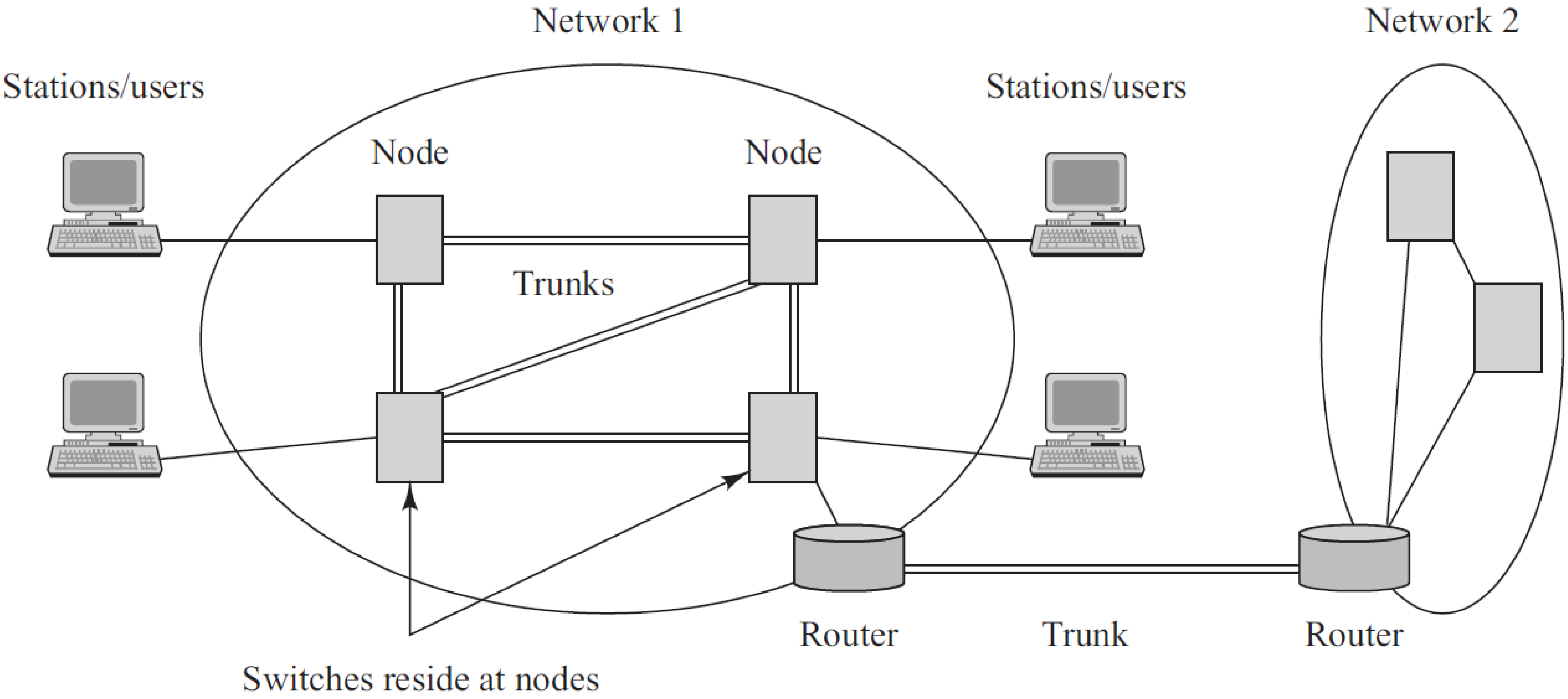
INTRODUCTION

- Telephone companies and community access television (CATV) providers are competing to offer subscribers the triple play services of voice, video, and high-speed data access.
- Both telephone and CATV networks have relied on copper cables to connect through the last mile to their subscribers, but a coaxial cable of the CATV companies has superior bandwidth capabilities relative to the twisted pair
- The main characteristics of optical fibers compared to other transmission mediums- wide bandwidth in the 1,550 nm range with a very low attenuation around 0.2 dB/km
- This bandwidth enables transmission bit rates up to the Gbps range on point-to-point fiber links of a few tens of km

Network


Network 1
Network 2
Stations/users
Stations/users
Node
Node
Trunks
Router
Trunk
Router
Switches reside at nodes

General Network terminology

- **Stations:** Devices that network subscribers use to communicate are called stations. These may be computers, monitoring equipment, telephones, fax machines, or other telecommunication equipment.
- **Networks:** To establish connections between these stations, transmission paths run between them to form a collection of interconnected stations called a network.
- **Node:** Within this network, a node is a point where one or more communication lines terminate and/or where stations are connected. Stations also can be connected directly to a transmission line.
- **Trunk:** The term trunk normally refers to a transmission line that runs between nodes or networks and supports large traffic loads.
- **Topology:** The topology is the logical manner in which nodes are linked together by information transmitting channels to form a network (bus, ring, star, mesh etc.)
- **Switching and routing:** The transfer of information from source to destination through a series of intermediate nodes is called switching, and the selection of a suitable path through a network is referred to as routing.

OPTICAL NETWORK

- A telecommunications network with **optical fiber as the primary transmission medium**, which is designed to take advantage of the unique characteristics of optical fibers.

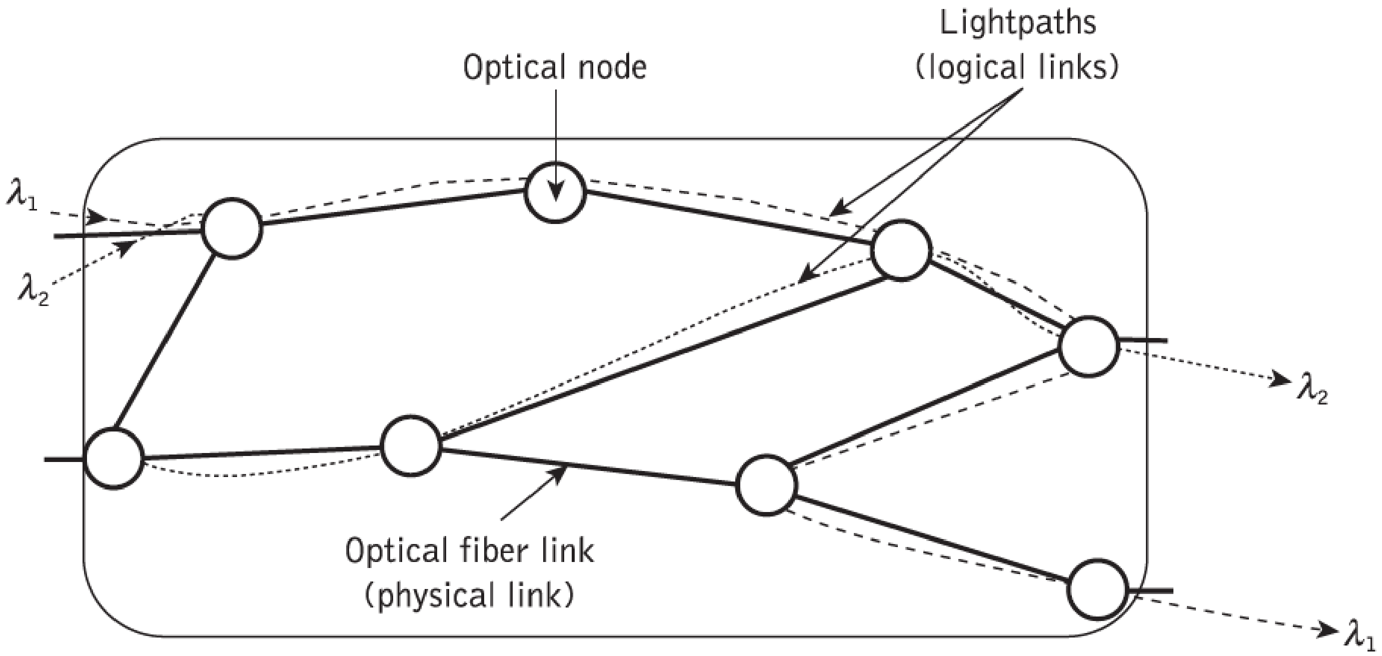
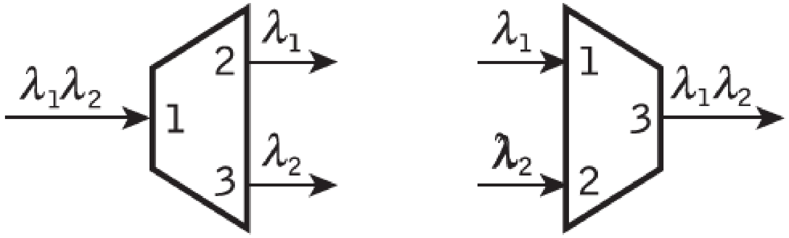
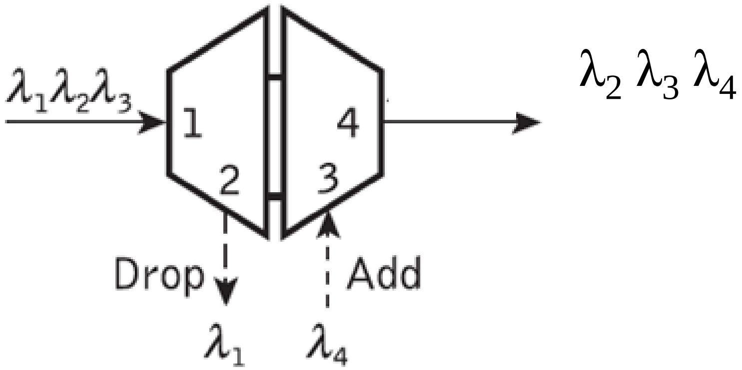


Fig: Optical network structure

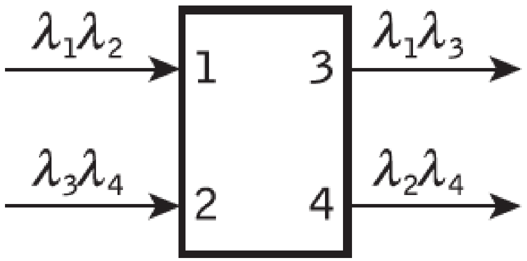
Optical networking node elements



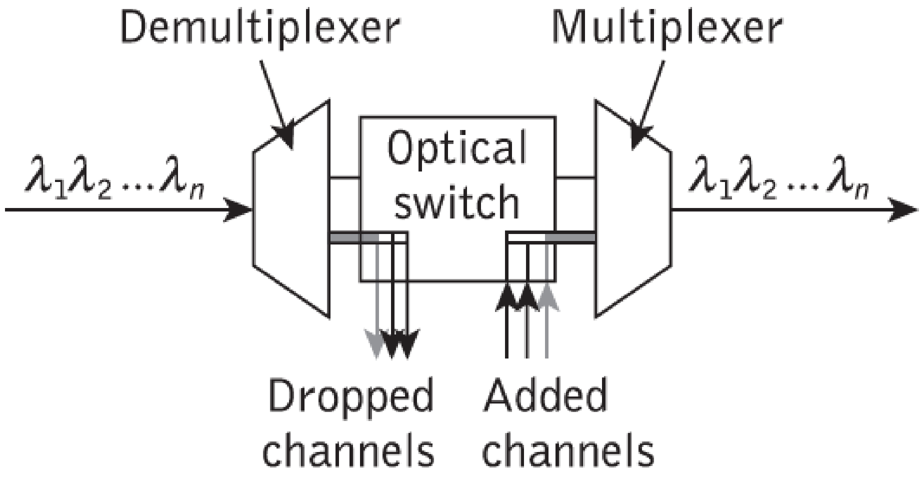
(a) wavelength demultiplexer and multiplexer



(b) optical add/drop multiplexer

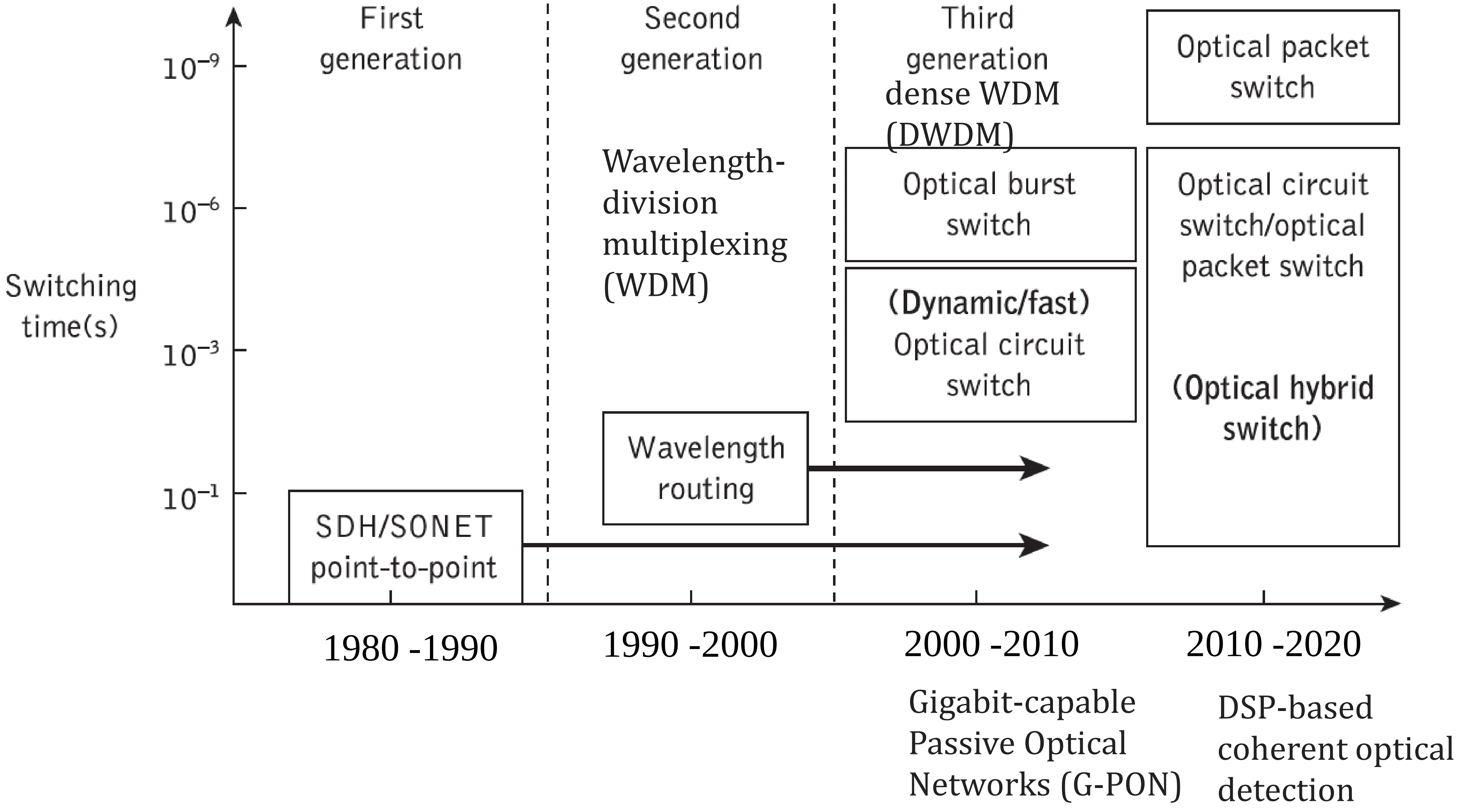


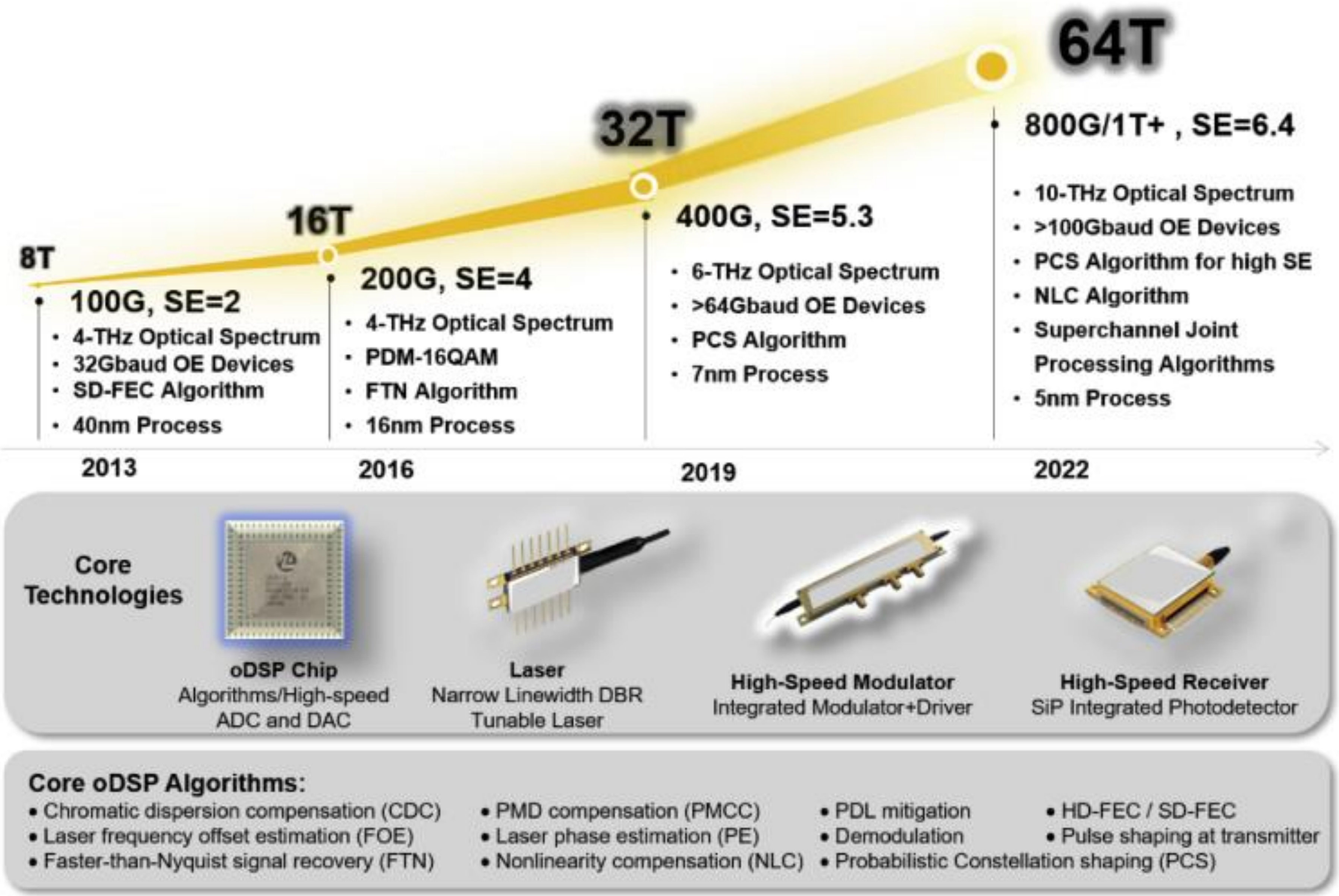
(c) 2x2 optical switch



(d) reconfigurable optical add/drop multiplexer

OPTICAL FIBER NETWORK EVOLUTION





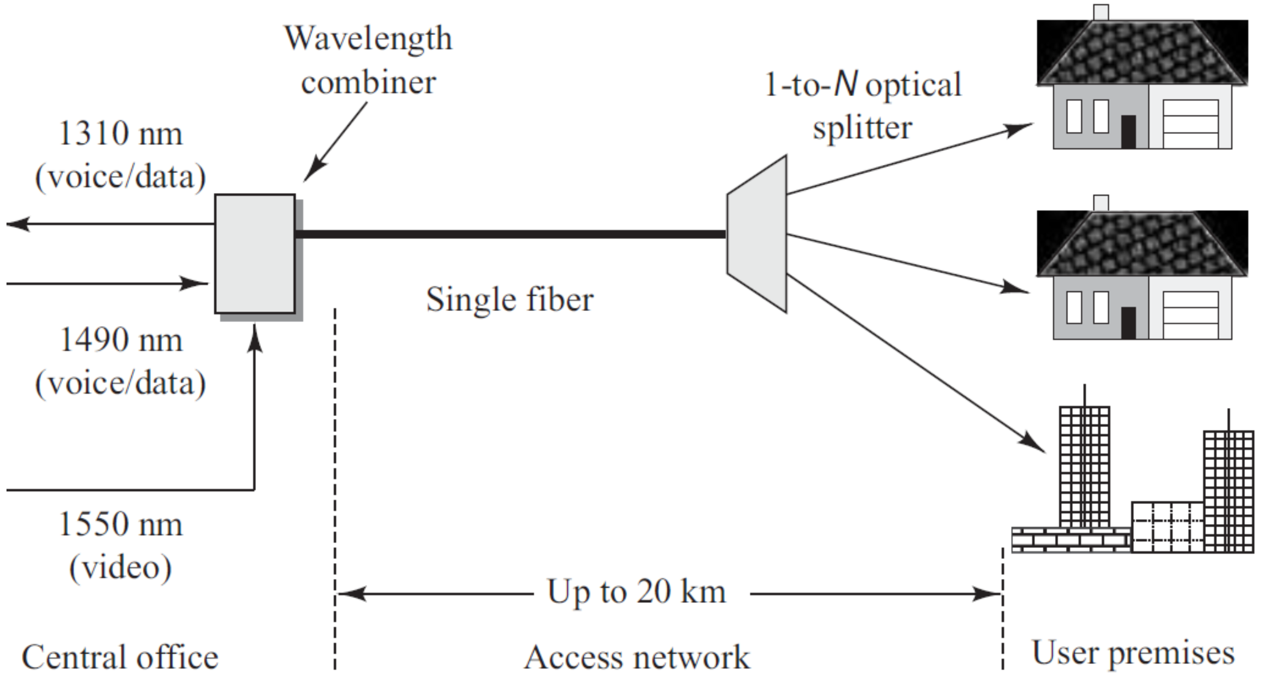
Probabilistic constellation shaping (PCS)

nonlinearity compensation (NLC)

Ref: Liu, X. (2019). Evolution of Fiber-Optic Transmission and Networking toward the 5G Era. *IScience*, *22*, 489-506. https://doi.org/10.1016/j.isci.2019.11.026

PASSIVE OPTICAL NETWORKS (PON)

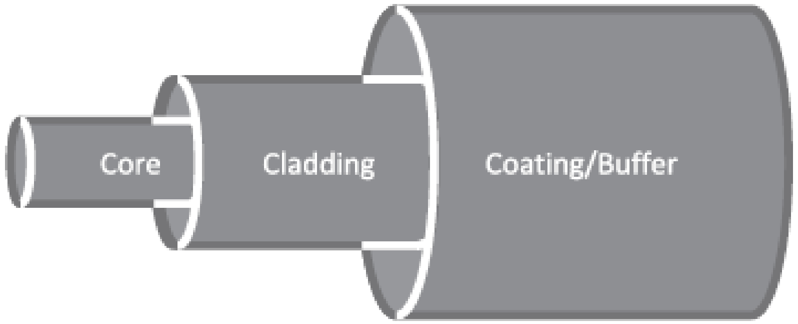
- A **passive optical network** (**PON**) is a optical fiber telecommunication technology used to deliver broadband services to the subscriber
- As the name implies, there is no active component between the central office and the user premises.
- Both ITU and IEEE have standardized solutions for PONs operating at Gbps line rates
- The application of PON technology for providing broadband connectivity in the access network to homes, multiple-occupancy units, and small businesses commonly is called fi ber-to-the-x (FTTx).
- Basic Optical Access Network Components: Optical Fiber, Optical Power Splitter, Wavelength Routing Devices



Architecture of a typical passive optical network

Optical Fiber Structure

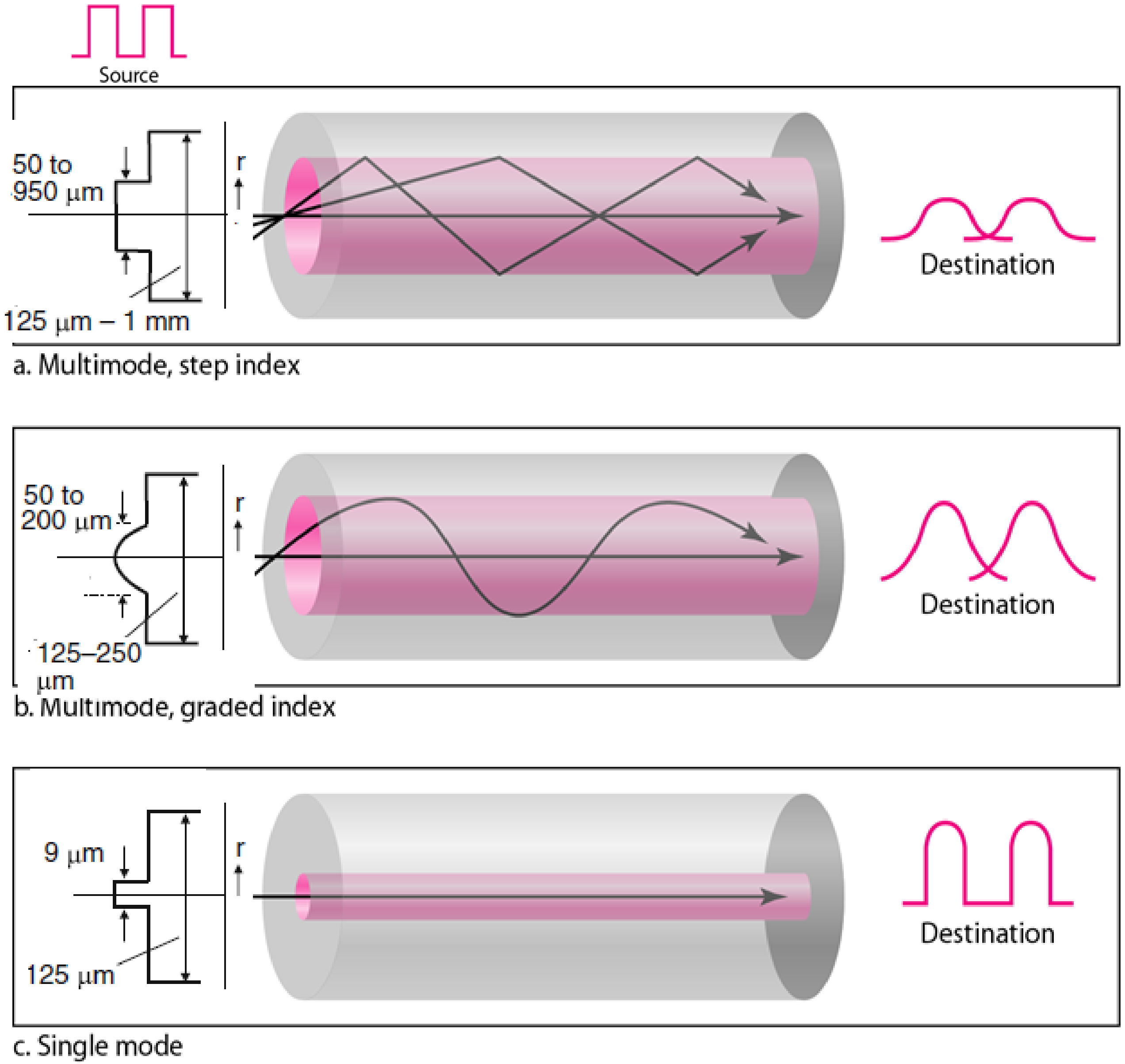
- Optical fiber used in optical communications consists of a cylindrical dielectric core surrounded by dielectric cladding.



Optical fiber structure.

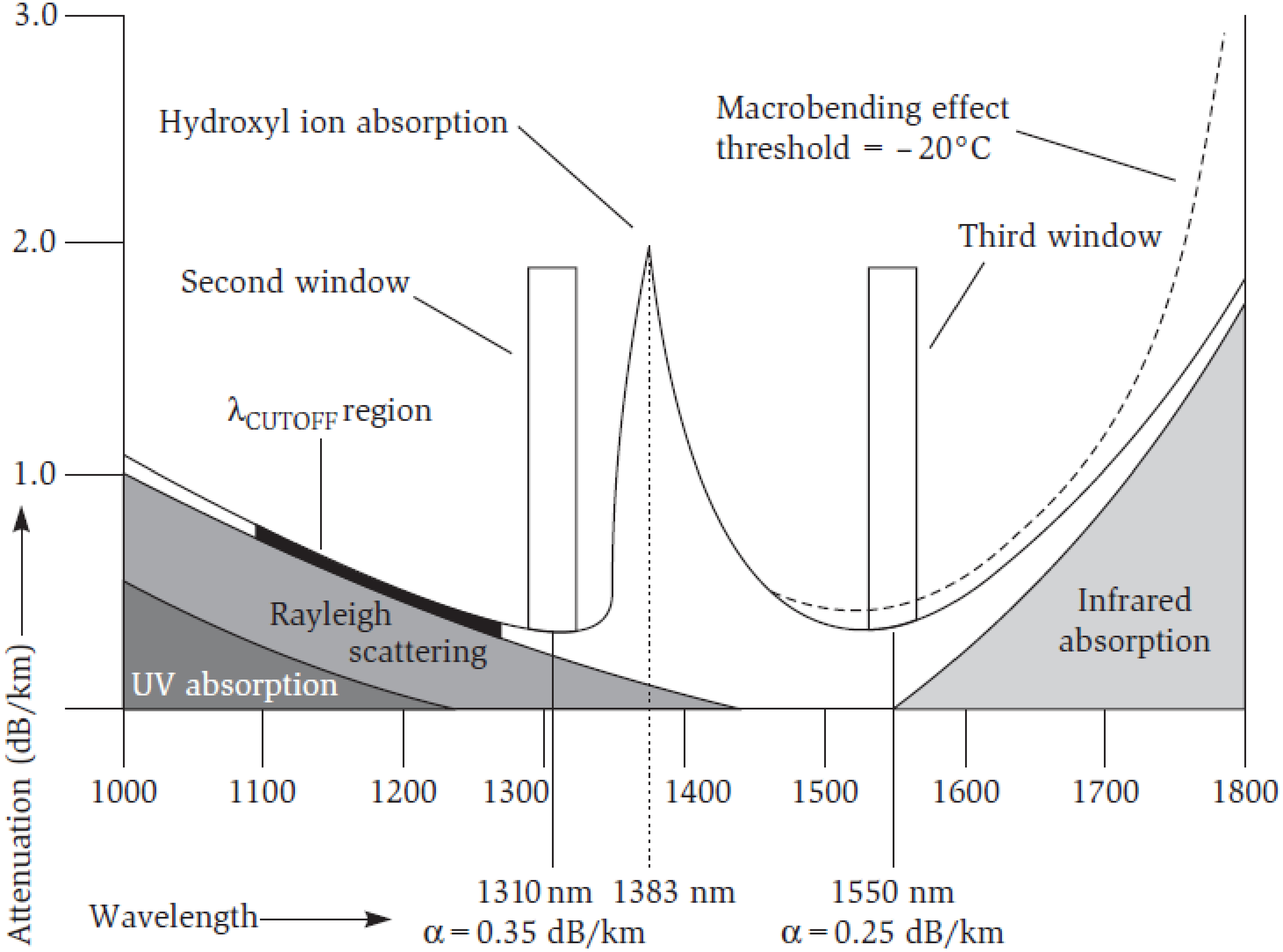
- A polymer buffer coating is commonly used to enhance its mechanical strength and protect it from environmental effects.
- Both the core and the cladding are made of silica (SiO_2) or plastics
- Used to transmits signals in the form of light.

PROPAGATION OF LIGHT



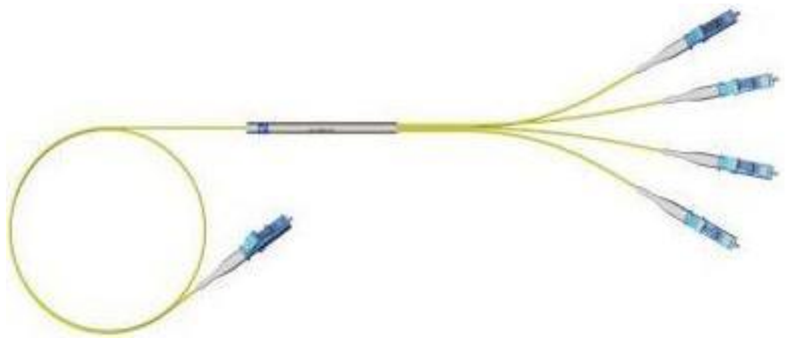
- Density of the core remains constant from center to the edge
- Density of the core is highest at the center and decreases gradually to its lowest at the edge.
- Single mode fiber is made of much smaller diameter and with low density which results in critical angle close to 90^0.

- A typical silica glass fiber exhibits different path losses at different wavelengths.
- Path loss is minimum in three regions of light 'color' with wavelengths of 1.2, 1.3 and 1.5 μm with losses of less than 1 dB/km.



Optical Power Splitters

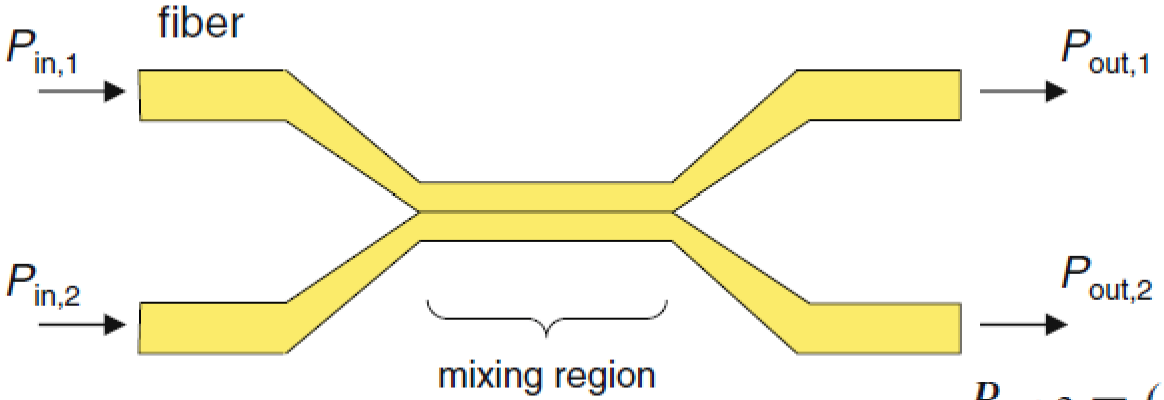
- Optical power splitting devices enable the distribution of light from its input port to multiple output ports (i.e. Splits an incoming light source into two separate paths)
- The light is replicated and has no affect on bandwidth
- If the splitter is designed to divide the incident optical power evenly into N separate paths and if P is the optical power entering the splitter, then the power level going to each subscriber is P/N.
- Designs of power dividers with other splitting ratios are also possible depending on the application. The number of splitting paths can vary from 2 to 64, but in a PON they typically are 8, 16, or 32.
- optical point-to-multipoint access networks.
- Types of splitters
  - Fused Biconical Taper (FBT) – low split count
  - Planar Lightwave Circuits (PLC) – high split count



Optical Power Splitter

- Basic optical power splitter is a 2 × 2 fused fiber coupler, schematically shown in Fig

$$P_{\text{out},1} = x \cdot \varepsilon P_{\text{in},1} + (1 - x) \cdot \varepsilon P_{\text{in},2}$$

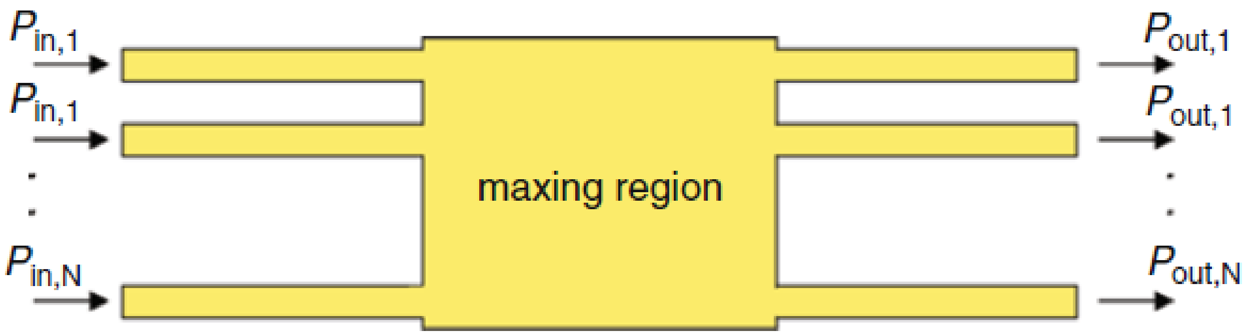


$$P_{\text{out},2} = (1 - x) \cdot \varepsilon P_{\text{in},1} + x \cdot \varepsilon P_{\text{in},2}$$

where the excess loss factor

$\varepsilon = (P_{\text{out},1} + P_{\text{out},2})/(P_{\text{in},1} + P_{\text{in},2})$ with $\varepsilon \leq 1$

the slitting ration is $x/(1 - x)$

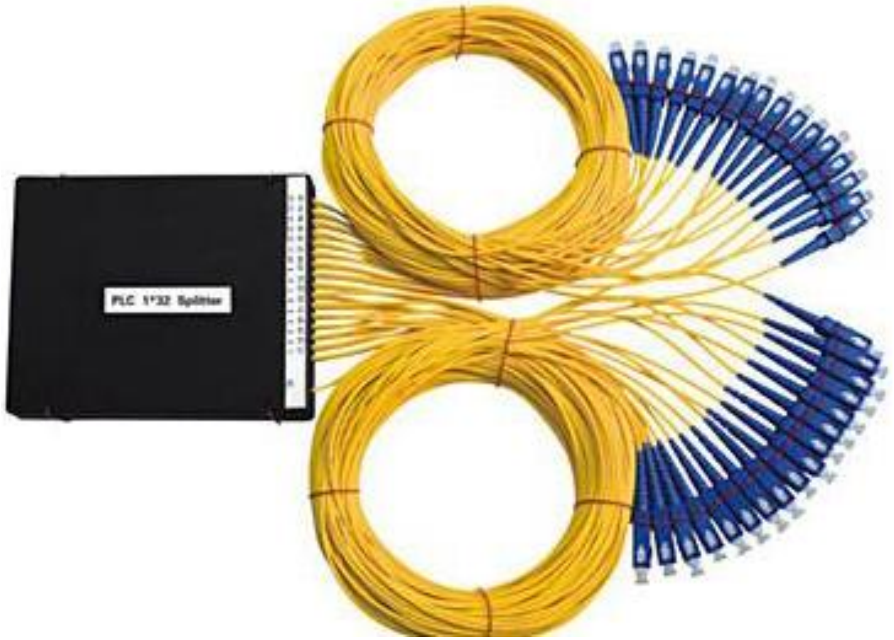


$N \times N$ power splitter

The relation between the input and output powers is

$$P_{out,j} = \varepsilon \sum_{i=1}^{N} x_{ij} P_{in,i}$$

$$\varepsilon = \sum_{j=1}^{N} P_{out,j} / \sum_{i=1}^{N} P_{in,i} \text{ with } \varepsilon \leq 1.$$

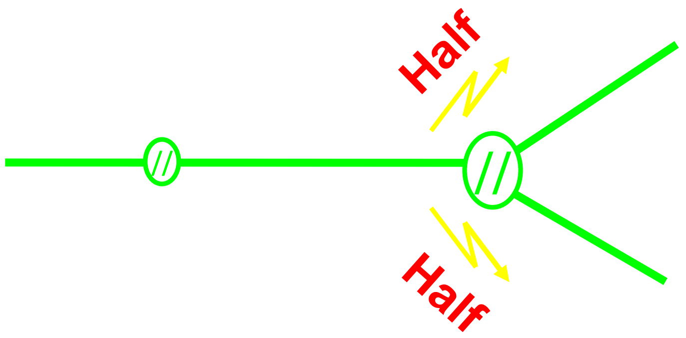


Fiber Loss in PON

- In PONs, the channel loss consists of fiber and splitter losses (neglecting connector and splice losses), given by
- where α_f is the fiber loss in dB/km, L the fiber length, and C_{splitter} the splitter loss.

$$C_L = \alpha_f L + C_{splitter}$$

- Typical fiber loss per km: 0.25 dB for1550 nm and 0.4 dB 1260 - 1360 nm
- When the signal is split two ways, half the power goes one way and half goes the other.
- So each direction gets half the power, or the signal is reduced by 10log(0.5)=3 dB.



PON LINK BUDGETS

- In optical communication system design, a certain power budget is required to ensure that enough power will reach the receiver to maintain reliable performance
- The minimum average power required by the optical receiver is specified by the receiver sensitivity P_s , and the average launch power of a transmitter P_t . Then the power budget is expressed in the equation

$$P_t - P_s > C_L + M_s$$

$$P_{budget}(dB) > \alpha L + 10\ \log_{10}(N) + M_s(dB)$$

- The maximum transmission distance in PONs is given by

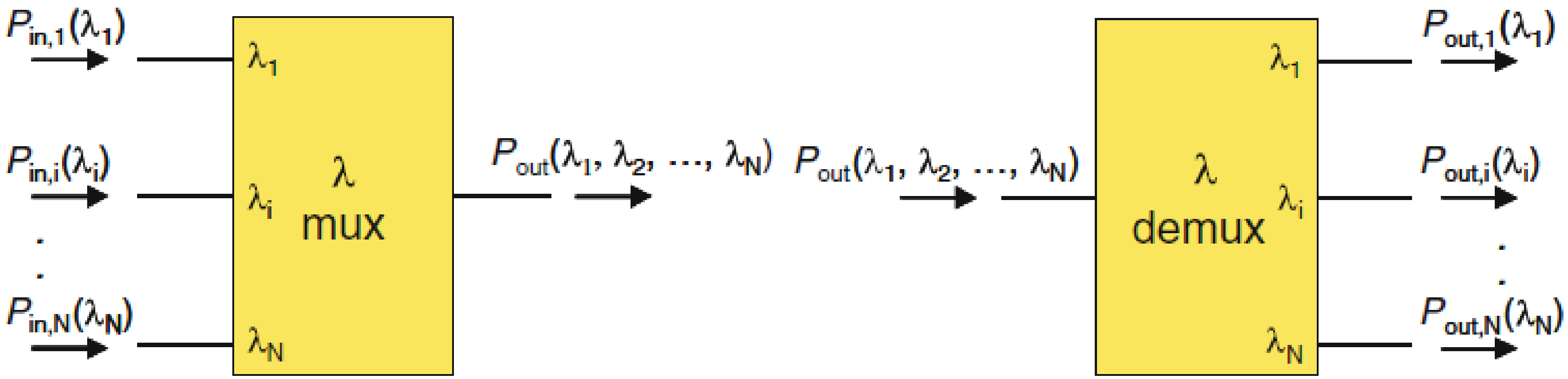
$$L \leq \frac{P_{budget}(dB) - C_{splitter} - M_s}{\alpha}$$

EXAMPLE

- Link budget (Maximum loss planned) is 21 dB
- Typically, at 1550 nm, fiber exhibits loss of about 0.25 dB/km & at 1310 nm loss is 0.4 db/km.
- The Maximum distance without amplification is about 80 km
- Each two-way split results in a loss of nominally ~3.5 dB of level, assume 4 dB worst case.
  - Thus, each two-way split costs about 16 km distance for 1550 nm & 10 km for 1310 nm

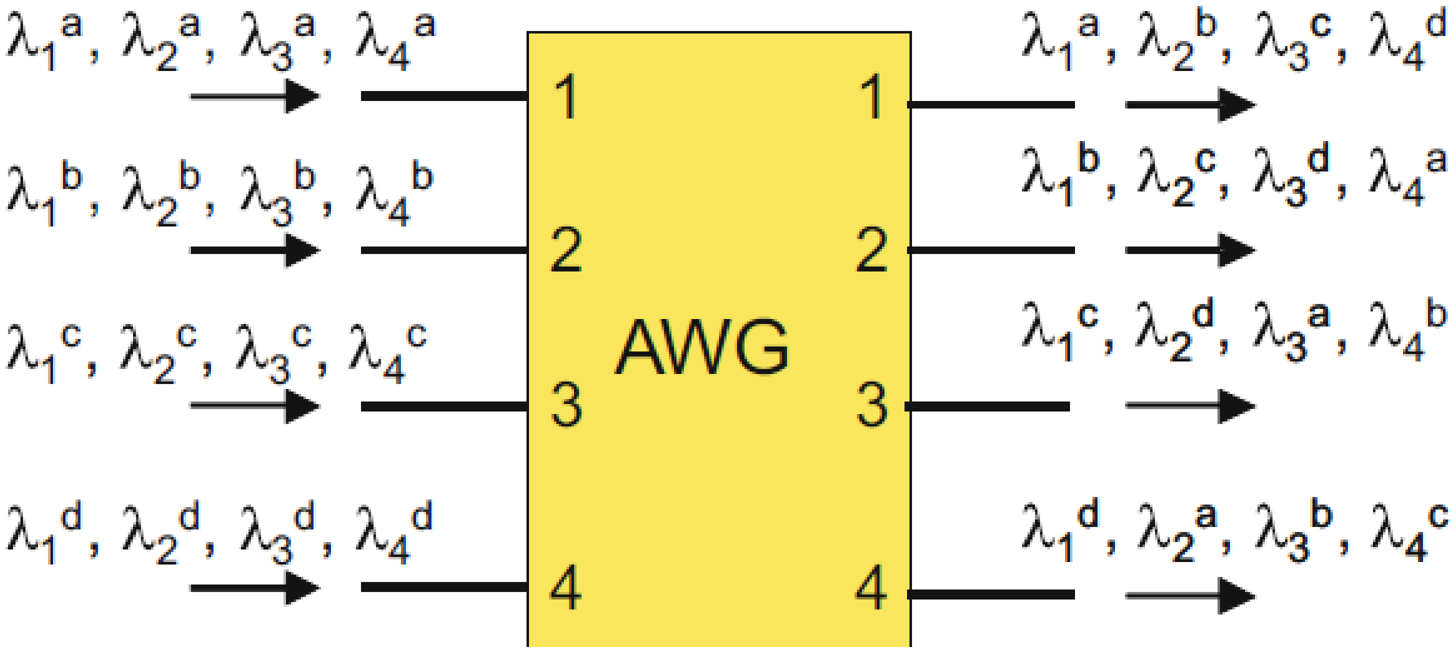
WAVELENGTH ROUTING DEVICES

- A wavelength multiplexer accepts optical signals inserted at its input ports and routes these signals to its output port
- At each input port, it accepts only a signal which is positioned in a specific wavelength band
- As the routing of each signal is dependent on its wavelength, there are no power splitting losses
- The wavelength-dependent routing can be accomplished by means of wavelength dependent refraction, such as in a **prism, or by means of multiple beam interference processe**s such as in **grating structures or multilayer interference filters**.



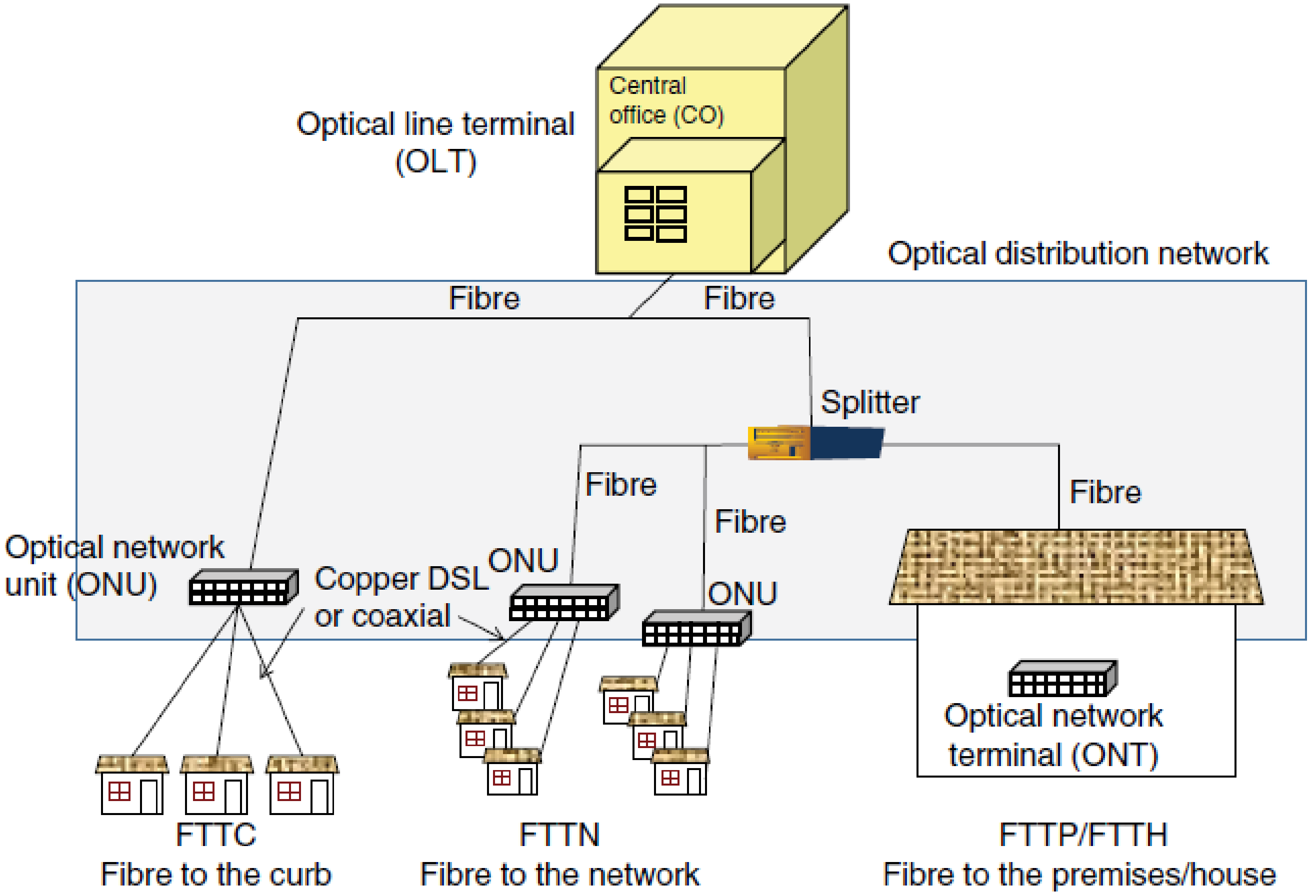
(a) Wavelength multiplexer (b) Wavelength demultiplexer

A wavelength router with multiple input ports and output ports can perform more comprehensive wavelength routing actions. The so-called **arrayed waveguide grating router (AWG) performs** a cyclic routing of the wavelengths injected at its input ports toward its output ports.



PON ARCHITECTURE

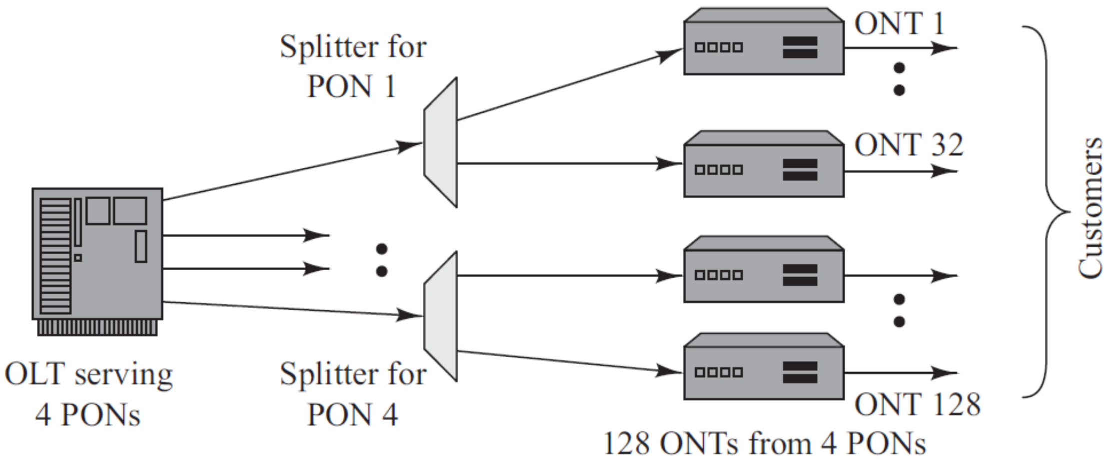
- A PON implements point – to – multipoint architecture, where a single optical line is divided into many optical splitters to serve multiple customers.
- PON systems are limited in range and bandwidth.
- Current PONs typically support up to 32 to 64 splits and up to 20 km.
- The dimension of a PON system is restricted in part by the power budget.
- In realistic deployment, this dimension is further restricted by the fiber dispersion and dynamic range of the upstream receiver
- The active devices exist only in the central office and at the user end.
  - optical line terminal (OLT)
  - optical network units (ONUs)



A passive optical network architecture

OPTICAL LINE TERMINAL (OLT)

- The OLT is located in a central office and controls the bidirectional flow of information across the network.
- It must be able to support transmission distances of up to 20 km and transmits signals to all optical network units (ONUs), which forward the downstream packets to all subscribers within their networks.
- A typical OLT is designed to control more than one PON. In this case, if there are 32 connections to each PON, then the OLT can distribute information to 128 users.
- Downstream traffic is sent from OLTs using a 1490-nm wavelength, and upstream traffic (voice and data) from ONUs is carried on a 1310 nm wavelength and a 1550-nm wavelength for video distribution.



OPTICAL NETWORK UNIT (ONU)

- At the user end, an optical network unit (ONU), also called an optical network terminal (ONT), transmits upstream data at 1310-nmwavelength and has interfaces to user devices like PC, TV set, telephone set, etc.
- The link from the ONU to the customer premises can be a twisted-pair copper wire, a coaxial cable, an independent optical fiber link, or a wireless connection.

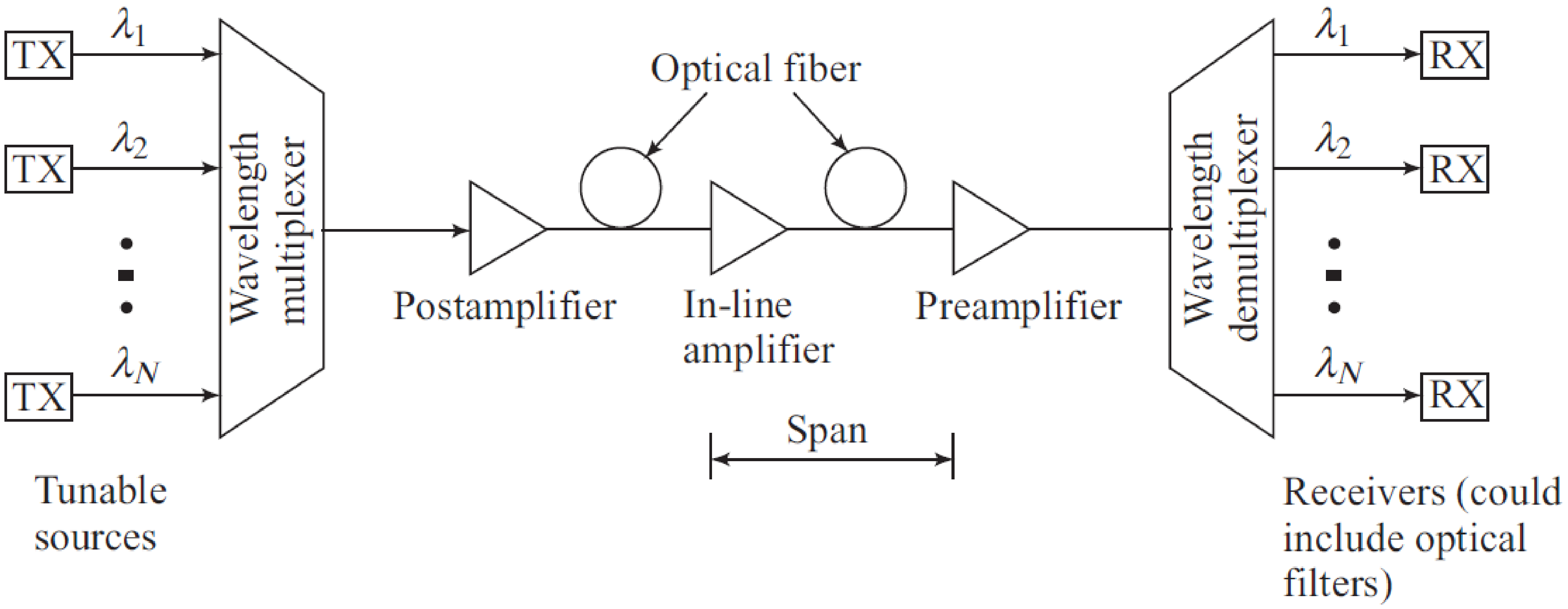
Types of PONs

- **Asynchronous Transfer Mode PONs (APON)**
  - the first standardized PON solution, supports the legacy of ATM protocols at 622 Mb/s (OC-12) of downstream bandwidth and 155 Mb/s (OC-3) of upstream bandwidth
- **Broadband PONs (BPONs)**
  - improved solution for ITU-T G.983.1
  - relatively high cost compared to Ethernet
- **Gigabit- PONs (GPONs)**
  - combines the features of both ATM and Ethernet to provide a more efficient and flexible network usage.
  - GPON provides downstream speeds of 2.5 Gb/s and upstream speeds of 1.25 Gb/s. It is based on the G.984.1 to G.984.6 series of ITU-T Recommendations
- **Ethernet PONs (EPONs)/ gigabit Ethernet PON (GE-PON)**
  - the Ethernet in the first-mile (EFM) 802.3ah study group has standardized Ethernet PON (EPON) to leverage the commercial success of Ethernet as a local area network (LAN) technology
- **WDM PON** uses a different wavelength for each user to greatly enhance network capacity. In this architecture a wavelength multiplexer (usually an AWG) is used in place of the power splitter

WAVELENGTH DIVISION MULTIPLEXING (WDM)

- The basic principle of WDM is that the discrete wavelengths form an orthogonal set of carriers that can be separated, routed, and switched without interfering with each other.
- The implementation of sophisticated WDM networks requires a variety of **passive and active devices to combine, distribute, isolate, and amplify optical power** at different wavelengths.
- Passive devices require **no external control for their operation**, so they are somewhat limited in their application flexibility. These components are mainly used to **split and combine or tap off optical signals**.
- The wavelength-dependent performance of active devices can be **controlled electronically or optically**, thereby providing a **large degree of network flexibility**. Active WDM components include **tunable optical filters, tunable sources, and optical amplifiers**.

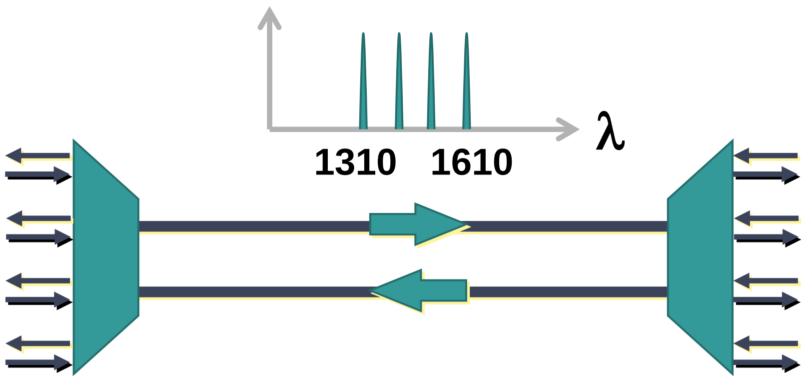
WDM

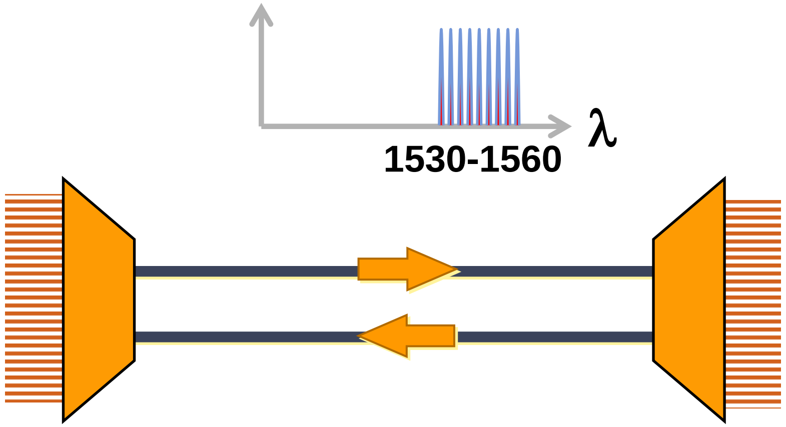


- At the transmitting end there are several independently modulated light sources, each emitting signals at a unique wavelength. Here a multiplexer is needed to combine these optical outputs into a continuous spectrum of signals and couple them onto a single fiber.
- At the receiving end a demultiplexer is required to separate the optical signals into appropriate detection channels for signal processing.

Variations in WDM

- **CWDM—Coarse Wavelength Division Multiplexing**
  - Typically 4–16 wavelengths per fiber
  - Wavelengths spread farther apart
  - Difficult to amplify
  - Low cost
- **DWDM—Dense Wavelength Division Multiplexing**
  - Typically 16+ wavelengths per fiber
  - Wavelengths close together: less than 200 GHz
  - Increased density and capacity

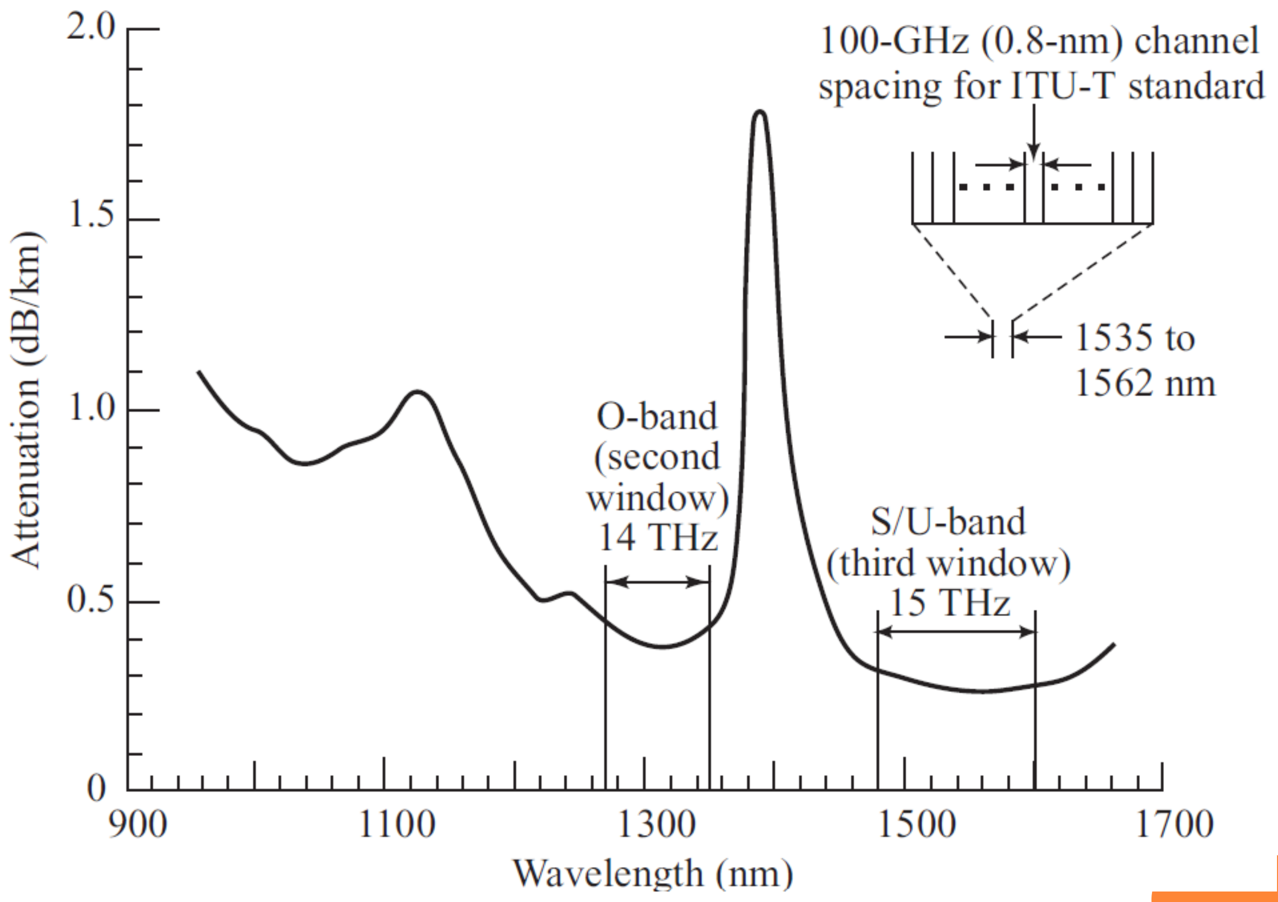




Spectrum Partitioning

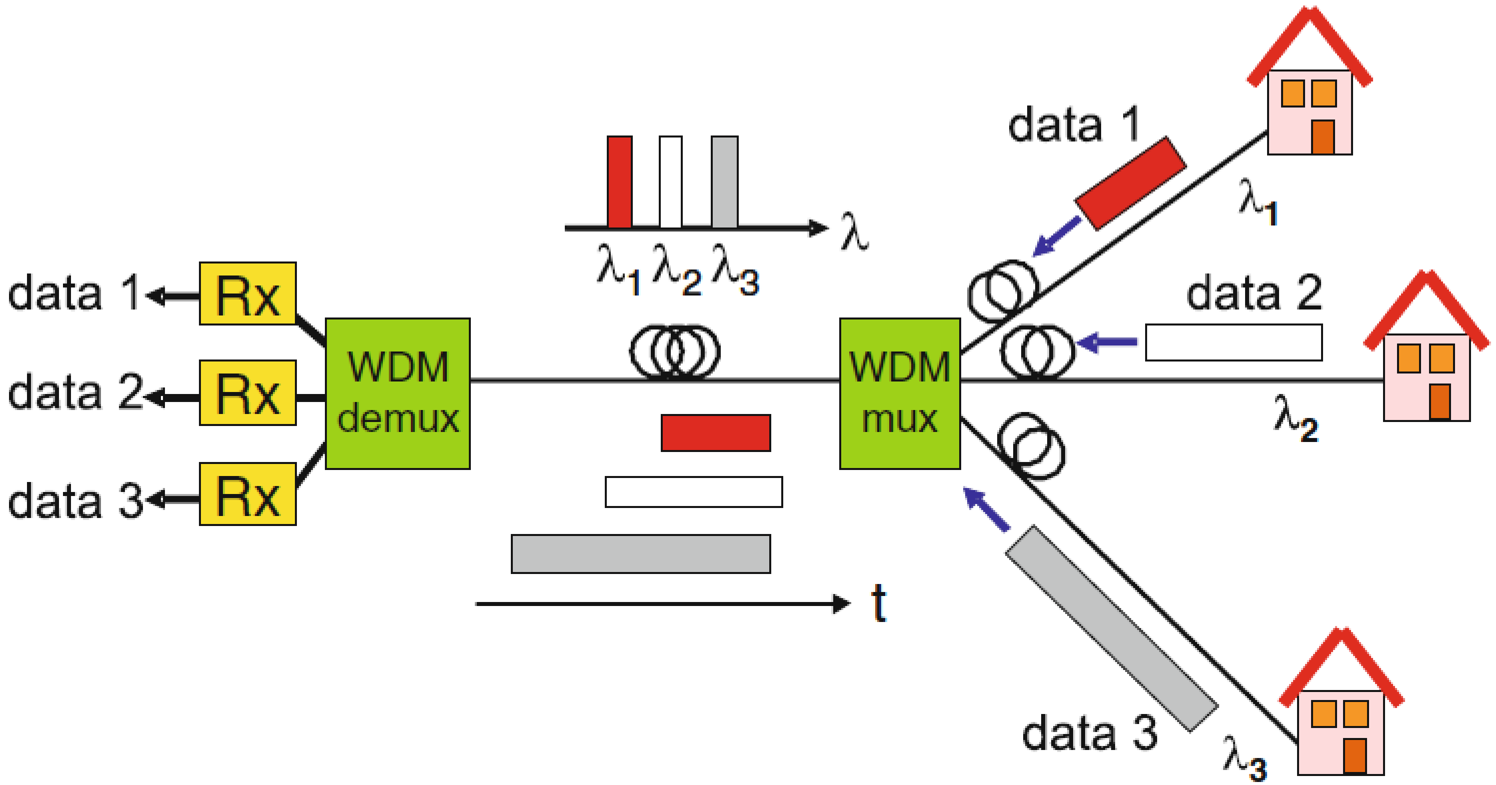
- there are many independent operating regions across the spectrum ranging from the O-band through the L-band in which narrow-linewidth optical sources can be used
- To find the optical bandwidth corresponding to a particular spectral width in these regions, we use the fundamental relationship f = c/λ.

$$\Delta f = \frac{c}{\lambda^2}\Delta\lambda$$



WAVELENGTH DIVISION MULTIPLE ACCESS (WDMA)

- Each channel uses a specific wavelength, and in the splitter point of the PON a wavelength multiplexer/de-multiplexer is used to combine/ separate these wavelength channels into/from the feeder fiber



SONET & SDH Standards

- **SONET** (Synchronous Optical NETwork) is the network standard used in north America & **SDH** (Synchronous Digital Hierarchy) is used in other parts of the world.

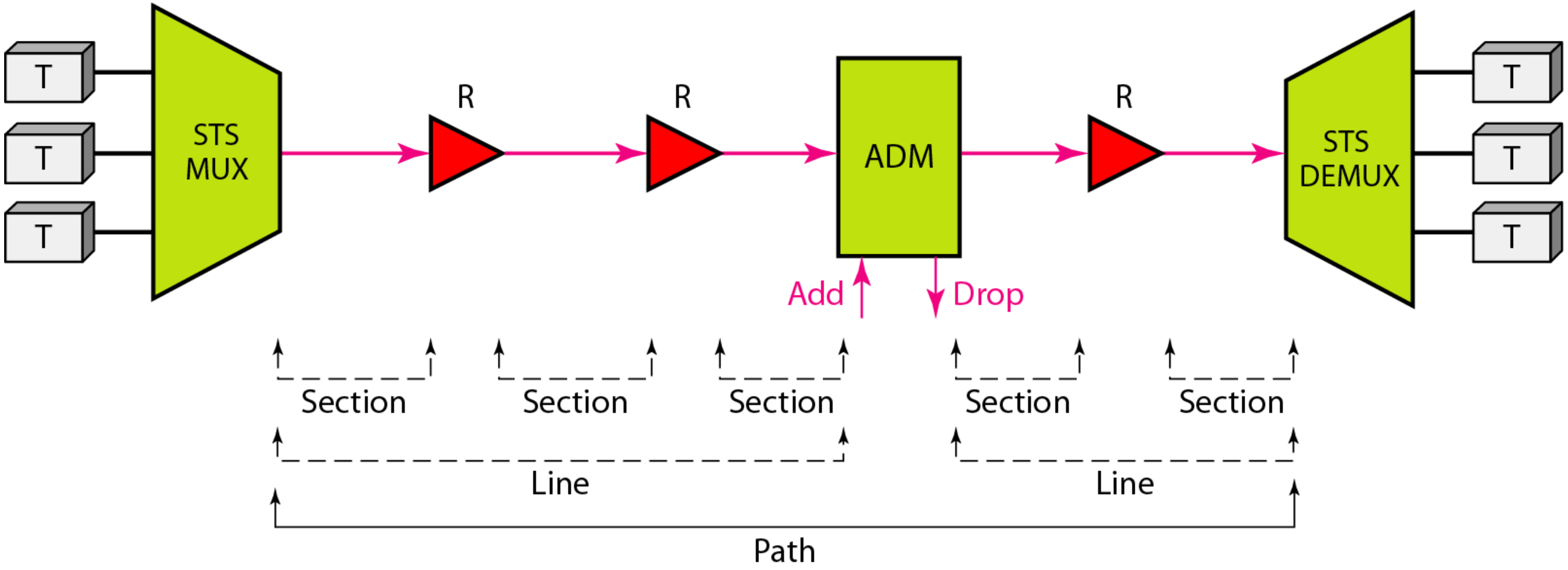
ADM: Add/drop multiplexer

STS MUX: Synchronous transport signal multiplexer

STS DEMUX: Synchronous transport signal demultiplexer

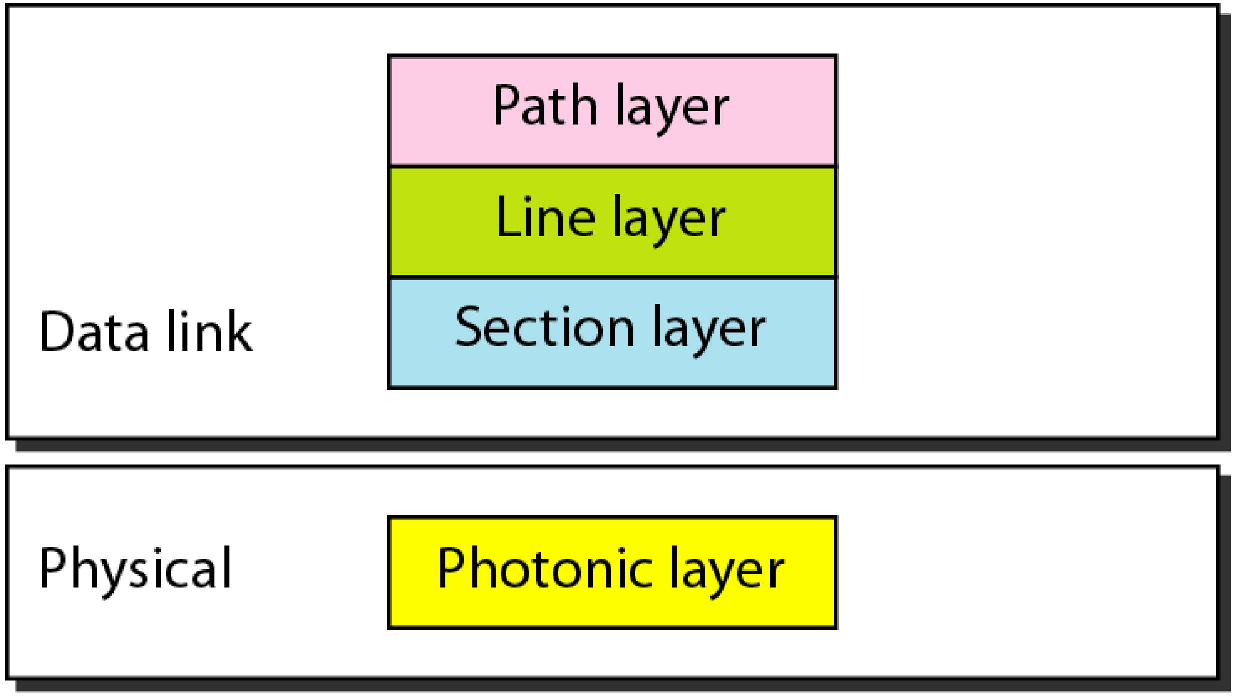
R: Regenerator

T: Terminal

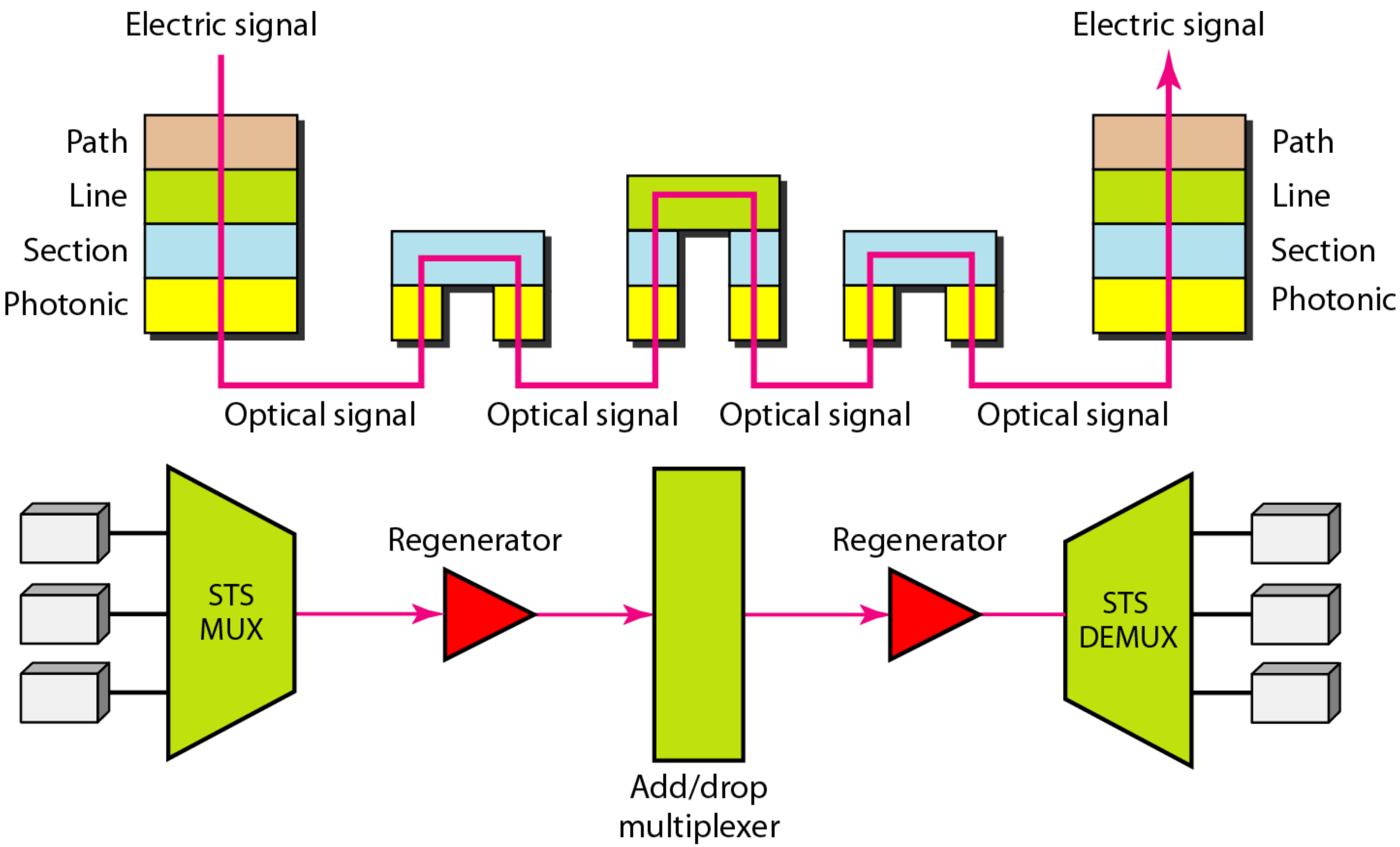


SONET layers

The SONET standard includes four functional layers: the **photonic(/Physical)**, the **section**, the **line**, and the **path layer**. They correspond to both the physical and the data link layers.



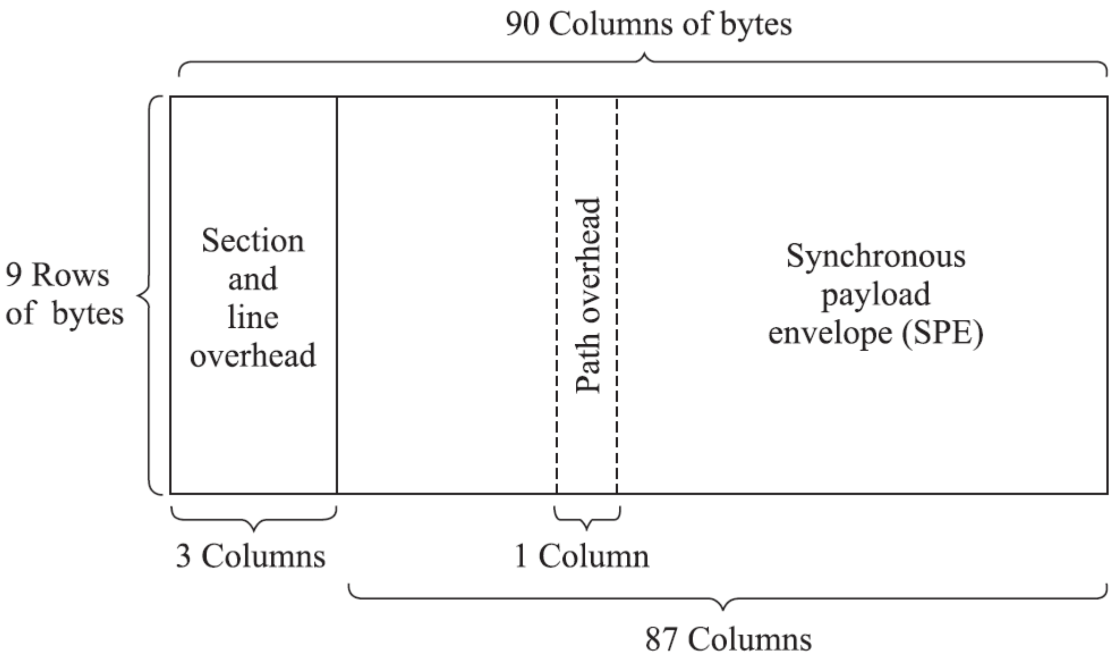
Device layer relationship in SONET



BASIC STRUCTURE OF AN STS-1 SONET FRAME

- It define a synchronous frame structure for sending multiplexed digital traffic over fiber optic trunk lines.
- The basic building block of SONET is called **STS-1** (Synchronous Transport Signal)

- This is a two-dimensional structure consisting of **90 columns by 9 rows of bytes**, where one byte is eight bits.
- The first three columns comprise transport overhead bytes that carry network management information.
- The remaining field of 87 columns is called the synchronous payload envelope (SPE) and carries user data plus nine bytes of path overhead (POH).
- The POH supports performance monitoring by the end equipment, status, signal labeling, a tracing function, and a user channel.
- The nine path-overhead bytes are always in a column and can be located anywhere in the SPE.



SONET Frame structure

- The fundamental SONET frame has a 125-µs duration. Thus, the transmission bit rate of the basic SONET signal is $\frac{9\times90\times8}{125\ \mu s/frame} = 51.84\ Mbps$
- All other SONET signals are integer multiples of this rate, so that an STS-N signal has a bit rate equal to N times 51.84 Mb/s.
- Higher-rate SONET signals are obtained by byte-interleaving *N* STS-1 frames
- After undergoing electrical-to-optical conversion, the resultant physical-layer optical signal is called **OC-N**, where OC stands for **optical carrier.**
- The basic building block of SDH is called **STM-1** (Synchronous Transport Module) with 155.52 Mbps data rate.
- Higher-rate SDH signals are achieved by synchronously multiplexing *N* different STM-1 to form **STM-N** signal.
- SDH does not distinguish between a logical electrical signal (e.g., STS-N in SONET) and an optical signal (e.g., OC-N), so that both signal types are designated by STM-M.

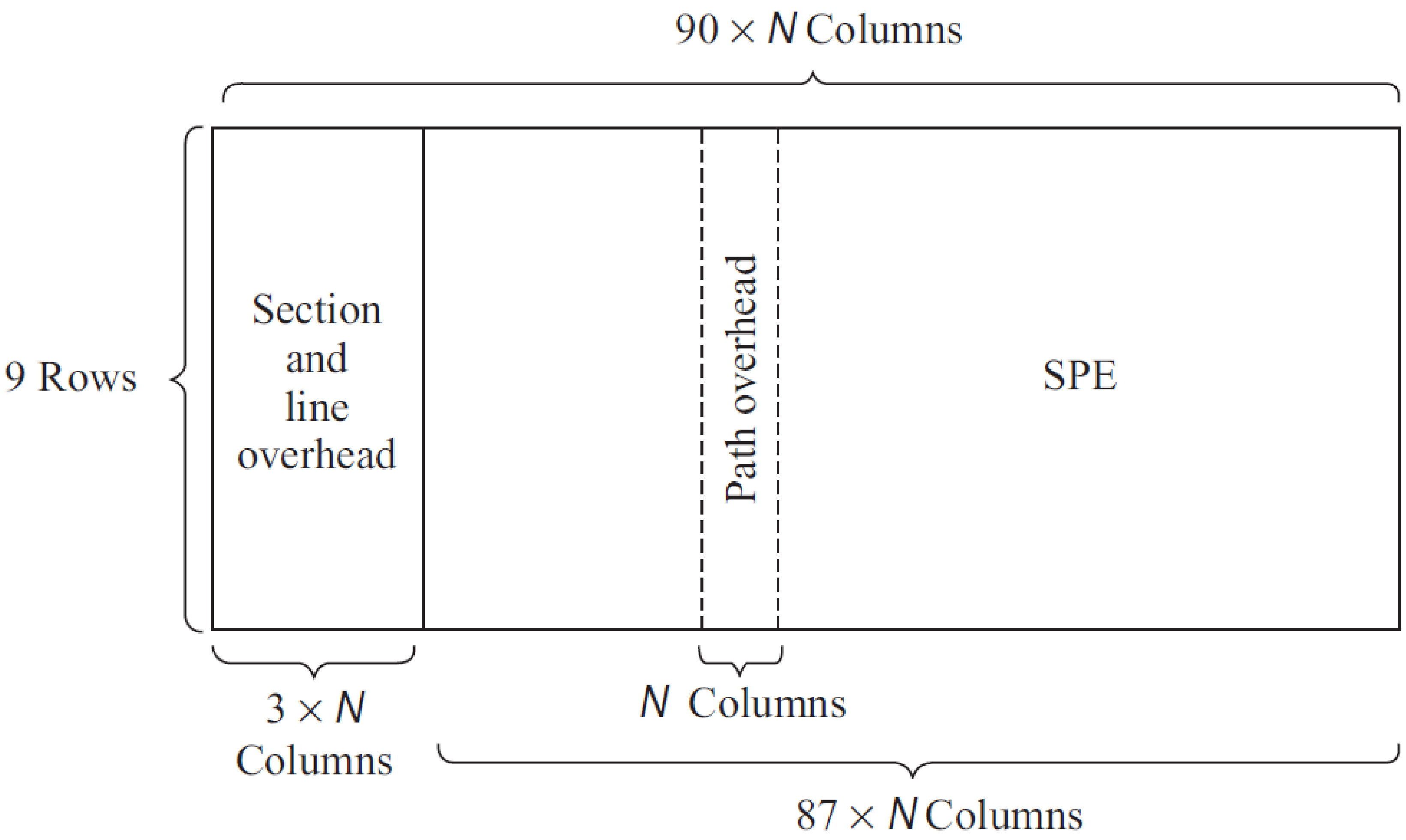


Fig: Basic formats of an STS-N SONET frame

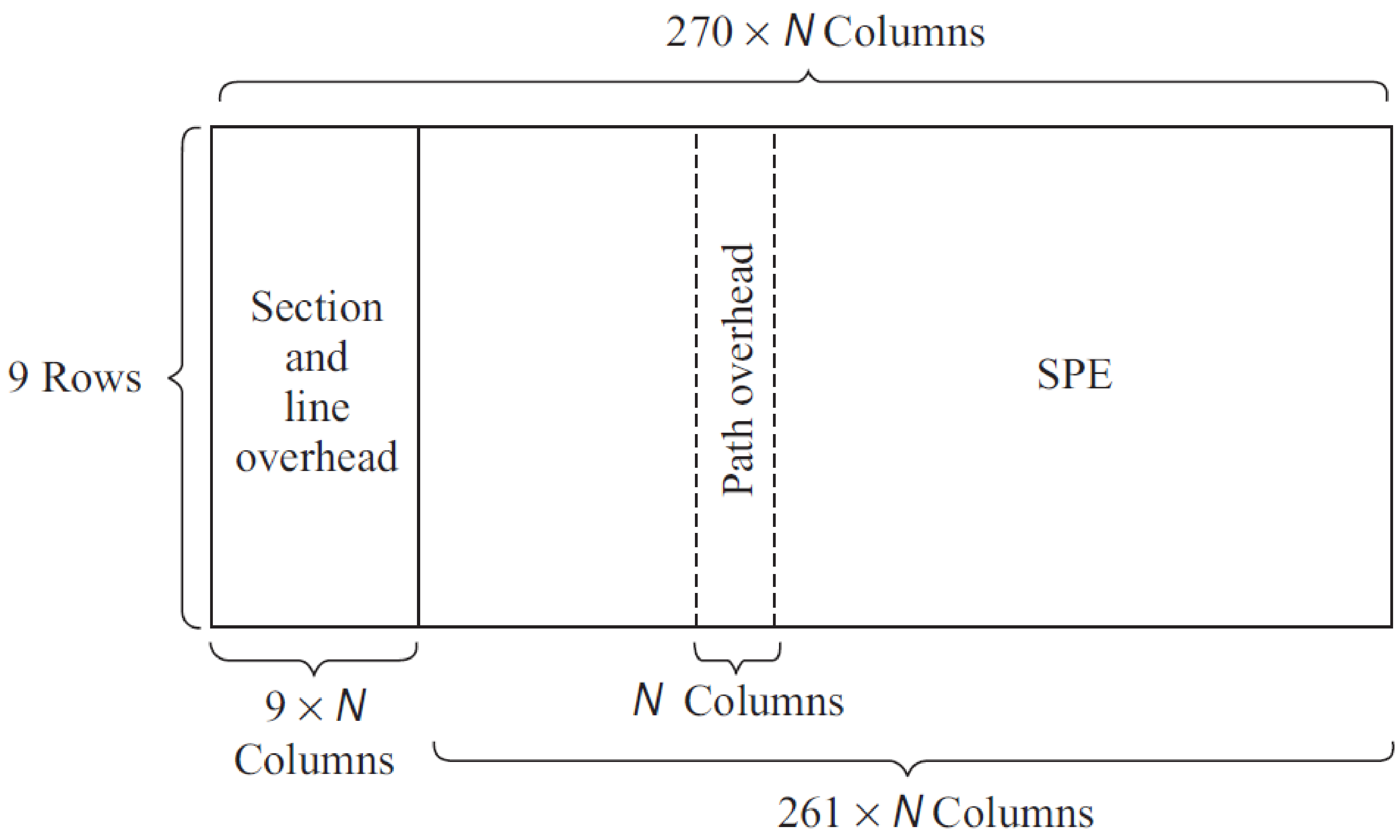


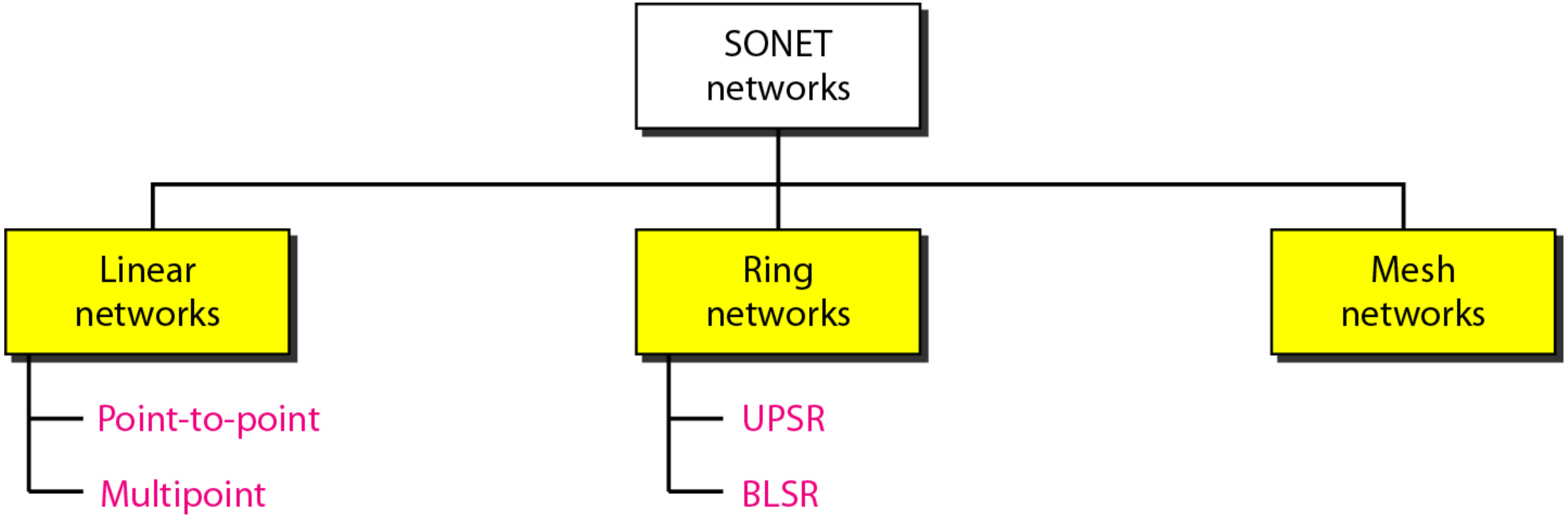
Fig: Basic formats of an STM-N SDH frame

SONET/SDH Bit Rates

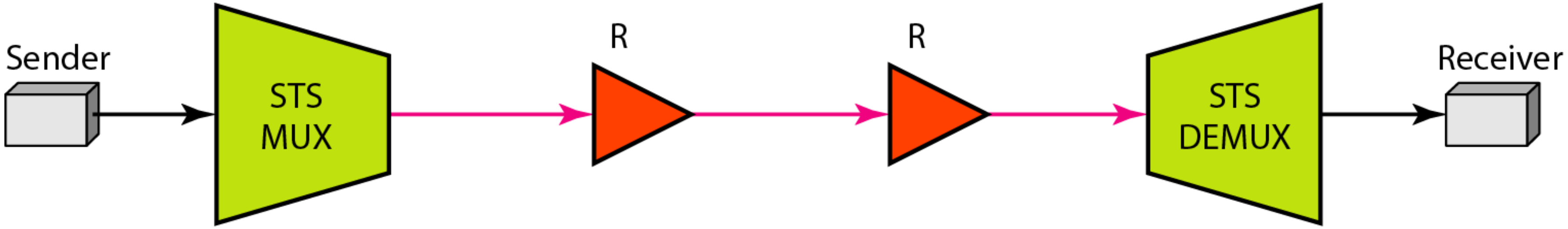
SONET	Bit Rate (Mbps)	SDH
OC-1	51.84	-
OC-3	155.52	STM-1
OC-12	622.08	STM-4
OC-24	1244.16	STM-8
OC-48	2488.32	STM-16
OC-96	4976.64	STM-32
OC-192	9953.28	STM-64
OC-768	39813 (40 Gbps)	STM-256

SONET networks topologies

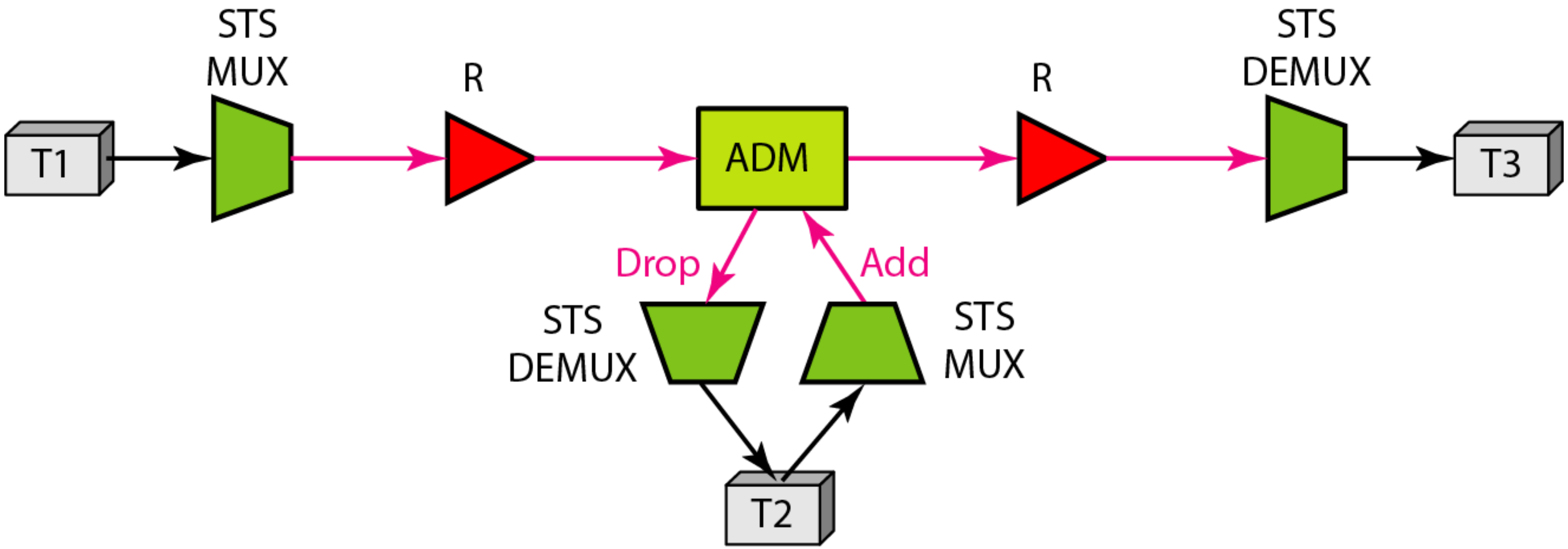
Using SONET equipment, it can roughly divide SONET networks into three categories: linear, ring, and mesh networks.



A point-to-point SONET network



A multipoint SONET network

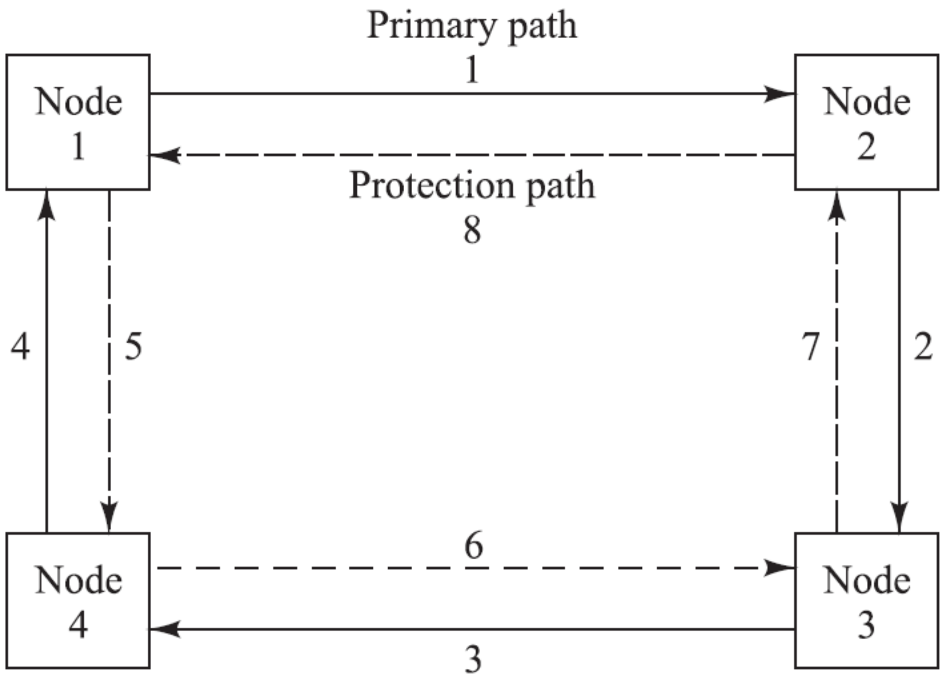


SONET & SDH RINGS

- SONET/SDH are usually configured as a **ring architecture**, which is achieved by creating **loop diversity** for uninterrupted service protection purposes in case of link or equipment failures.
- The SONET/SDH rings are also called as ***self-healing rings*** because the traffic flowing along a certain path can **automatically be switched to an alternate or standby path following failure or degradation of the link segment**.
- Three main features, each with two alternatives, thus yielding eight possible combinations of SONET/SDH ring types.
  - First, there can be **either two or four fibers** running between the nodes on a ring.
  - Second, the operating signals can be **unidirectional** or **bidirectional** .
  - Third, protection switching can be performed **either via a line-switching** or a **path-switching scheme**
- Upon link failure or degradation, **line switching** moves all signal channels of an entire OC-N channel to a protection fiber. Conversely, **path switching** can move individual payload channels within an OC-N channel (e.g., an STS-1 subchannel in an OC-12 channel) to another path.

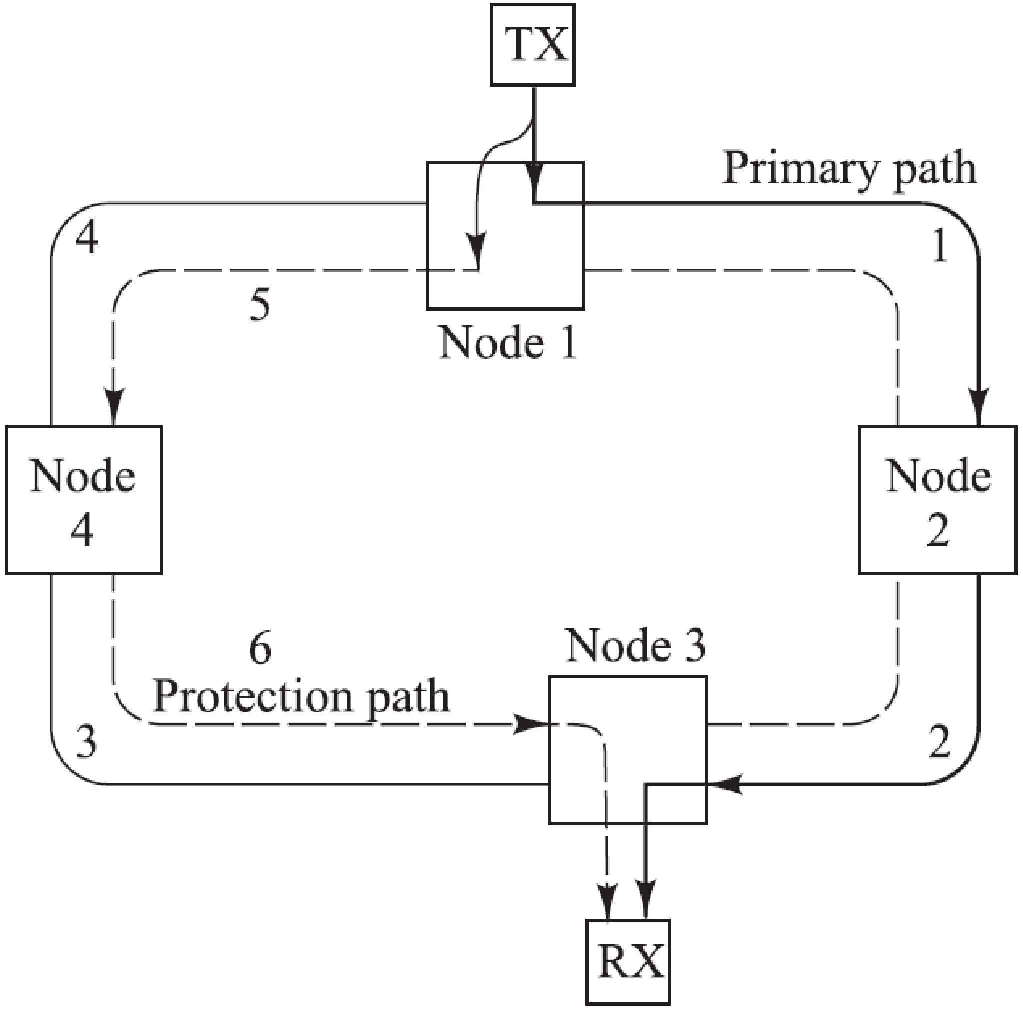
TWO FIBER UNIDIRECTIONAL PATH SWITCHED RING (UPSR)- USHR

- In a unidirectional ring the normal working traffic travels clockwise around the ring, on the primary path.
- The counter clockwise path is used as an alternate route for protection against link or node failures. This protection path is indicated by dashed lines.
- To achieve protection, the signal from a transmitting node is dual-fed into both the primary and protection fibers.
- The receiver selects the signal from the primary path, but it compares the fidelity of each signal and chooses alternate signal in case of severe degradation or loss of the primary signal.



- For example, the connection from node 1 to node 3 uses links 1 and 2, whereas the traffic from node 3 to node 1 traverses links 3 and 4. Thus, two communicating nodes use a specific bandwidth capacity around the entire perimeter of the ring.

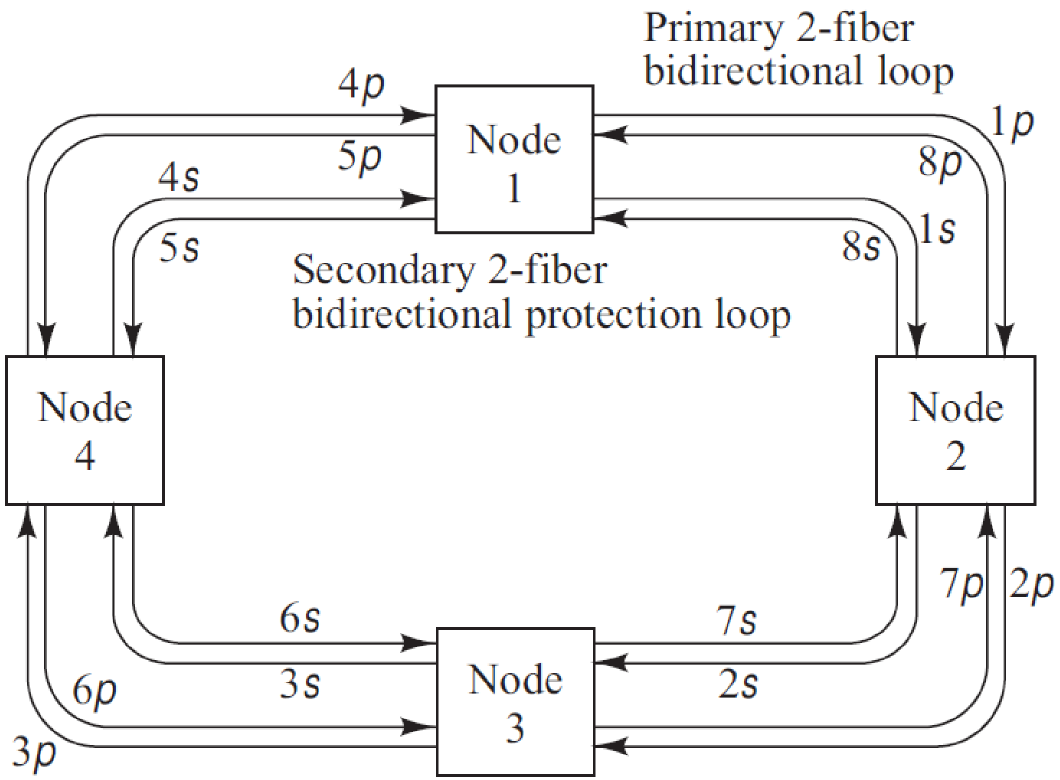
Two fiber unidirectional path switched ring (UPSR)- USHR



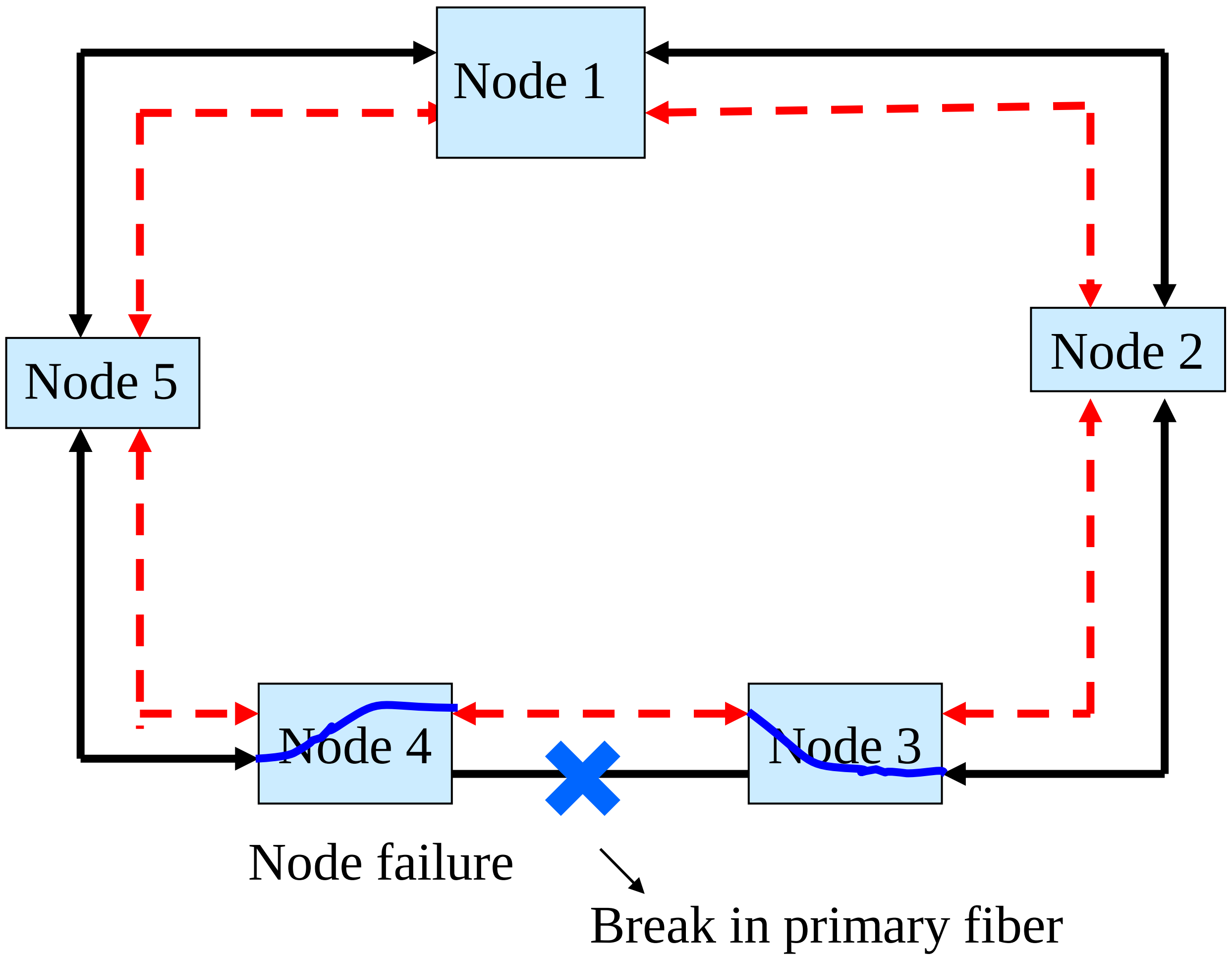
- Two identical signals from a particular node arrive at their destination from opposite directions, usually with different delays
- The receiver normally selects the signal from the primary path.
- However, it continuously compares the fidelity of each signal and chooses the alternate signal in case of severe degradation or loss of the primary signal.
- For example, if path 2 breaks or equipment in node 2 fails, then node 3 will switch to the protection channel to receive signals from node 1.

A bidirectional line switched ring (BLSR) (Two-fiber or four-fiber BLSR)

- Two primary fiber loops (with fiber segments labeled 1p through 8p) are used for normal bidirectional communication, and the other two secondary fiber loops are standby links for protection purposes (with fiber segments labelled 1s through 8s)

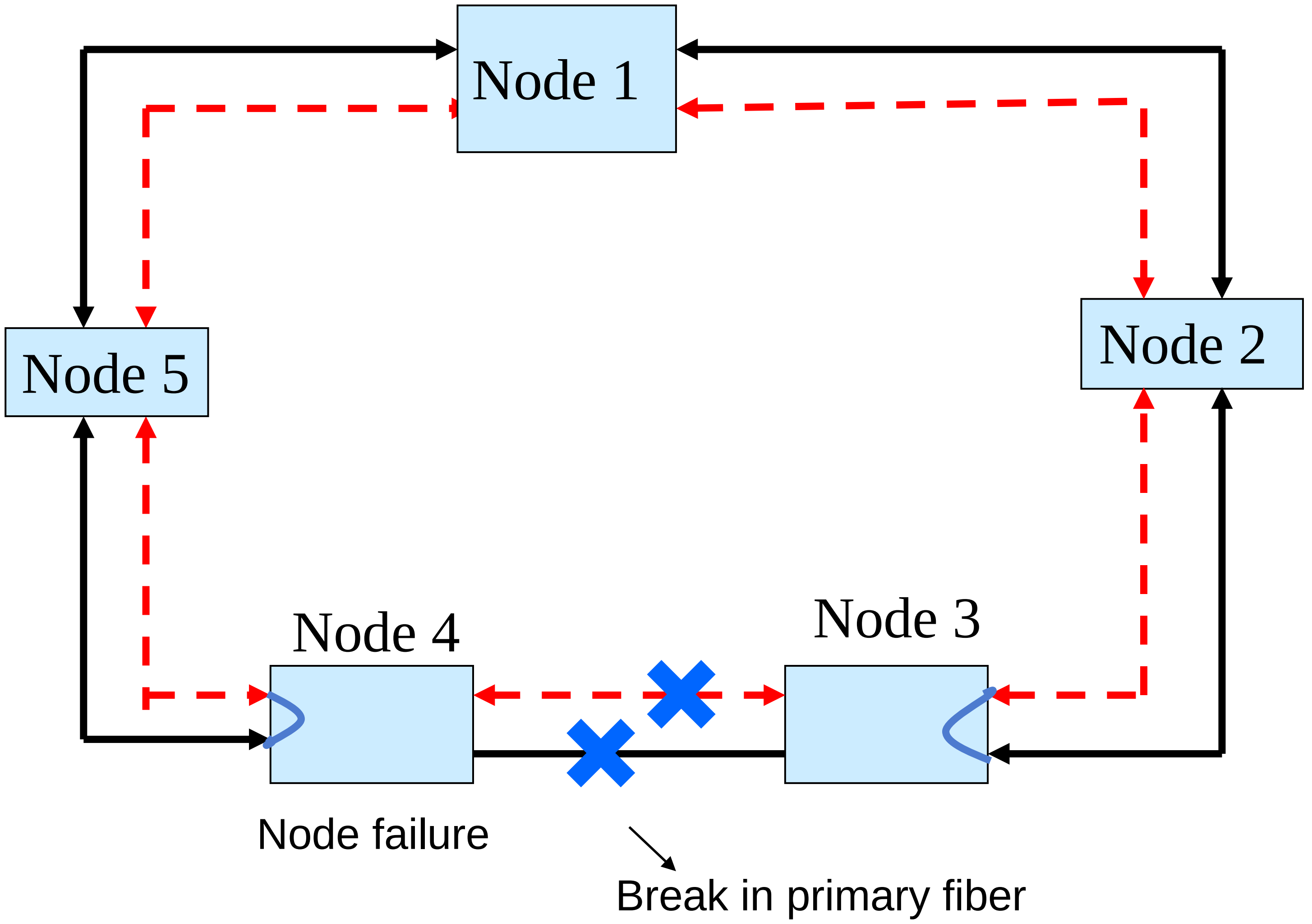


Case1: What happens when both primary fibers in a given span are failed?

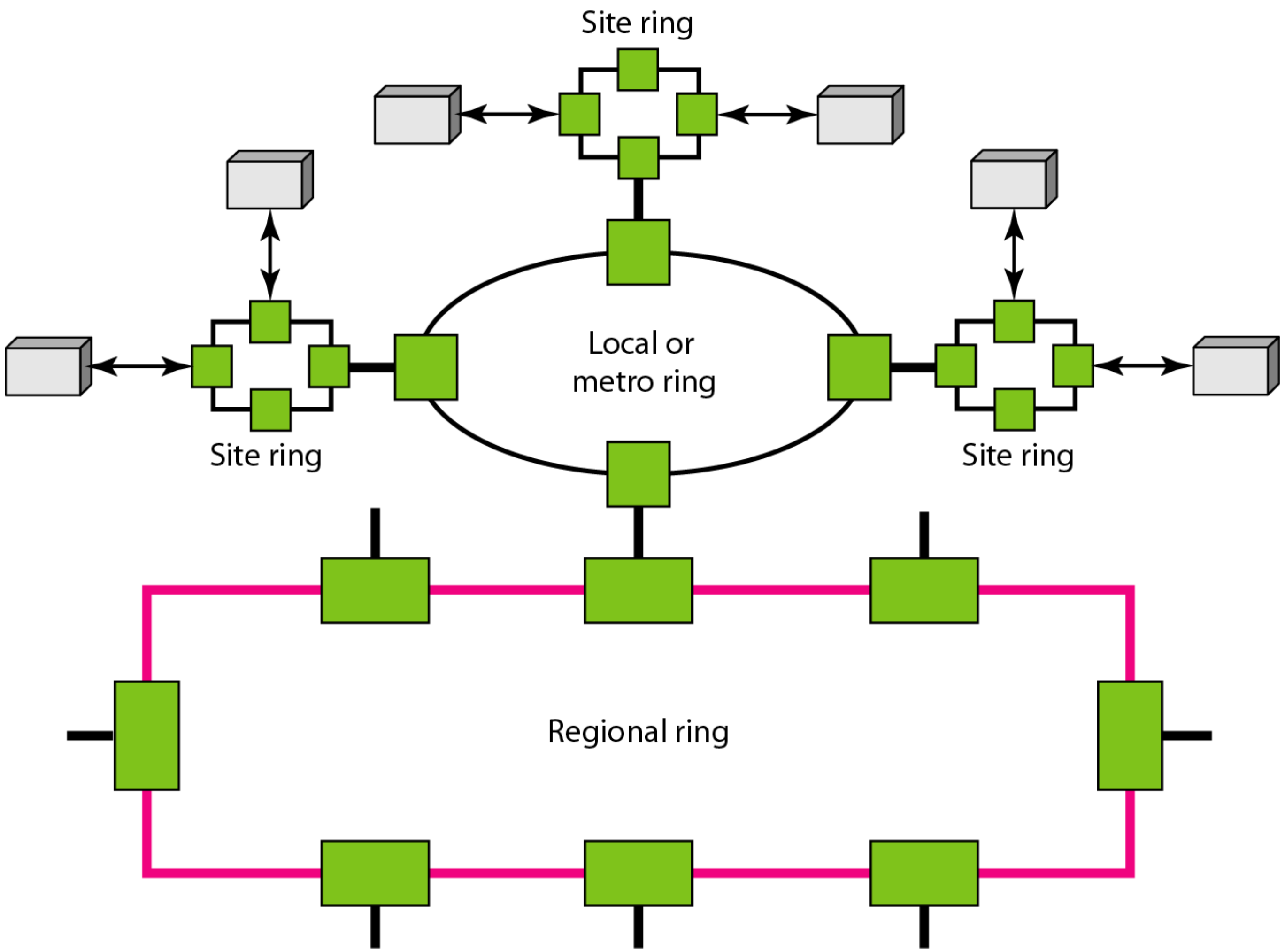


- In this situation, the affected nodes detect a loss-of-signal condition and switch both primary fibers connecting these nodes to the secondary protection pair
- The protection segment between nodes 3 and 4 now becomes part of the primary bidirectional loop. The exact same reconfiguration scenario will occur when the primary fiber connecting nodes 3 and 4 breaks.

Case 2: What happens when both primary and protection fibers in a given span are failed?



A combination of rings in a SONET network



TEXT BOOKS

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