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Optical Networks – Basic Concepts (Part 1)

thinking forward

Introduction

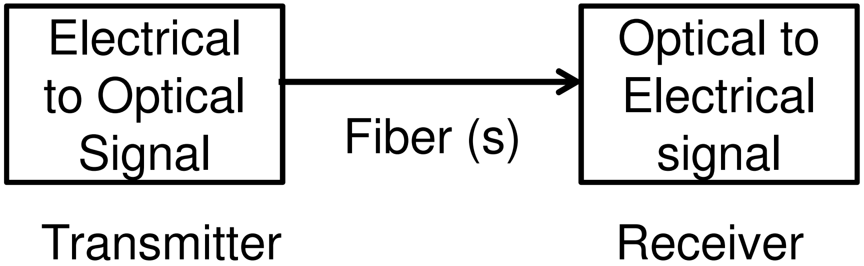
- What is an optical network?
- Optical devices and components
- Basic concepts in optical networking
- Optimization of optical network design
- How to handle faults in optical networks?
- Some recent research topics

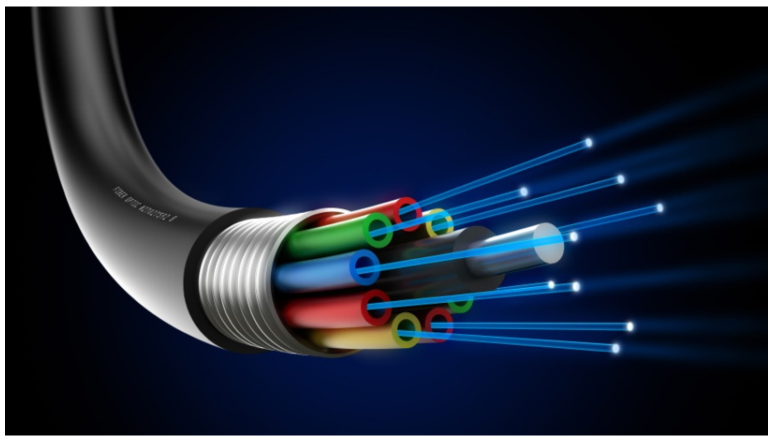
What is an optical network?

- An ***optical network*** connects computers (or any other device which can generate or store data in electronic form) using optical fibers.

- ***Optical fibers*** are essentially very thin glass cylinders or filaments which carry signals in the form of light (optical signals).

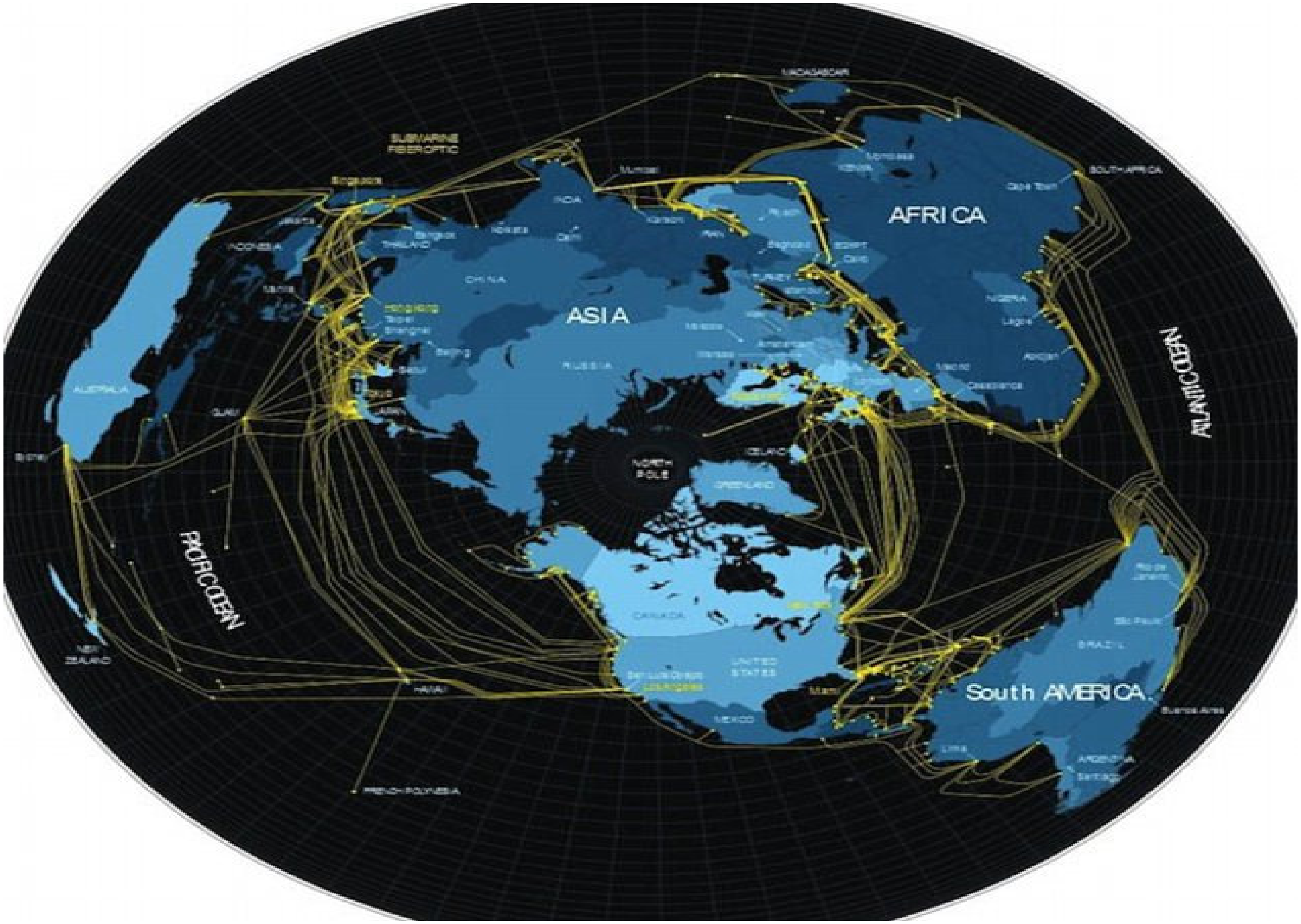
A transmitter connected to a receiver in an optical network





A lit-up bundle of fibers

Global Optical Fiber Network



Why do we need optical networks?

- Demand for bandwidth
  - ✓The tremendous growth of connected users online
  - ✓More and more bandwidth-intensive network applications:
    - data browsing on the WWW
    - Applications requiring large bandwidth
    - video conferencing
    - download movie

Advantages of optical networks

- High speed capability (theoretically possible to send 50 Terabits per second using a single fiber)
- Low signal attenuation
- Low signal distortion
- Low power requirement
- Low material usage
- Small space requirements
- Low cost
- Immunity to electrical interference

Optical Devices/components

- Optical Fiber
  - consists of a cylindrical *core* of silica, with a refractive index μ_1, surrounded by cylindrical *cladding*, also of silica, with a lower refractive index μ_2.

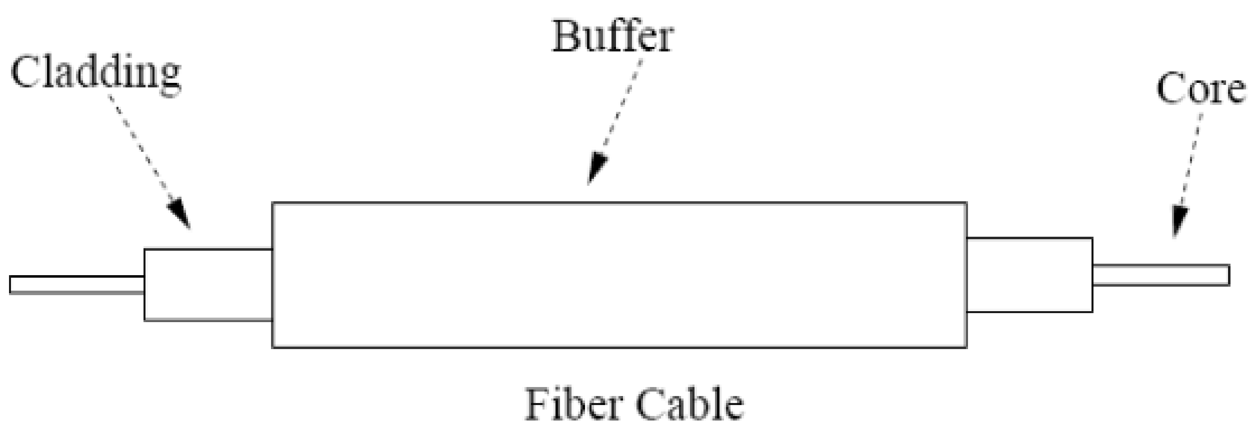


Figure 1: A fiber

An Optical Fiber

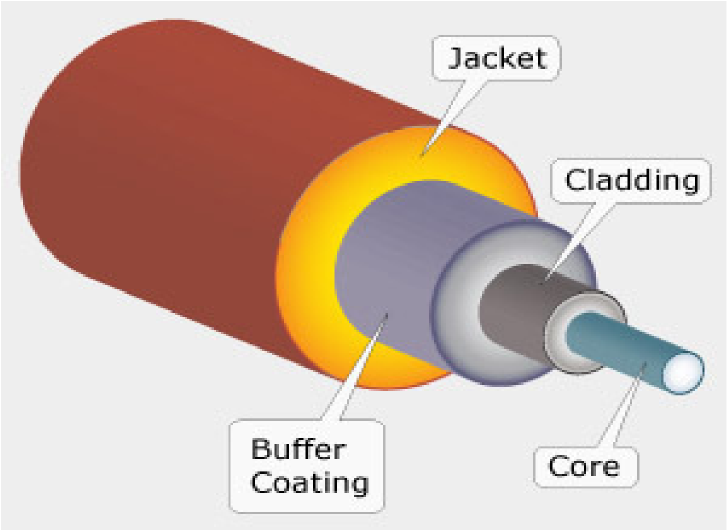


Figure 2: Structure of an Optical Fiber

Propagation of a signal through a fiber

- How does an optical signal move through a fiber network
  - send the optical signal at an angle greater than the critical angle $\sin^{-1} \mu_2 / \mu_1$.
  - Optical signals propagate through the core using a series of *total internal reflections*.

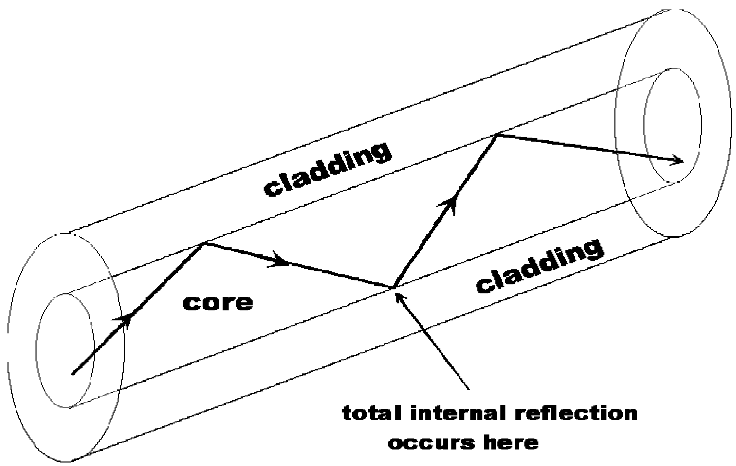


Figure 3: Propagation using total internal reflectiobn

Optical fibers (Cont'd)

- data communication in an optical network
  - use an optical carrier signal at some wavelength in the band of 1450 to 1650 nm,
  - at the source of the data, modulate the carrier with the data to be communicated,
  - send the modulated carrier towards the destination using a path involving one or more fibers,
  - when the signal reaches the destination, extract the data from the incoming signal using demodulation.

Wavelength Division Multiplexing

- The technology of using multiple optical signals on the same fiber is called ***wavelength division multiplexing*** *(WDM)*.
- WDM Optical Network
  - Divide the vast transmission bandwidth available on a fiber into several different smaller capacity “channels” – non-overlapping bandwidths,
  - Each of these channels can be operated at a moderate bit rate (2.5-40 Gb/s) that electronic circuits can handle,
  - Each of these channels corresponds to a different carrier wavelength.

Transmission spectrum of fibers

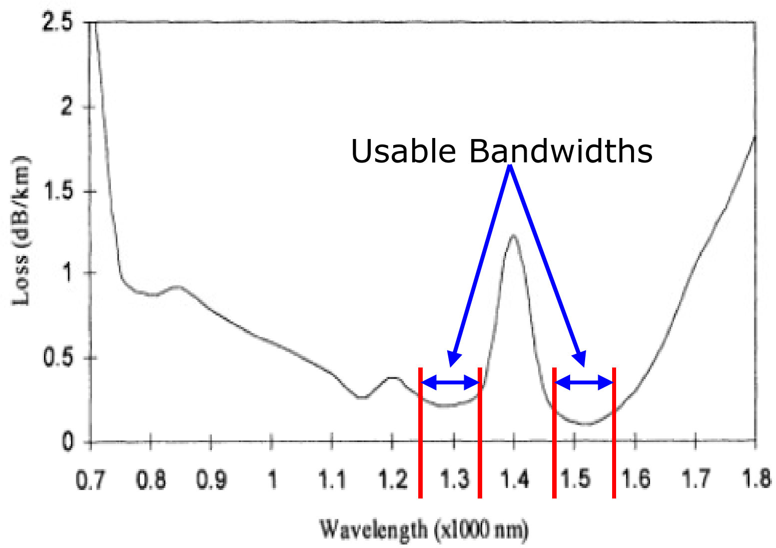


Figure 4: Transmission spectrum of optical fibers.

Channel spacing or guard band in WDM

- In WDM networks, each signal on a fiber is given a fixed bandwidth.
- In order to avoid interference between signals, a fixed spacing is maintained between signals using adjacent <u>bandwidths</u>, called as “guard band”.
- Signal Bandwidth = 10 GHz
- Channel Spacing = 100 GHz

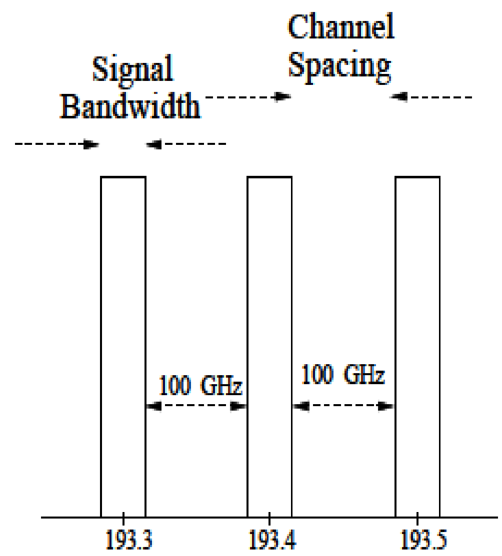


Figure 5: channels on a fiber

Data Transmission in WDM networks

- Carrier Frequency:
- Digital Data
- Modulated signal

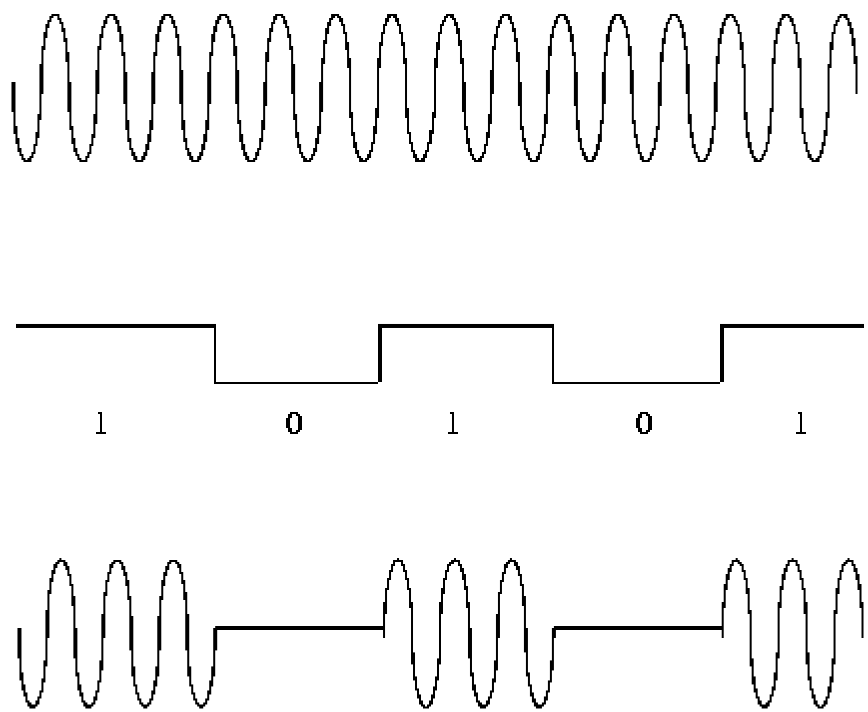


Figure 6: Modulated optical signal

http://epq.com.co/softw_internet/nag1/c4049.htm

What do we need to achieve WDM Communication

Transmitter – convert data to a modulated optical signal
Receiver – Convert a modulated optical signal to data
Multiplexer – to combine multiple optical signals
Demultiplexer – to separate signals having different carrier wavelengths
Routers – to direct the signals from the source to the destination
Add- drop multiplexers – to add new signals to a fiber and extract some signals

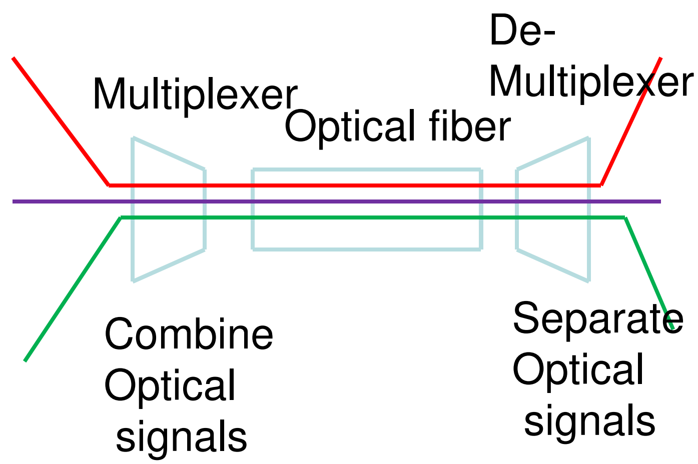


Figure 7: Wavelength Division Multiplexing (WDM)

Optical Devices/components

- Multiplexer (MUX)
  - has a number of inputs, each carrying signals using a distinct channel.
  - generates an output that combines all the signals.

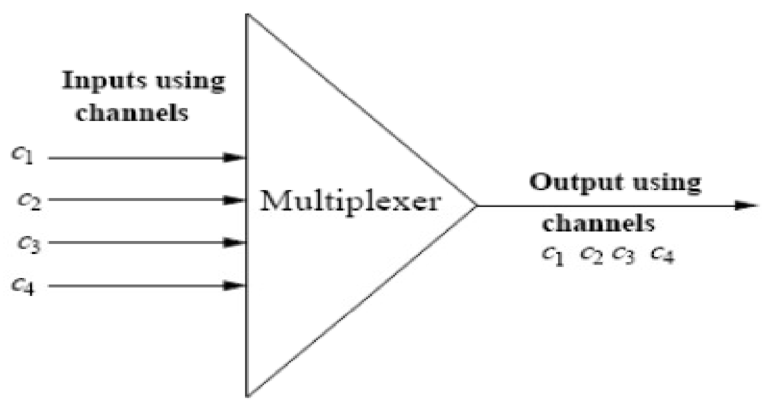


Figure 8: A 4-input Multiplexer

Optical Devices/components

- Demultiplexer (DEMUX)
  - serves the opposite purpose -- its input is a fiber carrying n optical signals, with the i^{th} signal using channel c_i.
  - has at least m outputs, with the i^{th} output carrying the optical signal using channel c_i, for all i; $1 \leq i \leq n$.

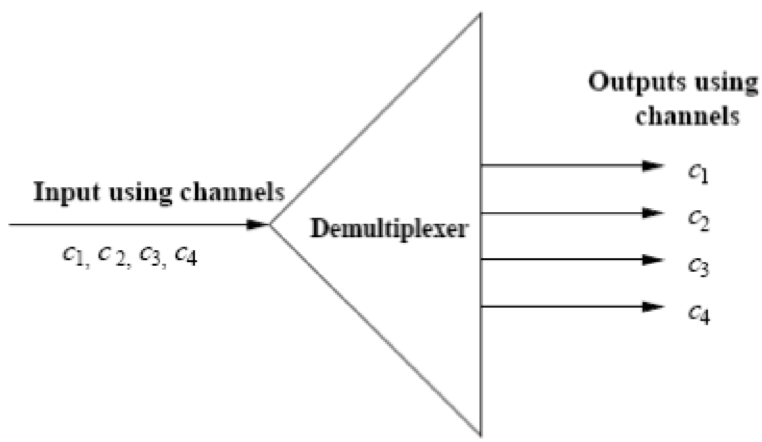


Figure 9: A 4-output Demultiplexer

Optical Devices/components

- Optical add-drop multiplexer (OADM)
  - **ADM**: A pair consisting of a MUX and a DEMUX, where some of the outputs from the DEMUX are not connected to any of the inputs of the MUX.
    - Each output of the DEMUX, not connected to an input of the MUX, is connected to a receiver.
    - Each input to the MUX which is not connected to an output of the DEMUX is connected to the output of a transmitter/modulator.
  - Add-drop multiplexers using optical devices are called *Optical Add/drop Multiplexers* (OADM).

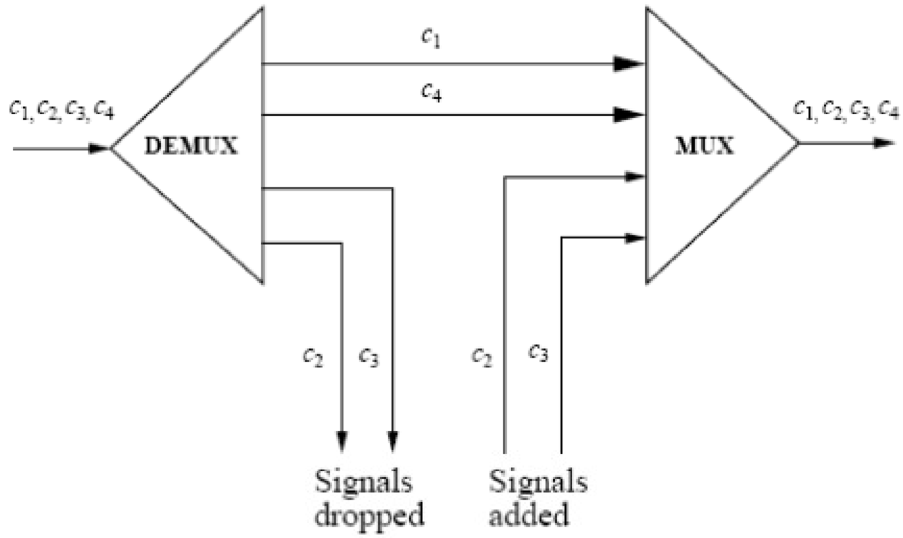


Figure 10: An optical add-drop multiplexer (OADM)

Optical Devices/components

- *End nodes*: sources or destinations of data (typically computers).
- *Optical routers*: direct each incoming optical signal to an appropriate outgoing fiber.

Optical Devices/components

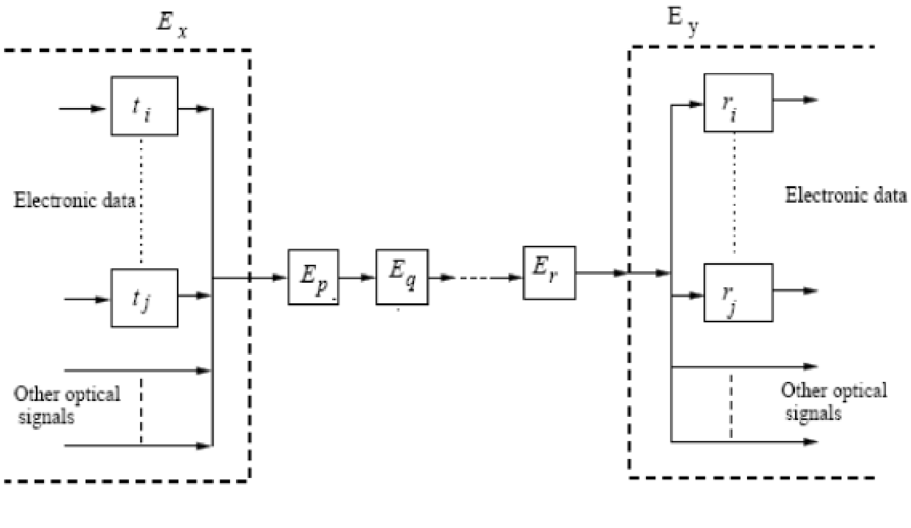


Figure 12: Use of add drop multiplexers and demultiplexers

- End node E_x (E_y) has transmitters (receivers) $t_i, \ldots t_j$ ($r_i, \ldots r_j$) tuned to wavelengths $\lambda_i, \ldots, \lambda_j$.
- The data in electronic form is the input to transmitter t_i, and is converted to optical signals using wavelength λ_i.
- The optical signal using λ_i is routed through a number of intermediate end-nodes $E_p, E_q, \ldots, E_r$ to the destination E_y.

Optical Devices/components

- Tasks of End-Node
- receive optical signals from the preceding node,
- separate the different optical signals on the input fiber,
- Convert incoming signals, intended for itself to electronic form,
- forward, without electronic processing, other incoming signals intended for other end-nodes,
- convert, to optical signal(s), electronic data that have to be communicated to other end-node(s),
- combine the optical signals send these optical signals using the outgoing fiber from itself.

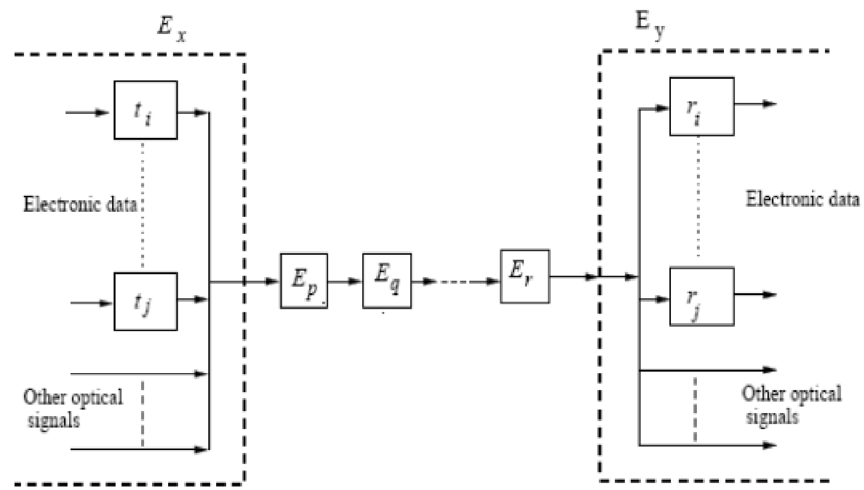


Figure 12: Use of add drop multiplexers and demultiplexers

Point to point communication in an Optical Network

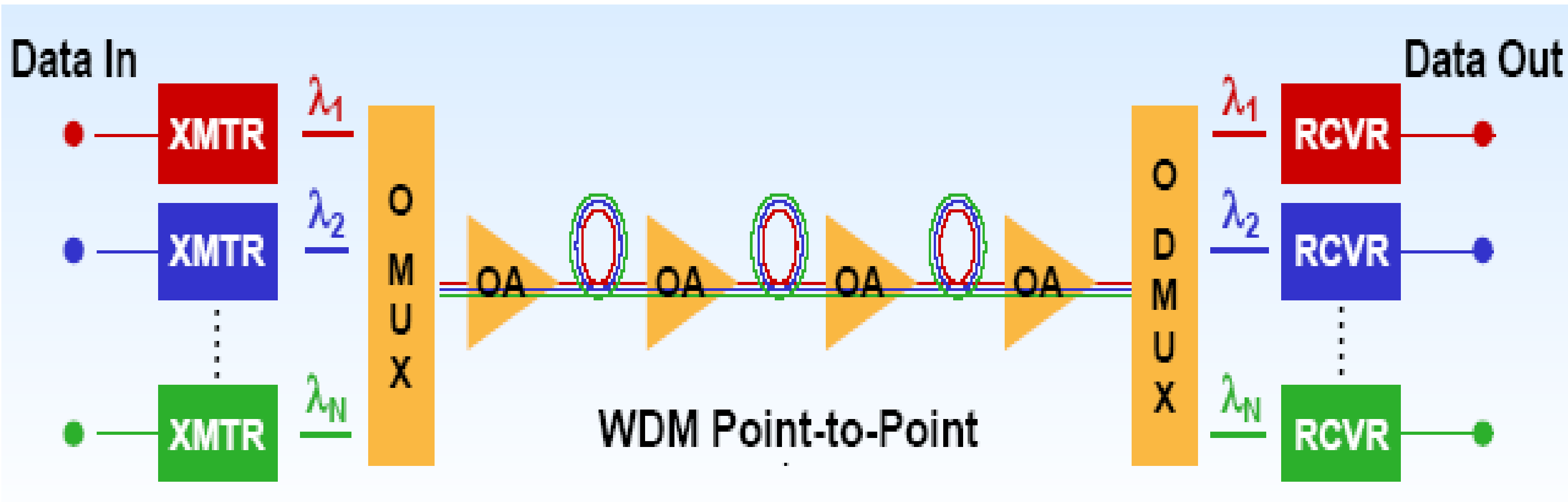


Figure 11: Point to point communication in an optical network

Types of WDM networks

- Categorizations of WDM Networks
  - Broadcast-and-select Networks
  - Wavelength-Routed Networks

Broadcast-and-select Networks

- Typically a local network with a small number (N_E) of end-nodes,
- Each end-node equipped with one or more transmitters and receivers.
- All the end-nodes are connected to a passive star coupler.
- Capable of supporting both unicast and multicast communication
- May be either a single-hop or a multi-hop network.

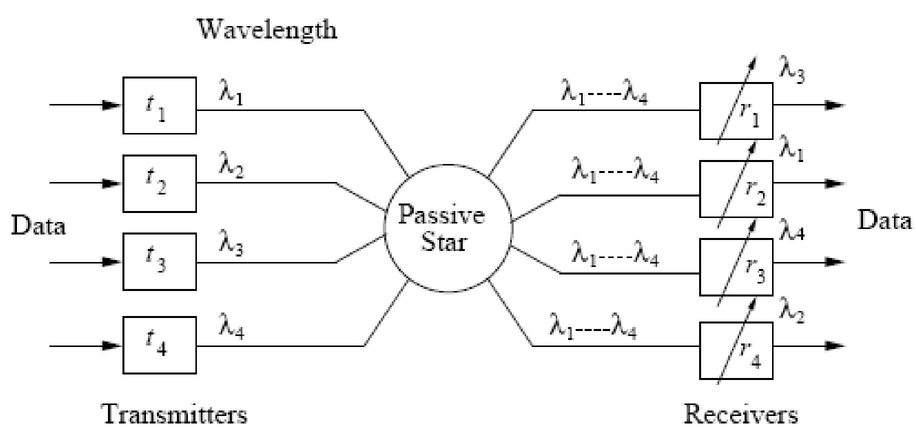


Figure 15: A broadcast-and-select network

Broadcast-and-select Networks

- Unicast communication:
  - the source end node selects an appropriate wavelength λ_p and broadcasts the data to all end nodes using the wavelength λ_p.
  - Receiver at destination tuned to λ_p ; receivers at all other end nodes are tuned to wavelengths different from λ_p.
  - Data is detected and processed only at the destination node.
- A broadcast-and-select network is simple and easy to implement but the size of the network is limited due to the requirement that the signal has to be broadcast to all end nodes.

Wavelength-Routed Networks

- the wavelength of the optical signal and the fiber it is using determine the subsequent path used by the signal.
- Since each optical signal is sent along a specified path and not broadcast to all nodes in the network, the power requirement of such a network is lower than that of a broadcast-and-select network.

Physical Topology of a wavelength routed network

- A circle represents an end node.
- A rectangle represents a router node.
- A directed line represents a fiber.
- These fibers are unidirectional and the arrow on the line gives the direction in which optical signals can flow.

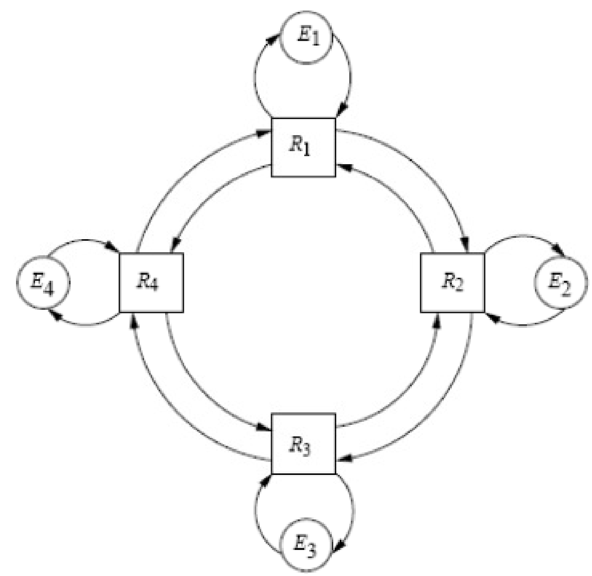


Figure 16: The physical topology of a typical WDM network

Lightpath

- an optical connection from one end node to another.
- starts from an end node, traverses a number of fibers and router nodes, and ends in another end node.
- used to carry data in the form of encoded optical signals.

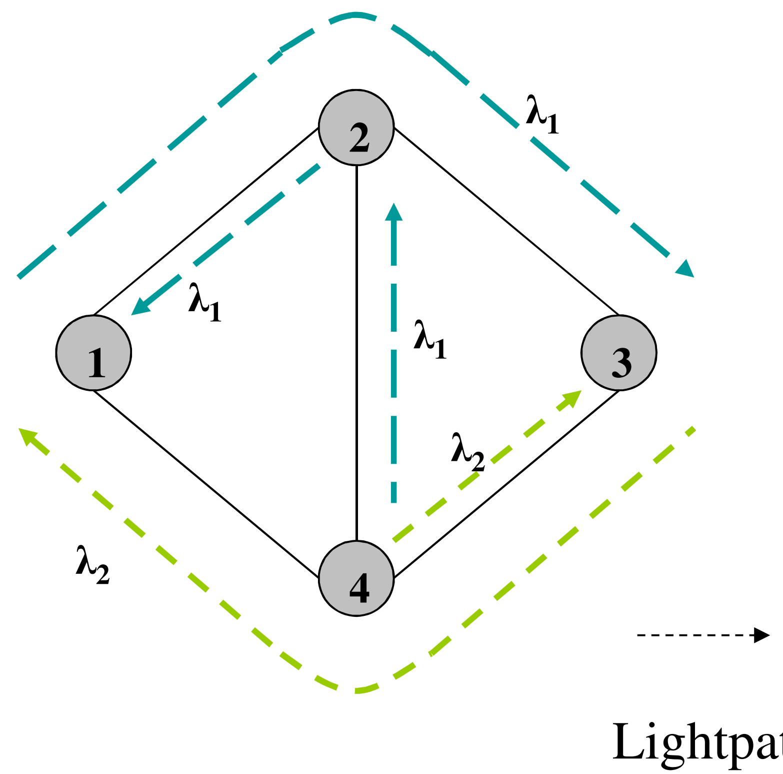


Figure 17: Lightpaths in an optical network

Logical Topology (Virtual Topology)

- view the *lightpaths* as edges of a directed graph G_L where the nodes of G_L are the end nodes of the physical topology.
- the edges of such a graph G_L are called *logical edges*.
- A directed path through a logical topology is called a *logical path*.

Lightpath and Logical Topology

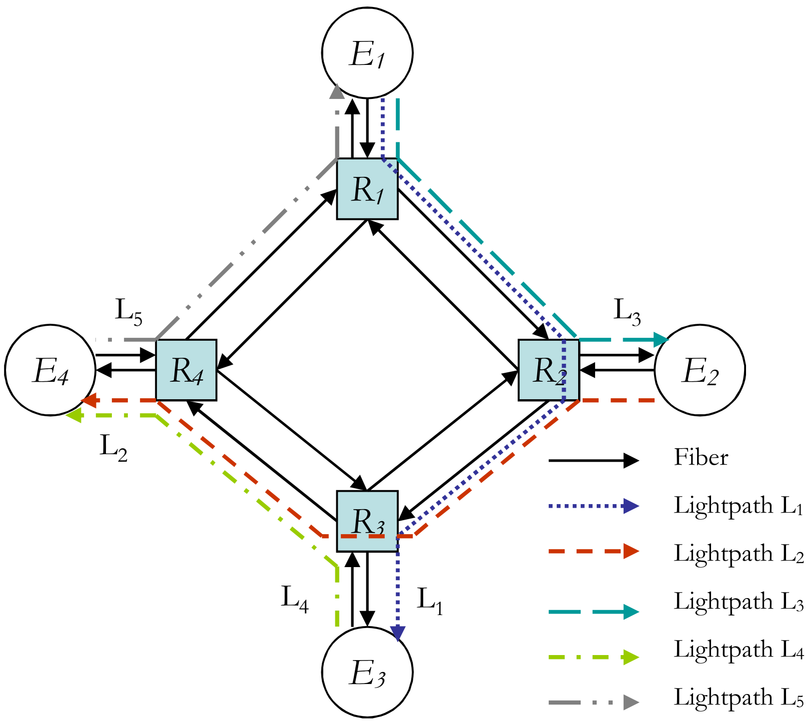


Figure 18: Some lightpaths on the physical topology shown in figure 10.

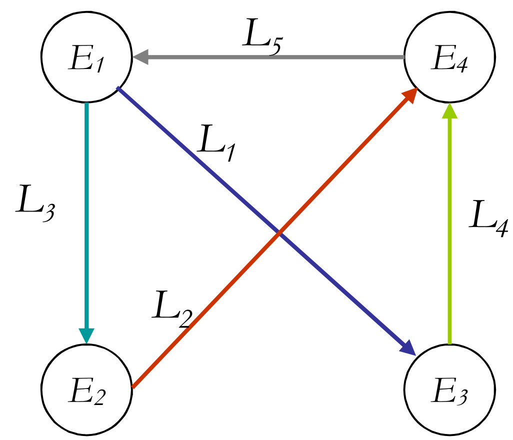


Figure 19: The logical topology G_L corresponding to the lightpaths shown in Figure 18.

Wavelength Routed Networks

- In summary, wavelength routed WDM networks
  - Route signals selectively based on wavelength
  - Routing is done in the optical domain
  - Lightpath – a basic communication mechanism

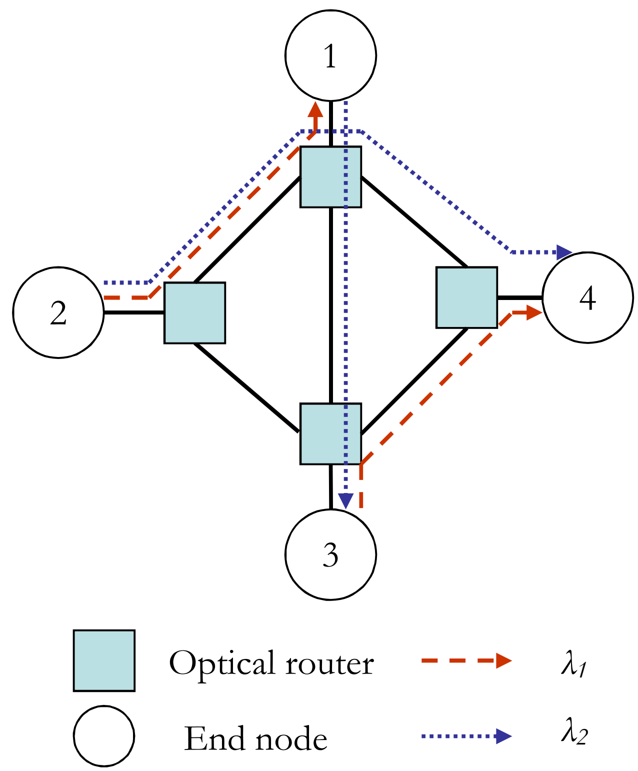
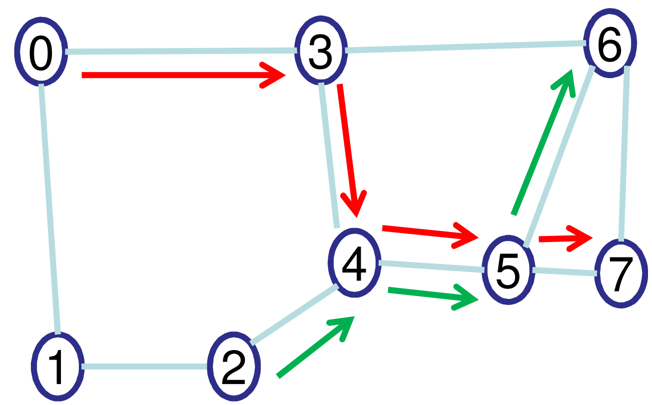


Figure 20: lightpaths on a network

Wavelength Clash Constraint

- No two lightpaths may use the same wavelength, if they share any fiber link.



L1(λ1) : 0 → 3 → 4 → 5 → 7
L2(λ2) : 2 → 4 → 5 → 6

Figure 21: wavelength clash must be avoided

Wavelength Continuity Constraint

- A lightpath from a source E_x to a destination E_y, on all fibers in its path $E_x \rightarrow R_i \rightarrow R_j \rightarrow \ldots \rightarrow R_k \rightarrow E_y$, uses the same channel c_i. no other signal on the fibers $E_x \rightarrow R_i$, $R_i \rightarrow R_j, \ldots, R_k \rightarrow E_y$ is allowed to use the channel c_i. (See previous slide)
- The carrier wavelength of a lightpath does not change from fiber to fiber.
- When considering a route for a lightpath, some channel c_i, $1 \leq i \leq n_{ch}$ must be available on every fiber on the route.
- See previous slides for an example

Design objectives of wavelength routed WDM networks

- Minimize the capital and operational costs.
- Maximize the network
  - throughput.
  - scalability.
  - survivability.
  - quality of service (QoS)

RWA in Wavelength Routed Networks

- Routing and wavelength assignment (RWA)
- Each lightpath must be assigned a route over the physical network, and a specific channel on each fiber it traverses.

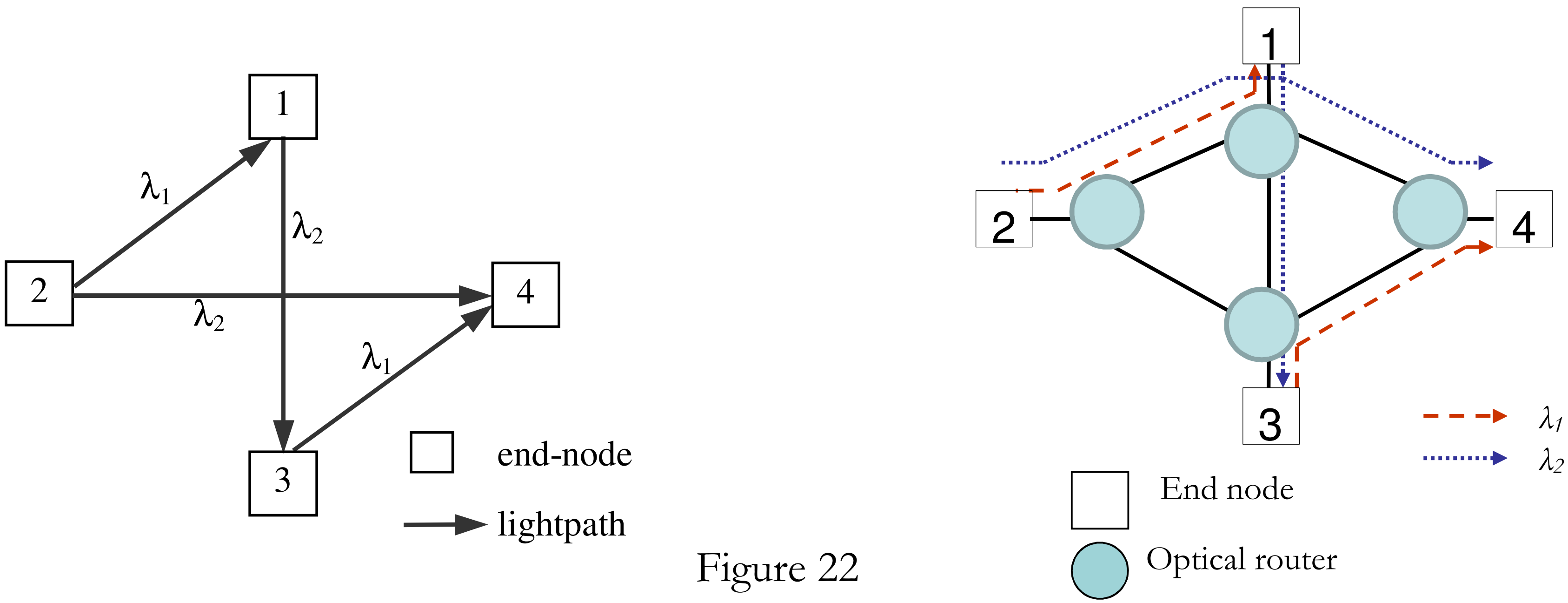


Figure 22

Static Lightpath Allocation in Wavelength Routed Networks

- Set up lightpaths on a semi-permanent basis.
- The lightpaths will continue to exist for a relatively long period of time (weeks or months) once set-up.
- When the communication pattern changes sufficiently, the existing lightpaths will be taken down and new lightpaths will be set up to handle the changes in traffic.

Connection Requests (static allocation)

Static Requests:

Source → Destination
1 → 6
3 → 6
1 → 4
1 → 5

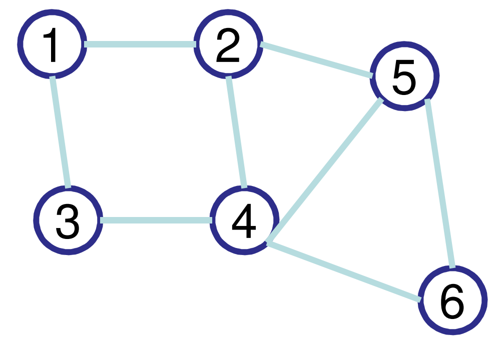


Figure 23: Physical topology of an optical network

Notes:

- For 1 → 6 there are many routes (e.g., 1 → 3 → 4 →6, 1 → 2 → 4 → 6)
- On each fiber we have many channels
- Wavelength continuity constraint and wavelength clash constraint must be satisfied
- Problem known to be NP-complete

Dynamic Lightpath Allocation

- Lightpaths are set up on demand.
- When a communication is over, the corresponding lightpath is taken down.

Connection Requests (Dynamic Requests)

Source → Destination	Start Time	Duration	Event Type
1 → 6	10	30	Setup
3 → 6	25	75	Setup
1 → 6	40	-	Tear down
1 → 4	60	25	Setup
3 → 6	100	-	Tear down

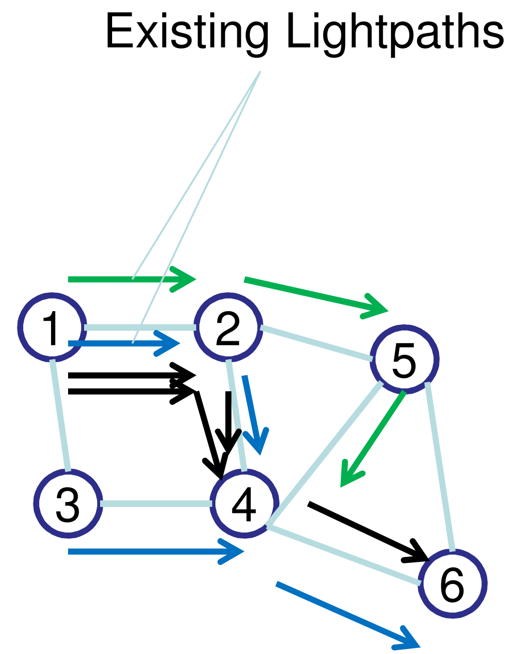


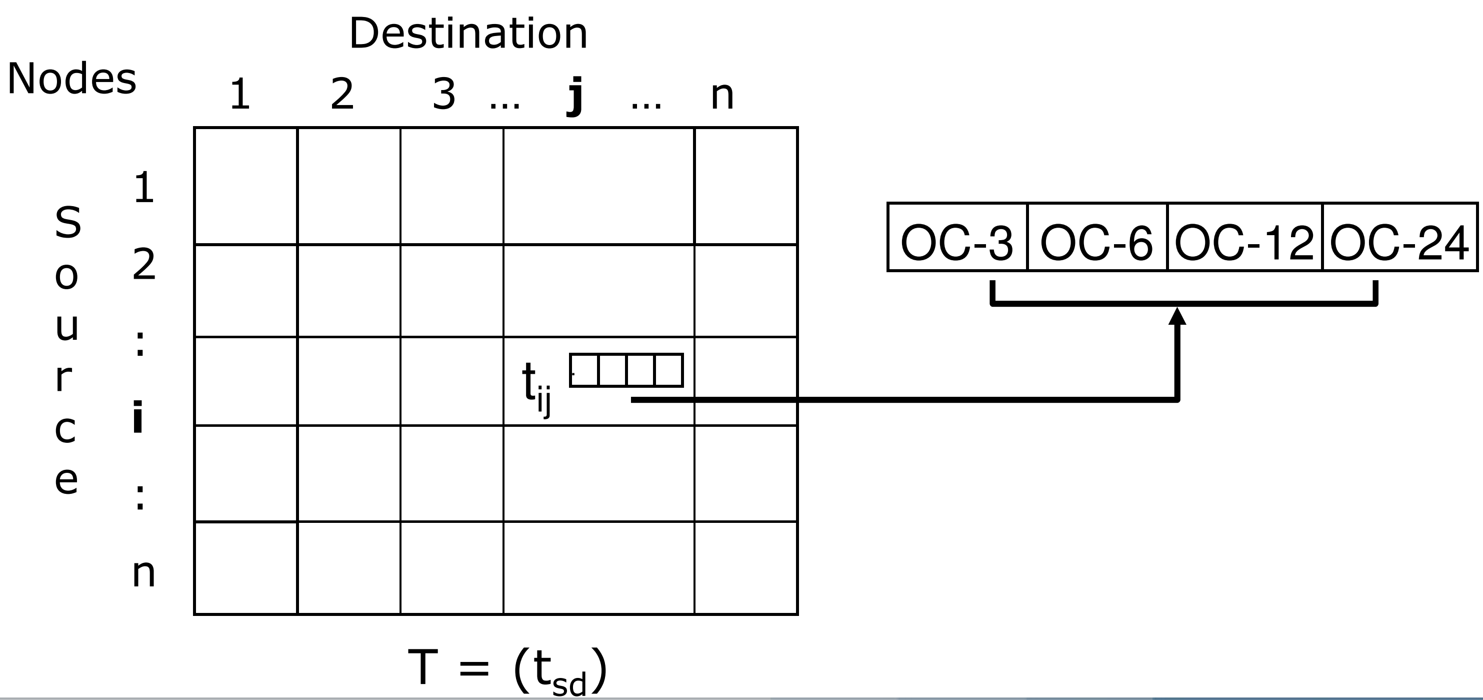
Figure 24: Dynamic RWA

Random arrival time and random duration
Tear down time = Start time + Duration

- Traffic matrix T = [$t(i,j)$] represents the traffic requirements. The entry $t(i,j)$ in row i and column j of traffic matrix T denotes the amount of traffic from end node E_i to E_j, $i \neq j$.

A Traffic Matrix

- Specify the data communication requests between a node-pair.
- Often expressed in OC-n notation.
  - OC-n = n X 51.8 Mbps



- Some popular units for specifying data communication:
  - megabits/second (Mbps),
  - gigabits/second (Gbps),
  - the signal rate, using the Optical Carrier level notation (OC-*n*), where the base rate (OC-*1*) is 51.84 Mbps and OC-*n* means *n* x 51.84 Mbps.
  - As a fraction of lightpath capacity

Types of scenarios

- Single-hop vs. Multi-hop networks
- In a *single-hop network*, all communication uses a path length of *one* logical edge.
  - Direct lightpath from source to destination
- also called all-optical networks,
  - communication always in ***optical*** domain.
  - No opto-electronic conversion in the intermediate node
- Example: 0 → 1, 1→2, 2 → 0, 2 → 3.

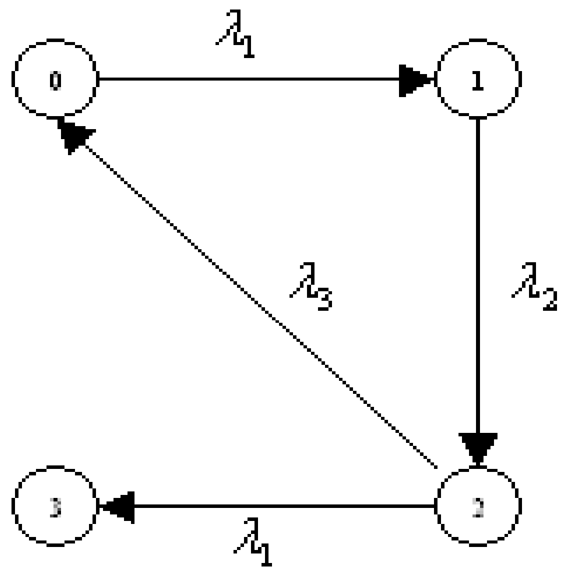


Figure 25: The logical topology of an all-optical network

Multi-hop networks

- In a *multi-hop network*, some data communication involves *more than one lightpath*.
- Uses a sequence of lightpaths
- Hop through intermediate nodes
- Opto-electronic conversions needed
- Example: 0→1→2, 1→2→0 needs multi-hop

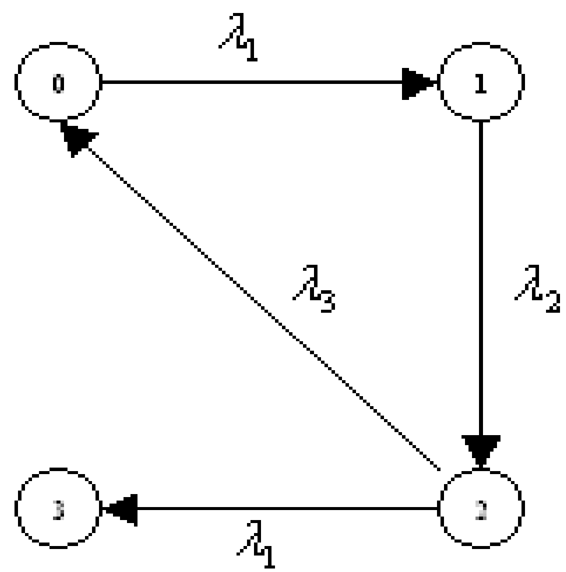


Figure 26: Communication from 0 to 2 (or 1 to 0) requires multi-hop

Multihop WDM Network design

- The constraints in designing a multi-hop wavelength-routed network using static lightpath allocation:
- The physical topology of the network.
- The optical hardware available at each end node which determines how many lightpaths may originate from or end at that end node.
- The characteristics of the fibers, which, for example, determine how many lightpaths may be allowed in a single fiber.
- the amount of data that may be carried by a single lightpath,
- The traffic requirements between each pair of end nodes.

Optimal solution for static RWA

Static RWA

- Given:
  - A physical fibre topology
  - Number of wavelengths (channels) available on each fibre.
  - A set of lightpaths to be established over the physical topology. A lightpath is specified by the *source* and *destination* node corresponding to the start and end of the lightpath.
- Goal:
  - ✓ Find a route over the physical topology, for each lightpath.
  - ✓ Find a single wavelength to be used for each lightpath on all its hops.
  - ✓ Minimize the total number of hops, considering all lightpaths.

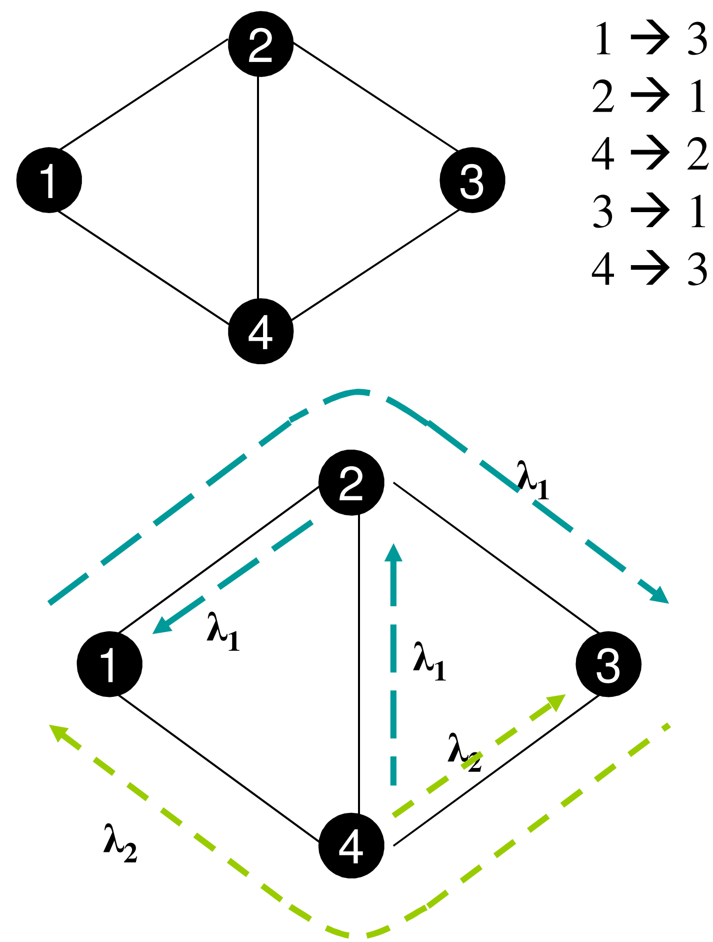


Figure 27: static RWA illustrated

ILP for Multi-hop network design

Integer Variables

- x_{ij}^{l} = 1, if and only if the l^{th} lightpath uses physical link $e(i \rightarrow j)$.
- $w_{k,l}$ = 1, if and only if the l^{th} lightpath is assigned channel k.

Continuous Variables

- $\delta_{ij}^{k,l}$ = 1, if and only if the l^{th} lightpath is assigned channel k on physical link e.

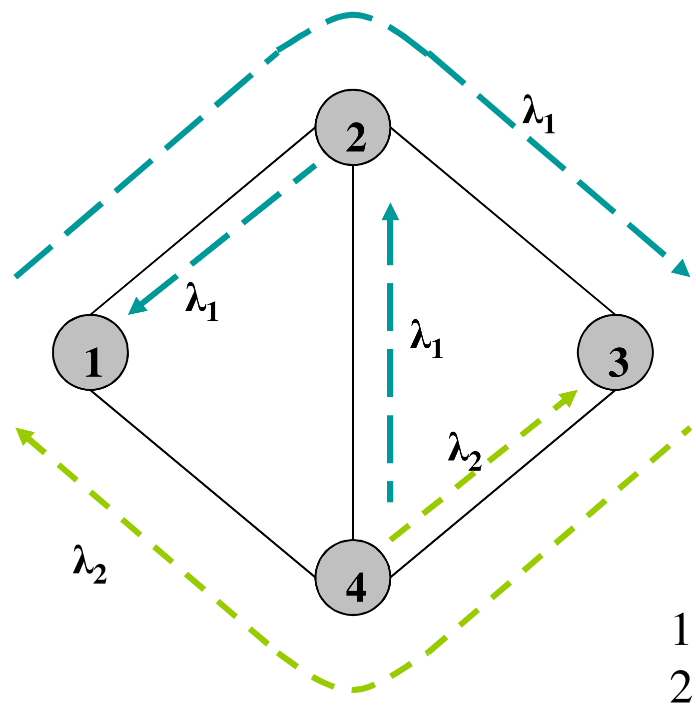


Figure 28

1 → 3
2 → 1
4 → 2
3 → 1
4 → 3

ILP for Multi-hop network design

Min $\sum_{l} \sum_{i \to j \in E} x_{ij}^{l}$

Subject to:

$$\sum_{j \ni i \to j \in E} x_{ij}^{l} - \sum_{j \ni j \to i \in E} x_{ji}^{l} = \begin{cases} 1, \text{ if } i = s \\ -1, \text{ if } i = d \\ 0, \text{ otherwise} \end{cases} \quad \forall i \in N, \forall l \in L$$

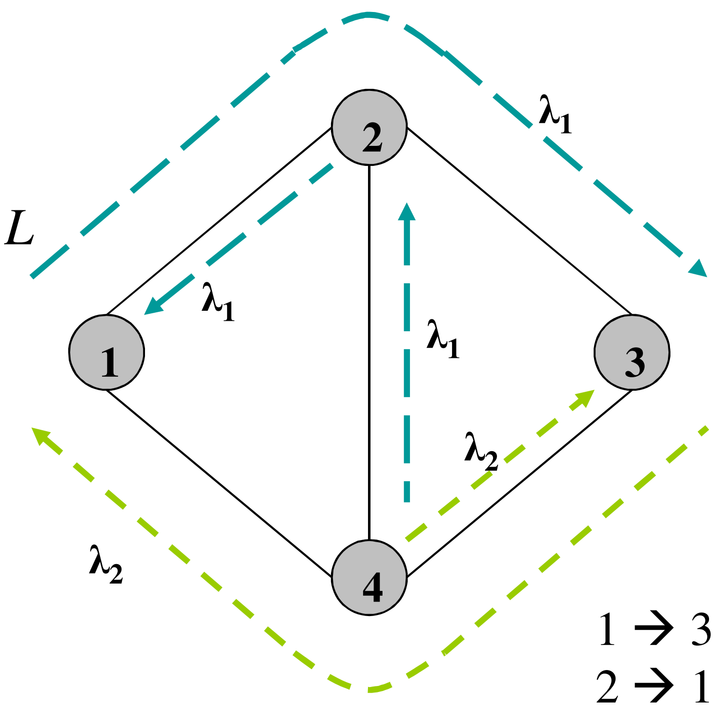
$$\sum_{k=1}^{K_{\max}} w_{k,l} = 1 \quad \forall l$$

$$x_{ij}^{l} + w_{k,l} - \delta_{ij}^{k,l} \le 1, \quad \forall i \to j \in E, \forall l \in L, \forall k \in K$$

$$x_{ij}^{l} \ge \delta_{ij}^{k,l}, \quad \forall i \to j \in E, \forall l \in L, \forall k \in K$$

$$w_{k,l} \ge \delta_{ij}^{k,l}, \quad \forall i \to j \in E, \forall l \in L, \forall k \in K$$

$$\sum_{l} \delta_{ij}^{k,l} \le 1, \forall i \to j \in E, \forall k \in K$$



1 → 3
2 → 1
4 → 2
3 → 1
4 → 3