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TSIN02 Internetworking

Lecture 4 – Optical Networking – Transmission and components

Outline

- Introduction to Optical Fiber Systems
- Optical Communication Windows and System Elements
- Data Rate and Multiplexing Techniques
- Coarse vs. Dense Wavelength Division Multiplexing (WDM)
- Client Layers for WDM Networks

Optical Networks

- **Definition:** An optical network is a telecommunication network
  - with transmission links that are optical fibers **and**
  - with an architecture that is designed to exploit the unique features of fibers.
- It is **NOT NECESSARILY** all optical

- **Characteristics of an optical network:**

  Transmission: optical

  Switching: could be optical, could be electronic, could be hybrid
  could be circuit, could be packet, could be burst
- **Most used approach today:**

  Mixed electronic and optical switching

  Circuit based

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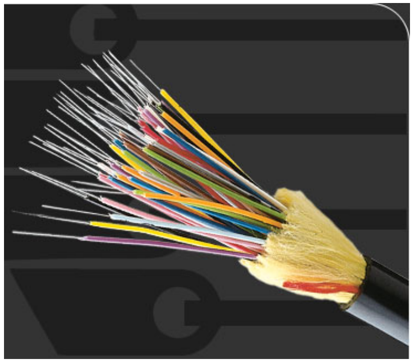
Why Optical Networks?

- Optical fiber is the **backbone** of the modern communication networks.
- The optical fiber carries:
  - Almost all long distance phone calls
  - Most Internet traffic (Dial-up, DSL or Cable)
  - Most television channels (Cable or DSL)

  } **'Triple Play'**
- One fiber can carry up to 6.4 Tb/s (10^{12} b/s) or 100 million conversations simultaneously.
- **Information revolution** wouldn't have happened without the optical fiber.
- The bandwidth made possible by optical fiber communications has made the Internet economically feasible.

Optical Technology - Advantages

- Long Distance Transmission: The lower transmission losses in fibers compared to copper wires allow data to be sent over longer distances.
- Large Information Capacity: Fibers have wider bandwidths than copper wires; more information can be sent over a single physical line.
- Small Size and Low Weight: The low weight and the small dimensions of fibers offer a distinct advantage over heavy, bulky wire cables in crowded underground city ducts or in ceiling-mounted cable trays.



Optical Technology - Advantages

- Immunity to Electrical Interference: The dielectric nature of optical fibers makes them immune to the electromagnetic interference effects.

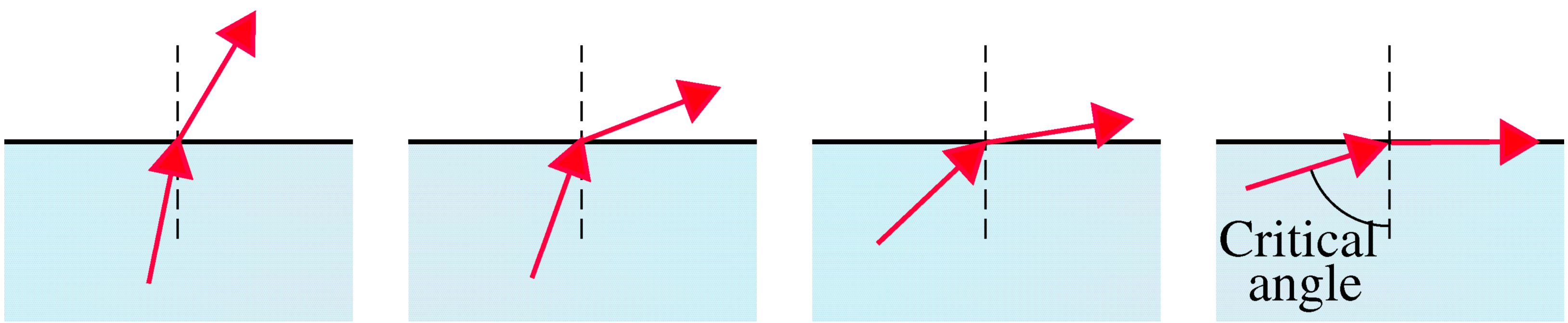
- Enhanced Safety: Optical fibers do not have the problems of ground loops, sparks, and potentially high voltages inherent in copper lines.
- Increased Signal Security: A signal is well-confined within the fiber and an opaque coating around the fiber absorbs any signal emissions.

Optical Technology - Disadvantages

- Cost : Optical fibers are expensive.
- Installation/maintenance: Any crack in the core will degrade the signal, and all connections must be perfectly aligned.

Optical Fibers- Light Guiding Principle

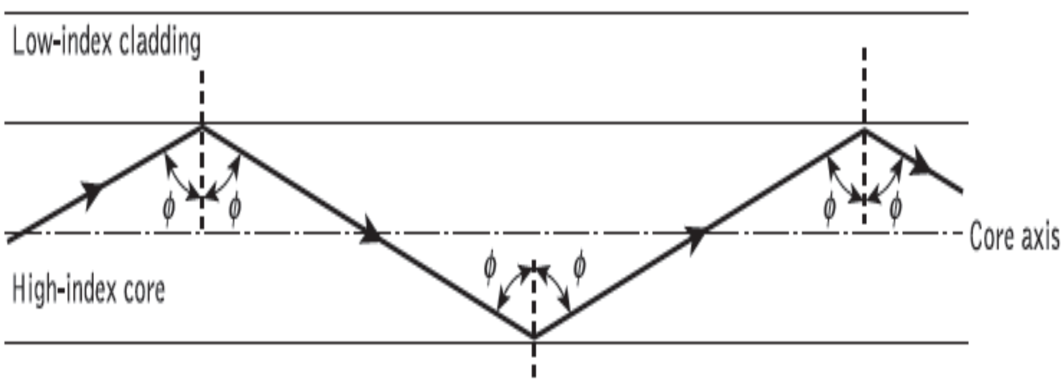
- Light travels at 3×10^8 ms^{-1} in free space and is the fastest possible speed in the Universe.
- Light slows down in denser media, e.g. glass.
- **Refraction** occurs at interface bending light away from the normal when it enters a less dense medium.

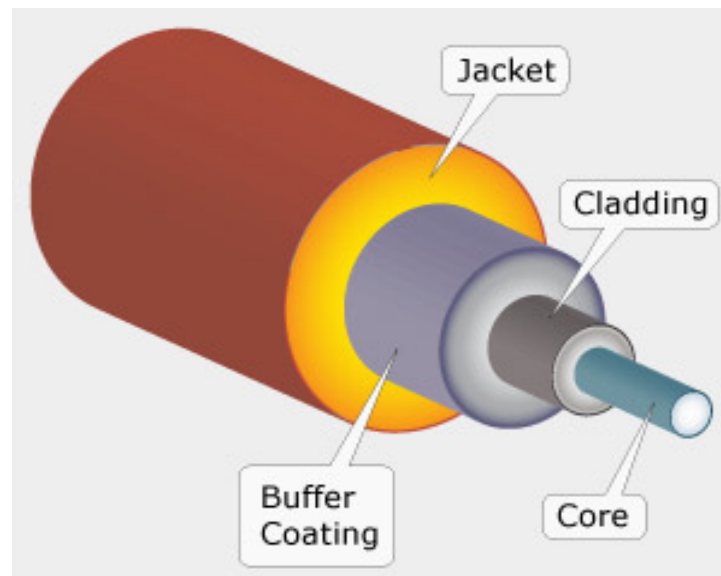


- Beyond the ***critical angle*** $\Rightarrow$ total internal reflection.

Optical Fibers- Light Guiding Principle

- An optical fiber consists of a **core** (denser material) and a **cladding** (less dense material).
- The core and cladding have different refractive indexes and are designed to guide the light signals by successive reflections along the inside of the fiber core.
- The core and the cladding are usually made of high quality silica glass.





The era of Commercial Fiber Transmission Systems

1980s The **first generation** of fiber-optic communication systems operated at a bit rate of **45 Mb/s** and required signal regeneration every ~**10 km**.

1990s Bit rate increased to **10 Gb/s**, allowed regeneration after ~**80 km**

Development and commercialization of **erbium-doped fiber amplifiers (EDFA),** fiber Bragg gratings, and **wavelength-division-multiplexed (WDM)** systems.

2000s Capacity of commercial terrestrial systems exceeded **1.6 Tb/s**

A single transpacific system bit rate exceeded 1 Tb/s over a distance of 10,000 km without any signal regeneration.

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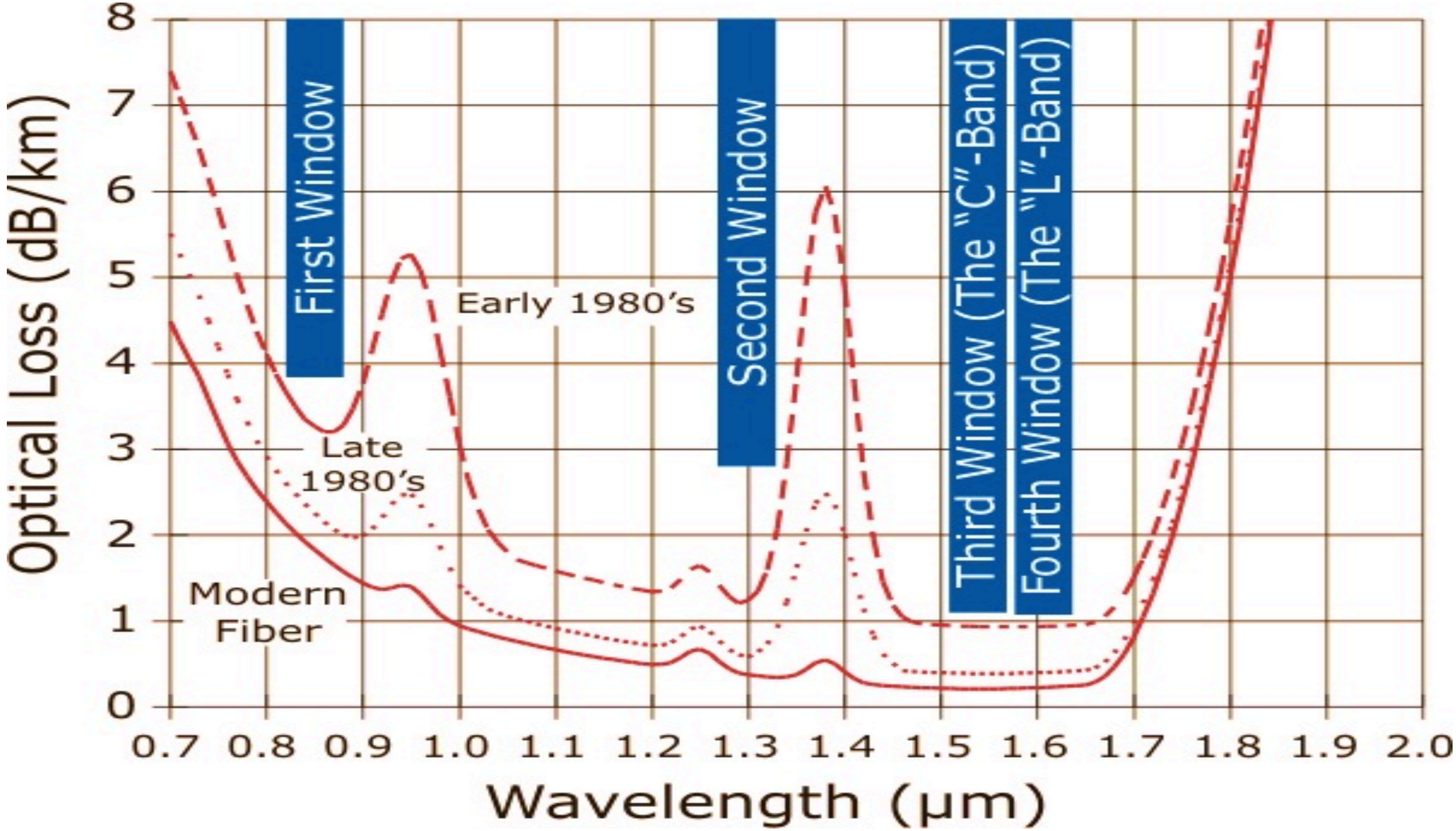
Transmission Windows



Conventional Band (C-Band): 1530nm to 1565nm

Long Band (L-Band): 1565nm to 1625nm

Shannon theorem

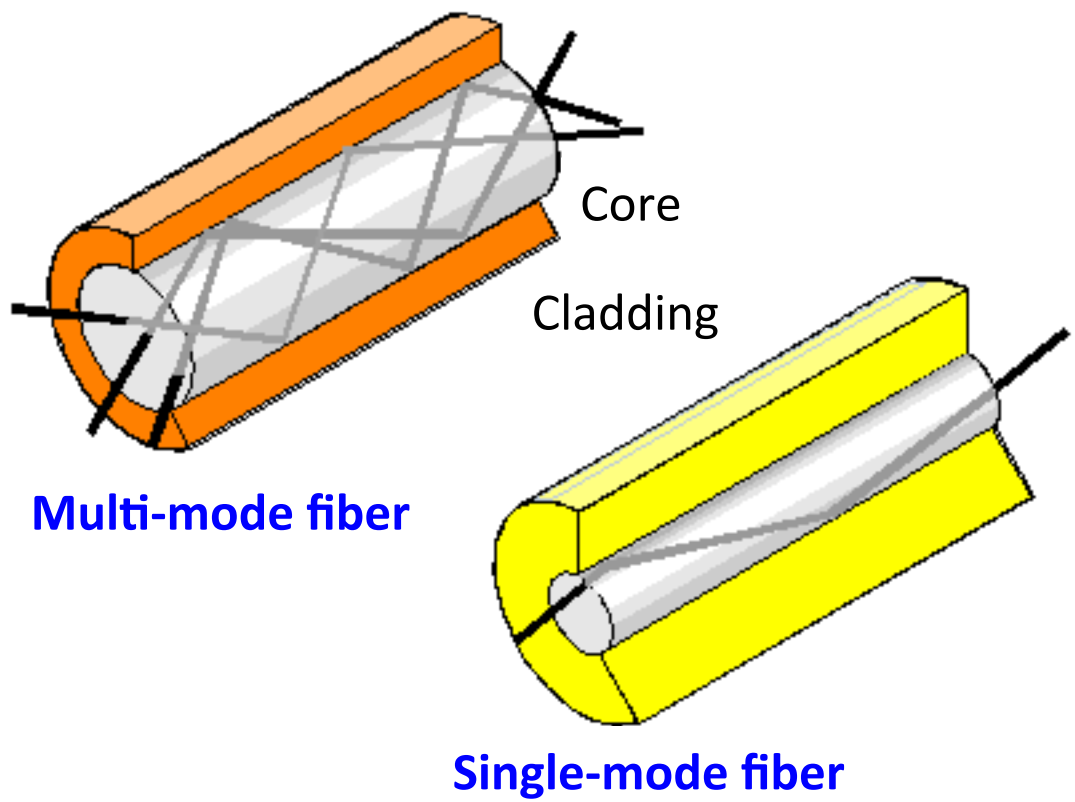
$C = B . \log_2(1+ \text{SNR})$

Optical Communication Elements (Transmitter)

- **Optical Transmitter** converts the electrical information to optical format (E/O).
  - Light Emitting Diode (LED): cheap, robust and used with multi-mode fibers in short range applications.
    - Surface emitting and edge emitting LED.
  - LASER Diode: high performance and more power, used with single-mode fibers in high speed links.
    - Distributed Feedback (DFB) Laser – high performance single mode laser.
    - Fabry-Perot (FP) lasers – low performance multimode laser.

Optical Communication Elements (Fiber)

- Two main types of **optical fiber** are used in communications: **multi-mode** and **single-mode** optical fibers.
- A multi-mode fiber has a larger core (50 – 85 micrometers), while single-mode has a much smaller core (<10 micrometers).

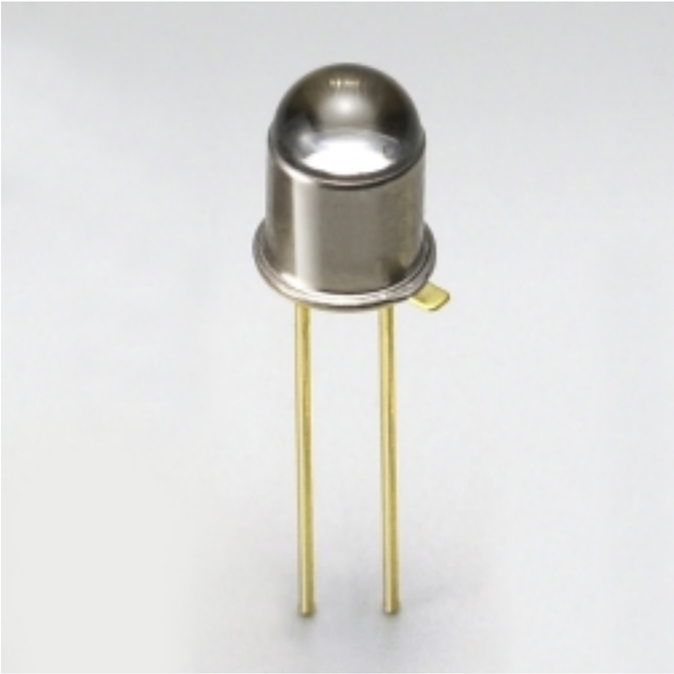


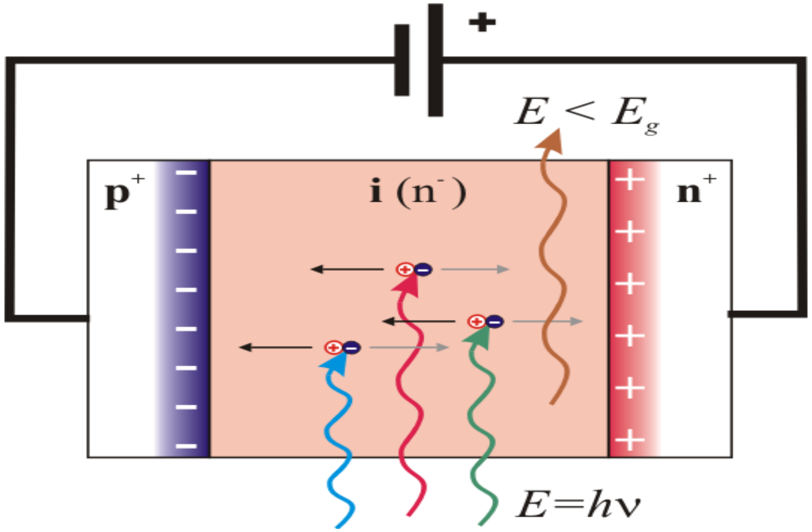
Optical Communication Elements (Fiber)

- The larger core of multi-mode fiber allows less precise, **cheaper** transmitters and receivers to connect to it as well as cheaper connectors.
- In a long cable run, the multiple paths of light cause signal distortion at the receiving end, resulting in unclear and incomplete data transmission. **Not suitable for long distance transmission.**
- The small core of single-core fiber and single light-wave virtually eliminate any distortion that could result from overlapping light pulses. **Best choice for much longer, high performance optical links of several 100's km.**

Optical Communication Elements

- **Optical Receiver** converts the optical signal into appropriate electrical format (E/O).
  - PIN Photo Diode: Low performance, no internal gain, low cost, widely used.





Optical Communication Elements

- **Optical Receiver** converts the optical signal into appropriate electrical format (E/O).
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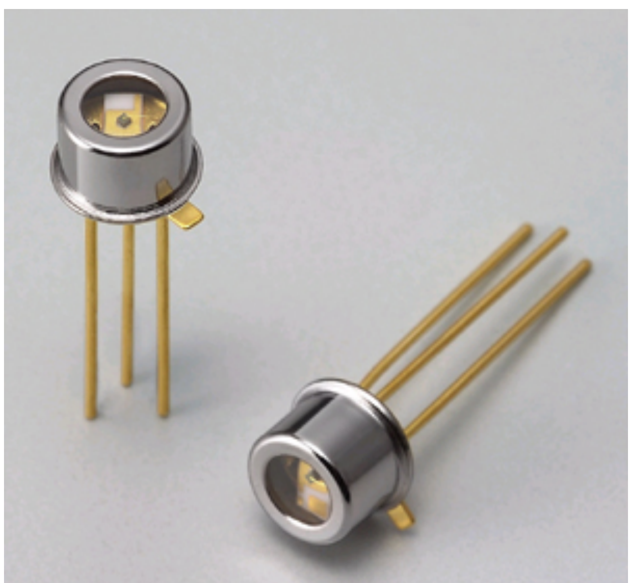
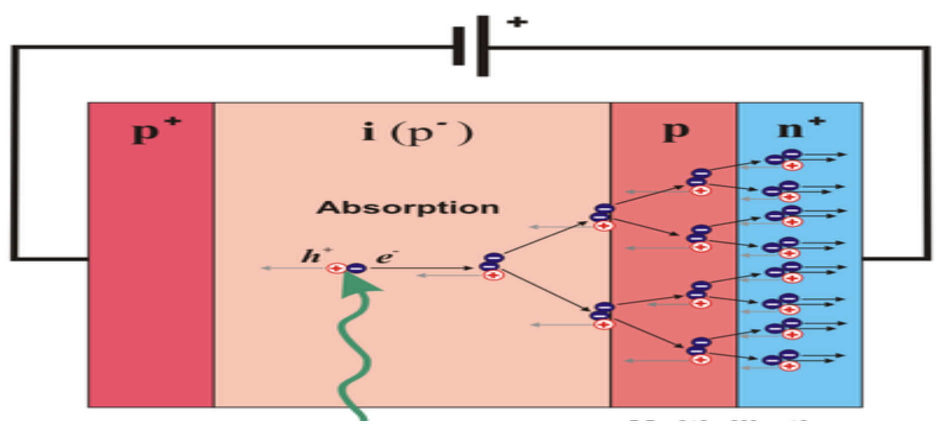
  - Avalanche Photo Diode (APD): High performance with internal (avalanche) gain.





Optical Communication Elements

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- **Regenerator:** neutralizes dispersion by receiving weak light signal, cleaning-up, amplifying and retransmission (O/E/O).

- **Optical Amplifier:** amplifies light in fiber **without** O/E/O.

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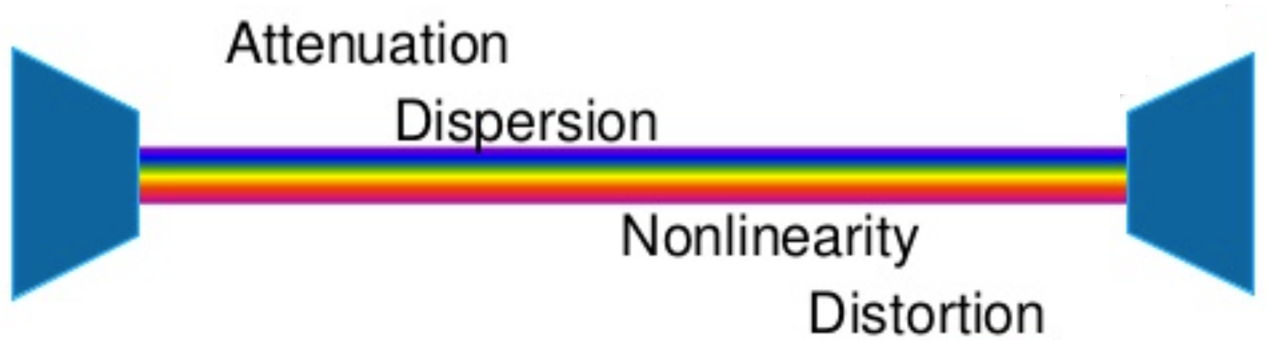
Propagation Issues



Attenuation or loss: Transmitted signal loses its power as it travels along the fiber. The further the distance, the higher the loss.

Dispersion: Different components of the transmitted signal travel at different speeds, and thus arriving at different times at the receiver.

Intermodal dispersion arises from the different path lengths associated with various modes in a multi-mode fiber.

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Propagation Issues

Intramodal/Chromatic dispersion results from the finite spectral linewidth of the optical source. Degrades the signal shape in single-mode fiber.

Nonlinear Effect: The response of any dielectric to light becomes nonlinear for intense electromagnetic fields.

Nonlinear effects are weak at low powers but they can become much stronger at high optical intensities.

Interactions between lightwaves and the material transmitting them introduce scattering.

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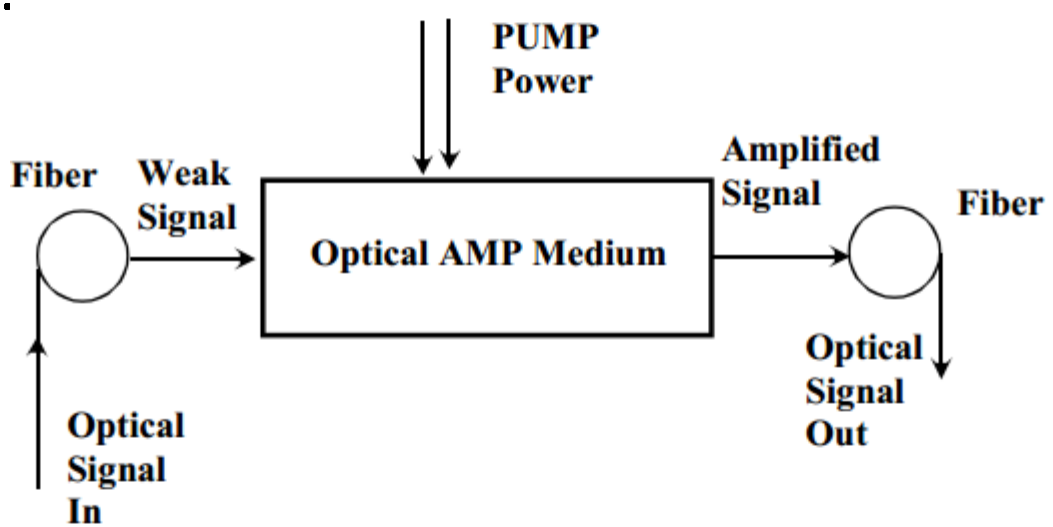
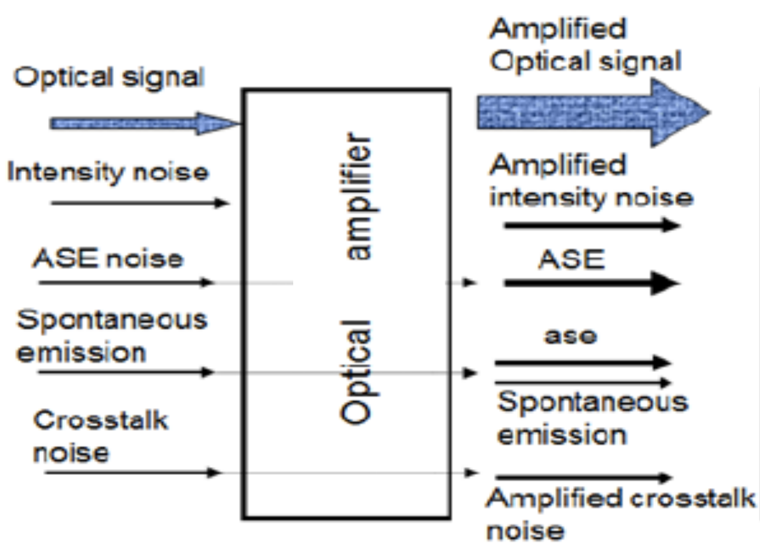
Optical Amplifier (OA)

- Optical amplifiers are used to regain optical power and enable bridging of distances up to the point where chromatic dispersion of the fiber sets the limit.
- The optical amplifier works fully in the **optical domain**.
- There are several different physical mechanisms that can be used to amplify a light signal. Most common is the Erbium-doped fiber amplifier (EDFA).



Optical Amplifier (OA)

- OA amplifiers not only amplify the legitimate signal but also the unwanted signals (noises).
- Optical amplification add noise to the signal at every amplifier, called Amplified Spontaneous Emission (ASE).
- OAs can extend the optical reach over single-mode fiber from about 100 km to some 800 km, and even up to 1500 km if the link has forward error correction (FEC).



Crosstalk noise: Noise due to other signals interferes with the signal in question

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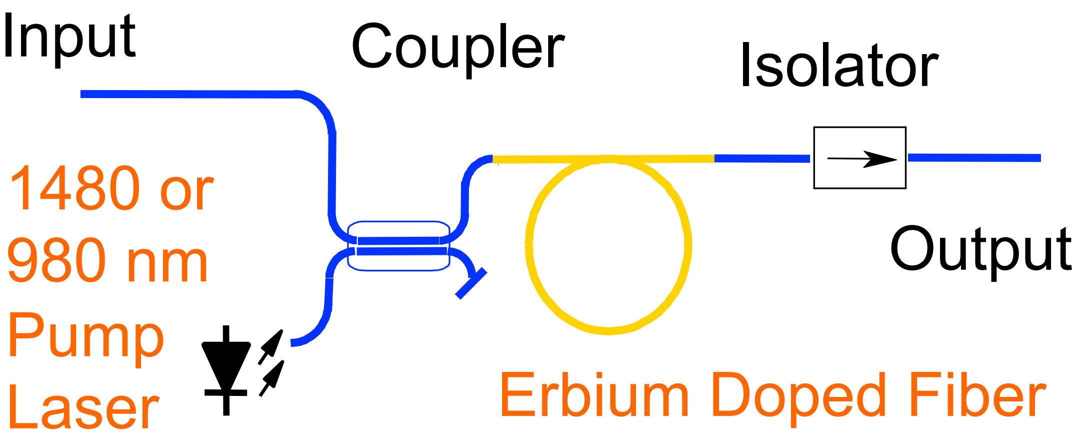
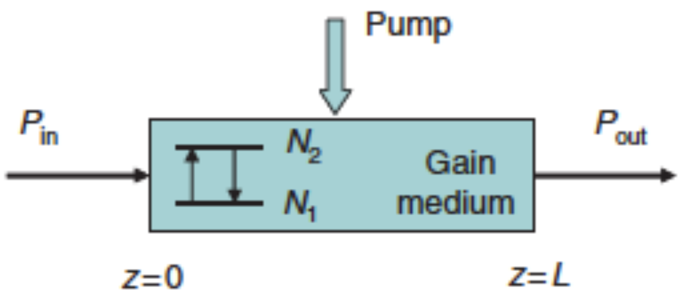
Erbium-doped Fiber Amplifier (EDFA)





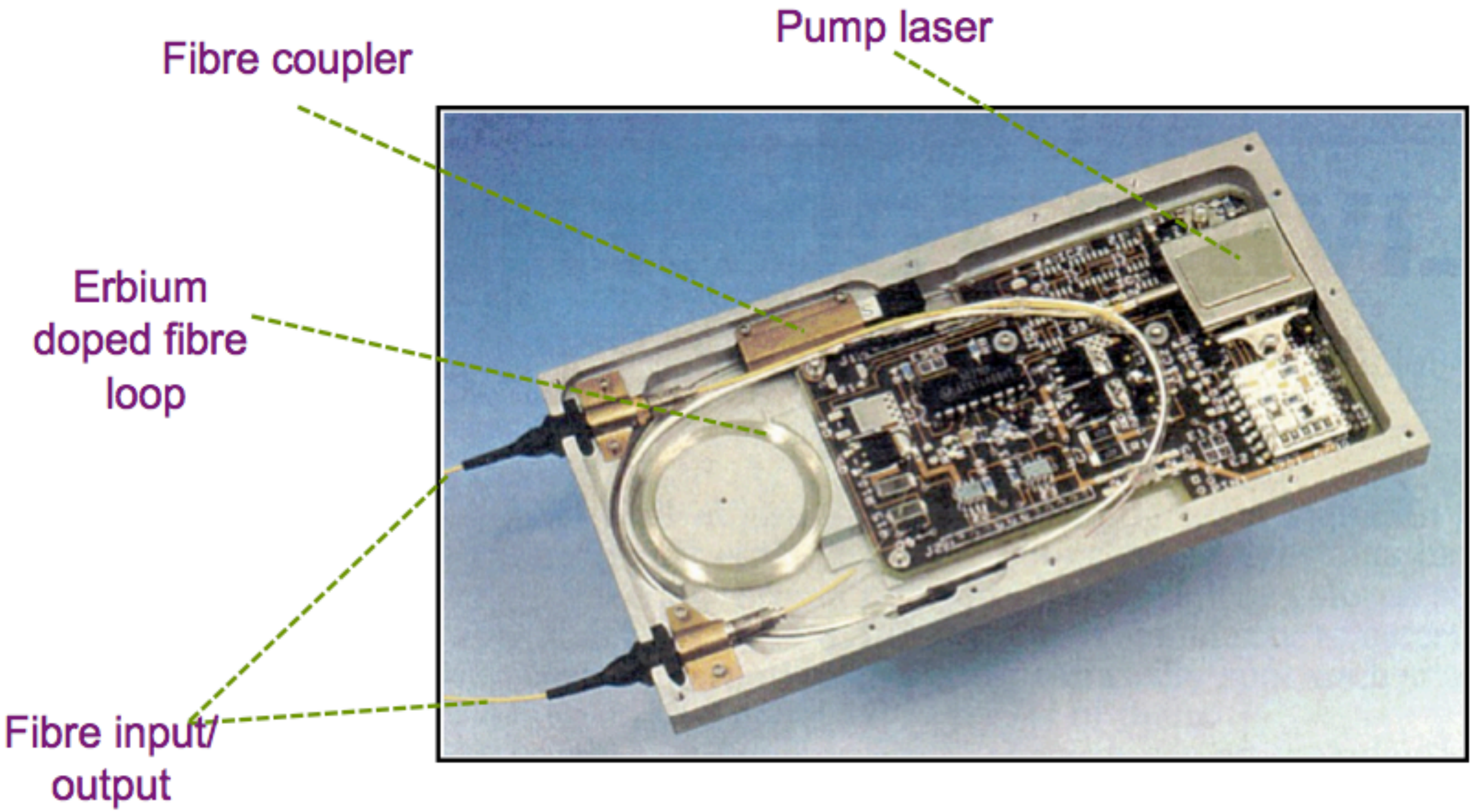
Energy from an external higher frequency source (pump laser) excites ions in the erbium doped fiber and the signal is amplified through interaction with the ions.

Commercially available since the early 1990's.

Works best in the range of <u>1530 to 1565 nm</u>.

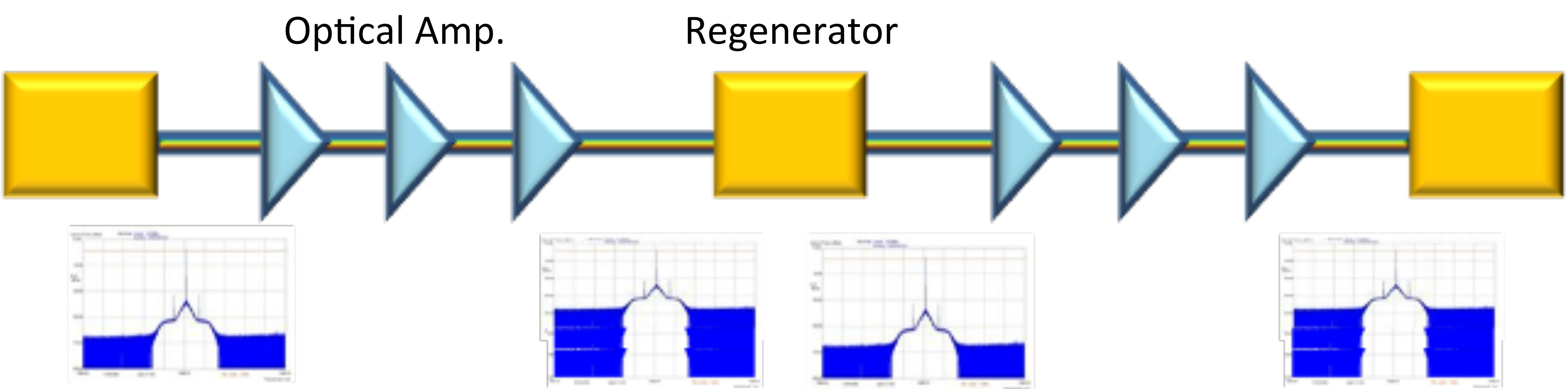
Gain up to **<u>30 dB</u>** (1000 photons out per one photon in).

Inside an EDFA

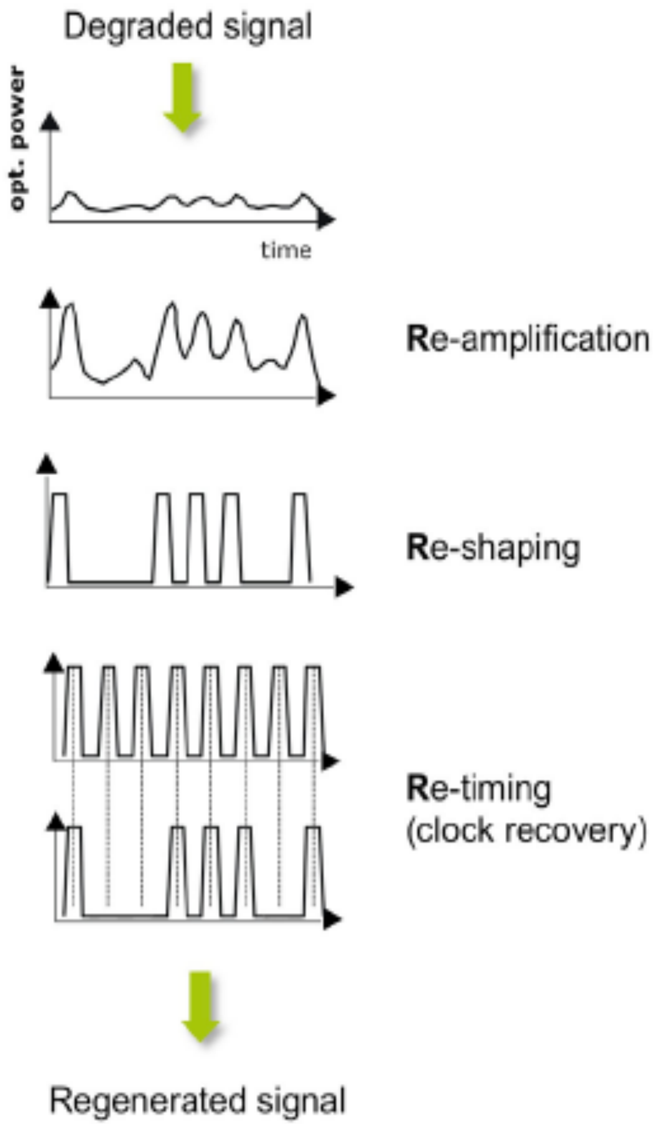


Regenerator

- After a number of optical amplifications, the signal is hidden in noise.
- Regenerator is needed after several 100's km to clean up the legitimate signal.



Regeneration (3R)



1R (Re-amplification)

2R (1R+R, Re-amplification + Re-shaping)

3R (2R+R, Re-amplification + Re-shaping + Re-timing)

Since the signal is converted from optical (O) to electrical (E) and back to optical (O) again, regenerator is sometimes referred as an OEO regenerator.

The regeneration hardware depends on the number of channels, as well as the bit-rate, protocol, and modulation format of each individual channel.

Any upgrade to the link would automatically require upgrades to regenerator hardware.

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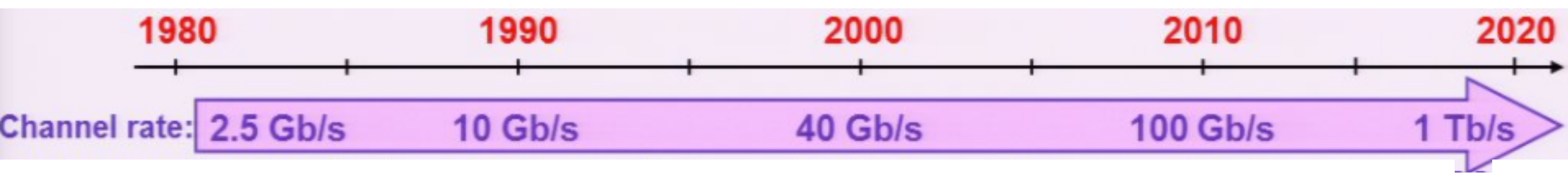
Information Rates and Channel Rate

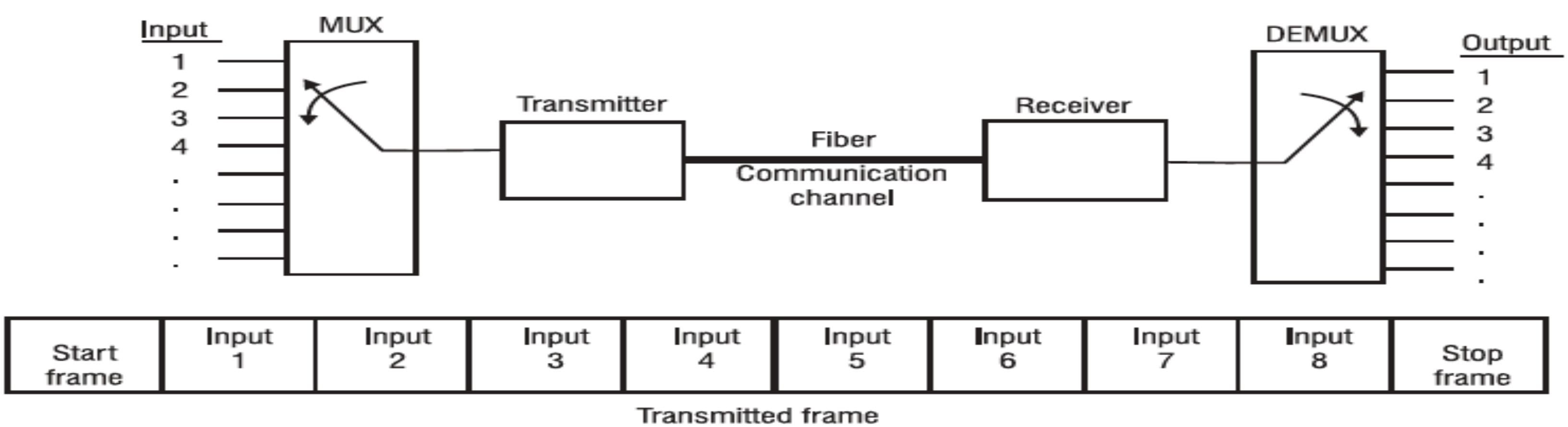
Type of service	Data rate
Video on demand/interactive TV	1.5 to 6 Mbps
Video games	1 to 2 Mbps
Remote education	1.5 to 3 Mbps
Electronic shopping	1.5 to 6 Mbps
Data transfer or telecommuting	1 to 3 Mbps
Video conferencing	0.384 to 2 Mbps
Voice (single channel)	64 kbps



To send these services from one user to another, network providers combine the signals from many different users and send the aggregate signal over a single transmission line.

Time Division Multiplexing (TDM)

- In TDM, lower speed input channels are each allocated a defined timeslot on the outgoing higher speed channel – physically they are "taking turns" on the outgoing fiber.
- Using a framing mechanism in the data stream or by other means of synchronization, it is possible for the receiving end to extract the respective lower speed channels again.
- Synchronous Digital Hierarchy (SDH) and Synchronous Optical Network (SONET) are typical examples of TDM systems used in optical networks.



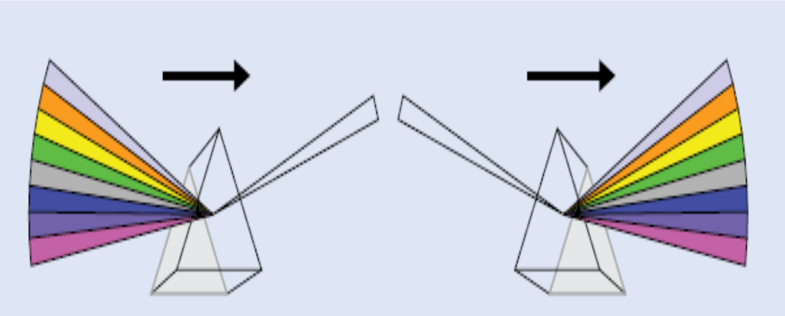
SONET/SDH

- SONET/SDH are physical layer standards **for time division multiplexing** of multiple bit streams over an optical fiber.
- Originally designed to support the multiplexing of real-time, uncompressed, circuit-switched voice circuits **(telephony)**.
- The basic structure in SONET is a frame of 810 bytes.
- The electrical signals (synchronous transport signals (STSs)) is converted to optical signals (optical carriers (OCs)) and are transmitted at 8000 frames per second.
- Minimum speed at which SONET operates:

810 bytes/frame x 8000 frames/sec x 8 (bits) = **51.84 megabits/sec**

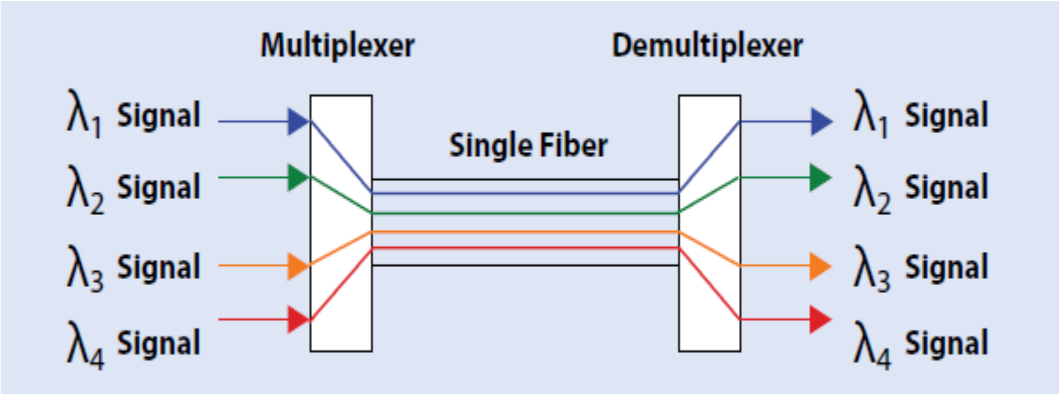
Wavelength Division Multiplexing (WDM)

- In WDM, each input channel is assigned a unique wavelength (i.e., color of light), thus the channels can traverse the fiber in parallel.
- WDM utilizes the properties of refracted light to both combine and separate optical signals based on their wavelengths within the optical spectrum.
- This technique enables multiplication of the capacity, but also bidirectional communication over one single fiber – a fact of significant importance when fiber is scarce or expensive to lease.



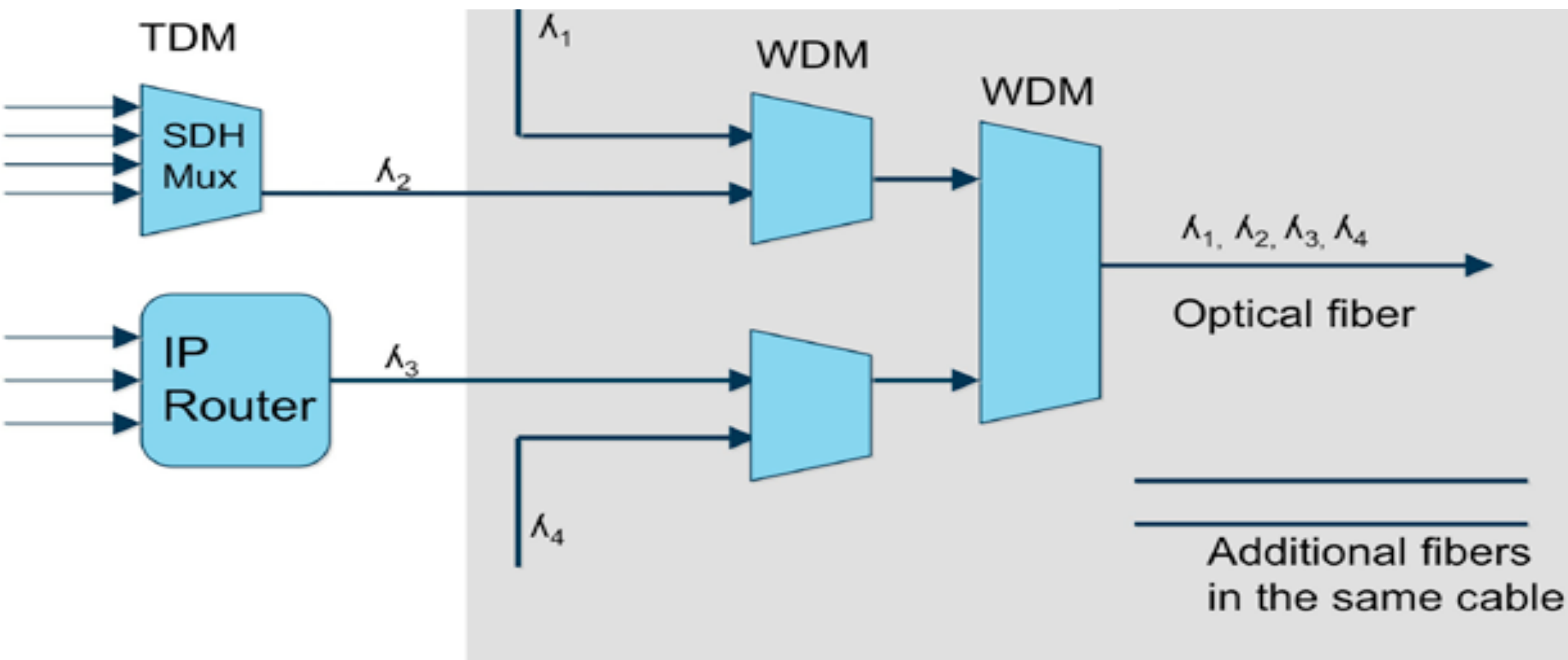
At ingress

At egress



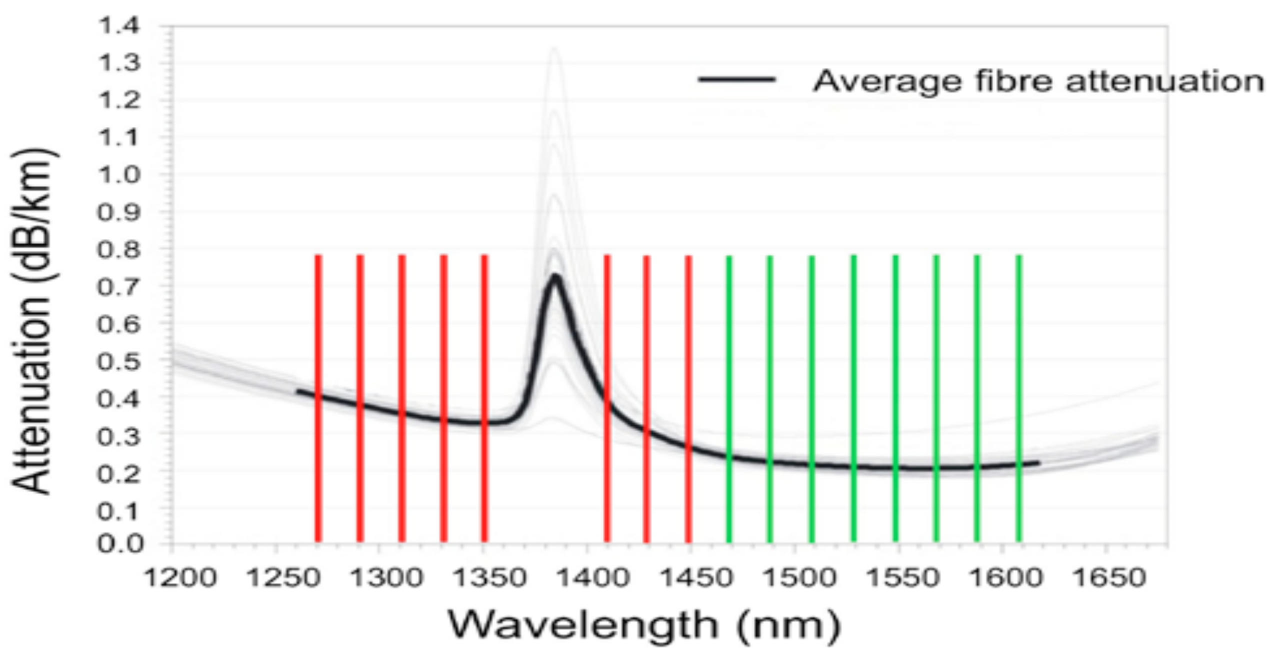
Multiplexing Techniques in Hierarchy

- Nothing stops a network designer from combining the two multiplexing techniques into a hierarchy.



Coarse WDM (CWDM)

- CWDM systems provide up to 16 channels (i.e., wavelengths) in the 1270 to 1610 nm range.
- The standardized CWDM wavelengths do not fit well with optical amplification techniques; hence the optical distance that can be bridged is typically limited to some 60 – 100 km for a 2.5 Gb/s signal.



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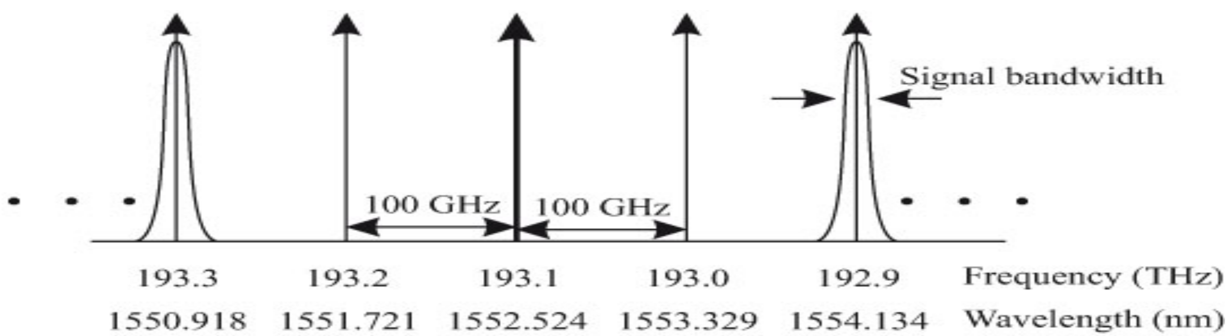
Dense WDM (DWDM)

- DWDM uses a smaller transmission window (C-band 1530-1565 nm) than CWDM but with <u>much denser channel spacing</u>.
- 40 channels with 100 GHz spacing or 80 channels with 50 GHz spacing in the C-band.
- DWDM systems have to maintain <u>more stable wavelengths/ frequencies</u> than those needed for CWDM because of the closer spacing of the wavelengths.
- Precision <u>temperature control</u> of the laser transmitter is required to prevent drift from the central frequency and maintain a very narrow frequency window of the order of a few GHz.



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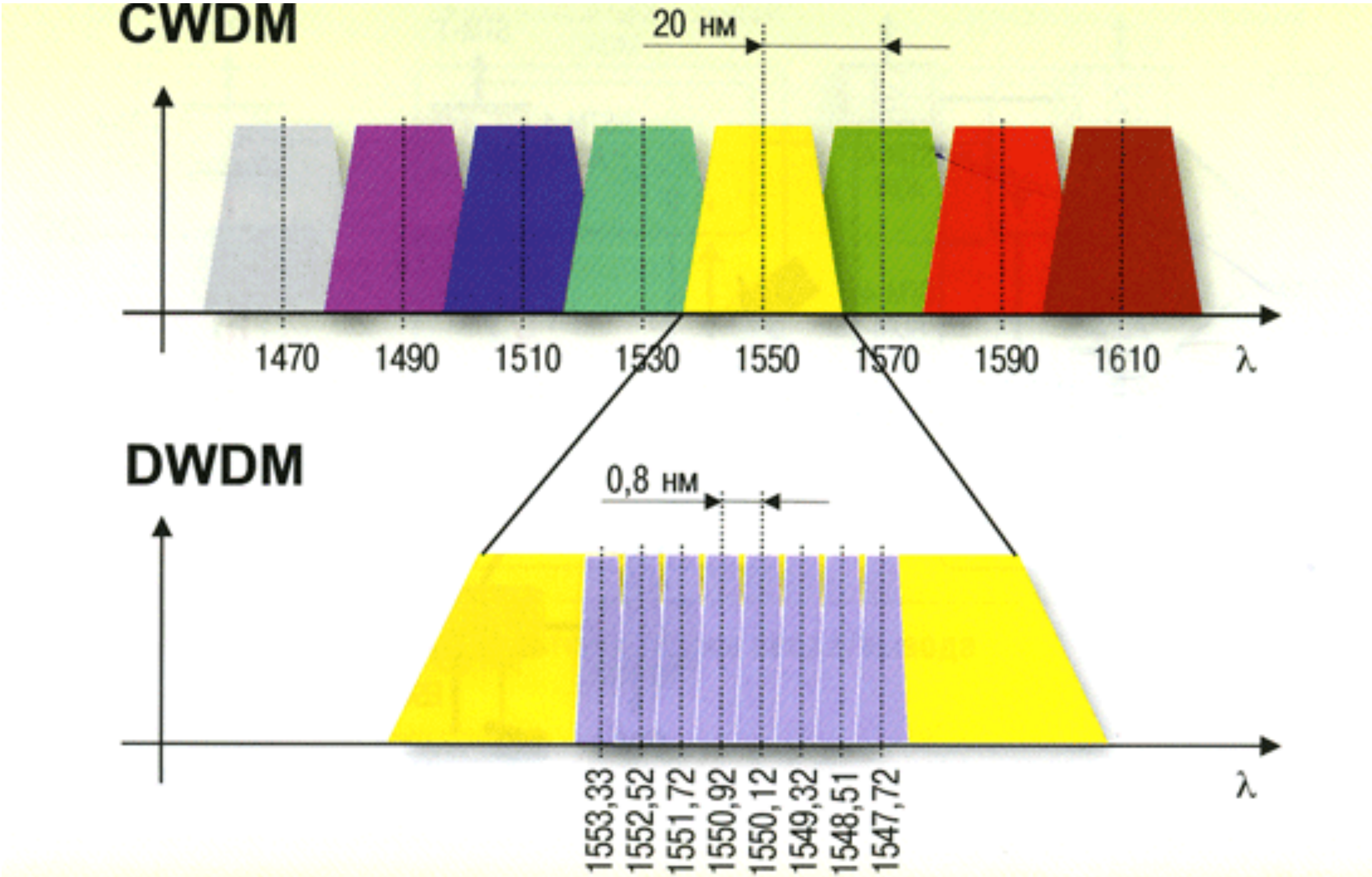
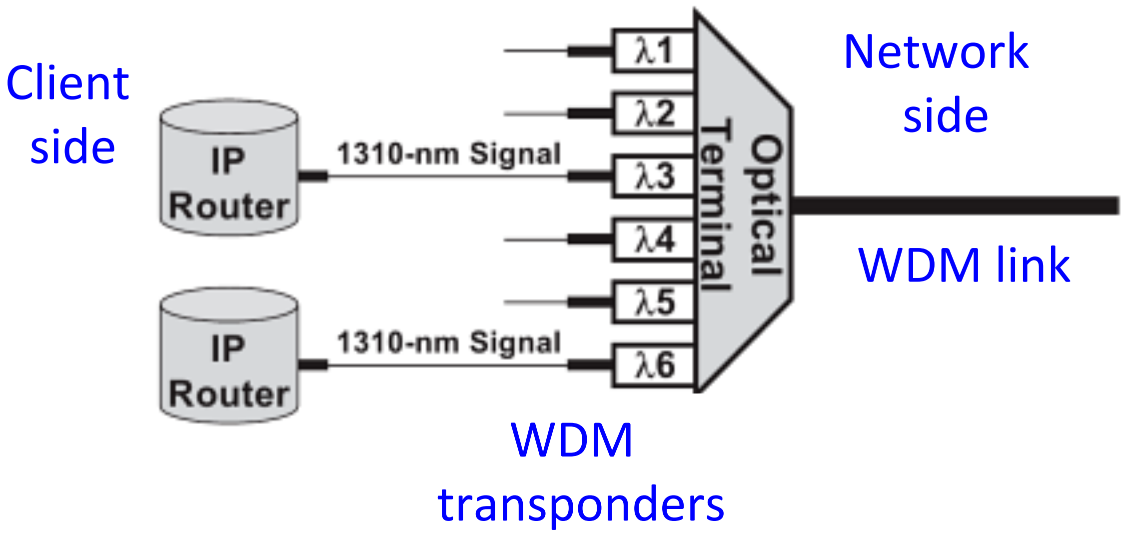
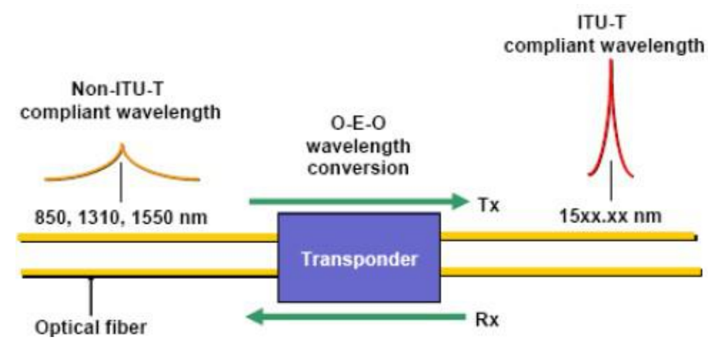
CWDM vs. DWDM



Client Systems for WDM Network

- Various external systems use the optical WDM network to transport information.
- The <u>transponders</u> (signal/wavelength converter) and <u>muxponders</u> (combine several client signals into one line signal) act as interfaces/buffers between the external systems (served traffic layer) and the WDM network.





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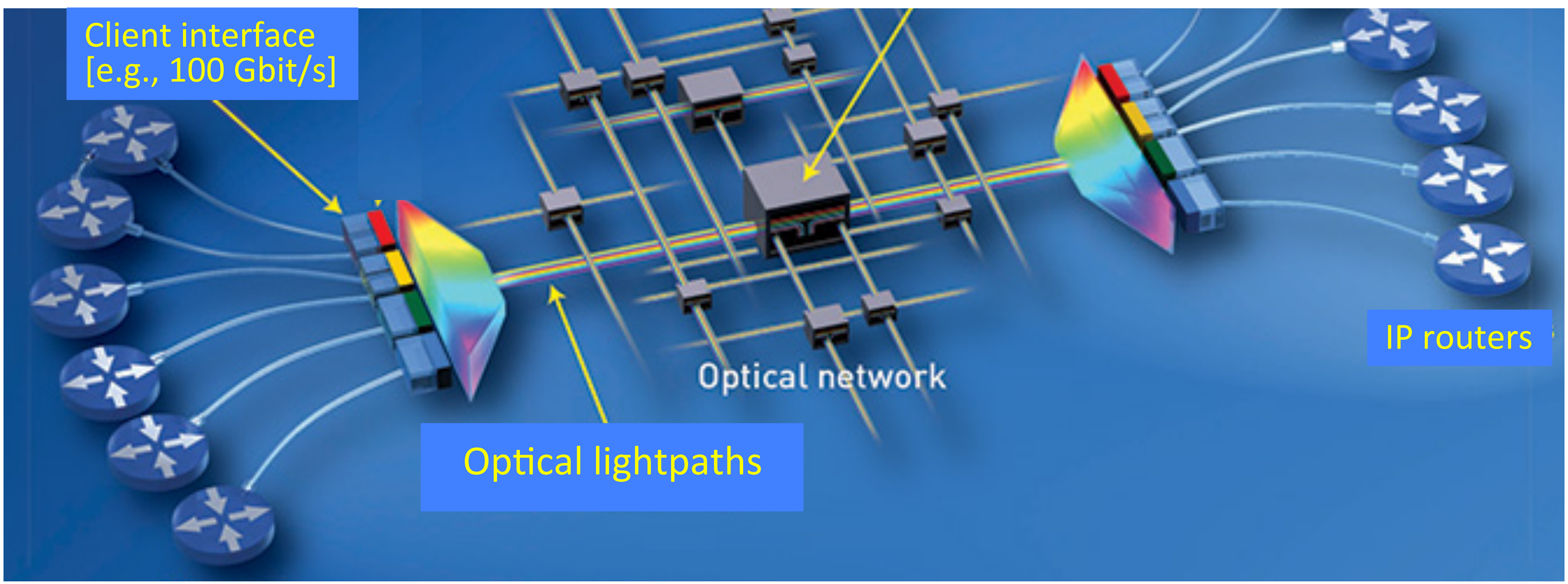
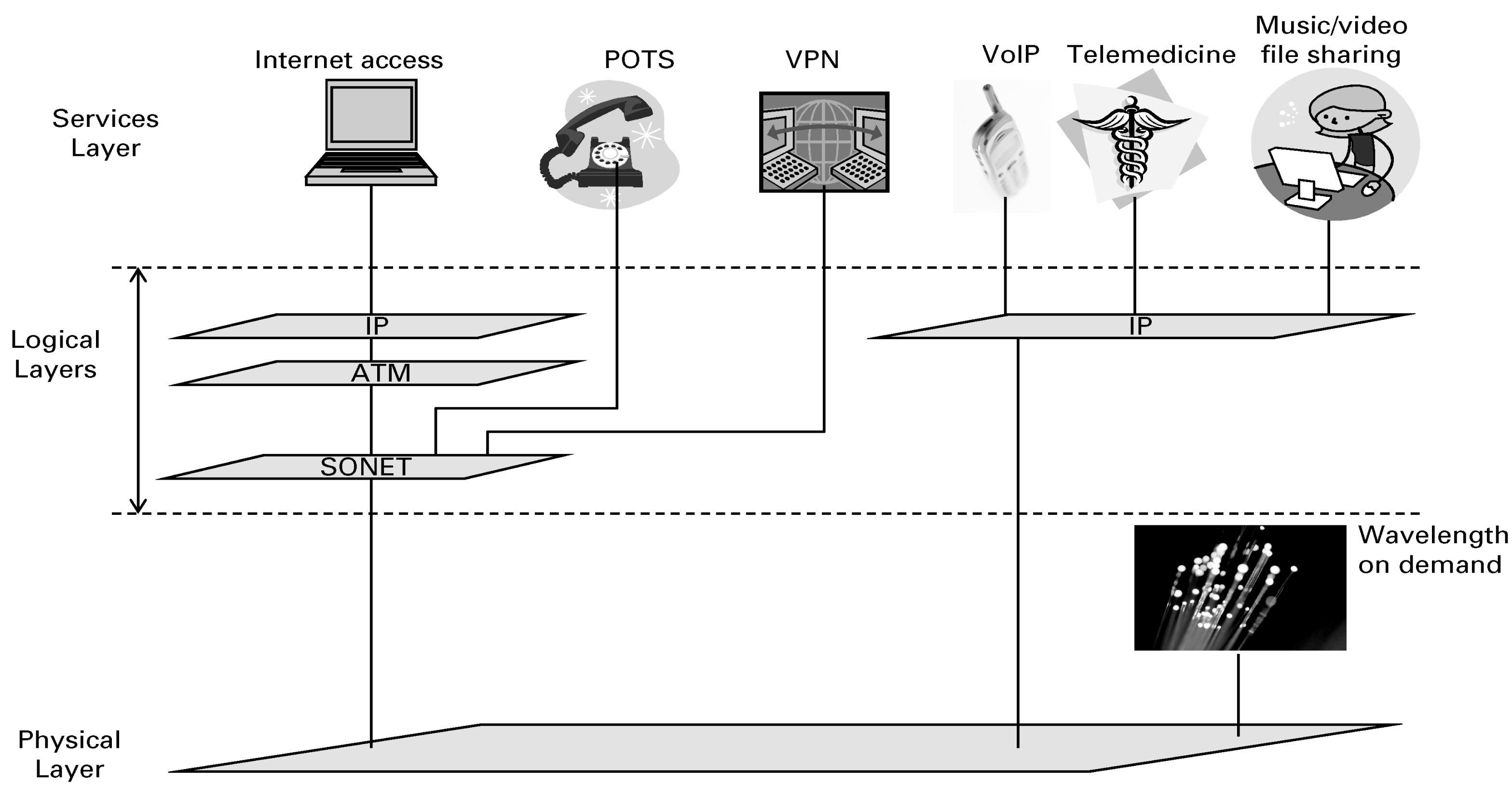
Client Systems for WDM Network

- **Lighthpaths** are established and managed in a WDM optical network. The lightpaths are the **circuits** of the optical network, which make up the physical transmission links between the client systems attached to the optical network.



Layered View for Today's Networks



Asynchronous Transfer Mode (ATM)

- Created by phone companies in 1990s.
- Main goal was the integration of voice and data networks and replacement for the Internet.
- Uses fixed length cells of **53 bytes**, which is a compromise between conflicting requirements of voice and data:

  Small packet size good for voice since delay is short.

  Large size good for data since overhead is small fraction of cell.
- Network guaranteed per-connection *Quality of service* (QoS): throughput, bound on delay, bound on jitter.
- Despite the failure of ATM, proponents still argue that Internet needs QoS.

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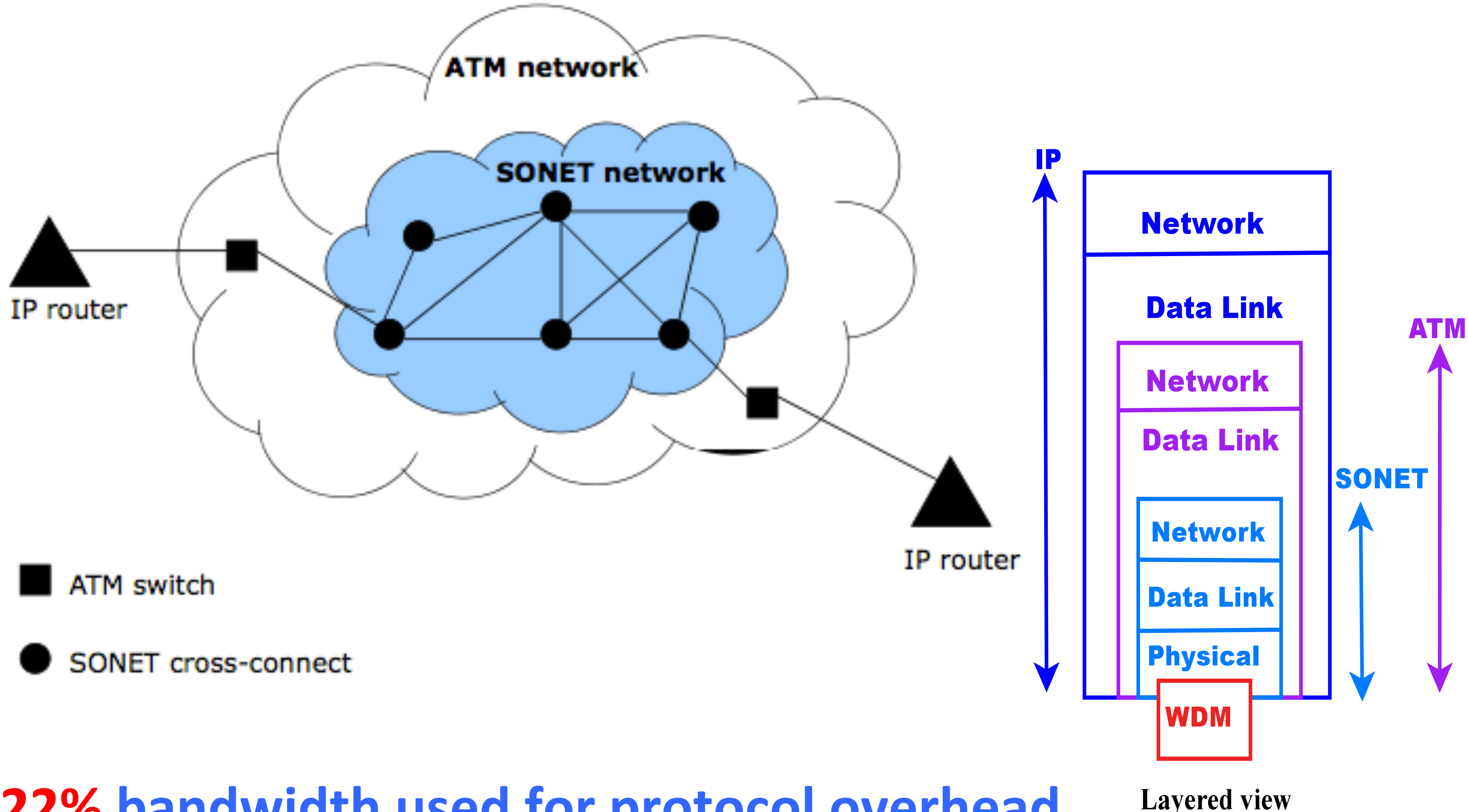
Current Multiple Protocol Stacks

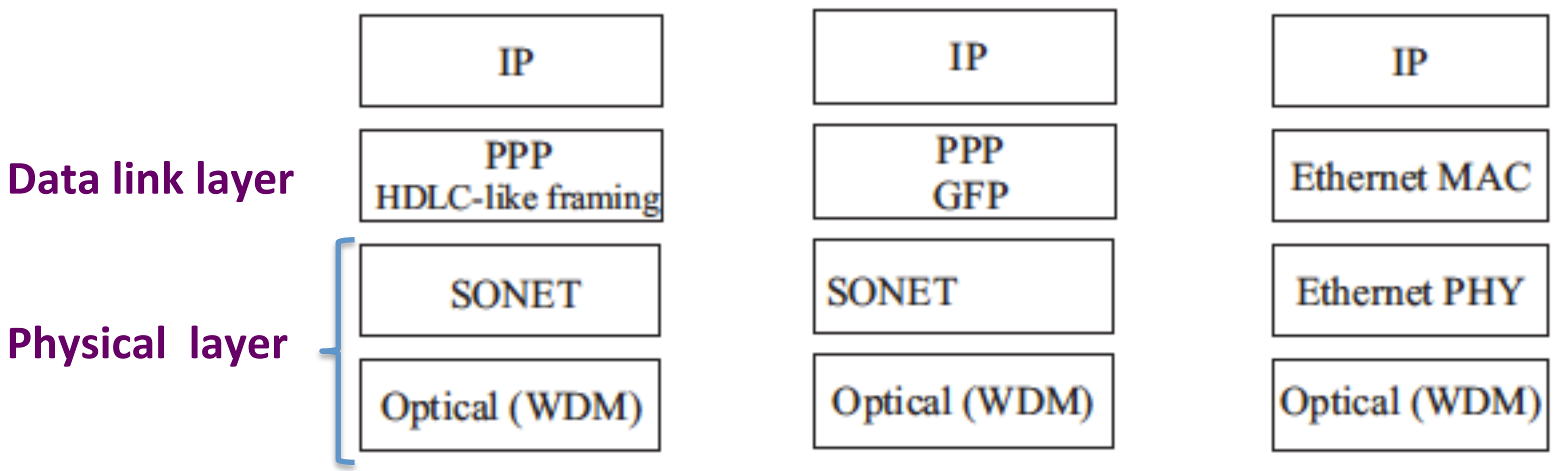


22% bandwidth used for protocol overhead

Various Implementations of IP Over WDM

PPP: Point to point protocol
HDLC: High level data link control
GFP: Generic framing procedure

} Data link layer protocols



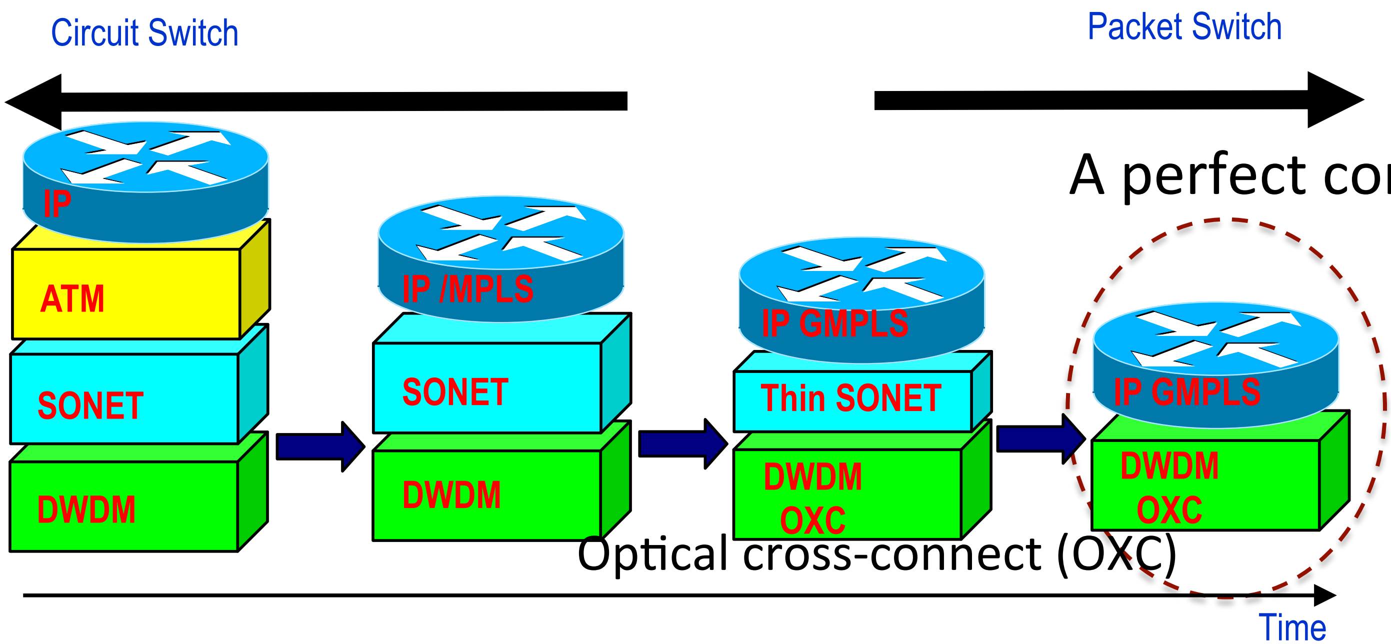
(a) (b) (c)

IP packets are encapsulated into PPP packets and then into HDLC frames, and then encoded into SONET frames for transmission over a wavelength

IP packets are encapsulated into PPP packets and then into GFP frames and then into SONET frames for transmission over a wavelength

Ethernet as the underlying link (media access control) layer and Ethernet physical layer for encoding the frames for transmission over a wavelength

Towards a two Layer Network Architecture



A perfect combination

Flexibility

Capacity

Future protocol stacks

Less latency

Higher bandwidth utilization