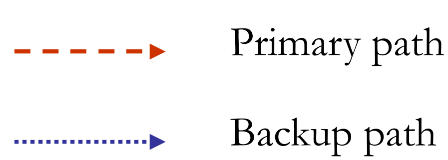


Figure 2: Link protection scheme

- 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



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

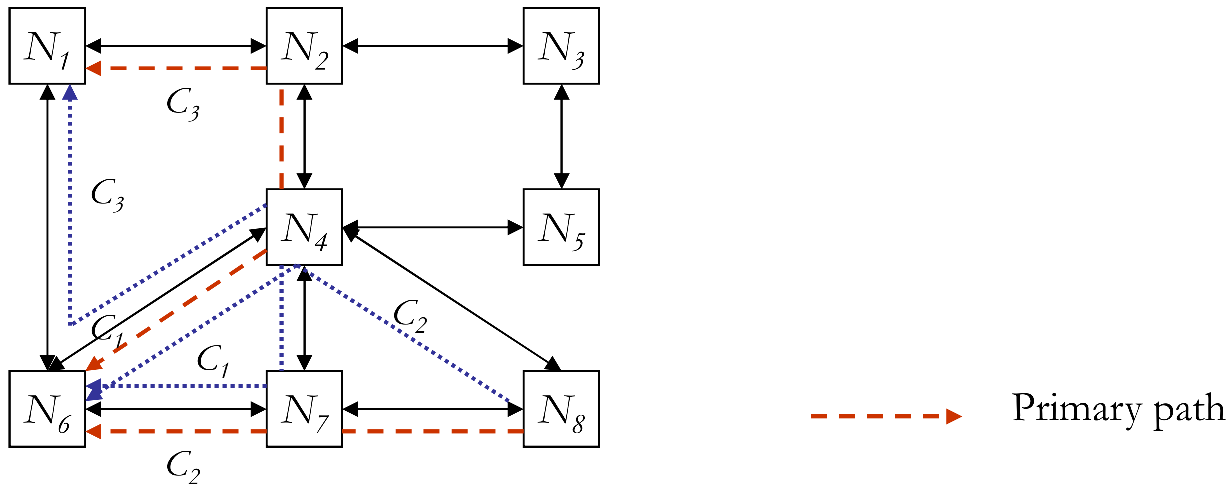


Figure 3: Path protection scheme

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.

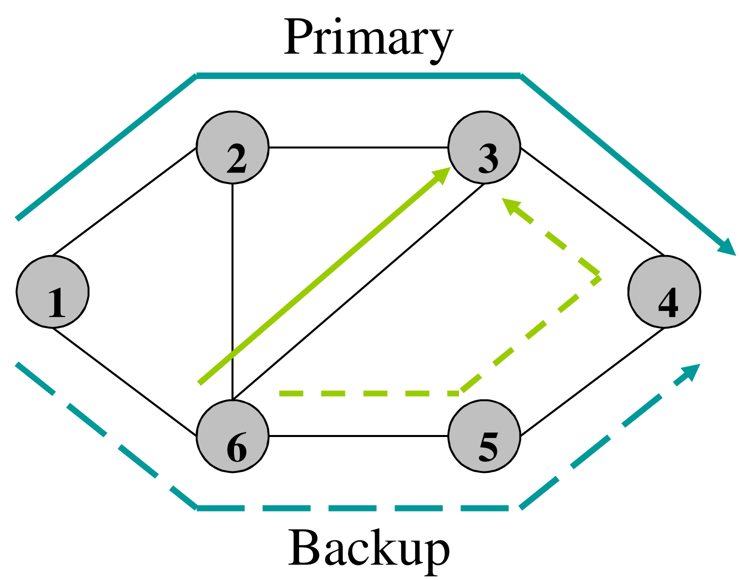


Figure 4: 1:1 Protection

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.

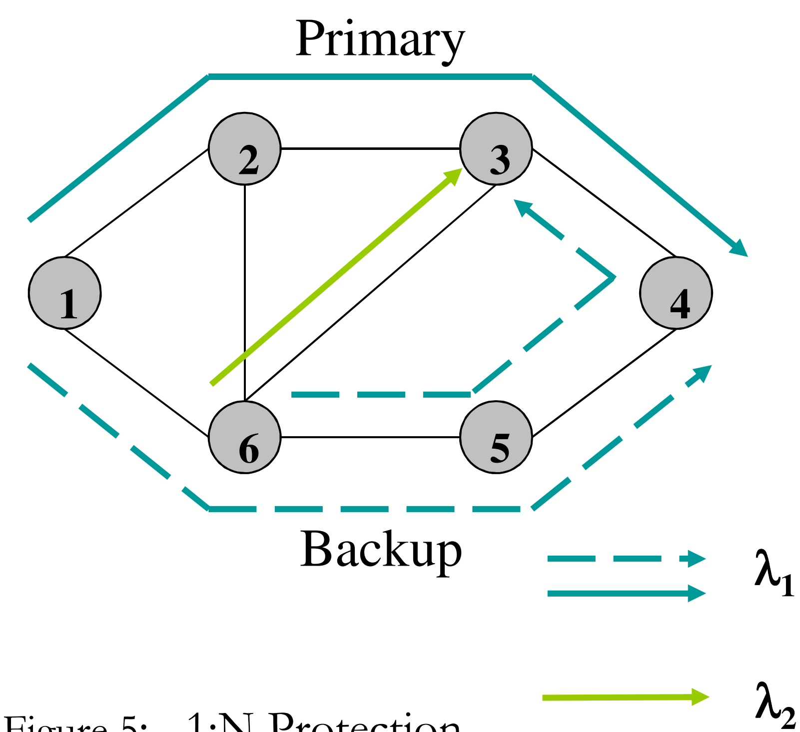


Figure 5: 1:N Protection

Physical Layer Impairments

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

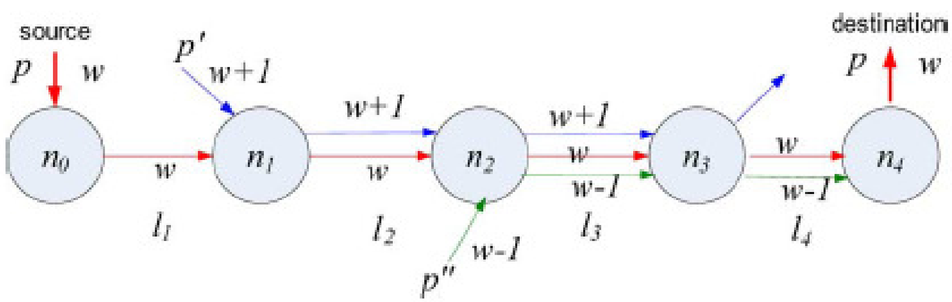
Note: PLI are not defects, but characteristics
of the fiber

Physical Layer Impairments (PLI)

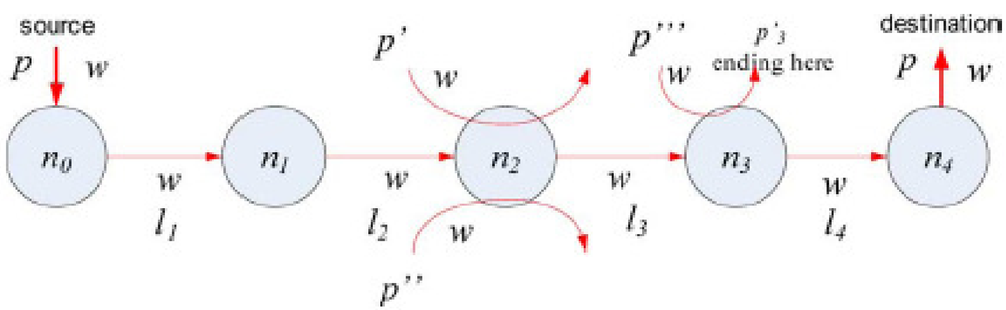
- Physical layer impairments are broadly classified into 2 types namely: **Linear** & **Non-Linear**.
- **Linear Impairments:** **Affect** a **lightpath individually** and are not dependant on other lightpaths in the network. **Examples:** Amplified Spontaneous Emission (ASE), Chromatic Dispersion (CD), 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



Adjacent channel interference.



Same channel interference.

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** (**R**e-amplification, **R**e-shaping and **R**e-timing) - performed in the **electronic domain**. OEO is expensive.

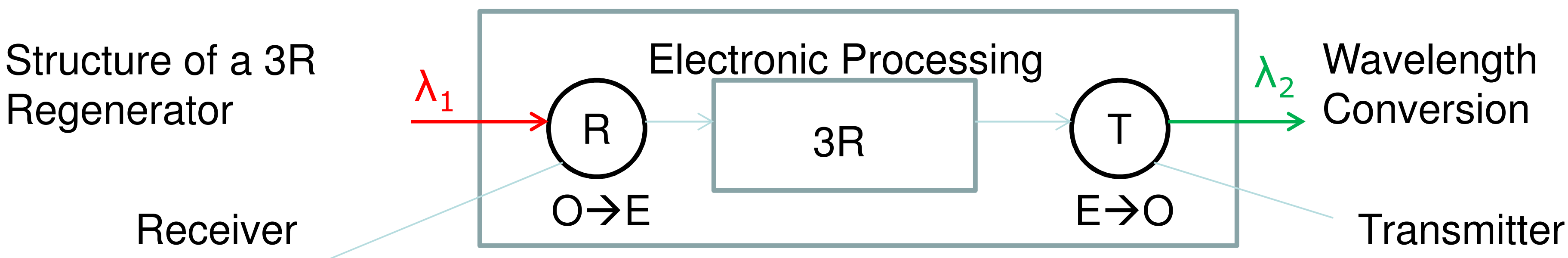
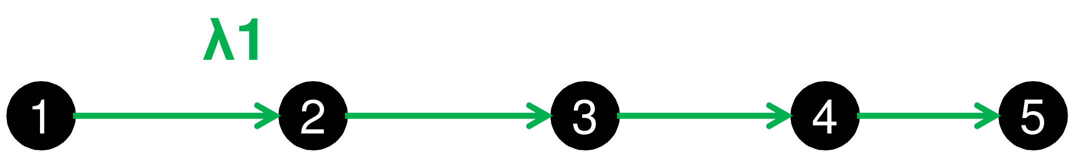


Figure 7: 3R regeneration

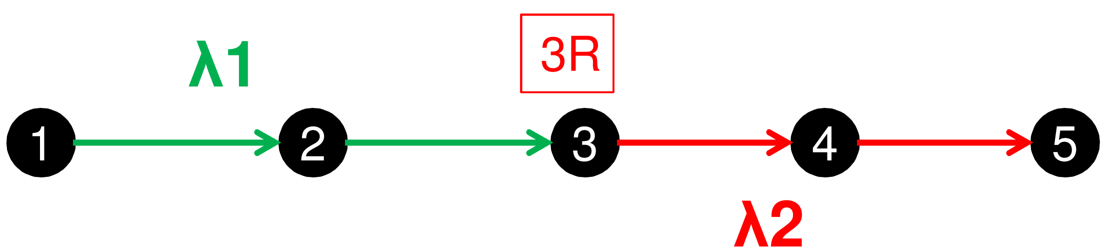
Translucent Lightpath & Wavelength Conversion

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



Transparent Lightpath

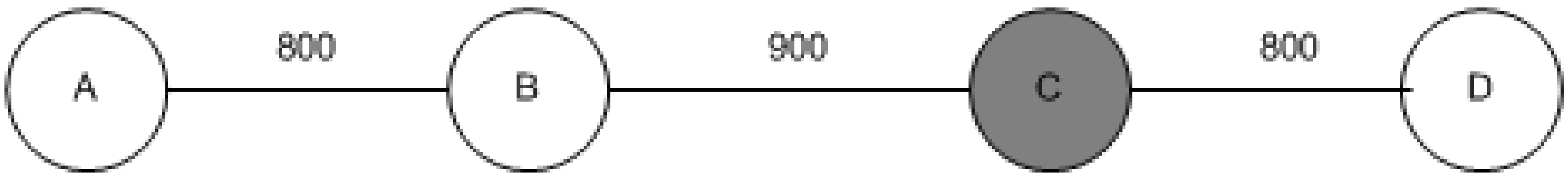
Fig 8:
Transparent and translucent lightpath



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

Figure 9: a translucent lightpath

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

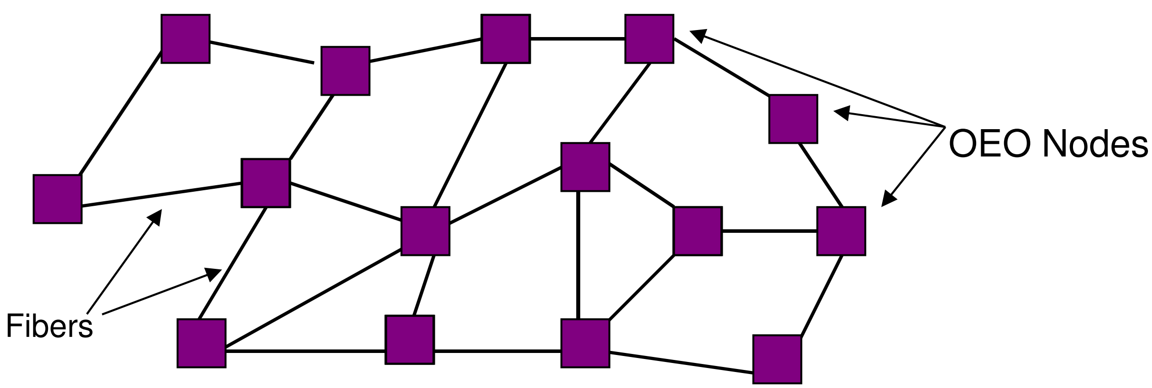


Figure 10: An opaque network

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.

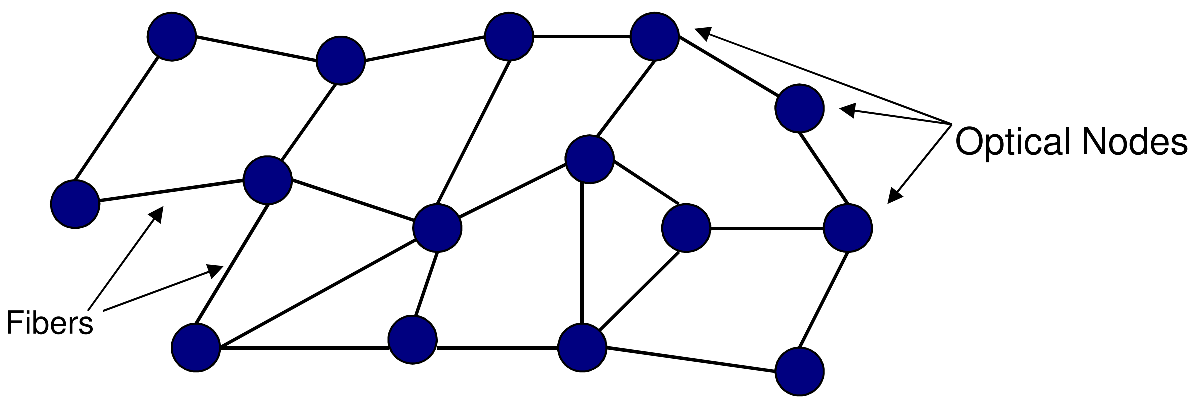
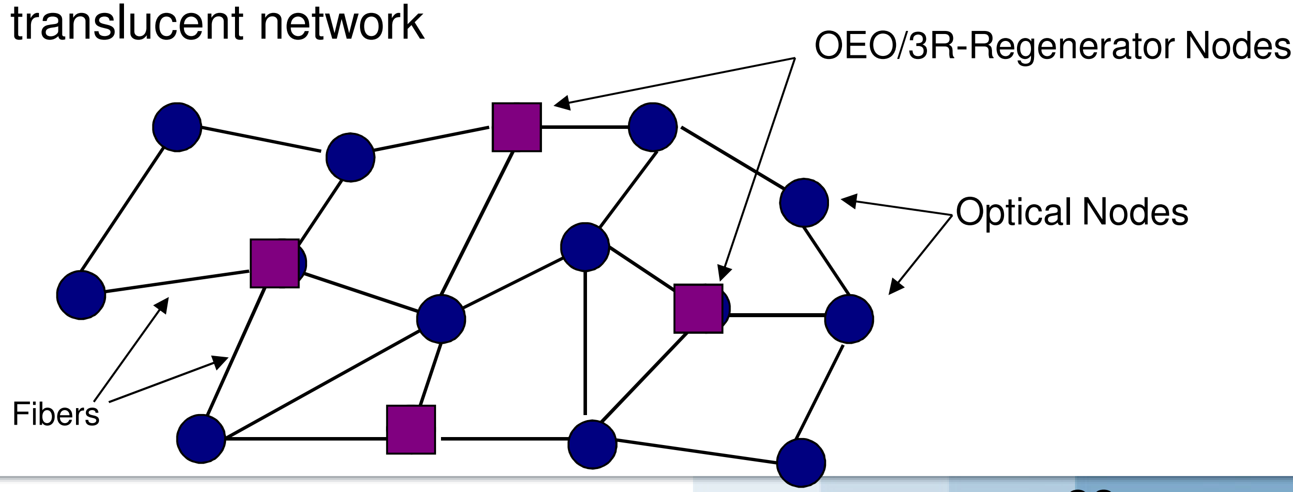


Figure 11: An all-optical network

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



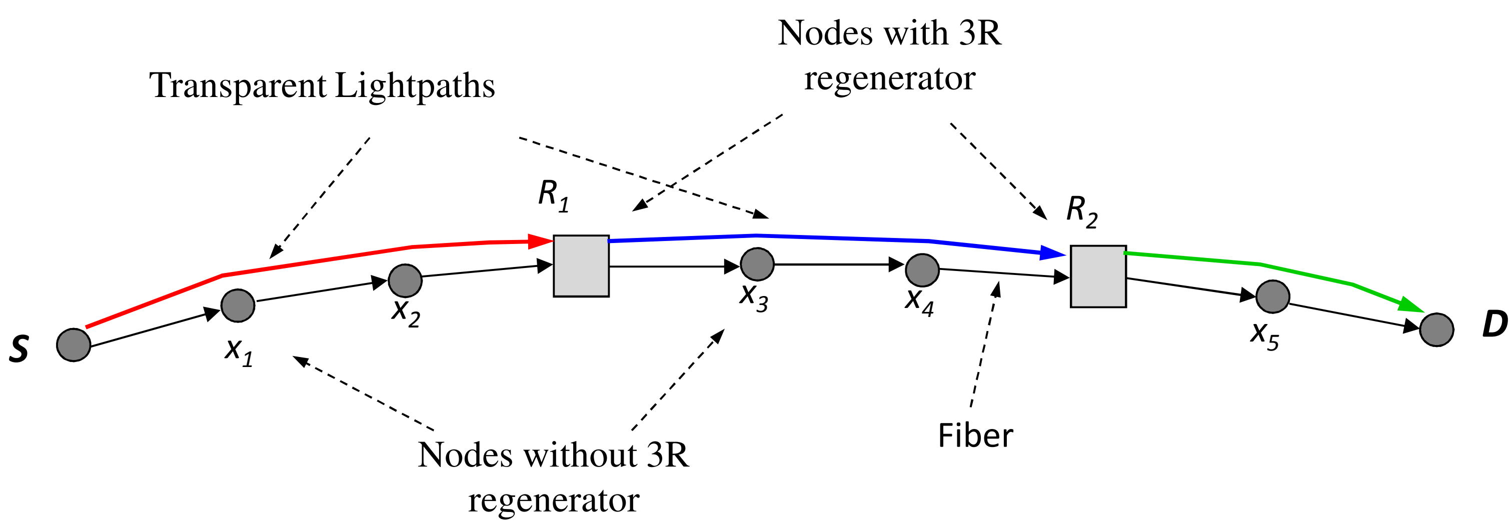
Translucent networks

- 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

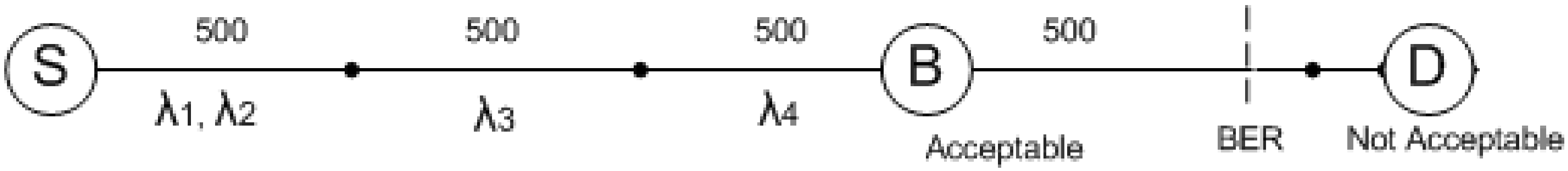


Figure 14: A lightpath may be blocked for 2 reasons

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

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.

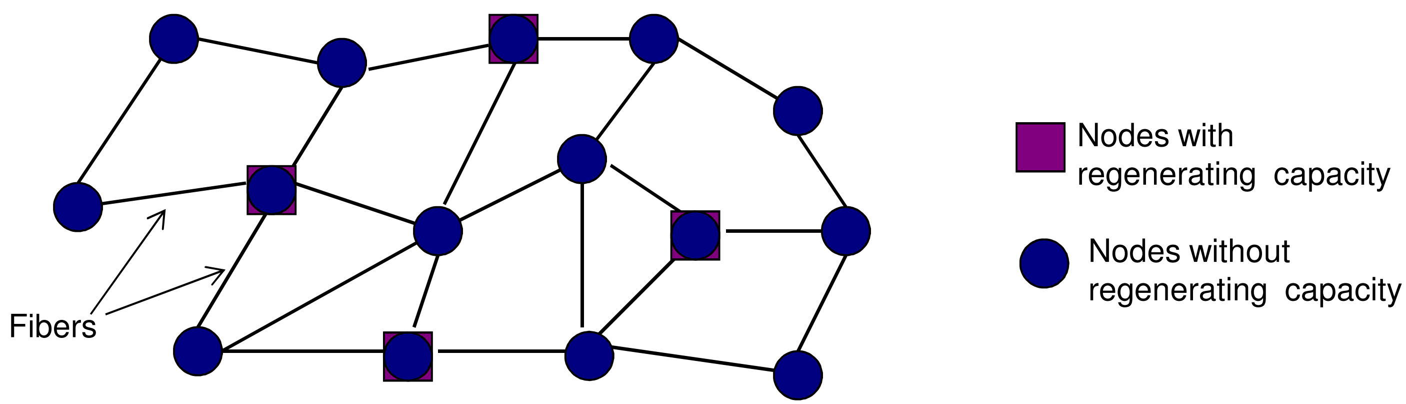
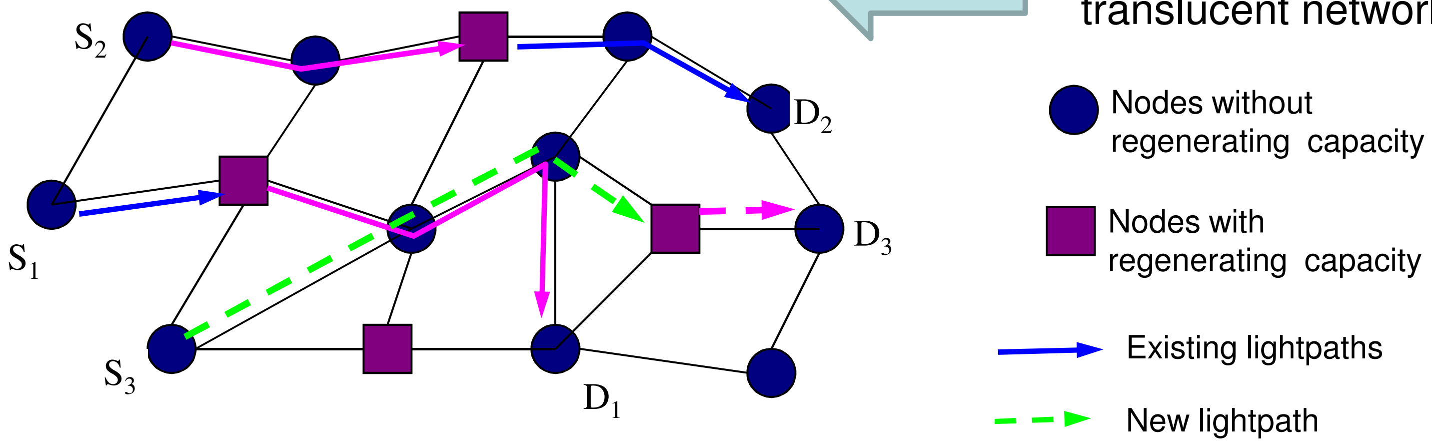


Figure 15: A network with sparsely distributed regenerating nodes

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



Loops in translucent lightpaths

- Loops - An interesting feature of translucent lightpaths

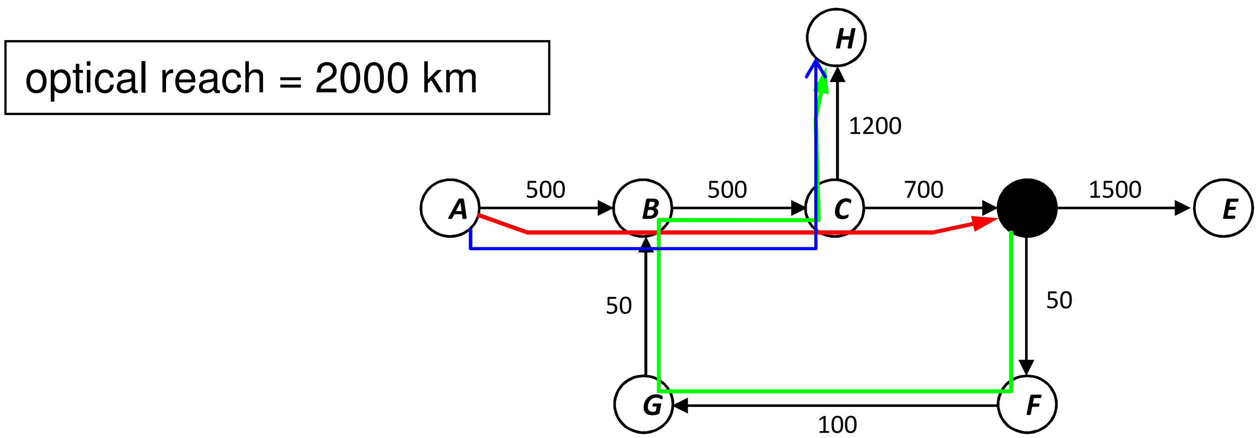


Figure 17: Loops in a translucent network

- 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 1GHz, 90% of the spectrum is wasted.

– Further, if the user requires 12GHz, 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.

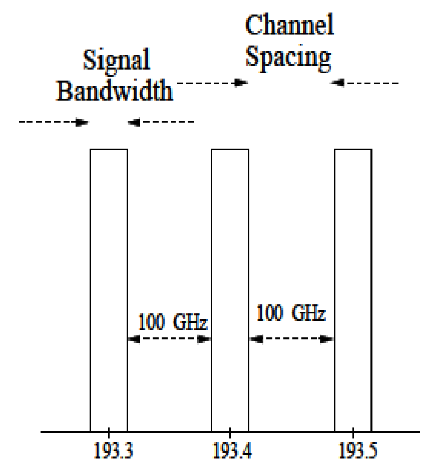


Figure 18: WDM channels

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

Optical OFDM Technology

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

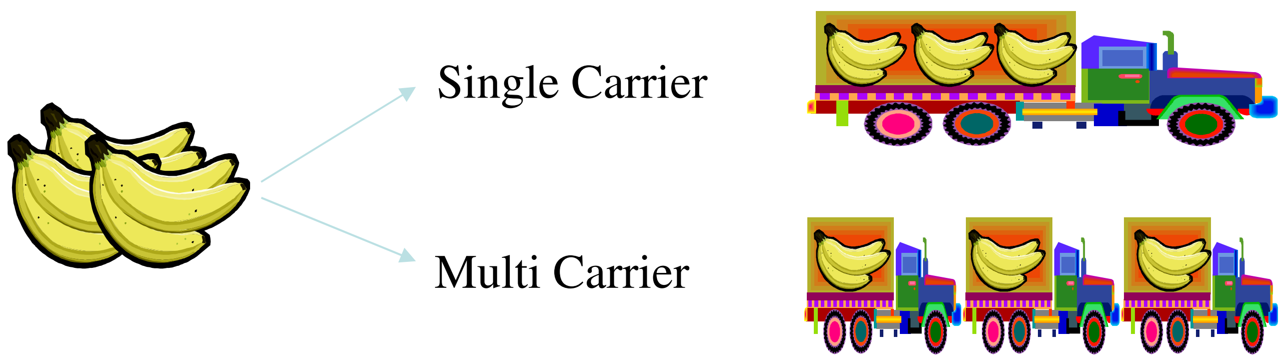


Figure 19: A simple way to visualize OFDM vs WDM

Optical OFDM Benefits

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

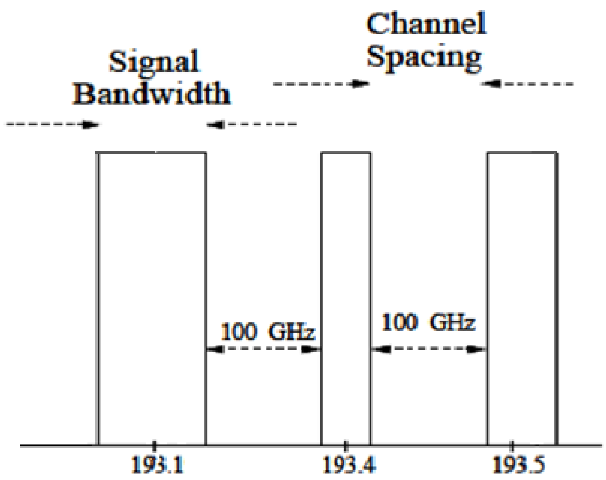


Figure 20: Elastic bandwidth

Notion of Routing and Spectrum Assignment (RSA)

- Assigning a route and bandwidth/spectrum to lightpath requests.
- In this case, the spectrums of L1and L2 cannot overlap, as they share a common edge.

L1 : 0 → 3 → 4 → 5 → 7
L2 : 2 → 4 → 5 → 6

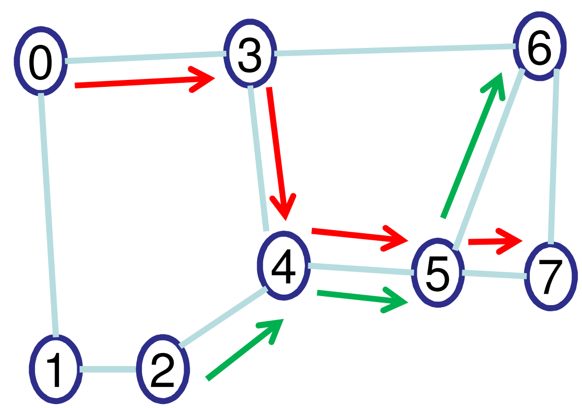


Figure 21: Spectrum allocation in OFDM networks

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.

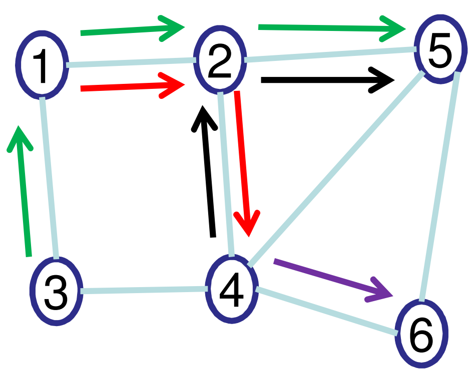
Importance of an efficient path selection

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

1. Inefficient Path Selection

Source → Destination	Traffic
3 → 5	10
1 → 4	12
4 → 5	15
4 → 6	6

Figure 22: RSA in OFDM network



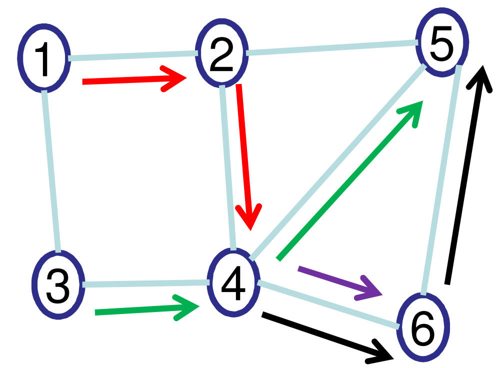
Total required spectrum = 37

Importance of an efficient path selection in routing phase

Efficient Path Selection for the same situation

Source → Destination	Traffic
3 → 5	10
1 → 4	12
4 → 5	15
4 → 6	6

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.

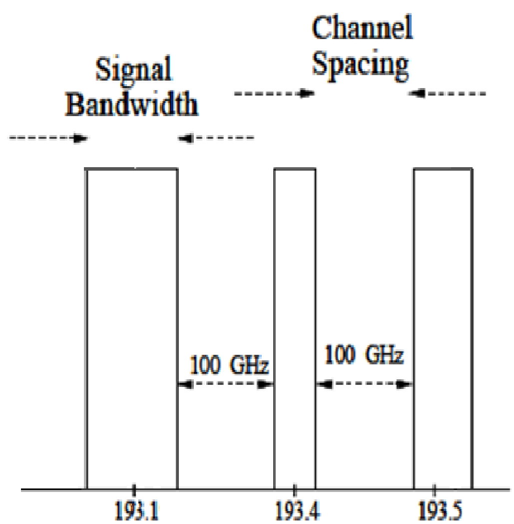


Figure 24: Elastic bandwidth allocation

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:

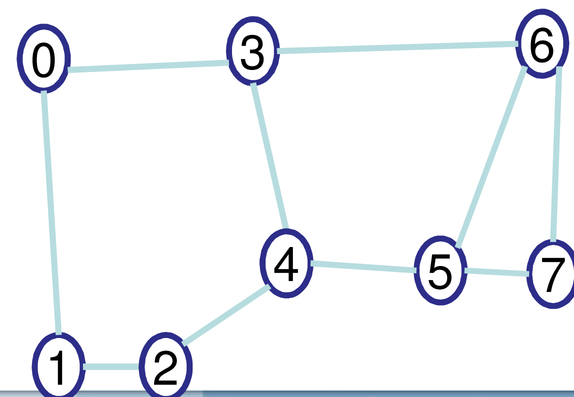
L1 : 0 to 7

L2 : 2 to 6

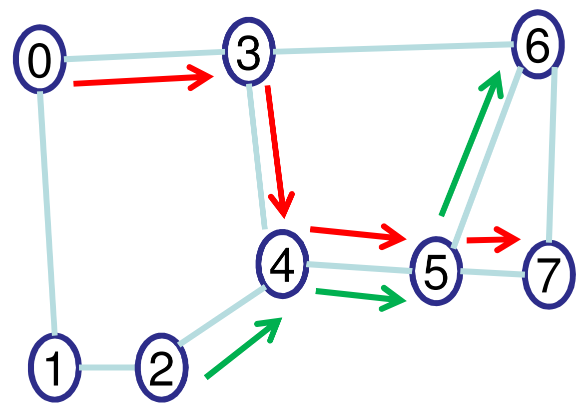
What do we need to do?

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