Lecture 8: Introduction to Multiwavelength Optical Networks

Stern and Bala (1999)
Multiwavelength Optical Networks
Chapters 1-2

Contents

Optical network

- Why optical networks?
  - "The information superhighway is still a dirt road; more accurately, it is a set of isolated multilane highways with cow paths for entrance."
- Definition: An **optical network** is a telecommunications network
  - with transmission links that are optical fibers, and
  - with an architecture that is designed to exploit the unique features of fibers.
- Thus, the term optical network (as used here)
  - does not necessarily imply a purely optical network,
  - but it does imply something more than a set of fibers terminated by electronic switches
- The "glue" that holds the purely optical network together consists of
  - optical network nodes (ONN) connecting the fibers within the network
  - network access stations (NAS) interfacing user terminals and other nonoptical end systems to the network

Network categories

- **Multiwavelength optical network**
  = WDM network
  = optical network utilizing wavelength division multiplexing (WDM)

  – **Transparent optical network** = purely optical network
    - **Static network** = broadcast-and-select network
    - **Wavelength Routed Network** (WRN)
    - **Linear Lightwave Network** (LLN) = waveband routed network

  – **Hybrid optical network** = layered optical network
    - **Logically Routed Network** (LRN)

Physical picture of the network

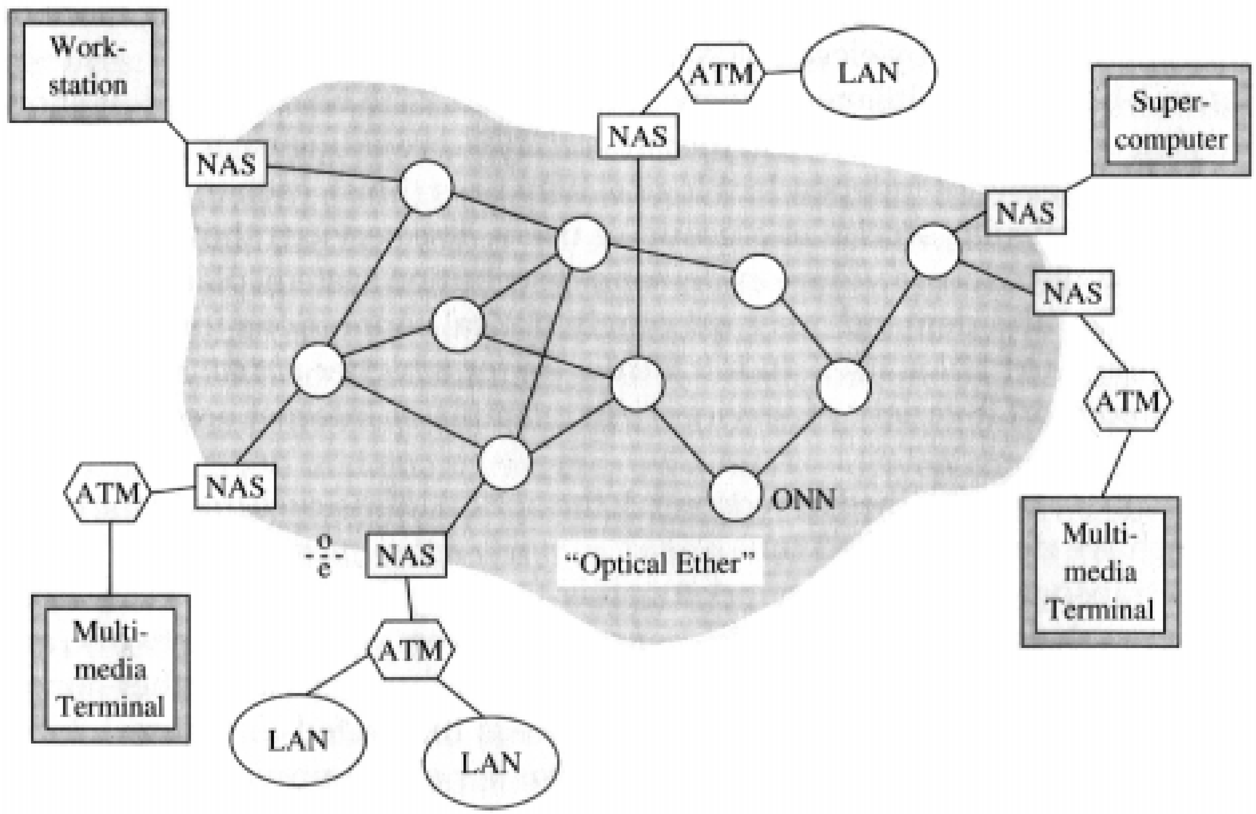

FIGURE 1.2 Physical picture of the network.

Wide area optical networks: a wish list

- **Connectivity**
  - support a very large number of stations and end systems
  - support a very large number of concurrent connections including multiple connections per station
  - support multicast connections efficiently
- **Performance**
  - high aggregate network throughput (hundreds of Tbps)
  - high user bitrate (few Gbps)
  - small end-to-end delay
  - low error rate (d) / high SNR (a)
  - low processing load in nodes and stations
  - adaptability to changing and unbalanced loads
  - efficient and rapid means of fault identification and recovery
- **Structural features**
  - scalability
  - modularity
  - survivability (fault tolerance)
- **Technology/cost issues**
  - access stations: small number of optical transceivers per station and limited complexity of optical transceivers
  - network: limited complexity of the optical network nodes, limited number and length of cables and fibers, and efficient use (and reuse) of optical spectrum

Optics vs. electronics

- **Optical domain**
  - photonic technology is well suited to certain simple (linear) signal-routing and switching functions
    - optical power combining, dividing and filtering
    - wavelength multiplexing, demultiplexing and routing
  - channelizing needed to make efficient use of the enourmous bandwith of the fiber
    - by wavelength division multiplexing (WDM)
    - many signals operating on different wavelengths share each fiber
- Thus, optics is fast but dumb
  - **connectivity bottleneck**

- **Electrical domain**
  - electronics is needed to perform more complex (nonlinear) functions
    - signal detection, regeneration and buffering
    - logic functions (e.g. reading and writing packet headers)
  - however, these complex functions limit the throughput
  - electronics also gives a possibility to include inband control information (e.g. in packet headers)
    - enabling a high degree of virtual connectivity
  - easier to control
- Thus, electronics is slow but smart
  - **electronic bottleneck**

Optics and electronics

- Hybrid approach:
  - a multiwavelength purely optical network as a physical foundation
  - one or more logical networks (LN) superimposed on the physical layer, each of which
    - designed to serve some subset of user requirements and
    - implemented as an electronic overlay
  - electronic switching equipment in the logical layer acts as a middleman
    - taking the high-bw transparent channels provided by the physical layer and organizing them into a acceptable and cost-effective form
- Why this hybrid approach?
  - Purely optical wavelength selective switches:
    - huge aggregate throughput of few connections
  - Electronic packet switches:
    - large number of relatively low bitrate virtual connections
  - Hybrid approach exploits the unique capabilities of each while circumventing their limitations

Example: LAN interconnection

- Consider a future WAN serving as a backbone that interconnects a large number of high-speed LANs (say, 10,000), accessing the WAN through LAN gateways
  - with aggregate traffic of tens of Tbps
- Purely optical approach
  - each NAS connects its LAN to the other LAN's through individual optical connections $\Rightarrow$ 9,999 connections per NAS
  - this is far too much for current optical technology
- Purely electronic approach
  - electronics easily supports the required connectivity via virtual connections
  - however, the electronic processing bottleneck in the core network does not allow such traffic
- Hybrid approach: both objectives achieved, since
  - LN composed of ATM switches provides the necessary connectivity
  - the optical backbone at the physical layer supports the required throughput

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Network links

- A large number of concurrent connections can be supported on each network link through successive levels of **multiplexing**
  - **Space division multiplexing** in the fiber layer:
    - A cable consists of several (sometimes more than 100) fibers, which are used as bidirectional pairs
  - **Wavelength division multiplexing** (WDM) in the optical layer:
    - A fiber carries connections on many distinct wavelengths (λ-channels)
    - The assigned wavelengths must be spaced sufficiently apart to keep neighbouring signal spectra from overlapping (to avoid interference)
  - **Time division multiplexing** (TDM) in the transmission channel sublayer:
    - A λ-channel is divided (in time) into frames and timeslots
    - Each timeslot in a frame corresponds to a transmission channel, which is capable to carry a logical connection
    - The location of the timeslot within the frame identifies the transmission channel

Fiber resources

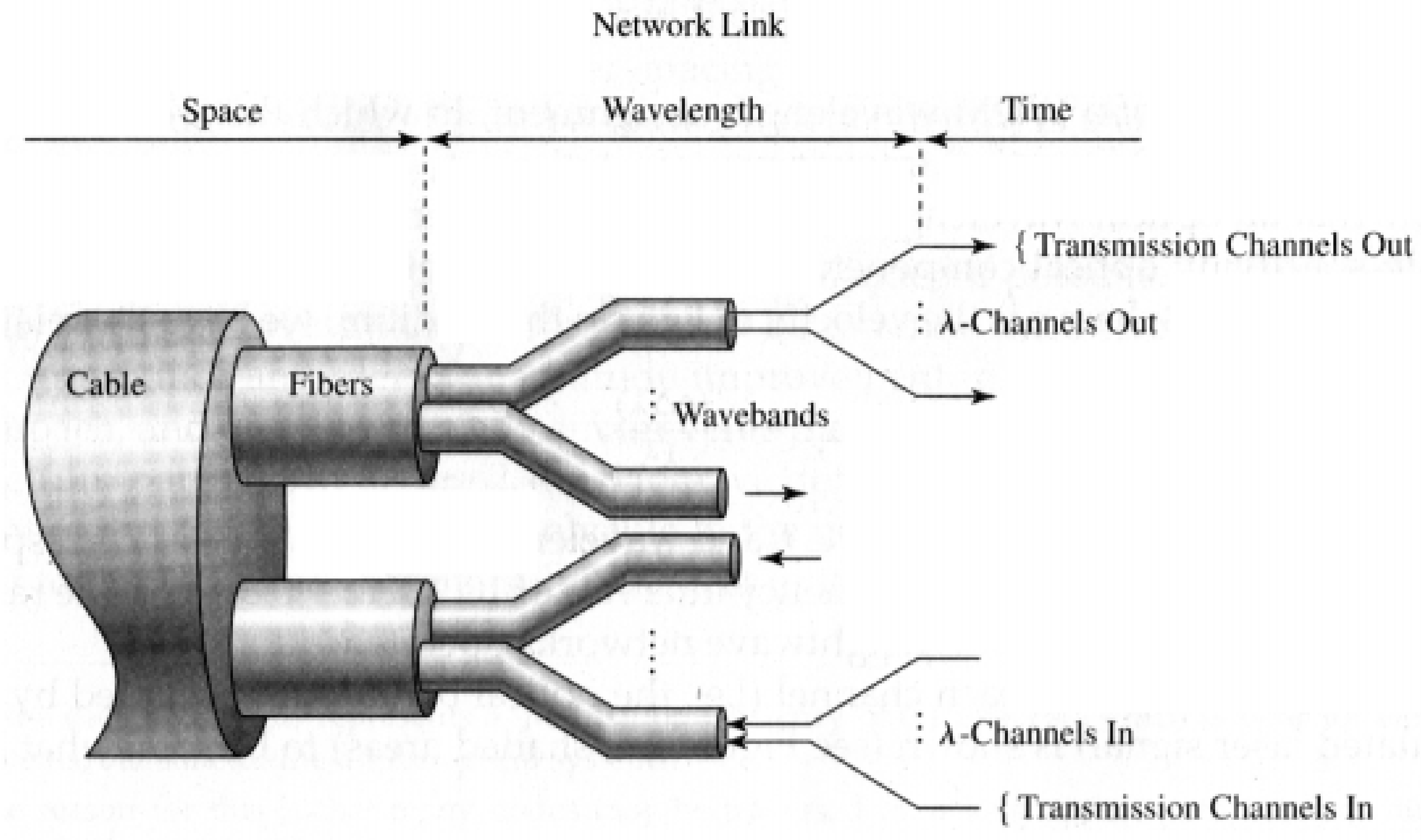


FIGURE 2.3 Fiber resources.

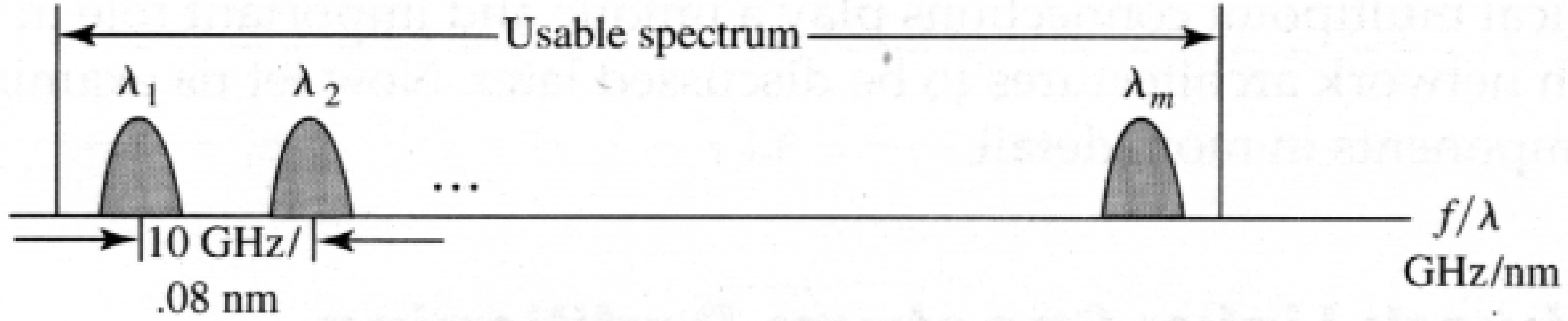
Optical spectrum

- Since wavelength λ and frequency f are related by $f\,\lambda = c$, where c is the velocity of light in the medium, we have the relation

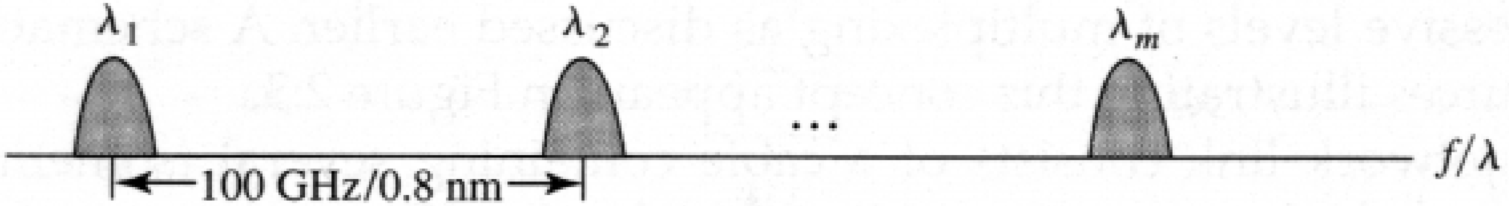
$$\Delta f \approx -\frac{c\,\Delta\lambda}{\lambda^2}$$

- Thus, 10 GHz ≈ 0.08 nm and 100 GHz ≈ 0.8 nm in the range of 1,550 nm, where most modern lightwave networks operate
- The 10-GHz channel spacing is sufficient to accommodate λ-channels carrying aggregate digital bitrates on the order of **1 Gbps**
  - assumed a modulation efficiency of 0.1 bps/Hz typical for optical systems
- The 10-GHz channel spacing is suitable for optical receivers, but much too dense to permit independent **wavelength routing** at the network nodes. For this, 100-GHz channel spacing is needed.
- In a **waveband routing** network, several λ-channels (with 10-GHz channel spacing) comprise an independently routed waveband (with 100-GHz spacing between wavebands).

Wavelength partitioning of the optical spectrum



(a) λ-channel Spacing for Separability at Receivers



(b) λ-channel Spacing for Separability at Network Nodes

Waveband partitioning of the optical spectrum

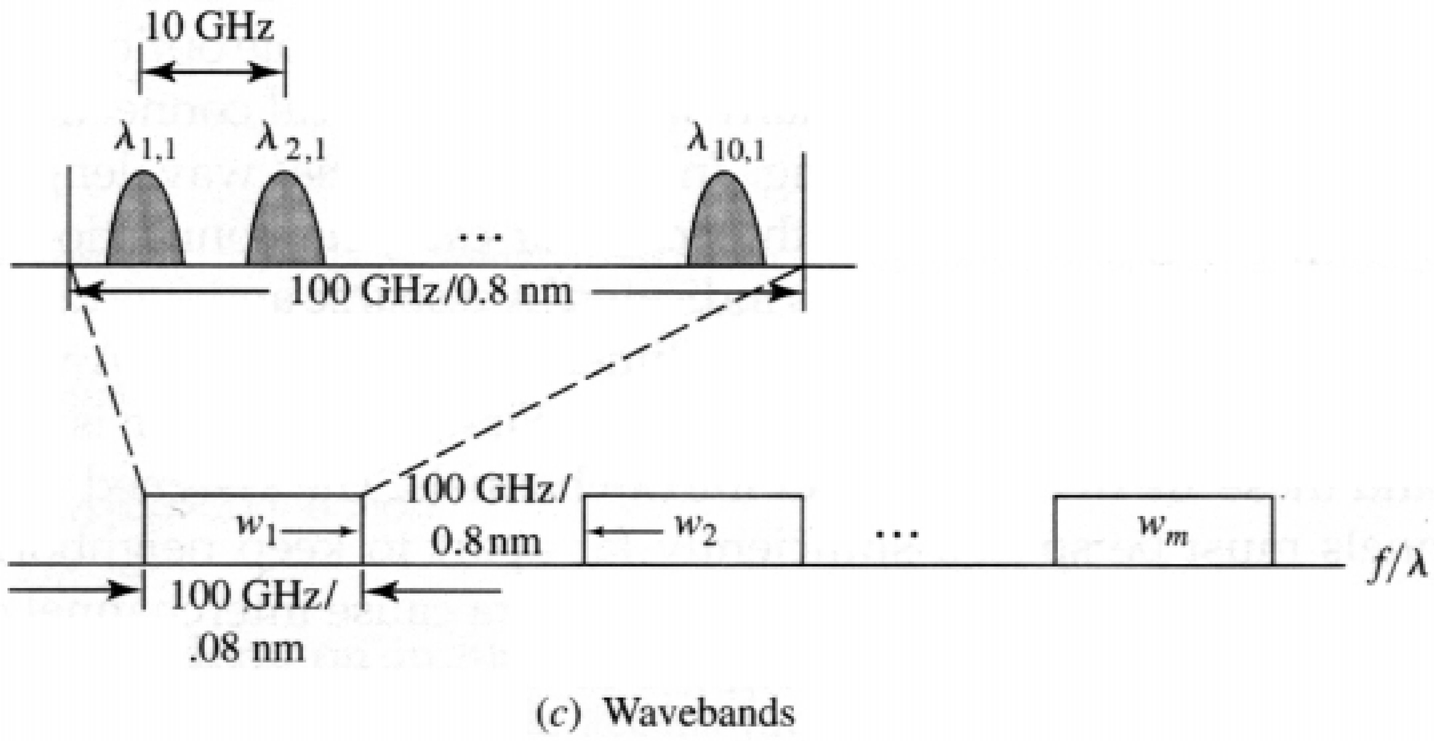


FIGURE 2.4 Wavelength and waveband partitioning of the optical spectrum.

Network picture based on spectrum partitioning

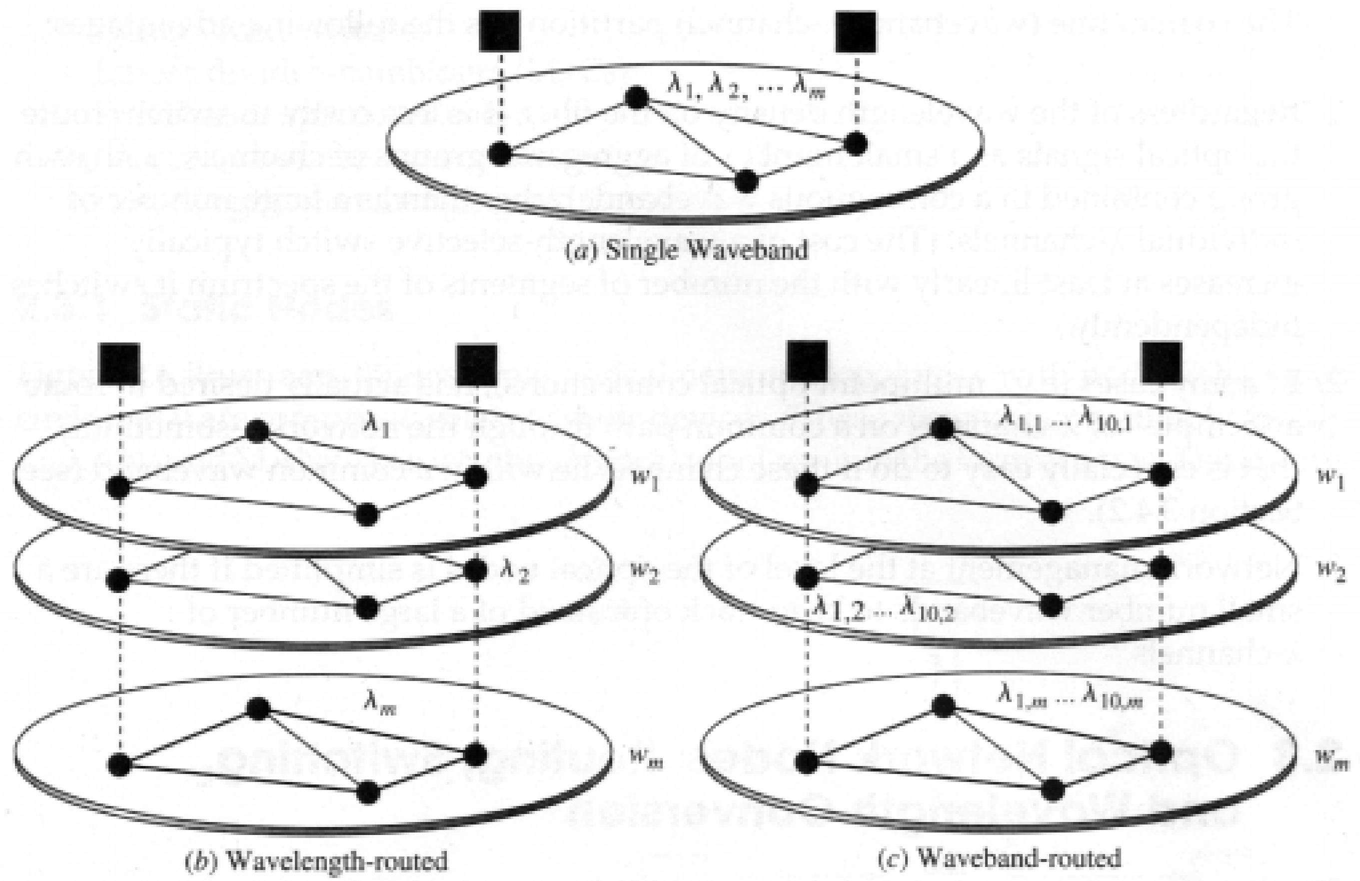


FIGURE 2.5 Network picture based on spectrum partitioning.

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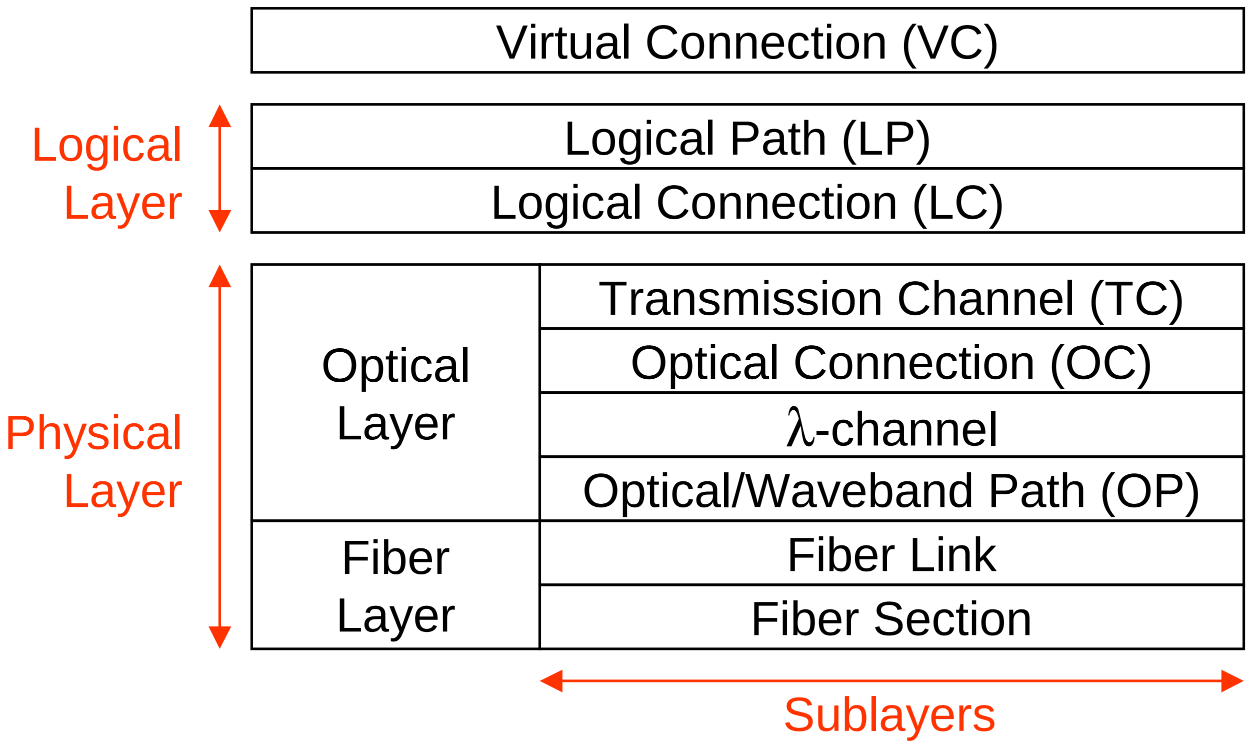
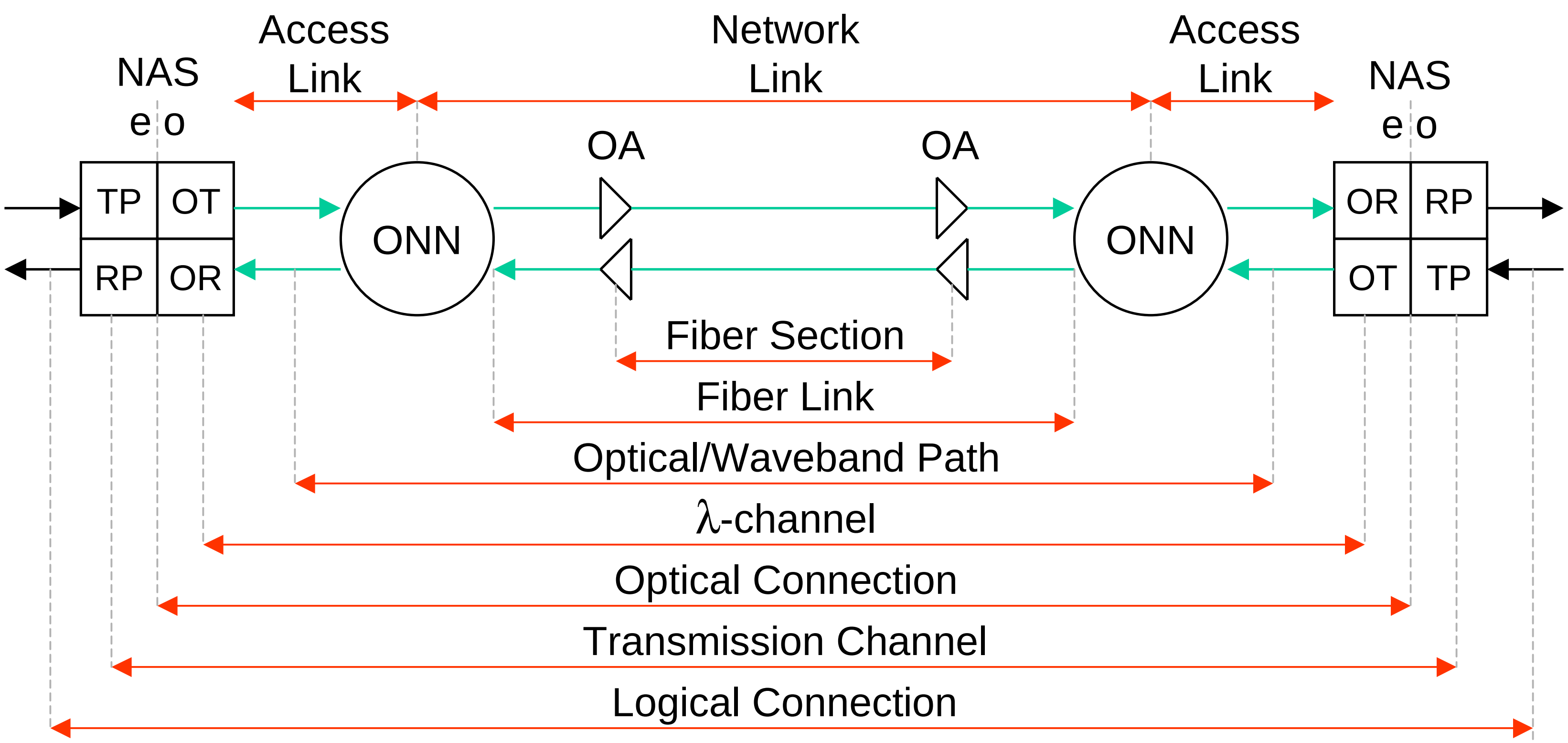
Layered view of the optical network (1)



Layered view of the optical network (2)



Layers and sublayers

- The main consideration in breaking down the optical layer into sublayers is to account for
  - multiplexing,
  - multiple access (at several layers), and
  - switching
- Using **multiplexing**,
  - several logical connections may be combined on a λ-channel originating from a station
- Using **multiple access**,
  - λ-channels originating from several stations may carry multiple logical connections to the same station
- Through **switching**,
  - many distinct optical paths may be created on different fibers in the network, using (and reusing) λ-channels on the same wavelength

Typical connection

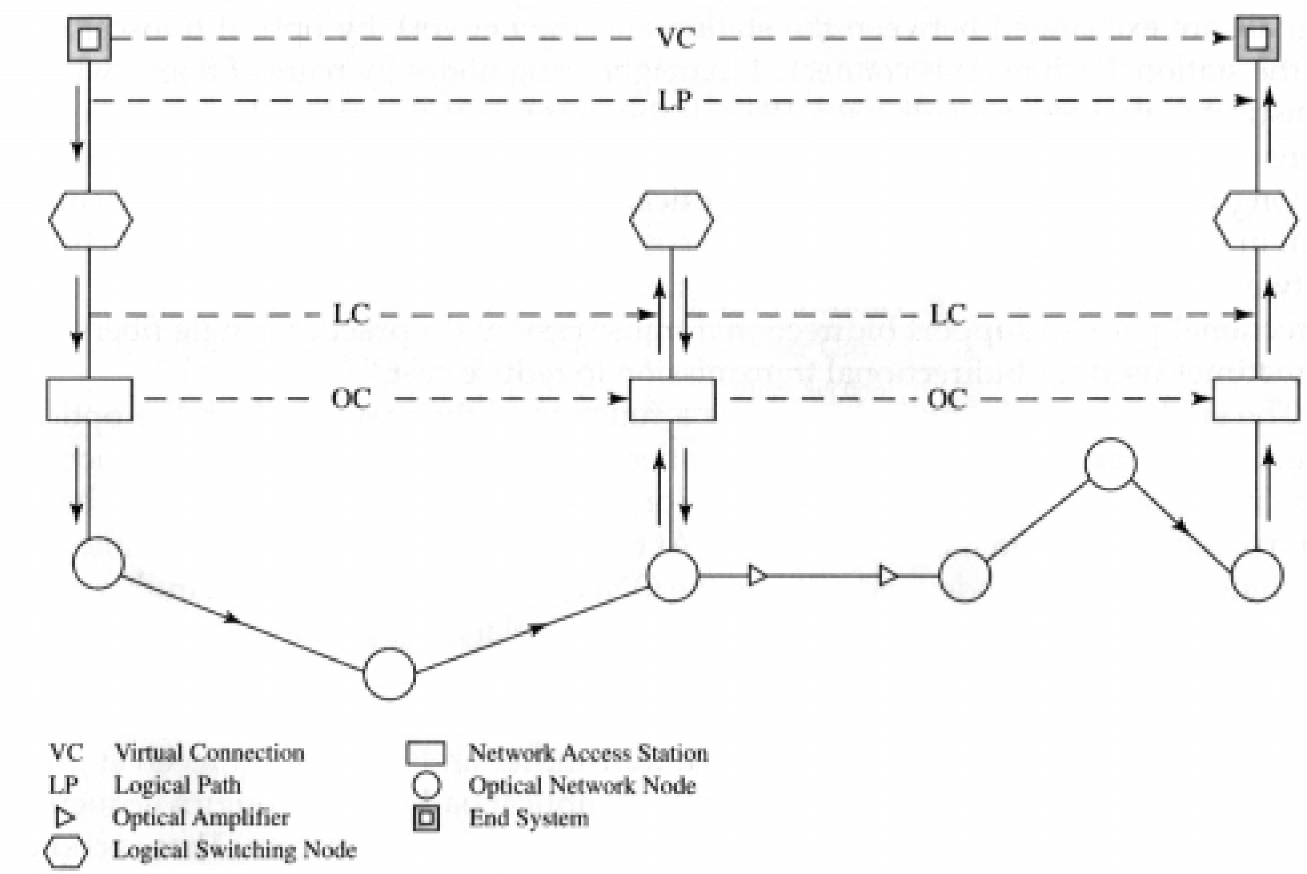


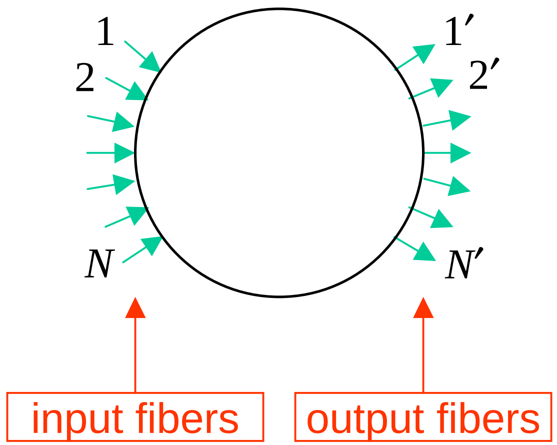
FIGURE 2.2 A typical connection.

Contents

Optical network nodes (1)

- **Optical Network Node** (**ONN**) operates in the optical path sublayer connecting N input fibers to N outgoing fibers
- ONNs are in the optical domain

- **Basic building blocks**:
  - wavelength multiplexer (WMUX)
  - wavelength demultiplexer (WDMUX)
  - directional coupler (2x2 switch)
    - static
    - dynamic
  - wavelength converter (WC)



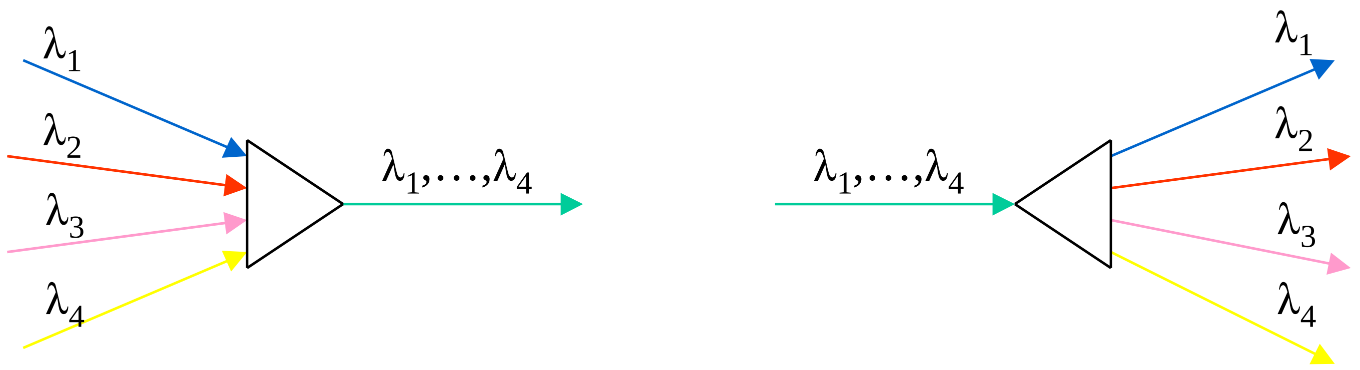
Optical network nodes (2)

- **Static** nodes
  - without wavelength selectivity,
    - NxN **broadcast star** (= **star coupler**)
    - Nx1 **combiner**
    - 1xN **divider**
  - with wavelength selectivity,
    - NxN **wavelength router** (= **Latin router**)
    - Nx1 **wavelength multiplexer** (WMUX)
    - 1xN **wavelength demultiplexer** (WDMUX)

Optical network nodes (3)

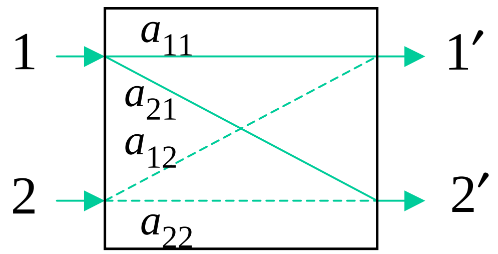
- **Dynamic** nodes
  - without wavelength selectivity (optical crossconnect (OXC)):
    - NxN **permutation switch**
    - RxN **generalized switch**
    - RxN **linear divider-combiner** (LDC)
  - with wavelength selectivity,
    - NxN **wavelength selective crossconnect** (WSXC) with M wavelengths
    - NxN **wavelength interchanging crossconnect** (WIXC) with M wavelengths
    - RxN **waveband selective LDC** with M wavebands

Wavelength multiplexer and demultiplexer



WMUX WDMUX

Directional Coupler (1)



- **Directional coupler** (= 2x2 switch) is an optical four-port
  - ports 1 and 2 designated as input ports
  - ports 1’ and 2’ designated as output ports
- Optical power
  - enters the coupler through fibers attached to input ports,
  - is divided and combined **linearly**, and
  - leaves via fibers attached to output ports
- Power relations for input signal powers P_1 and P_2 and output powers $P_{1'}$ and $P_{2'}$ are given by

$$P_{1'} = a_{11}P_1 + a_{12}P_2$$

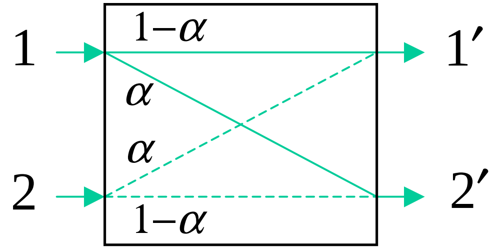
$$P_{2'} = a_{21}P_1 + a_{22}P_2$$

- Denote the **power transfer matrix** by $A = [a_{ij}]$

Directional Coupler (2)

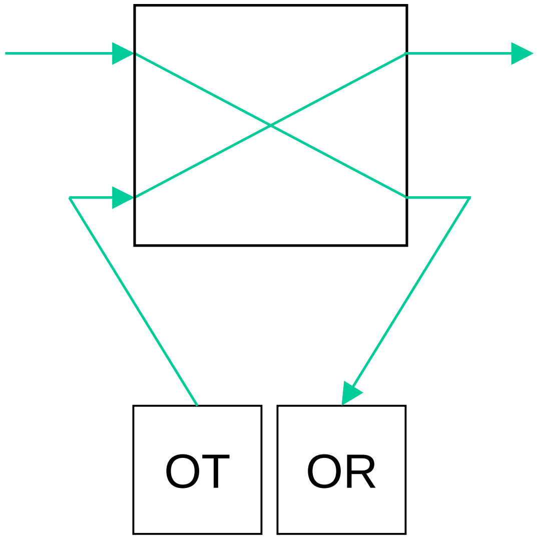
- Ideally, the power transfer matrix A is of the form

$$A = \begin{bmatrix} 1-\alpha & \alpha \\ \alpha & 1-\alpha \end{bmatrix}, \qquad 0 \le \alpha \le 1$$

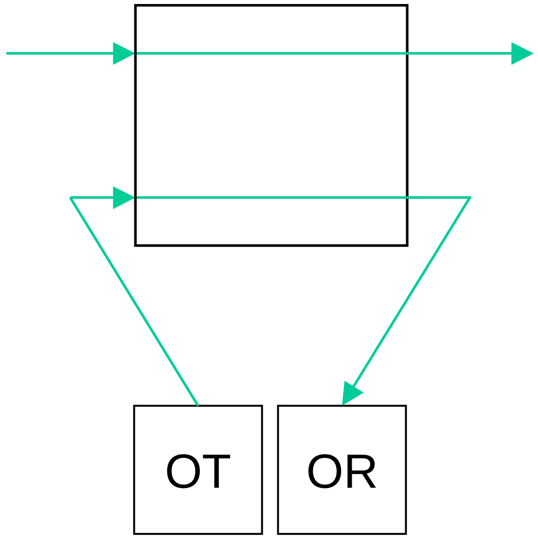


- If the parameter α is fixed, the device is **static**
    - e.g. with α = 1/2 and signals present at both inputs, the device acts as a 2x2 star coupler
- If α can be varied through some external control, the device is **dynamic** or controllable
    - e.g. add-drop switch
- If only input port 1 is used (i.e., $P_2 = 0$), the device acts as a 1x2 **divider**
- If only output port 1' is used (and 2' terminated), the device acts as a 2x1 **combiner**

Add-drop switch



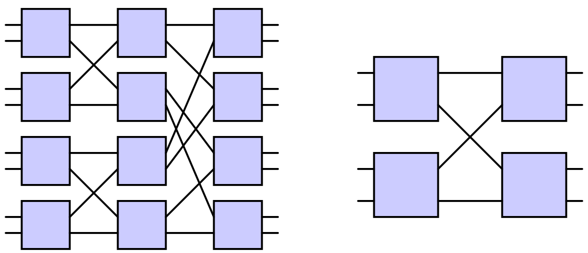
Add-drop state

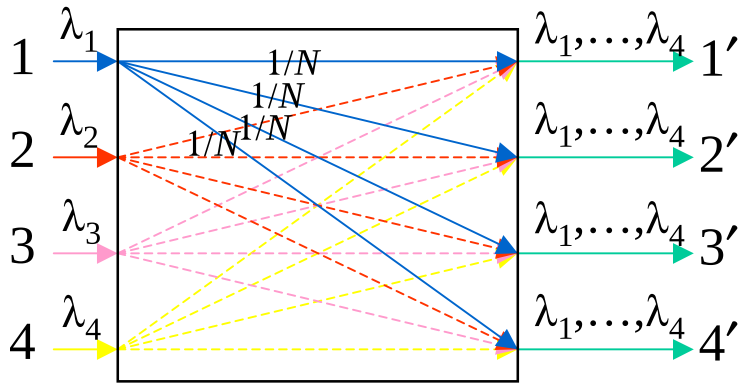


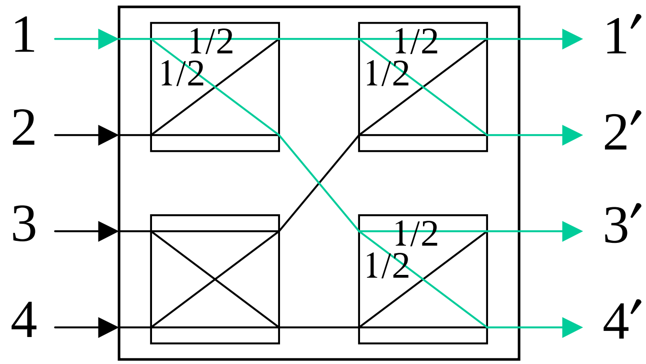
Bar state

Broadcast star

- Static NxN **broadcast star** with N wavelengths can carry
  - N simultaneous **multicast** optical connections (= full multipoint optical connectivity)
- Power is divided uniformly
- To avoid collisions:
  - each input signal must use different wavelength
- Directional coupler realization
  - (N/2) $\log_2 N$ couplers needed



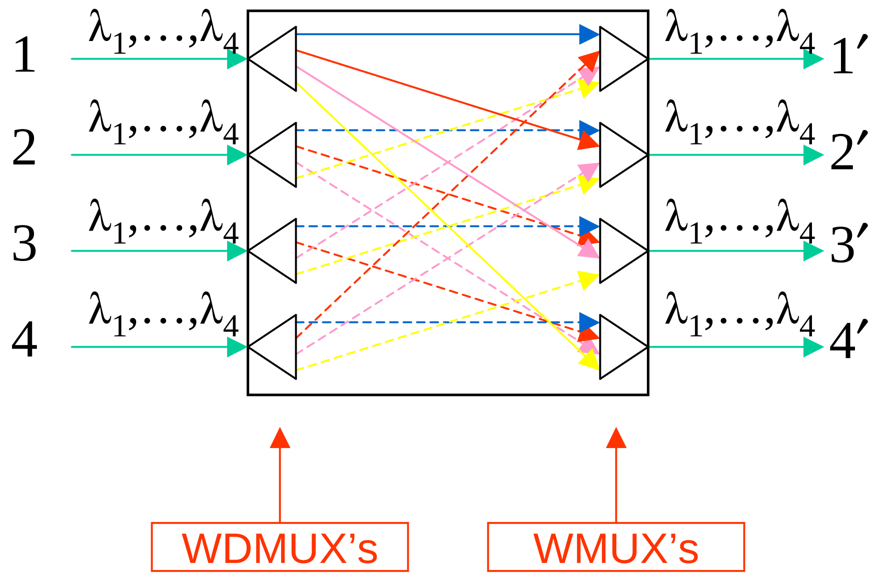




broadcast star realized by directional couplers

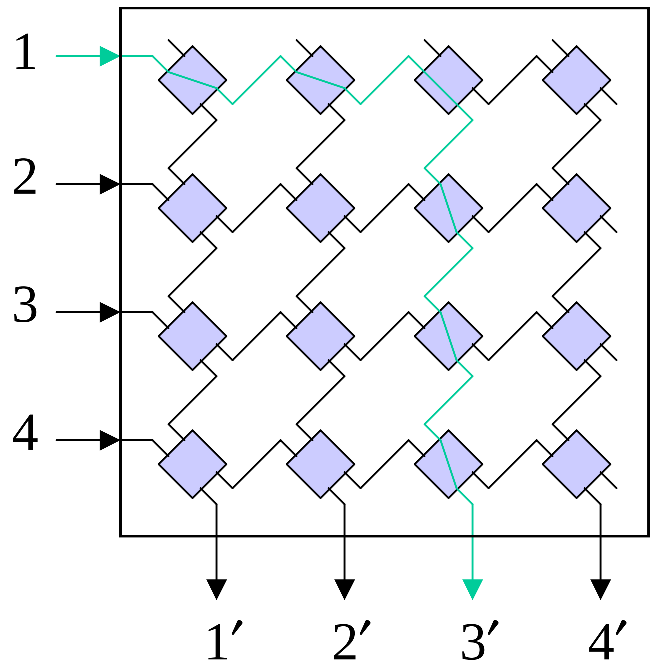
Wavelength router

- Static NxN **wavelength router** with N wavelengths can carry
  - N^2 simultaneous **unicast** optical connections (= full point-to-point optical connectivity)
- Requires
  - N 1xN WDMUX's
  - N Nx1 WMUX's



Crossbar switch

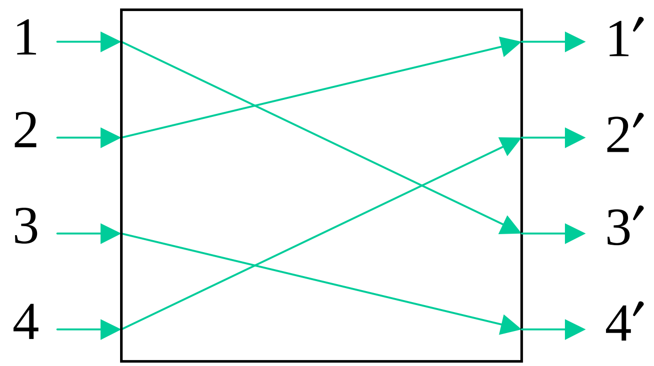
- Dynamic RxN **crossbar switch** consists of
  - R input lines
  - N output lines
  - RN crosspoints
- Crosspoints implemented by **controllable** optical couplers
  - thus, RN couplers needed
- A crossbar can be used as
  - a NxN **permutation switch** (then R = N) or
  - a RXN **generalized switch**



crossbar used as a permutation switch

Permutation switch

- Dynamic NxN **permutation switch** (e.g. crossbar switch)
  - unicast optical connections between input and output ports
  - N! **connection states** (if nonblocking)
  - each connection state can carry N simultaneous unicast optical connections
  - representation of a connection state by a NxN **connection matrix**



output ports

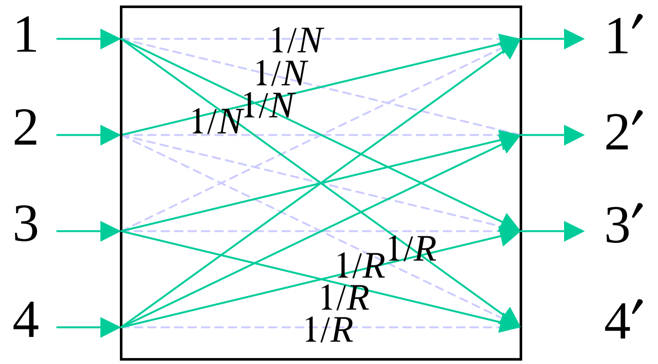
input ports

	1′	2′	3′	4′
1			1	
2	1			
3				1
4		1		

Generalized switch

- Dynamic RxN **generalized switch** (e.g. crossbar switch)
  - any input/output pattern possible
  - 2^{NR} **connection states**
  - each connection state can carry (at most) R simultaneous multicast optical connections
  - representation of a connection state by a RxN **connection matrix**
- Input/output power relation $P' = AP$ with NxR power transfer matrix $A = [a_{ij}]$, where

$$a_{ij} = \begin{cases} \frac{1}{NR}, & \text{if switch } (i,j) \text{ is on} \\ 0, & \text{otherwise} \end{cases}$$

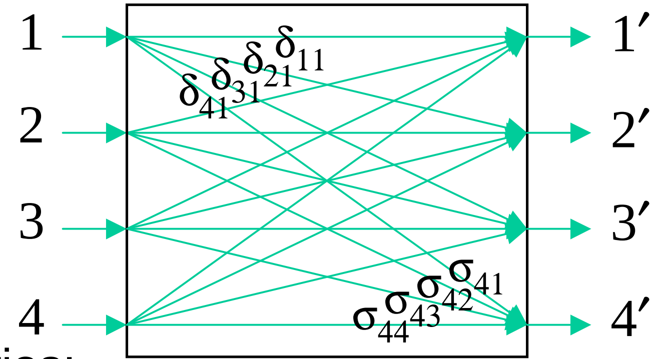


output ports

input ports

	1′	2′	3′	4′
1			1	1
2	1			
3		1		1
4	1	1	1	

Linear Divider-Combiner (LDC)



- **Linear Divider-Combiner** (LDC) is a generalized switch that
  - controls power-dividing and power-combining ratios
  - resulting in less inherent loss than the crossbar
- Power-dividing and power-combining ratios:
  - δ_{ij} = the fraction of power from input port j directed to output port i'
  - σ_{ij} = the fraction of power from input port j combined onto output port i
- In the ideal case of lossless couplers, we have constraints

$$\sum_i \delta_{ij} = 1 \quad \text{and} \quad \sum_j \sigma_{ij} = 1$$

- The resulting power transfer matrix $A = [a_{ij}]$ is such that

$$a_{ij} = \delta_{ij}\sigma_{ij}$$

LDC and generalized switch realizations

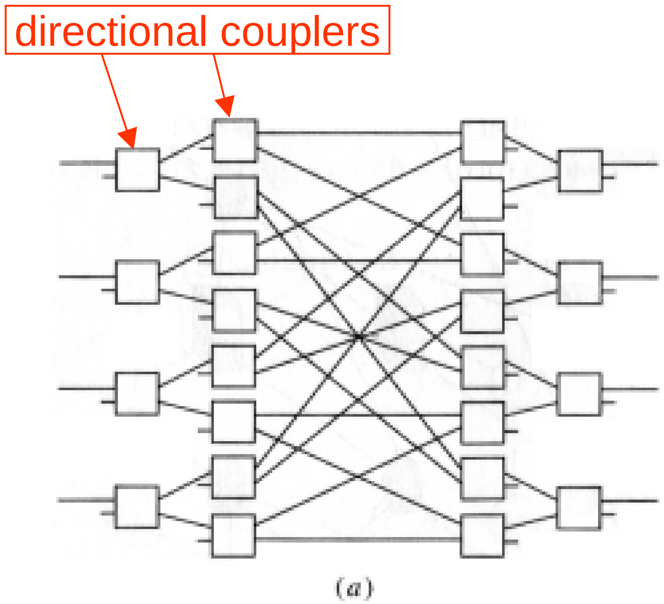


FIGURE 2.20 δ–σ Linear divider-combiner.

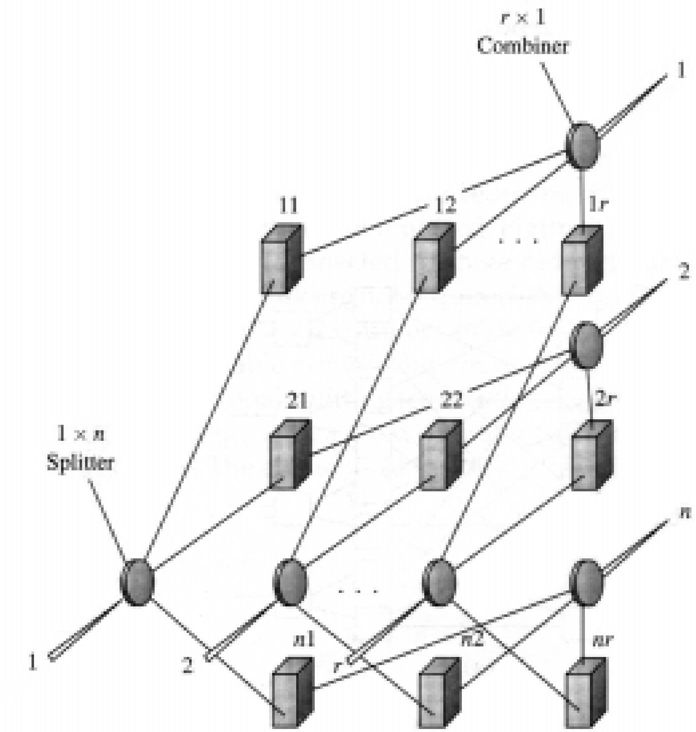
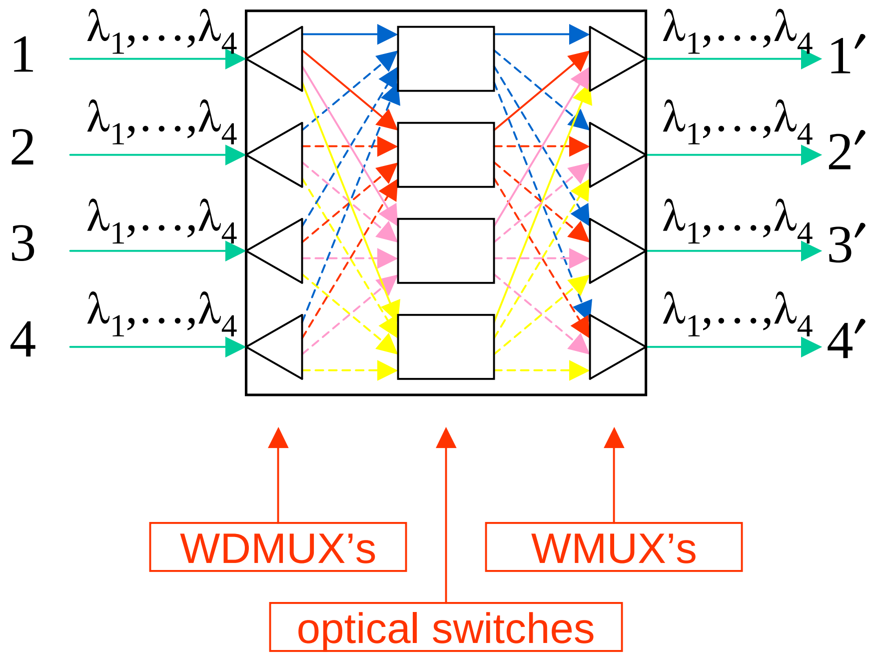


FIGURE 2.19 Generalized optical switch.

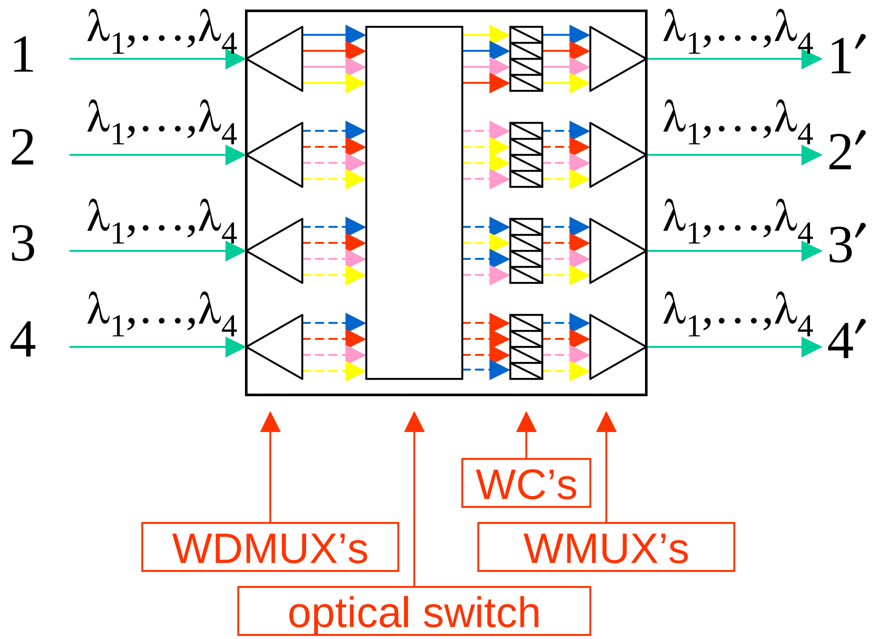
Wavelength selective cross-connect (WSXC)

- Dynamic NxN **wavelength selective crossconnect** (WSXC) with M wavelengths
  - includes N 1xM WDMUXs, M NxN permutation switches, and N Mx1 WMUXs
  - $(N!)^M$ connection states if the permutation switches are nonblocking
  - each connection state can carry NM simultaneous unicast optical connections
  - representation of a connection state by M NxN **connection matrices**



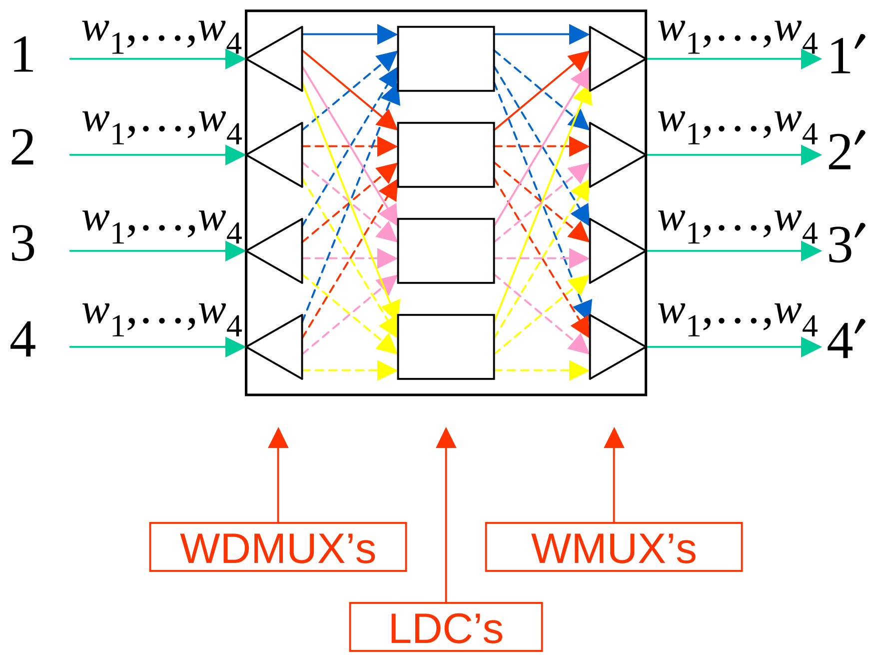
Wavelength interchanging cross-connect (WIXC)

- Dynamic NxN **wavelength interchanging crossconnect** (WIXC) with M wavelengths
  - includes N 1xM WDMUXs, 1 NM x NM permutation switch, NM WCs, and N Mx1 WMUXs
  - (NM)! connection states if the permutation switch is nonblocking
  - each connection state can carry NM simultaneous unicast connections
  - representation of a connection state by a NMxNM **connection matrix**



Waveband selective LDC

- Dynamic RxN **waveband selective LDC** with M wavebands
  - includes R 1xM WDMUXs, M RxN LDCs, and N Mx1 WMUXs
  - 2^{RNM} connection states (if used as a generalized switch)
  - each connection state can carry (at most) RM simultaneous multicast connections
  - representation of a connection state by a M RxN **connection matrices**

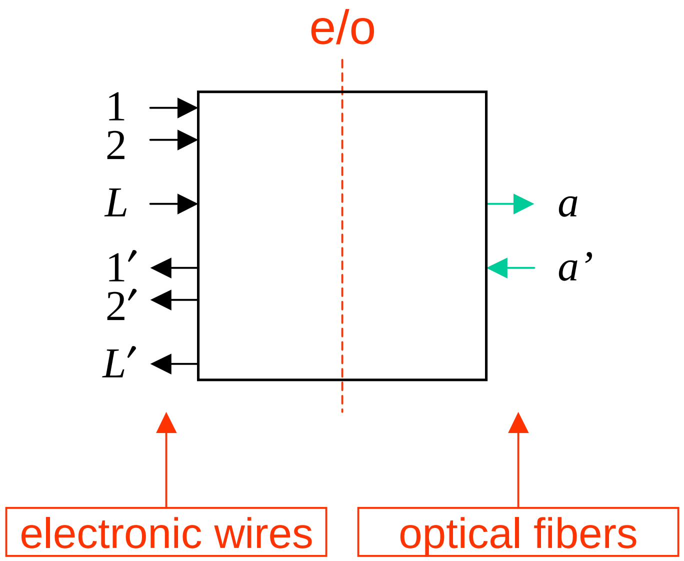


Contents

Network access stations (1)

- **Network Access Station** (**NAS**) operates in the logical connection, transmission channel and λ-channel sublayers
- NAS's are the gateways between the electrical and optical domains

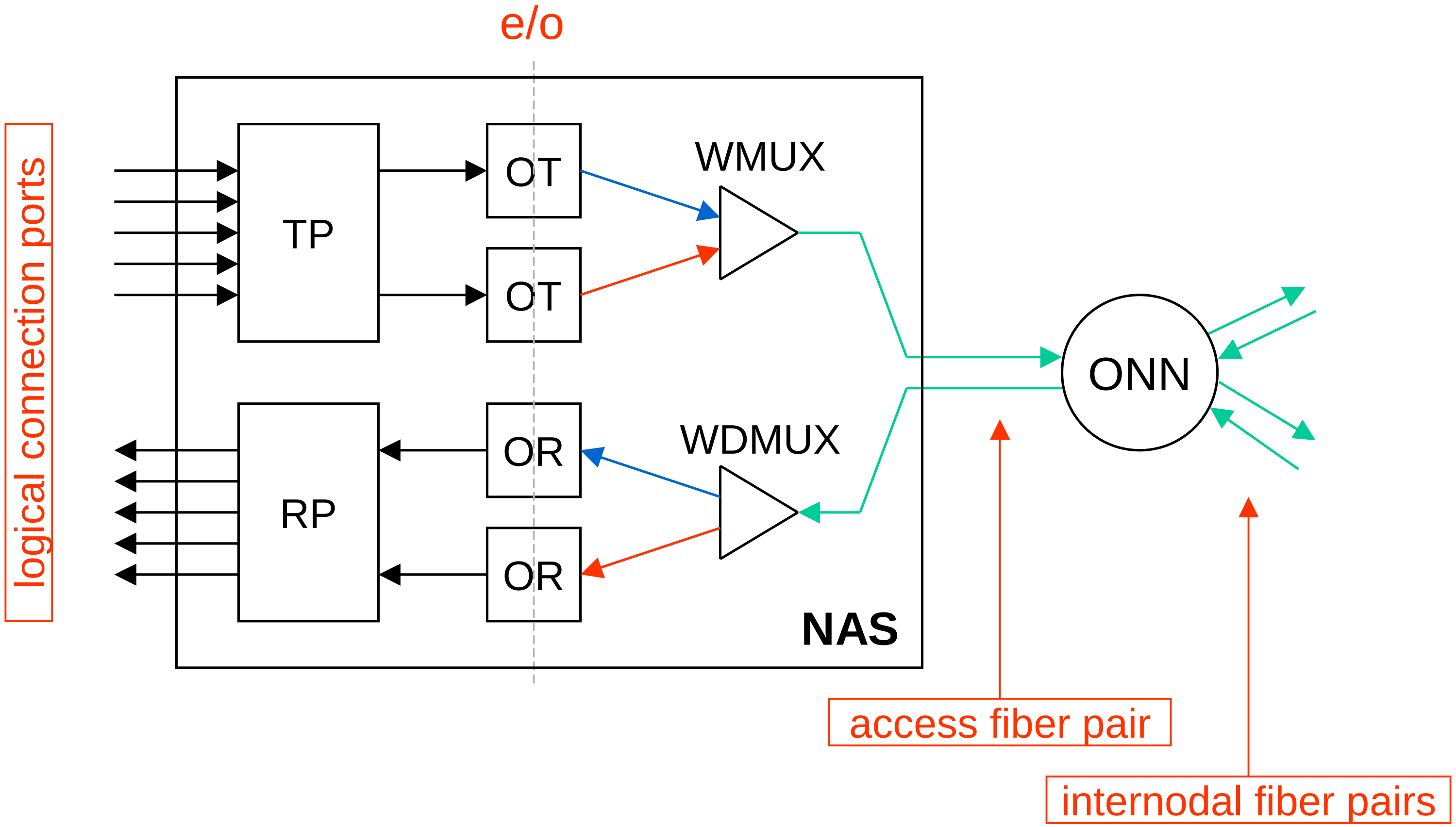
- **Functions**:
  - interfaces the external LC ports to the optical transceivers
  - implements the functions necessary to move signals between the electrical and optical domains



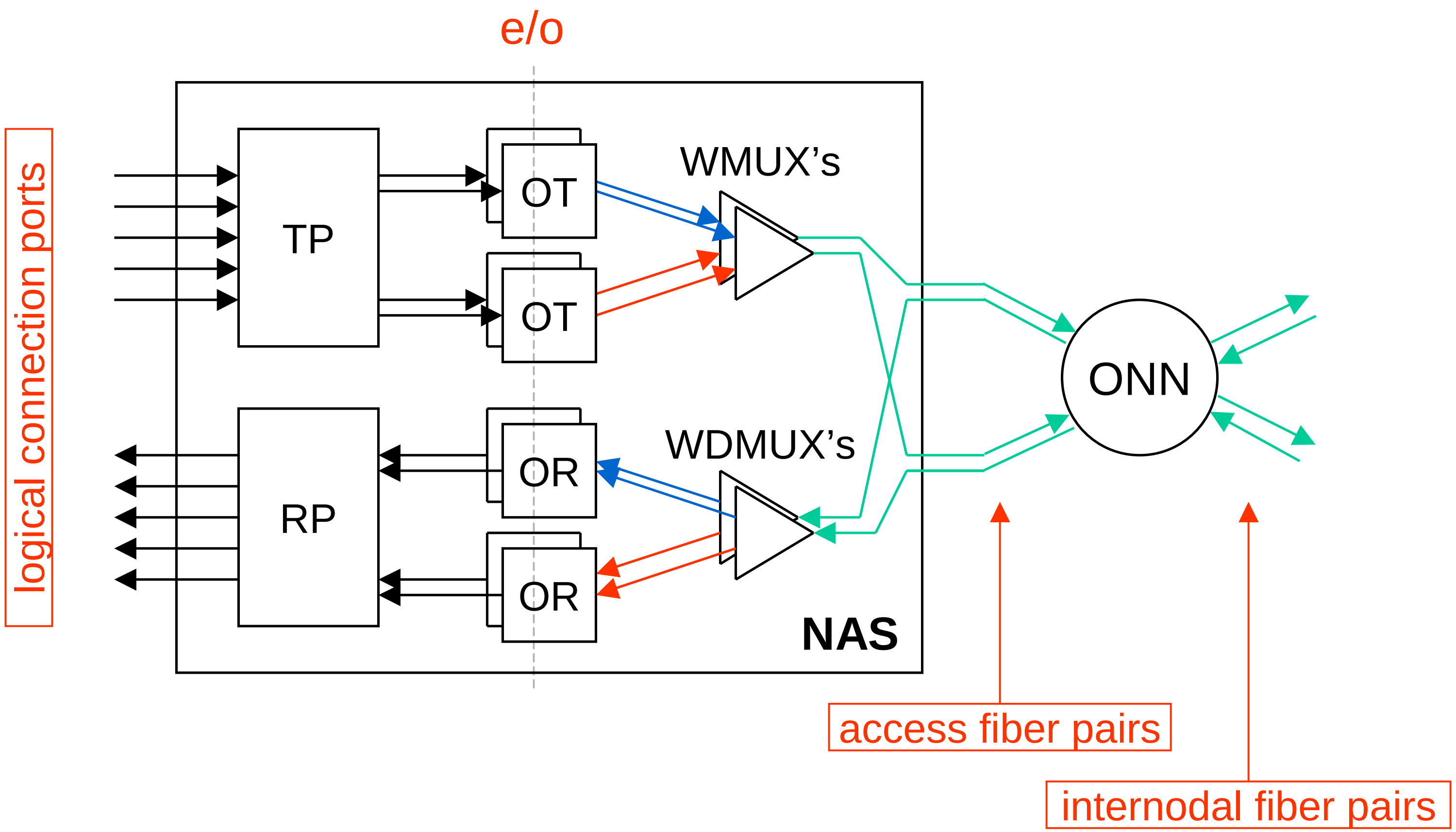
Network access stations (2)

- **Transmitting side** components:
  - **Transmission Processor** (TP) with a number of LC input ports and transmission channel output ports connected to optical transmitters
    - converts each logical signal to a transmission signal
  - **Optical Transmitters** (OT) with a laser modulated by transmission signals and connected to a WMUX
    - generates optical signals
  - **WMUX** multiplexes the optical signals to an outbound access fiber
- **Receiving side** components:
  - **WDMUX** demultiplexes the optical signals from an inbound access fiber and passes them to optical receivers
  - **Optical Receivers** (OR) convert the optical power to electrical transmission signals, which are corrupted versions of the original transmitted signals
  - **Reception Processor** (RP) converts the corrupted transmission signal to a logical signal (e.g. regenerating digital signals)

Elementary network access station



Nonblocking network access station



Wavelength add-drop multiplexer (WADM)

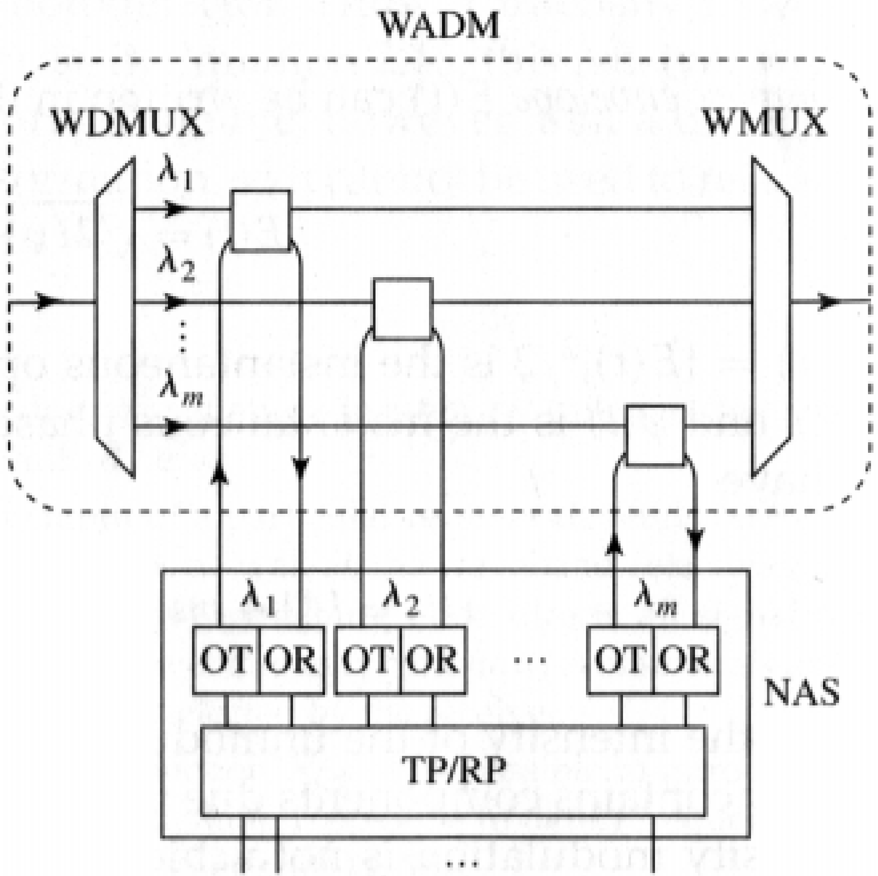


FIGURE 2.31 WADM–NAS combination.

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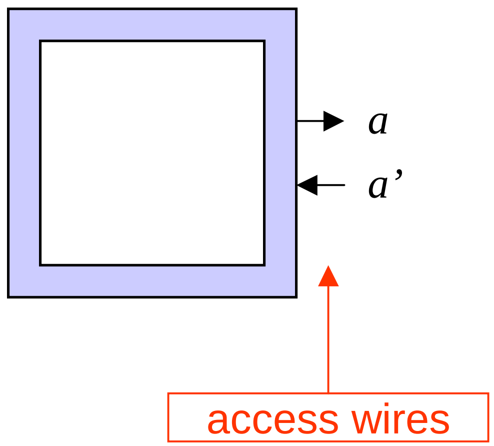
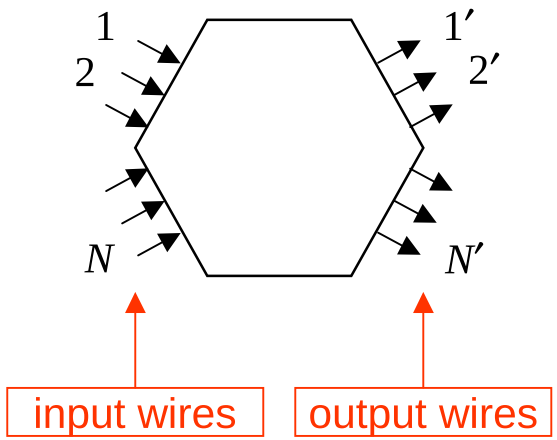
End System

- **End systems** are in the electrical domain
- In transparent optical networks, they are directly connected to NAS's
  - Then, the purpose is to create full logical connectivity between end stations
- In hybrid networks, they are connected to LSN's
  - Then, the purpose is to create full virtual connectivity between end stations



Logical Switching Node (LSN)

- **Logical switching nodes** (LSN) are needed in hybrid networks, i.e. **logically routed networks** (LRN)
- LSNs are in the electrical domain
- They may be e.g.
  - SONET digital cross-connect systems (DCS), or
  - ATM switches, or
  - IP routers



Logically routed network

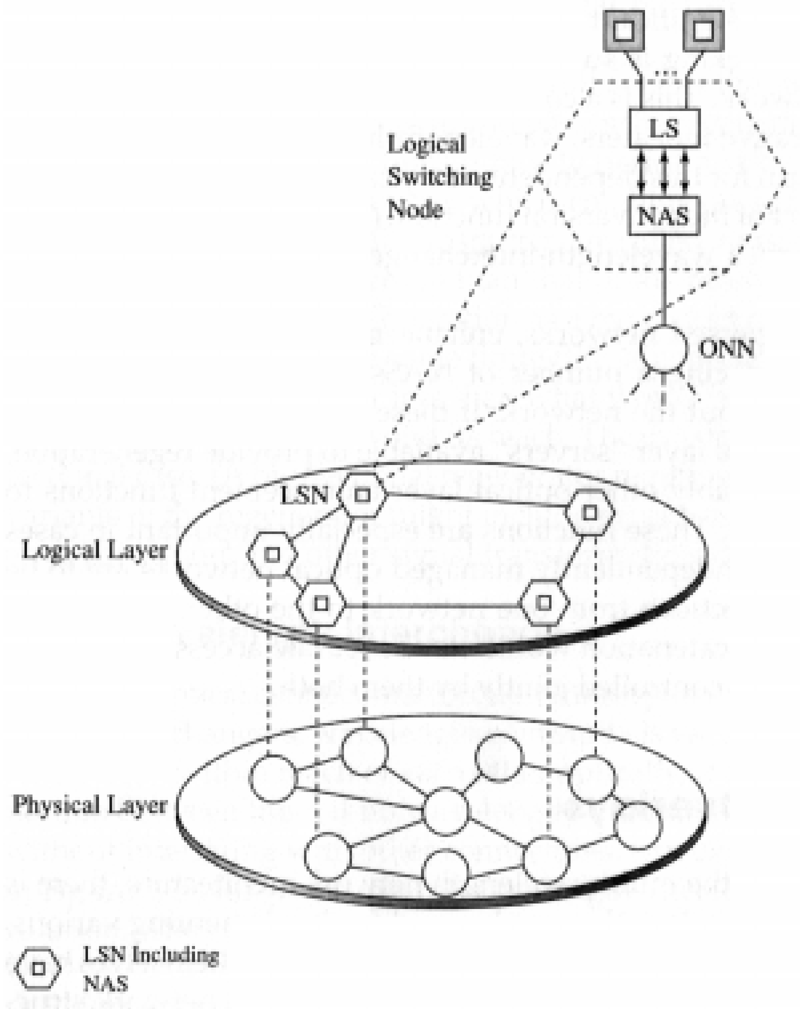


FIGURE 2.36 Logically routed network.

Contents

Connectivity

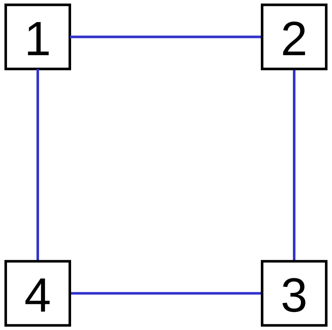
- **Transmitting side**:
  - **one-to-one**
    - (single) unicast
  - **one-to-many**
    - multiple unicasts
    - (single) multicast
    - multiple multicasts

- **Receiving side**:
  - **one-to-one**
    - (single) unicast
    - (single) multicast
  - **many-to-one**
    - multiple unicasts
    - multiple multicasts

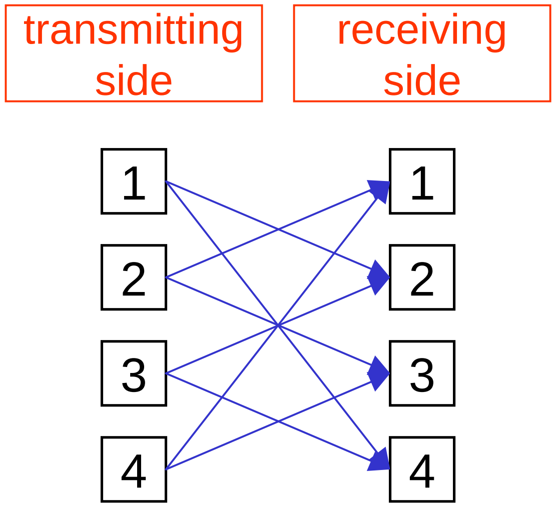
- **Network wide**:
  - point-to-point
  - multipoint

Connection Graph (CG)

- Representing **point-to-point** connectivity between end systems



Connection graph

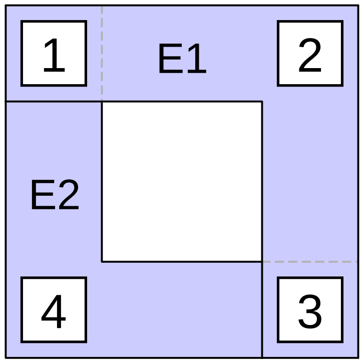


Bipartite representation

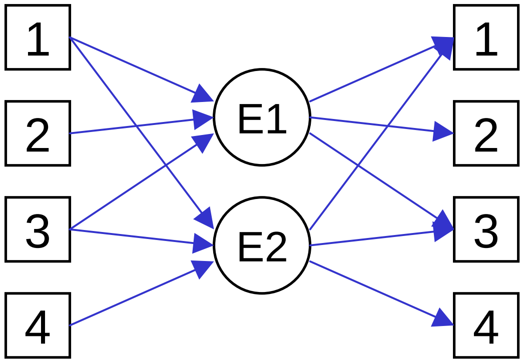
Connection Hypergraph (CH)

- Representing **multipoint** connectivity between end systems

transmitting side | hyper-edges | receiving side



Connection hypergraph



Tripartite representation

Contents

Connections in various layers

- **Logical connection** sublayer:
  - Logical connection (LC) is a unidirectional connection between external ports on a pair of source and destination network access stations (NAS)
- **Optical connection** sublayer:
  - Optical connection (OC) defines a relation between one transmitter and one or more receivers, all operating in the same wavelength
- **Optical path** sublayer:
  - Optical path (OP) routes the aggregate power on one waveband on a fiber, which could originate from several transmitters within the waveband

Notation for connections in various layers

- **Logical connection** sublayer:
  - $[a,b]$ = point-to-point logical connection from an external port on station a to one on station b
  - $[a,\{b,c,\ldots\}]$ = multicast logical connection from a to set $\{b,c,\ldots\}$
    - station a sends the *same* information to all receiving stations
- **Optical connection** sublayer:
  - (a,b) = point-to-point optical connection from station a to station b
  - $(a,b)_k$ = point-to-point optical connection from a to b using wavelength λ_k
  - $(a,\{b,c,\ldots\})$ = multicast optical connection from a to set $\{b,c,\ldots\}$
- **Optical path** sublayer:
  - $\langle a,b\rangle$ = point-to-point optical path from station a to station b
  - $\langle a,b\rangle_k$ = point-to-point optical path from a to b using waveband w_k
  - $\langle a,\{b,c,\ldots\}\rangle$ = multicast optical path from a to set $\{b,c,\ldots\}$

Example of a logical connection between two NAS's

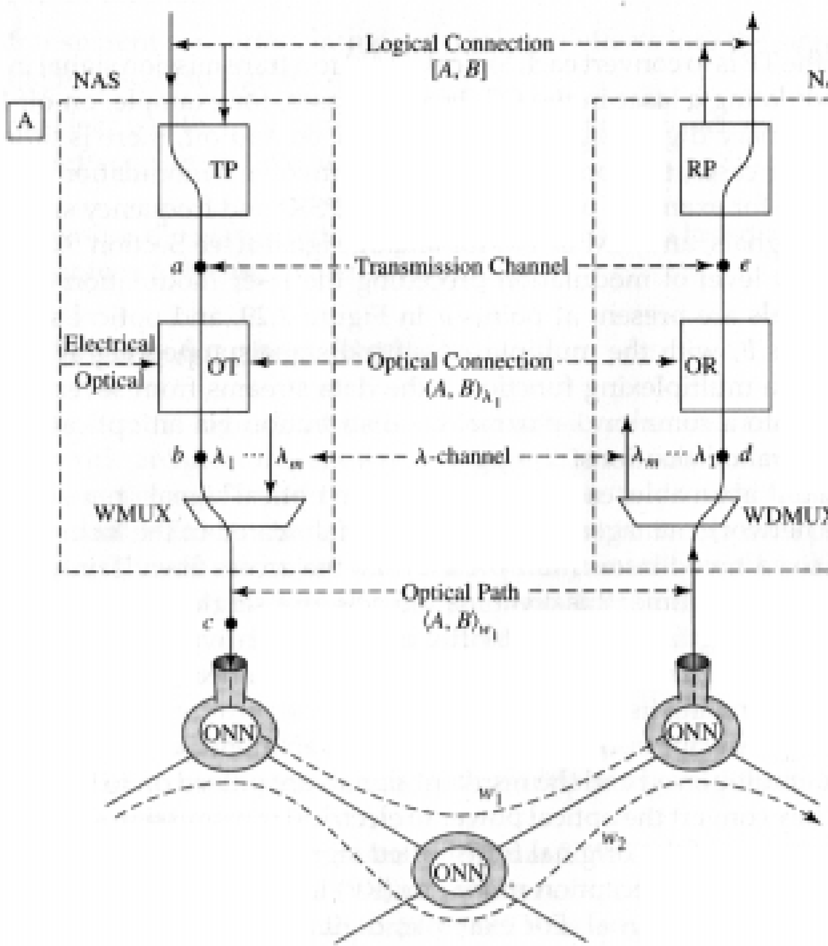
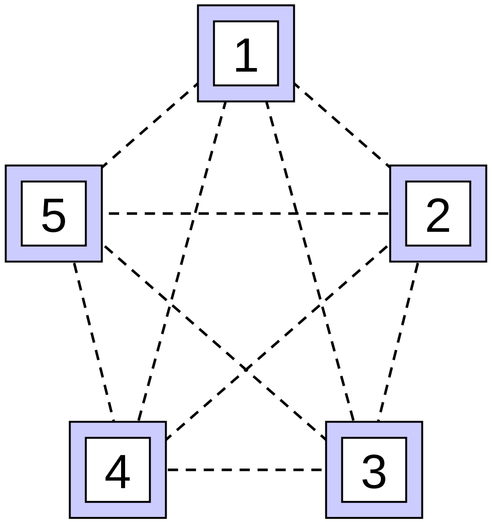


FIGURE 2.30 Example of a logical connection between two NASs.

Contents

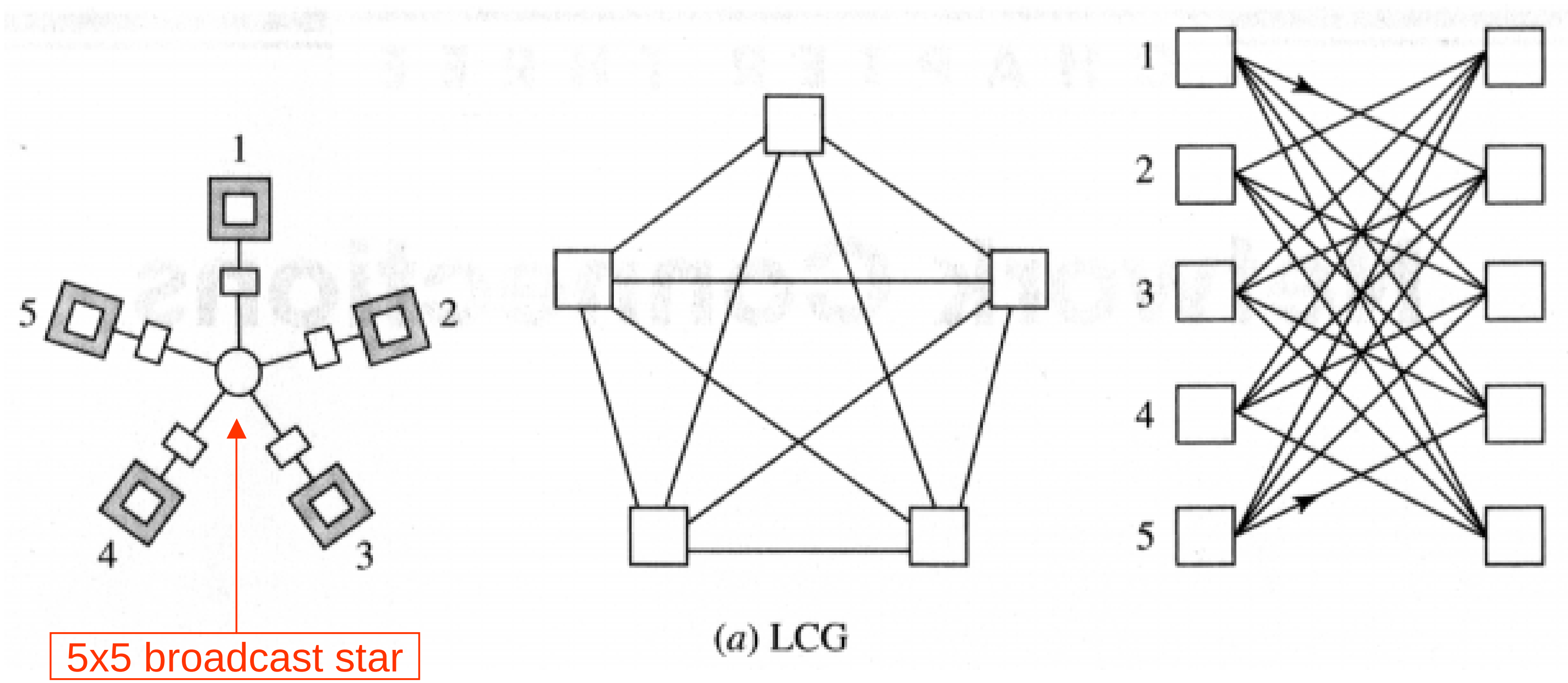
Example: realization of full connectivity between 5 end systems



Solutions

- **Static network** based on star physical topology
  - full connectivity in the logical layer (20 logical connections)
  - 4 optical transceivers per NAS, 5 NAS’s, 1 ONN (broadcast star)
  - 20 wavelengths for max throughput by WDM/WDMA
- **Wavelength routed network** (WRN) based on bidirectional ring physical topology
  - full connectivity in the logical layer (20 logical connections)
  - 4 optical transceivers per NAS, 5 NAS’s, 5 ONN’s (WSXC’s)
  - 4 wavelengths (assuming elementary NAS’s)
- **Logically routed network** (LRN) based on star physical topology and unidirectional ring logical topology
  - full connectivity in the virtual layer
    but only partial connectivity in the logical layer (5 logical connections)
  - 1 optical transceiver per NAS, 5 NAS’s, 1 ONN (WSXC), 5 LSN’s
  - 1 wavelength

Static network realization



(a) LCG

Wavelength routed network realization

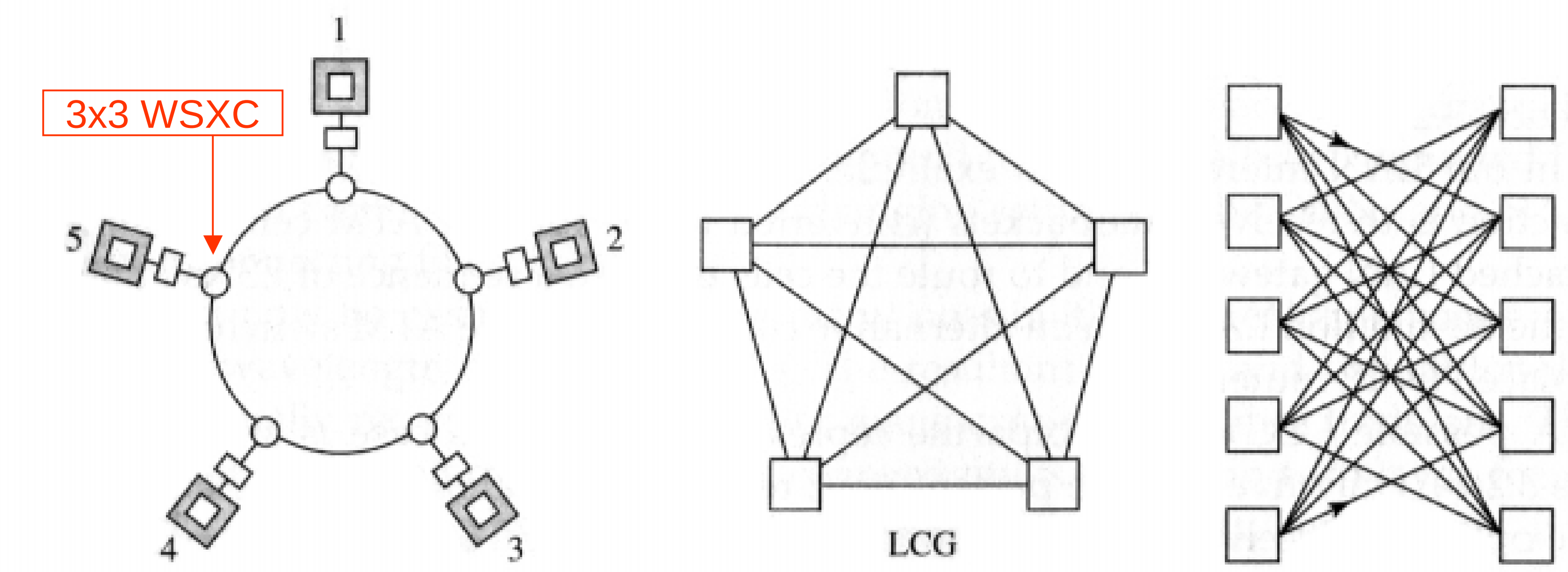
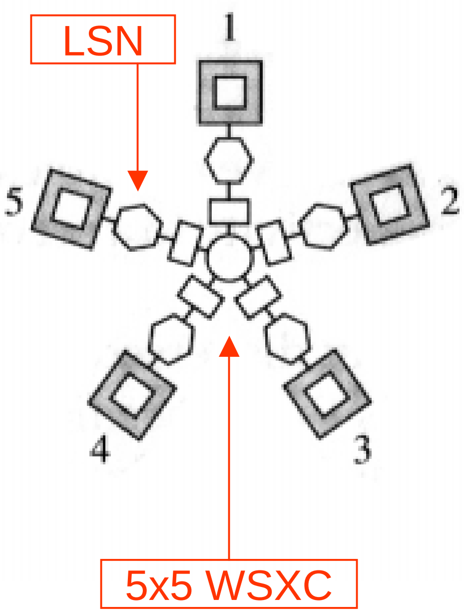
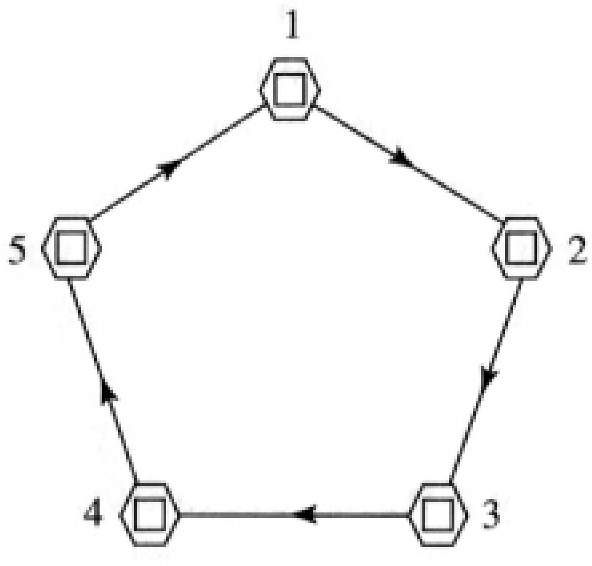


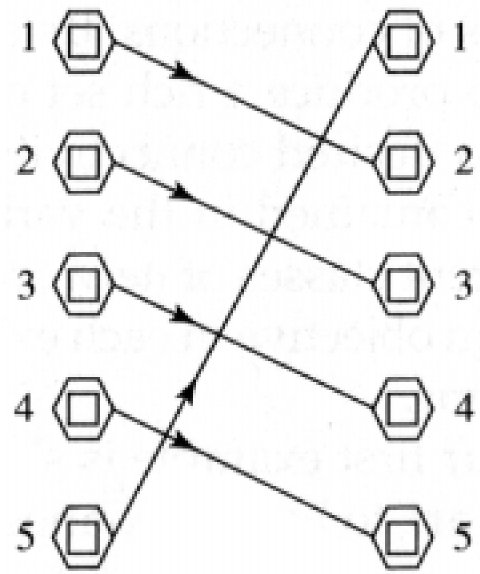
FIGURE 3.3 Bidirectional ring physical topology.

Logically routed network realization





(*b*) LCG



THE END