Chapter 13

Optical Networks

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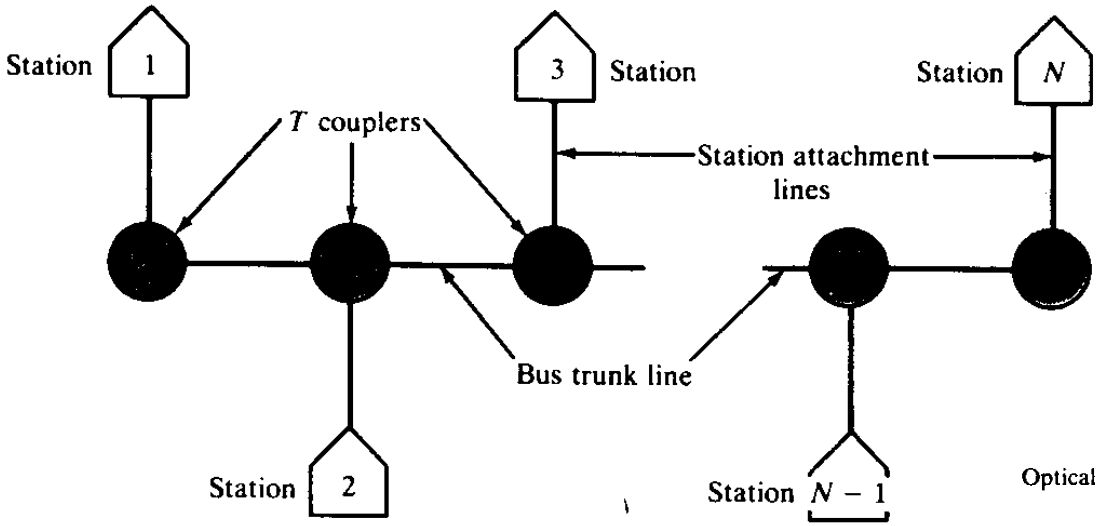
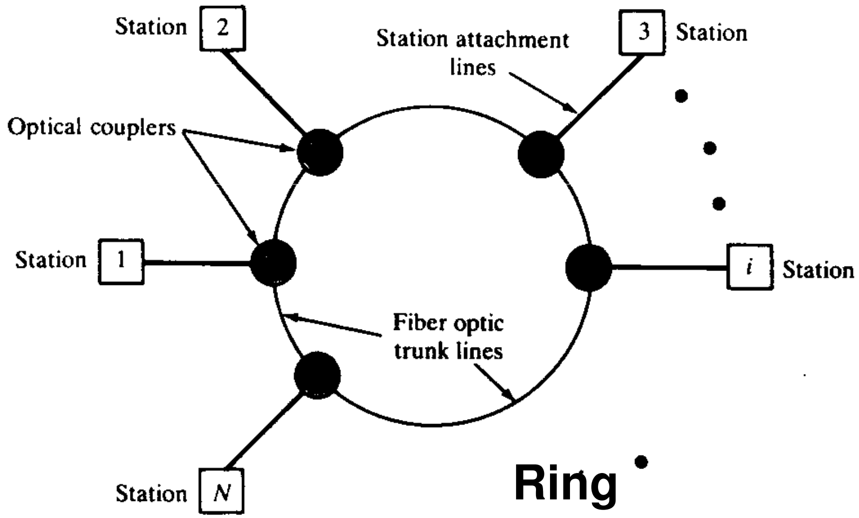
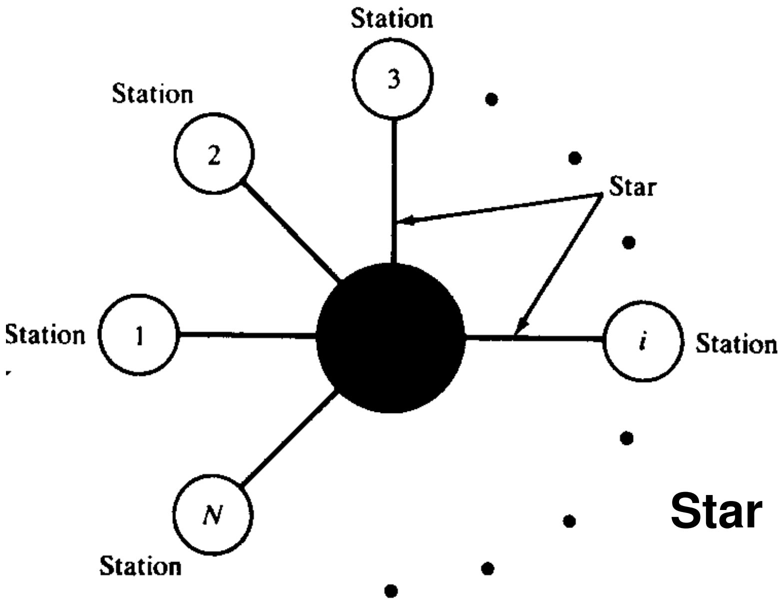
Network Topologies



Linear bus



Ring



Star

Network Topologies (2)

- Access to an optical data bus is achieved by means of a coupling element. An *active coupler* converts the optical signal on the data bus to its electric baseband counterpart before any data processing is carried out. A *passive coupler* employs no electronic elements. It is used passively to tap off a portion of the optical power from the bus.
- In a ring topology, consecutive nodes are connected by point-to-point links that are arranged to form a single closed path. Information in the form of data packets is transmitted from node to node around the ring. The interface at each node is an active device that has the ability to recognize its own address in a data packet in order to accept messages. The active node forwards those messages that are not addressed to itself on to its next neighbor.

Network Topologies (3)

- In a star architecture, all nodes are joined at a single point called the *central node* or *hub*.

  Using an active hub, one can control all routing of messages in the network from the central node.

  In a star network with a passive central node, a power splitter is used at the hub to divide the incoming optical signals among all the outgoing lines to the attached stations.

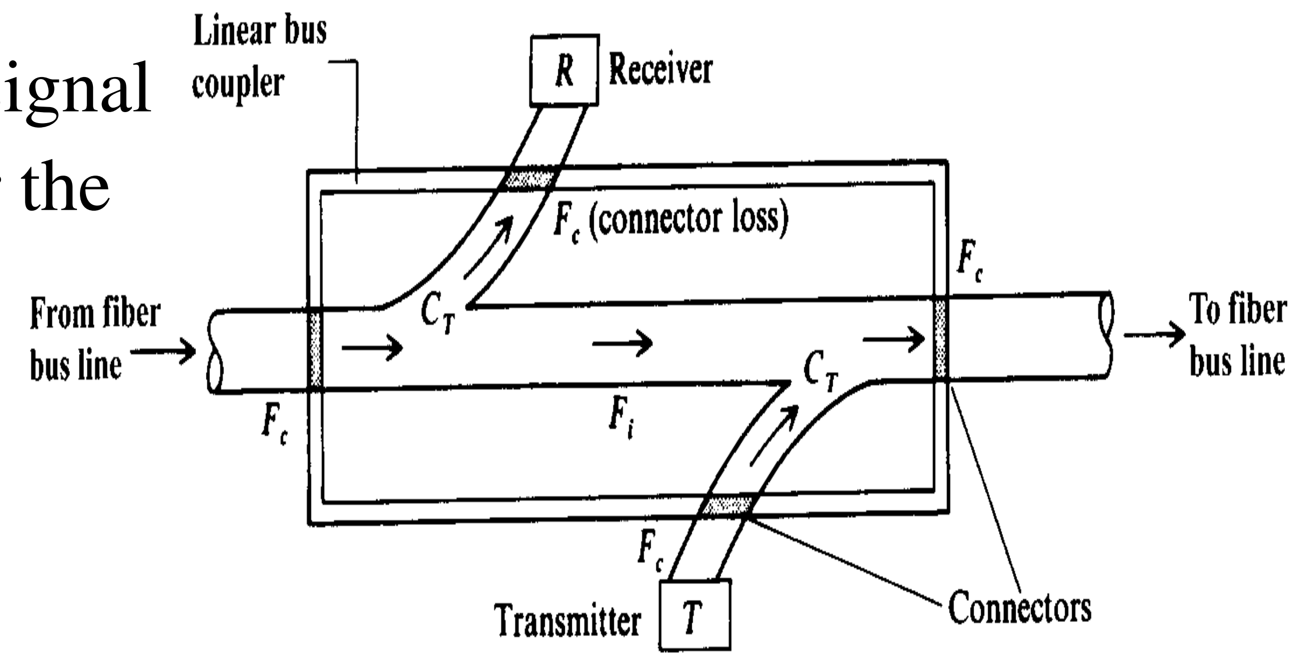
Performance of Passive Linear Buses

- Over an optical fiber of length x (in km), the ratio A_0 of received power $P(x)$ to transmitted power $P(0)$ is given by

$$A_0 = P(x)/P(0) = 10^{-\alpha x/10} \qquad (13\text{-}1)$$

where α is the fiber attenuation in units of dB/km.

- The coupler has four functioning ports: two for connecting the coupler onto the fiber bus, one for receiving tapped-off light, and one for inserting optical signal onto the line after the tap-off to keep the signal out of the local receiver.



Performance of Passive Linear Buses

- If a fraction F_c of optical power is lost at each port of the coupler, then the *connecting loss* L_c is

$$L_c = -10 \log(1-F_c) \qquad (13\text{-}2)$$

For example, if we take this fraction to be 20%, then L_c is about 1 dB; that is, the optical power gets reduced by 1 dB at any coupling junction.

- Let C_T represent the fraction of power that is removed from the bus and delivered to the detector port. The power extracted from the bus is called a *tap loss* and is given by

$$L_{tap} = 10 \log C_T \qquad (13\text{-}3)$$

- For a symmetric coupler, C_T is also the fraction of power that is coupled from the transmitting input port to the bus.

Performance of Passive Linear Buses

- If P_0 is the optical power launched from a source flylead, the power coupled to the bus is $C_T P_o$. The *throughput coupling loss* L_{thru} is then given by

$$L_{thru} = -10 \log(1 - C_T)^2$$
$$= -20 \log(1 - C_T) \qquad (13\text{-}4)$$

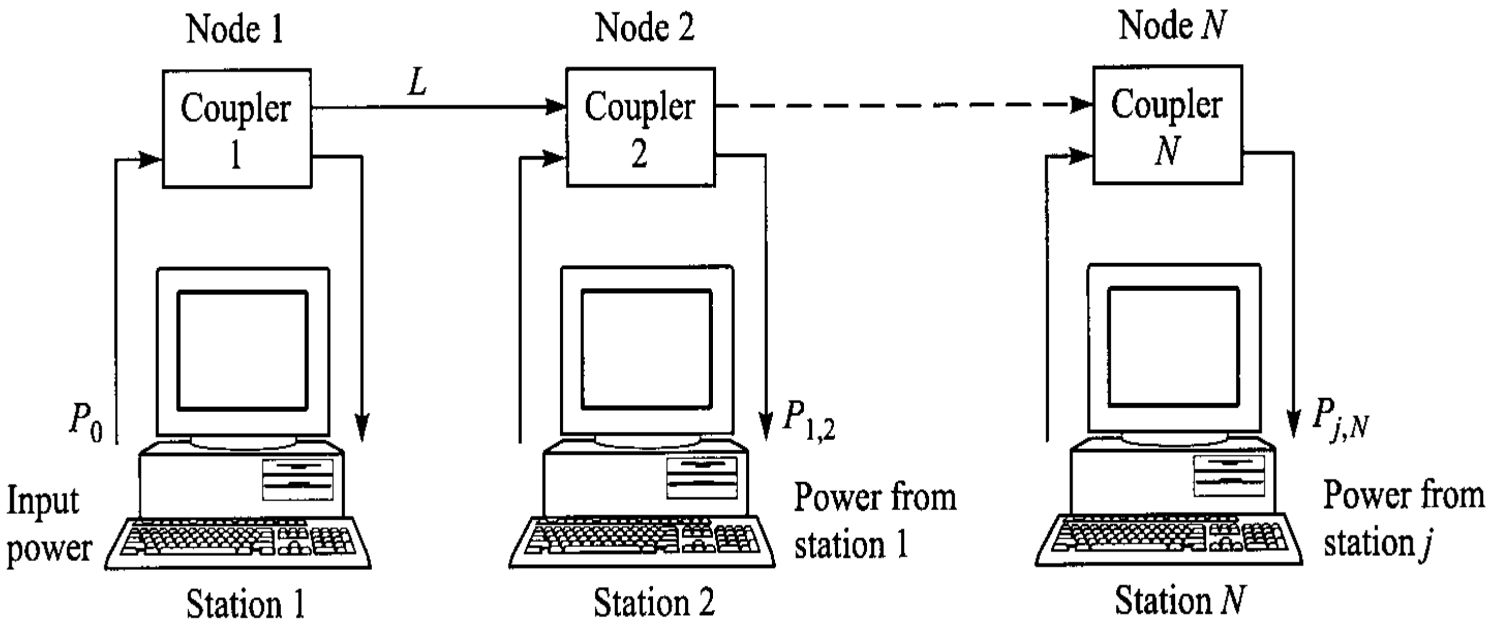
- In addition to connection and tapping losses, there is an intrinsic transmission loss L_i associated with each bus coupler.
- If the fraction of power lost in the coupler is F_i, then the *intrinsic transmission loss* L_i is

$$L_i = -10 \log(1 - F_i) \qquad (13\text{-}5)$$

Performance of Passive Linear Buses

- Consider a simplex linear bus of N stations uniformly separated by a distance L.
- From Eq. (12-1) the fiber attenuation between any two adjacent stations is

$$L_{\text{fiber}} = -10 \log A_0 = \alpha L \qquad (13\text{-}6)$$



Nearest-Neighbor Power Budget

- ✓ The smallest distance in transmitted and received power occurs for adjacent stations, such as between stations 1 and 2. If P_0 is the optical power launched from a source at station 1, then the power detected at station 2 is

$$P_{1,2} = A_0 C_T^2 (1-F_c)^4 (1-F_i)^2 P_0 \qquad (13\text{-}7)$$

- The optical power flow encounters the following loss-inducing mechanisms:
  - One fiber path with attenuation A_0.
  - Tap points at both the transmitter and the receiver, each with coupling efficiencies C_T.
  - Four connecting points, each of which passes a fraction $(1 - F_c)$ of the power entering them.
  - Two couplers which pass only the fraction $(1 - F_i)$ of the incident power owing to intrinsic losses.
- The losses between stations 1 and 2 can be expressed as

$$10 \log(P_o/P_{1,2}) = \alpha L + 2L_{tap} + 4L_c + 2L_i. \qquad (13\text{-}8)$$

Largest-Distance Power Budget

- The largest distance occurs between stations 1 and N. The fractional power level coupled into the cable from the bus coupler at station 1 is

$$F_1 = (1\text{-}F_c)^2\, C_T\, (1–F_i) \qquad (13\text{-}9a)$$

At station N the fraction of power from the bus-coupler input port that emerges from the detector port is

$$F_N = (1\text{-}F_c)^2\, C_T\, (1–F_i) \qquad (13\text{-}9b)$$

- For each of the (N - 2) intermediate stations, the fraction of power passing through each coupling module is

$$F_{coup} = (1\text{-}F_c)^2(1\text{-}C_T)^2(1–F_i), \qquad (13\text{-}10)$$

since the power flow encounters two connector losses, two tap losses, and one intrinsic loss.

Largest-Distance Power Budget

- Combining the expressions from Eqs. (13-9a), (13-9b), and (13-10), and the transmission losses of the N – 1 intervening fibers,
- we find that the power received at station N from station 1 is

$$P_{1,\mathrm{N}} = A_0^{N\text{-}1} F_1 F_{\mathrm{coup}}^{N\text{-}2} F_{\mathrm{N}} P_0$$

$$= A_0^{N\text{-}1}(1\text{-}F_{\mathrm{c}})^{2N}(1\text{-}C_{\mathrm{T}})^{2(N\text{-}2)} C_{\mathrm{T}}^{2}(1\text{-}F_{\mathrm{i}})^{N} P_0 \qquad (13\text{-}11)$$

- Using Eqs. (13-2) ~ (13-6), the power budget for this link is

$$10\log\left(\frac{P_0}{P_{1,N}}\right) = (N-1)\alpha L + 2NL_c + (N-2)L_{thru} + 2L_{tap} + NL_i$$

$$= N(\alpha L + 2L_c + L_{thru} + L_i) - \alpha L - 2L_{thru} + 2L_{tap} \qquad (13\text{-}12)$$

- The losses increase linearly with the number of stations N.

Performance of Passive Linear Buses

Example 13-1 :

- Compare the power budgets of three linear buses, having 5, 10, and 50 stations, respectively.

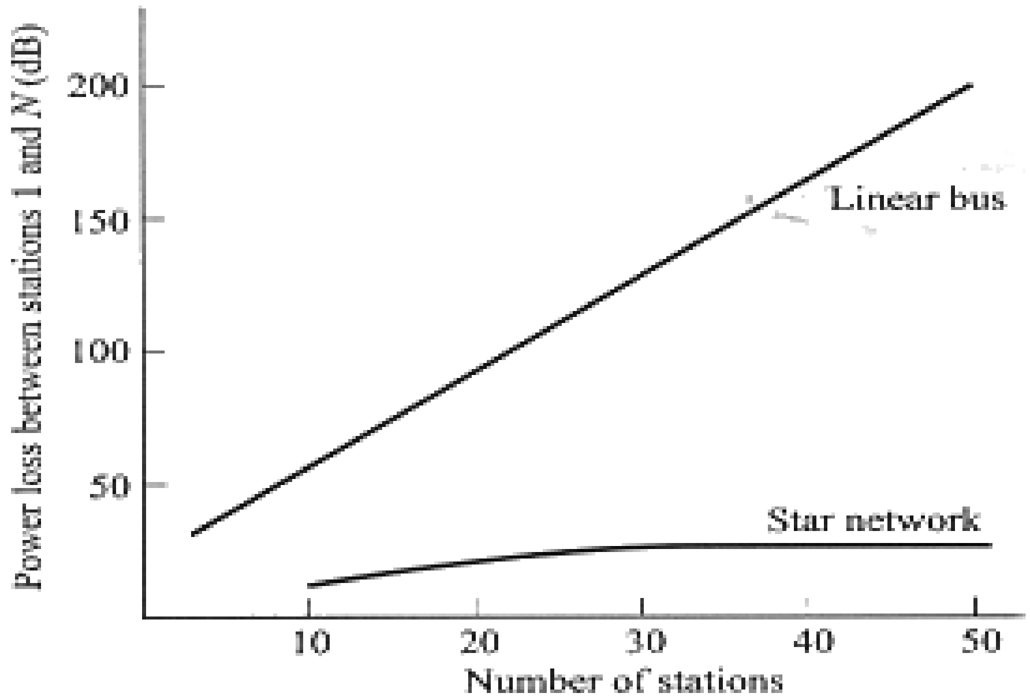
- Assume that $C_T = 10\ \%$, so that $L_{tap} = 10$ dB and $L_{thru} = 0.9$ dB. Let $L_i = 0.5$ dB and $L_c = 1.0$ dB.

- If the stations are relatively close together say 500 m, then for an attenuation of 0.4 dB/km at 1300 nm the fiber loss is 0.2 dB.

- Using Eq. (13-12), the power budgets for these three cases can be calculated as shown in Table 13-1.

- The total loss values given in Table 13-1 are plotted in Fig. 13-4, which shows that the loss increases linearly with the number of stations.

Coupling/loss factor	Loss expression	Loss (dB)	Losses for 5 stations	Losses for 10 stations	Losses for 50 stations
Source connector	Eq. (12-2)	1.0	1.0	1.0	1.0
Coupling (tap) loss	Eq. (12-3)	2×10.0	20.0	20.0	20.0
Coupler-to-fiber loss	Eq. (12-2)	$2(N-1) \times 1.0$	8.0	18.0	98.0
Fiber loss (500 m)	Eq. (12-6)	$(N-1) \times 0.2$	0.8	1.8	9.8
Coupler throughput	Eq. (12-4)	$(N-2) \times 0.9$	2.7	7.2	43.2
Intrinsic coupler loss	Eq. (12-5)	$N \times 0.5$	2.5	5.0	25.0
Receiver connector	Eq. (12-2)	1.0	1.0	1.0	1.0
Total loss (dB)	Eq. (12-12)	—	36.0	54.0	198.0



Example 13-2 :

- For the Example 13-1, suppose that for implementing a 10-Mb/s bus we gave a choice of an LED that emits -10 dBm or a LD capable of emitting +3 dBm of optical power.
- APD receiver with sensitivity of -48 dBm is used at the destination.
- In the LED case, the power loss allowed up to 5 stations on the bus.
- For the LD, we gave an additional 13 dB of margin, so we can have a maximum of 8 stations connected to the bus.

Dynamic Range

- System dynamic range is the maximum optical power range to which any detector must be able to respond.
- The worst-case dynamic range (DR) is found from the ratio of Eq. (13-7) to Eq. (13-11):

$$\begin{aligned}\mathrm{DR} &= 10\log\left(P_{1,2} / P_{1,N}\right) = -10\log\left\{\left[A_0(1-F_c)^2(1-C_T)^2(1-F_i)^2\right]^{N-2}\right\} \\ &= (N-2)(\alpha L + 2L_c + L_{thru} + L_i)\end{aligned} \qquad (13\text{-}13)$$

- Power levels received may differ at station N from station (N - 1) and from station 1 (i.e., $P_{1,2} = P_{N\text{-}1,N}$).

<u>Example 13-3</u> : Consider the linear buses described in Example 13-1. For $N = 5$ stations, from Eq. (13-13) the dynamic range is

DR = 3[0.2 + 2(1.0) + 0.9 + 0.5] dB = 10.8 dB.

For $N = 10$ stations,

DR = 8[0.2 + 2(1.0) + 0.9 + 0.5] dB = 28.8 dB.

Performance of Star Architectures

- For a single input power P_{in} and N output powers, the excess loss is given by

$$\text{excess loss} = L_{excess} = 10\log\left(\frac{P_{in}}{\sum_{i=1}^{N} P_{out,i}}\right) \qquad (12\text{-}14)$$

- The total loss of the device consists of its splitting loss plus the excess loss in each path through the star.
- The *splitting loss* is given by

$$\text{splitting loss} = L_{split} = -10\log\left(\frac{1}{N}\right) = 10\log N \qquad (12\text{-}15)$$

Performance of Star Architectures

- For power-balance equation, the following parameters are used:
  - P_S is the fiber-coupled output power from a source in dBm.
  - P_R is the minimum optical power in dBm required at the receiver to achieve a specific BER.
  - α is the fiber attenuation.
  - All stations are located at the same distance L from the star coupler.
  - L_c is the connector loss in decibels.
- The power-balance equation for a particular link between two stations in a star network is

$$P_S - P_R = L_{excess} + \alpha(2L) + 2L_c + L_{split}$$

$$= L_{excess} + \alpha(2L) + 2L_c + L_{split} + 10\log N$$

- Losses increase as $\log N$ in contrast with N for linear buses.

Performance of Star Architectures

Example 13-4 : Consider two star networks that have 10 and 50 stations, respectively. Assume each station is located 500 m from the star coupler and that the fiber attenuation is 0.4 dB/km. Assume that the excess loss is 0.75 dB for the 10-station network and 1.25 dB for the 50-station network. Let the connector loss be 1.0 dB.

For $N = 10$, from Eq. (13-16) the power margin between the transmitter and the receiver is

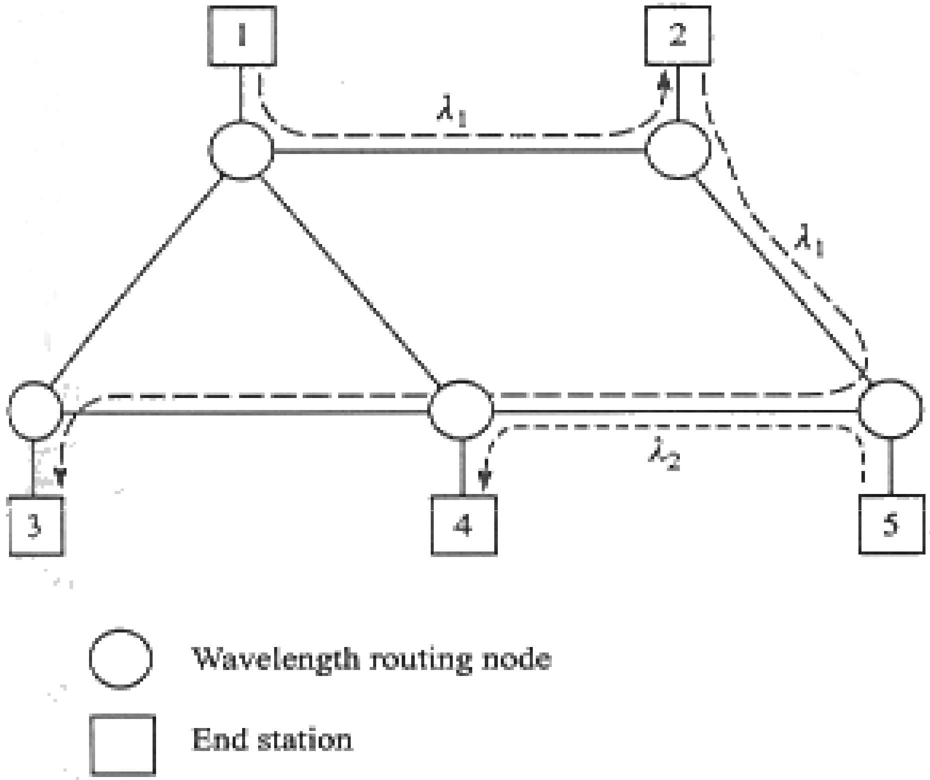
$$P_S - P_R = [0.75 + 0.4(1.0) + 2(1.0) + 10\log 10]\ \text{dB} = 13.2\ \text{dB}$$

For $N = 50$, the power margin is

$$P_S - P_R = [1.25 + 0.4(1.0) + 2(1.0) + 10\log 50]\ \text{dB} = 20.6\ \text{dB}$$

Wavelength-Routed Networks

- Wavelength-routed network consists of optical wavelength routers interconnected by pairs of point-to-point fiber links in a mesh configuration, as shown.



- In the figure, the connection from node 1 to node 2 and from node 2 to node 3 can both be on λ_1, whereas the connection between nodes 4 and 5 requires a different wavelength λ_2.

Optical Cross-Connects

- Consider the OXC architecture shown in Fig. 13-30 that uses space switching without wavelength conversion.
- The space switches can be cascaded electronically controlled optical directional-coupler elements or semiconductor-optical-amplifier switching gates.
- Each of the input fibers carries *M* wavelengths, any of which could be added or dropped at a node.

Optical Cross-Connects (2)

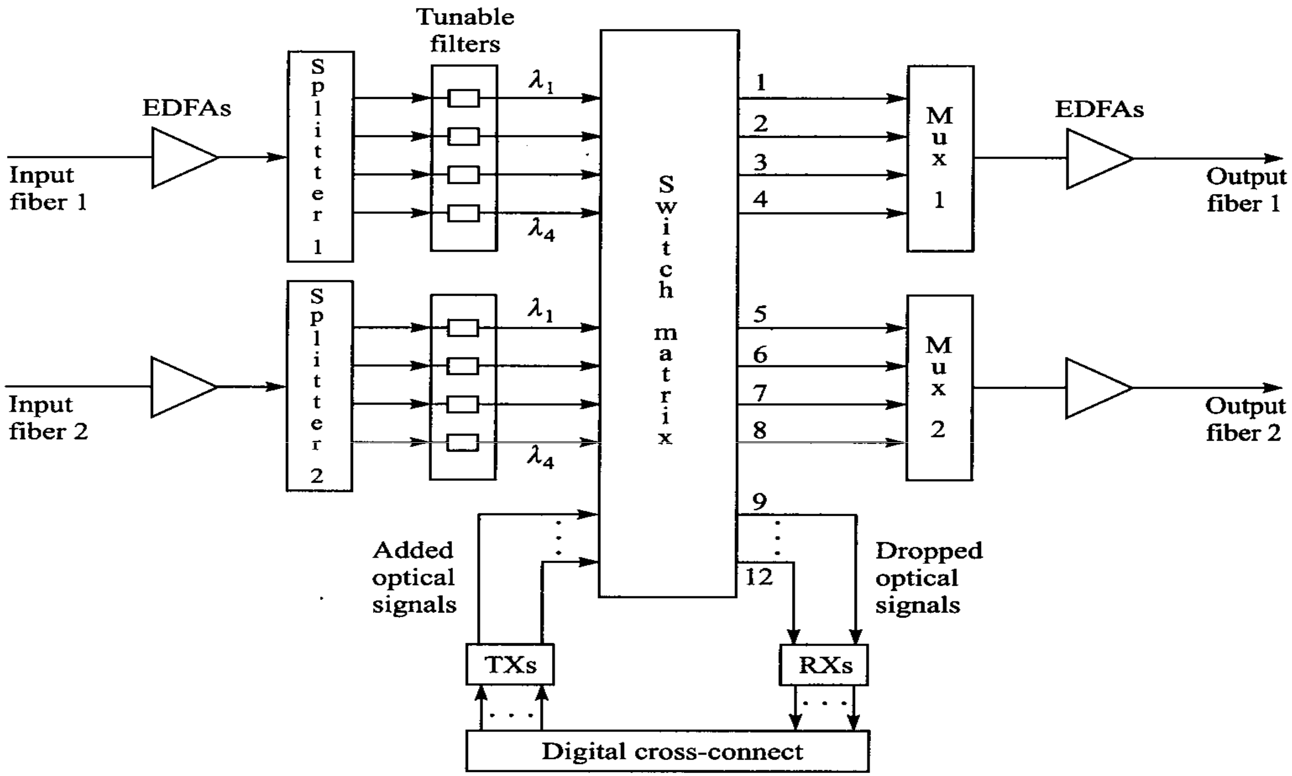


Figure 13-30. Optical cross-connect architecture using optical space switches and no wavelength converters.

Optical Cross-Connects (3)

- At the input, the arriving signal wavelengths is amplified and passively divided into *N* streams by a power splitter or AWG demultiplexer.
- Tunable filters then select individual wavelengths, which are directed to an optical space-switching matrix.

- The switch matrix directs the channels either to one of the eight output lines if it is a through-traveling signal,
- or to a particular receiver attached to the OXC at output ports 9 through 12 if it has to be dropped to a user at that node.

Optical Cross-Connects (4)

- Signals that are generated locally by a user get connected electrically via the DXC to an optical transmitter. The switch matrix directs them to the appropriate output line.

- The *M* output lines, each carrying separate wavelengths, are fed into a wavelength multiplexer to form a single aggregate output stream.

- Contentions arise in the architecture shown in Fig. 12-20 when channels having the same wavelength but traveling on different input fibers enter the OXC and need to be switched simultaneously to the same output fiber.

Optical Cross-Connects (5)

- The contentions could be resolved by assigning a fixed wavelength to each optical path throughout the network, or by dropping one of the channels and retransmitting it at another wavelength.

- In the first case, wavelength reuse and network scalability are reduced.
- In the second case, the add/drop flexibility of the OXC is lost.

- These blocking characteristics can be eliminated by using wavelength conversion at any output of the OXC.

Optical Cross-Connects (6)

Example 13-6 :

- Consider the 4 x 4 OXC shown in Fig.12-21. The OXC consists of three 2 x 2 switch elements.
- Suppose that λ_2 on input fiber 1 needs to be switched to output fiber 2 and that λ_1 on input fiber 2 needs to be switched to output fiber 1.
- This is achieved by having the 1st two switch elements set in the bar-state and the 3rd elements set in the cross-state, as indicated in Fig. 13-31.
- Obviously, without wavelength conversion there would be wavelength contention at both mux output ports.
- By using wavelength converters ahead of the multiplexer, the cross-connected wavelengths can be converted to noncontending wavelengths.

Optical Cross-Connects (7)

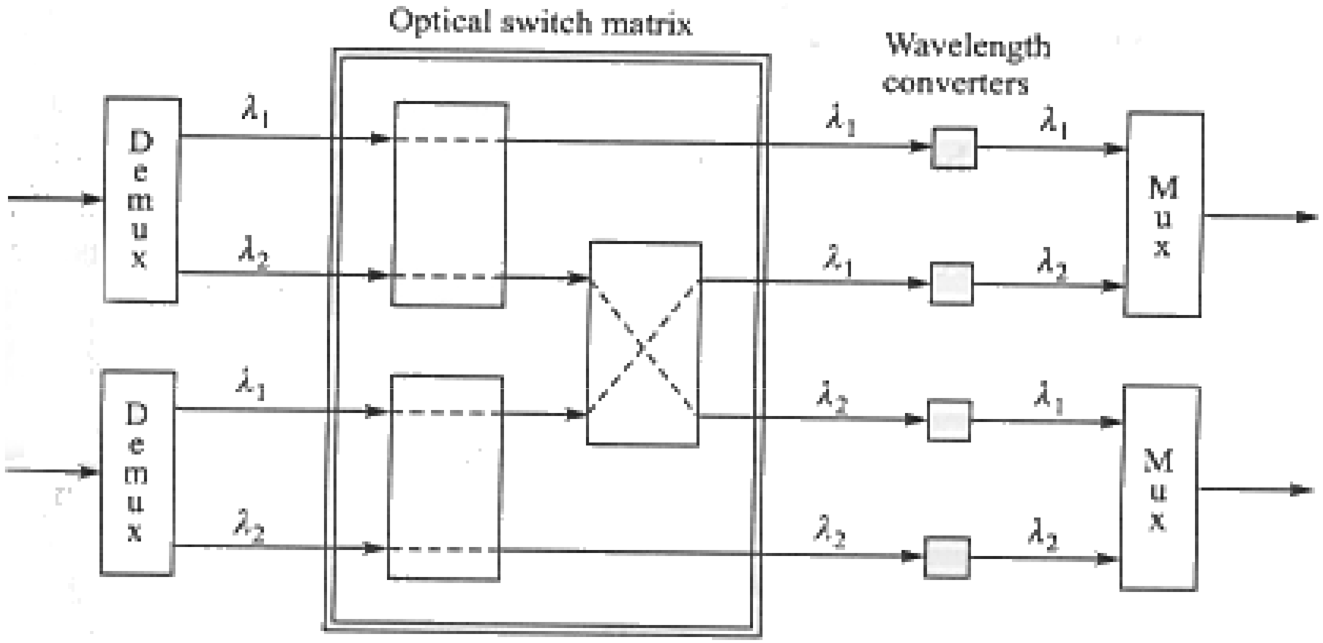


Figure 13-31. Example of a simple 4×4 OXC architecture using optical space switches and wavelength converters.

Performance of Wavelength Conversion

- Assume that there are H links (or hops) between nodes A and B. Take the number of available wavelengths per fiber link to be F, and let ρ be the probability that a wavelength is used on any fiber link. Then ρF is the expected number of busy wavelengths on any link, thus ρ is a measure of the *fiber utilization* along the path.
- In the case of wavelength conversion, a connection request between nodes A and B is blocked if one of the H intervening fibers is full. The probability P_b' that the connection request from A to B is blocked is the probability that there is a fiber link in this path with all F wavelengths in use, so that

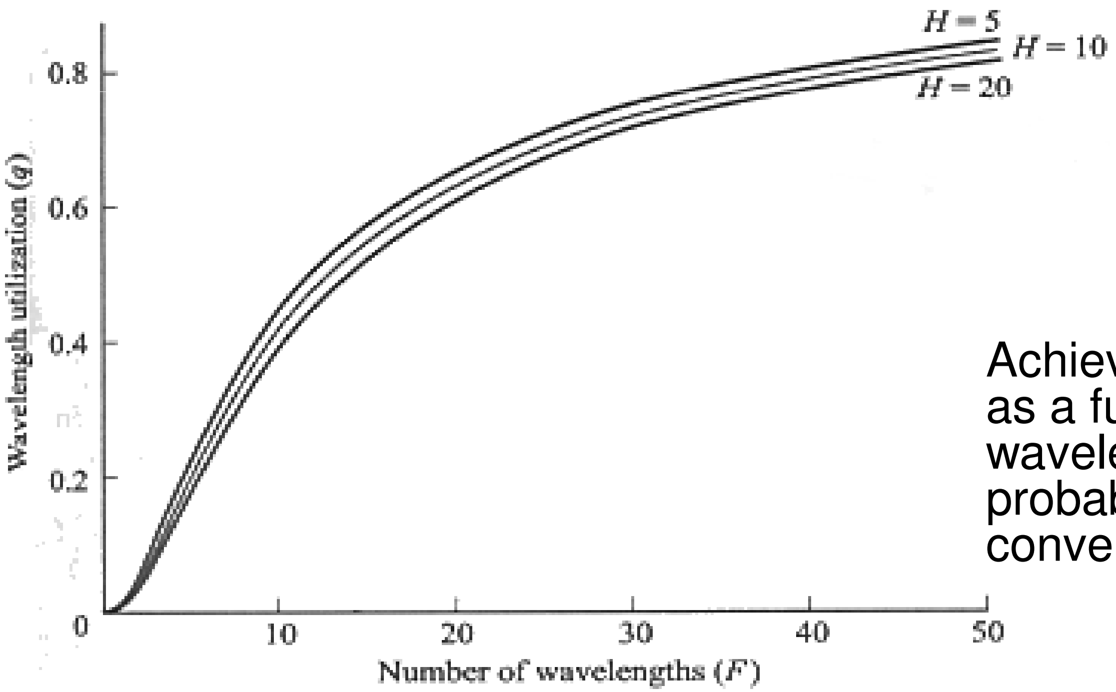
$$P_b' = 1 - (1 - \rho^F)^H$$

Performance of Wavelength Conversion (2)

- Let q be the *achievable utilization* for a given blocking probability in a network with wavelength conversion,

$$q = \left[1 - (1 - P_b')^{1/H}\right]^{1/F} \approx \left(\frac{P_b'}{H}\right)^{1/F}$$

where the approximation holds for small values of P_b'/H.



Achievable wavelength utilization as a function of the # of wavelengths for a 10^{-3} blocking probability in a network using λ-conversion.

Note q rapidly approaches 1 as F becomes large.

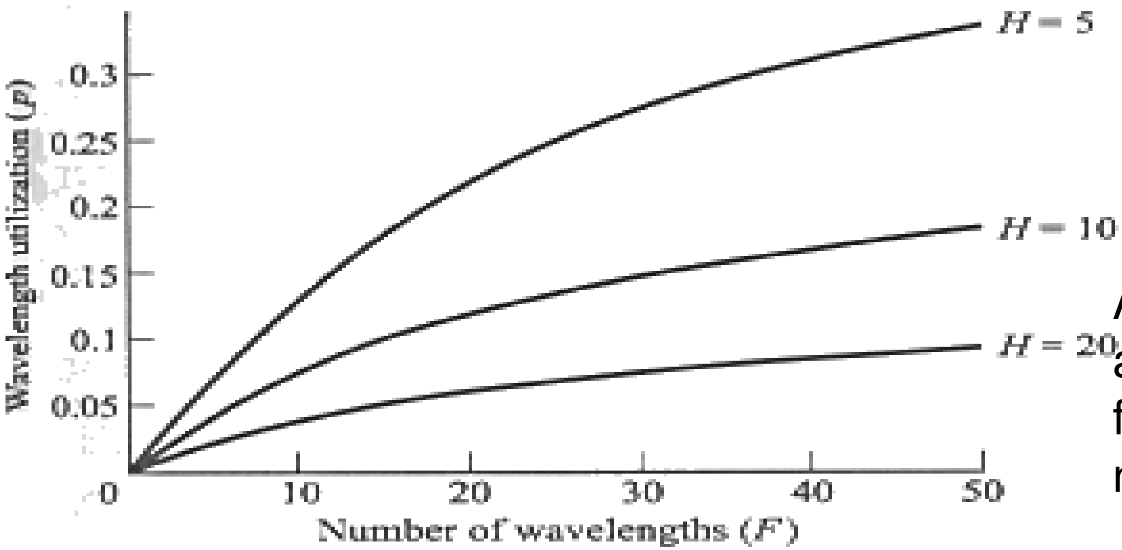
Performance of Wavelength Conversion (3)

- The probability P_b that the connection request from A to B is blocked is the probability that each wavelength is used on at least one of the H links is given by

$$P_b = \left[1-(1-\rho)^H\right]^F$$

- Letting p be the *achievable utilization* for a given blocking probability *without* wavelength conversion, then

$$p = 1-(1-P_b^{1/F})^{1/H} \approx -\frac{1}{H}\ln(1-P_b^{1/F})$$



Achievable wavelength utilization as a function of the # of wavelengths for a 10^{-3} blocking probability in a network not using λ-conversion.

Performance of Wavelength Conversion (4)

- Define the gain $G=q/p$ to be the increase in fiber or wave-length utilization for the same blocking probability. Setting $P_b'=P_b$ yields:

$$G \equiv \frac{q}{p} = \frac{\left[1-(1-P_b)^{1/F}\right]^{1/H}}{1-(1-P_b^{1/F})^{1/H}} \approx H^{1-1/F} \frac{P_b^{1/F}}{-\ln(1-P_b^{1/F})}$$

The figure shows that as F increases, the gain increases, and peaks at about $H/2$. The gain then slowly decreases, since large trunking networks are more efficient than small ones.