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TSIN02 Internetworking

Lecture 5 – Optical Networking – The Internet backbone

Outline

- Networking Hierarchy
- Evolution of Optical Networks
- Optical Network Node and Switching Elements
- Routing and Wavelength Assignment (RWA) Problem
  - RWA Constraints and Wavelength Converter
  - Static/Planning/Offline RWA
  - Dynamic/Operational/Online RWA
- Network Survivability and Protection

Telecom Network Hierarchy

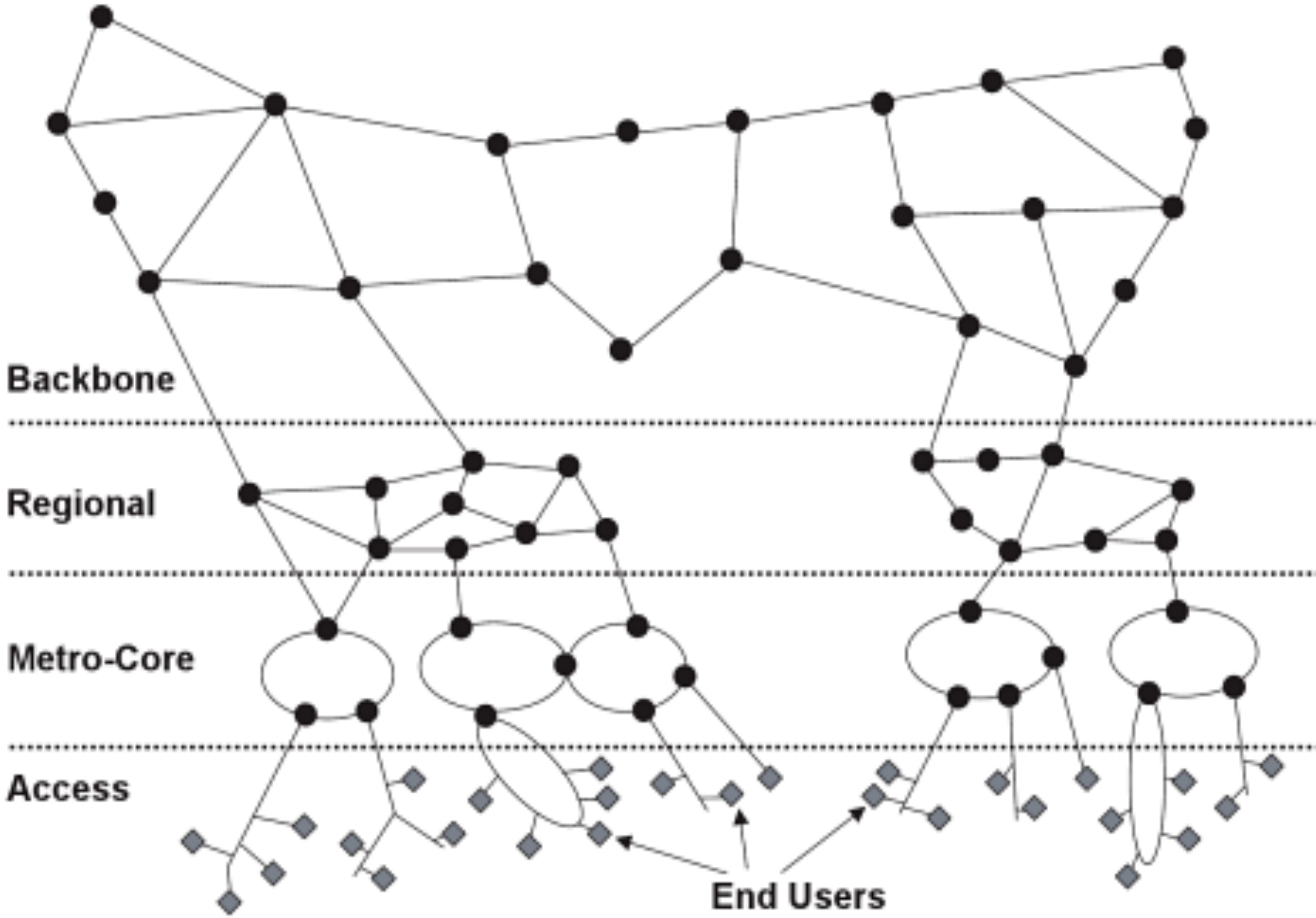

Figure from: Jane M. Simmons, Optical Network Design and Planning

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Backbone Network

- Backbone network interconnects different regions and countries, often covering distance of 1000's of km.
- Such long distances between nodes require amplification and regeneration of the transmitted optical signals at the intermediate points.
- **Nodes** are the points in the network that source/terminate and switch traffic.
- A backbone network may serve several network operators, each having millions of users and many services.
- Backbone network is normally designed as a mesh of alternative links between important cities/hubs, each link being implemented with multiple fiber pairs using highest quality, single-mode optical fiber.

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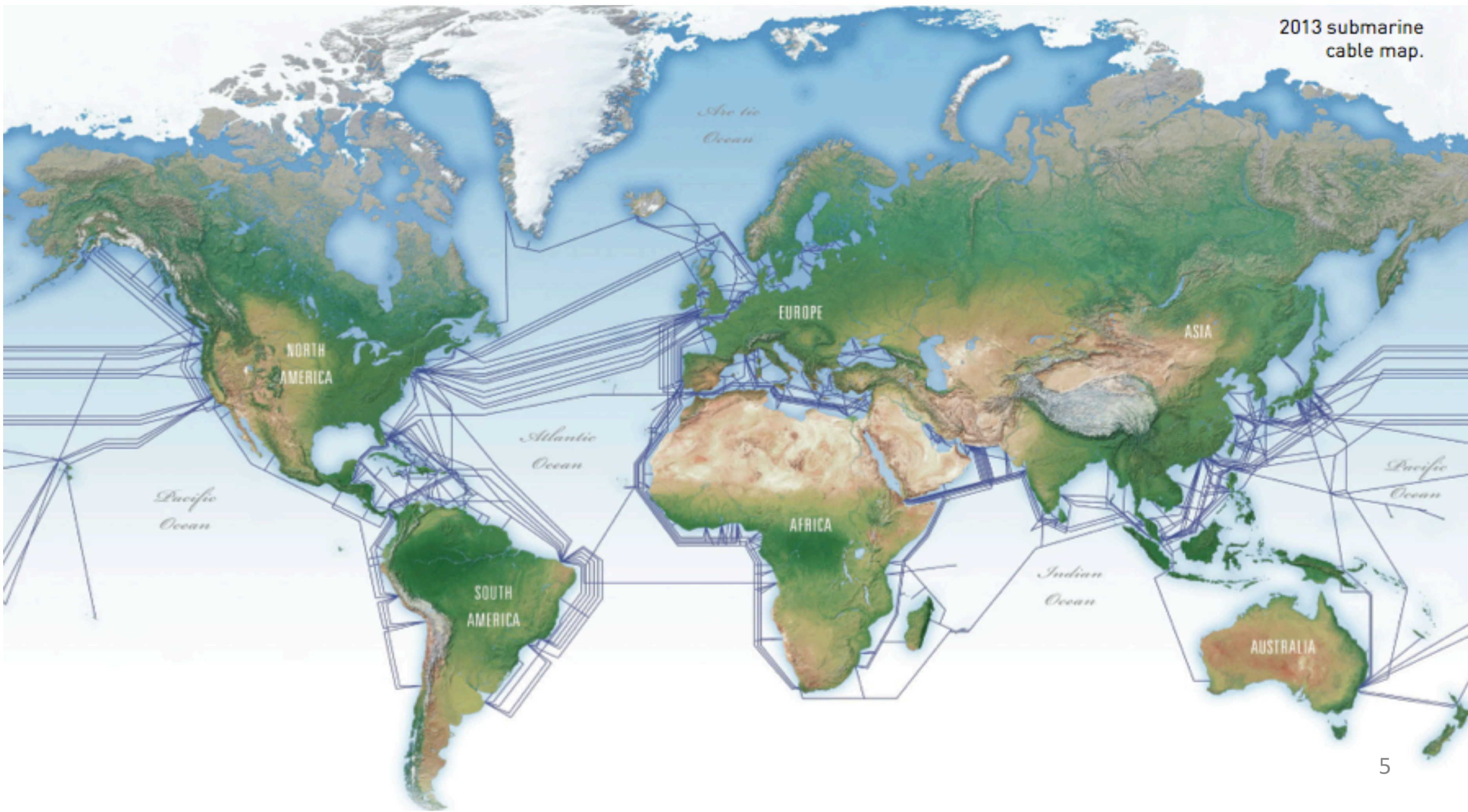
Part of Backbone Network – Submarine Optical Cables

The longest submarine cable is the Southeast Asia—Middle East—Western Europe (SEA-ME-WE 3) system stretching 39,000 km from **Norden**, Germany, to **Keoje**, South Korea



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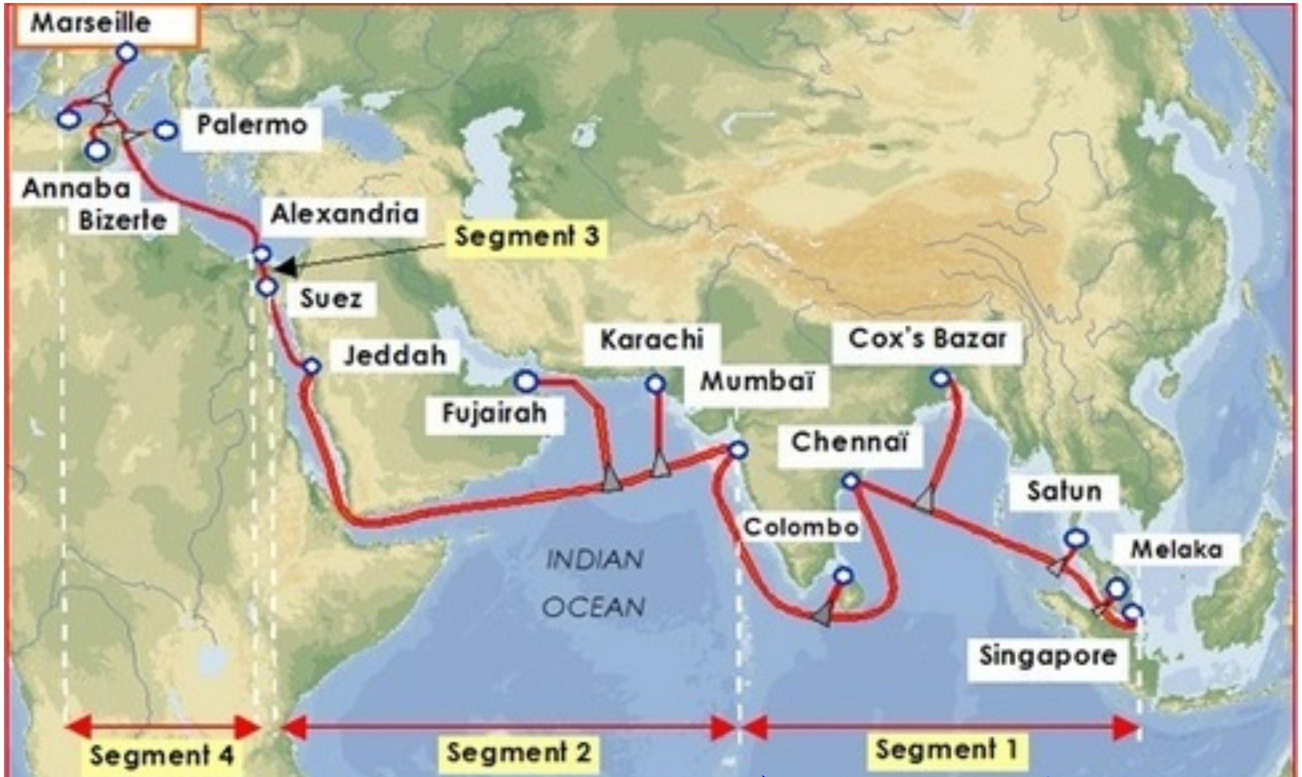
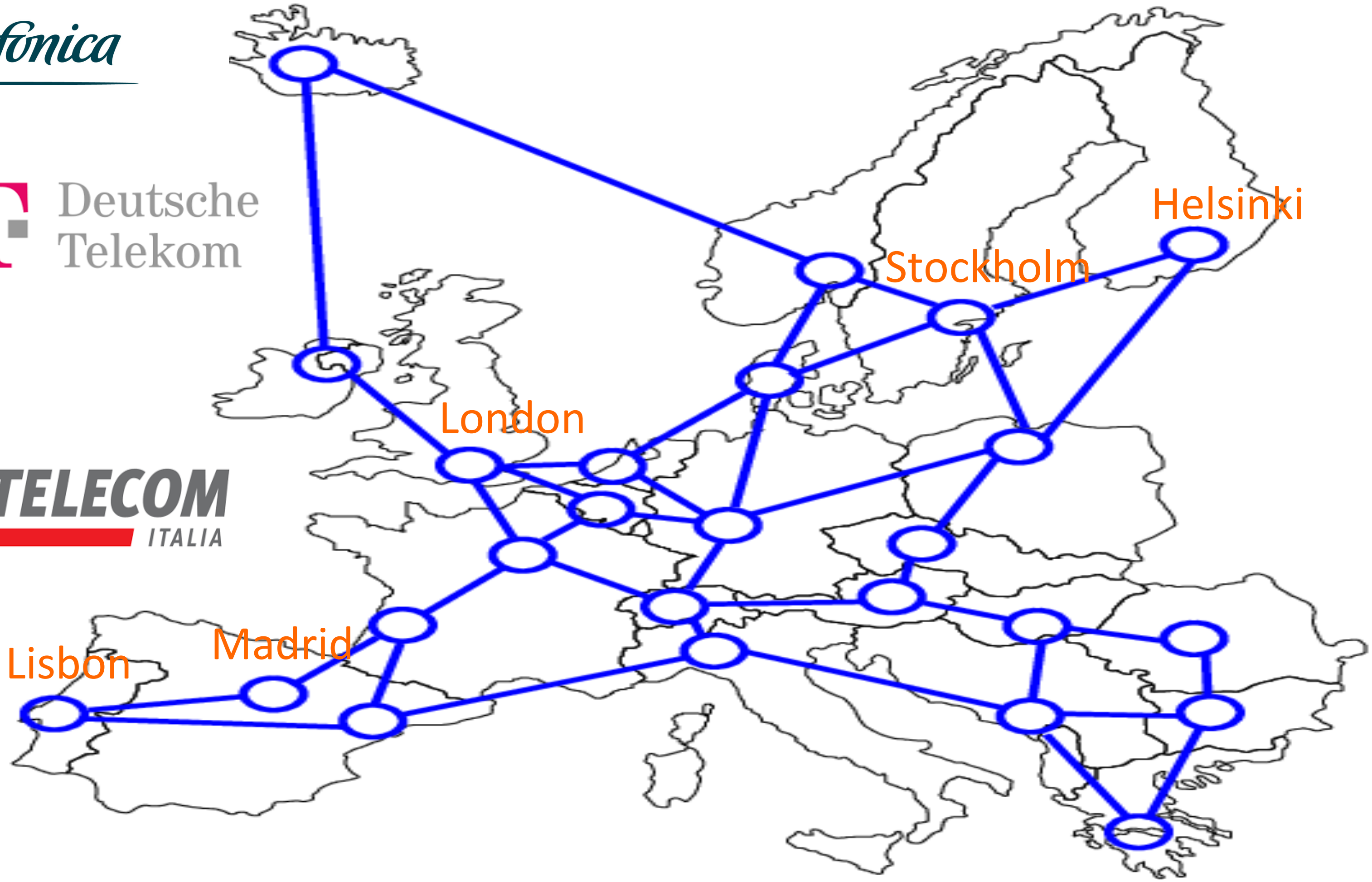
Part of Backbone Network – Submarine Optical Cables

The SEA ME WE 4 (South East Asia, Middle East and Western Europe) cable system own by several telecommunication companies



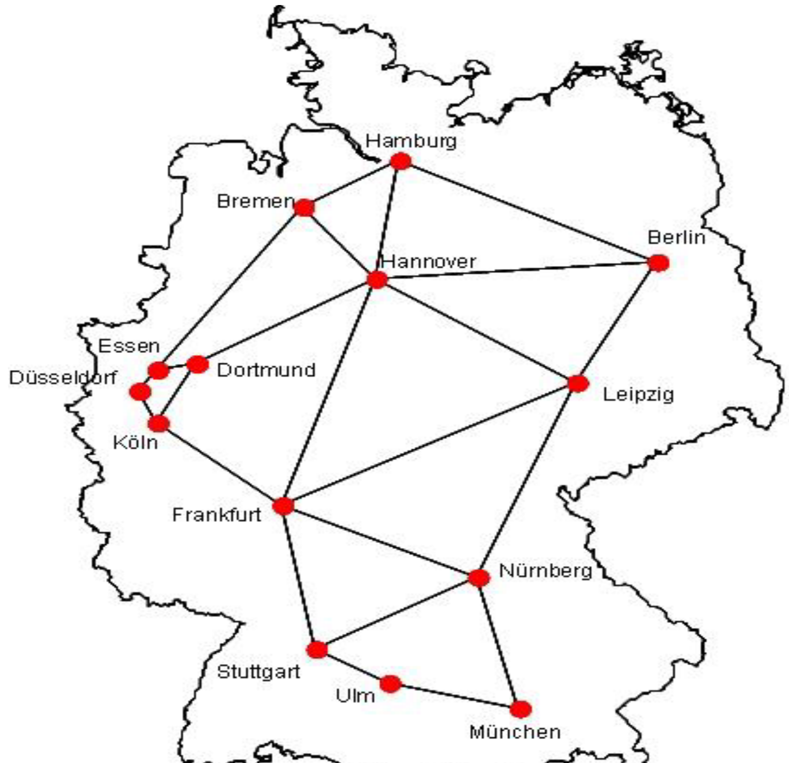
- Algérie Télécom
- Bharti Infotel Limited
- CAT Telecom Public Company Limited
- Emirates Telecommunication Corporation
- France Telecom - Long Distance Networks, France
- MCI, UK
- Singapore Telecommunications Limited
- Telecom Egypt (TE)
- Telecom Italia Sparkle S.p.A.
- Telekom Malaysia Berhad
- Tunisie Telecom
- Tata Communication

European Optical Backbone Topology

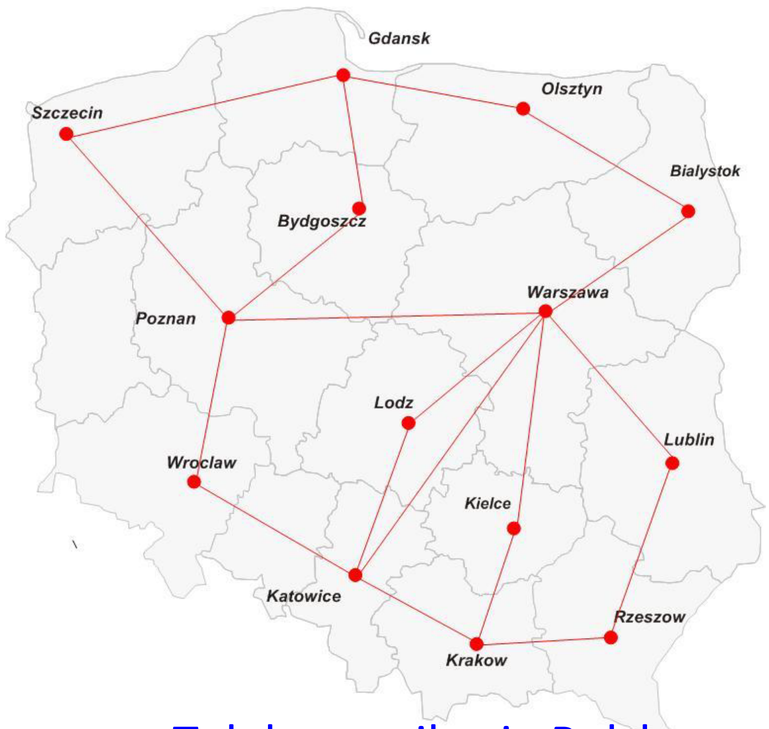


Regional Networks

- Regional network connects metro-core networks and carries the portion of the traffic that spans multiple metro-core areas.
- Regional network is shared among 100's of thousands of customers, with a geographic extend of several 100's km.



Deutsche Telekom
national network topology



Telekomunikacja Polska
backbone network topology

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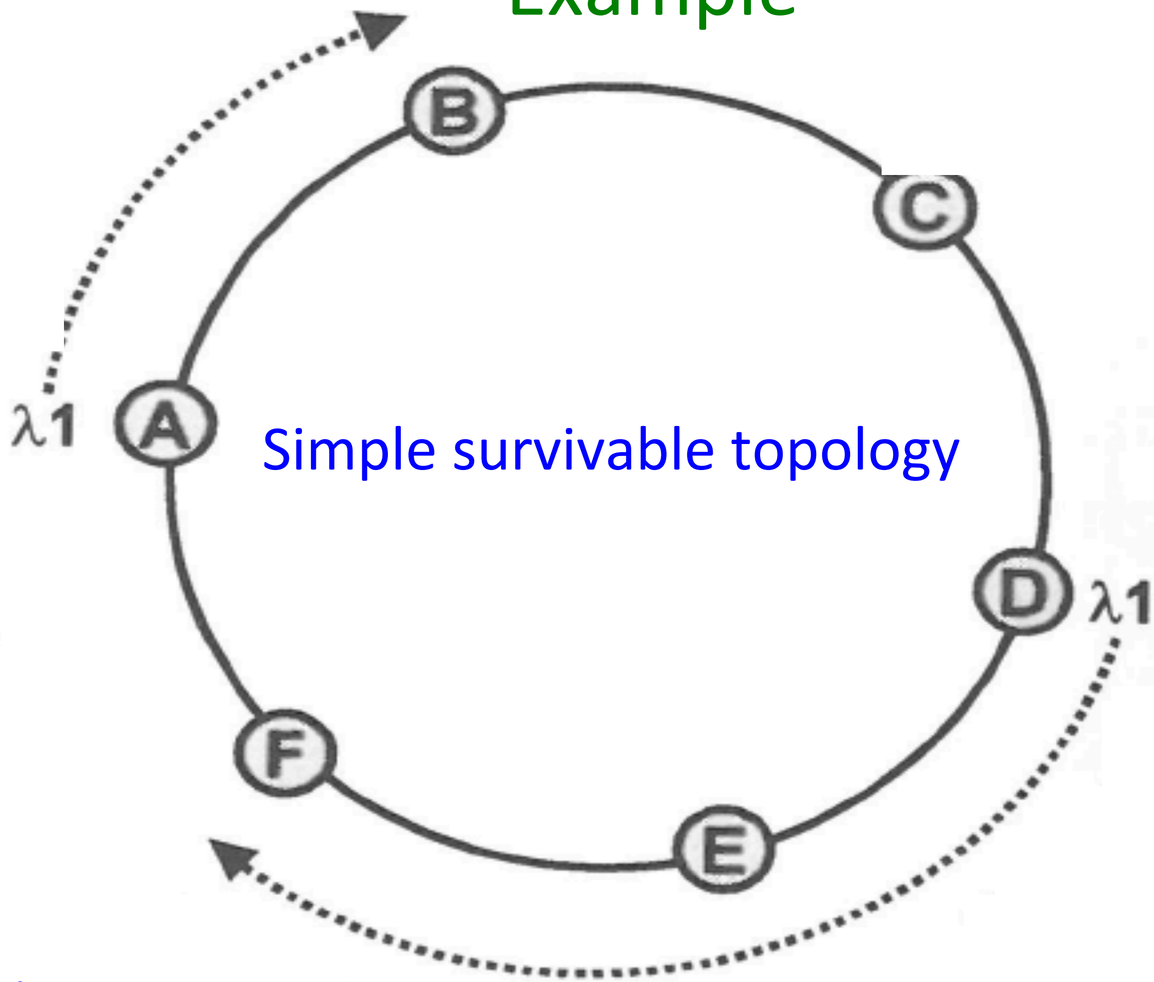
Metro-core Networks

- The metro-core network is responsible for aggregating the traffic from the access networks, and typically **interconnects** a number of **telecommunications central offices or cable distribution head-end offices**.
- A metro-core network aggregates the traffic of 1000’s of customers and span 10’s to 100’s of km.
- Metro-core networks are often build as rings to save on fiber deployment costs. The ring allows an alternative route towards the central office node in the other direction, should the fiber accidentally be cut.

Self-Healing Property of Ring Topology

Example



Simple survivable topology

If a single link/node failure occurs, all traffic that was routed over the failed link/node is routed in the reverse direction around the ring to avoid the failure.

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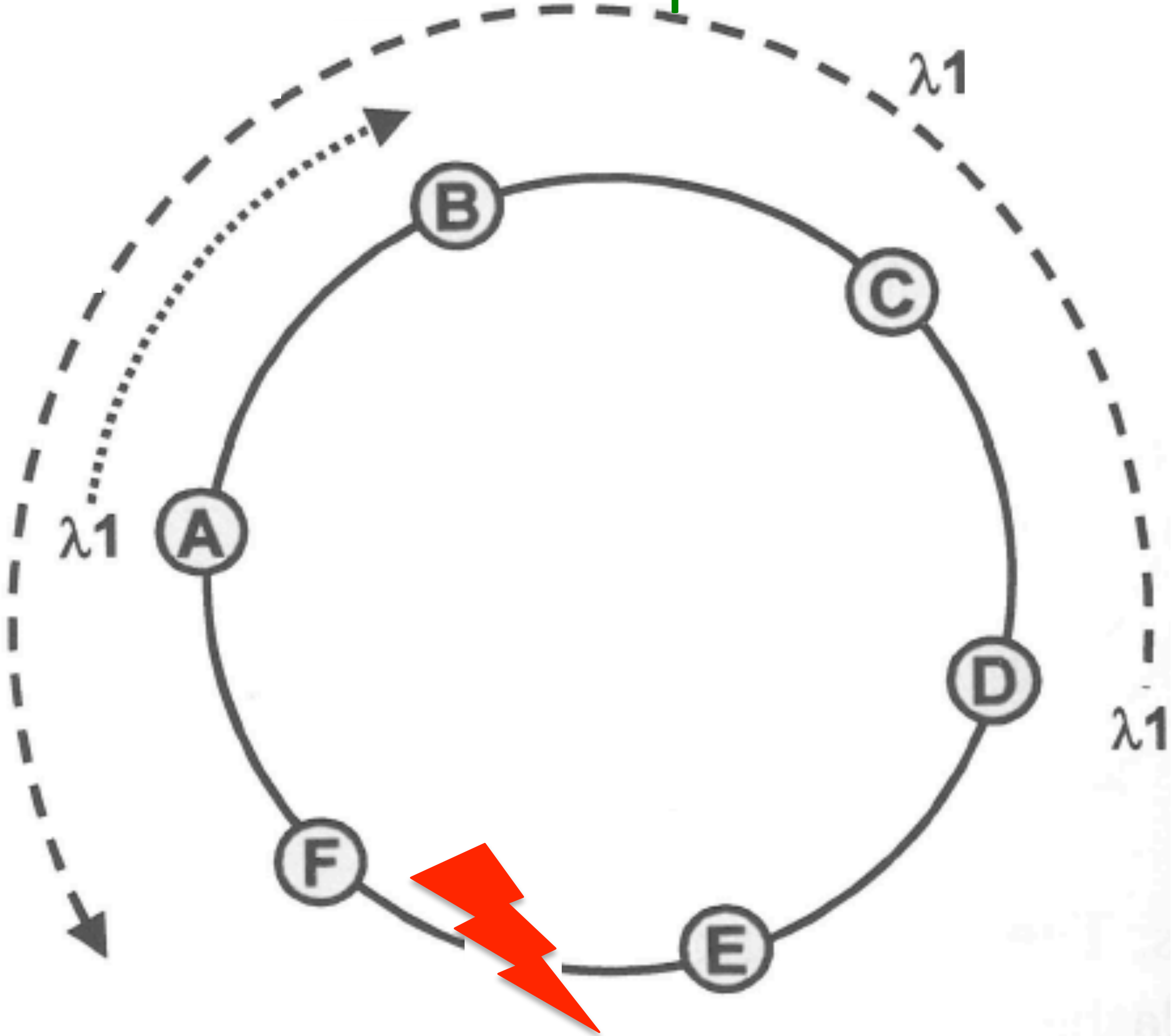
Self-Healing Property of Ring Topology

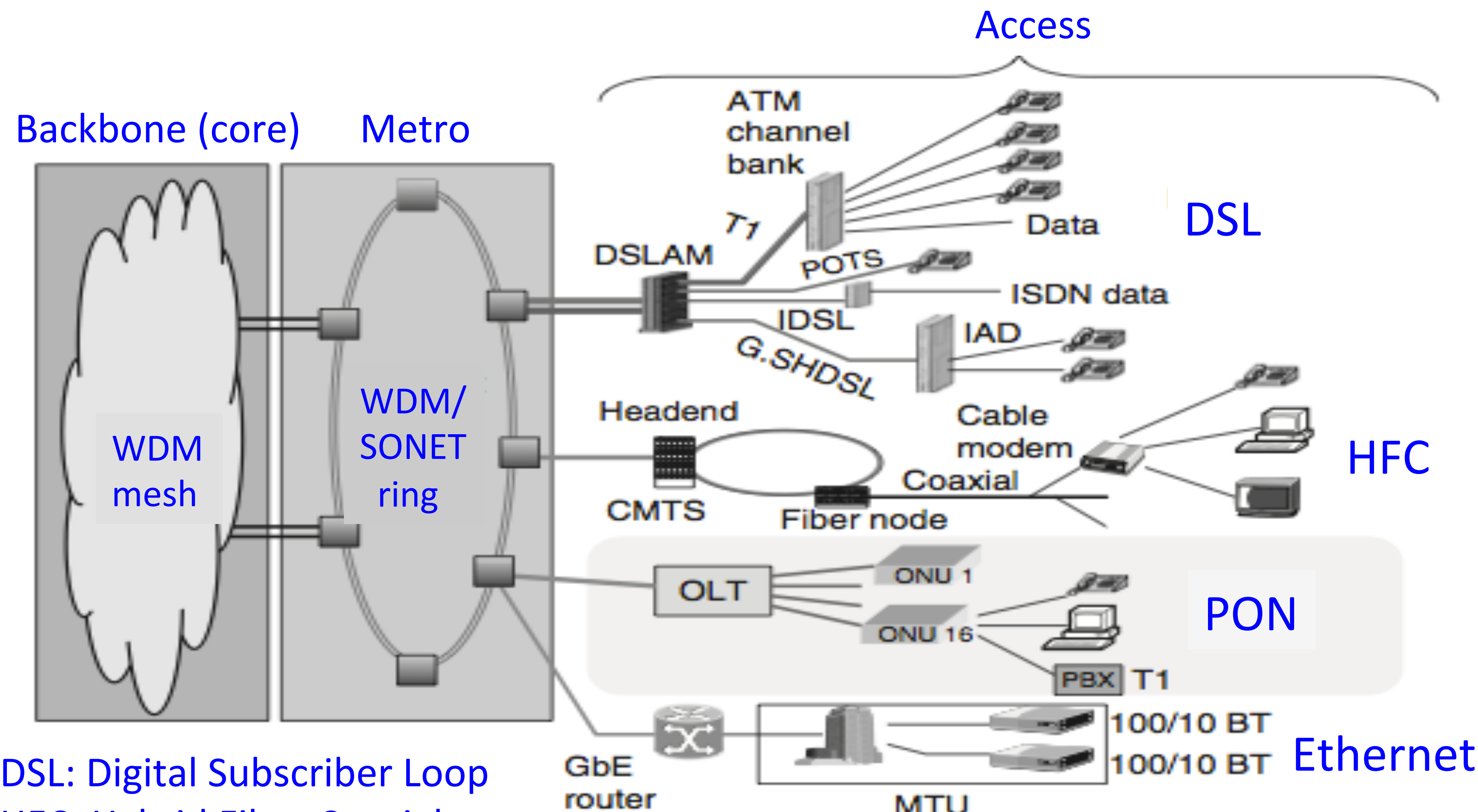
Example



Access Networks

- At the edge of the hierarchy, closest to the user is the access network, which distributes/collects traffic to/from the customers of the network.
- Access networks generally serve 10's to 100's of customers and span a few km.
- The **cost** of access network is amortized over fewer end users, and is thus a more **critical concern**.
- New technologies are often deployed in the backbone network first due to the cost issue. As they mature and achieve a lower price, they gradually extend closer towards the edge.
- A good example of this trend is the deployment of WDM technology.

Technologies for Different Tiers

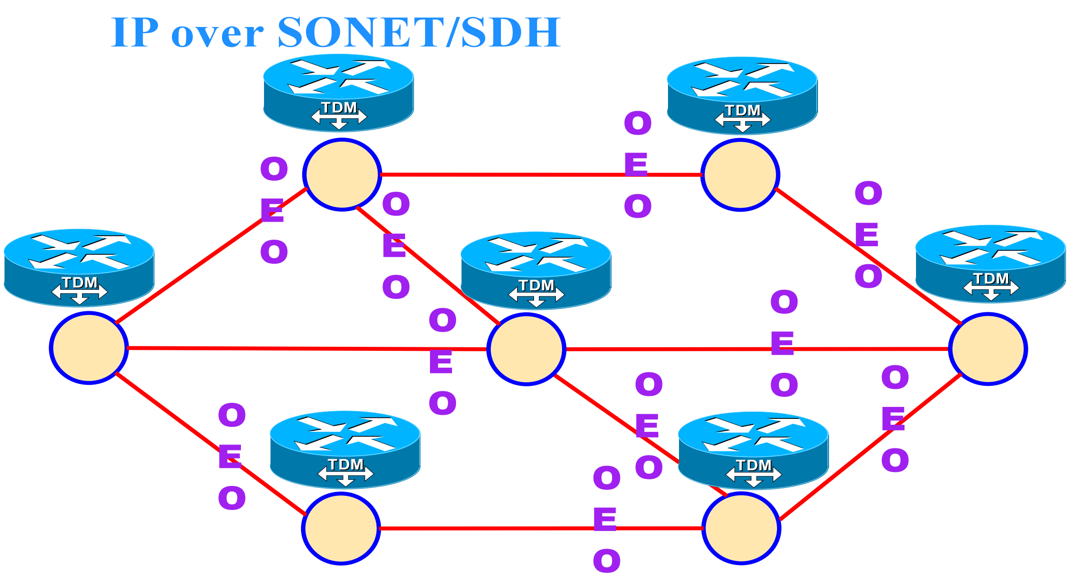


DSL: Digital Subscriber Loop
HFC: Hybrid Fiber Coaxial
PON: Passive Optical Network

Evolution of Optical Networks

Opaque (Point-to-Point) Network

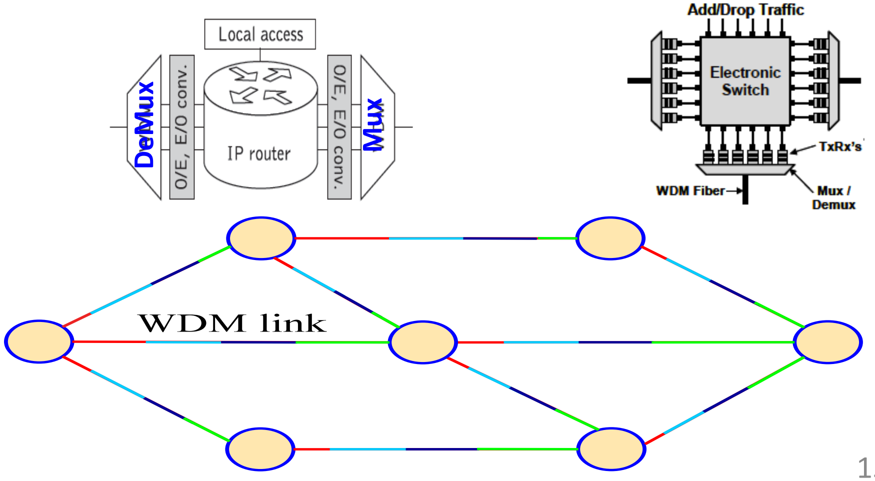
- Optics are used for transmission & providing capacity.
- Switching & other intelligent network functions are handled by electronics.



Evolution of Optical Networks

Opaque (Point-to-Point) Network

- Optical transmission capacity is further increased (several-fold) by WDM technology.
- The incoming WDM link/fiber is terminated in a demultiplexer (DeMux) that separates the WDM signal into its constituent wavelengths.
- O/E (E/O) converts signals into the electrical (optical) domain. Electronic switch (SONET), IP router are used for switching the signals.
- The outgoing wavelengths are combined in a WDM multiplexer (Mux) onto an outgoing link/fiber.



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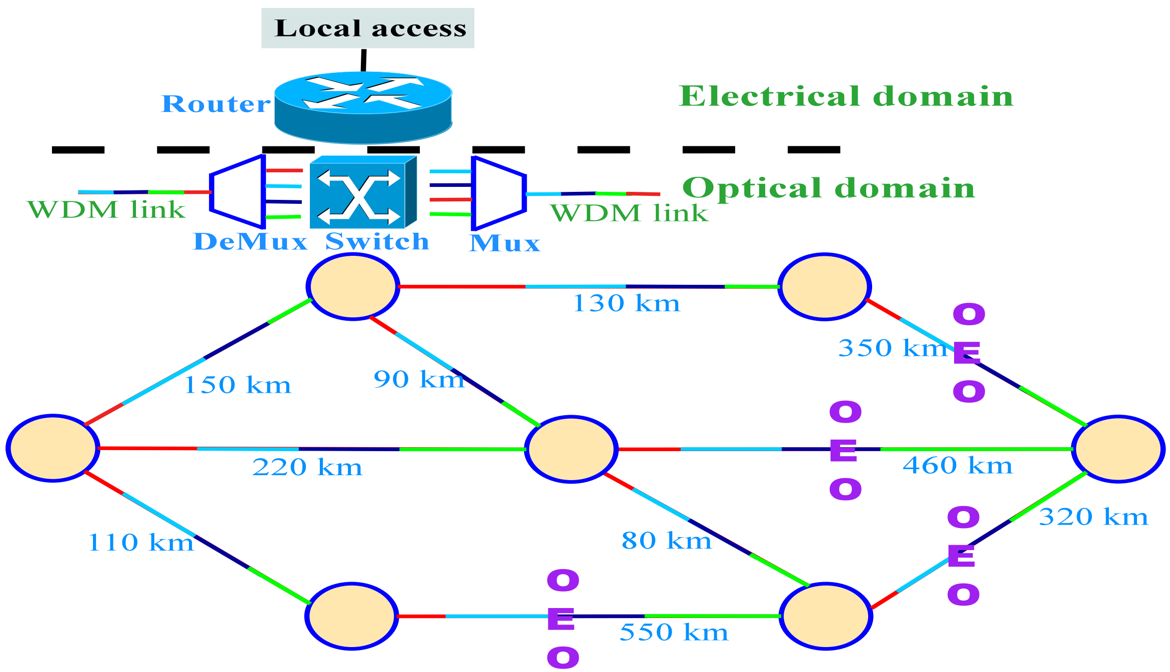
Evolution of Optical Networks

Translucent (Semi-transparent) Network

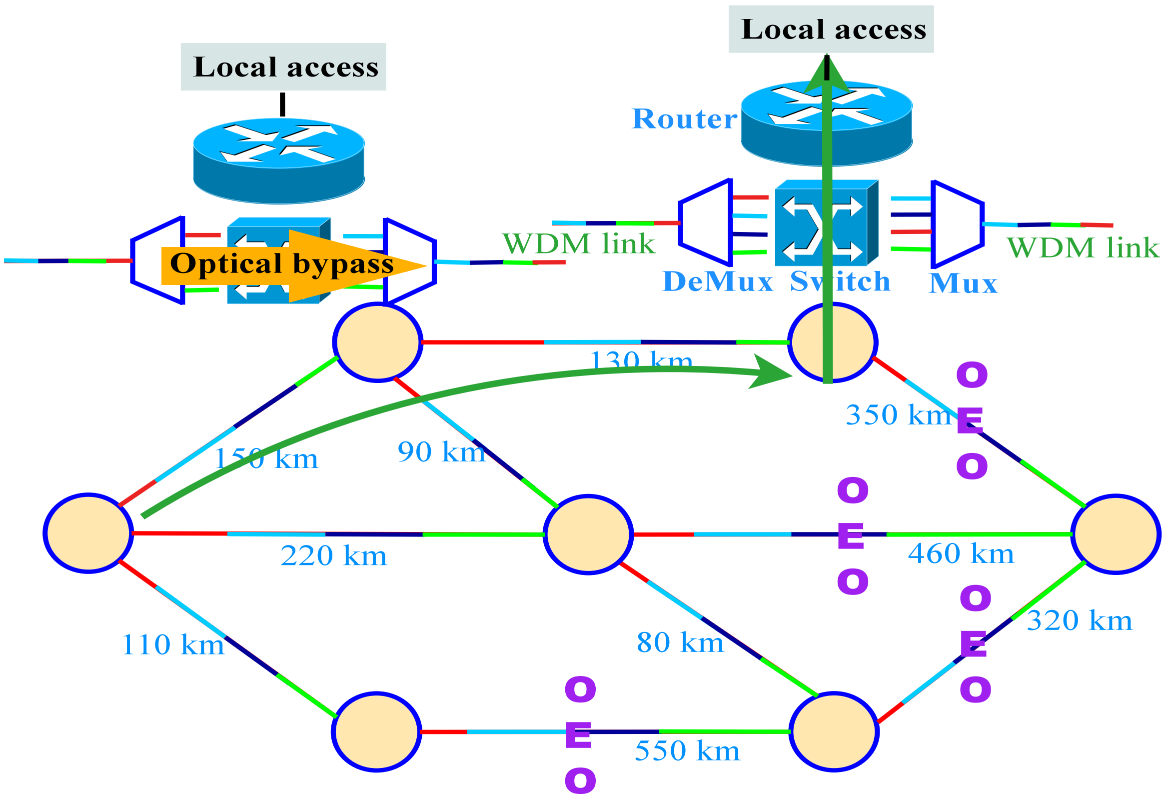
- Routing, switching is partly done in the optical domain.
- Use fewer OEO transponders/regenerators.
- **Lightpath**: a circuit switched connection between two nodes set up by assigning a dedicated wavelength on each link in its path.



Evolution of Optical Networks

Translucent (Managed Reach) Network

- Some **lightpaths** stay in the optical domain (depending on the signal quality) throughout the network and are converted to electrical only at the edges of the network.



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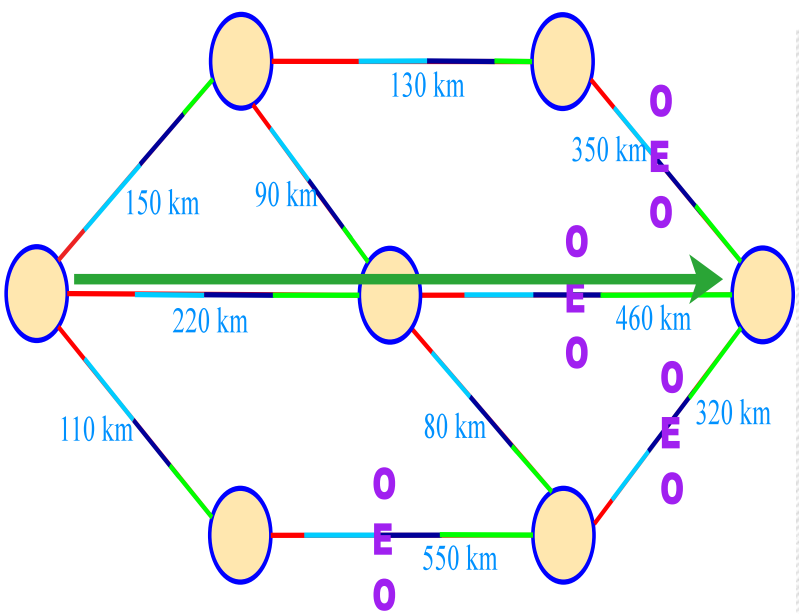
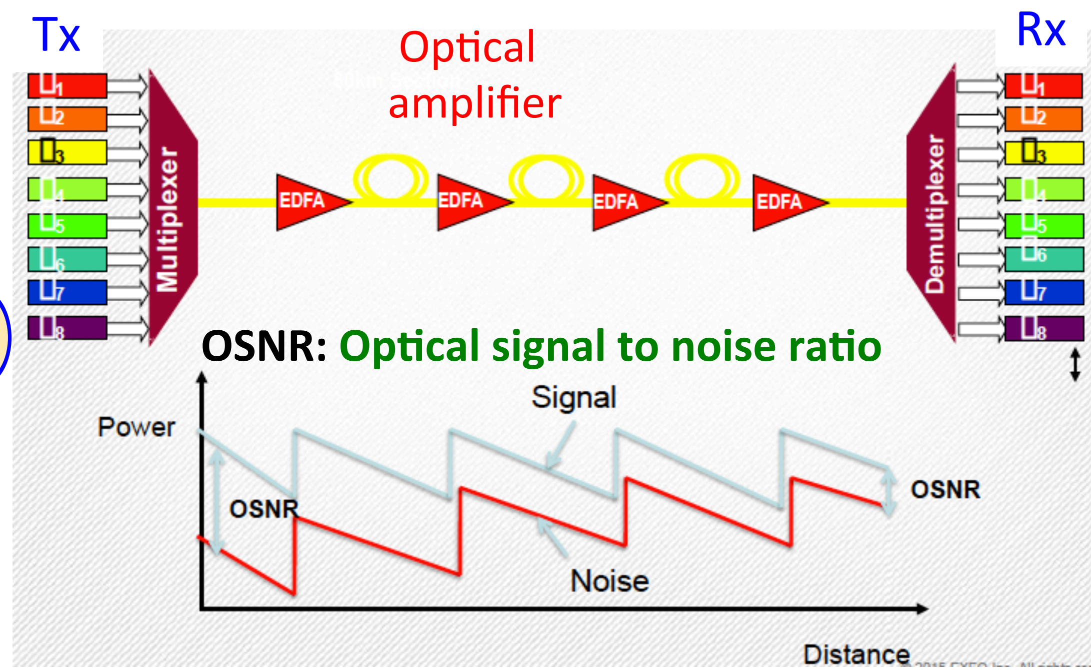
Evolution of Optical Networks

Translucent (Managed Reach) Network

- Some lightpaths are converted to electrical domain at the intermediate links or nodes to clear up the signals from optical noises.

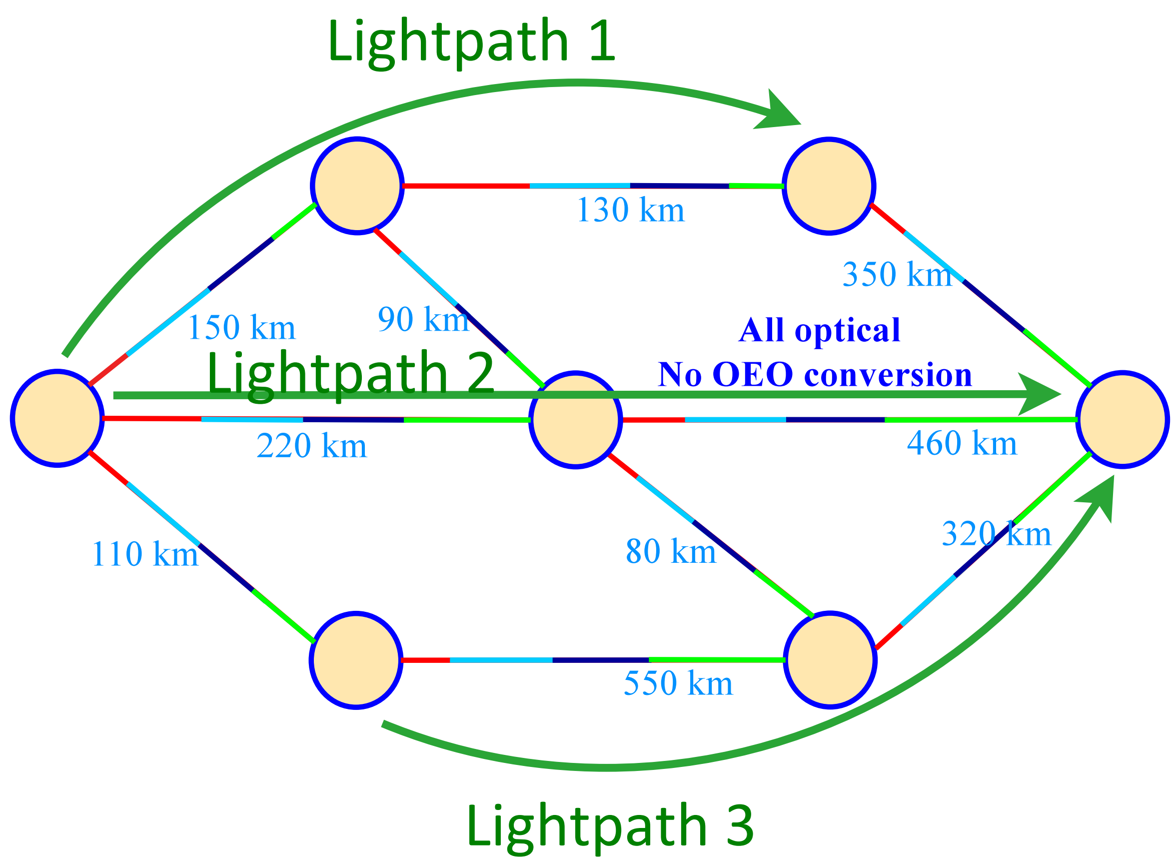




Evolution of Optical Networks

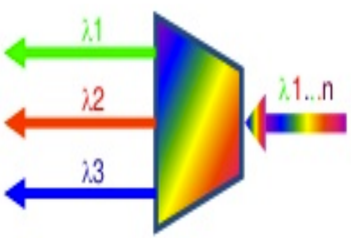
Transparent (All Optical) Network

- All optical connections (lightpaths) stay in the optical domain throughout the network.

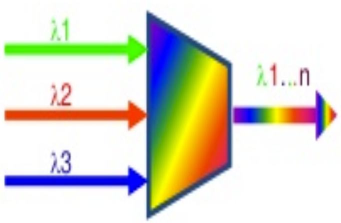


Optical Network Node and Switching Elements

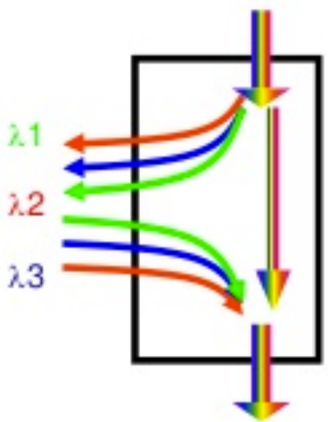
- An optical node (also called optical cross-connect (OXC)) is a multifunctional element that performs several tasks depending upon its type and network requirements.
- Essentially, it sends, receives and redirects optical signals to its neighboring connected nodes (**optical router**).
- Four different functions of an optical router: wavelength demultiplexing, multiplexing, adding/dropping wavelength, optical switching.



Wavelength demultiplexer



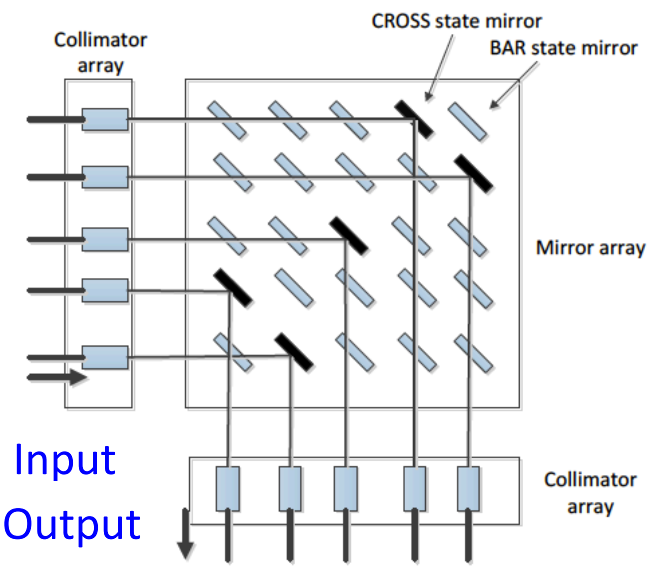
Wavelength multiplexer



Optical add/drop multiplexer

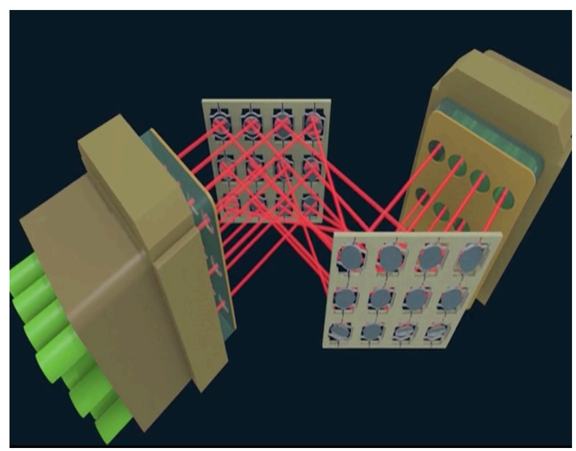
Optical Network Node and Switching Elements

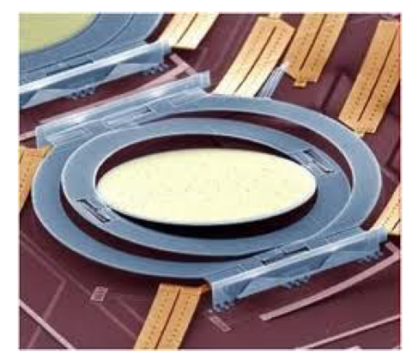
- An <u>optical switch</u> is the unit that actually switches (on the granularity of a wavelength) light between fibers.
- Switch with optical fabric is referred as <u>photonic switch</u>. Incoming optical signal does not have to convert to the electrical domain.



Input
Output

Schematic of a 2D MEMS-based switch fabric



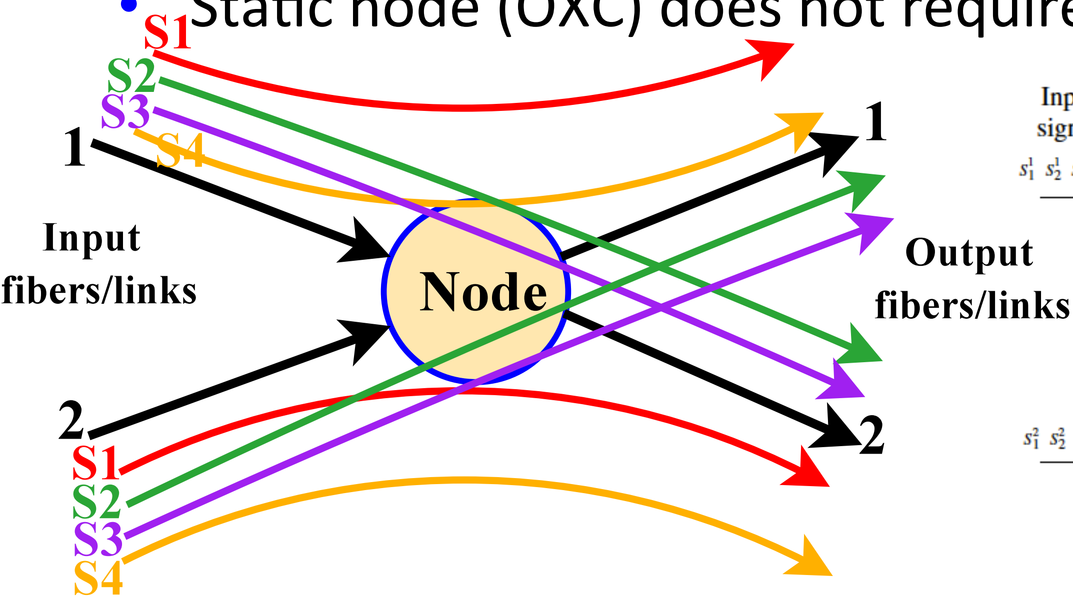


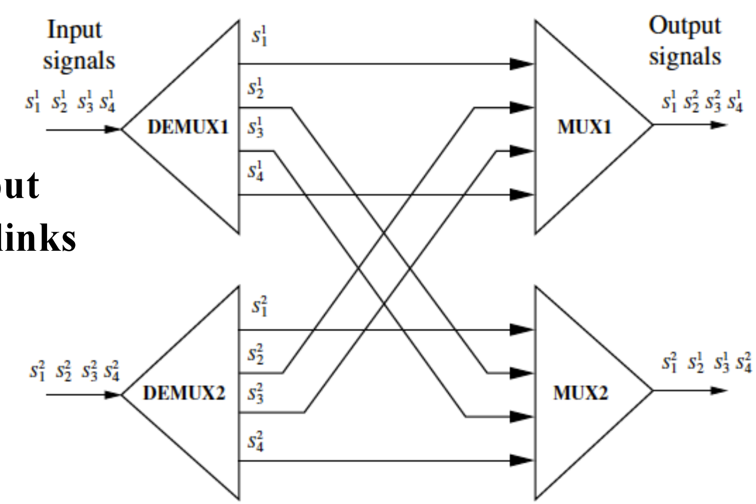
Schematic of a 3D MEMS-based switch fabric

MEMS: micro-electro-mechanical systems

Static/Non-Reconfigurable Optical Node

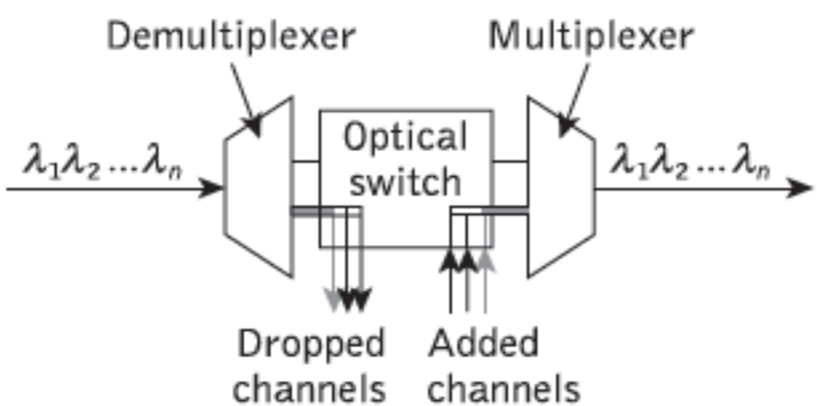
- The connections between the outputs of the demultiplexers (at the input links) and the inputs of multiplexers (at the output links) are fixed.
- The routing achieved by static node (OXC) cannot be changed, so the routes taken by the lightpaths in a network are determined at the time the network is set up.
- Static node (OXC) does not require optical switches.

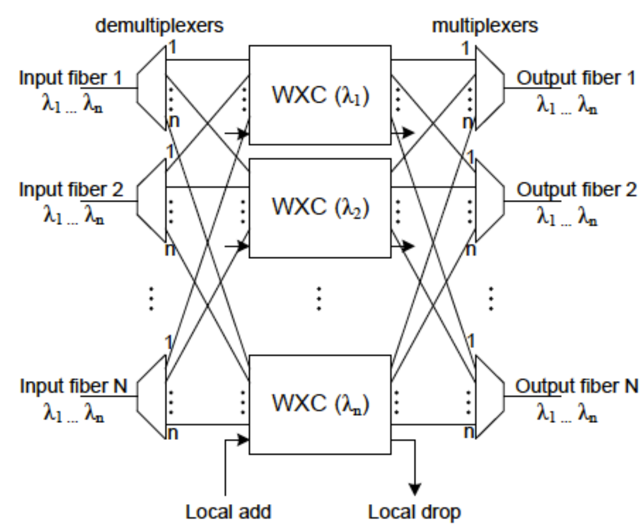




Dynamic/Reconfigurable Optical Node

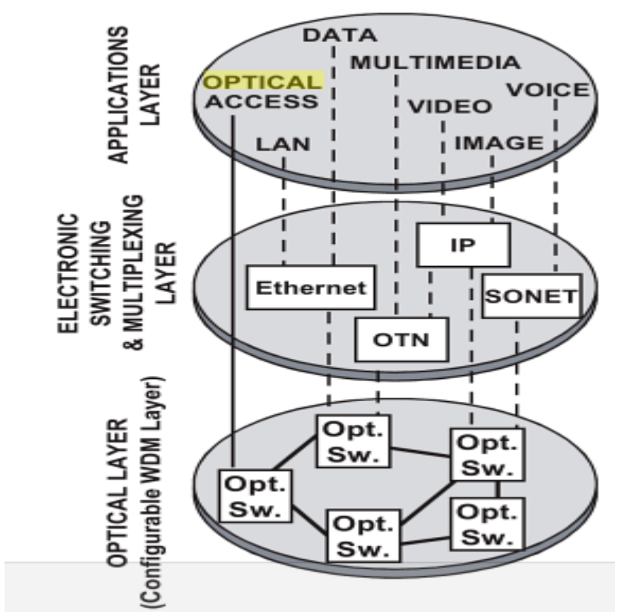
- ROADM: A combination of an optical add/drop multiplexer (OADM) and optical switch producing a reconfigurable optical add/drop multiplexer (ROADM).
- ROADM can drop one or a desired number of wavelength channels after demultiplexing a wavelength multiplexed signal.
- Similarly, it can add a new single or more wavelength channels through an optical switch. The multiplexer unit brings together all the wavelength channels to produce a combined wavelength multiplexed output signal.

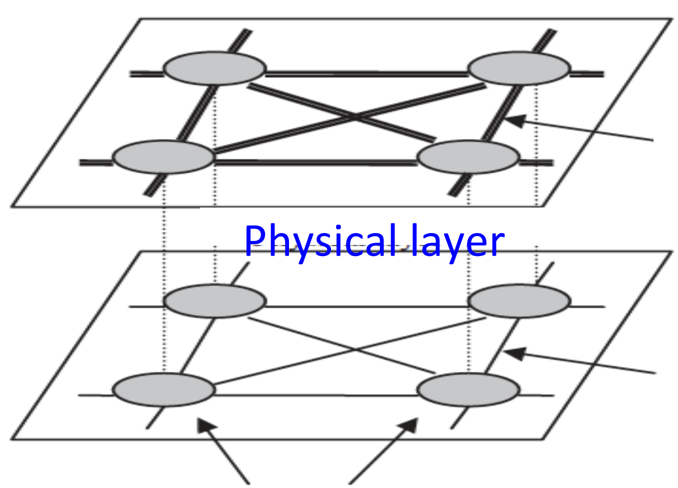




Optical Layer

- The optical layer is a virtual layer lying just above the physical layer.
- The physical layer provides a physical connection between two nodes, the optical layer provides lightpath services (optical circuit-switched connections) over that link.
- **For example**, in an eight-channel WDM link there are eight lightpaths, which may go over a single physical line.





Optical Layer

- The optical layer may carry out processes such as wavelength multiplexing, adding and dropping of wavelengths, and support of wavelength switching.
- Networks which have these optical layer functions are referred to as wavelength-routed networks.
- The optical layer has several other significant characteristics, such as **transparency, wavelength reuse, and reliability**.
- Transparency: Lightpath can carry data traffic at a variety of bit rates and in a variety of protocol format.
- Wavelength reuse: Two lightpaths can use the same wavelength on different links.
- Reliability: Capability to recover from network failures.

Wavelength Routed Network

- The wavelength routing utilizes the concept of circuit switching to establish all-optical connections (lightpaths), which traverse multiple fiber links and optical nodes.
- A lightpath is realized by **finding a path** between the source and the destination and **assigning a free wavelength** on all the links of the path.
- The selection of the path and the wavelength to be employed by a lightpath is an important optimization problem, known as the **routing and wavelength assignment** (**RWA**) problem.

RWA Problem

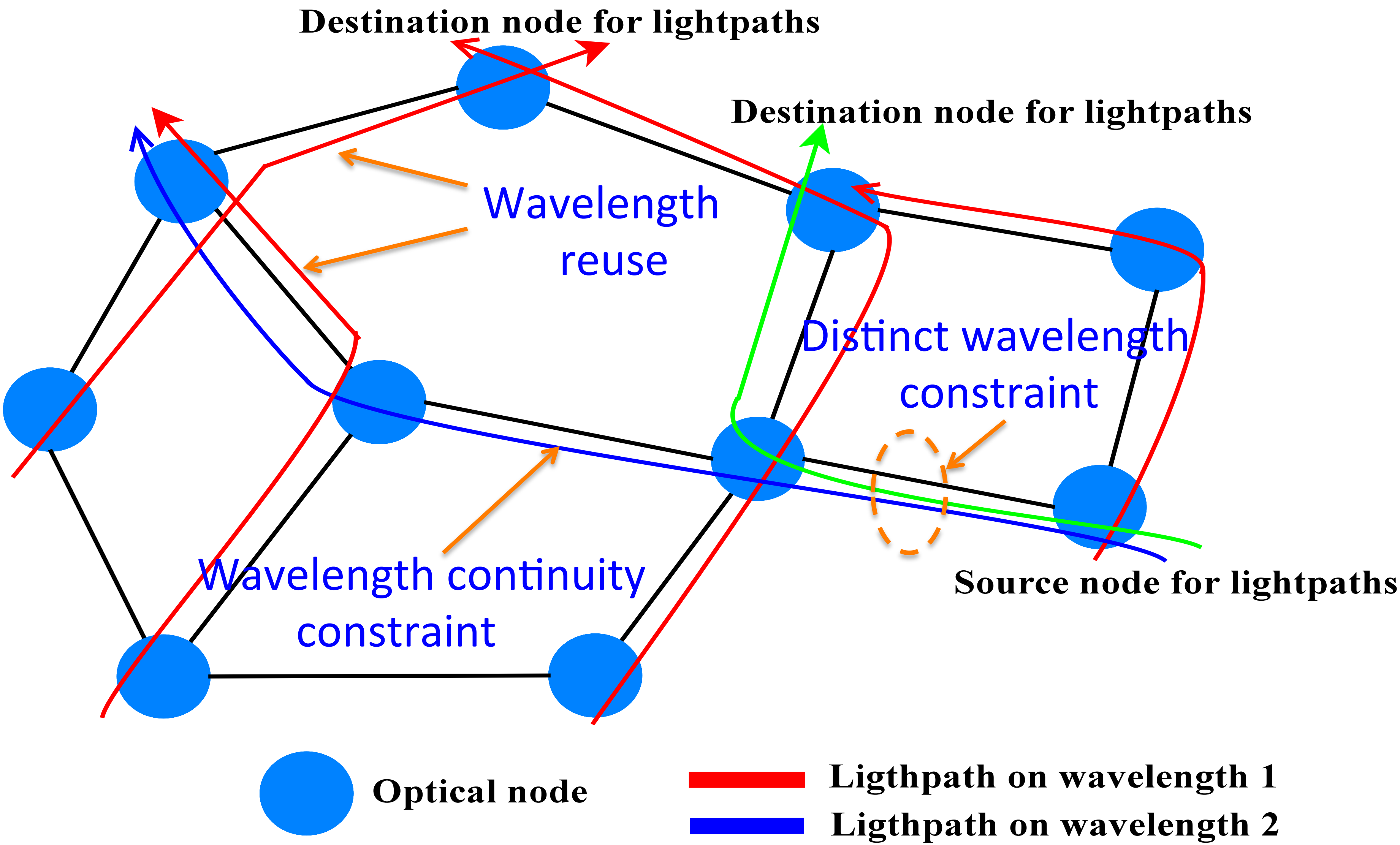
- Establishing an optical connection (lightpath) deal with both routing (selecting a suitable path) and wavelength assignment (allocating an available wavelength for the connection).

- The RWA problem is significantly more difficult than the routing problem in electronic networks. The additional complexity arises from the fact that RWA is subject to the following two constraints:

  Wavelength continuity constraint: a lightpath must use the same wavelength on all the links along its path from source to destination node.

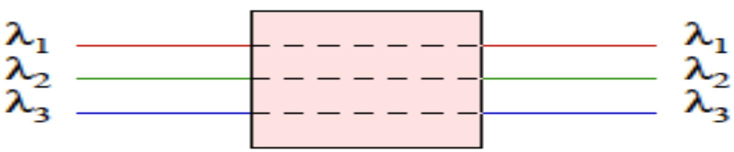
  Distinct wavelength constraint: all lightpaths using the same link (fiber) must be allocated distinct wavelengths.

Example

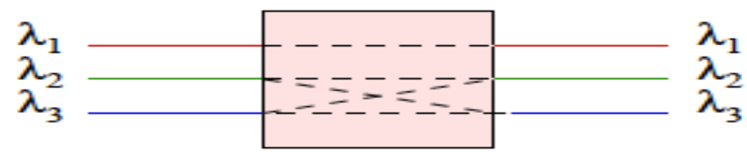

Destination node for lightpaths
Destination node for lightpaths
Wavelength reuse
Distinct wavelength constraint
Wavelength continuity constraint
Source node for lightpaths
Optical node
Ligthpath on wavelength 1
Ligthpath on wavelength 2
Ligthpath on wavelength 3

Wavelength Converter (WA)

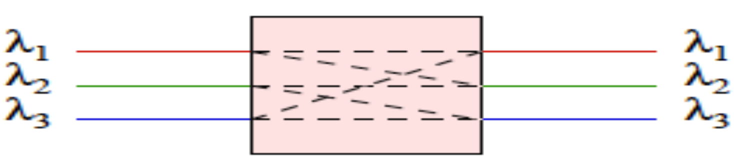
- The wavelength continuity constraint can be relaxed if the nodes are equipped with wavelength converters.
- A wavelength converter is a single input/output device that converts the wavelength of an optical signal arriving at its input port to a different wavelength as the signal departs from its output port.
- Wavelength conversion allows a lightpath to use different wavelengths along different physical links.



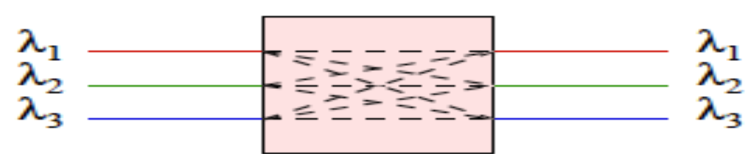
No conversion



Fixed conversion



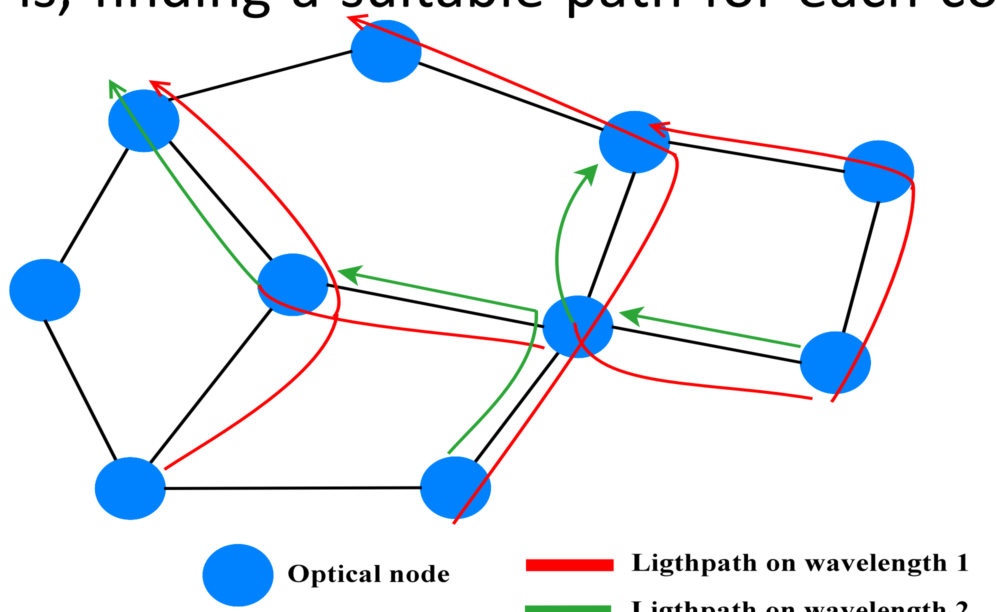
Limited conversion



Full conversion

Advantage of Full Conversion

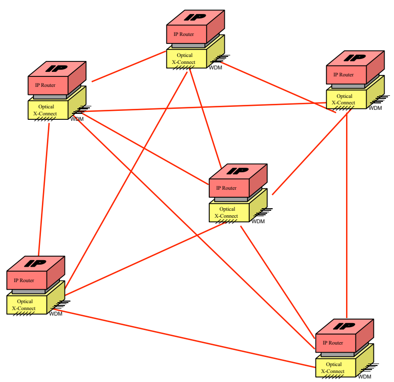
- The advantage of full wavelength conversion is that it <u>removes the wavelength continuity constraint</u>, making it possible to establish a lightpath as long as each link along the path from source to destination has a <u>free wavelength</u> (which could be different for different links).
- As a result, the RWA problem reduces to the classical routing problem, that is, finding a suitable path for each connection in the network.



Static RWA Problem

- Static RWA problem deals with traffic patterns of the network that are reasonably well-known in advance and traffic variations take place over long time scales.
- The objective of static RWA is to set up lightpaths (optical connections) for the given traffic/demand in such a way to minimize optical network resources e.g., the number of wavelengths or the number of fibers in the network.
- Alternatively, one may attempt to set up as many of these connections as possible for a given fixed number of wavelengths.
- These connections are assumed to remain in place for relatively long periods of time, it is worthwhile to attempt to optimize the way in which network resources are assigned to each connection, even though optimization may require a considerable computational effort.
- Static RWA problem is also sometimes called as the planning problem and offline RWA problem.

Planning WDM Networks



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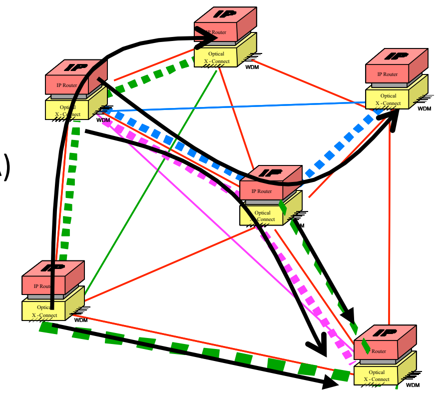
$$\begin{bmatrix} 0 & 1 & 2 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 2 & 0 \\ 2 & 1 & 0 & 1 & 0 & 1 \\ 0 & 2 & 1 & 1 & 1 & 0 \end{bmatrix}$$

Routing and Wavelength Assignment (RWA)



- **Input:** Network topology, traffic matrix
- **Output:** Routes and wavelengths (RWA)
- **Network layer**: Satisfy traffic and minimize the number of used wavelengths
- **Constraints:**

  Discrete wavelength assignment

  Wavelength continuity (if wavelength converters are not available)

Dynamic RWA

- During real-time network operation, edge nodes submit to the network requests for lightpaths to be set up as needed.
- Connection requests are initiated in some random fashion.
- Depending on the state of the network at the time of a request, the available resources may or may not be sufficient to establish a lightpath between the corresponding source-destination edge node pair.
- The network state consists of the physical path (route) and wavelength assignment for all active lightpaths.
- The state evolves randomly in time as new lightpaths are admitted and existing lightpaths are released.

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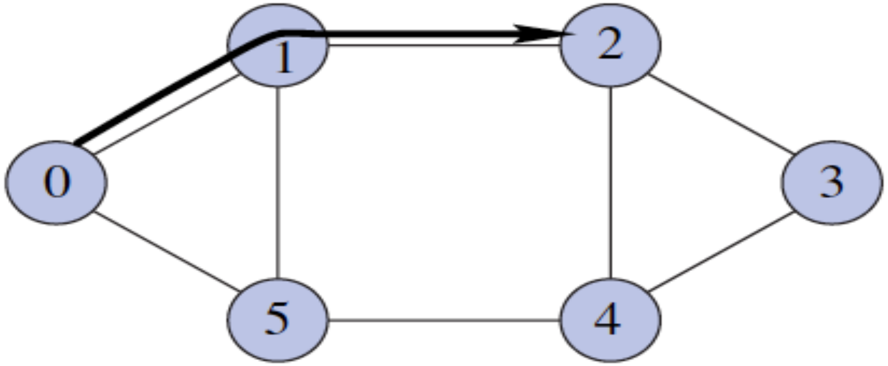
Dynamic RWA

- Each time a request is made, an algorithm must be executed in real time to determine whether it is feasible to accommodate the request, and, if so, to perform routing and wavelength assignment.
- If a request for a lightpath cannot be accepted because of lack of resources, it is BLOCKED.
- Due to the real-time nature of the problem, RWA algorithms in a dynamic traffic environment must be very simple.
- Combined routing and wavelength assignment is a hard problem, a typical approach to designing efficient algorithms is to decouple the problem into two separate subproblems: the **routing** problem and the **wavelength assignment** problem.

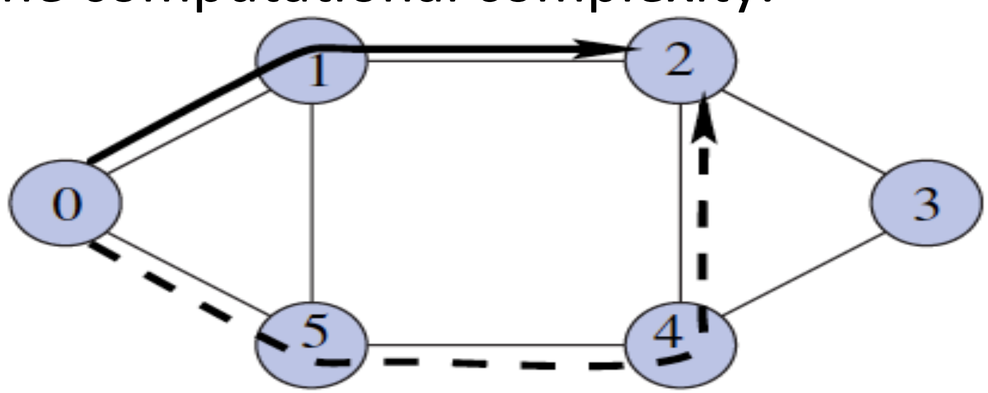
Routing

- There are typically three types of routing paradigms:
- **Fixed routing, fixed-alternate routing, adaptive routing**
- In fixed routing, there is only a single fixed route for each pair of network nodes.
- This fixed route is precomputed offline, and any connection between a pair of source and destination nodes use the same fixed route.
- Fixed route is simple to implement due to lower computational complexity, but can result in a higher request blocking probability in the network.



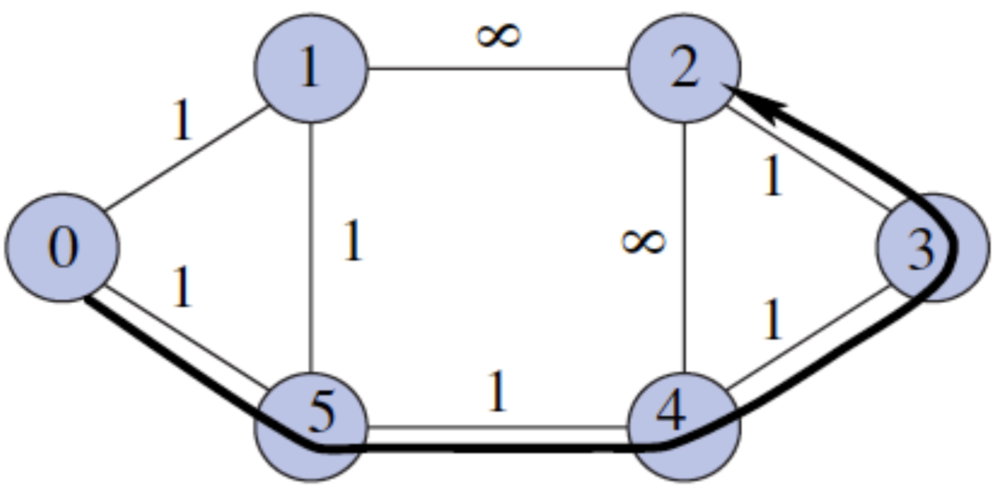
Fixed-alternate Routing

- In fixed-alternate routing, there is a set of alternate routes for each pair of network nodes.
- The actual route for a connection request can only be chosen from these alternate routes, which also imposes a restriction on route selection.
- These alternate routes are precomputed offline and are orderly stored in a routing table.
- Compared with fixed routing, fixed-alternate routing can significantly reduce the request blocking without largely increasing the computational complexity.



Adaptive Routing

- In adaptive routing, there is no restriction on route selection. Any possible route between a pair of source and destination nodes can be chosen as an actual route for the connection.
- The choice of a route is based on the current network state information as well as a **path-selection policy**, such as the least-cost path or the least-congested path first.
- Can further reduce the request blocking, however, it may largely increase the computational complexity.



Wavelength Assignment (WA)

WA techniques	Characteristics	Advantage	Drawback
Random	Select one of the wavelength at random.	Simple with no communication overhead.	Does not provide optimal WA.
First-Fit	The wavelengths are indexed, and a lightpath will attempt to select the wavelength with the lowest index before attempting to select with a higher index.	Low computational cost than Random WA.	Possible blocking if simultaneous lightpath connections.
Least-Used	The wavelength which is the least used in the rest of the network is selected.	Spreads the load evenly across all wavelengths.	Global information needed.
Most-Used	The wavelength which is the most used in the rest of the network is selected.	Provides maximum wavelength reuse in the network.	Global information needed.

Network Survivability

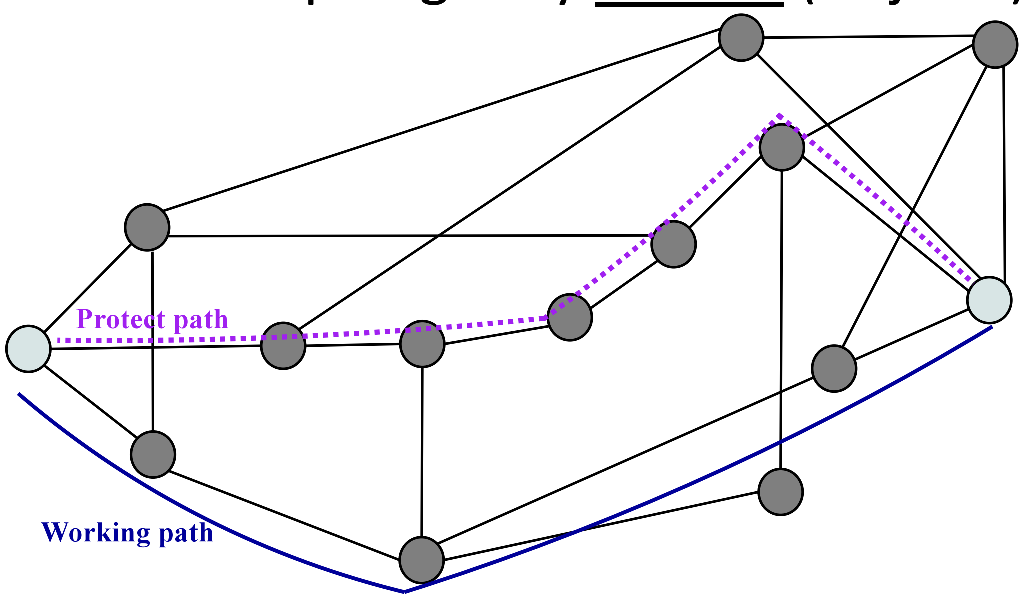
- In wavelength-routed WDM network, the failure of a network element:
  - can cause the failure of several lightpaths.
  - leading to large data and revenue loss.
- Fault recovery mechanisms, such as protection and restoration are essential for a network to survive from failures.
- **Protection scheme**: backup resources (routes and wavelength) are pre-computed and reserved in advance.
- **Restoration scheme:** another route and a free wavelength have to be discovered after the failure is detected.

Optical Protection

Working path/Primary path: The connection path from source to destination that is used under the condition of no failures.

Protect/Backup/Secondary path: The path that is used after a failure occurs.

To withstand physical link failures, the working path, and its protect path must be topologically diverse (disjoint).

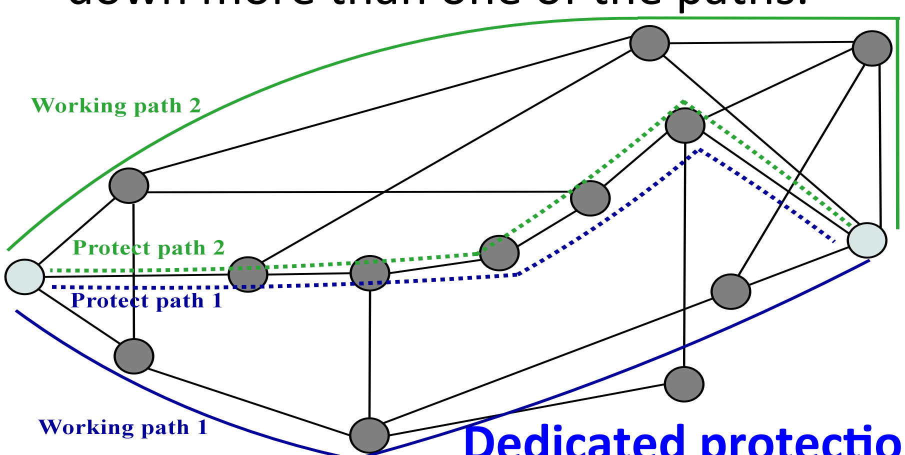


Dedicated Versus Shared Protection

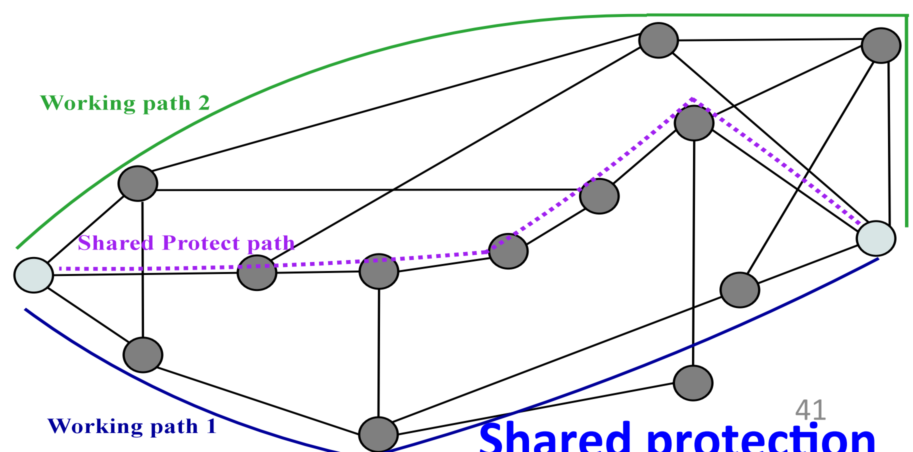
<u>Dedicated protection</u>: Spare resources are specifically allocated for a particular connection. Dedicated protection guarantees fast failure recovery but require a large amount of spare capacity.

<u>Shared protection</u>: Spare resources are shared by multiple working paths. Shared protection potentially requires less spare resources but contention for the resources may arise if there are multiple concurrent failures.

NOTE: The working paths that share protection resources should have no link or intermediate nodes in common so that a single network failure does not bring down more than one of the paths.



Dedicated protection



Shared protection