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HUT Communications Laboratory

S-72.3340 Optical Networks Course

Lecture 7: Optical Network Design

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Lecture Outline

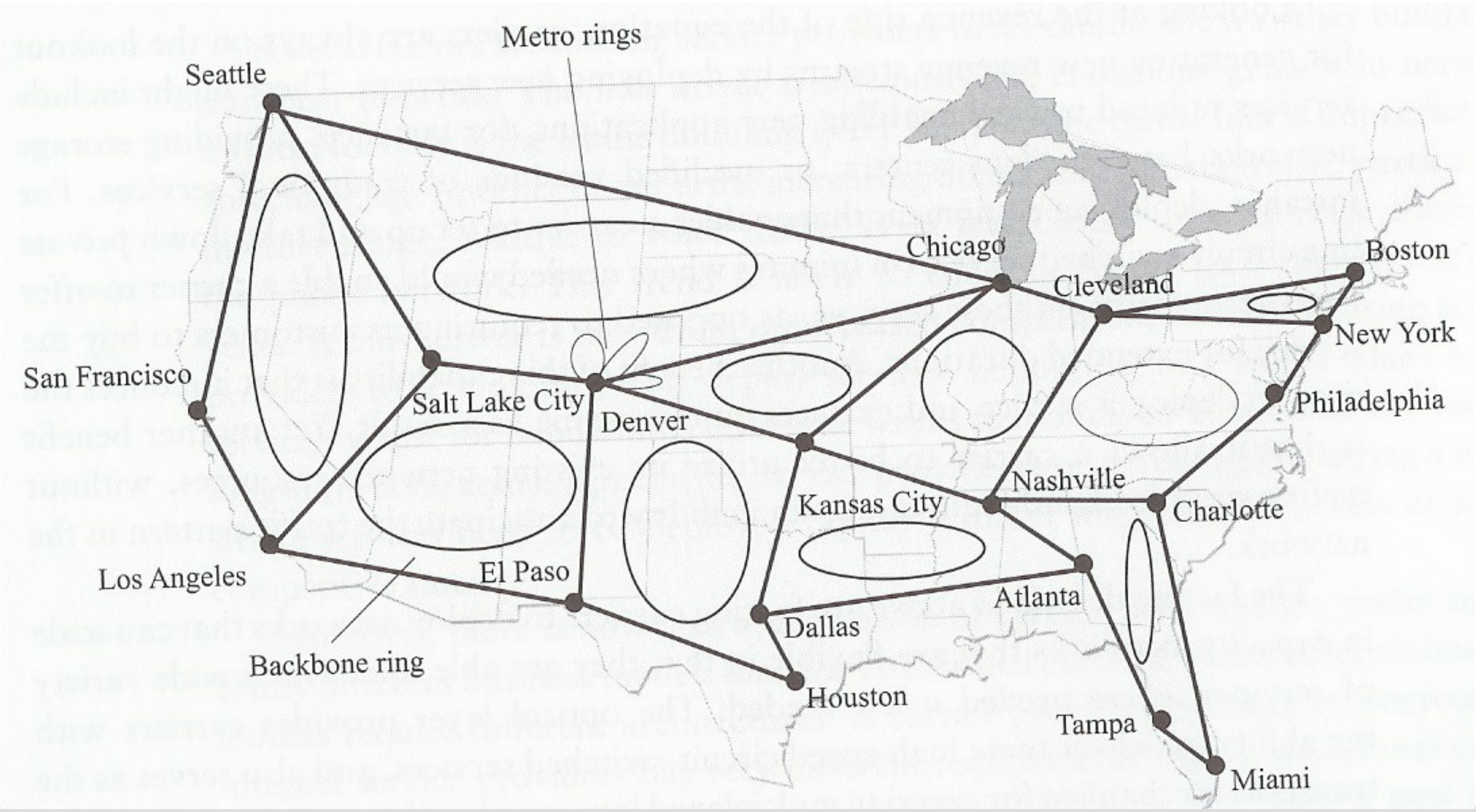
- Introduction
- Network Elements
  - Multiplexers/demultiplexers
  - Regenerators
  - Optical line terminals
  - Optical switches and nodes
- Network design
  - Resource allocation
  - Design tools
- Conclusion

1. Introduction

- Last week
  - Focus on client layer networks (SDH, IP, Ethernet etc.)
  - Evolving to support multiservice provisioning
- The next two lectures focus on the optical layer
  - Provide optical capacity for the client layer networks
  - WDM (CWDM or DWDM) $\Rightarrow$ the underlying transmission technique

1. Introduction

- SDH/SONET dominates current backbone networks
  - Stacked (multiple) SDH/SONET rings connecting same node set
  - Typical backbone rates STM 16 (2.5 Gb/s) to STM 64 (10 Gb/s)



1. Introduction

- Multiple STM circuits provisioned
  - Over different fibers
  - Or over different wavelengths (WDM) within same fiber

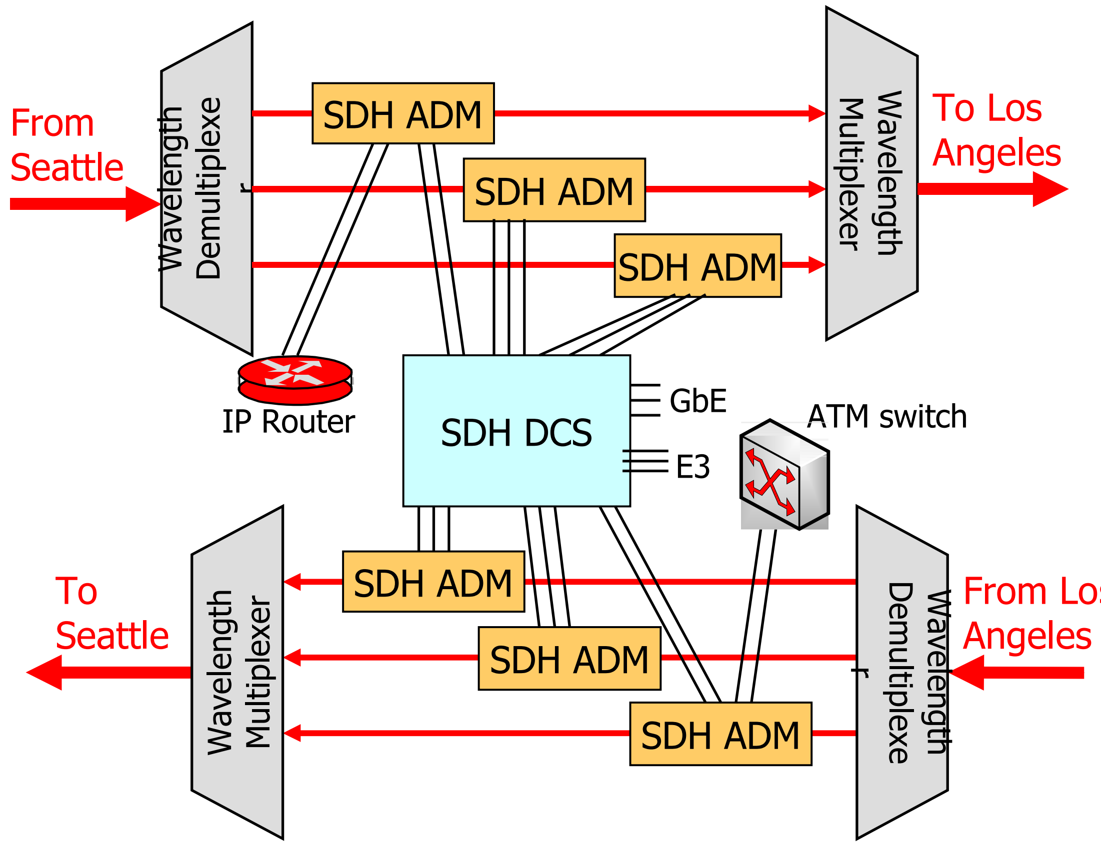
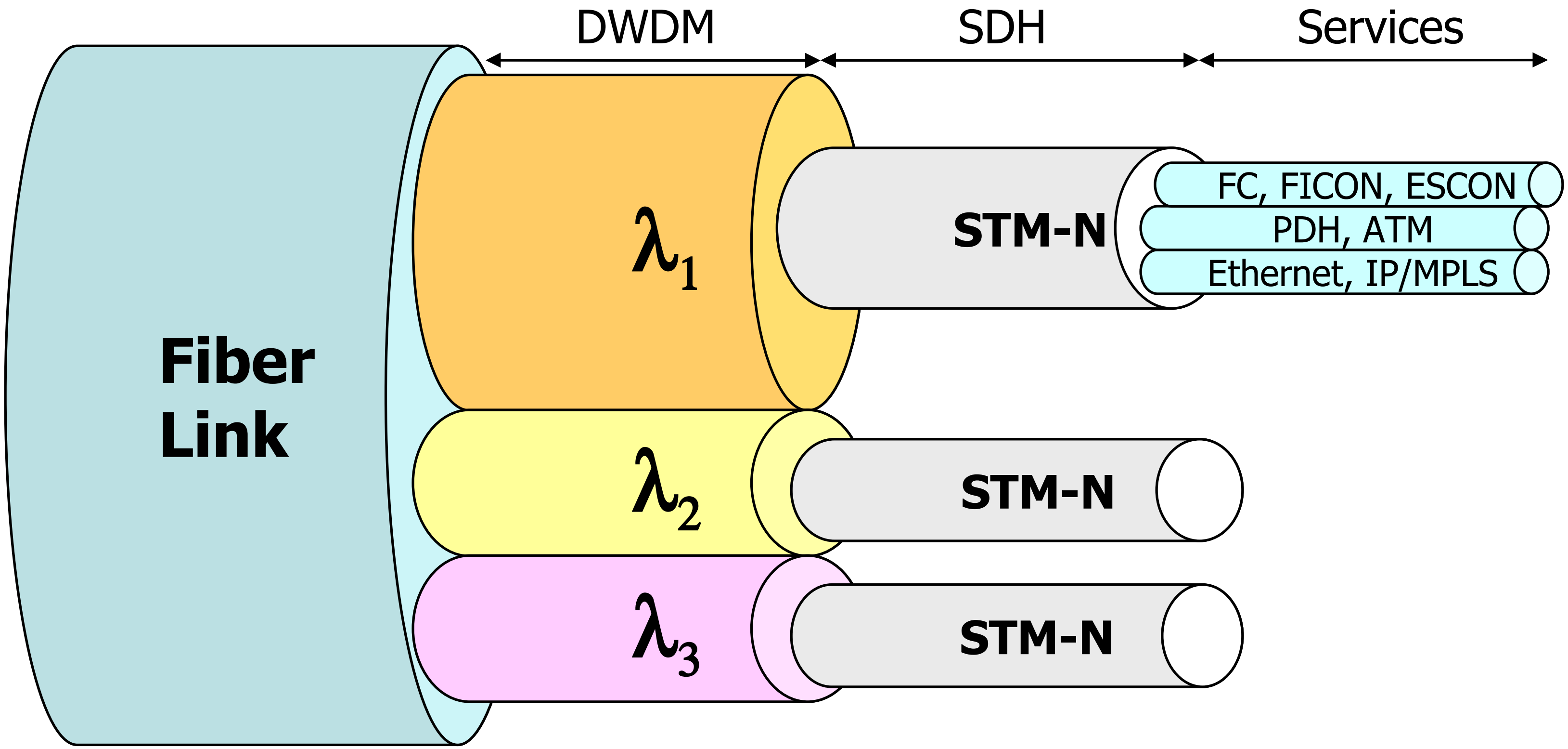


Figure: Possible equipment at the San Francisco site (previous slide). Includes WDM equipment, routers, stacked up SDH ADMs, and DCS

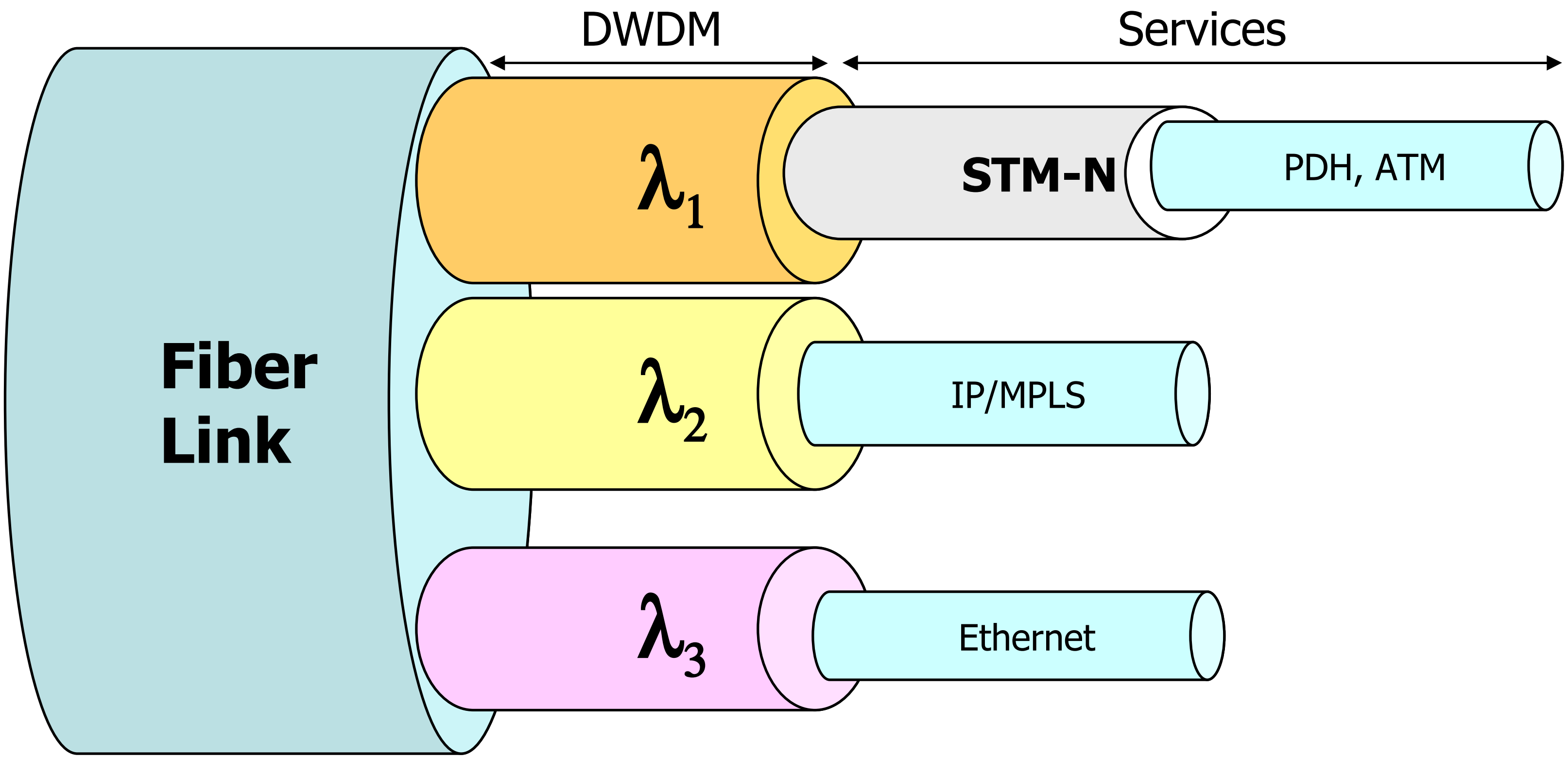
1. Introduction

- Optical Layer WDM not just for boosting utilization of fiber capacity
  - May also reduce dependency on SDH/SONET



1. Introduction

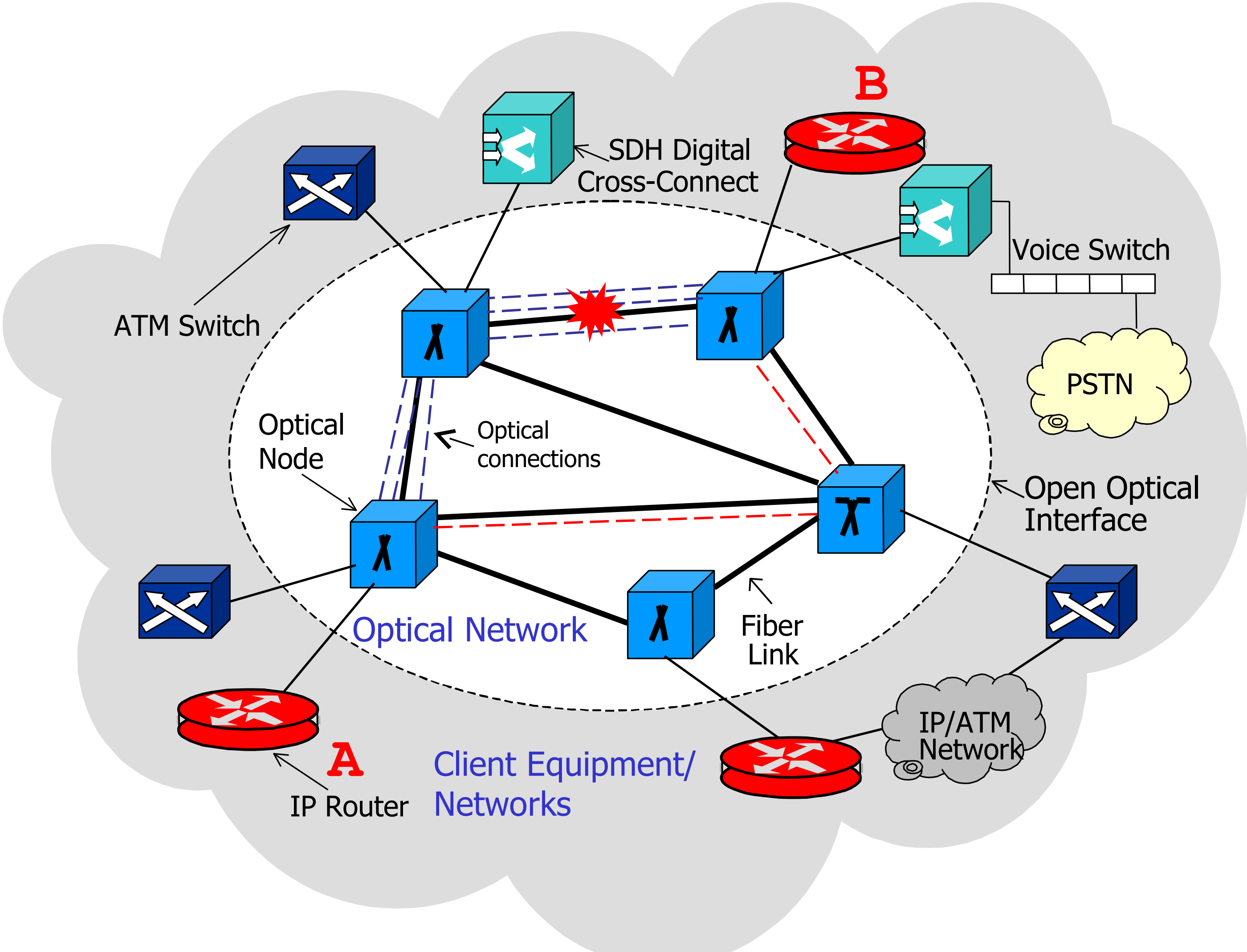
- Optical WDM network with open interfaces simplifies direct access to fiber capacity sharing by different clients



1. Introduction

- WDM enables wavelength-based intelligent optical networking allowing operators to perform:
  - Wavelength routing
  - Wavelength re-routing to avoid failures, congestion etc.
  - Wavelength monitoring and management
  - Wavelength leasing or trading services
  - Optical virtual private networks

1. Introduction

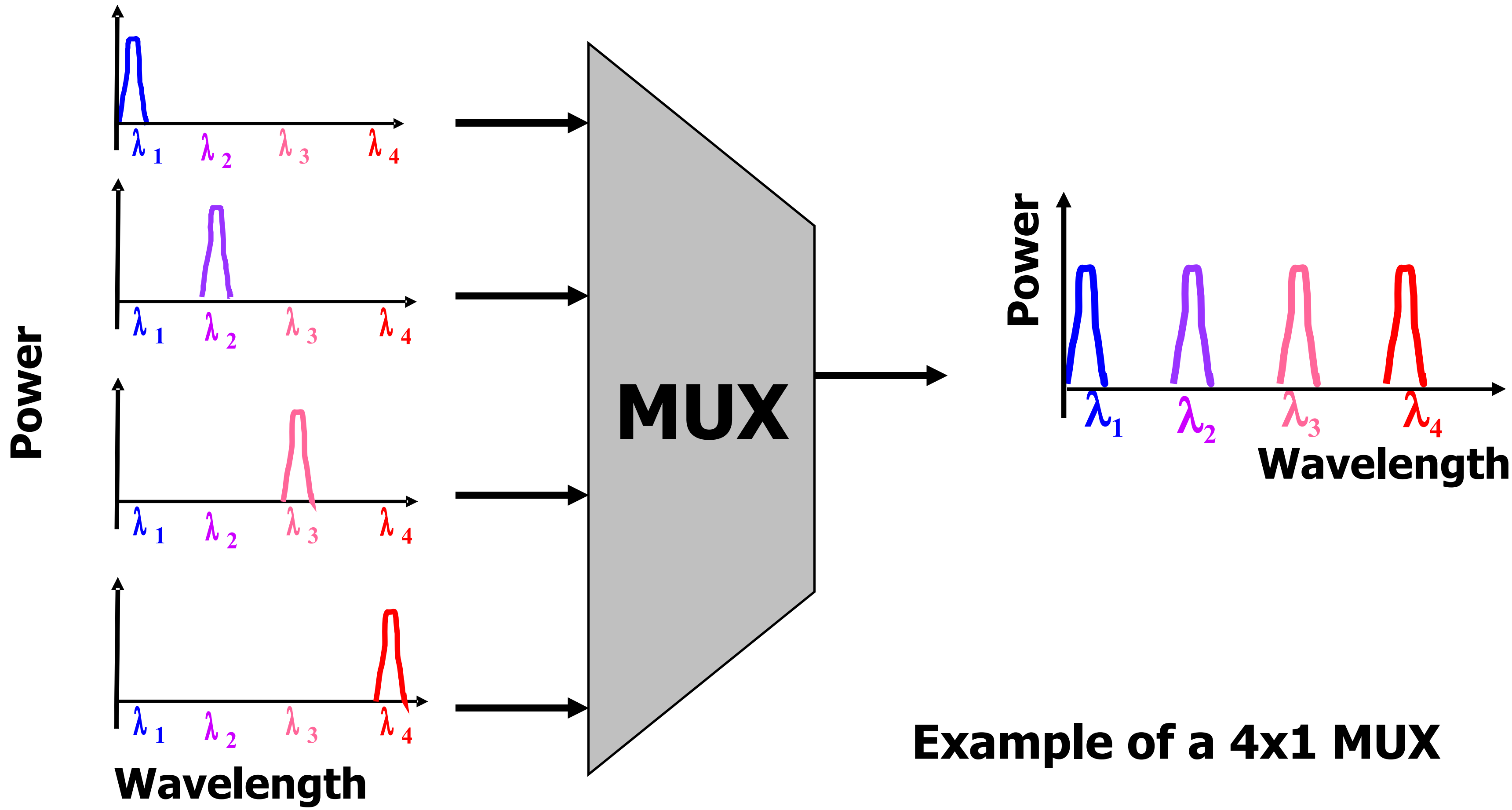


2. WDM Network Elements

- WDM Networks constitutes various components or network elements
  - Multiplexers/demultiplexers
  - Regenerators (e.g. optical line amplifiers, transponders)
  - Optical line terminals
  - Optical nodes
    - Optical add-drop multiplexers
    - Optical crossconnects

2.1 Multiplexers/Demultiplexers

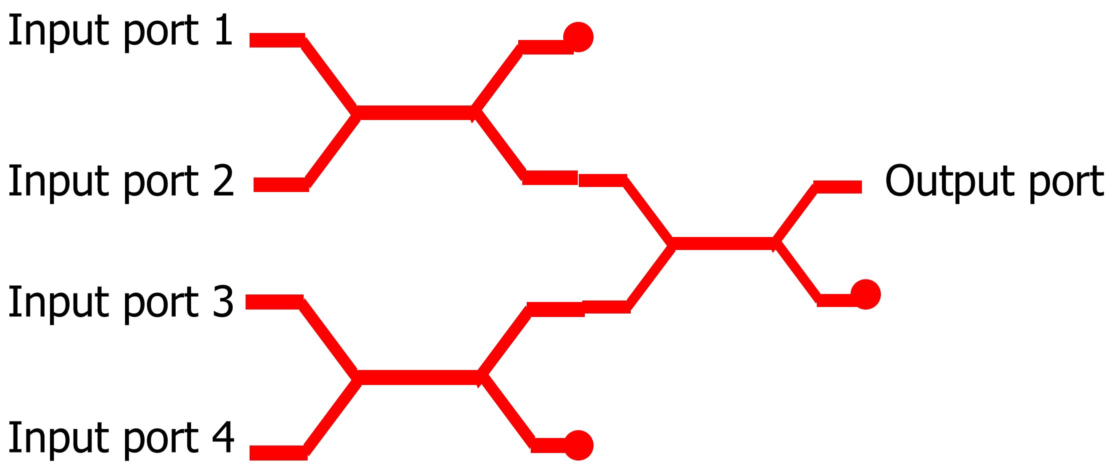
- Wavelength Multiplexer (MUX) combines multiple wavelengths into a single fiber



Example of a 4x1 MUX

2.1 Multiplexers/Demultiplexers

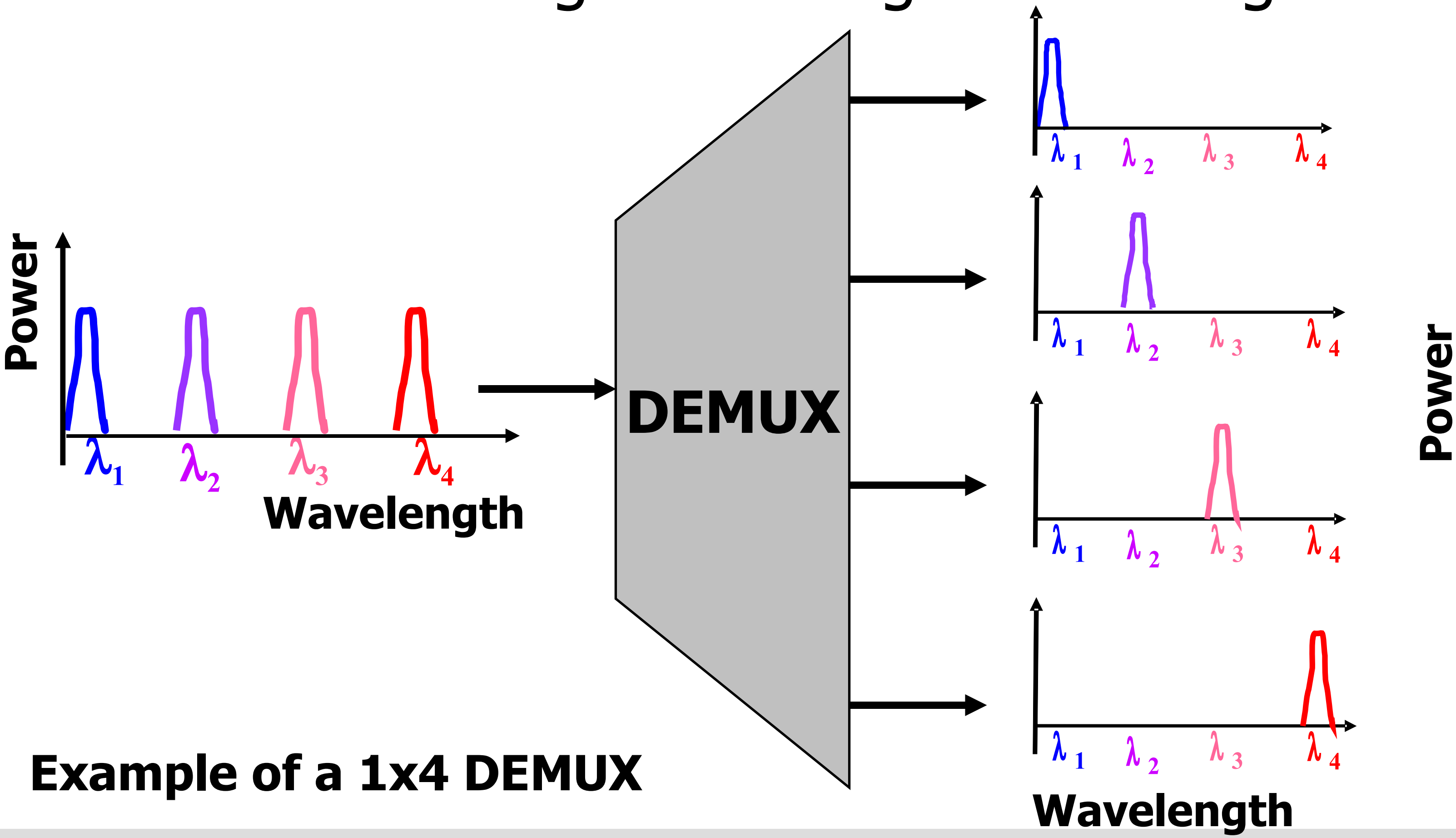
- Simple MUX can be implemented using a passive power combiners



Example: Implementing a 4x1 MUX using a 4x1 combiner

2.1 Multiplexers/Demultiplexers

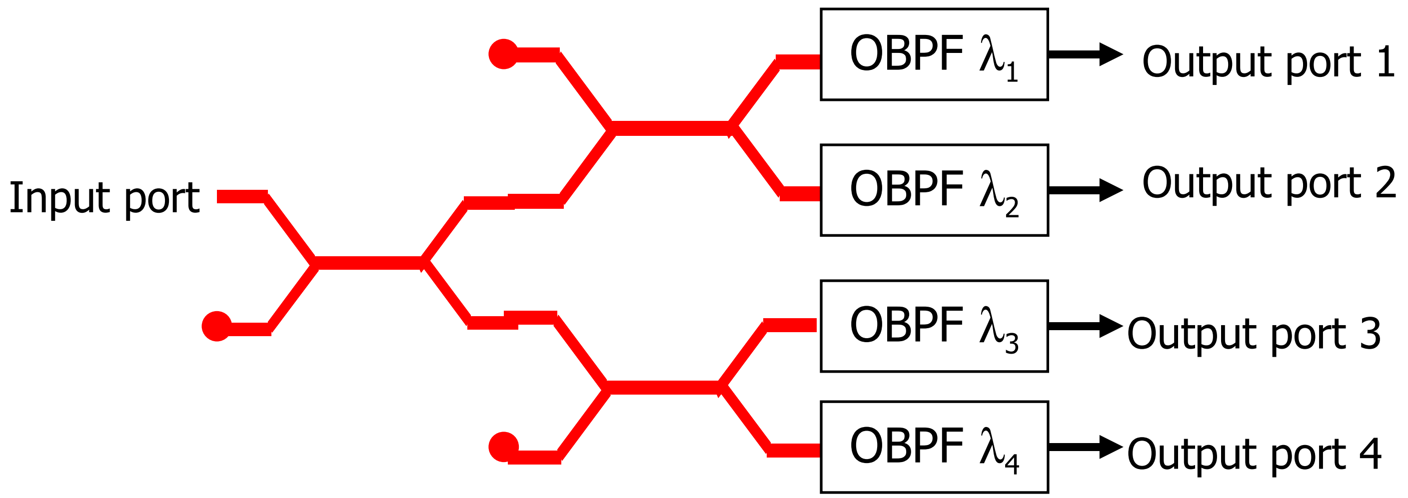
- Wavelength Demultiplexer (DEMUX) separates different wavelengths coming from a single fiber



Example of a 1x4 DEMUX

2.1 Multiplexers/Demultiplexers

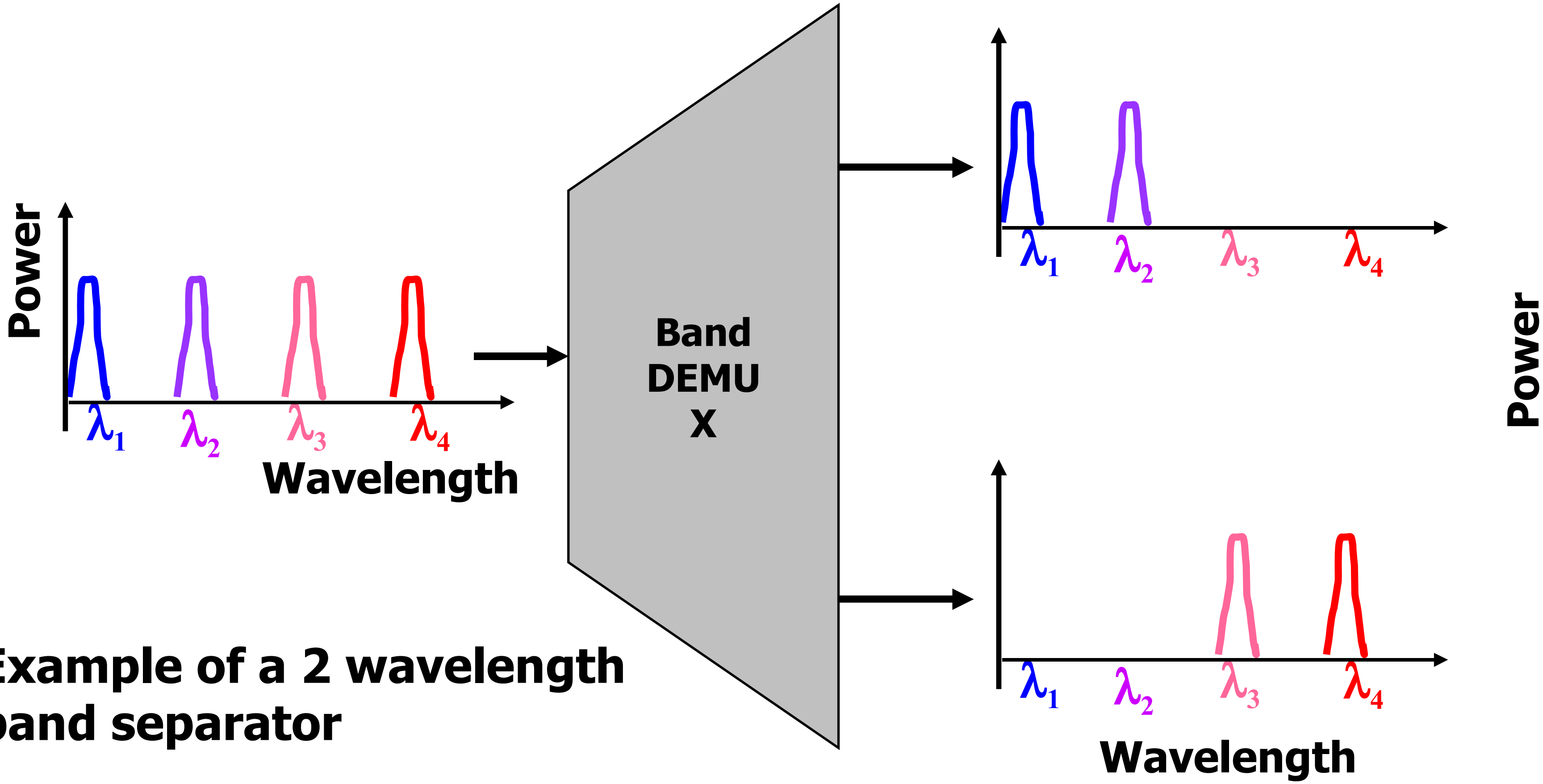
- Simple DEMUX implemented using a passive power splitters and optical band-pass filters (OBPF)



Example: implementing a 1x4 DEMUX using a 1x4 splitter and 4 OBPF

2.1 Multiplexers/Demultiplexers

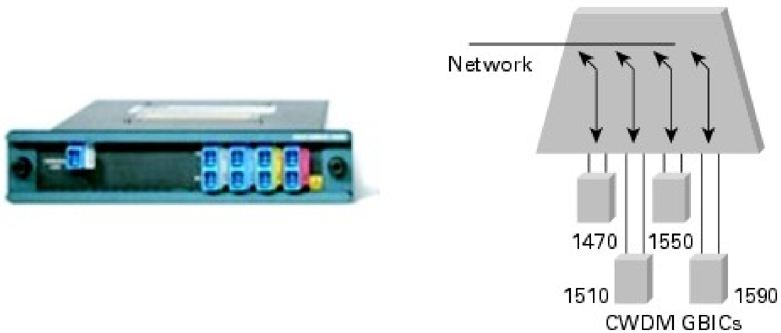
- Wavelength band separation for separating different bands



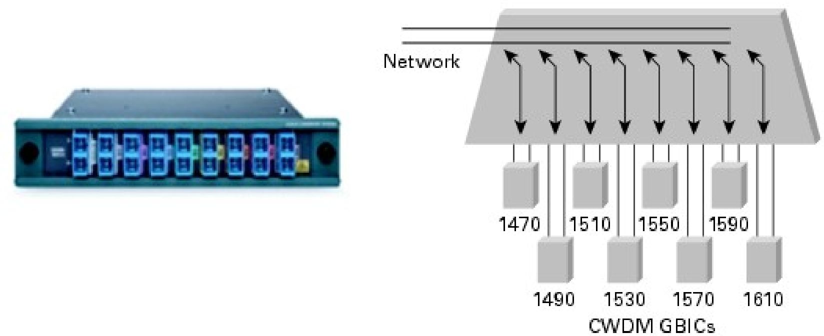
Example of a 2 wavelength band separator

2.1 Multiplexers/Demultiplexers

- MUX and DEMUX could be integrated in same module



4-Channel Single Fiber CWDM Multiplexer/Demultiplexer Module



8-Channel CWDM Multiplexer/Demultiplexer Module

2.2 Regenerators

- Optical line amplifiers ⇒ 1R (Re-amplifying) regenerator
  - EDFAs deployed periodically over fiber link (80-120 km intervals)
  - Sometimes completed with fiber Raman amplifiers
  - A single site may have multiple gain stages (EDFAs)
  - Configuration duplicated in opposite direction

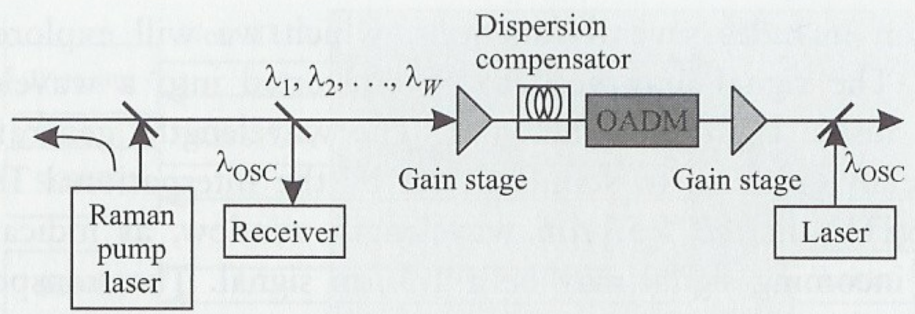
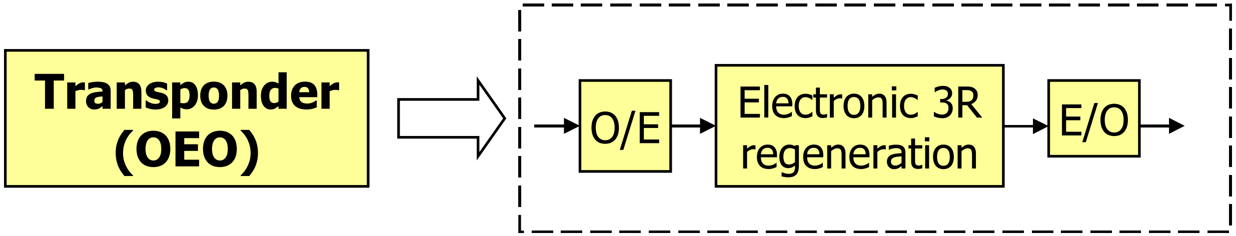


Figure 7.3 Block diagram of a typical optical line amplifier. Only one direction is shown. The amplifier uses multiple erbium gain stages and optionally includes dispersion compensators and OADMs between the gain stages. A Raman pump may be used to provide additional Raman gain over the fiber span. The OSC is filtered at the input and terminated, and added back at the output.

2.2 Regenerators

- Optical 3R regeneration (Re-amplify, Reshape, Retime) yet to reach commercial maturity
  - Continued reliance on electronic regenerators
- Transponder box has electronic regenerator between O/E and E/O converters
  - Or simply known as an OEO
  - Also used for wavelength conversion and monitoring of signal quality



2.2 Regenerators

- Ideally transponders should be avoided in optical networks
  - Only have a transparent "all-optical" network
  - But accumulated signal impairments will limit range of the network

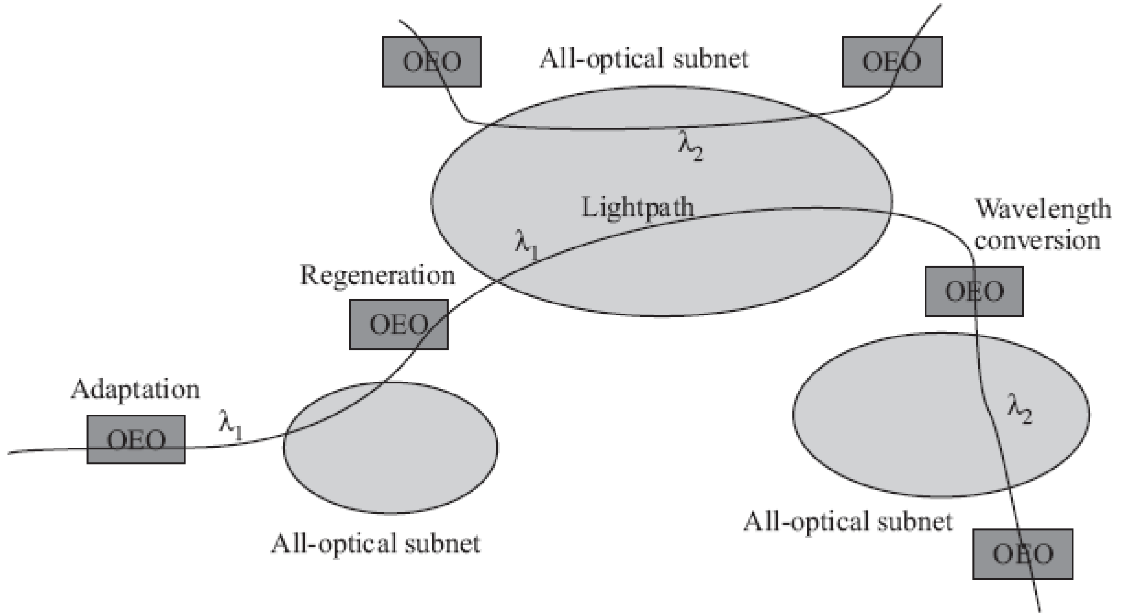


Figure 1.12 An optical network consisting of all-optical subnetworks interconnected by optical-to-electrical-to-optical (OEO) converters. OEO converters are used in the network for adapting external signals to the optical network, for regeneration, and for wavelength conversion.

2.2 Regenerators

- Transponders are a significant fraction of WDM network cost
  - One required per wavelength channel per direction at a regeneration site

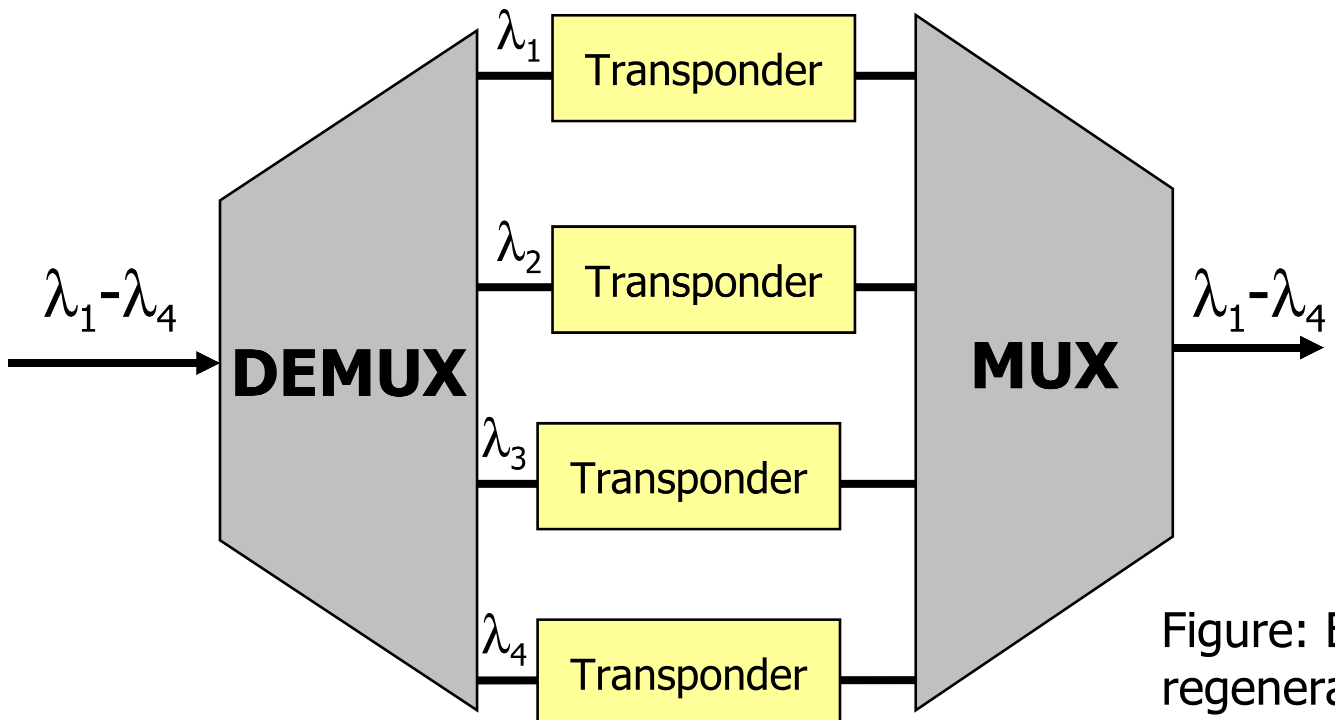
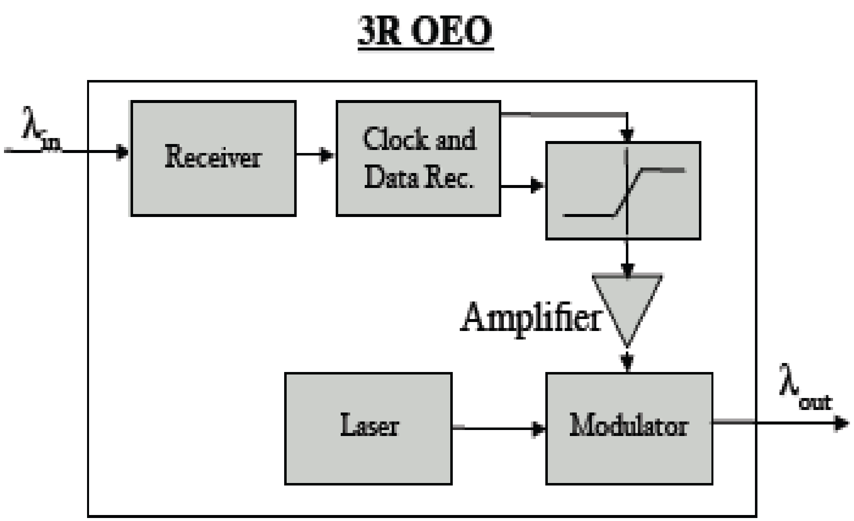
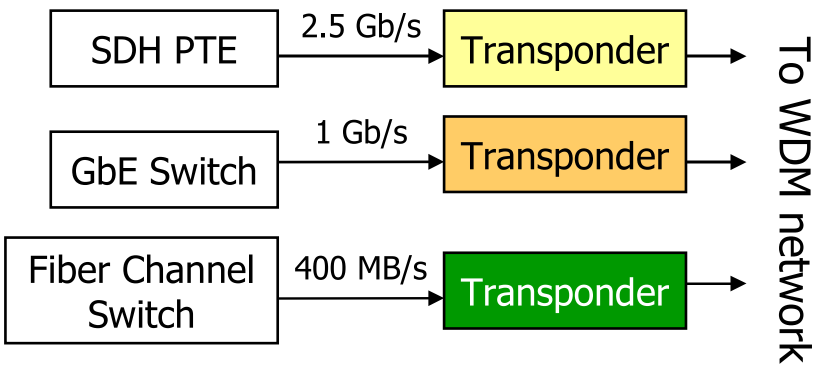


Figure: Equipment at regeneration site (in one direction)

2.2 Regenerators

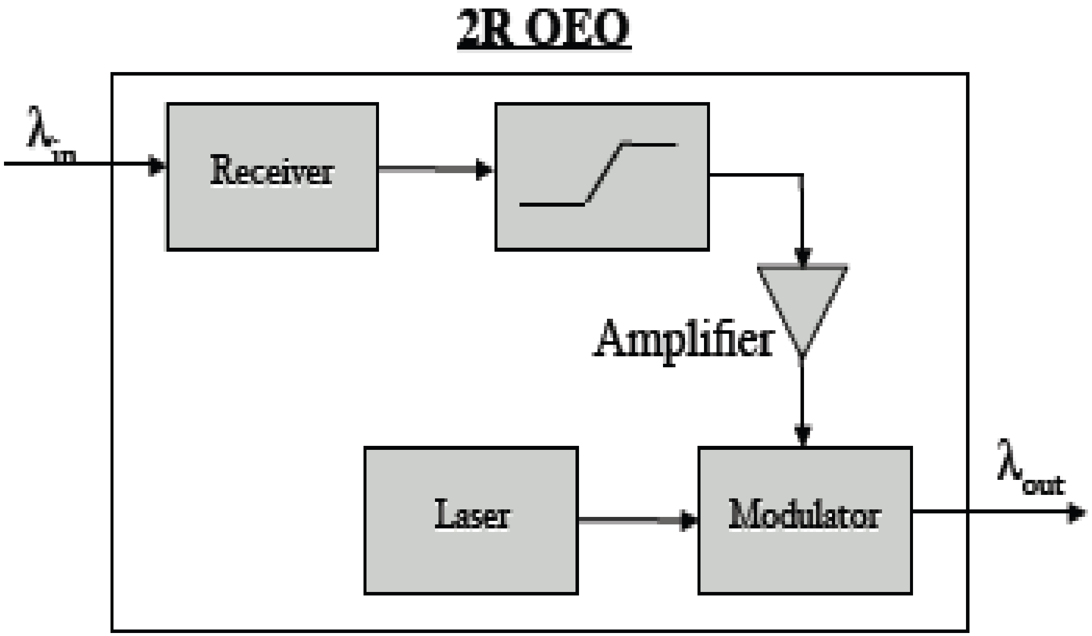
- Simple 3R transponders are fixed to a particular bit rate and client protocol (e.g. SDH, GbE, Fiber Channel, ESCON)
  - Retiming (clock recovery) function difficult to implement for different bit rates
  - Different transponders needed for different bit rates and client protocols

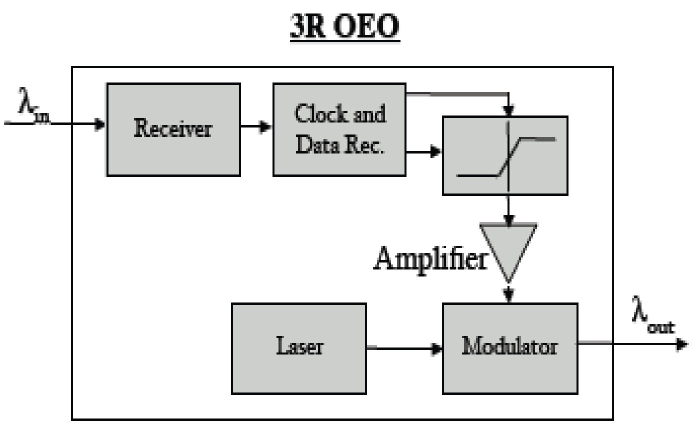




2.2 Regenerators

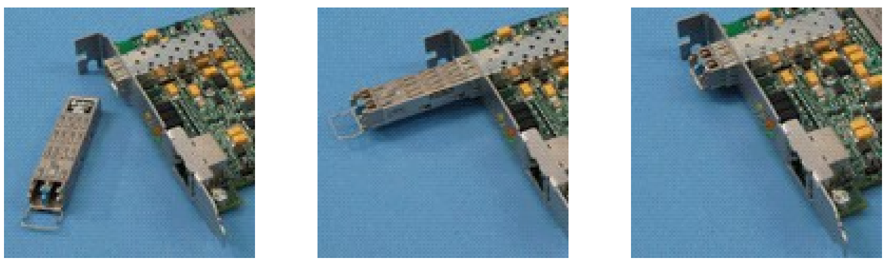
- Simplified transponders with only 2R (Reamplify and Reshape) functions may handle different rates





2.2 Regenerators

- Recently there has been significant developments increasing commercial availability of flexible transponders
  - Programmable retiming enabling design of multirate transponders
  - Rapid and cheap support of different client protocols by just swapping pluggable optics transievers in transponder cards



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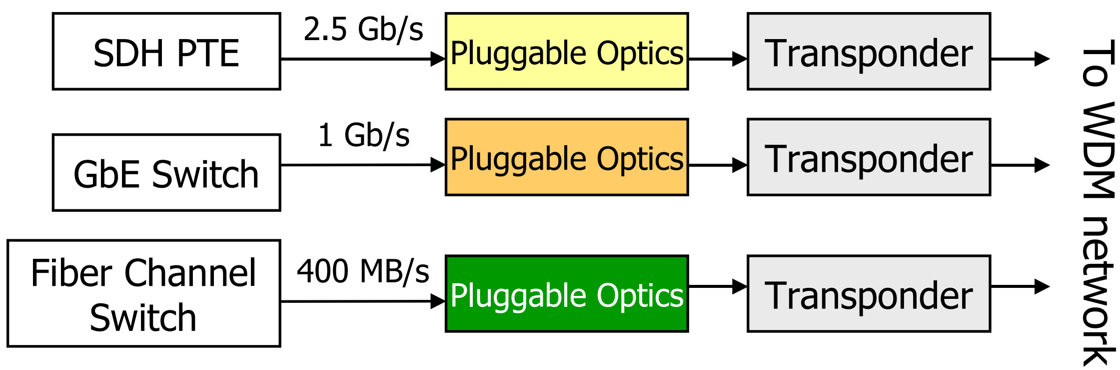


2.2 Regenerators

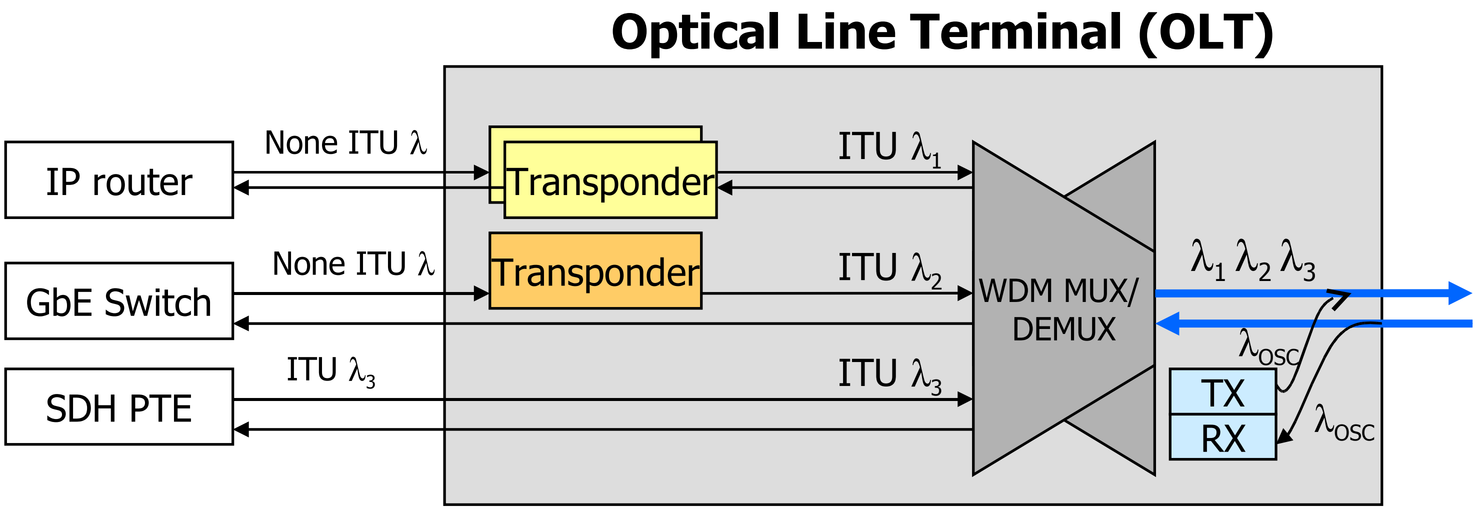
- Example: Cisco 2.5 Gbps Multirate Transponder Card
  - Supports bit rates from 155 Mbit/s to 2.5 Gbit/s
  - Support multiple client interfaces (by swapping SFP transceivers)
    - SAN (ESCON, Fiber Channel, FICON)
    - SDH (STM-1, STM-4 and STM-16)
    - Gigabit Ethernet
    - Video (HDTV, D1/SDI video, DV6000)
  - DWDM grid-compliant output
  - Works in both 2R and 3R modes
  - Can add OTN G.709 FEC to improve range

Figure 1

Cisco ONS 15454 SONET/SDH MSTP 2.5-Gbps Multirate Transponder Cards

2.3 Optical Line Terminals (OLTs)

- OLTs used at source and destination sites to originate and terminate WDM signals respectively
  - May include transceivers for sending or retreiving the optical supervisory channel (OSC) signal
  - Transponders in OLTs adapt client protocol signals for the WDM network (according to ITU-T CWDM or DWDM wavelength grids)

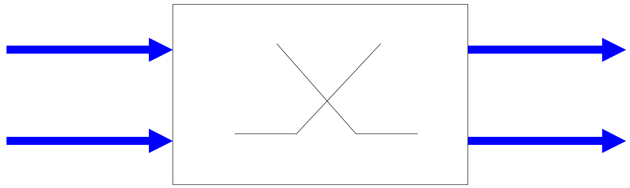


2.3 Optical Line Terminals (OLTs)

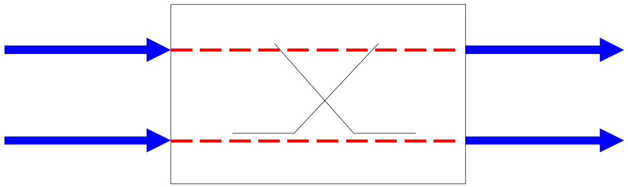
- OLTs enable point-to-point WDM link topologies

2.4 Optical Switches

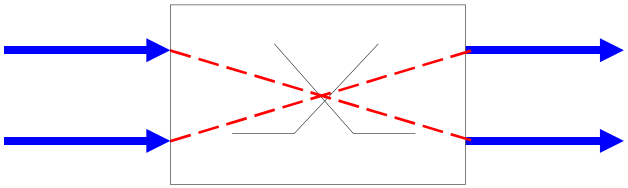
- Enables switching of a signal in optical format
  - Used in network routing nodes
  - Also for protection switching after network failure



2x2 switch



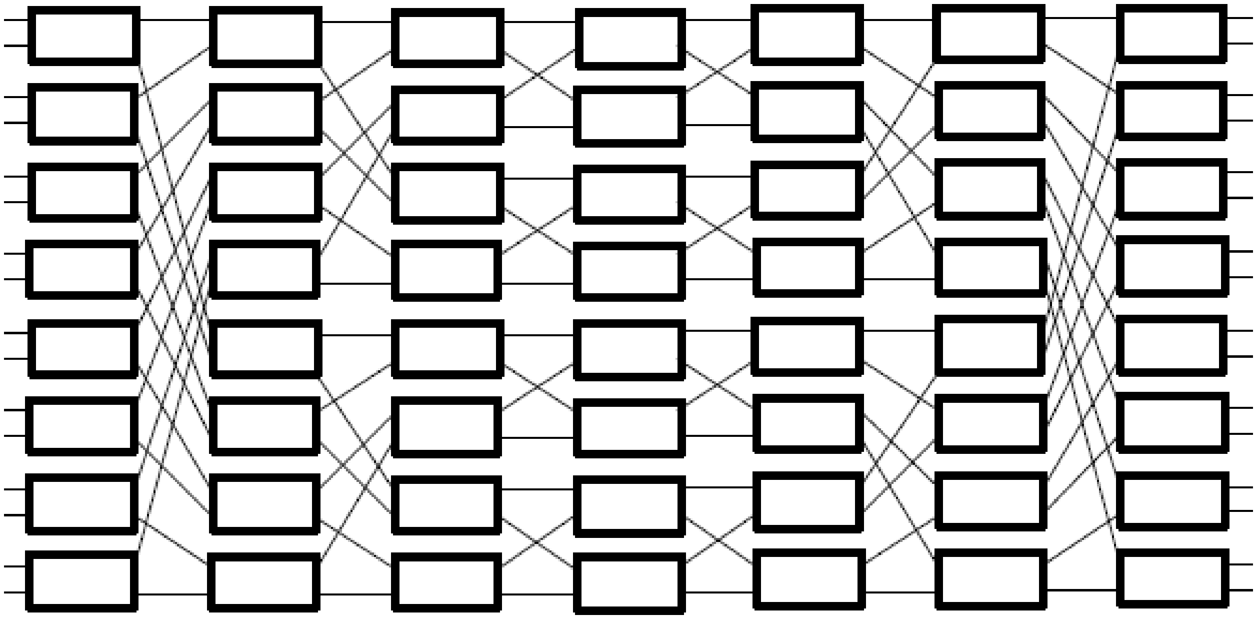
2x2 switch (bar state)



2x2 switch (cross state)

2.4 Optical Switches

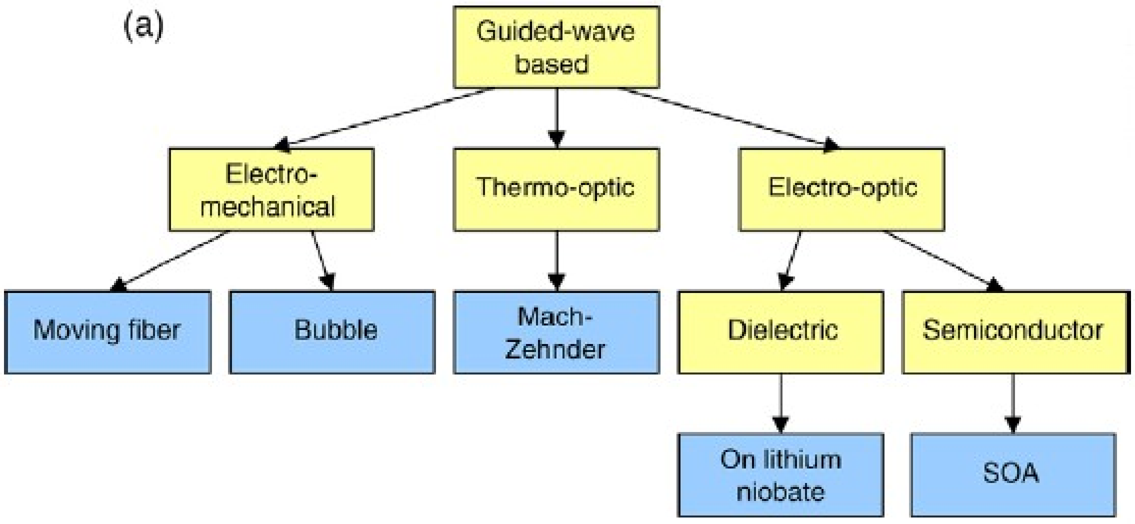
- Switching fabrics with large dimensions may be implemented by a network of smaller switching elements

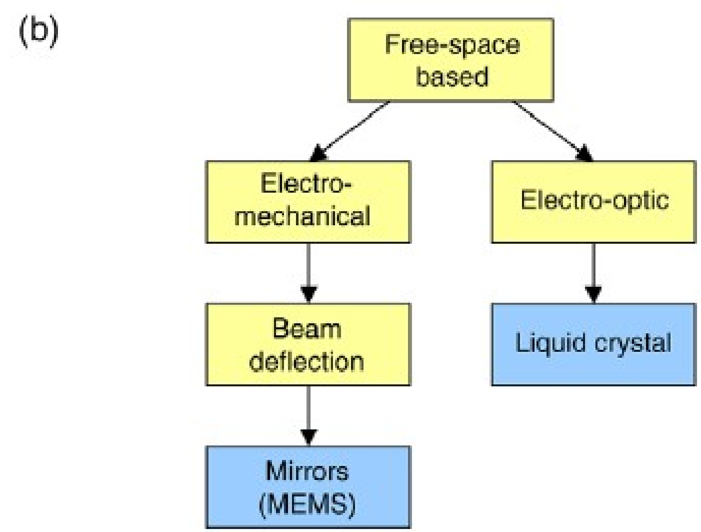


Example: A 16x16 switch implemented by 56 2x2 switching elements in a Beneš network arrangement

2.4 Optical Switches

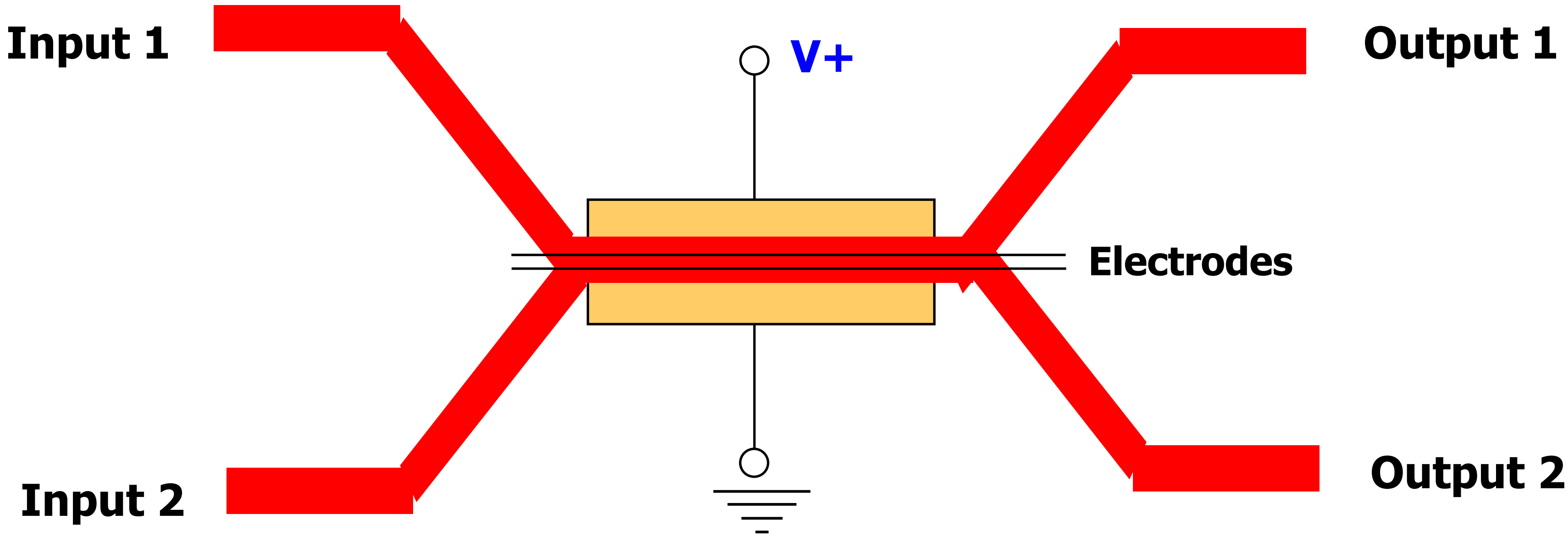
- A diverse range of optical switches has been proposed





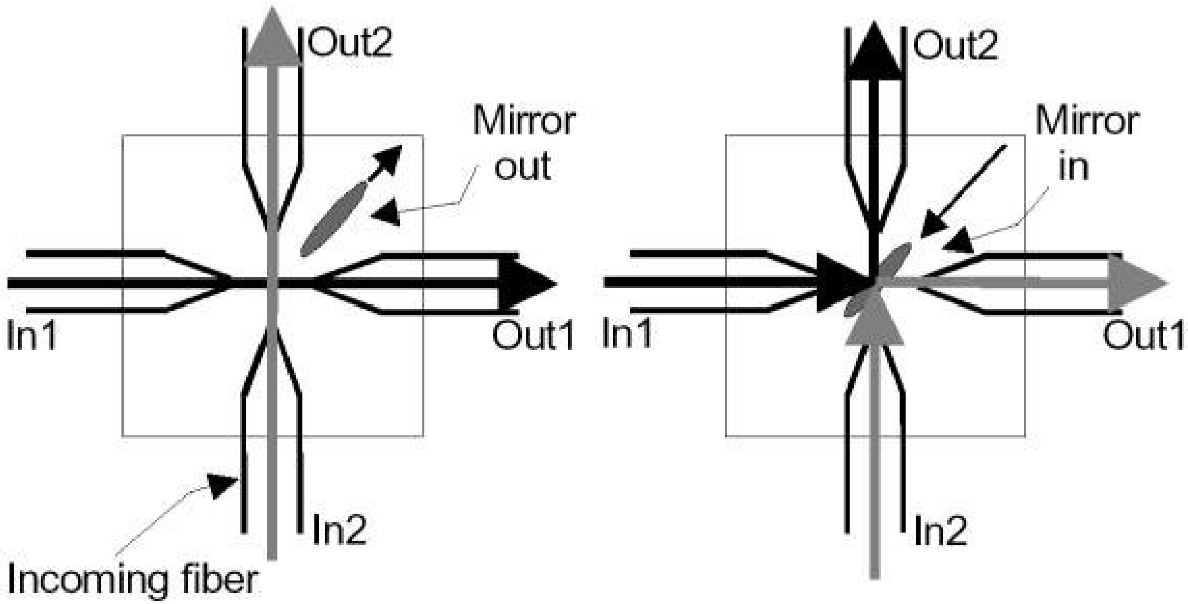
*Source: A. Jajszczyk, Optical Switching and Networking Journal, Vol. 1, No. 1, Jan. 2005

2.4 Optical Switches



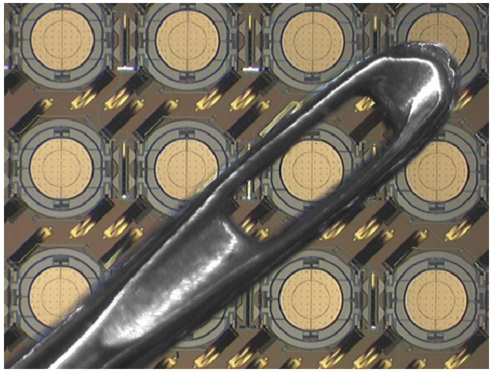
Example: A 2x2 electro-optic directional coupler switch. Switching by varying coupling ratio using an applied electric voltage.

2.4 Optical Switches



A 2x2 Micro Electro Mechanical Systems (MEMS) switch

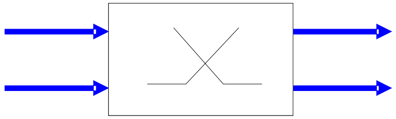
Magnified view of a 2D MEMS mirror array



2.4 Optical Switches

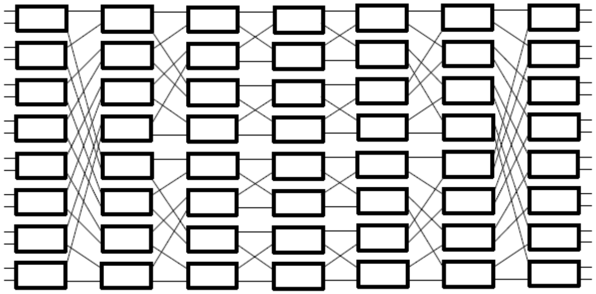
- Parameters of interest when selecting a switch
  - Insertion loss ⇒ optical power budget
  - Crosstalk isolation ⇒ crosstalk power penalties
  - Polarization dependent loss ⇒ optical power budget
  - Power requirements ⇒ powering costs
  - Switching time or speed ⇒ rapid reconfiguration
  - Size or footprint ⇒ shipping and rental costs

Example specs: 1 dB loss,
45 dB crosstalk isolation



2x2 switch

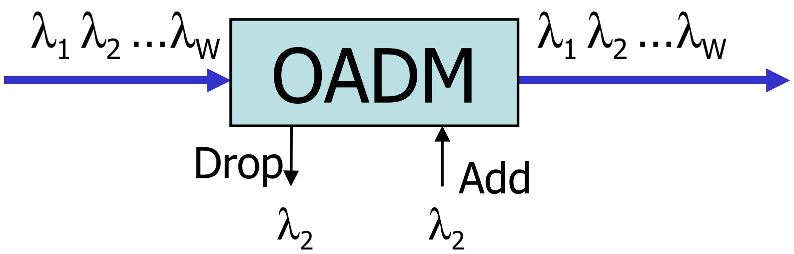
Example specs: >7 dB loss,
20 dB crosstalk isolation

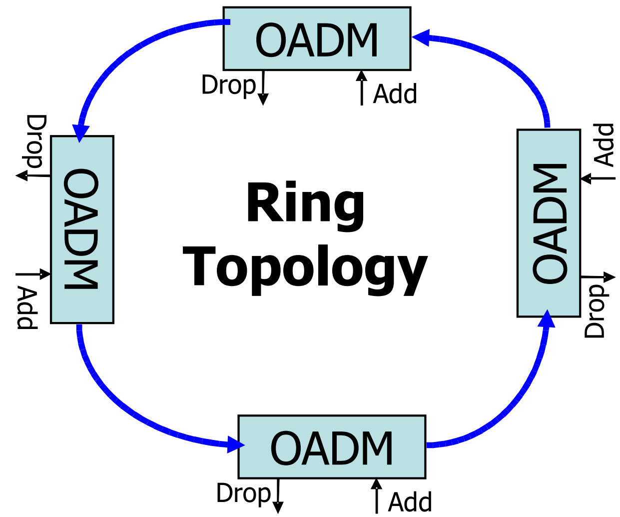


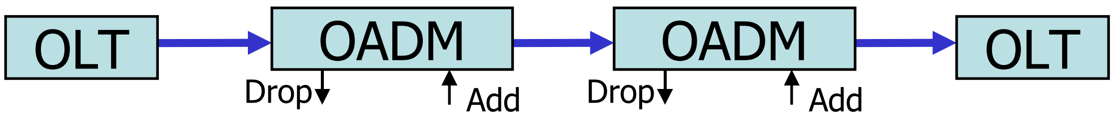
16x16 Beneš switch

2.5 Optical Add/Drop Multiplexers

- Optical add/drop multiplexers (OADM) are used to retrieve or insert wavelength channels at transit sites
  - Enable optical linear add/drop and ring topologies



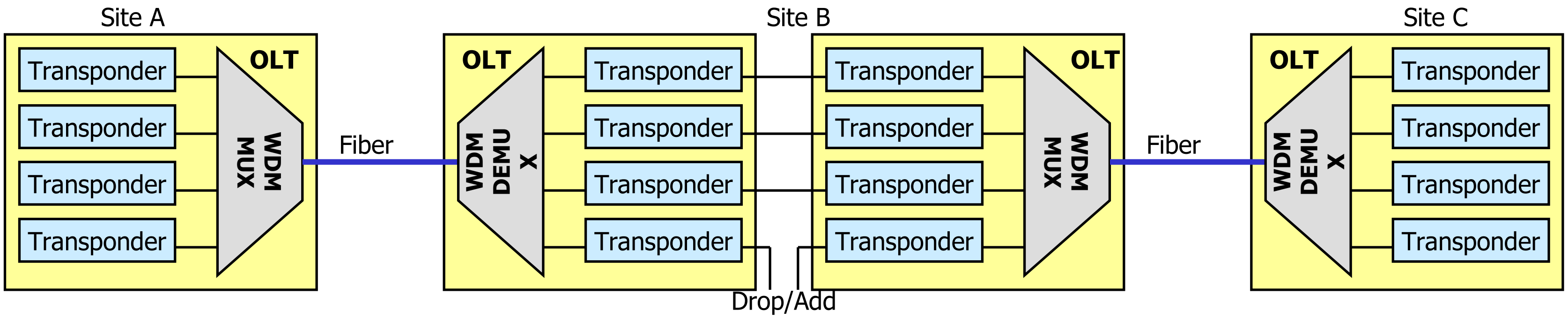




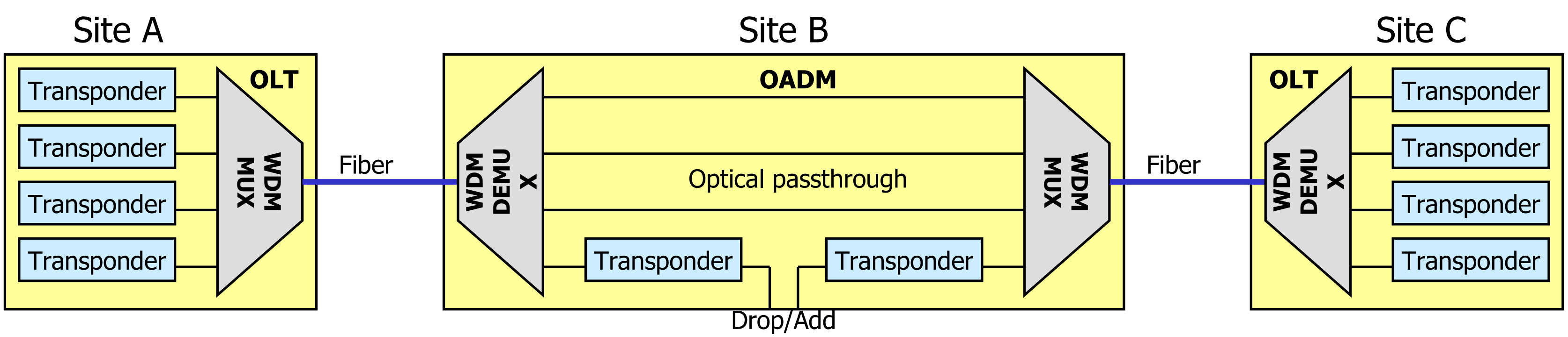
Linear Topology

2.5 Optical Add/Drop Multiplexers

- OADM provide cost-effective means for handling the majority pass-through or express traffic
  - Significant reduction in number of require transponders



(a) Three node point-to-point WDM systems (before OADMs became available)



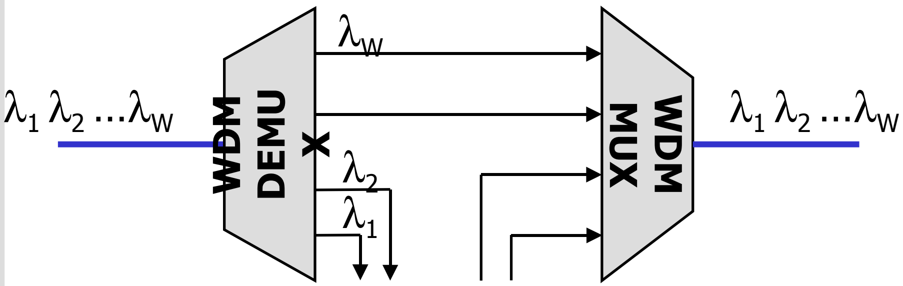
(b) Three node linear network using OADM at Site B

2.5 Optical Add/Drop Multiplexers

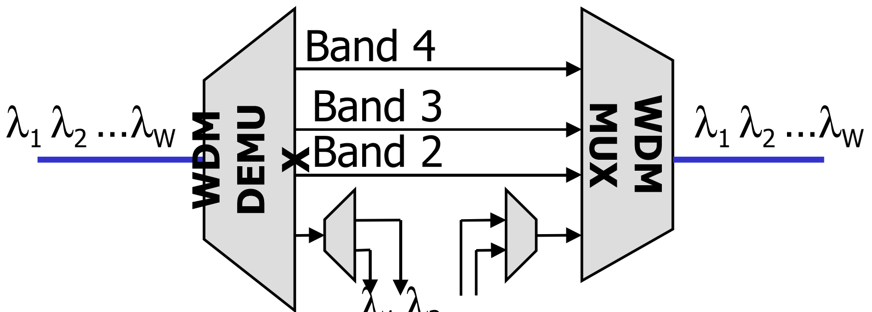
- Attributes considered in selection of a particular OADM
  - OADM size ⇒ Total wavelength number supported
  - Hitless (without taking down other channels) add/drop operation
  - Modular architecture
    - Enable "pay as you grow" OADM scaling with increasing traffic (wavelength channels)
  - Optical physical layer impairments (losses, imperfect filtering etc.)
    - Is it dependent on number of add/dropped channels?
    - How many OADMs cascadable before 3R transponders are needed?
  - Reconfigurability
    - Add/drop configuration changed by remote software control
    - Flexible networking planning and provisioning of connections
  - Cost
    - Power consumption, footprint, cost per wavelength

2.5 Optical Add/Drop Multiplexers

- Fixed OADM architectures
  - Permanently adds or drops particular wavelength channels
  - Operator needs to plan ahead (e.g. have spare add/drop ports) and deploy appropriate equipment
- Types of fixed OADM architectures
  - Parallel or serial
  - Individual channel or wavelength band add/drop



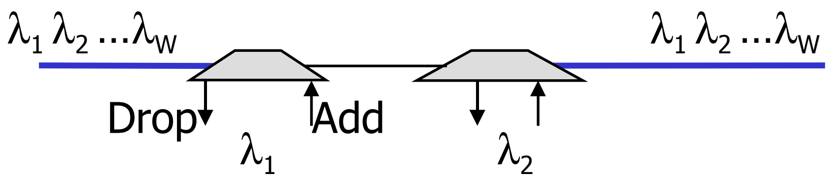
(a) Parallel



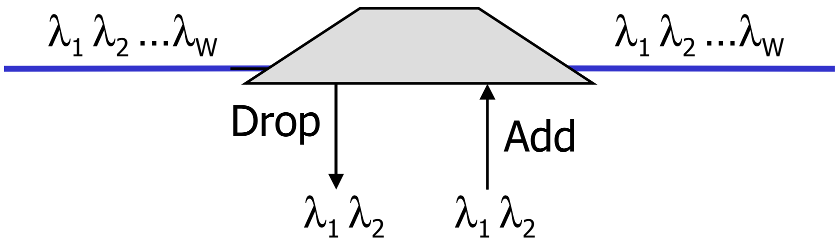
(b) Parallel Band Add/Drop

2.5 Optical Add/Drop Multiplexers

- Serial fixed OADMs



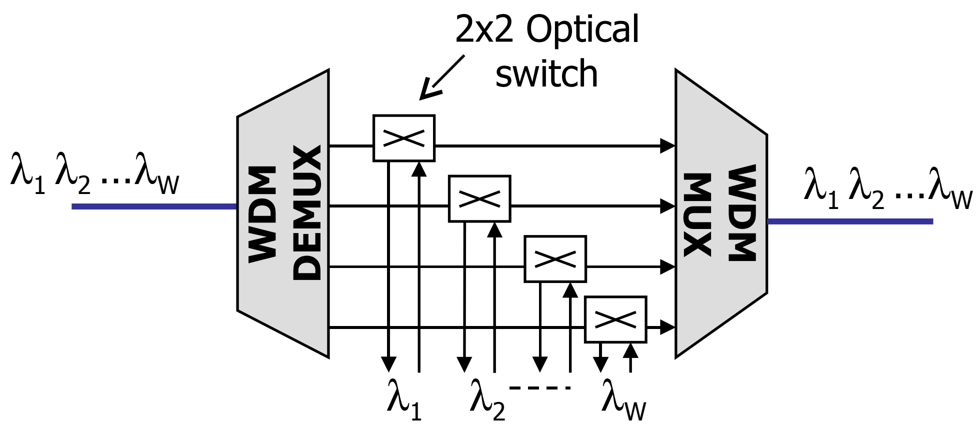
(c) Serial using single channel OADMs in series



(d) Serial Band Add/drop

2.5 Optical Add/Drop Multiplexers

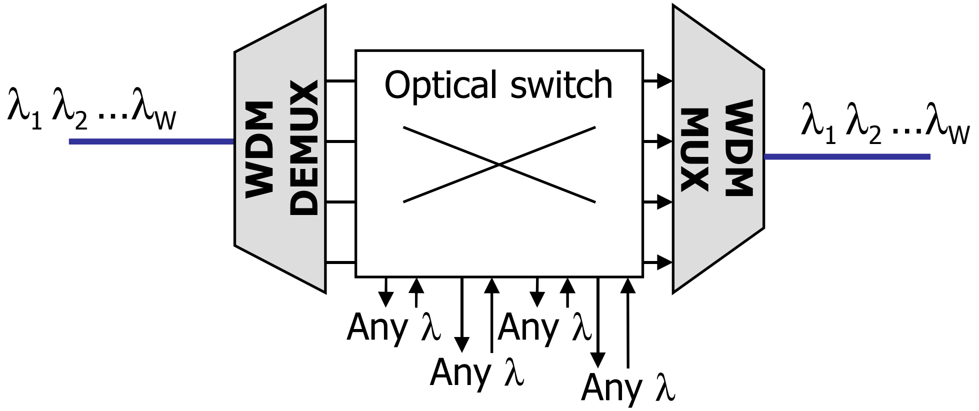
- Reconfigurable OADM (ROADM) architectures
  - Desired wavelengths to added or dropped selected on the fly (dynamically)
  - Increased flexibility for operator in setting-up/breaking connections



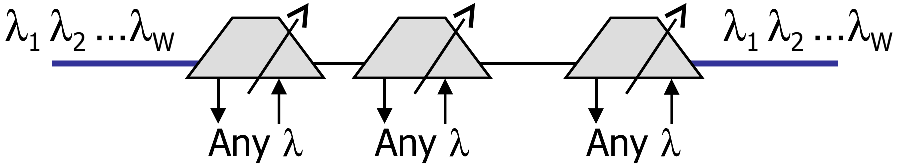
(a) Partial tunable OADM using parallel architecture with 2x2 optical switches

2.5 Optical Add/Drop Multiplexers

- Reconfigurable OADM (ROADM) architectures



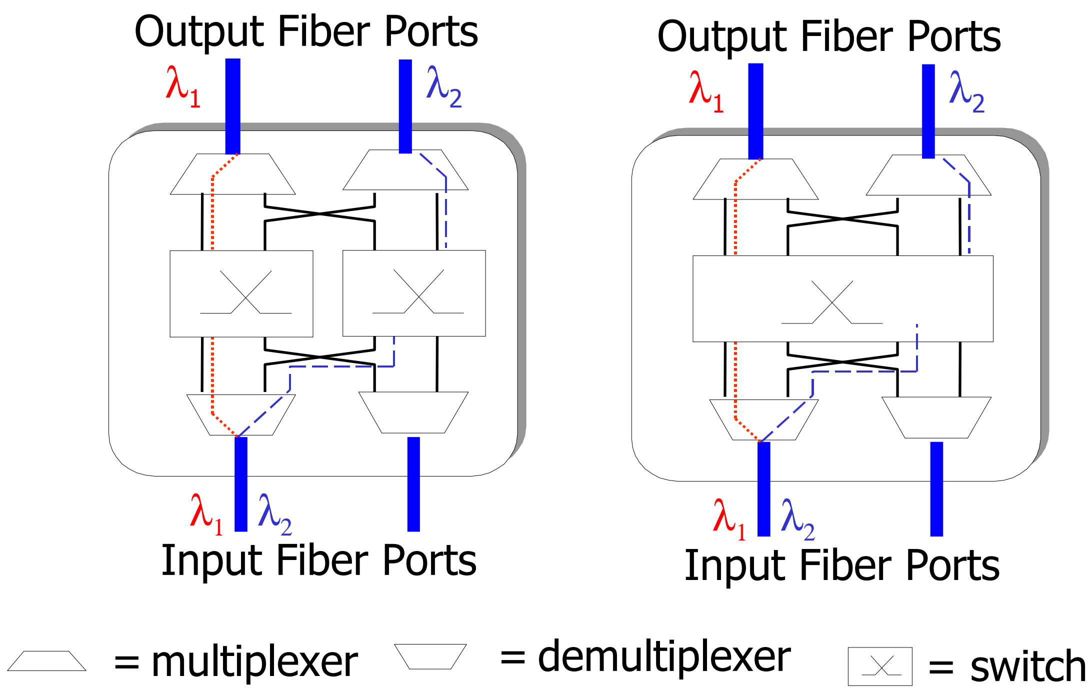
(b) Fully tunable OADM using a large multiport optical switch



(c) Fully tunable serial OADM using tunable single channel OADMs in series

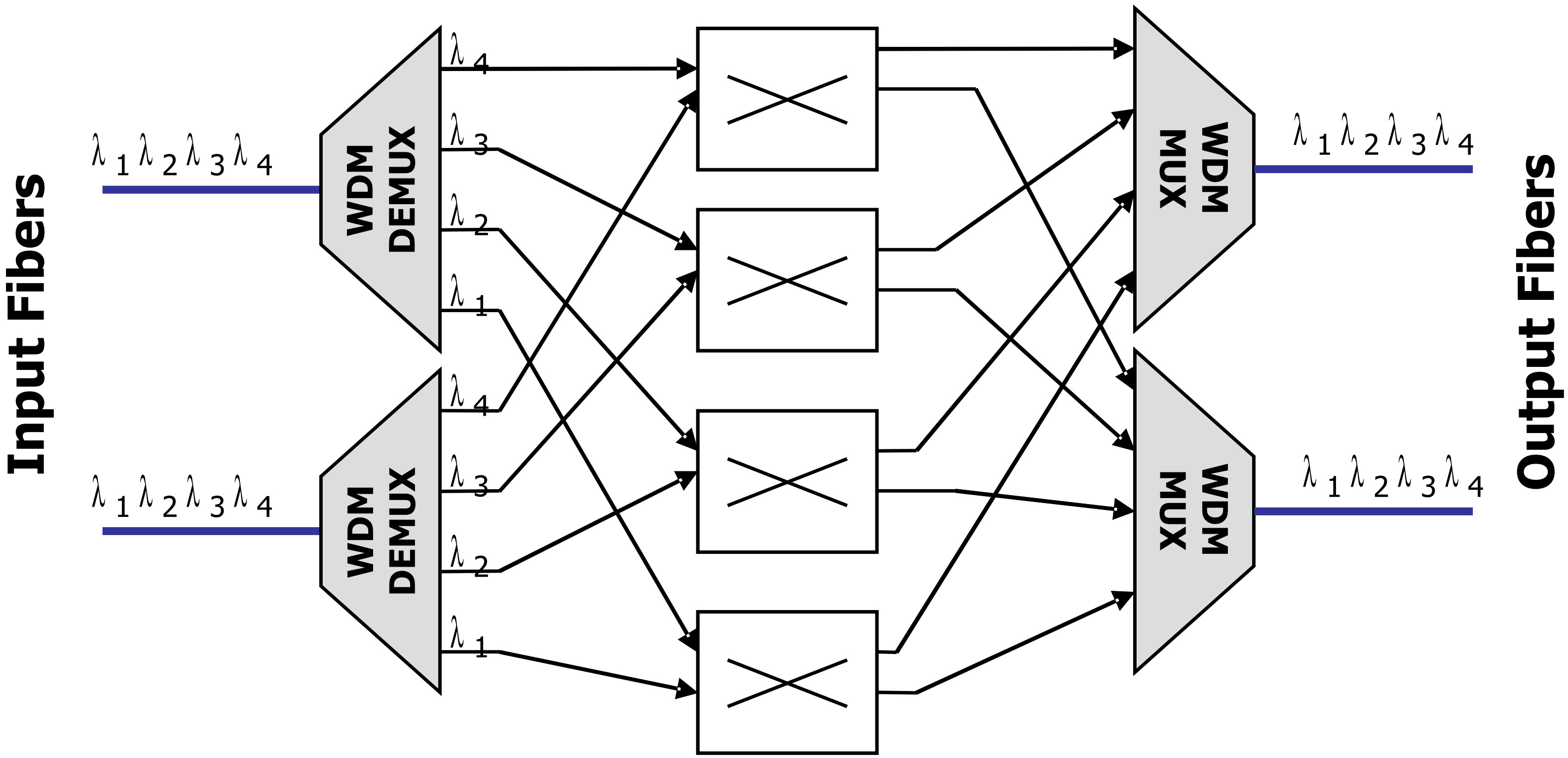
2.6 Optical Cross-Connects

- Optical cross-connects (OXC)
  - Direct a wavelength channel at an input fiber port to one of the two or more output fiber ports
  - Add or drop wavelength channels locally



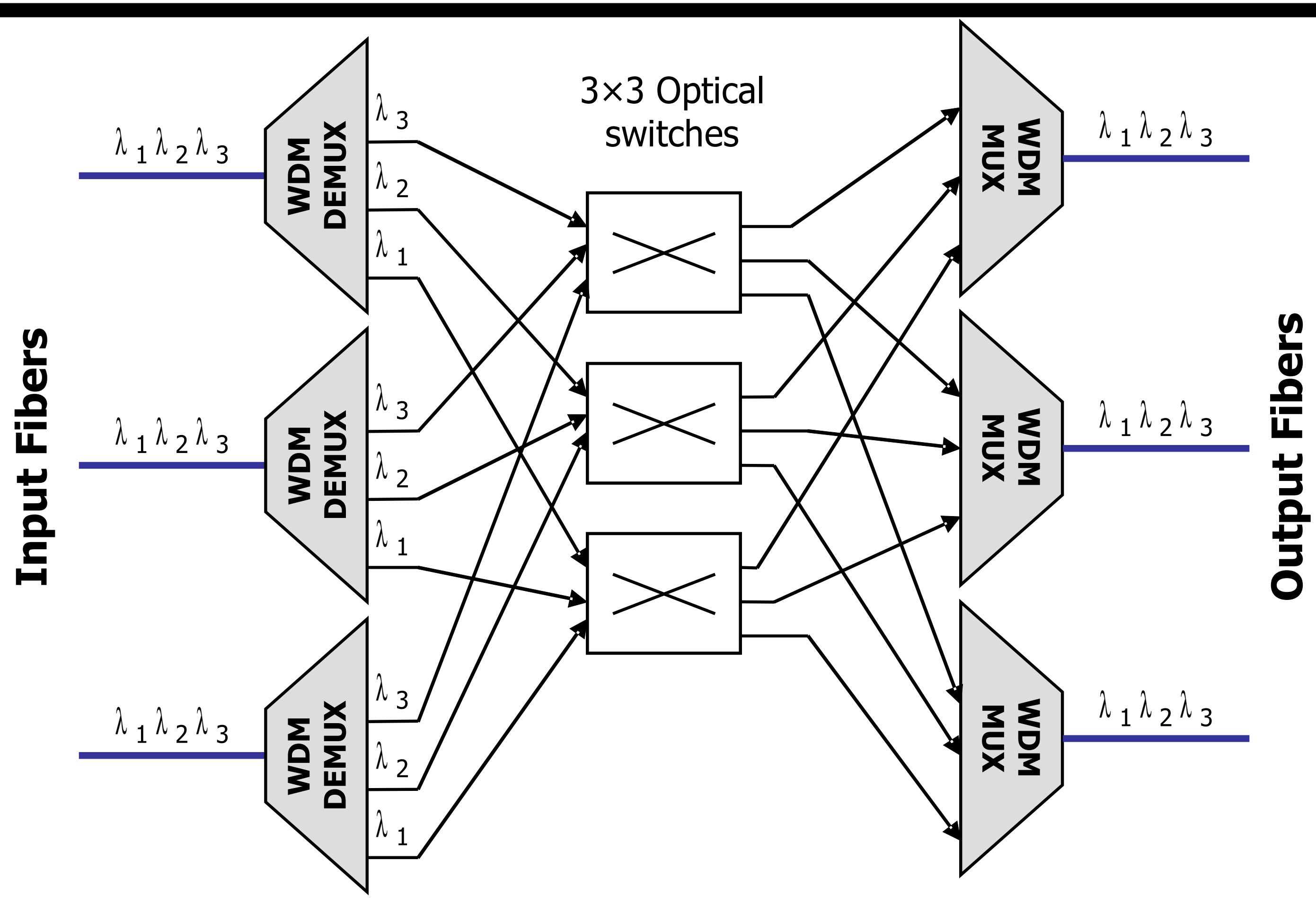
An example OXC with 2 input and 2 output fibers implemented using two 2x2 switches (left) or one 4x4 switch. Each fiber carries 2 wavelength channels

2.6 Optical Cross-Connects



The example OXC scaled to handle 4 wavelength channels on each fiber port

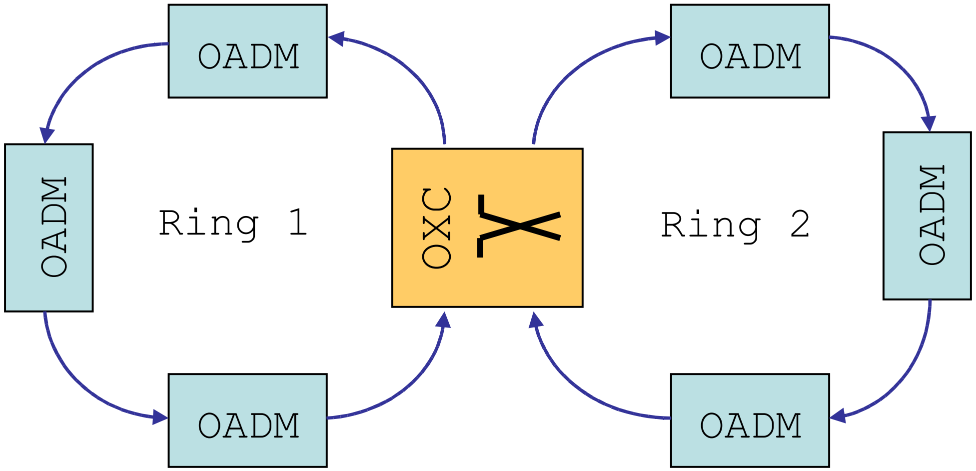
2.6 Optical Cross-Connects

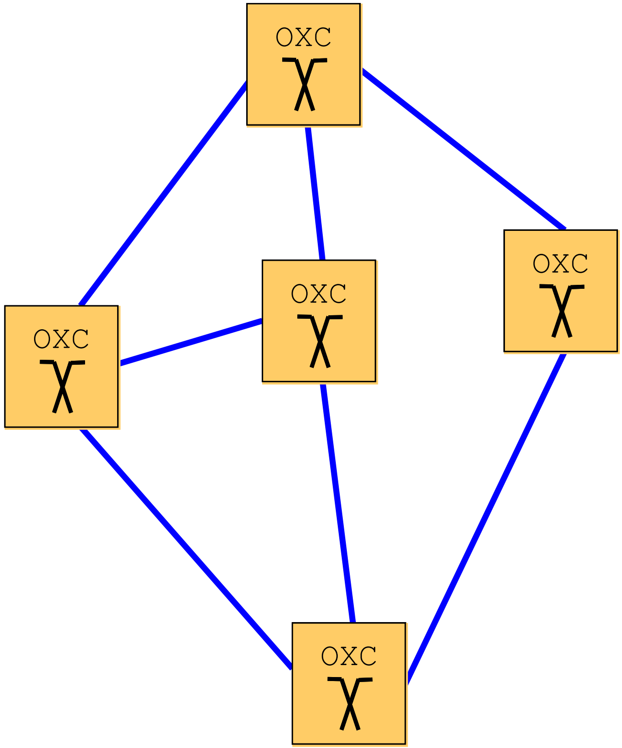


The example OXC now scaled to handle 3 wavelength channels on each fiber port and an extra input/output fiber port

2.6 Optical Cross-Connects

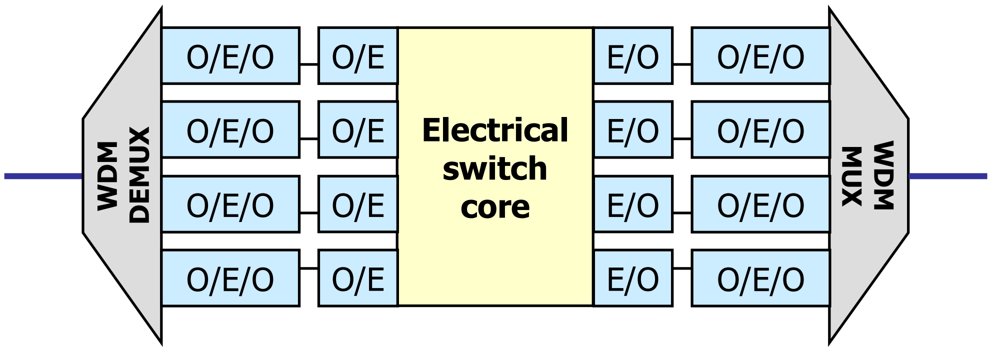
- OXCs enable mesh topologies and optical ring interconnection





2.6 Optical Cross-Connects

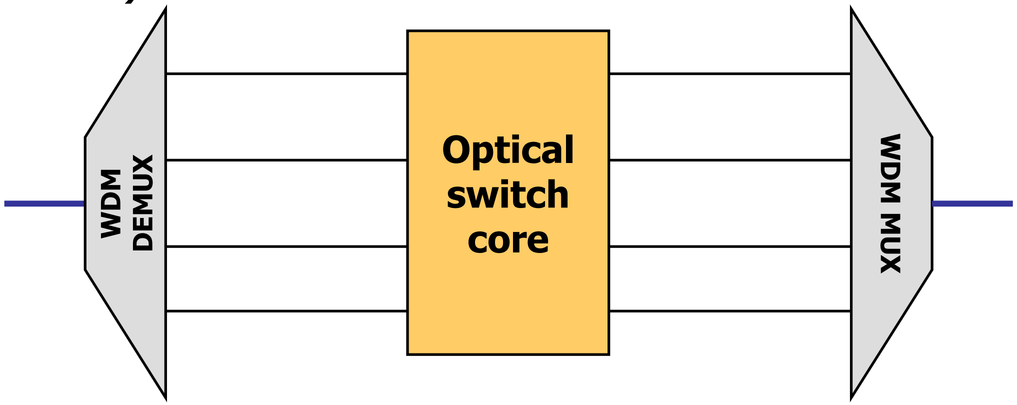
- Could use all-optical or electrical switch fabrics
- Electrical switching and transponders (OEOs)
  - Mature technology
  - Possible monitoring (e.g. BLER, Q-factor) and 3R regeneration
  - Limited switching capacity ⇒ becomes too complex and costly for switching 10s of Gbit/s
  - Dependent on bit rate and client signal
  - Large footprint and power consumption



(a) Opaque electrical switching core

2.6 Optical Cross-Connects

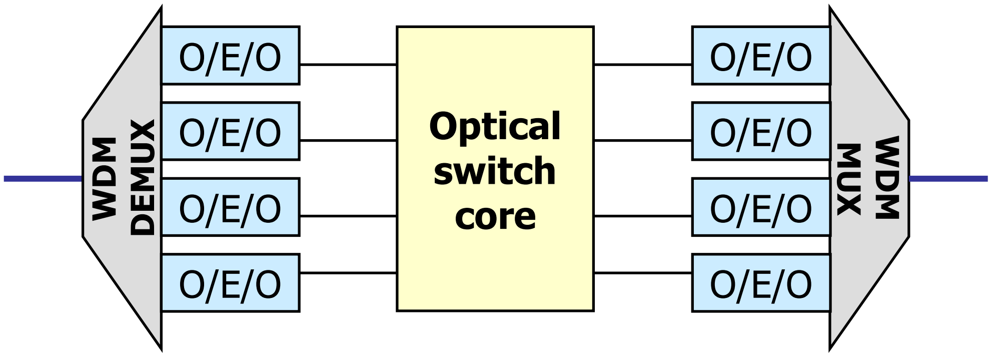
- All-optical switching
  - Bit rate and client independent ⇒ switches optical channels
  - More scalable in capacity e.g. switching 2.5 Gb/s to 40 Gb/s for same cost/port
  - Smaller footprint and power consumption
  - New technology, no digital monitoring, only 1R regeneration (optical amplification)



(b) All-optical optical switch connected directly to WDM MUX/DEMUX

2.6 Optical Cross-Connects

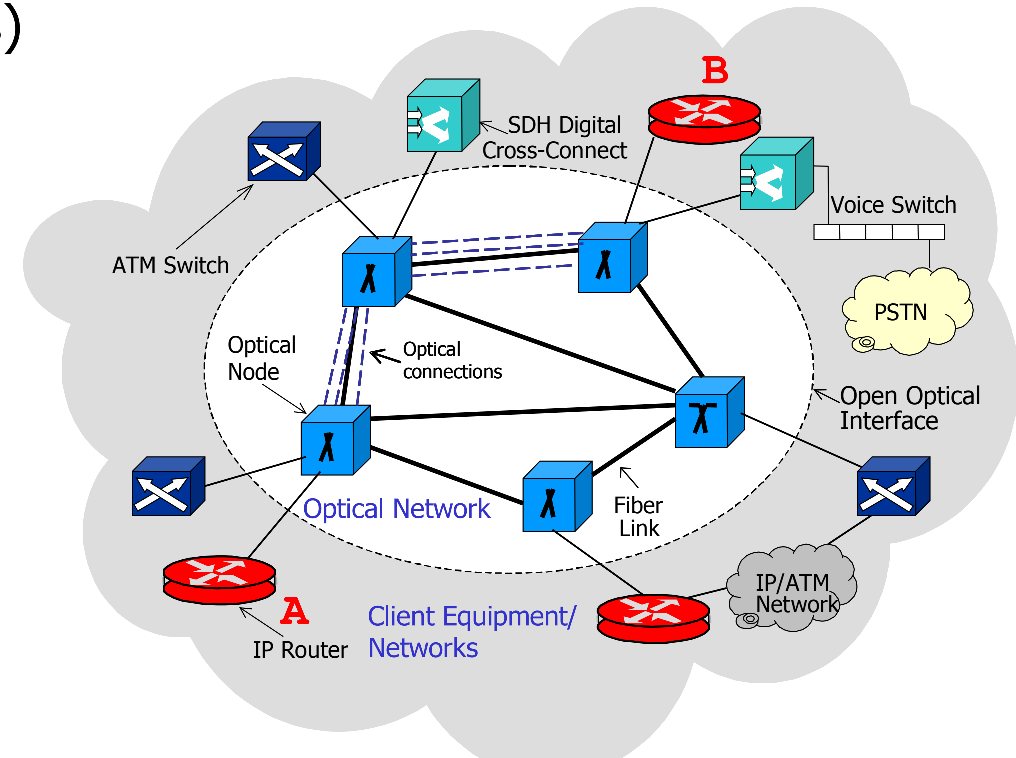
- Optical switching with OEOs
  - Combine advantages of optical switching with the digital monitoring and regeneration capabilities of transponders
  - Retain problems of reduced transparency, large footprint and power consumptions



(c) Opaque optical switching core connected directly to transponders

3. WDM Network Design

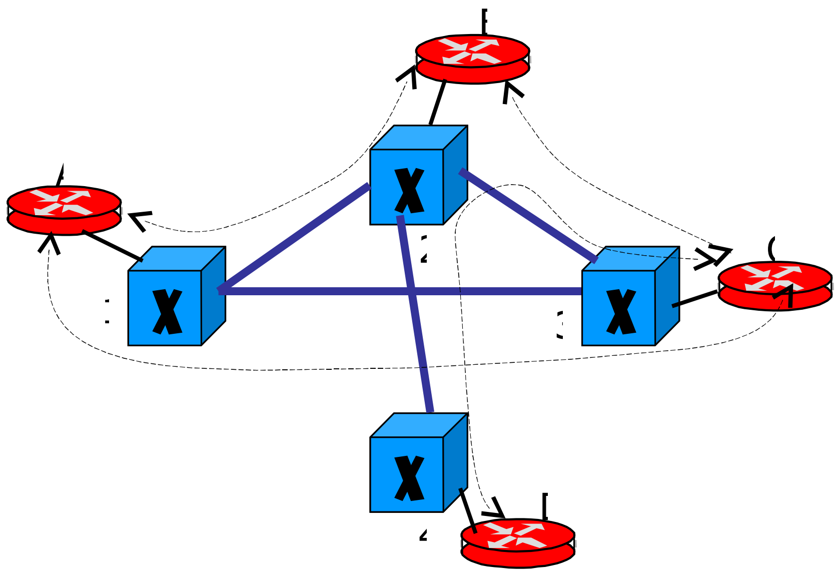
- Optical layer (WDM network) design
  - Realizing connections over physical fibers using WDM network elements (OADMs, OXCs, OLTs etc.)
  - Lightpath ⇒ an optical connection assigned a distinct wavelength over a span of fiber(s)



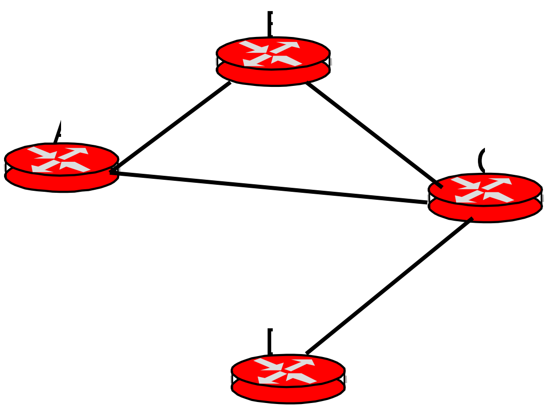
3. WDM Network Design

- **Physical topology**
  - Optical nodes and fiber topology supporting the creation of lightpaths
- **Lightpath (logical or virtual) topology**
  - Topology seen by the client layer equipment (e.g. IP routers)

Physical Topology



Lightpath Topology



3. WDM Network Design

- In practice WDM network design split into separate (manageable) design problems
  - Less complex to solve
- A WDM network may be realized by solving:
  - Physical topology design (PTD) problem
  - Lightpath topology design (LTD) problem
  - Routing and wavelength assignment (RWA) problem
- PTD problem solved initially during network construction and later when physically expanding the network
- The LTD and RWA are solved more frequently to enable optimum provisioning of optical capacity

3.1 Physical Topology Design (PTD)

*Source:, Journal of lightwave Technology, Vol. 16, No. 11, Nov. 1998

Solve PTD Problem

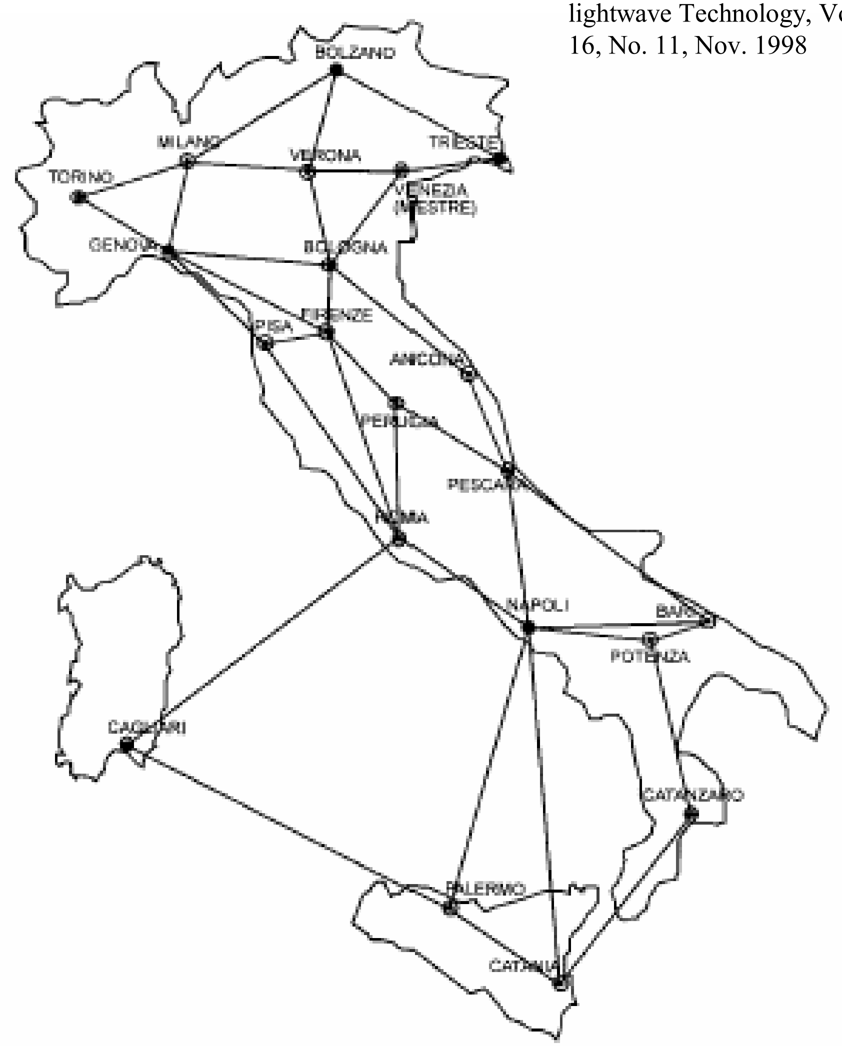
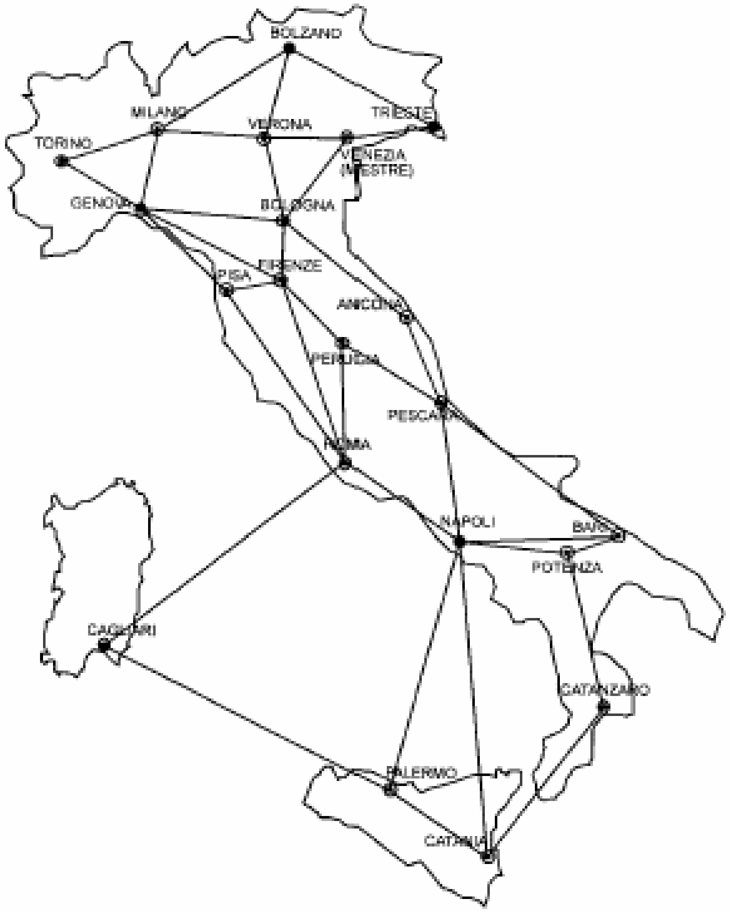


Figure: Example solving of PTD problem to obtain Italian backbone

3.1 Physical Topology Design (PTD)

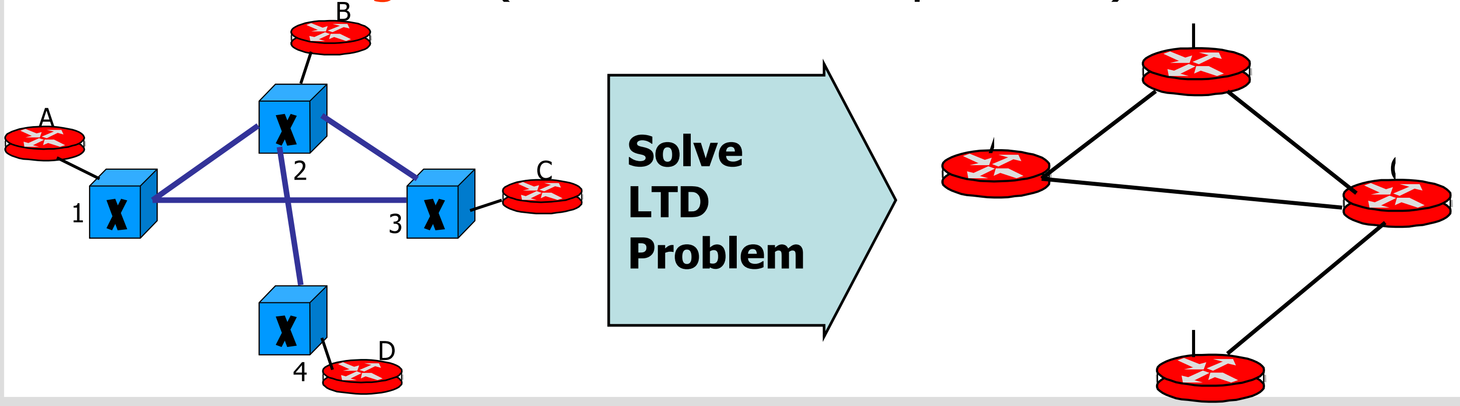
- PTD problem constituents
  - Optimal node placement algorithms
  - Optimal fiber placement algorithms
- Node placement algorithms constraints
  - Cost of nodes and connecting the nodes
  - Proximity to significant customer base
- Fiber placement algorithms constraints
  - Cost of deploying or leasing fibers
  - Length of link (fiber impairments increase, EDFAs/OEOs required etc.)
  - Network availability or reliability (connectivity)

*Source:, Journal of lightwave Technology, Vol. 16, No. 11, Nov. 1998



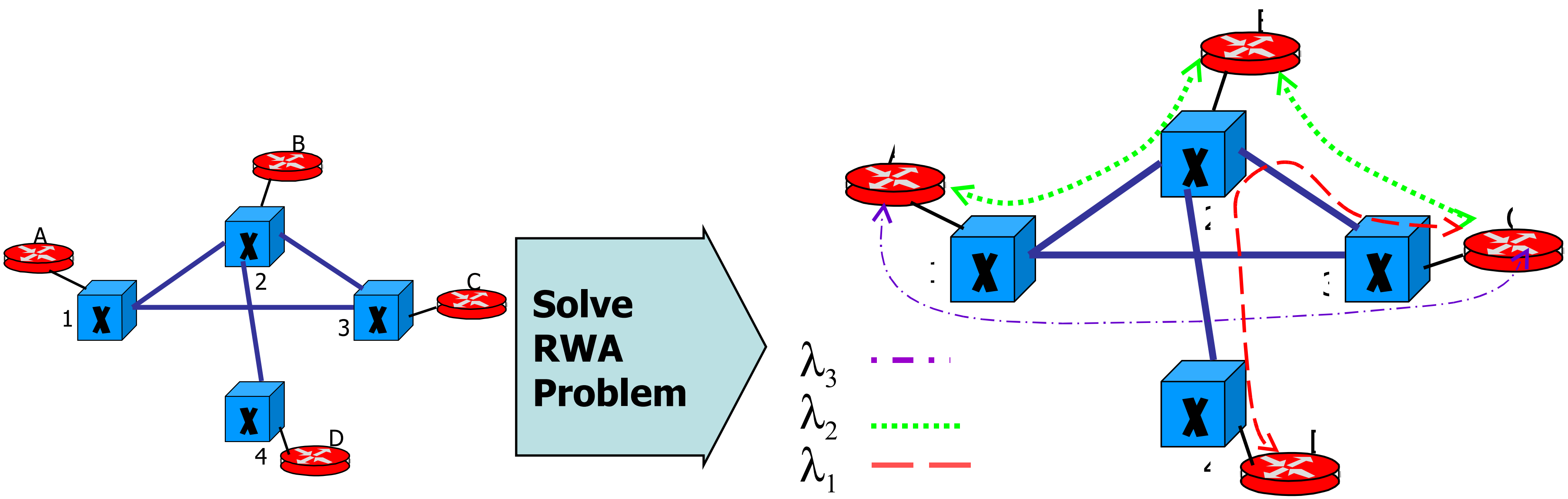
3.2 Lightpath Topology Design (LTD)

- LTD problem
  - Interconnecting client layer equipment to realize a lightpath topology that meets client layer traffic requirements
  - Routing client layer packets or TDM circuits over the lightpath topology
- LTD constraints
  - Flow conservation (net flow of traffic in/out of nodes)
  - Link capacity
  - Node degree (number of in/output links)



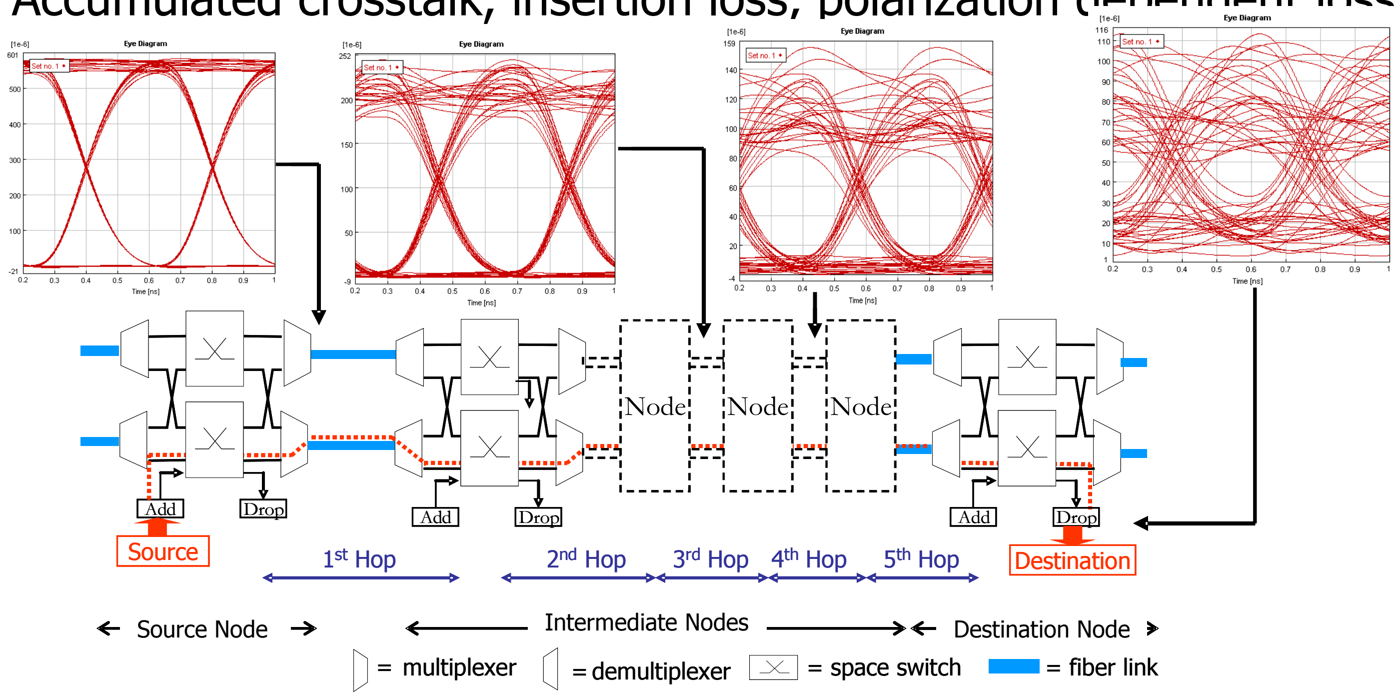
3.3 Routing & Wavelength Assignment (RWA)

- RWA problem ⇨ Given a physical network topology and a set of end-to-end lightpath requests determine route and wavelengths
  - Routing sub-problem ⇒ how to route a lightpath through various intermediate nodes within a network
  - Wavelength assignment sub-problem ⇒ how to assign wavelength channels to different lightpaths
    - Possible lightpath request blocking (denial) if no free channels available



3.3 Routing & Wavelength Assignment (RWA)

- Constraints in routing sub-problem
  - Route (fiber) length
    - Accumulated fiber impairments (EDFAs, OEOs, FEC etc. required)
  - Hop number (nodes passed)
    - Accumulated crosstalk, insertion loss, polarization dependent loss etc.



3.3 Routing & Wavelength Assignment (RWA)

- Constraints on wavelength sub-problem
  - Number of wavelengths
    - Only 18 channels available on CWDM wavelength grid
    - <200 channels available on DWDM wavelength grid
  - Wavelength continuity
    - Same wavelength channel must be used between end-points
  - Distinct wavelength assignment
    - Wavelength only used by one lightpath on any link

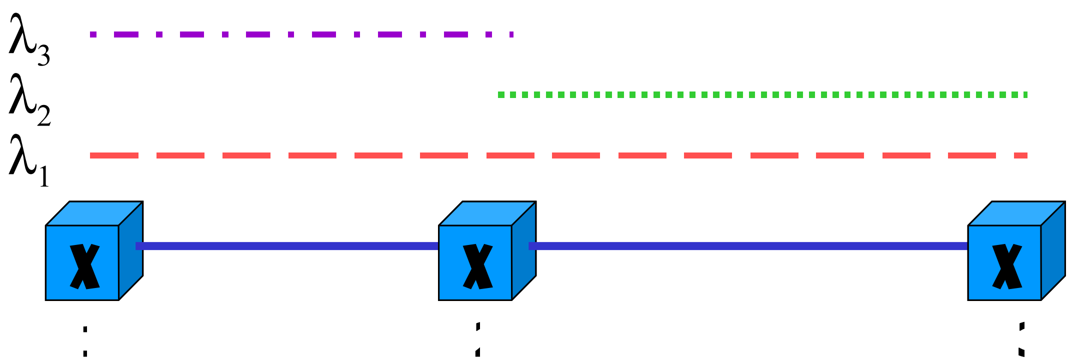


Figure: Example wavelength assignment for a 3 node linear network

3.3 Routing & Wavelength Assignment (RWA)

- RWA problem may be classified as static or dynamic
- Static RWA problem
  - Entire set of connections (demand traffic matrix) known in advance
  - Routing and wavelength assignment performed offline
  - Possible over estimates in requirements ⇒ idle capacity

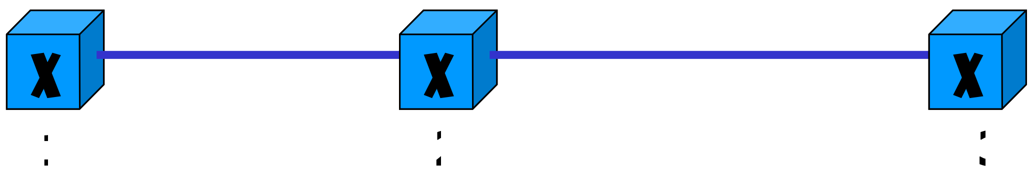


Table: Example fixed demand traffic matrix showing the number of required lightpaths between nodes 1, 2 and 3

	Node 1	Node 1	Node 3
Node 1	-	3	5
Node 2	3	-	1
Node 3	5	1	-

3.3 Routing & Wavelength Assignment (RWA)

Dynamic RWA problem

- Routing and wavelength assignment performed online
- Time varying demand matrix
- Lightpath established for each connection as it arrives and is released after some finite time ⇒ efficient capacity utilization
- Connection request blocking is possible

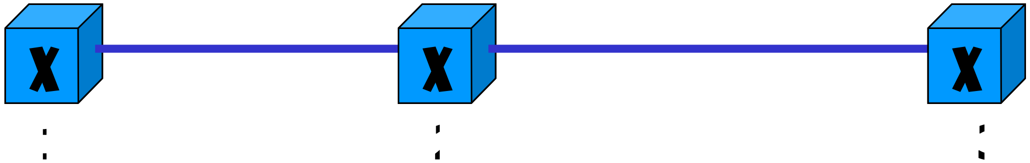


Table: Example varying demand traffic matrix showing the number of required lightpaths between nodes 1, 2 and 3

	Node 1	Node 1	Node 3
Node 1	-	Between 1-3	Between 2-7
Node 2	Between 1-3	-	Between 1-2
Node 3	Between 2-7	Between 1-2	-

3.3 Routing & Wavelength Assignment (RWA)

- Performance comparison of dynamic RWA algorithms
  - Plotting blocking probability versus offered traffic (incoming lightpath requests measured in Erlang)

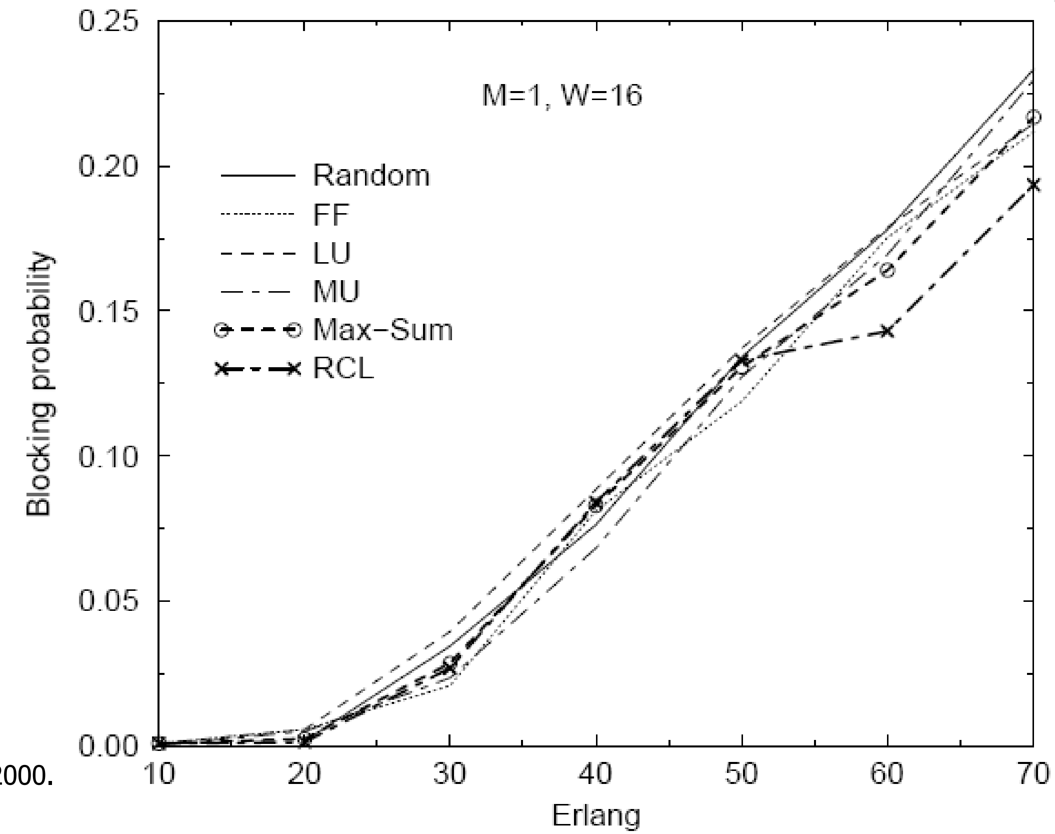


Figure: Example comparison of various wavelength assignment schemes for a single fiber network with 16 wavelengths

Source: H. Zang et al, Optical Networks Magazine, January 2000.

3.3 Routing & Wavelength Assignment (RWA)

- Wavelength converters (WCs)
  - Devices that change the wavelength of input signal to a different wavelength on the ITU grid
  - Implemented using transponders (OEOs) or preferably all-optical WC technologies
  - Has significant impact on RWA problem

3.3 Routing & Wavelength Assignment (RWA)

- WCs eliminate wavelength continuity constraints of the wavelength assignment sub-problem of RWA
  - Increases wavelength channel reuse ⇨ reduce number of required wavelengths
  - Reduces probability of connection blocking

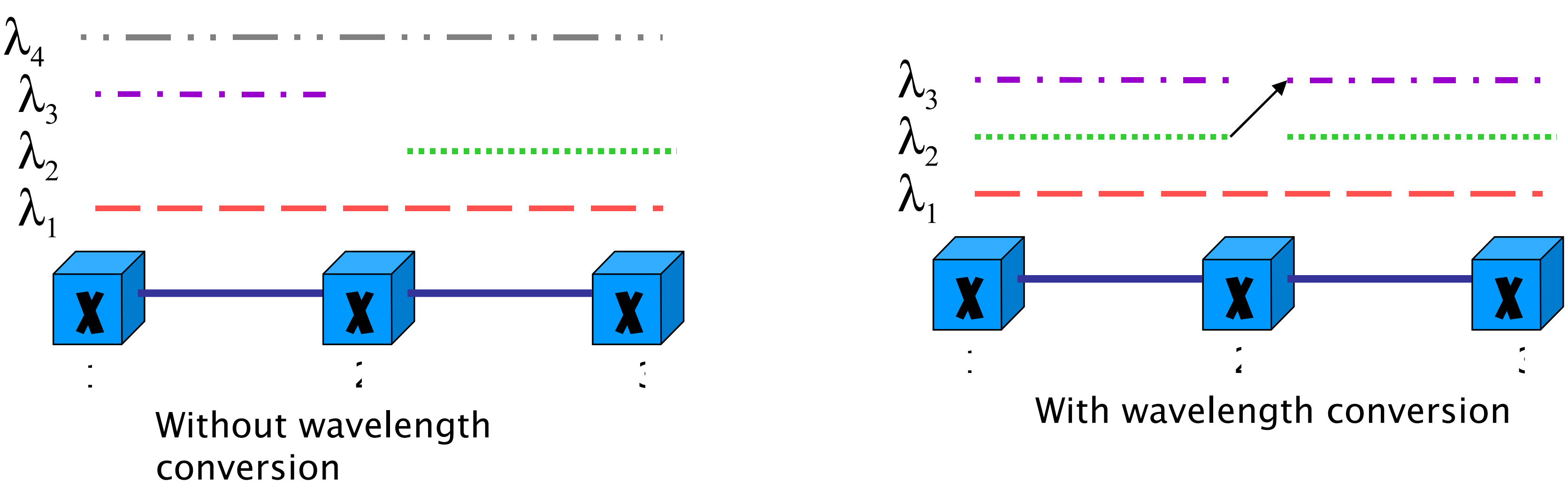


Figure: Example wavelength assignment for a 3 node linear point-to-point network, where 2 wavelength channels needed between node 1 and node 3.

3.3 Routing & Wavelength Assignment (RWA)

- Deployment of full WCs in all network nodes is costly and/or infeasible
- Strategic placements of WCs in parts of network with heavy loads
  - Sparse WC placement problem
  - There has been many proposals for WC placement algorithms

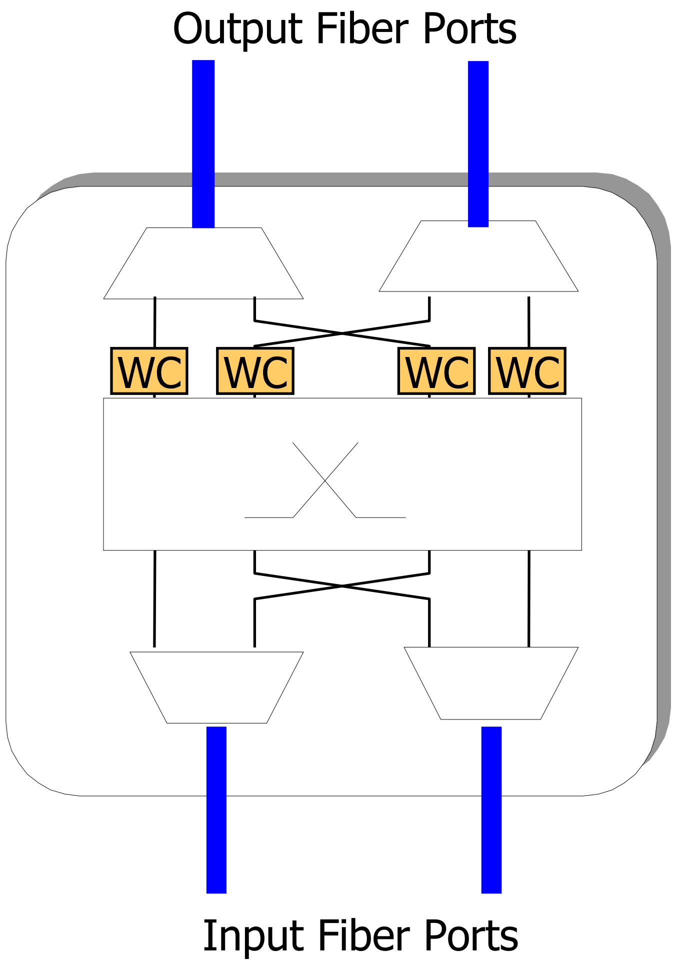


Figure: 2x2 OXC fully equipped with WCs.

3.3 Routing & Wavelength Assignment (RWA)

- Alternatively deploy cheap but limited or fixed WCs

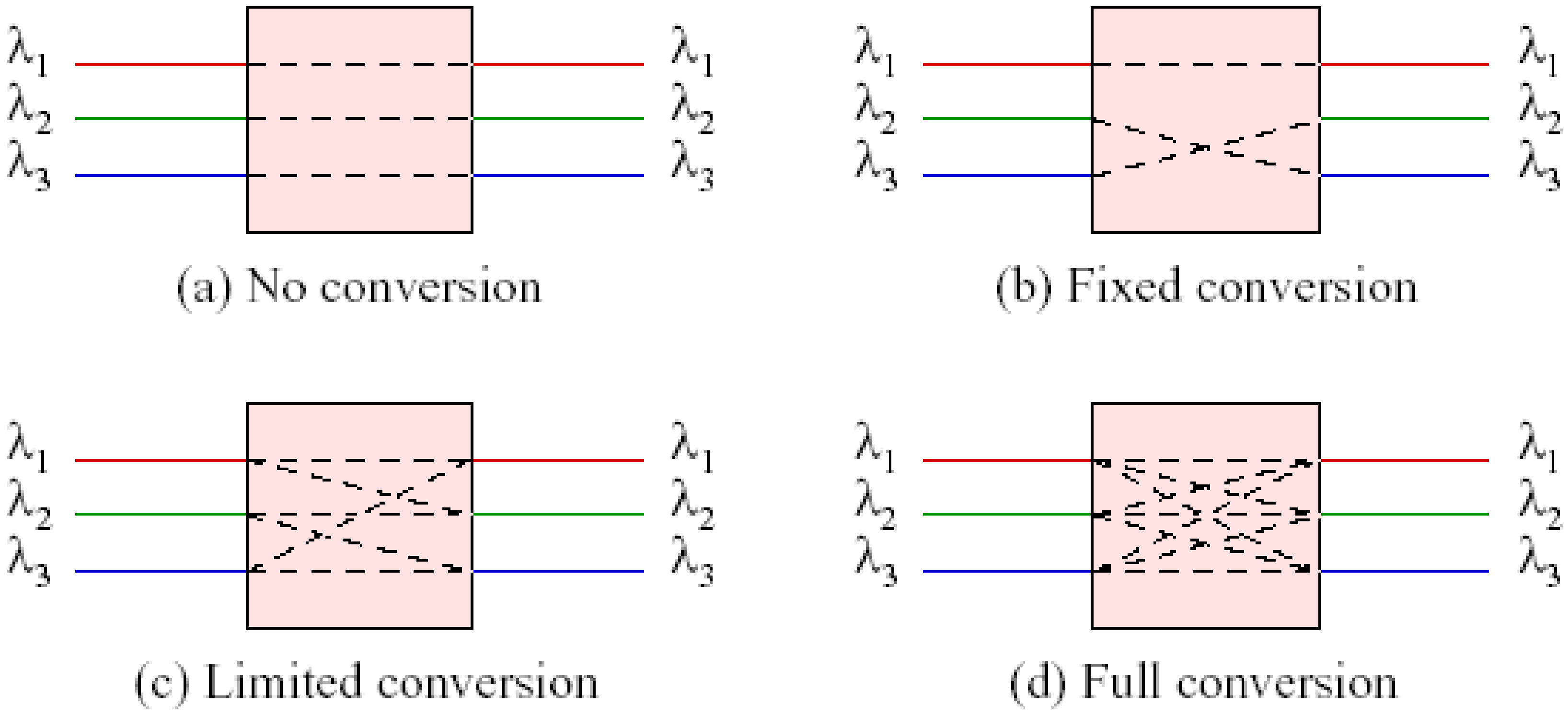


Figure: Wavelength conversion classified according to flexibility of output wavelength

Conclusions

- Optical Networks
  - Network elements
  - Network design
- All-optical networks yet to make a significant commercial case
  - Opaque segments will continue to exist for a while
  - Long term network evolution will necessitate all-optical networking
  - OADMs/ROADMs have had more commercial success than OXCs
- Next lecture
  - System, test, measurement, simulation

Thank You!

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