Multiwavelength Optical Network Architectures

Switching Technology S38.3165
http://www.netlab.hut.fi/opetus/s383165

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

Contents

- **Static networks**
- Wavelength Routed Networks (WRN)
- Linear Lightwave Networks (LLN)
- Logically Routed Networks (LRN)

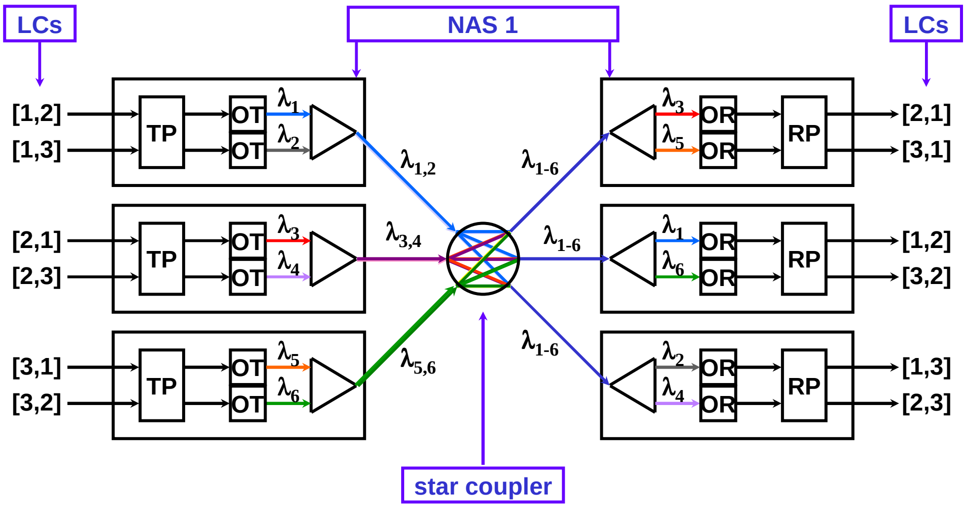
Static networks

- **Static network** (= **broadcast-and-select network**) is a purely optical shared medium network
  - passive splitting and combining nodes are interconnected by fibers to provide static connectivity among some or all OTs and ORs
  - OTs broadcast and ORs select
- **Broadcast star network** is an example of such a static network
  - star coupler combines all signals and broadcasts them to all ORs
    - static optical multi-cast paths from any station to the set of all stations
    - no wavelength selectivity at the network node
  - optical connection is created by tuning the source OT and/or destination OR to the same wavelength
  - two OTs must operate at different wavelengths (to avoid interference)
    - this is called the **distinct channel assignment** (DCA) constraint
  - however, two ORs can be tuned to the same wavelength
    - by this way, optical multi-cast connections are created

Realization of logical connectivity

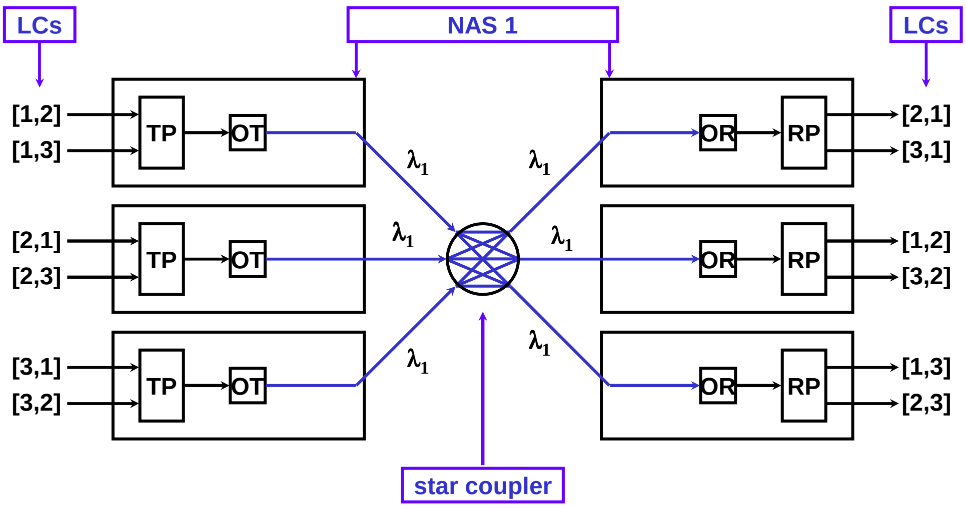
- Methods to realize full point-to-point logical connectivity in a broadcast star with N nodes:
  - **WDM/WDMA**
    - a **whole λ-channel allocated for each LC**
    - **N(N-1) wavelengths needed (one for each LC)**
    - **N-1 transceivers needed in each NAS**
  - **TDM/TDMA**
    - **1/[N(N-1)] of a λ-channel allocated for each LC**
    - **1 wavelength needed**
    - **1 transceiver needed in each NAS**
  - **TDM/T-WDMA**
    - **1/(N-1) of a λ-channel allocated for each LC**
    - **N wavelengths needed (one for each OT)**
    - **1 transceiver needed in each NAS, e.g. fixed OT and tunable OR (FT-TR), or tunable OT and fixed OR (TT- FR)**

Broadcast star using WDM/WDMA

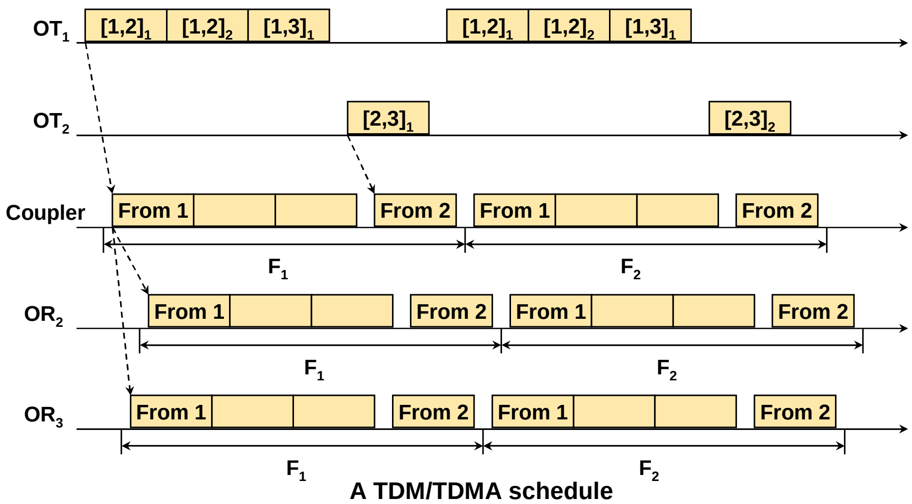


[*a*, *b*] = logical connection from port on station *a* to one on station *b*

Broadcast star using TDM/TDMA

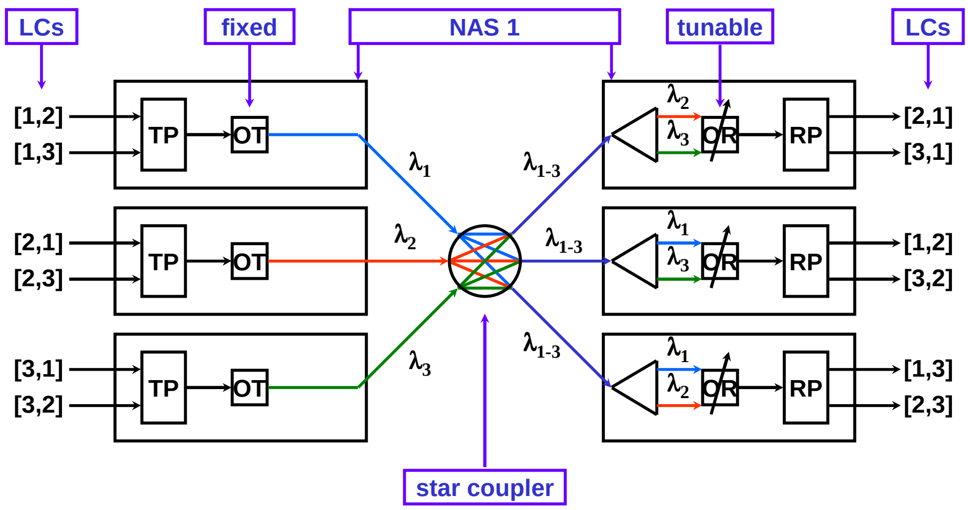


Effect of propagation delay on TDM/TDMA

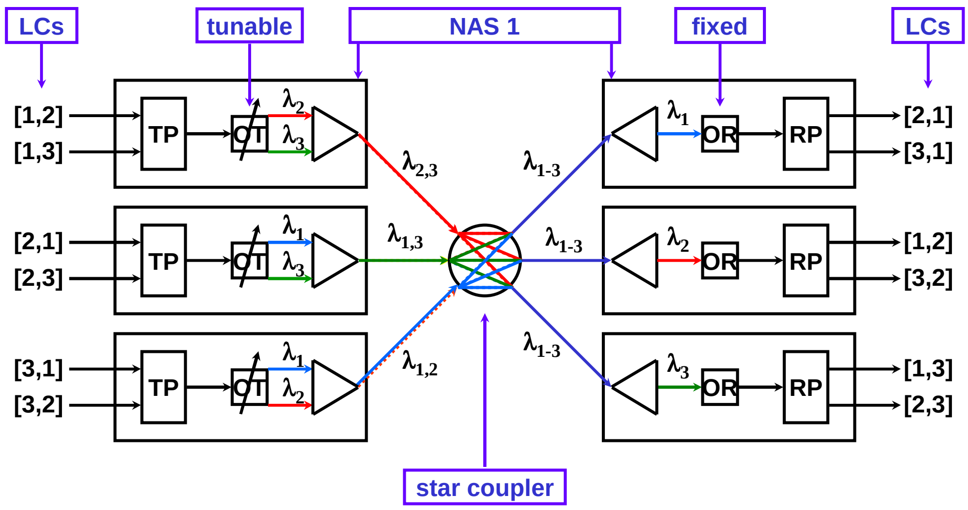


A TDM/TDMA schedule

Broadcast star using TDM/T-WDMA in FT-TR mode



Broadcast star using TDM/T-WDMA in TT-FR mode



Channel allocation schedules for circuit switching

WDM/WDMA

λ_1	[1,2]	[1,2]	[1,2]	[1,2]
λ_2	[1,3]	[1,3]	[1,3]	[1,3]
λ_3	[2,1]	[2,1]	[2,1]	[2,1]
λ_4	[2,3]	[2,3]	[2,3]	[2,3]
λ_5	[3,1]	[3,1]	[3,1]	[3,1]
λ_6	[3,2]	[3,2]	[3,2]	[3,2]

frame

TDM/T-WDMA with FT-TR

λ_1	[1,2]	[1,3]	[1,2]	[1,3]
λ_2	[2,3]	[2,1]	[2,3]	[2,1]
λ_3	[3,1]	[3,2]	[3,1]	[3,2]

frame

TDM/T-WDMA with TT-FR

λ_1	[2,1]	[3,1]	[2,1]	[3,1]
λ_2	[3,2]	[1,2]	[3,2]	[1,2]
λ_3	[1,3]	[2,3]	[1,3]	[2,3]

frame

Channel allocation schedule (CAS) should be
- **realizable** = only one LC per each OT and time-slot
- **collision-free** = only one LC per each λ and time-slot
- **conflict-free** = only one LC per each OR and time-slot

TDM/TDMA

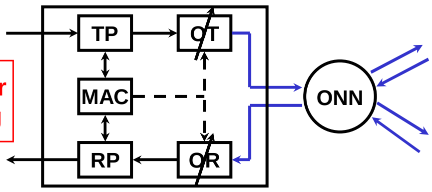
λ_1	[1,2]	[1,3]	[2,1]	[2,3]	[3,1]	[3,2]	[1,2]	[1,3]	[2,1]	[2,3]	[3,1]	[3,2]

frame

Packet switching in the optical layer

- **Fixed capacity allocation,** produced by periodic frames, is well adapted to stream-type traffic. However, in the case of bursty packet traffic this approach may produce a very poor performance
- By implementing **packet switching in the optical layer**, it is possible to maintain a very large number of LCs simultaneously using **dynamic capacity allocation**
  - packets are processed in TPs/RPs of the NASs (but **not** in ONNs)
  - TPs can schedule packets based on instantaneous demand
  - as before, broadcast star is used as a **shared medium**
  - control of this shared optical medium requires a Medium Access Control (MAC) protocol

NAS equipped for packet switching



Additional comments on static networks

- The broadcast-and-select principle **cannot be scaled** to large networks for three reasons:
  - **Spectrum use:** Since all transmissions share the same fibers, there is no possibility of optical spectrum reuse => the required spectrum typically grows at least proportionally to the number of transmitting stations
  - **Protocol complexity:** Synchronization problems, signaling overhead, time delays, and processing complexity all increase rapidly with the number of stations and with the number of LCs.
  - **Survivability:** There are no alternate routes in case of a failure. Furthermore, a failure at the star coupler can bring the whole network down.
  - For these reasons, a practical limit on the number of stations in a broadcast star is approximately 100

Contents

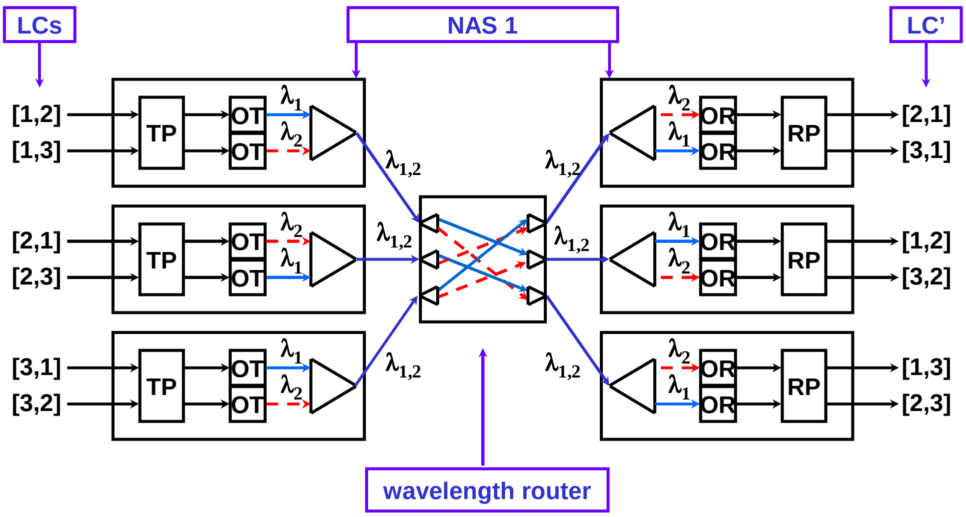
Wavelength Routed Networks (WRN)

- **Wavelength routed network (WRN**) is a purely optical network
  - each λ-channel can be recognized in the ONNs (= wavelength selectivity) and routed individually
  - ONNs are typically wavelength selective cross-connects (WSXC)
    - network is **dynamic** (allowing **switched** connections)
    - a static WRN (allowing only **dedicated** connections) can be built up using static wavelength routers
- All optical paths and connections are **point-to-point**
  - each point-to-point LC corresponds to a point-to-point OC
  - full point-to-point logical/optical connectivity among N stations requires N-1 transceivers in each NAS
  - multipoint logical connectivity only possible by several point-to-point optical connections using WDM/WDMA

Static wavelength routed star

- Full point-to-point logical/optical connectivity in a static wavelength routed star with N nodes can be realized by **WDM/WDMA**
  - a whole λ-channel allocated for each LC
  - N-1 wavelengths needed - spectrum reuse factor is N (= N(N-1) optical connections / N-1 wavelengths)
  - N-1 transceivers needed in each NAS

Static wavelength routed star using WDM/WDMA

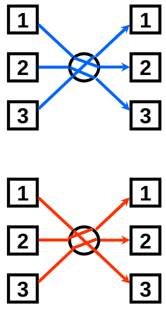


Routing and channel assignment

- Consider a WRN equipped with WSXCs (or wavelength routers)
  - no wavelength conversion possible
- Establishment of an optical connection requires
  - channel assignment
  - routing
- **Channel assignment** (executed in the λ-channel sublayer) involves
  - allocation of an available wavelength to the connection and
  - tuning of the transmitting and receiving station to the assigned wavelength
- **Routing** (executed in the optical path sublayer) involves
  - determination of a suitable optical path for the assigned λ-channel
  - setting-up of the switches in the network nodes to establish that path

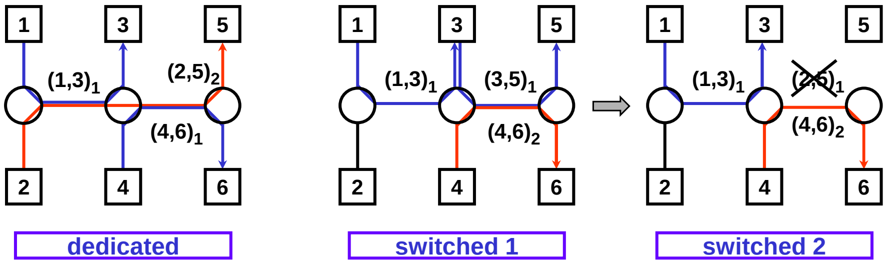
Channel assignment constraints

- Following two channel assignment constraints apply to WRNs
  - **wavelength continuity**: wavelength of each optical connection remains the same on all links it traverses from source to destination
    - wavelength continuity is unique to transparent optical networks, making routing and wavelength assignment a more challenging task than the related problem in conventional networks
  - **distinct channel assignment** (DCA): all optical connections sharing a common fiber must be assigned distinct λ-channels (i.e. distinct wavelengths)
    - this applies to access links as well as inter-nodal links
    - although DCA is necessary to ensure distinguishability of signals on the same fiber, it is possible (and generally advantageous) to reuse the same wavelength on fiber-disjoint paths



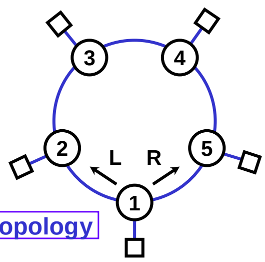
Routing and channel assignment (RCA) problem

- **Routing and channel assignment** (**RCA**) is a fundamental control problem in large optical networks
  – Generally, the RCA problem for **dedicated** connections can be treated off-line => computationally intensive optimization techniques are appropriate
  – On the other hand, RCA decisions for **switched** connections must be made rapidly, and hence suboptimal heuristics must normally be used

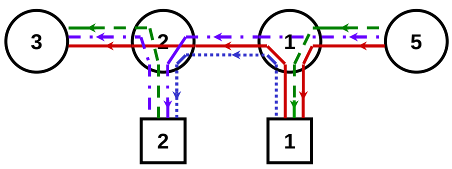


Example bi-directional ring with elementary NASs

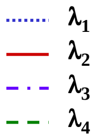
- Consider a bi-directional ring of 5 nodes and stations with single access fiber pairs
- Full point-to-point logical/optical connectivity requires
  - 4 wavelengths => spectrum reuse factor is 20/4 = 5
  - 4 transceivers in each NAS



physical topology



Fiber from ONN1 to ONN2



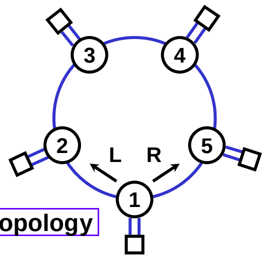
Destination

Source	1	2	3	4	5
1	--	1L	2L	3R	4R
2	1R	--	3L	4L	2R
3	3R	4R	--	2L	1L
4	4L	2R	1R	--	3L
5	2L	3L	4R	1R	--

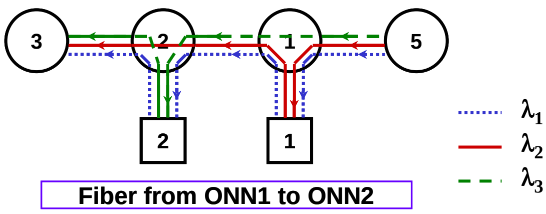
RCA

Example bi-directional ring with non-blocking NASs

- Consider a bi-directional ring of 5 nodes and stations with two access fiber pairs
- Full point-to-point logical/optical connectivity requires
  - 3 wavelengths => spectrum reuse factor is 20/3 = 6.67
  - 4 transceivers in each NAS



physical topology



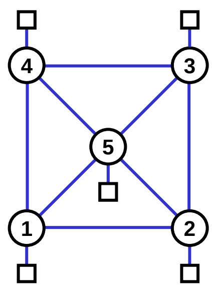
Fiber from ONN1 to ONN2

Source \ Destination	1	2	3	4	5
1	--	1L	2L	2R	1R
2	1R	--	1L	3L	3R
3	2R	1R	--	2L	1L
4	2L	3R	2R	--	3L
5	1L	3L	1R	3R	--

RCA

Example mesh network with elementary NASs

- Consider a mesh network of 5 nodes and stations with single access fiber pairs
- Full point-to-point logical/optical connectivity requires
  - 4 wavelengths => spectrum reuse factor is 20/4 = 5
  - 4 transceivers in each NAS
  - despite the richer physical topology, no difference with the corresponding bi-directional ring (thus, the access fibers are the bottleneck)

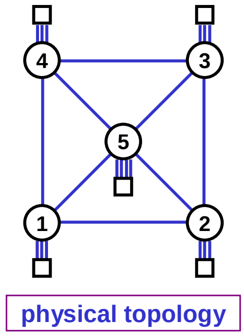


physical topology

RCA?

Example mesh network with non-blocking NASs

- Consider a mesh network of 5 nodes and stations with three/four access fiber pairs
- Full point-to-point logical/optical connectivity requires
  - only 2 wavelengths
    => spectrum reuse factor is 20/2 = 10
  - 4 transceivers in each NAS



RCA?

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- Static networks
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- **Linear Lightwave Networks (LLN)**
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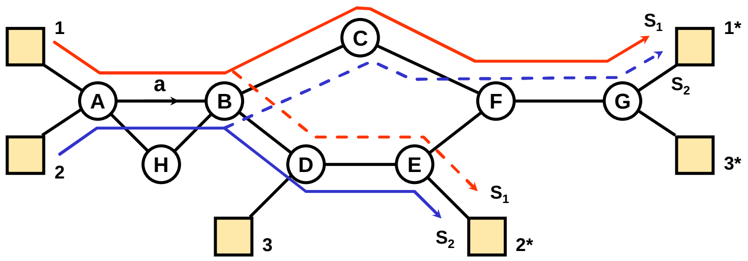
Linear Lightwave Networks (LLN)

- **Linear lightwave network** (**LLN**) is a purely optical network
  - nodes perform (only) strictly linear operations on optical signals
- This class includes
  - both static and wavelength routed networks
  - but also something more
- The most general type of LLN has **waveband selective LDC** nodes
  - LDC performs controllable optical signal dividing, routing and combining
  - these functions are required to support **multipoint optical connectivity**
- Waveband selectivity in nodes means that
  - optical path layer routes signals as **bundles** that contain all λ-channels within one waveband
- Thus, all layers of connectivity and their interrelations must be examined carefully

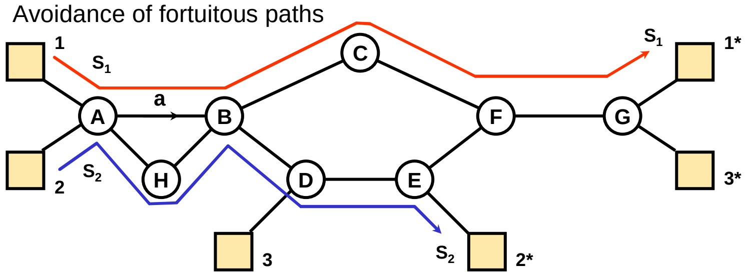
Routing and channel assignment constraints

- Two constraints of WRNs need also to be satisfied by LLNs
  - **Wavelength continuity:** wavelength of each optical connection remains the same on all the links it traverses from source to destination
  - **Distinct channel assignment (DCA):** all optical connections sharing a common fiber must be assigned distinct λ-channels
- Additionally, the following two routing constraints apply to LLNs
  - **Inseparability:** channels combined on a single fiber and located within the same waveband cannot be separated within the network
    - this is a consequence of the fact that the LDCs operate on the aggregate power carried within each waveband
  - **Distinct source combining (DSC):** only signals from distinct sources are allowed to be combined on the same fiber
    - DSC condition forbids a signal from splitting, taking multiple paths, and then recombining with itself
    - otherwise, combined signals would interfere with each other

Inseparability



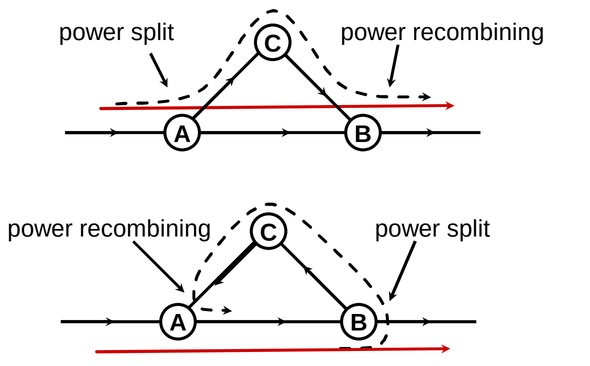
Avoidance of fortuitous paths



Inseparability (cont.)

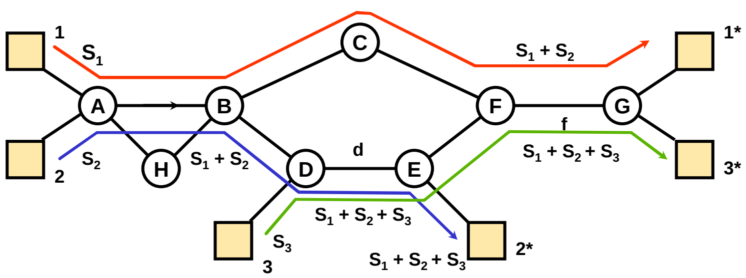
- Two connections (that use signals $\mathbf{S_1}$ and $\mathbf{S_2}$) are in the same waveband
- Power of $\mathbf{S_1}$ and $\mathbf{S_2}$ combined on link **a**
  => to avoid interference, connections should use different wavebands or different time-slots on a common wavelength
- At node **B**, both connections routed towards their destinations
- Since $\mathbf{S_1}$ and $\mathbf{S_2}$ are in the same waveband, both signals are multicasted towards destination 1' and 2'
  => both signals branch out from their original paths (to fortuitous paths)
  => waste of fiber resources
  => waste of signal power
- A good design principle includes avoidance of fortuitous paths

Two violations of DSC



=> Combining signals interfere with each other
=> Garbling of information

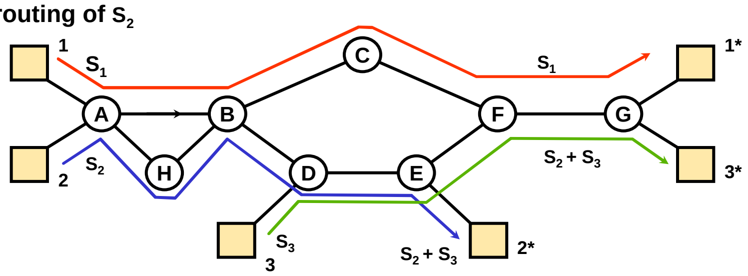
Inadvertent violation of DSC



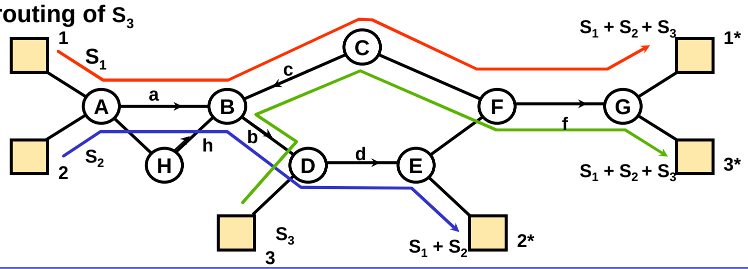
- Correct but poor routing decisions may produce inadvertent violation of DSC constraint
- Due to inseparability $\mathbf{S_3}$ carries $\mathbf{S_1}$+ $\mathbf{S_2}$ with it
  => all three connections in the same waveband on different λs (on link **f**)
  => $\mathbf{S_1}$ information (at destination 1') garbled
- Problem avoided if $\mathbf{S_3}$ in different waveband

Two other ways to avoid DSC violations

Rerouting of S_2

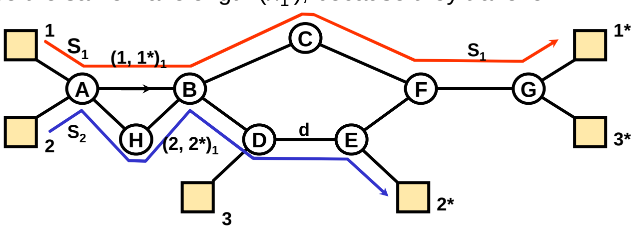


Rerouting of S_3

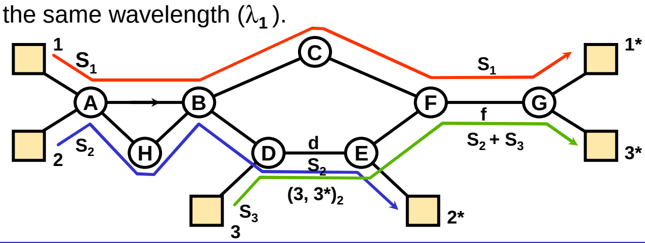


Color clash

Connection 1 and 2 can use the same wavelength (λ_1), because they travel on different links.



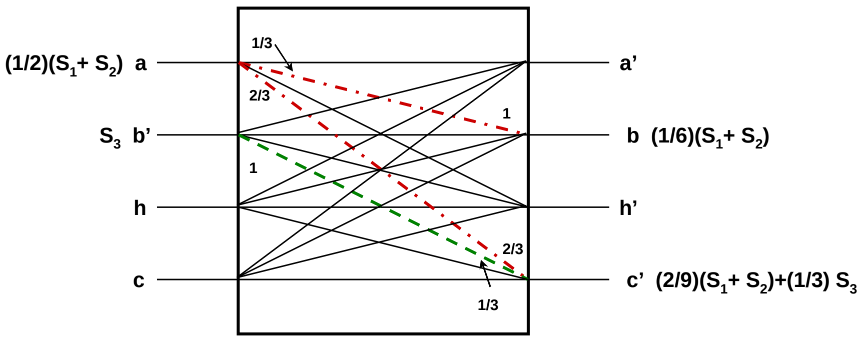
New connection 3 uses signal $\mathbf{S_3}$, which is in the same band as $\mathbf{S_1}$. => $\mathbf{S_1}$ and $\mathbf{S_2}$ collide, because they use the same wavelength (λ_1).



Power distribution

- In a LDC it is possible to specify combining and dividing ratios
  - ratios determine how power from sources is distributed to destinations
  - combining and dividing ratios can be set differently for each waveband
- How should these ratios be chosen?
- The **objective** could be
  - to split each source's power equally among all destinations it reaches
  - to combine equally all sources arriving at the same destination
- Resultant end-to-end power transfer coefficients are independent of
  - routing paths through the network
  - number of nodes they traverse
  - order in which signals are combined and split
- Coefficients depend only on
  - number of destinations for each source
  - number of sources reaching each destination

Illustration of power distribution

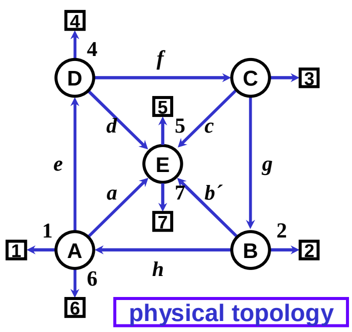


Multipoint subnets in LLNs

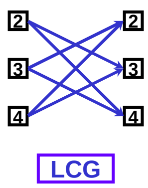
- Attempt to set up several point-to-point optical connections within a common waveband leads to unintentional creation of multipoint paths
  => complications in routing, channel assignment and power distribution
- On the other hand, waveband routing leads to more efficient use of the optical spectrum
- In addition, the multipoint optical path capability is useful when creating intentional multipoint optical connections
  - LLNs can deliver a high degree of logical connectivity with minimal optical hardware in the access stations
  - this is one of the fundamental advantages of LLNs over WRNs
- Multipoint optical connections can be utilized when creating a full logical connectivity among specified clusters of stations within a larger network => such fully connected clusters are called **multipoint subnets** (**MPS**)

Example - seven stations on a mesh

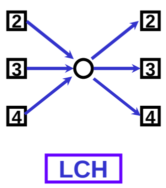
- Consider a network containing seven stations interconnected on a LLN with a mesh physical topology and bi-directional fiber links
  - notation for fiber labeling: *a* and *a´* form a fiber pair with opposite directions
- Set of stations {2,3,4} should be interconnected to create a MPS with full logical connectivity
- This can be achieved, e.g. by creating an **optical path on a single waveband** in the form of a tree joining the three stations (**embedded broadcast star**)



physical topology

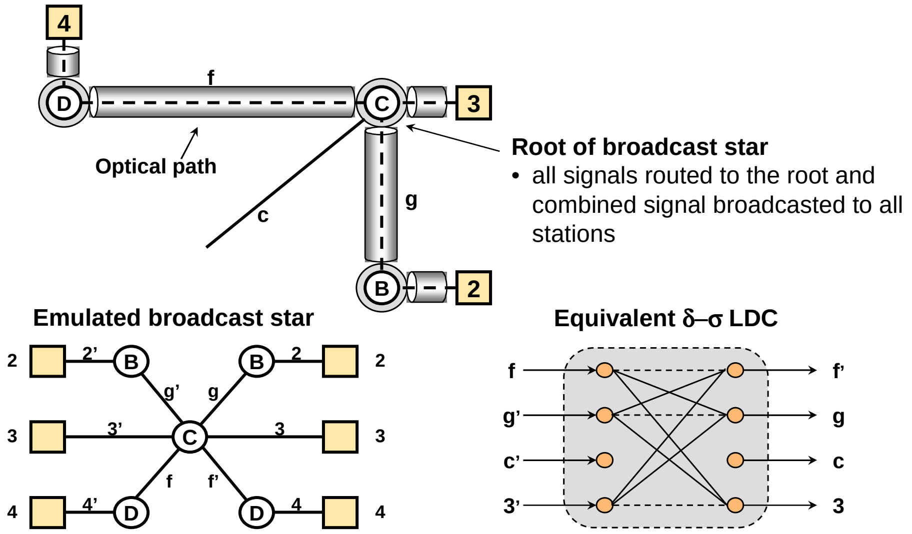


LCG



LCH

Realization of MPS by a tree embedded in mesh



Root of broadcast star
- all signals routed to the root and combined signal broadcasted to all stations

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- **Linear Lightwave Networks (LLN)**
  - **Seven-station example**
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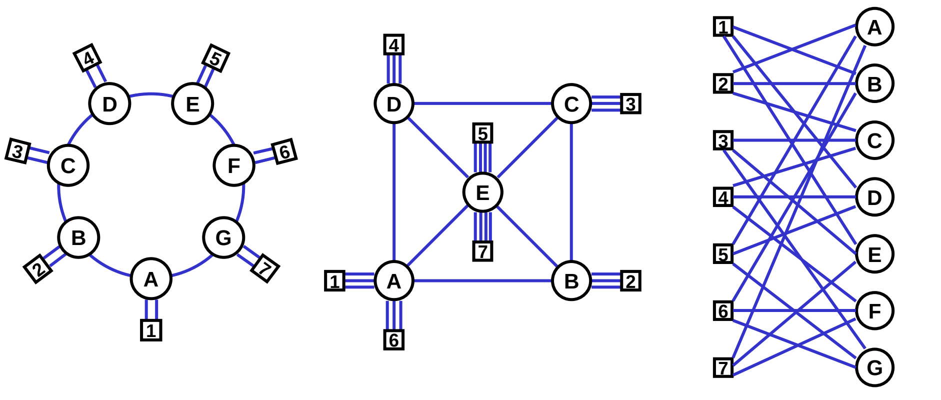
Seven-station example

- **Assume**:
  - non-blocking access stations
  - each transmitter runs at a bit rate of R_0
- **Physical topologies** (PT):
  - **bi-directional ring**
  - **mesh**
  - **multistar** of seven physical stars
- **Logical topologies** (LT):
  - **fully connected** (point-to-point logical topology with 42 edges) realized by using **WRN**
  - **fully shared** (hypernet logical topology with a single hyperedge) realized using a **broadcast-and-select network** (LLN of a single MPS)
  - **partially shared** (hypernet of seven hyperedges) realized by using **LLN** of seven MPSs

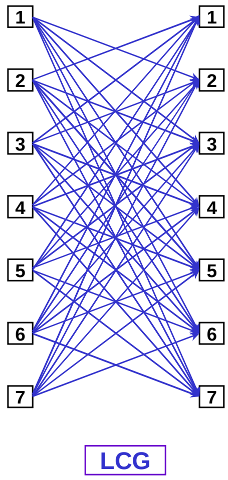
Physical topologies



ring mesh multistar

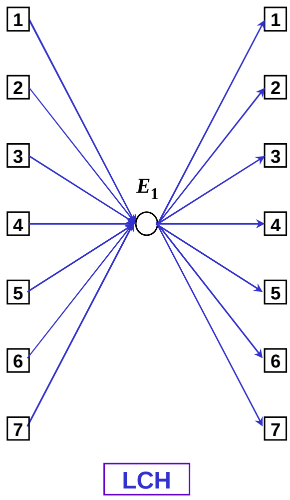
Fully connected LT - WRN realizations

- **Ring** PT:
  - 6 λs with spectrum reuse factor of 42/6 = 7 => RCA?
  - 6 transceivers in each NAS
    ⇒ network capacity = 7*6 = 42 R_0
- **Mesh** PT:
  - 4 λs with spectrum reuse factor of 42/4 = 10.5 => RCA?
  - 6 transceivers in each NAS
    ⇒ network capacity = 7*6 = 42 R_0
- **Multistar** PT:
  - 2 λs with spectrum reuse factor of 42/2 = 21 => RCA?
  - 6 transceivers in each NAS
    ⇒ network capacity = 7*6 = 42 R_0



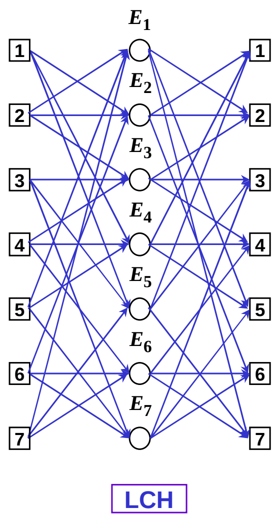
Fully shared LT - Broadcast and select network realizations

- Any PT
- WDM/WDMA:
  - 42 λs with spectrum reuse factor of 1
  - 6 transceivers in each NAS
    ⇒ network capacity = 7*6 = 42 R_0
- TDM/T-WDMA in FT-TR mode:
  - 7 λs with spectrum reuse factor of 1
  - 1 transceiver in each NAS
    ⇒ network capacity = 7*1 = 7 R_0
- TDM/TDMA:
  - 1 λ with spectrum reuse factor of 1
  - 1 transceiver in each NAS
    ⇒ network capacity = 7*1/7 = 1 R_0



Partially shared LT - LLN realizations

- **Note**: Full logical connectivity among **all** stations
- **Mesh** PT using **TDM/T-WDMA** in FT-TR mode:
  - 2 wavebands with spectrum reuse factor of 7/2 = 3.5 => RCA?
  - 3 λs per waveband
  - 3 transceivers in each NAS
    ⇒ network capacity = 7*3 = 21 R_0
- **Multistar** PT using **TDM/T-WDMA** in FT-TR mode:
  - 1 waveband with spectrum reuse factor of 7/1 = 7 => RCA?
  - 3 λs per waveband
  - 3 transceivers in each NAS
    ⇒ network capacity = 7*3 = 21 R_0



Contents

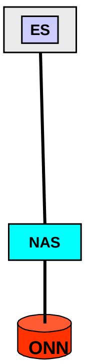
- Static networks
- Wavelength Routed Networks (WRN)
- Linear Lightwave Networks (LLN)
- **Logically Routed Networks (LRN)**

Logically Routed Networks (LRN)

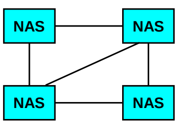
- For small networks, high logical connectivity is reasonably achieved by purely optical networks. However, when moving to larger networks, the transparent optical approach soon reaches its limits.
- For example, to achieve full logical connectivity among 22 stations on a bi-directional ring using wavelength routed point-to-point optical connections 21 transceivers are needed in each NAS and totally 61 wavelengths. Economically and technologically, this is well beyond current capabilities.
  => we must turn to electronics (i.e. logically routed networks)
- **Logically routed network** (**LRN**) is a hybrid optical network
  – which performs logical switching (by **logical switching nodes** (LSN)) on top of a transparent optical network
  – LSNs create an extra layer of connectivity between the end systems and NASs

Difference between logical connections in purely optical network and LRN

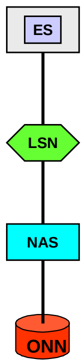
Purely optical network:
- End systems connect directly to external ports of NAS
- Transport of data between a pair of end systems is supported by logical connections originating and terminating at corresponding NAS ports



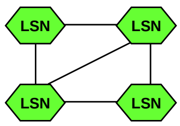
Example LCG



Logically routing network (LRN):
- Logically switching nodes (LSN) form an extra layer of connectivity between end system and NAS
  => ES accesses logical network through LSN and LSN accesses transparent optical network through NAS
- Logical connections formed between LSNs



Example LCG



ES = End System
LSN = Logical Switching Node
NAS = Network Access Node
ONN = Optical Network Node

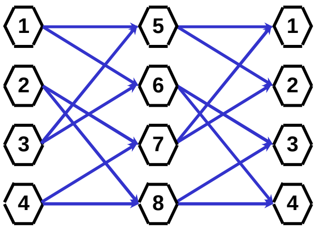
Two approaches to create full connectivity

- **Multihop networks** based on point-to-point logical topologies
  - realized by **WRN**s
- **Hypernets** based on multipoint logical topologies
  - realized by **LLN**s

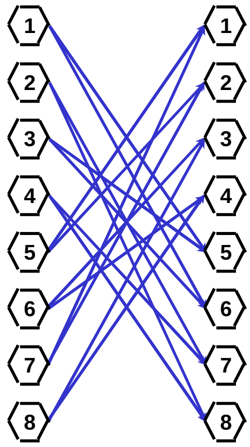
Point-to-point logical topologies

- In a point-to-point logical topology
  - a hop corresponds to a logical link between two LSNs
  - maximum throughput is inversely proportional to the average hop count
- One of the **objectives** of using logical switching on top of a transparent optical network is
  - to reduce cost of station equipment (by reducing the number of optical transceivers and complexity of optics) while maintaining high network performance
- Thus, we are interested in logical topologies that
  - achieve a small average number of logical hops at a low cost (i.e., small node degree and simple optical components)
- An example is a **ShuffleNet**
  - for example, an eight-node ShuffleNet has 16 logical links and an average hop count of 2 (if uniform traffic is assumed)
  - these networks are scalable to large sizes by adding stages and/or increasing the degree of the nodes

Eight-node ShuffleNet



logical topology



LCG

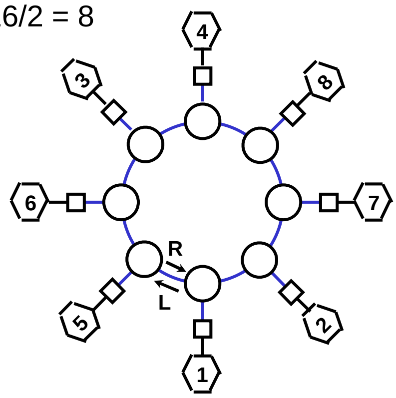
ShuffleNet embedded in a bi-directional ring WRN

- **Bi-directional ring WRN** with elementary NASs
  - 2 λs with spectrum reuse factor of 16/2 = 8
  - 2 transceivers in each NAS
  - average hop count = 2
    ⇒ network cap. = 8*2/2 = 8 R_0

Destination

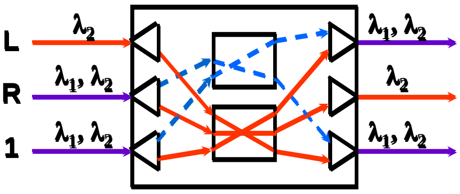
Source	1	2	3	4	5	6	7	8
1	--	--	--	--	1L	2L	--	--
2	--	--	--	--	--	--	1R	2R
3	--	--	--	--	2R	1R	--	--
4	--	--	--	--	--	--	2L	1L
5	1R	2R	--	--	--	--	--	--
6	--	--	1L	2L	--	--	--	--
7	2L	1L	--	--	--	--	--	--
8	--	--	2R	1R	--	--	--	--

RCA

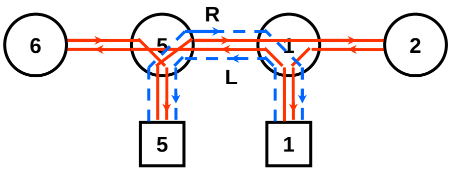


Note: station labeling!

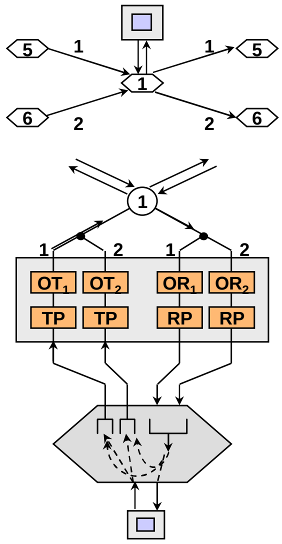
Details of a ShuffleNet node



ONN1



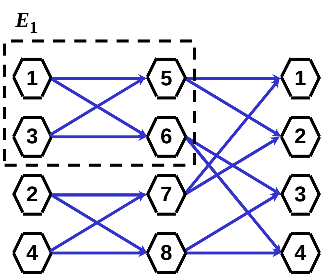
Fibers between ONN5 and ONN1



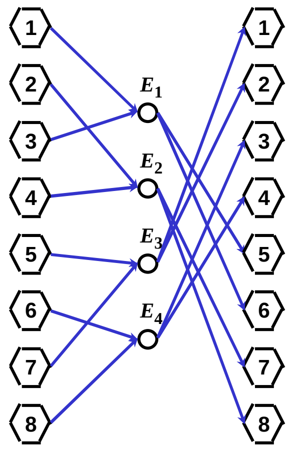
Multipoint logical topologies

- High connectivity may be maintained in transparent optical networks while economizing on optical resource utilization through the use of **multipoint connections**
- These ideas are even more potent when combined with logical switching
- For example, a ShuffleNet may be modified to a **Shuffle Hypernet**
  - an 8-node Shuffle Hypernet has 4 hyperarcs
  - each hyperarc presents a directed MPS that contains 2 transmitting and 2 receiving stations
  - an embedded directed broadcast star is created to support each MPS
  - for a directed star, a (physical) tree is found joining all stations in both the transmitting and receiving sets of the MPS
  - any node on the tree can be chosen as a root
  - LDCs on the tree are set to create optical paths from all stations in the transmitting set to the root node, and paths from the root to all receiving stations

Eight-node Shuffle Hypernet



transformation



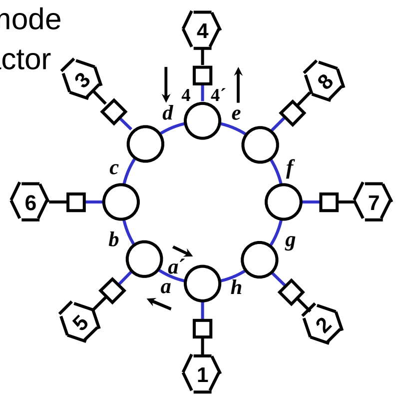
LCH

Shuffle Hypernet embedded in a bi-directional ring LLN

- **Bi-directional ring LLN** with elementary NASs using **TDM/T-WDMA** in FT-TR mode
  - 1 waveband with spectrum reuse factor of 4/1 = 4
  - 2 λs per waveband
  - 1 transceiver in each NAS
    $\Rightarrow$ network cap. = 8*1/2 = 4 R_0

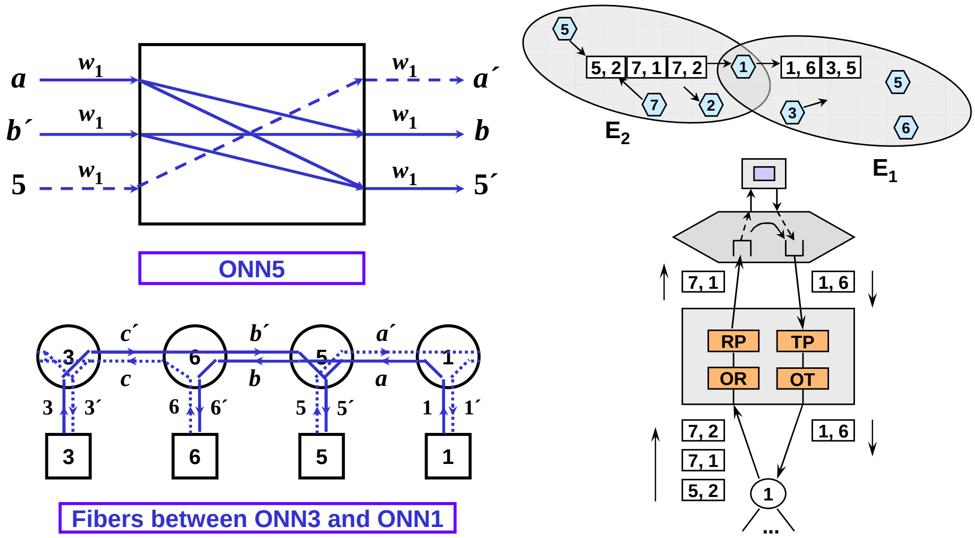
	inbound fibers	root	outbound fibers	wave-band
E_1	*a, b´, c´*	ONN5	*b*	1
E_2	*e, f´, g´*	ONN8	*f*	1
E_3	*g, a´, h´*	ONN2	*h*	1
E_4	*c, d´, e´*	ONN3	*d*	1

RCA



Note: station and fiber labeling!

Details of node in Shuffle Hypernet



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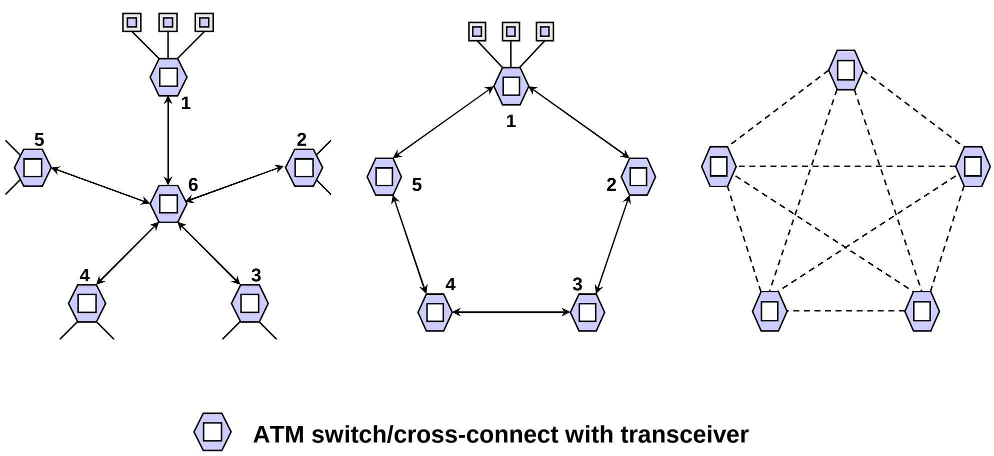
  - **Virtual connections: an ATM example**

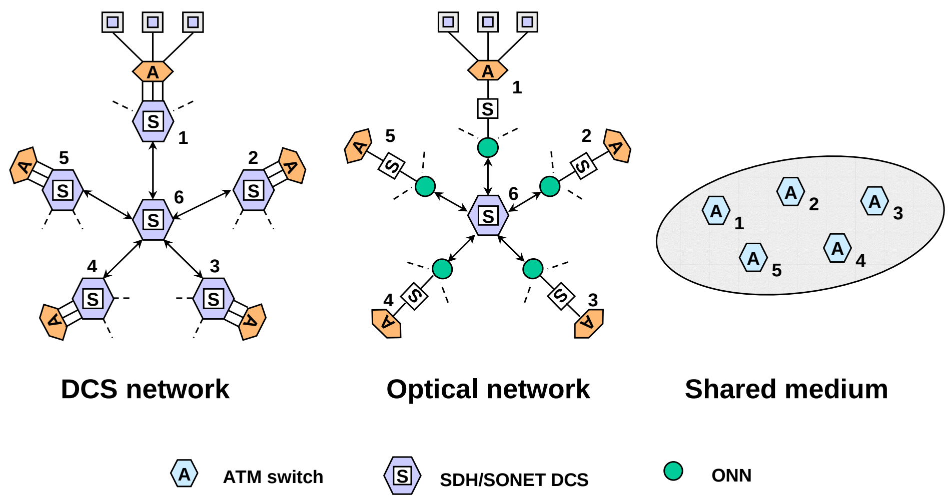
Virtual connections - an ATM example

- Recall the problem of providing full connectivity among five locations
  – suppose each location contains a number of end systems that access the network through an ATM switch. The interconnected switches form a transport network of 5*4 = 20 VPs.
- The following five designs are examined and compared:
  – **Stand-alone ATM star**
  – **Stand-alone ATM bi-directional ring**
  – **ATM over a network of SDH/SONET cross-connects**
  – **ATM over a WRN**
  – **ATM over a LLN**
- Traffic demand: each VP requires 600 Mbits/s (≈ STM-4/STS-12)
- Optical resources: λ-channels and transceivers run at the rate of 2.4 Gbits/s (≈ STM-16/STS-48)

Stand-alone ATM networks



Embedded ATM networks



Case 1 - Stand-alone ATM star

- Fiber links are connected directly to ports on ATM switches creating a point-to-point optical connection for each fiber
  - each link carries 4 VPs in each direction ⇒ each optical connection needs 2.4 Gbits/s, which can be accommodated by using a single λ-channel
  - one optical transceiver is needed to terminate each end of a link, for a total of 10 transceivers in the network
- Processing load is unequal:
  - end nodes process their own 8 VPs carrying 4.8 Gbits/s
  - center node processes all 20 VPs carrying 12.0 Gbits/s ⇒ **bottleneck**
- Inefficient utilization of fibers, because
  - even though only one λ-channel is used, the total bandwidth of each fiber is dedicated to this system
- Poor survivability, since
  - if any link is cut, network is cut in two
  - if center node fails, the network is completely destroyed

Case 2 - Stand-alone ATM bi-directional ring

- Fiber links are connected directly to ports on ATM switches, creating a point-to-point optical connection for each fiber
  - assuming shortest path routing, each link carries 3 VPs in each direction $\Rightarrow$ each optical connection needs 1.8 Gbits/s, which can be accommodated using a single λ-channel (leaving 25% spare capacity)
  - 1 optical transceiver is needed to terminate each end of a link, for a total of 10 transceivers in the network
- Equal processing load:
  - each ATM node processes its own 8 VPs and 2 additional transit VPs carrying an aggregate traffic of 6.0 Gbits/s
- Thus,
  - no processing bottleneck
  - the same problem with optical spectrum allocation as in case 1
  - but better survivability, since network can recover from any single link cut or node failure by rerouting the traffic

Case 3 - ATM embedded in DCS network

- ATM end nodes access DCSs through 4 electronic ports
- Fiber links are now connected to ports on DCSs, creating a point-to-point optical connection for each fiber
  - each link carries 4 VPs in each direction => each optical connection needs 2.4 Gbits/s, which can be accommodated using a single λ-channel
  - again, 1 optical transceiver is needed to terminate each end of a link
- Processing load is lighter
  - ATM nodes process their own 8 VPs carrying 4.8 Gbits/s
  - but it is much simpler to perform VP cross-connect functions at the STM-4/STS-12 level than at the ATM cell level (as was done in case 1)
  - a trade-off must be found between optical spectrum utilization and costs
  - the more λ-channels on each fiber (to carry "background" traffic), the more (expensive) transceivers are needed
- Survivability and reconfigurability are good
  - since alternate paths and additional bandwidth exist in the DCS network

Case 4 - ATM embedded in a WRN

- DCSs are now replaced by optical nodes containing WSXCs
- Each ATM end-node is connected electrically to a NAS
- Each VP in the virtual topology must be supported by
  - a point-to-point optical connection occupying one λ-channel
  - 4 tranceivers are needed in each NAS (and totally 20 transceivers)
  - however, no tranceivers are needed in the network nodes
- With an optimal routing and wavelength assignment,
  - the 20 VPs can be carried using 4 wavelengths (= 800 GHz)
- Processing load is very light
  - due to optical switching (without optoelectronic conversion at each node)
  - Note: ATM nodes still process their own 8 VPs carrying 4.8 Gbits/s
- As in case 3, survivability and reconfigurability are good
  - since alternate paths and additional bandwidth exist in the underlying WRN

Case 5 - ATM embedded in an LLN

- WSXCs are now replaced by LDCs
- A single waveband is assigned to the ATM network, and the LDCs are set to create an embedded tree (MPS) on that waveband
  - the 20 VPs are supported by a single hyperedge in the logical topology
  - since each λ-channel can carry 4 VPs, 5 λ-channels are needed totally, all in the same waveband (= 200 GHz)
  - only 1 transceiver is needed in each NAS (and totally 5 transceivers) using TDM/T-WDMA in FT-TR mode
- Processing load is again very light
  - due to optical switching (without optoelectronic conversion at each node)
  - Note: ATM nodes still process their own 8 VPs carrying 4.8 Gbits/s
- As in cases 3 and 4, survivability and reconfigurability are good
  - since alternate paths and additional bandwidth exist in the underlying LLN

Comparison of ATM network realizations

Case	Optical spectrum usage	Number of optical transceivers	Node processing load	Others
1	Very high	10	Very high	Poor survivability
2	Very high	10	High	-
3	Lowest	10	Medium	High DCS
4	Medium	20	Very low	-
5	Low	5	Very low	Rapid tunability required, optical multi-cast possible

Case 1 - Stand-alone ATM star
Case 2 - Stand-alone ATM bi-directional ring
Case 3 - ATM embedded in DCS network
Case 4 - ATM embedded in WRN
Case 5 - ATM embedded in LLN