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
  - “The information superhighway is still a dirt road; more accurately, it is a set of isolated multilane highways with cow paths for entrance.”
- Why not yet ?
  - optical last mile (also known as 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 network

Optical network (cont.)

ONN (Optical Network Node)

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

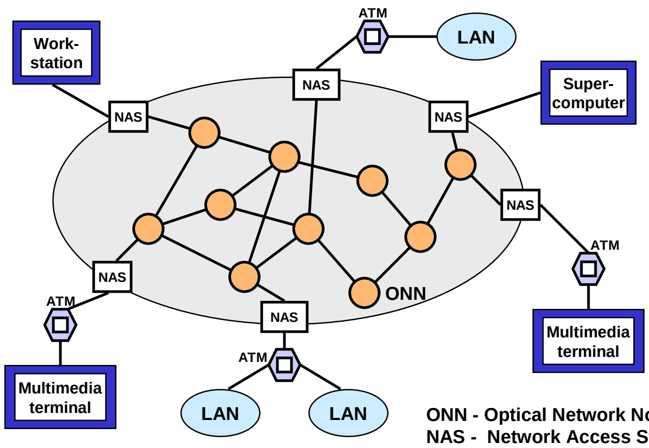
NAS (Network Access Station)

- 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



ONN - Optical Network Node
NAS - Network Access Station
LAN - Local Area 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

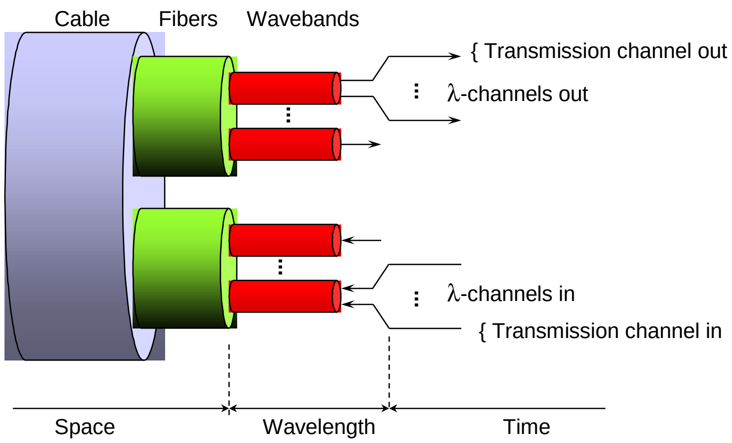
Contents

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



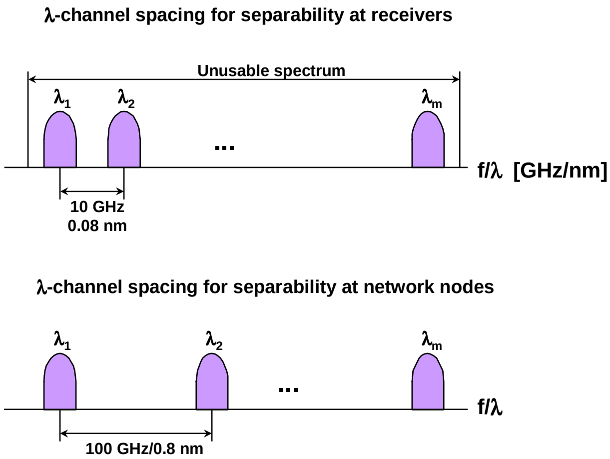
Optical spectrum

- 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

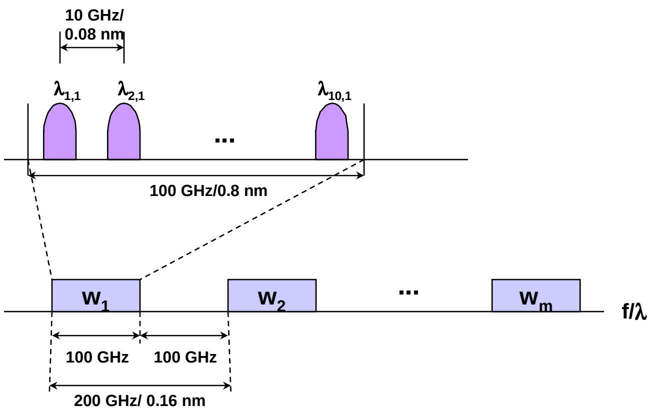
$$\Delta f \approx -\frac{c\,\Delta\lambda}{\lambda^2}$$

- Thus, 10 GHz ≈ 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 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



Wavelength and waveband partitioning of the optical spectrum

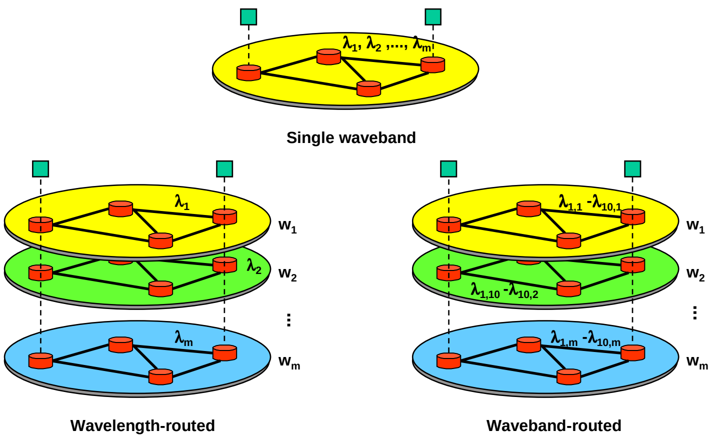


Capacity of wavelength and waveband routed networks

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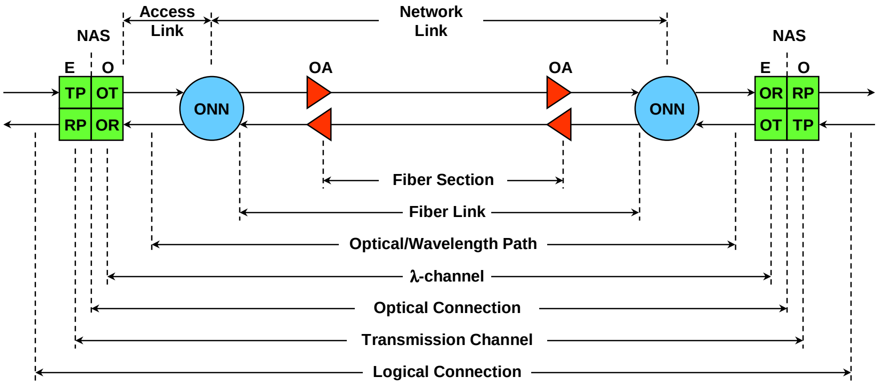
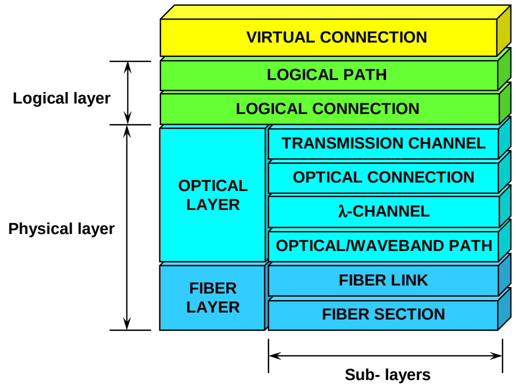
- **Network Resources**
  - Network Links: Spectrum Partitioning
  - **Layers and Sublayers**
  - Optical Network Nodes
  - Network Access Stations
  - Electrical domain resources
- Network Connections

Layered view of optical network (1)



- E Electronic
- O Optical
- OA Optical Amplifier
- ONN Optical Network Node
- OR Optical Receiver
- OT Optical Transmitter
- RP Reception Processor
- TR Transmission Processor

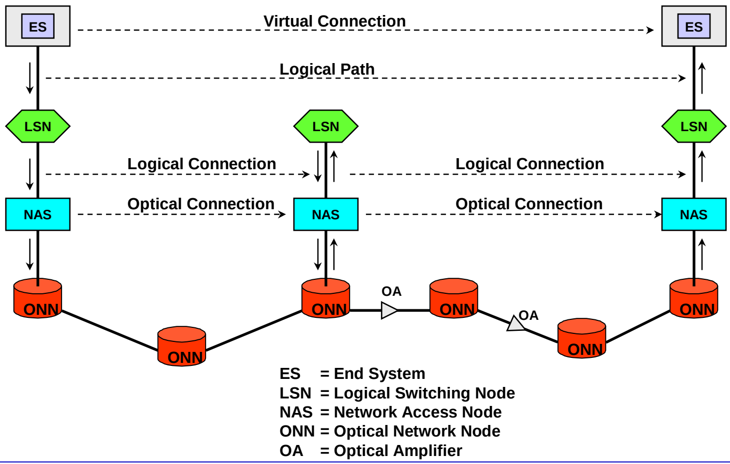
Layered view of optical network (2)



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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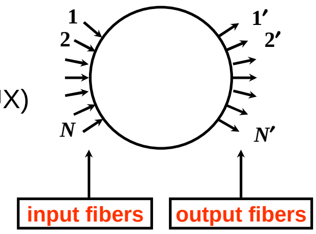
Optical network nodes (1)

- **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)



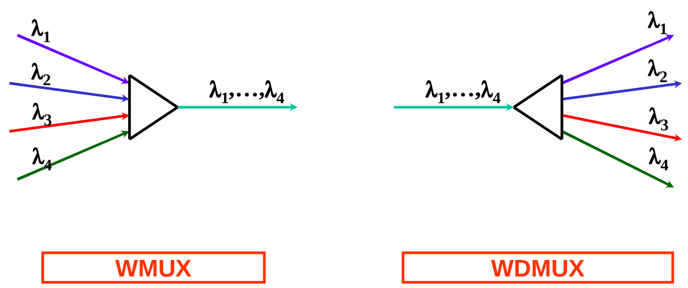
Optical network nodes (2)

- **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

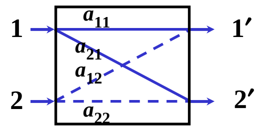
Wavelength multiplexer and demultiplexer



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

$$P_{1'} = a_{11}P_1 + a_{12}P_2$$
$$P_{2'} = a_{21}P_1 + a_{22}P_2$$



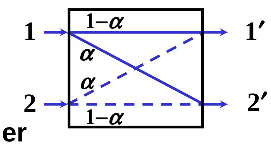
- Denote **power transfer matrix** by $\boldsymbol{A} = [a_{ij}]$ and **power matrix** by $\boldsymbol{P} = [P_i]$ => $\boldsymbol{P'} = \boldsymbol{AP}$

Directional Coupler (2)

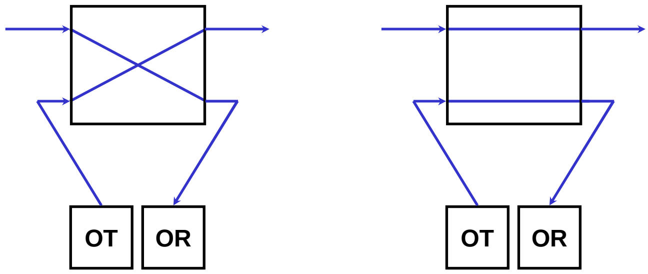
- Ideally, the power transfer matrix A is of the form

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

- If 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 port 2’ is terminated), the device acts as a 2x1 **combiner**



Add-drop switch



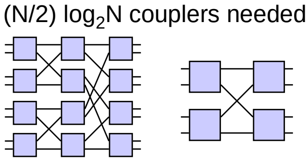
Add-drop state

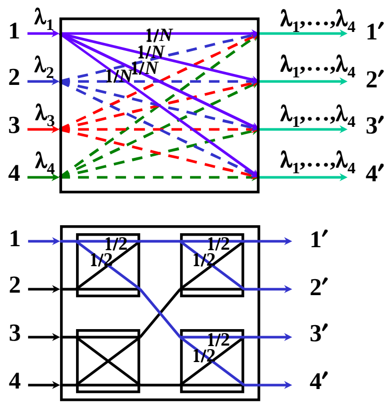
Bar state

OR - Optical Receiver
OT - Optical Transmitter

Broadcast star

- Static NxN **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

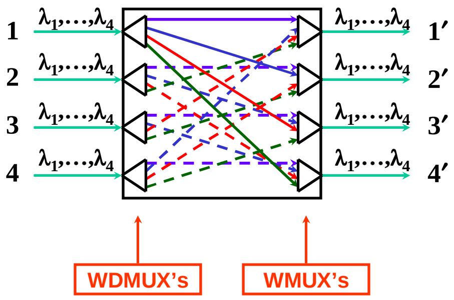




broadcast star realized by directional couplers

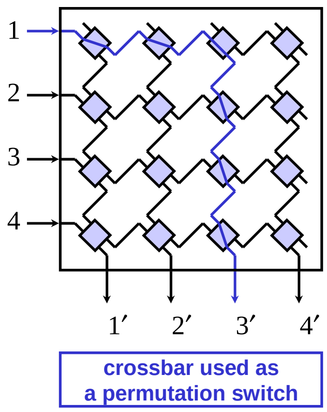
Wavelength router

- Static NxN **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 1xN WDMUX's
  - N Nx1 WMUX's



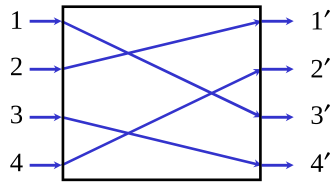
Crossbar switch

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



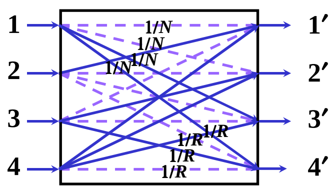
output ports

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

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

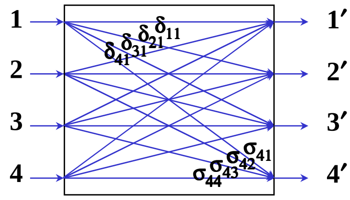


output ports

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
  - less inherent loss than in crossbar



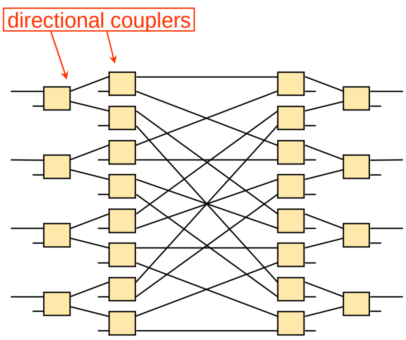
- Power-dividing and power-combining ratios
  - $\boldsymbol{\delta_{ij}}$ = fraction of power from input port *j* directed to output port *i'*
  - $\boldsymbol{\sigma_{ij}}$ = fraction of power from input port *j* combined onto output port *i'*
- In an ideal case of lossless couplers, we have constraints

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

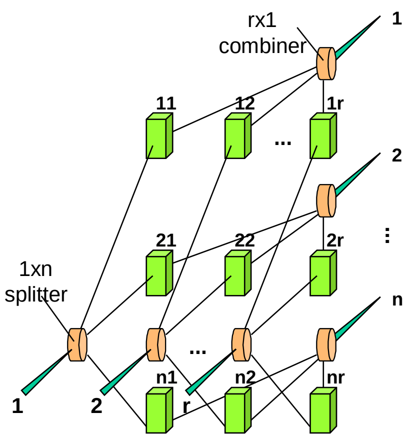
- The resulting power transfer matrix $A = [a_{ij}]$ is such that

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

LDC and generalized switch realizations



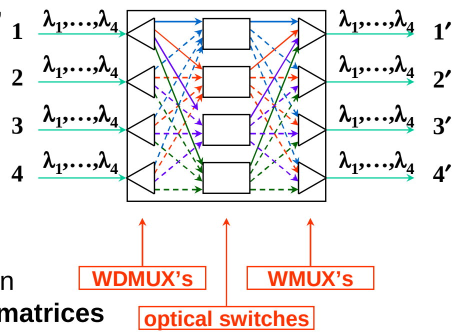
δ - σ linear divider-combiner



Generalized optical switch

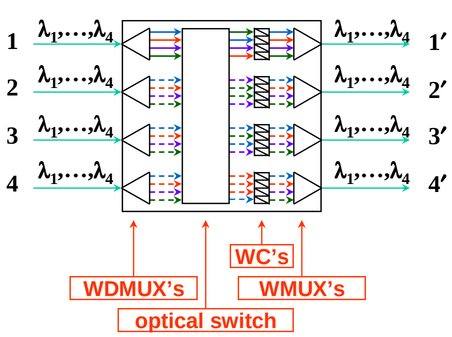
Wavelength selective cross-connect (WSXC)

- 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**



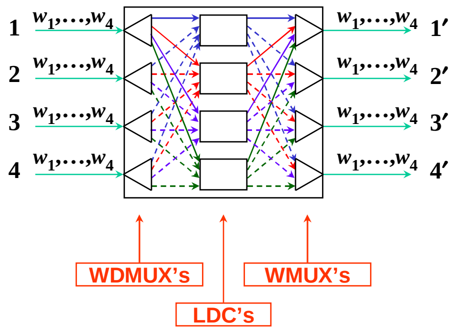
Wavelength interchanging cross-connect (WIXC)

- 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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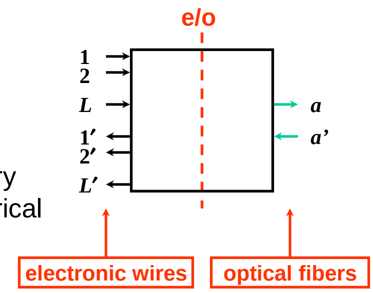
Network access stations (1)

- **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

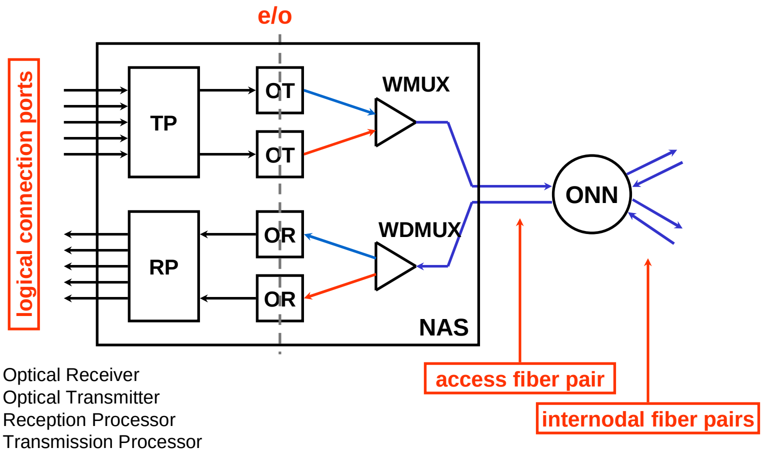
- **Functions**:
  - interfaces the external LC ports to the optical transceivers
  - implements the functions necessary to move signals between the electrical and optical domains



Network access stations (2)

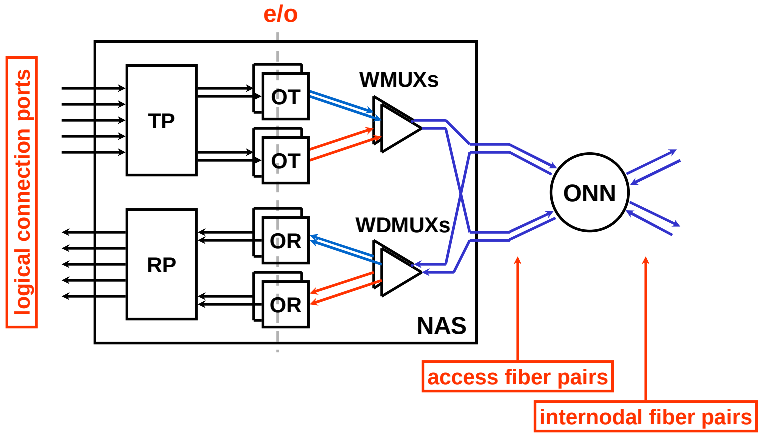
- **Transmitting side** components:
  - **Transmission Processor** (TP) with a number of LC input ports and transmission channel output ports connected to optical transmitters (converts each logical signal to a transmission signal)
  - **Optical Transmitters** (OT) with a laser modulated by transmission 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

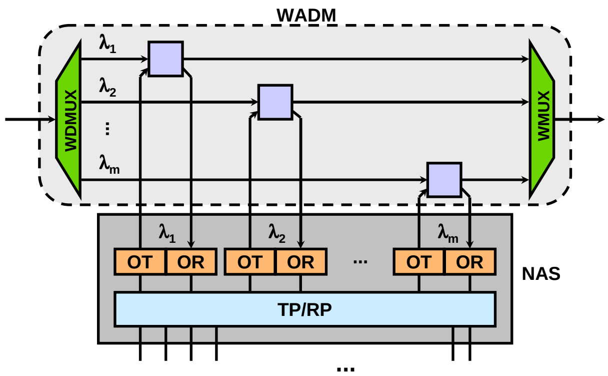


OR - Optical Receiver
OT - Optical Transmitter
RP - Reception Processor
TP - Transmission Processor

Non-blocking network access station



Wavelength add-drop multiplexer (WADM)



WADM combined with NAS

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  - **Electrical domain resources**
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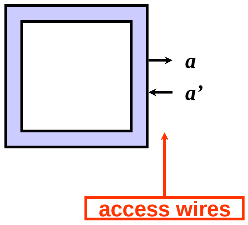
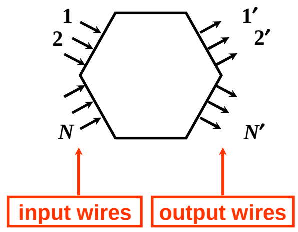
End System

- **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

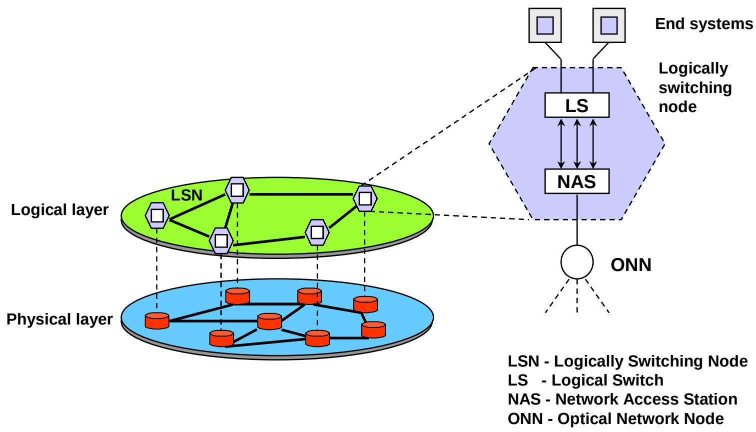


Logical Switching Node (LSN)

- **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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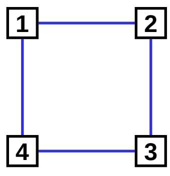
  - **Connectivity**
  - Connections in various layers
  - Example: realizing full connectivity between five end systems

Connectivity

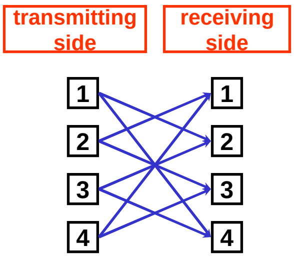
- **Transmitting side**:
  - **one-to-one**
    - (single) unicast
  - **one-to-many**
    - multiple unicasts
    - (single) multicast
    - multiple multicasts
- **Receiving side**:
  - **one-to-one**
    - (single) unicast
    - (single) multicast
  - **many-to-one**
    - multiple unicasts
    -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

Connection Graph (CG)

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



Connection graph

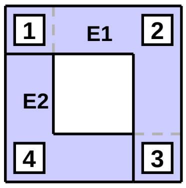


Bipartite representation

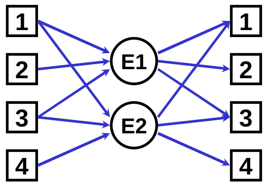
Connection Hypergraph (CH)

- Representing **multipoint** connectivity between end systems

transmitting side | hyper-edges | receiving side



Connection hypergraph



Tripartite representation

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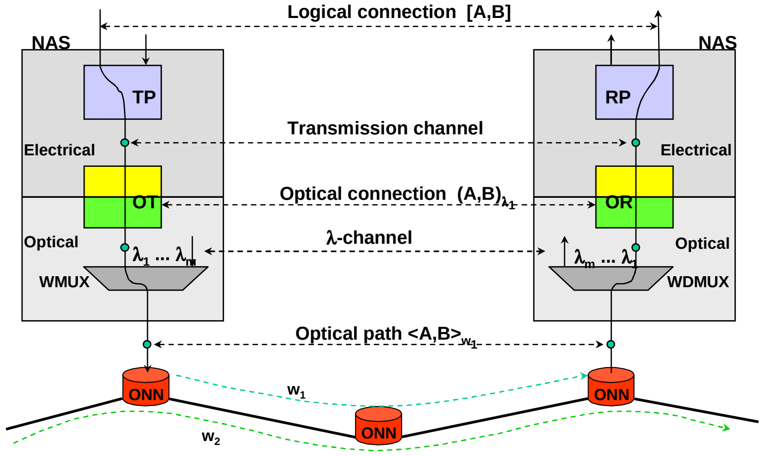
Connections in various layers

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

Example of a logical connection between two NASs



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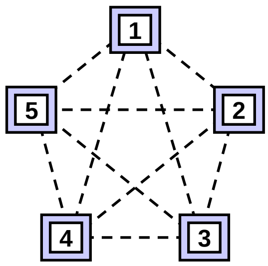
Example: realization of full connectivity between 5 end systems



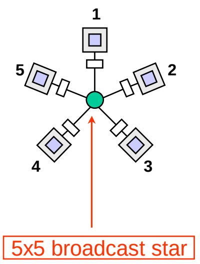
Solutions

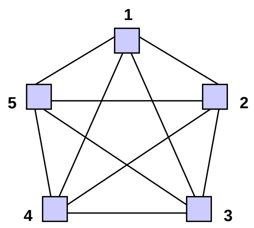
- **Static network** based on star physical topology
  - full connectivity in the logical layer (20 logical connections)
  - 4 optical transceivers per NAS, 5 NASs, 1 ONN (broadcast star)
  - 20 wavelengths for max throughput by WDM/WDMA
- **Wavelength routed network** (WRN) based on bi-directional ring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

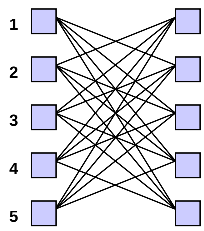
- End station
- Logical switching node, e.g. ATM switch
- Network access station
- Wavelength switching equipment, e.g. star coupler or wavelength selective cross-connect

Static network realization

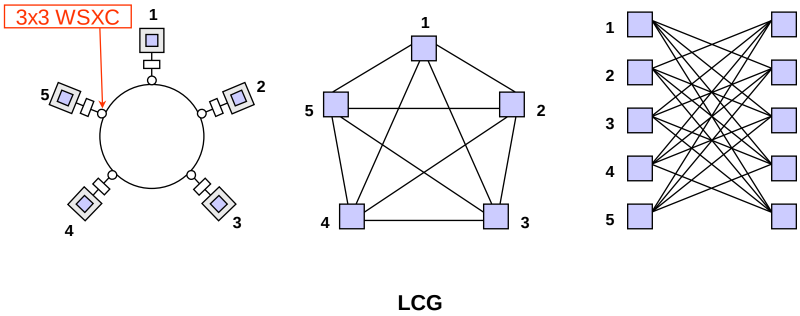




LCG



Wavelength routed network realization



Logically routed network realization