

Introduction to Multiwavelength Optical Networks

Switching Technology S38.165
<http://www.netlab.hut.fi/opetus/s38165>

Source: Stern-Bala (1999), Multiwavelength Optical Networks

Contents

- **The Big Picture**
- Network Resources
- Network Connections

Optical network

- Why ?
 - technology push, but no significant demand pull yet
 - evolving bandwidth hungry applications
 - optical transport already in the trunk network
 - Why not yet ?
 - optical last mile (a.k.a. the first mile) solutions still relatively primitive
 - still too expensive
 - administrative, political, etc. reasons
- => “The information superhighway is still a dirt road; more accurately, it is a set of isolated multilane highways with cow paths for entrance.”
- However, development getting pace

Optical network (cont.)

- An **optical network** is defined to be a telecommunications network
 - with transmission links that are optical fibers, and
 - with an architecture designed to exploit the unique features of fibers
- 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 devices
- 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 non-optical end-systems to the optical network

Optical network (cont.)

ONN (Optical Network Node)

- provides switching and routing functions to control optical signal paths, configuring them to create required connections

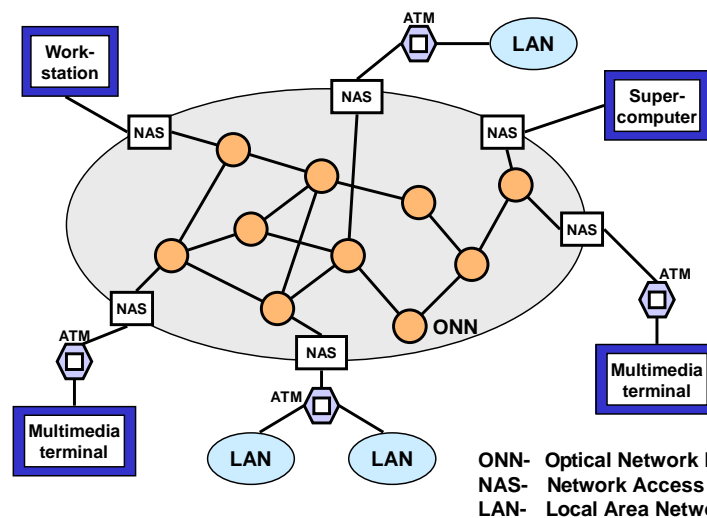
NAS (Network Access Station)

- provides termination point for optical paths within the optical network layer

Basic types of optical networks

- **transparent (purely optical) networks**
 - **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



A wish list of optical networks

- **Connectivity**

- support of a very large number of stations and end systems
- support of a very large number of concurrent connections including multiple connections per station
- efficient support of multi-cast connections

- **Performance**

- high aggregate network throughput (hundreds of Tbps)
- high user bit rates (few Gbps)
- small end-to-end delay
- low error rate (digital) / high SNR (analog)
- low processing load in nodes and stations
- adaptability to changing and unbalanced loads
- efficient and rapid means of fault identification and recovery

A wish list of optical networks (cont.)

- **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
- static photonic devices offer
 - optical power combining, slitting and filtering
 - wavelength multiplexing, demultiplexing and routing
- channelization needed to make efficient use of the enormous bandwidth of the fiber
 - by wavelength division multiplexing (WDM)
 - many signals operating on different wavelengths share each fiber

=> optics is fast but dumb

=> connectivity bottleneck

Optics vs. electronics (cont.)

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 in-band control information (e.g. in packet headers)
 - enabling a high degree of virtual connectivity
- easier to control

=> 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
 - designed to serve some subset of user requirements and
 - implemented as an electronic overlay
- an electronic switching equipment in the logical layer acts as a middleman
 - taking the high-bandwidth transparent channels provided by the physical layer and organizing them into an acceptable and cost-effective form

Why hybrid approach ?

- purely optical wavelength selective switches offer huge aggregate throughput of few connections
- electronic packet switches offer large number of relatively low bit rate virtual connections
- hybrid approach exploits the unique capabilities of optical and electronic switching 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 LANs 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 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
 - optical backbone at the physical layer supports the required throughput

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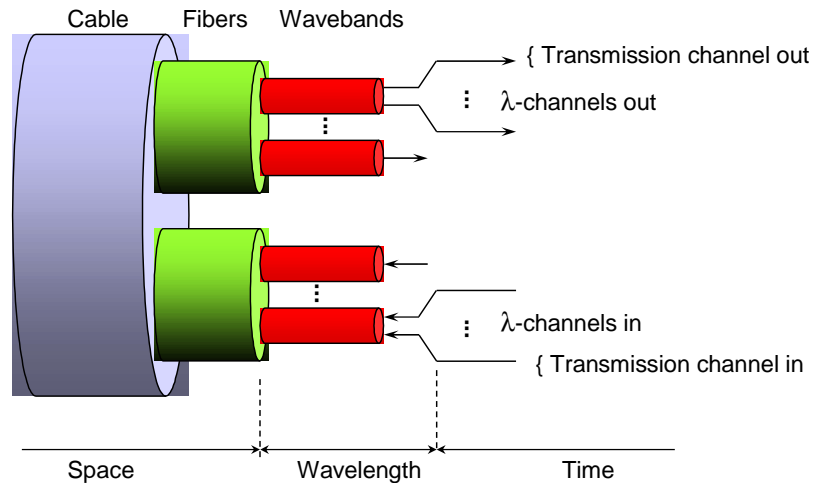
- The Big Picture
- **Network Resources**
 - **Network Links: Spectrum Partitioning**
 - Layers and Sublayers
 - Optical Network Nodes
 - Network Access Stations
 - Electrical domain resources
- Network Connections

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 bi-directional pairs
- **Wavelength division multiplexing (WDM)** in the optical layer:
 - a fiber carries connections on many distinct wavelengths (λ -channels)
 - assigned wavelengths must be spaced sufficiently apart to keep neighboring 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 time-slots
 - each time-slot in a frame corresponds to a transmission channel, which is capable of carrying a logical connection
 - location of a time-slot in a frame identifies a transmission channel

Fiber resources



Optical spectrum

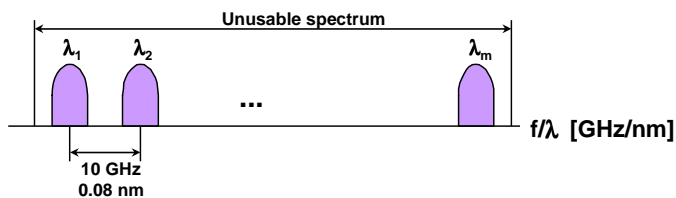
- Since wavelength λ and frequency f are related by $f\lambda = c$, where c is the velocity of light in the medium, we have the relation

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

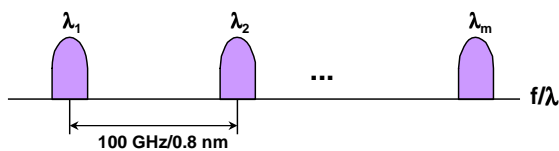
- Thus, 10 GHz \approx 0.08 nm and 100 GHz \approx 0.8 nm in the range of 1,550 nm, where most modern lightwave networks operate
- The 10-GHz channel spacing is sufficient to accommodate λ -channels carrying aggregate digital bit rates on the order of **1 Gbps** - modulation efficiency of 0.1 bps/Hz 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

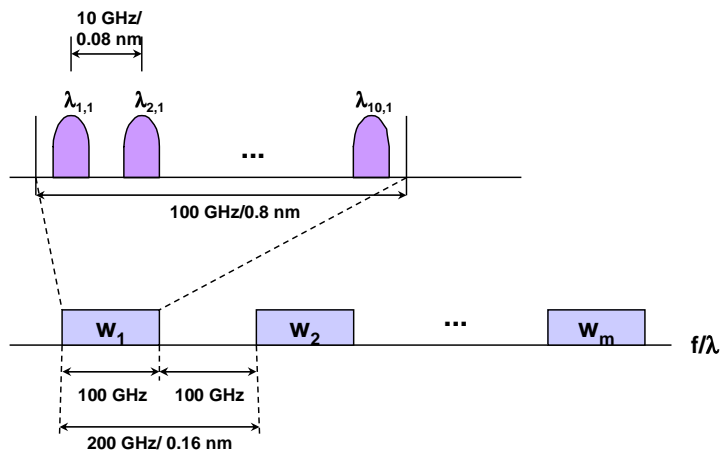
λ channel spacing for separability at receivers



λ channel spacing for separability at network nodes



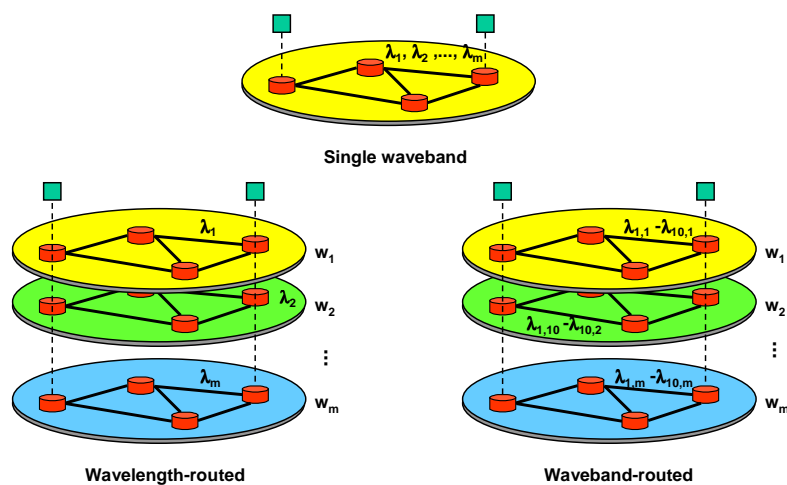
Wavelength and waveband partitioning of the optical spectrum



Capacity of wavelength and waveband routed networks

- Connections in optical networks usually require wavelength continuity, i.e., signal generated at a given wavelength must remain on that wavelength from source to destination
- Due to the current state of technology, imperfections in signal resolution at network nodes result in signal attenuation, distortion and cross-talk, which accumulate along the path
 - => channel spacing cannot be as dense in the network nodes as in the end-receivers
 - => loss of transport capacity
- Capacity losses can be avoided by switching wavebands (composed of a number of wave lengths) instead of individual wavelengths
 - => wavelength routed solutions have lower throughput than waveband routed solutions

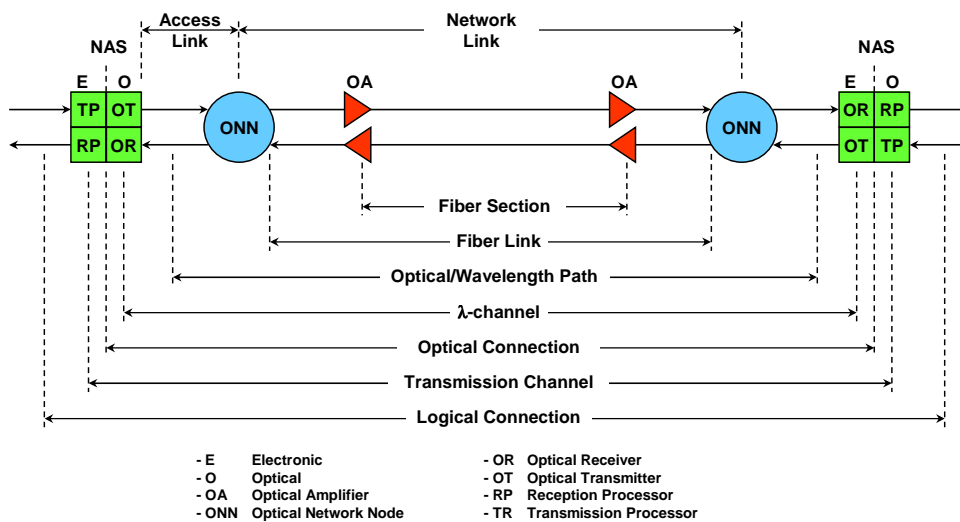
Network based on spectrum partitioning



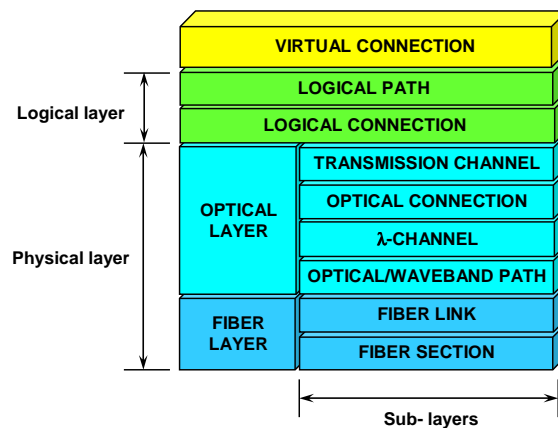
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Layered view of optical network (1)



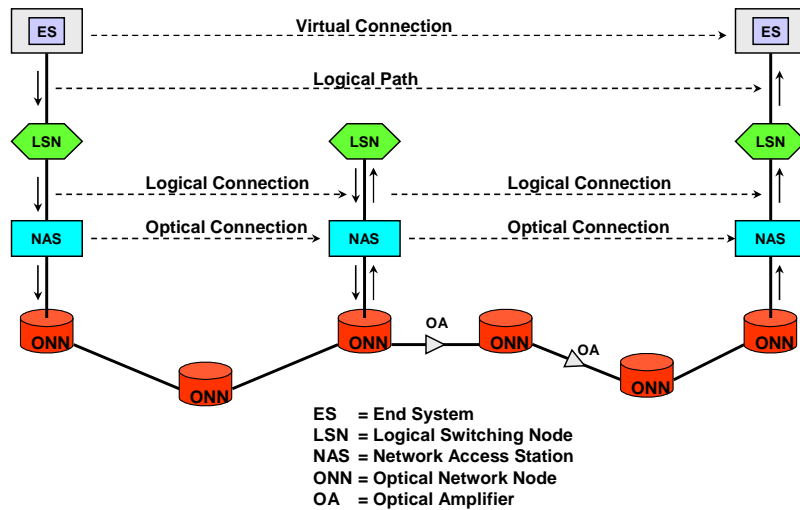
Layered view of optical network (2)



Layers and sublayers

- **Main consideration in breaking down optical layer into sublayers is to account for**
 - multiplexing
 - multiple access (at several layers)
 - 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



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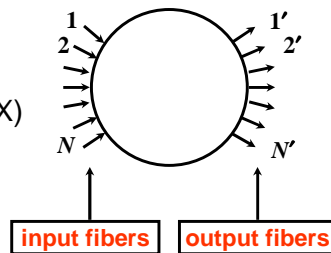
- The Big Picture
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Optical network nodes (1)

- **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**

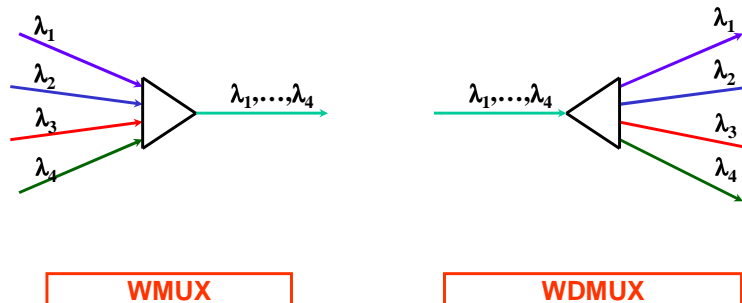
- without wavelength selectivity
 - $N \times N$ **broadcast star** (= star coupler)
 - $N \times 1$ **combiner**
 - $1 \times N$ **divider**
- with wavelength selectivity
 - $N \times N$ **wavelength router** (= Latin router)
 - $N \times 1$ **wavelength multiplexer** (WMUX)
 - $1 \times N$ **wavelength 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



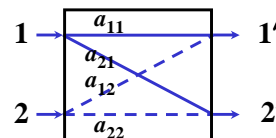
Directional Coupler (1)

- **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 a coupler through fibers attached to input ports
 - divided and combined **linearly**
 - 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 **power transfer matrix** by $A = [a_{ij}]$ and **power matrix** by $P = [P_i] \Rightarrow P' = AP$

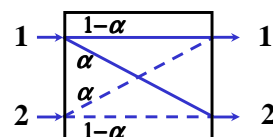


Directional Coupler (2)

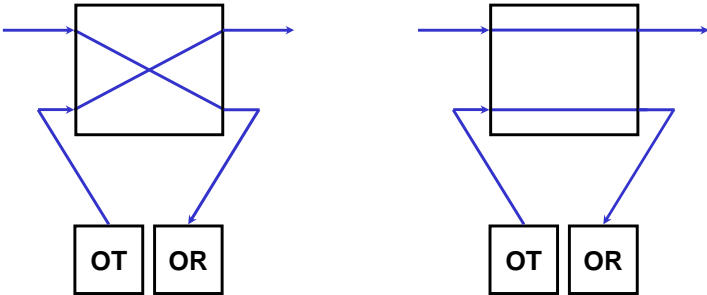
- Ideally, the power transfer matrix A is of the form

$$A = \begin{bmatrix} 1-\alpha & \alpha \\ \alpha & 1-\alpha \end{bmatrix}, \quad 0 \leq \alpha \leq 1$$

- If parameter α is fixed, the device is **static**, e.g. with $\alpha = 1/2$ 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 port 2' is terminated), the device acts as a 2x1 **combiner**



Add-drop switch



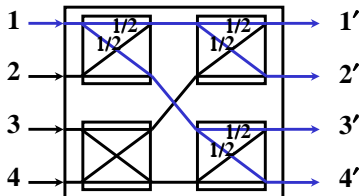
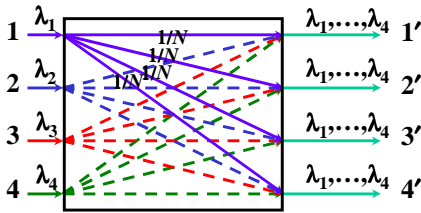
Add-drop state

Bar state

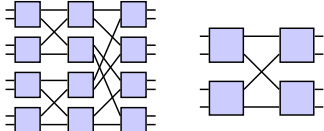
OR - Optical Receiver
 OT - Optical Transmitter

Broadcast star

- Static $N \times N$ **broadcast star** with N wavelengths can carry
 - N simultaneous **multi-cast** 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



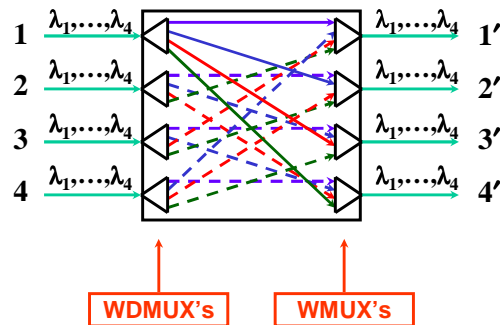
broadcast star realized by directional couplers



Wavelength router

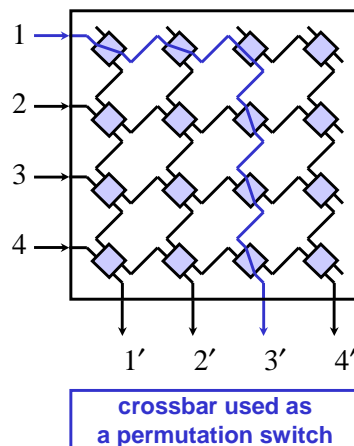
- Static $N \times N$ **wavelength router** with N wavelengths can carry
 - wavelengths from the different inputs are routed so that identical wavelengths do not enter the same outputs (Latin square principle)
 - N^2 simultaneous **unicast** optical connections (= full point-to-point optical connectivity)

- Requires
 - N $1 \times N$ WDMUX's
 - N $N \times 1$ WMUX's



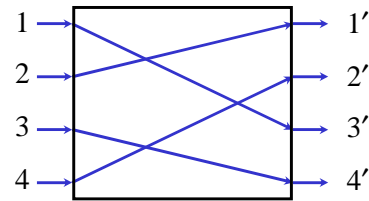
Crossbar switch

- Dynamic $R \times N$ **crossbar switch** consists of
 - R input lines
 - N output lines
 - RN crosspoints
- Crosspoints implemented by **controllable** optical couplers
 - RN couplers needed
- A crossbar can be used as
 - a $N \times N$ **permutation switch** (then $R = N$) or
 - a $R \times N$ **generalized 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** (exactly one connection “1” per each row and column)

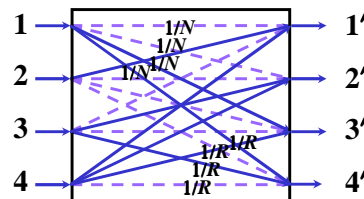


		output ports			
		1'	2'	3'	4'
input ports	1			1	
	2	1			
	3				1
	4		1		

Generalized switch

- Dynamic RxN **generalized switch** (e.g. crossbar switch)

- any input/output pattern possible (incl. one-to-many and many-to-one connections)
- 2^{NR} **connection states**
- each connection state can carry (at most) R simultaneous multicast optical connections
- a connection state represented by a RxN **connection matrix**



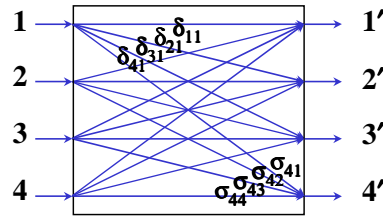
		output ports			
		1'	2'	3'	4'
input ports	1			1	1
	2	1			
	3		1		1
	4	1	1	1	

- Input/output power relation $\mathbf{P}' = \mathbf{A}\mathbf{P}$ with NxR power transfer matrix $\mathbf{A} = [a_{ij}]$, where

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

Linear Divider-Combiner (LDC)

- **Linear Divider-Combiner (LDC)** is a generalized switch that
 - controls power-dividing and power-combining ratios
 - less inherent loss than in crossbar
- Power-dividing and power-combining ratios



- δ_{ij} = fraction of power from input port j directed to output port i'
- σ_{ij} = fraction of power from input port j combined onto output port i'
- In an ideal case of lossless couplers, we have constraints

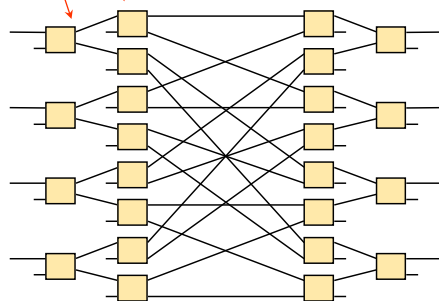
$$\sum_i \delta_{ij} = 1 \quad \text{and} \quad \sum_j \sigma_{ij} = 1$$

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

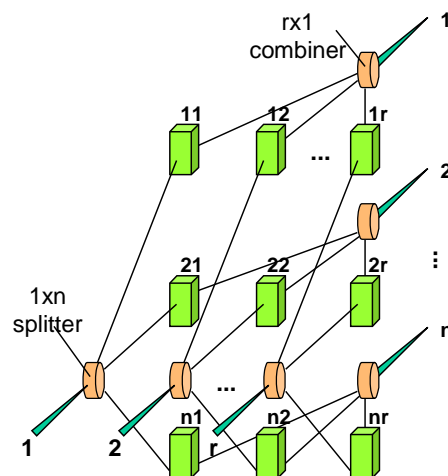
$$a_{ij} = \delta_{ij} \sigma_{ij}$$

LDC and generalized switch realizations

directional couplers



$\delta - \sigma$ linear divider-combiner

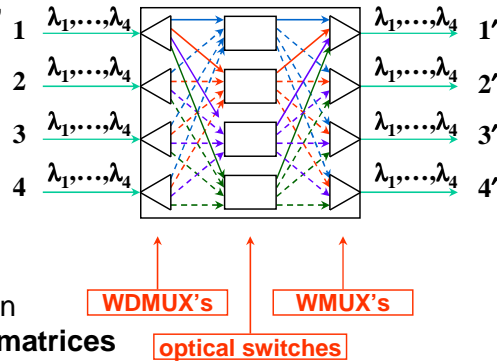


Generalized optical switch

Wavelength selective cross-connect (WSXC)

- Dynamic NxN **wavelength selective crossconnect** (WSXC) with M wavelengths

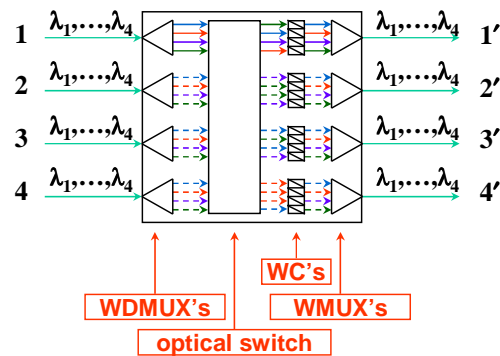
- includes N 1xM WDMUXs, M NxN permutation switches, and N Mx1 WMUXs
- $(N!)^M$ connection states if the permutation switches are nonblocking
- each connection state can carry NM simultaneous unicast optical connections
- representation of a connection state by M NxN **connection matrices**



Wavelength interchanging cross-connect (WIXC)

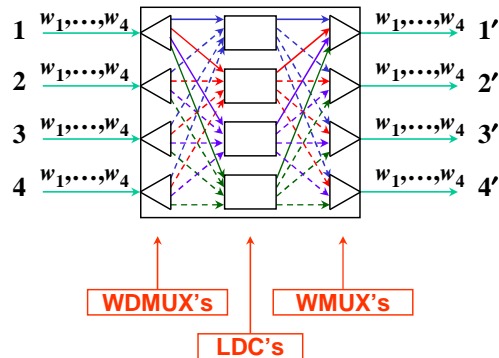
- Dynamic NxN **wavelength interchanging crossconnect** (WIXC) with M wavelengths

- 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 multi-cast connections
 - representation of a connection state by a M RxN **connection matrices**



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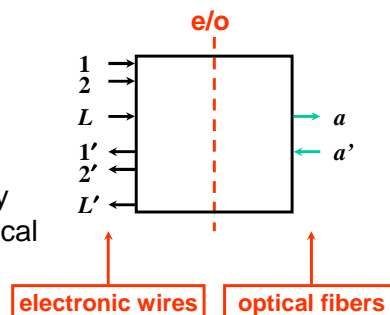
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Network access stations (1)

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

- **Functions:**

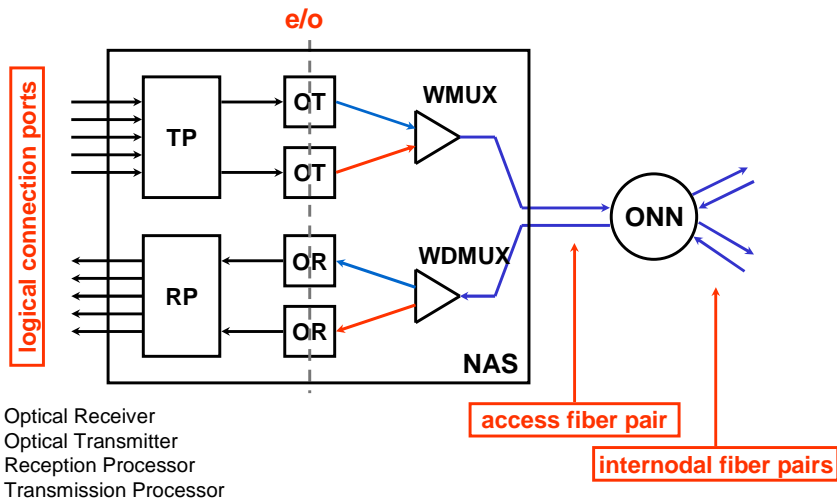
- interfaces the external LC ports to the optical transceivers
- implements the functions necessary to move signals between the electrical and optical domains



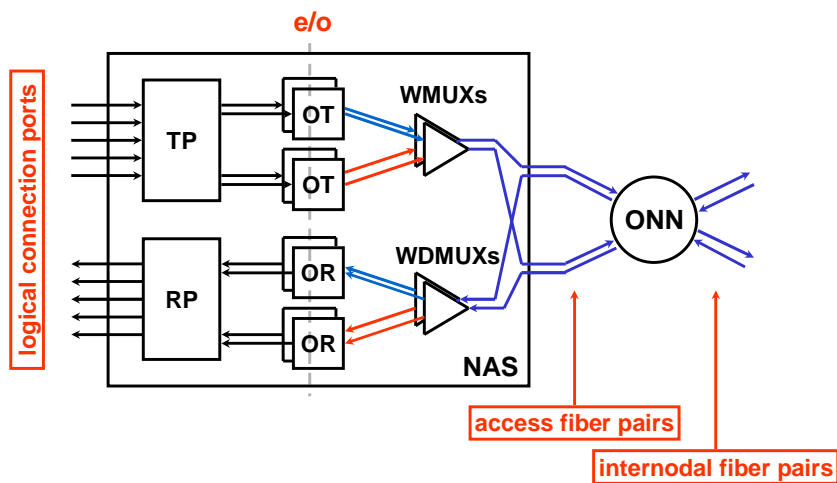
Network access stations (2)

- **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 optical signals from an inbound access fiber and passes them to optical receivers
 - **Optical Receivers (OR)** convert optical power to electrical transmission signals, which are corrupted versions of the original transmitted signals
 - **Reception Processor (RP)** converts the corrupted transmission signals to logical signals (e.g. regenerating digital signals)

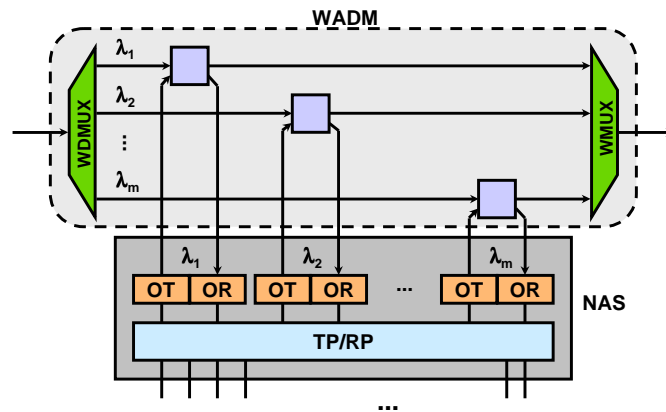
Elementary network access station



Non-blocking network access station



Wavelength add-drop multiplexer (WADM)



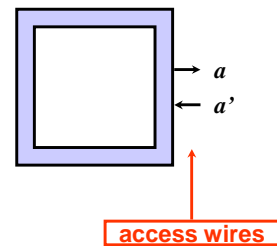
WADM combined with NAS

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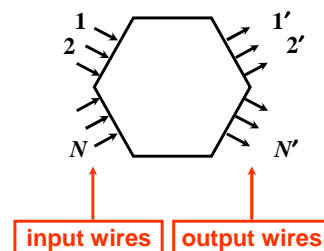
End System

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

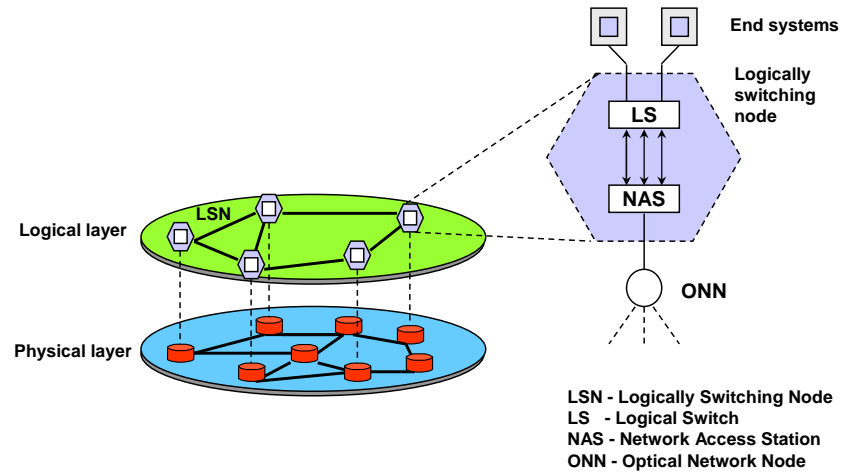


Logical Switching Node (LSN)

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



Logically routed network



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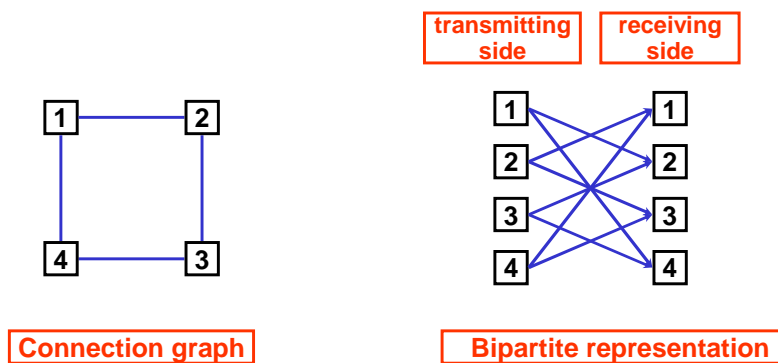
- The Big Picture
- Network Resources
- **Network Connections**
 - **Connectivity**
 - Connections in various layers
 - Example: realizing full connectivity between five end systems

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 side:**
 - point-to-point
 - multipoint

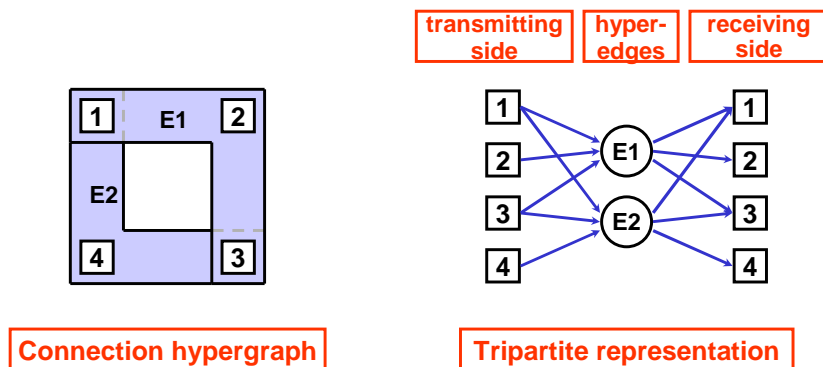
Connection Graph (CG)

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



Connection Hypergraph (CH)

- Representing **multipoint** connectivity between end systems



Contents

- The Big Picture
- Network Resources
- **Network Connections**
 - Connectivity
 - **Connections in various layers**
 - Example: realizing full connectivity between five end systems

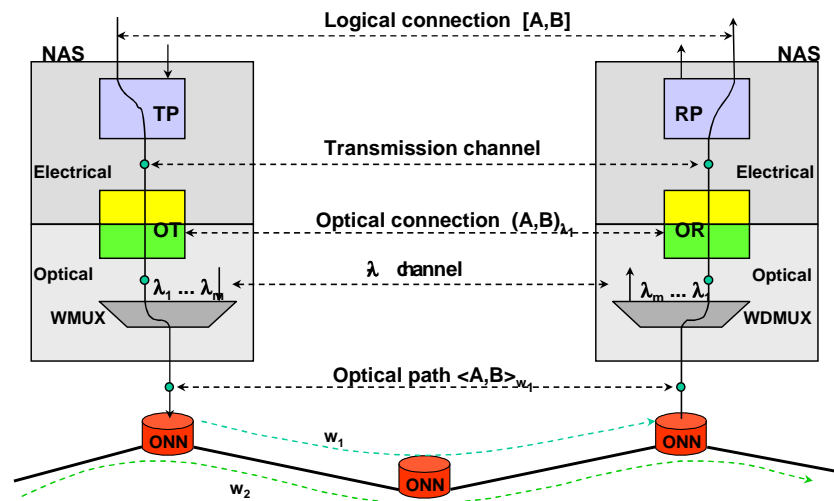
Connections in various layers

- **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
 - $[a, \{b, c, \dots\}]$ = multi-cast logical connection from a to set $\{b, c, \dots\}$
 - 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
 - $(a, \{b, c, \dots\})$ = multi-cast optical connection from a to set $\{b, c, \dots\}$
- **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
 - $\langle a, \{b, c, \dots\} \rangle$ = multi-cast optical path from a to set $\{b, c, \dots\}$

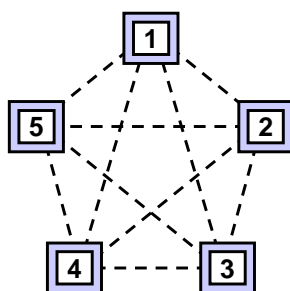
Example of a logical connection between two NASs



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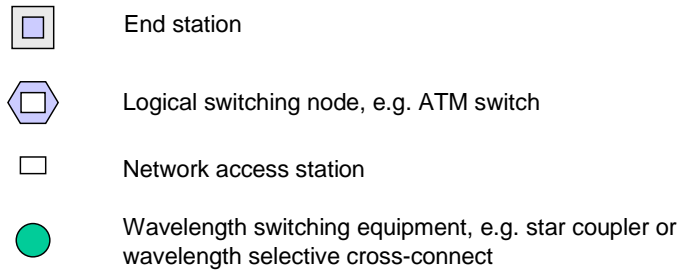
Example: realization of full connectivity between 5 end systems



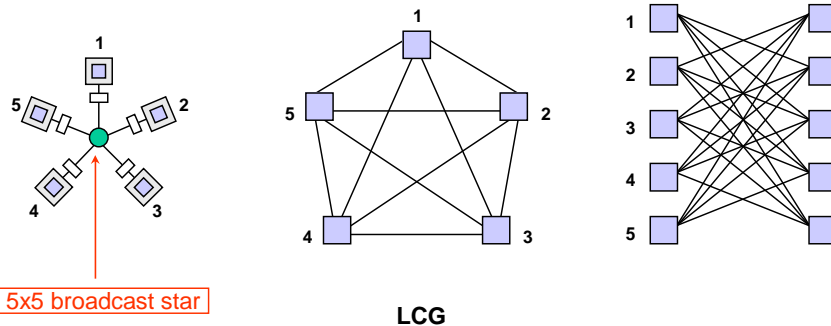
Solutions

- **Static network** based on star physical topology
 - full connectivity in the logical layer (20 logical connections)
 - 4 optical transceivers per NAS, 5 NASs, 1 ONN (broadcast star)
 - 20 wavelengths for max throughput by WDM/WDMA
- **Wavelength routed network (WRN)** based on bi-directional ring physical topology
 - full connectivity in the logical layer (20 logical connections)
 - 4 optical transceivers per NAS, 5 NASs, 5 ONNs (WSXCs)
 - 4 wavelengths (assuming elementary NASs)
- **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 NASs, 1 ONN (WSXC), 5 LSNs
 - 1 wavelength

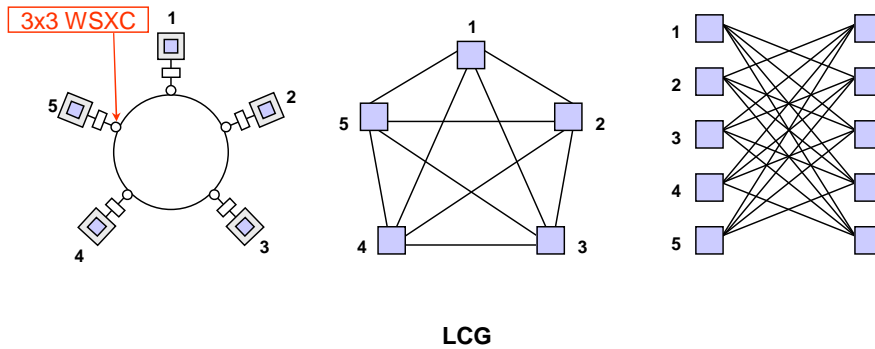
Solution markings



Static network realization



Wavelength routed network realization



Logically routed network realization

