



Zavod za telekomunikacije  
Sveučilište u Zagrebu, Hrvatska

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# **WDM systems and optical networks. DWDM** *(Sustavi multipleksiranja s valnom podjelom i optičke mreže. DWDM)*

Fotoničke telekomunikacijske mreže  
(2016./2017.)

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# Lecture overview

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- ◆ Wavelength Division Multiplexing (WDM) systems
  - Dense WDM (DWDM)
- ◆ Optical network structure
- ◆ WDM network architectures
  - Broadcast & Select (B&S) networks
  - Optical access networks
  - SDH/WDM ring networks
  - Wavelength-routed networks

# WDM principles (1)

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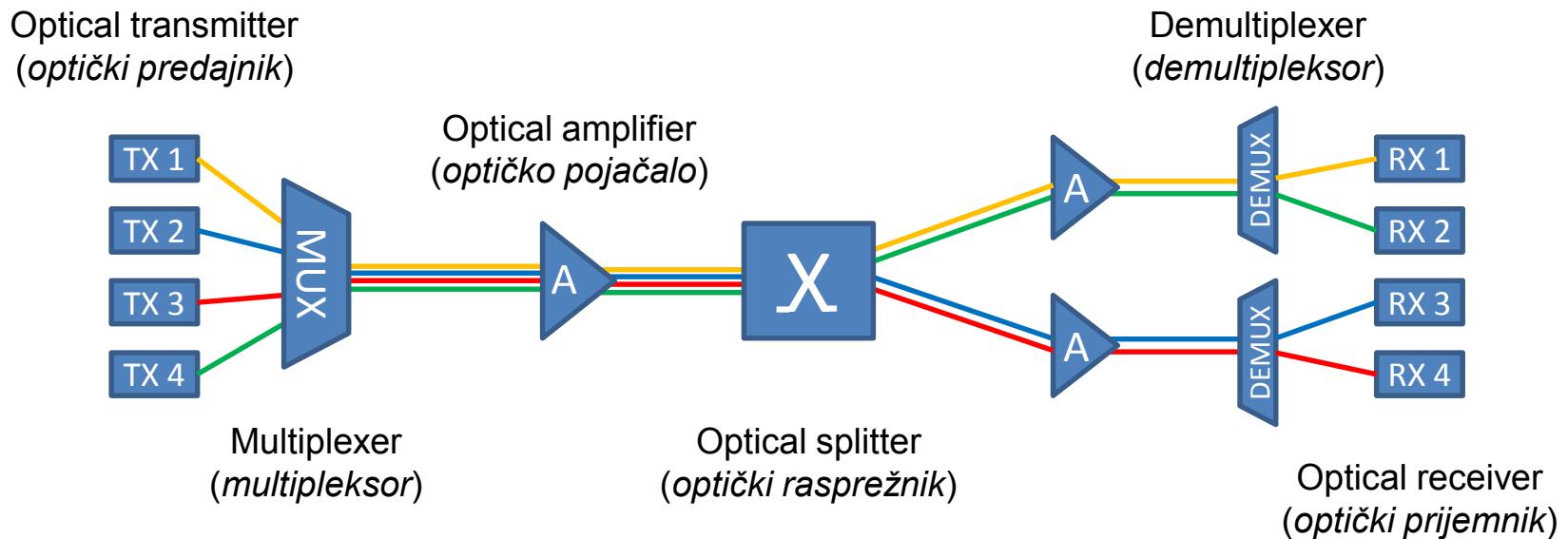
- ◆ Optical transmission spectrum is divided up into a number of non-overlapping wavelength bands
  - Each wavelength supports a single communication channel that operates at needed (traffic) rate
- ◆ WDM channels from different end-users may be multiplexed onto the same optical fiber
  - Efficient usage of fiber capacity
  - Multiple channels coexist on a single fiber → „huge” bandwidth

# WDM principles (2)

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- ◆ Each optical transmitter emits light on a different wavelength
- ◆ Optical signals may be multiplexed onto and simultaneously carried over the same fiber
- ◆ At a receiver side optical signals are demultiplexed
- ◆ Each optical receiver selects signal of its interest (corresponding to a specific wavelength)

# WDM system illustration



# WDM systems classification

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- ◆ According to different wavelength/channel spacing (S)
- ◆ Normal WDM
  - Two wavelengths, 1310 and 1550 nm
- ◆ Coarse WDM (CWDM)
  - Up to 16 wavelengths, with  $S = 20 \text{ nm}$
- ◆ Dense WDM (DWDM)
  - Up to 160 wavelengths, with  $S < 1 \text{ nm}$

# DWDM principles

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- ◆ Typically uses wavelength bands (1530-1565 nm) / (1565-1625 nm)
  - Denser wavelength spacing
- ◆ A DWDM system commonly utilizes:
  - 40 wavelengths with  $S = 0.8 \text{ nm}$ , or
  - 80 wavelengths with  $S = 0.4 \text{ nm}$
  - (160 wavelengths with  $S = 0.2 \text{ nm}$ )

# DWDM grid

## Dense Wavelength Division Multiplexing (DWDM)

*ITU Grid: C-Band, 100 GHz Spacing*

Channel (#)	Frequency (GHz)	Wavelength (nm)	Channel (#)	Frequency (GHz)	Wavelength (nm)
1	190100	1577.03	37	193700	1547.72
2	190200	1576.20	38	193800	1546.92
3	190300	1575.37	39	193900	1546.12
4	190400	1574.54	40	194000	1545.32
5	190500	1573.71	41	194100	1544.53
6	190600	1572.89	42	194200	1543.73
7	190700	1572.06	43	194300	1542.94
8	190800	1571.24	44	194400	1542.14
9	190900	1570.42	45	194500	1541.35
10	191000	1569.59	46	194600	1540.56
11	191100	1568.11	47	194700	1539.77
12	191200	1567.95	48	194800	1538.98
13	191300	1567.13	49	194900	1538.19
14	191400	1566.31	50	195000	1537.40
15	191500	1565.50	51	195100	1536.61
16	191600	1564.68	52	195200	1535.82
17	191700	1563.86	53	195300	1535.04
18	191800	1563.05	54	195400	1534.25
19	191900	1562.23	55	195500	1533.47
20	192000	1561.42	56	195600	1532.68
21	192100	1560.61	57	195700	1531.90
22	192200	1559.79	58	195800	1531.12
23	192300	1558.98	59	195900	1530.33
24	192400	1558.17	60	196000	1529.55
25	192500	1557.36	61	196100	1528.77
26	192600	1556.56	62	196200	1527.99
27	192700	1555.75	63	196300	1527.22
28	192800	1554.94	64	196400	1526.44
29	192900	1554.13	65	196500	1525.66
30	193000	1553.33	66	196600	1524.89
31	193100	1552.52	67	196700	1524.11
32	193200	1551.72	68	196800	1523.34
33	193300	1550.92	69	196900	1522.56
34	193400	1550.12	70	197000	1521.79
35	193500	1549.32	71	197100	1521.02
36	193600	1548.52	72	197200	1520.25

**Note:** for 200GHz spacing use either odd or even numbered channels.

# DWDM - pros & cons

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- ◆ Divides the transmission spectrum into narrow bands
- ◆ Tightly close wavelengths
  - High capacity
- ◆ Needs precise and highly stable optical transmitters (lasers)
  - High cost

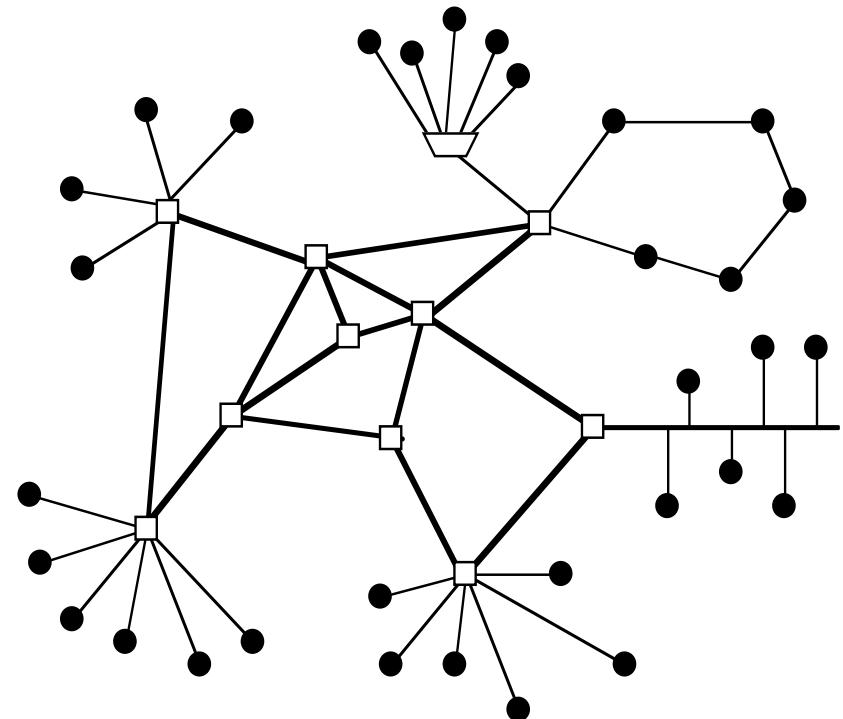
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# Telecommunication network structure

- ◆ Three different parts:
  - Backbone/transport network
  - Metropolitan/regional network
  - Access network



From: B. Mukherjee, „Optical WDM Networks”, Springer

# Access network

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- ◆ Allows residential and business customers (*end-users*) to connect to the rest of the network infrastructure
- ◆ Spans a distance of up to a few (10s of) kilometers
- ◆ A resource bottleneck?
  - End-users always call for more and more network bandwidth
- ◆ Passive optical networks are an attractive solution for this network part

# Metropolitan network

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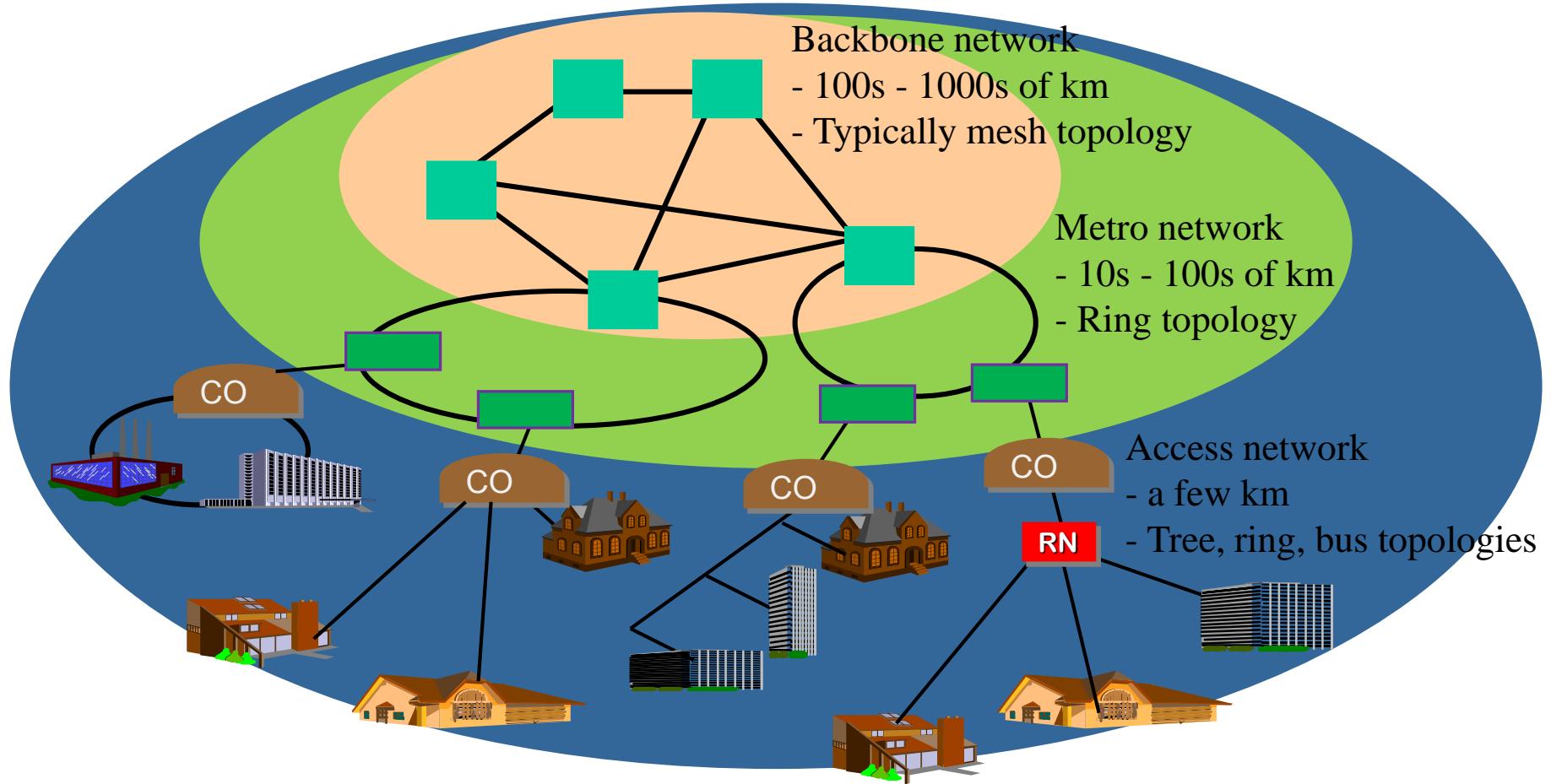
- ◆ Spans distances of a few 10s to a few 100s of kilometers
- ◆ Deployed as SDH/WDM ring networks or wavelength-routed networks

# Backbone network

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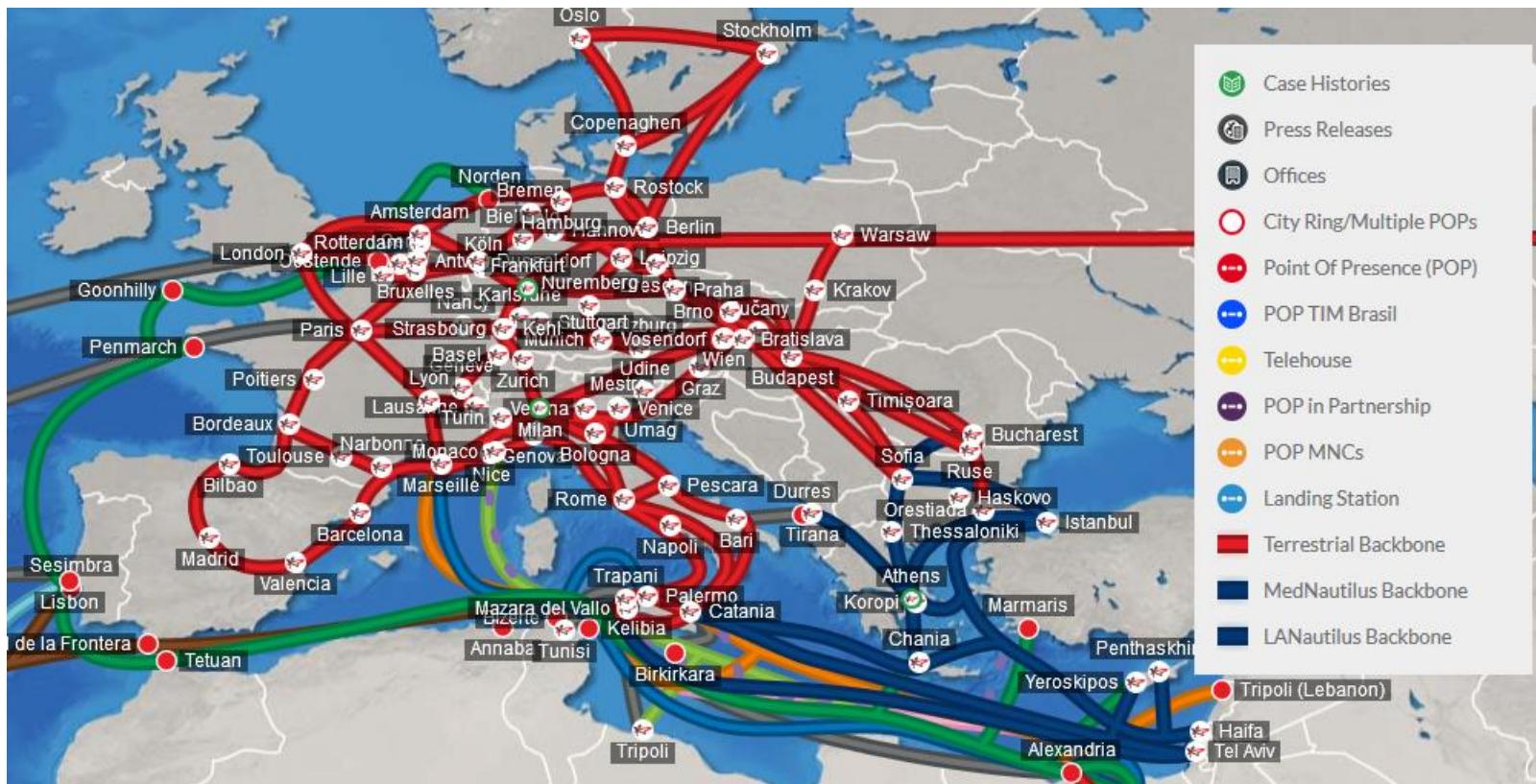
- ◆ Spans long distances
  - A network link could be a few 100s to a few 1000s of kilometers in length
- ◆ Can be set up to offer a nation-wide or global coverage
- ◆ Deployed as:
  - an interconnection of SDH/WDM rings, or
  - mesh wavelength-routed networks (with an arbitrary interconnection)
    - Fibers typically interconnect optical cross-connects (OXCs)

# Optical network architecture



# Optical network architecture - example

- ◆ Telecom Italia Sparkle
  - <http://www.world.tisparkle.com/>

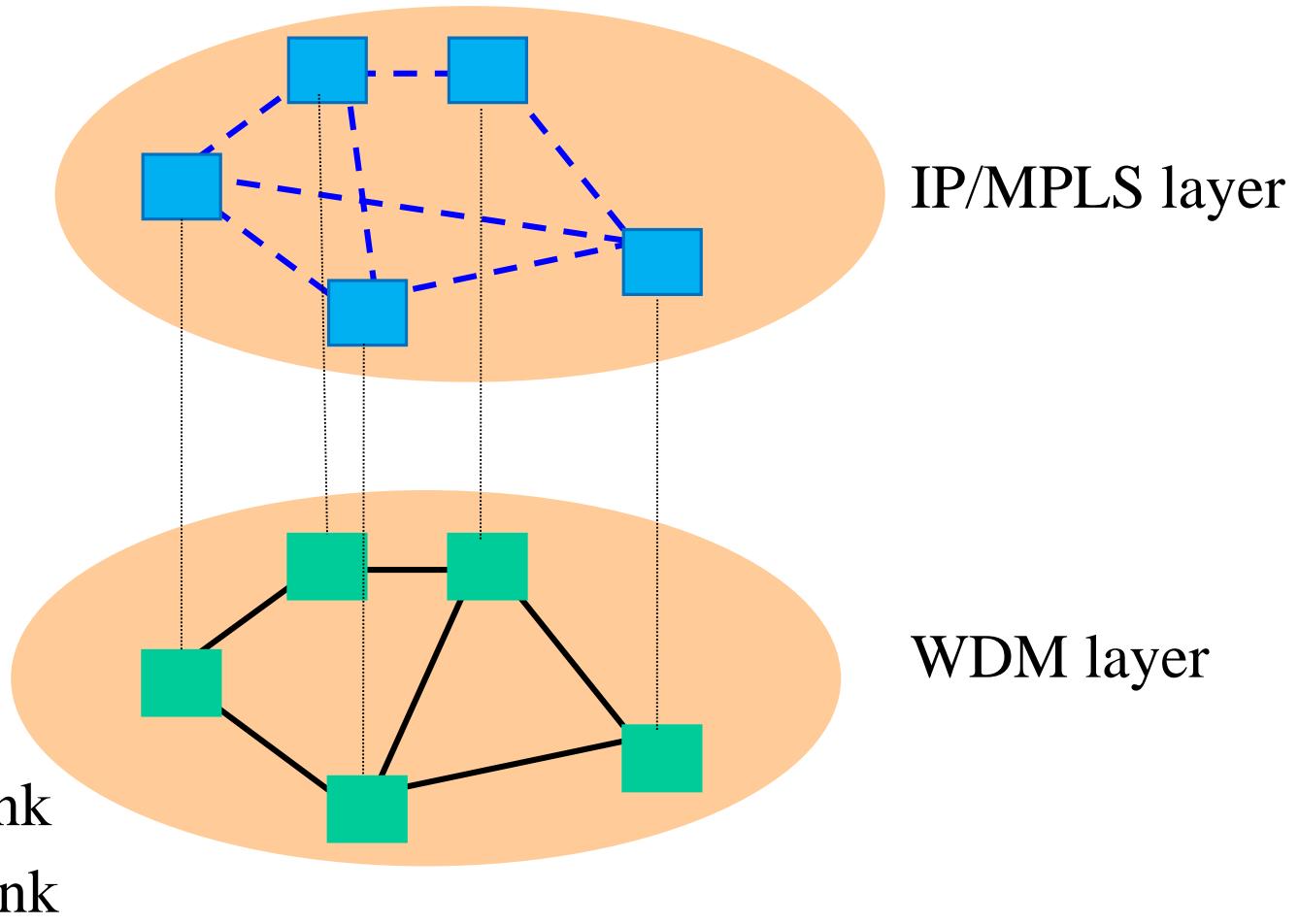


# WDM in practice

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- ◆ WDM devices available commercially
- ◆ Optical WDM networks dominantly deployed in telecom networks and the Internet
  - WDM-based optical backbone networks → *IP over WDM*
  - End-users connected to the network via, e.g., OXCs

# IP-over-WDM networks: logical vs. physical topology



# Lecture overview

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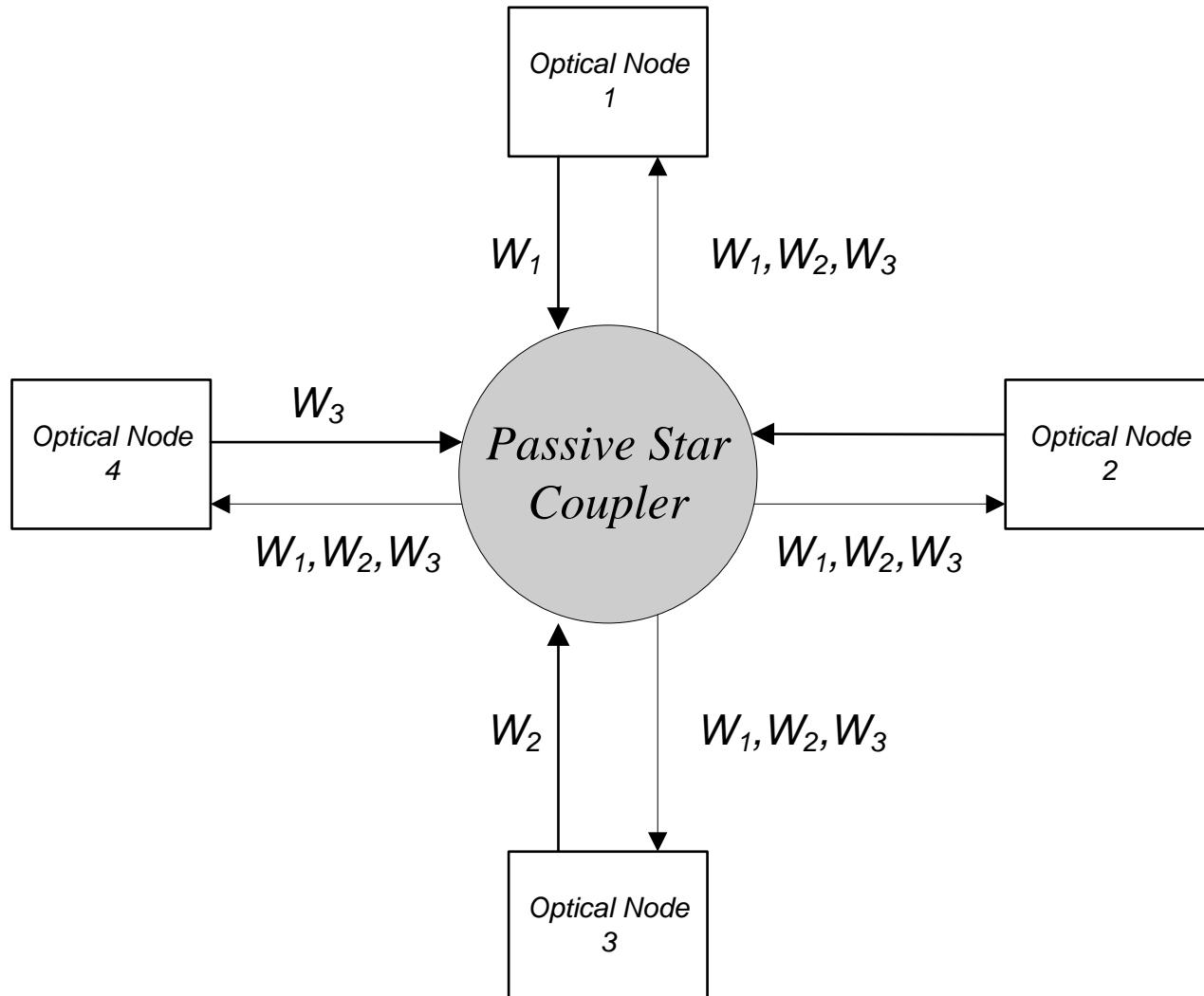
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# B&S network - basics

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- ◆ Used to build local optical networks
  - Single-hop B&S networks
  - Multi-hop B&S networks
- ◆ Network nodes are connected to a *passive star coupler* (PSC) via two-way fibers in a star topology
- ◆ Nodes contain 1 or more fixed or tunable transmitters and receivers

# B&S network - illustration



# B&S network - working principle

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- ◆ Nodes send signals simultaneously on different wavelengths
- ◆ The coupler is a „broadcast” device with multiple inputs and outputs
  - Combines all the signals optically and sends the combined signal back to all the nodes
  - A signal on a wavelength will have its power equally divided among all output ports
- ◆ Each node chooses which signal (wavelength) it will receive by tuning its receiver accordingly

# Single-hop B&S network - working principle (1)

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- ◆ Each transmitter can send information to any receiver in one hop
  - The signal arrives to the destinations in one hop (without OEO)
- ◆ Fast tuning of receivers may be required for packet traffic

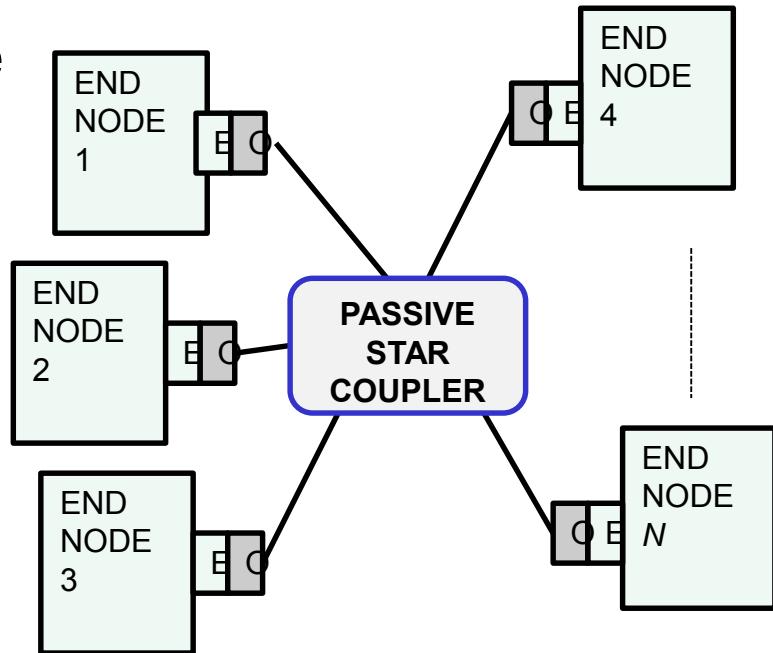
# Single-hop B&S network - working principle (2)

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- ◆ Main challenge: coordination of transmission between nodes to avoid collisions
  - A collision occurs
    - if 2 nodes send signals on the same wavelength at the same time, or
    - if 2 nodes send signals on different wavelengths, but to the same destination node which has only one receiver

# Single-hop B&S network - optimization

- $N$  nodes are connected to a passive star coupler
- $W$  wavelengths are available
  - Nodes with tunable or fixed transmitters
  - Nodes with tunable or fixed receivers
  - Nodes can transmit and receive at the same time
- This scheme inherently permits multicast/broadcast operation



From: Pablo Pavon Marino, "Broadcast and Select Networks",  
Optimization and planning in optical networks

# Single-hop B&S network - coordination

- Coordination needed because of the coupler (shared medium)
- Two main types of coordination:
  - MAC-based distributed coordination
  - Centralized coordination based
- Centralized coordination: a signaling system is supposed to exist, which coordinates the nodes following a scheduling plan that is previously calculated

Average traffic between nodes

Tunability of transmitters /  
receivers in each node



Create a periodic frame scheme,  
allocating collision-free time  
intervals and wavelengths to  
every (*source, destination*)  
connection

# Multi-hop B&S network - working principle (1)

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- ◆ A transmitter can only send information to a subset of receivers
  - Signals need to traverse multiple hops to arrive to their destination
  - OEO conversion
- ◆ Cons: increases propagation delay and queuing delay; can cause inefficient utilization of capacity
- ◆ Pros: fast receiver tuning not required

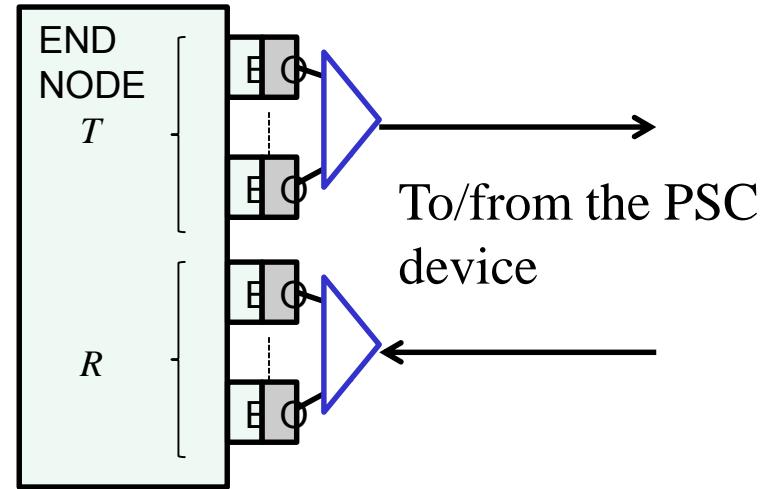
# Multi-hop B&S network - working principle (2)

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- ◆ Each node has a small number of fixed receivers and transmitters, which comprise a virtual topology (VT)
- ◆ VT nodes: physical nodes
- ◆ VT links: between nodes
  - Transmitters and receivers are operating on the same wavelength

# Multi-hop B&S network - optimization (1)

- The wavelength associated to each transmitter is supposed to be static along time (i.e. it is not expected to change until a global assignment is re-computed)
- Each node is (supposed to be) equipped with  $T$  transmitters and  $R$  receivers (each statically tuned to a different wavelength)



$T$  and  $R$  are usually  $\ll W$ ,  
the number of wavelength  
channels in the network

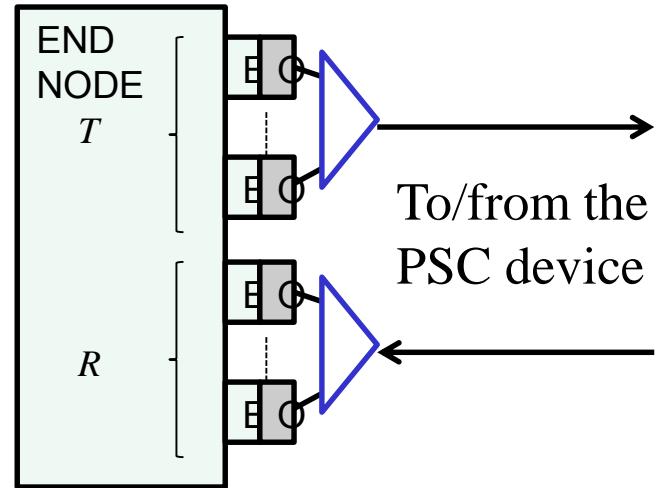


The traffic between two nodes, commonly  
needs to traverse more than once the PSC  
before arriving to its destination

# Multi-hop B&S network - optimization (2)

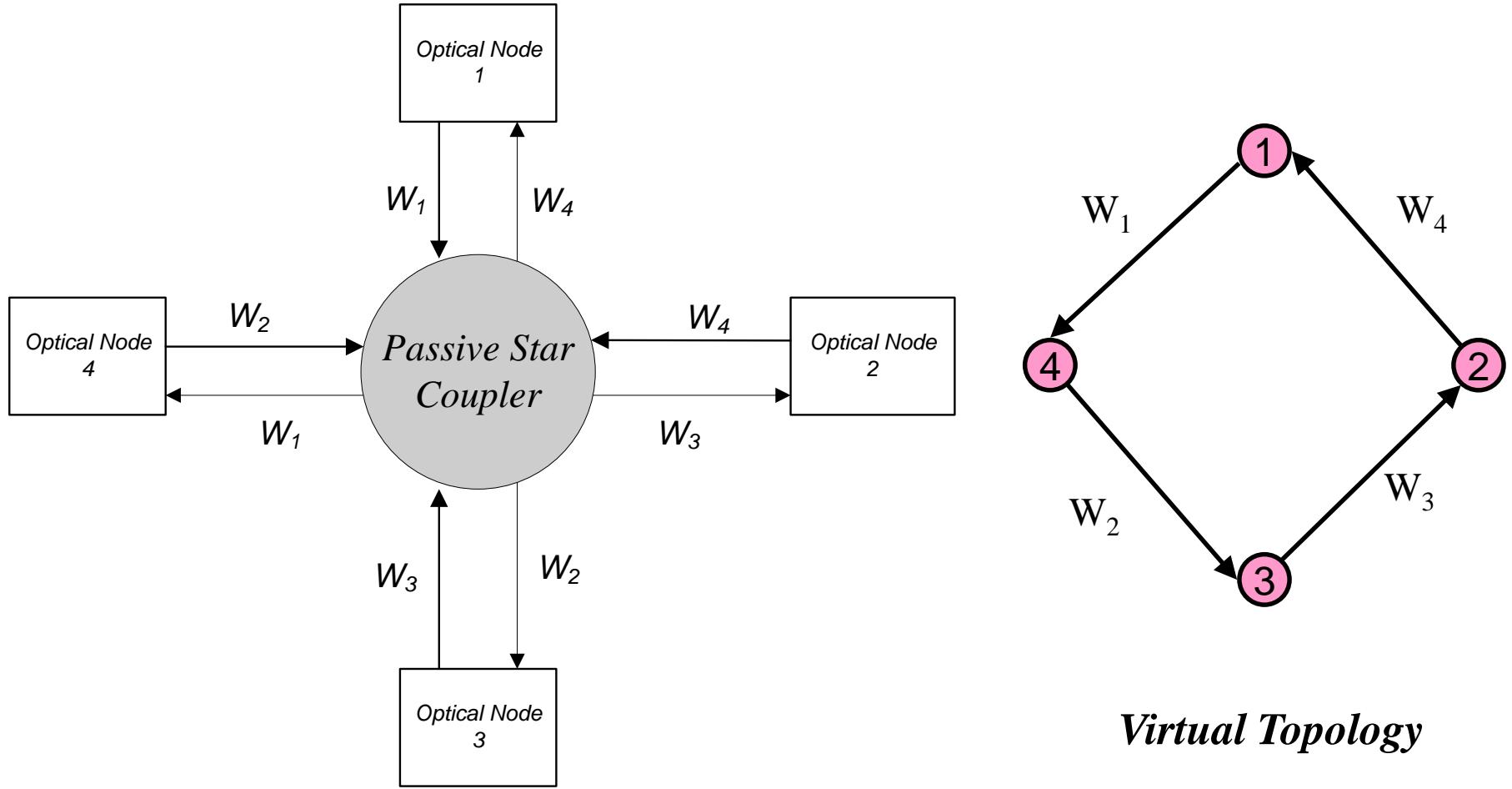
- Allocating wavelengths to the transmitters determines the *virtual topology* of connections between nodes

- Higher layer traffic is routed on top of this VT
- The VT must be feasible: no collisions in the physical layer



From: Pablo Pavon Marino, "Broadcast and Select Networks", Optimization and planning in optical networks

# Multi-hop B&S network - virtual topology illustration



*Physical topology*

*Virtual Topology*

# Multi-hop B&S network - summary

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- ◆ Advantages:
  - Simplicity
  - Free multicasting
- ◆ Constraints:
  - A large number of wavelengths needed (typically as many as nodes, since there is no wavelength reuse)
  - Limited distances because the transmission power is divided between all nodes
- ◆ Main applications: LAN, MAN

# Lecture overview

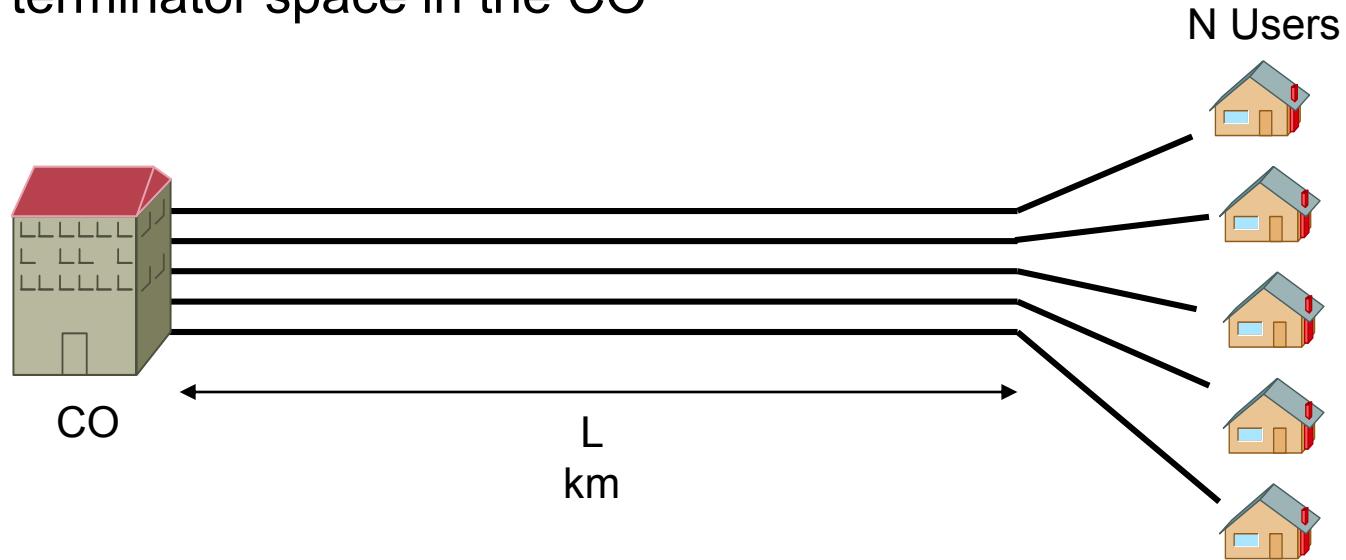
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# Optical Access Networks (1)

## ◆ Point-to-Point links

- Simple, standardized and mature technology
- $N$  fibers lines
- $2N$  transceivers
- Significant outside fiber plant deployment and connector terminator space in the CO

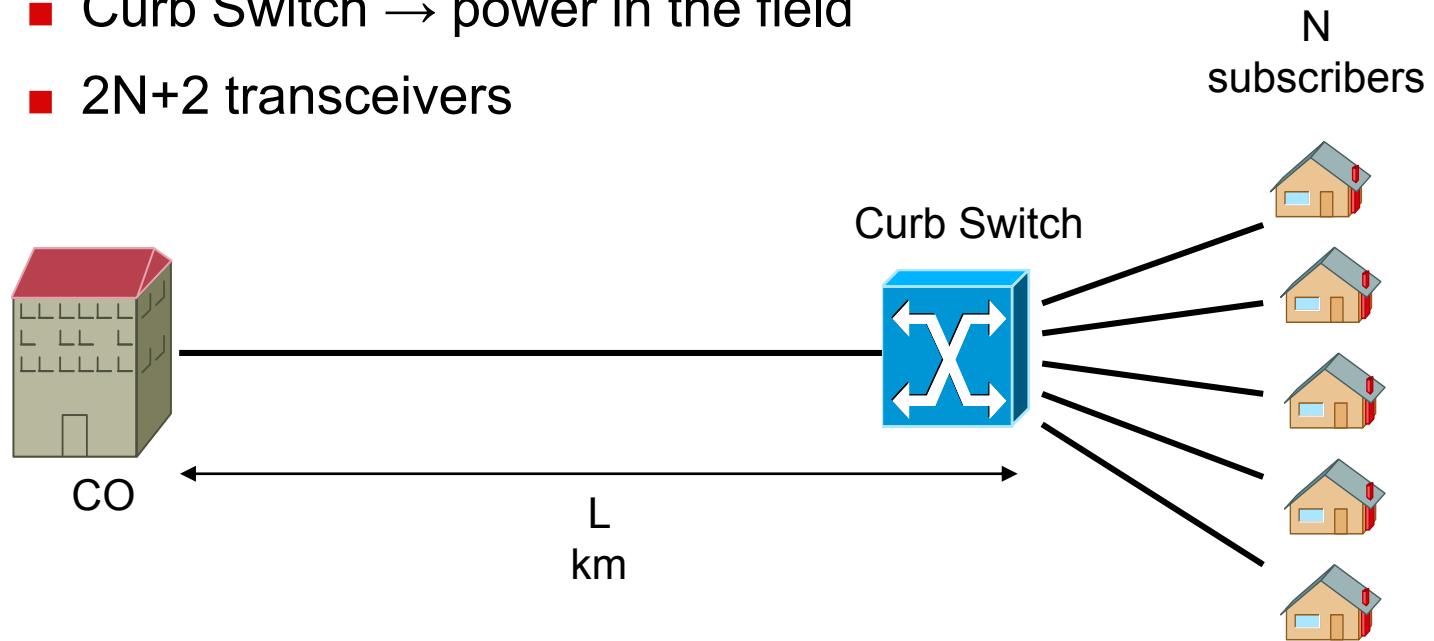


From: G. Maier, A. Pattavina, F. Neri, D. Carglio, „Optical Access and Metro Networks“

# Optical Access Networks (2)

## ◆ Active Optical Network

- Simple, standardized and mature technology
- 1 fiber line
- Curb Switch → power in the field
- $2N+2$  transceivers

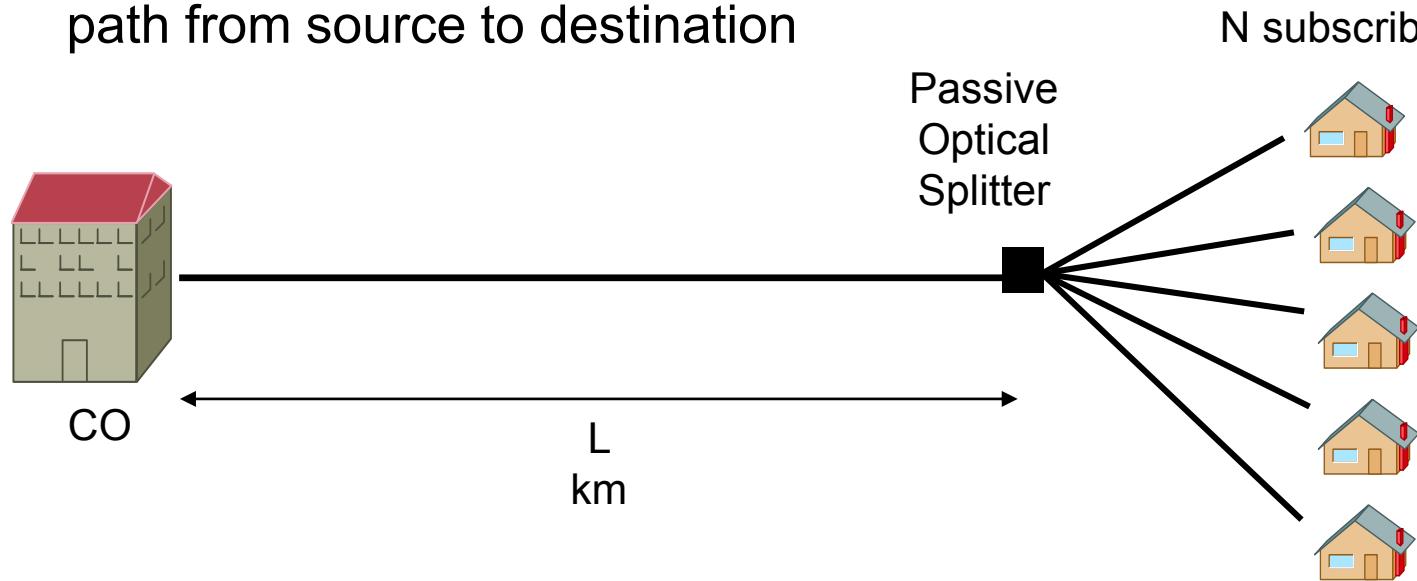


From: G. Maier, A. Pattavina, F. Neri, D. Cugellio, „Optical Access and Metro Networks“

# Optical Access Networks (3)

## ◆ Passive Optical Network (PON)

- Simple, under standardization technology
- 1 fiber line
- N+1 transceivers
- Passive devices (splitters): no active elements in the signal's path from source to destination



From: G. Maier, A. Pattavina, F. Neri, D. Cugellio, „Optical Access and Metro Networks“

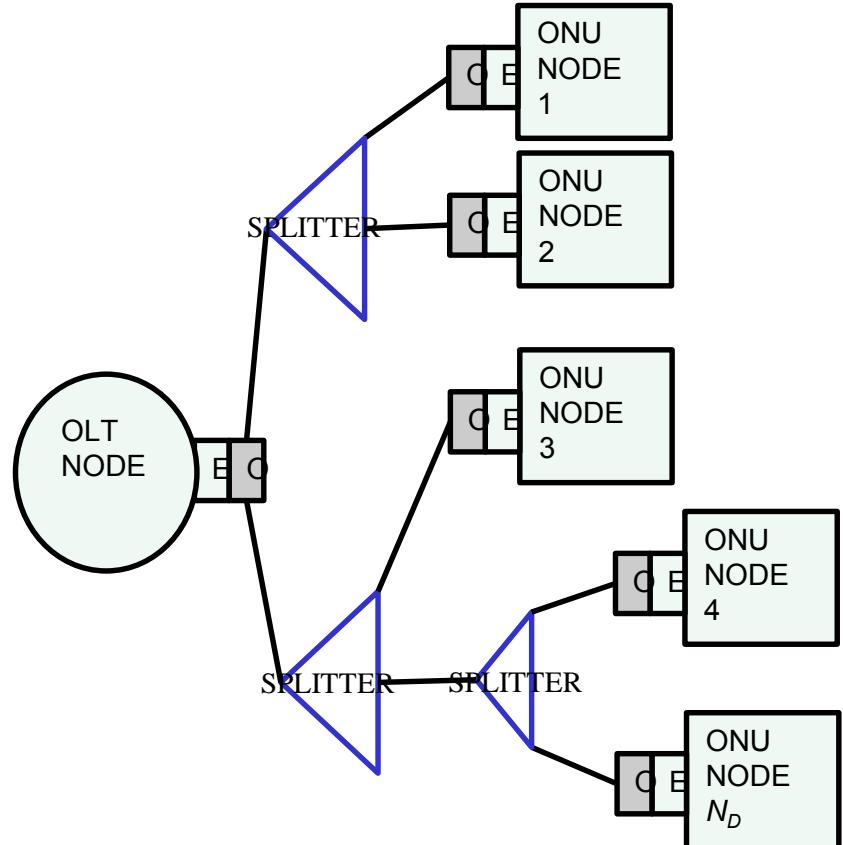
# Passive optical networks (1)

- Passive Optical Networks (PONs) are optical access point-to-multipoint networks with no active elements in the signal path
- Network elements:
  - a) Optical Line Terminal (OLT): service provider end-point that converts provider's electrical signals into PON's optical signals and multiplexes end-user optical signals
  - b) Optical Network Units (ONU): devices installed at a customer's premises that transform PON's optical signals into electrical ones used by the customers
  - c) Optical Distribution Network (ODN): passive splitters and optical fibers that connects the OLT with the ONUs

From: Ramon Aparicio Pardo, "Passive Optical Networks",  
Optimization and planning in optical networks

# Passive optical networks (2)

- Network scheme → tree graph:
  - 1 root node (OLT)
  - $N_D$  demand leaf nodes (ONUs)
  - Passive splitters at intermediate nodes between OLT and ONU nodes:
    - *Single Splitting*: 1 splitting level
    - *Distributed Splitting*: 2 or more splitting levels
  - 2 wavelength channels used:
    - downlink channel (OLT → ONUs)
    - uplink channel (ONUs → OLT)



# Passive optical networks (3)

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- The downlink channel permits the OLT multicast/broadcast operation by MAC-based mechanisms
- The uplink is a shared medium and needs coordination
- This coordination is usually centralized in the OLT by means of Distribution Bandwidth Allocation (DBA) mechanisms
- Other important design issue - location and the number of splitters:
  - if splitters are placed close to the OLT, each ONU needs to be connected directly from the splitter by a separate optical fiber (significantly increases fiber cost)
  - if splitters are placed close to the customer premises, then more splitters need to be installed (reduces fiber cost)

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# SDH/WDM ring networks (1)

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- ◆ SDH/WDM ring networks have evolved from SDH concepts
  - Idea: replace SDH timeslots with WDM wavelengths
- ◆ SDH/WDM ring networks offer better bandwidth scalability and multiple data rates
- ◆ SDH/WDM ring architectures vary from (simple) static setups to advanced sharing schemes
  - A ring consists of a set of SDH nodes connected by WDM links

# SDH/WDM ring networks (2)

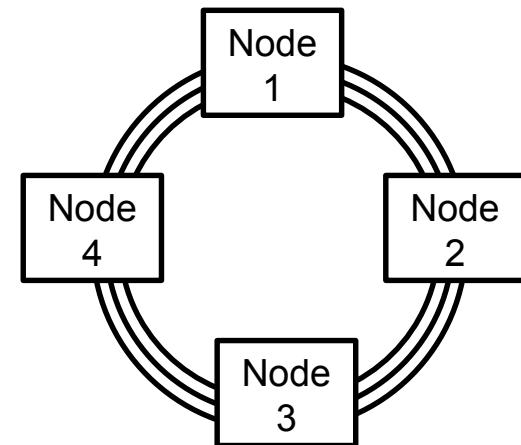
- ◆ Each wavelength carries a SDH frame of high hierarchy
- ◆ There is a traffic matrix of lower hierarchy SDH connections to be carried from input to output nodes
  - Occupy timeslots in the SDH frames of the traversed links

E.g.

$|N| = 4$  nodes

$|W| = 3$  wavelengths

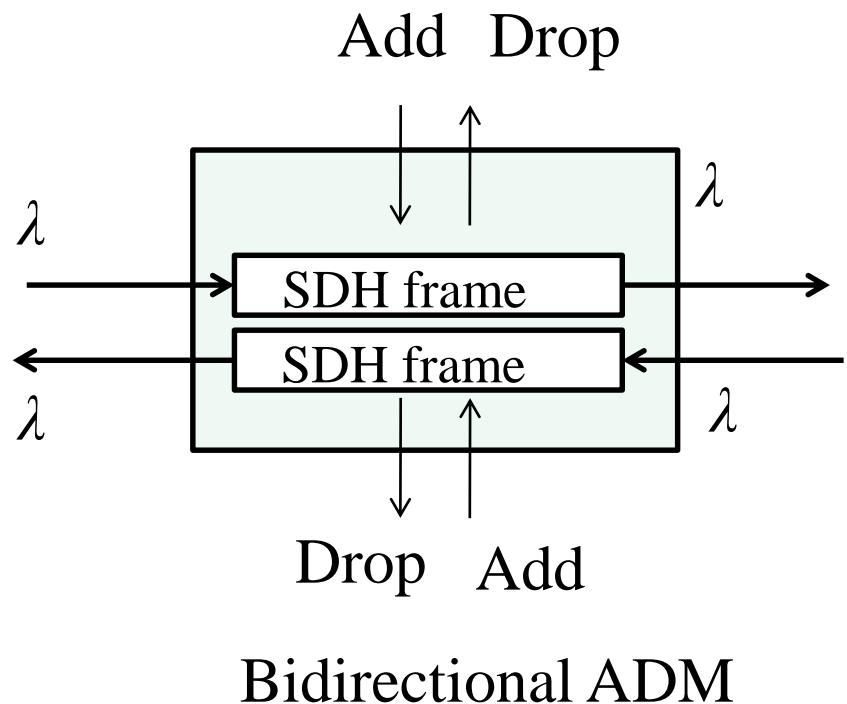
Each wavelength  $\sim$  STM-256  
frame



From: Pablo Pavon Marino, "SDH/WDM ring networks",  
Optimization and planning in optical networks

# SDH/WDM ring networks (3)

- ◆ Nodes are equipped with electronic Add/Drop Multiplexers (ADM)
  - ADM is needed to process the SDH frame inside a wavelength
  
- An ADM permits to add new connections in empty timeslots of the frame
- An ADM permits to drop connections in timeslots from the frame
- An ADM is NOT able to change the timeslot of traversing connections



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# Wavelength-routed networks - basics (1)

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- ◆ Used to build wide-area optical networks
- ◆ Solve disadvantages of B&S networks
  - Loss of power at splitters, no wavelength reuse
- ◆ Optical signal is sent via a specific network path
  - Without broadcasting

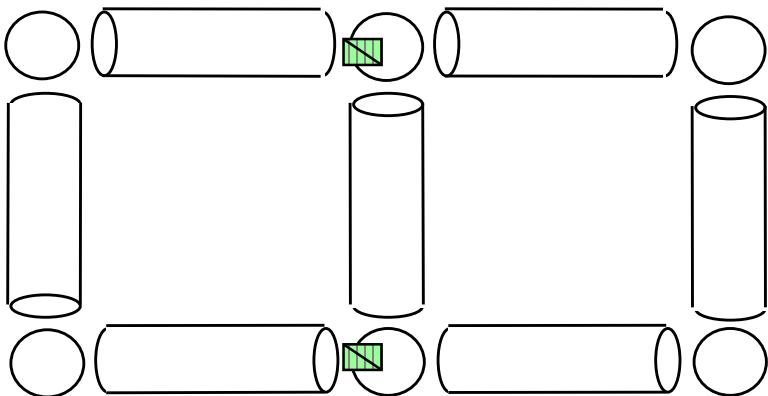
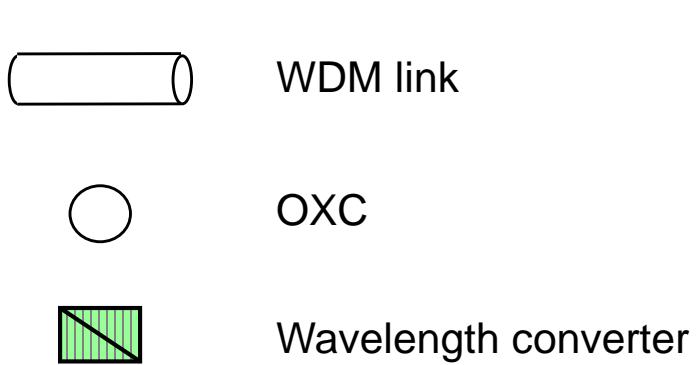
# Wavelength-routed networks - basics (2)

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- ◆ Consist of static/reconfigurable OXCs interconnected by optical fibers
  - Form an arbitrary physical topology
  - An end node is connected to OXC via a fiber link
- ◆ Every node has tunable or fixed transmitter and receivers

# Physical network topology

- ◆ A set of OXCs and optical fibers that interconnect them
  - Optical fibers ~ WDM links



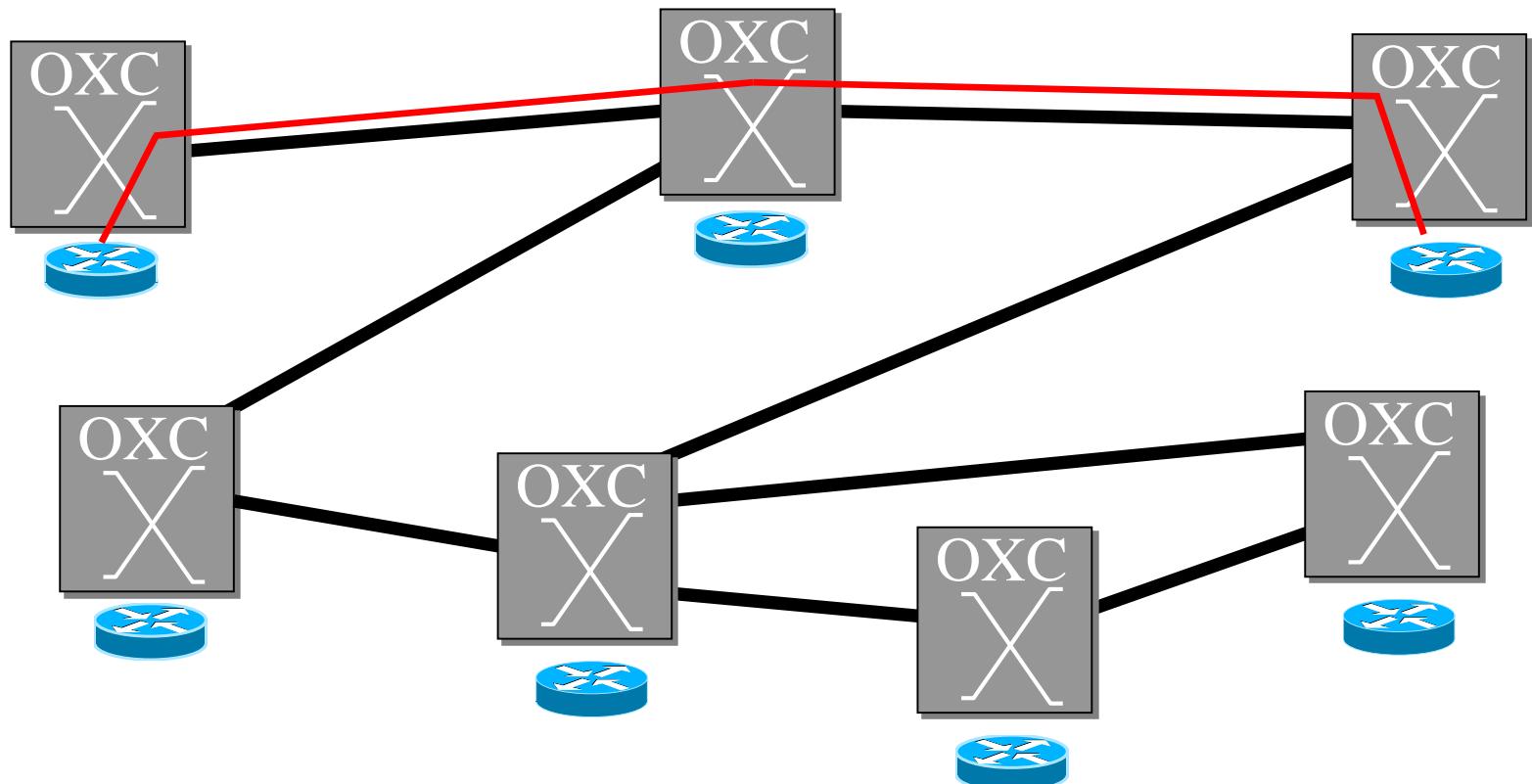
**Physical topology**

# Virtual network topology

- ◆ Which physical network path(s) will carry traffic (with as many OE conversions as possible)?
- ◆ A virtual topology (VT) is created over the physical topology
  - Links in VT: lightpaths
  - Lightpaths: all-optical connections between pairs of nodes
    - Can traverse multiple physical (fiber) links
    - Information does not require OE conversion at intermediate nodes

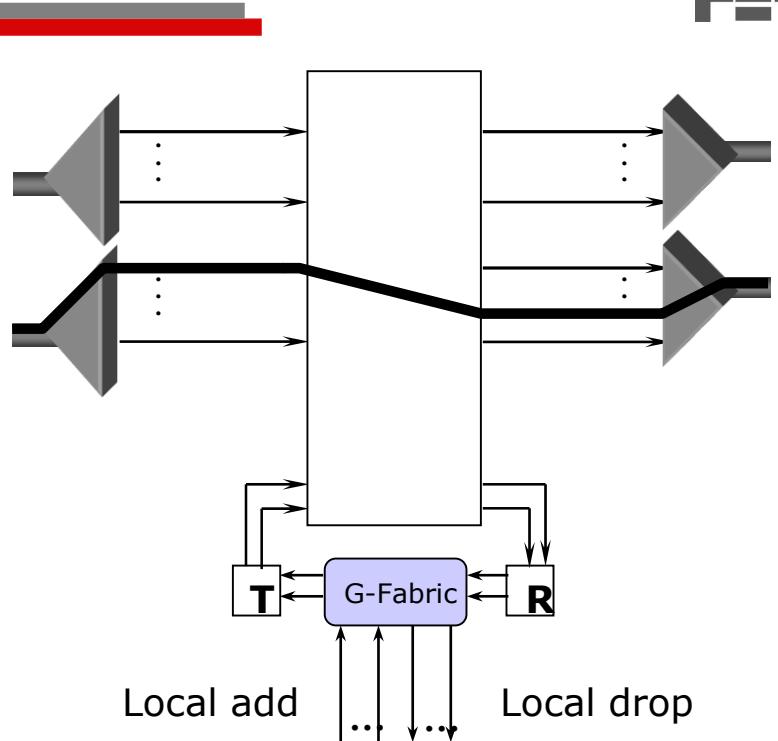
# Lightpath-based WDM networks

- Primarily deployed as a wide-area network (WAN)



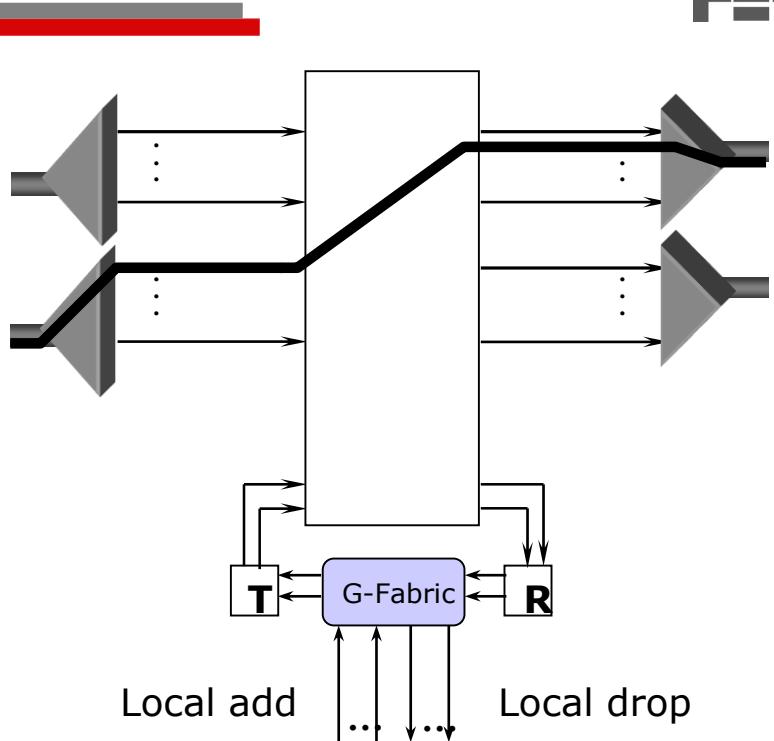
# Switching equipment (1)

- ◆ Two types of switching equipment in lightpath-based WDM networks
  - Non-reconfigurable (hard-wired)



# Switching equipment (2)

- ◆ Two types of switching equipment in lightpath-based WDM networks
  - Non-reconfigurable (hard-wired)
  - Reconfigurable: VT can change over time so as to adapt to traffic variations

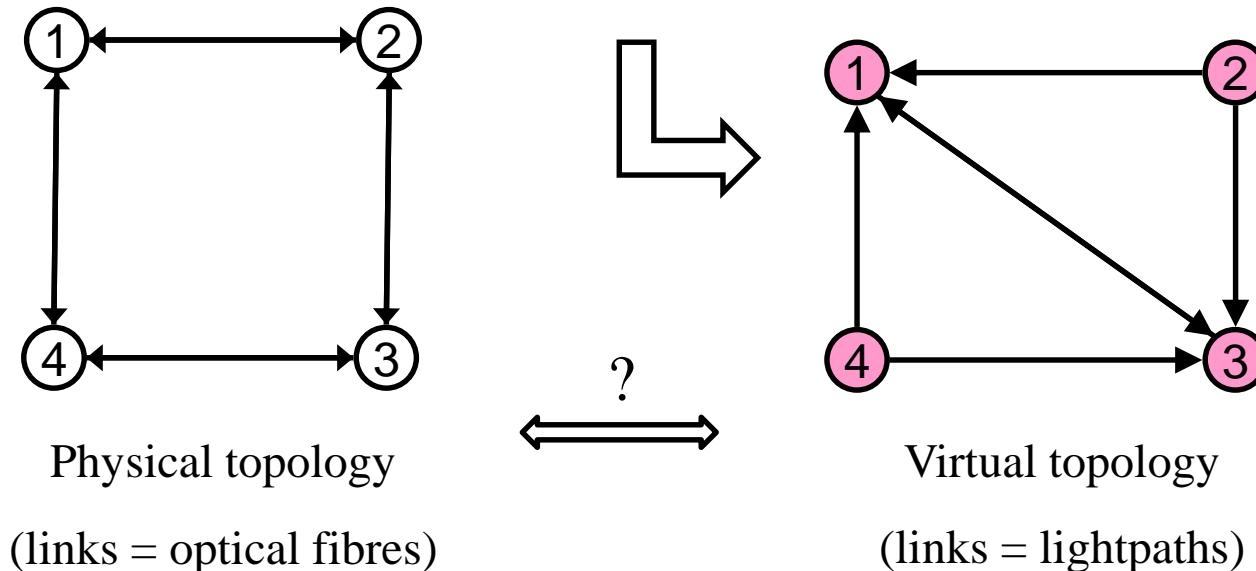


# Relation between physical and virtual topology (1)

- The set of lightpaths completely determines the VT

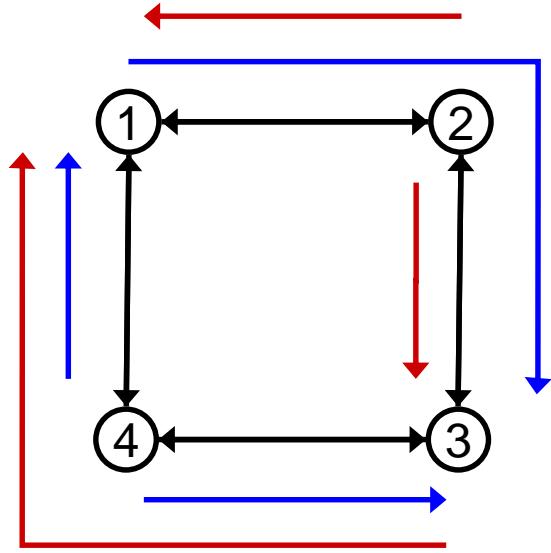
Example set of lightpaths (source/destination pairs):

$$\tau = \{(1,3), (4,3), (2,3), (4,1), (3,1), (2,1)\}$$



How to establish the virtual topology over the physical topology?

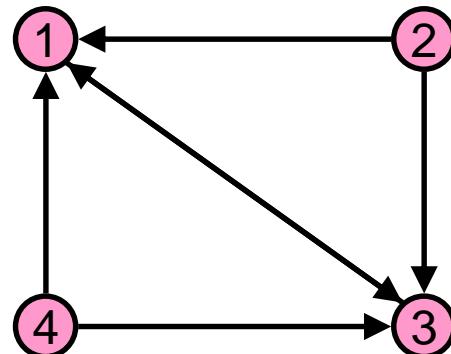
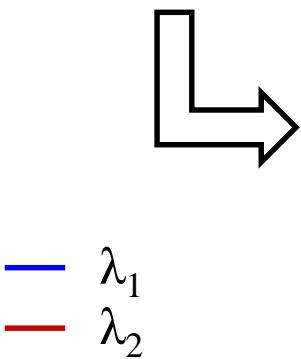
# Relation between physical and virtual topology (2)



*Physical topology*

Set of lightpath demands:

$$\tau = \{(1,3), (4,3), (2,3), (4,1), (3,1), (2,1)\}$$



*Virtual topology*

*Routing and wavelength assignment  
(RWA) problem*