University of Arizona
ECE 430/530: Optical Communication Systems
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Introduction to Fiber-Optics Communications

INTRODUCTION TO FIBER-OPTICS COMMUNICATIONS

- Optical communication systems are evolving quickly to adapt to the ever-increasing demands of telecommunication needs, mostly noticeably witnessed by the explosive growth in transmission capacity demands.
- The optical networking technology has become closely related to the Internet technology, and has the same ultimate goal: to satisfy high demands for high bandwidth and distance independent connectivity.

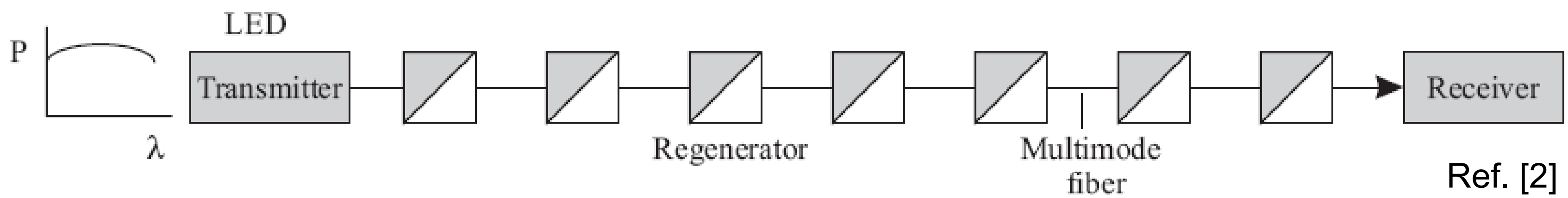
Historical perspective

- The earliest optical communications systems consisted of fire or **smoke signals**, **signaling lamps**, and **semaphore flags** to convey a single piece of information. Relay or regeneration systems were proposed by Claude Chappe in 1792 to transmit coded messages over distance of 100 km.

- In the 1830's electrical communication came into being with the use of **Morse Code keying** techniques. In *1866 the first transatlantic cable* was laid.
- In 1876 the **telephone** was invented that primarily used analog signals.
- **Coaxial cable** used in place of wire pairs greatly increased system capacity. The first coax cable was placed in service in 1940 was a 3 MHz system capable of carrying 300 voice channels or one television channel. This type of transmission medium is limited by frequency dependent cable losses that increase rapidly with frequencies above 10 MHz.
- **Microwave systems** extended the carrier frequency to about 4GHz and systems of this type were first placed into service in 1948.
- The carrier frequency and attenuation limit the performance of both microwave and coax systems.
- A common figure of merit for transmission systems of this type is the bit rate-distance product (B-L). The large improvement offered by the high carrier frequency of optical transmission fibers is the motivation for optical communications system development.
- During the 1960's the main drawback of optical fibers were their loss. During the 1960's the loss was ~ 1000 dB/km.
- In 1970 losses were reduced to 20 dB/km by using refined fiber fabrication techniques. At about the same time GaAs semiconductor lasers were able to operate at room temperature. This combination of developments led to development of a world-wide fiber optic systems.

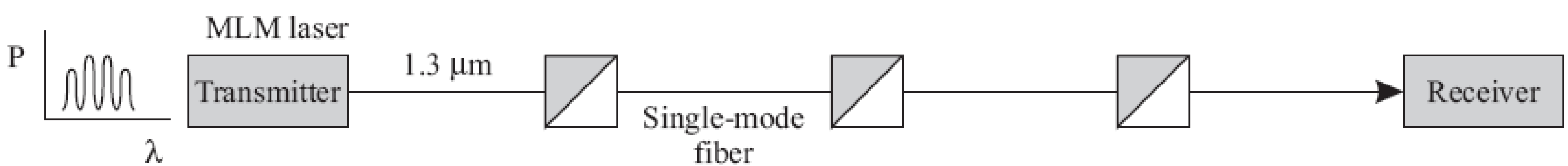
Optical Networks Evolution

- ***First Generation*** – 1980 operating at 0.8 μm wavelength and 45 Mb/s data rate. Repeater spacing was 10 km and was much greater than for comparable coax systems. Lower installation and maintenance costs resulted from fewer repeaters.



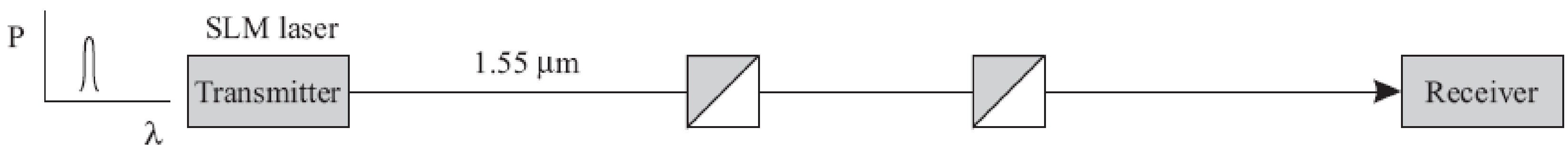
Ref. [2]

- ***Second Generation*** – Deployed during the early 80's. This generation was focused on using a transmission wavelength near 1.3 μm to take advantage of the low attenuation (< 1 dB/km) and low dispersion. Sources and detectors were developed that use InGaAsP semiconductor sources and detectors. The bit rate of these systems were limited to <100Mb/s due to dispersion in multi mode fibers. *Single mode fiber* was then incorporated. In 1981 a demonstration system was capable of transmitting 2Gb/s signals over 44 km of fiber without a repeater. By 1987 second generation systems were operating at 1.7 Gb/s at 1.3 μm with repeater spacing of 50 km.



Ref. [2]

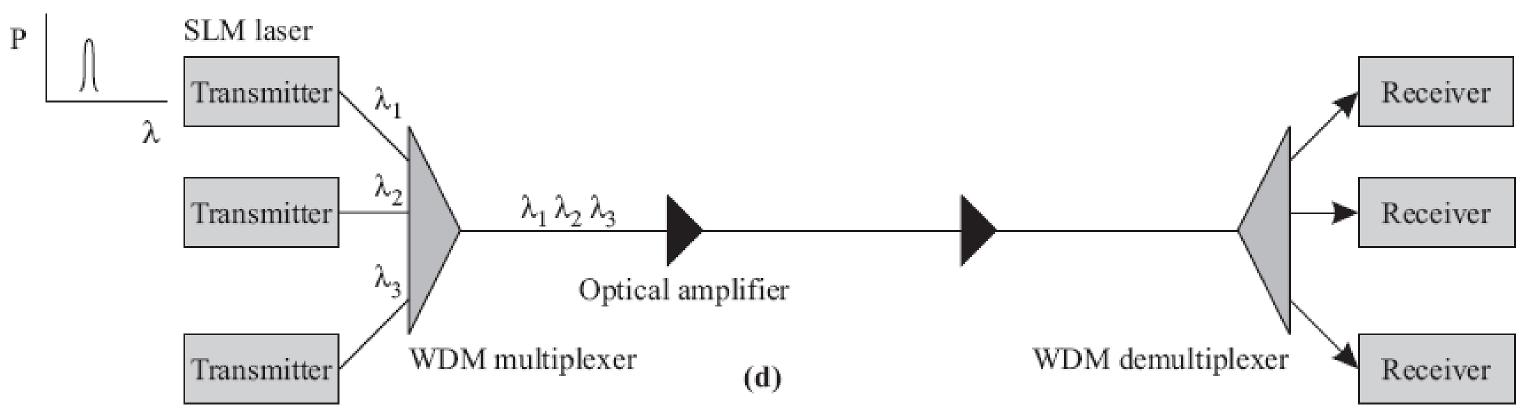
- ***Third Generation*** – these systems were based on the use of *1.55μm sources and detectors*. At this wavelength the attenuation of fused silica fiber is minimal. The deployment of these systems was delayed however due to the relatively large dispersion at this wavelength. Two approaches were taken to solve the dispersion problem. The first approach was to develop single mode lasers (SLM) and the second was to develop dispersion shifted fiber at 1.55 μm.



Ref. [2]

- In 1990 1.55 μm systems operating at 2.5 Gb/s were commercially available and were capable of operating at 10 Gb/s for distances of 100 km. Best performance was achieved with dispersion shifted fibers in conjunction with single mode lasers. A *drawback* of these systems was the need for *electronic regeneration with repeaters* typically spaced every 60-70 km. Coherent detection methods were investigated to increase receiver sensitivity however this approach was superceded by the development of the optical amplifier.

- ***Fourth Generation*** – These systems are based on the use of *optical amplifiers* to increase repeater spacing and *wavelength division multiplexing* (WDM) to increase aggregate bit rate. Erbium doped fiber amplifiers were developed to amplify signals without electronic regeneration during the 1980's. In 1991 signals could be transmitted 14,300 km at 5 Gb/s without electronic regeneration. The first transpacific commercial system went into operation sending signals over 11,300 km at 5 Gb/s and other systems are being deployed. System capacity is increased through use of WDM. Multiple wavelengths can be amplified with the same optical amplifier. In 1996 20 5 Gb/s signals were transmitted over 9100 km providing a total bit rate of 100 Gb/s and a B-L product of 910 (Tb/s)-km. In these broad band systems dispersion becomes more of an issue.

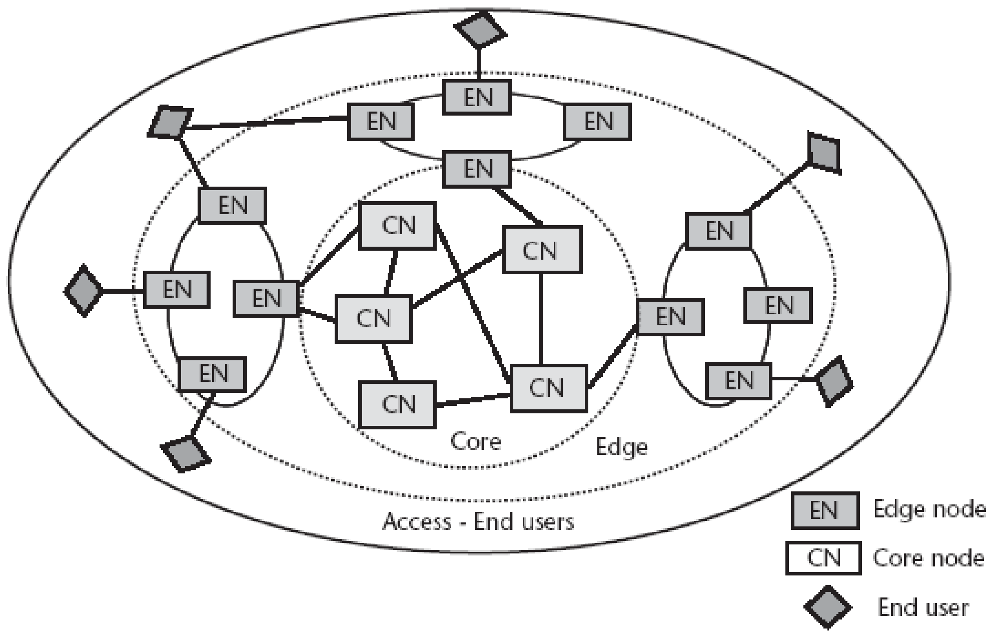


Ref. [2]

- ***Fifth Generation*** – This effort is primarily concerned with the fiber dispersion problem. Optical amplifiers solve the loss problem but increase the dispersion problem since dispersion effects accumulate over multiple amplification stages. An ultimate solution is based on the novel concept of *optical solitons.* These are pulses that preserve their shape during propagation in a loss less fiber by counteracting the effect of dispersion through fiber nonlinearity. Experiments using stimulated Raman scattering as the nonlinearity to compensate for both loss and dispersion were effective in transmitting signals over 4000 km. EDFAs were first used to amplify solitons in 1989. By 1994 a demonstration of soliton transmission over 9400 km was performed at a bit rate of 70 Gb/s by multiplexing 7, 10 Gb/s channels.
- ***Sixth Generation***- Recently efforts have been directed toward realizing greater capacity of fiber systems by multiplexing a large number of wavelengths. These systems are referred to as dense wavelength division multiplexing (DWDM) systems. Systems with wavelength separation of 0.8 nm are currently in operation and efforts are pushing to reduce this to < 0.5 nm. Controlling wavelength stability and the development of wavelength demultiplexing devices are critical to this effort. Systems are currently operating at either 10 Gb/s or 40 Gb/s.
- ***Future Systems –*** Most probably polarization-multiplexed QPSK systems with 100 Gb/s per wavelength will become reality soon. The research effort will focus on 400 Gb/s serial transmission and then on 1 Tb/s per wavelength optical transport.

Optical networking architecture

- In terms of ownership, networks and transmission systems can belong either to *private enterprises* or be owned by *telecommunication carriers*.
- Ownership can be related to networking equipment and infrastructure associated to with a specified network topology or to a logical entity, known as the optical virtual private network, within the physical network topology.
- Typical optical networking structure can be represented by three concentric “circles”.



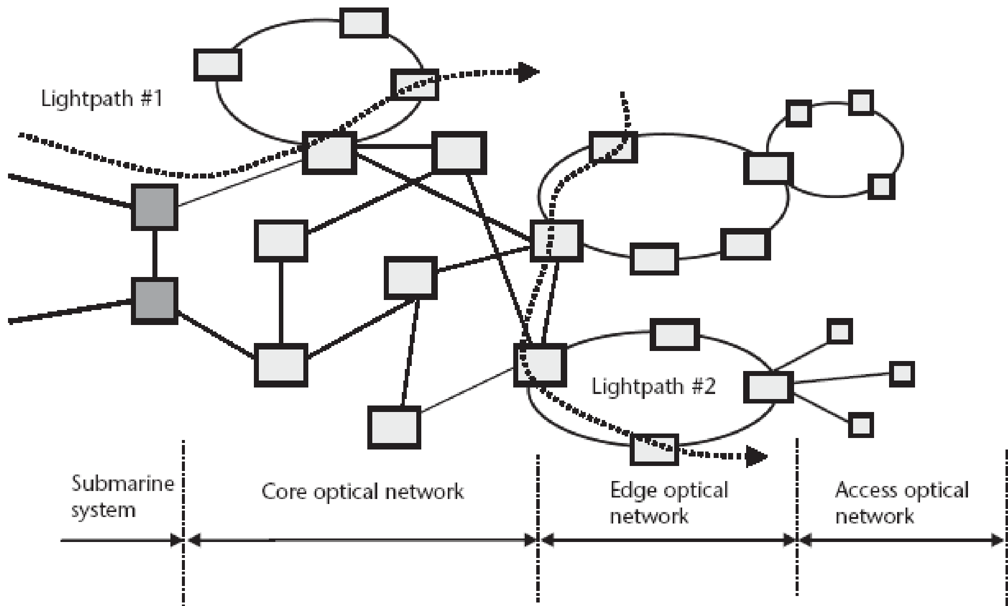
Ref. [3]

- *Core network*: wide area network (WAN) or interchange carrier (IXC)
- *Edge network*: metropolitan network (MAN) or local exchange carrier (LEC)
- *Access network*: LAN and a distribution network (connects the central office location of a carrier with individual users)

- The *physical networking topologies*:
  - Mesh (in the core and edge networks)
  - Ring (deployed in all portions of a global network)
  - Star (deployed mostly in an access network)
- From the optical transmission engineering perspective, the optical network configuration is just a mean to support an end-to-end connection via the *lightwave path*.

Lightwave signal path

- *Lightwave path*: the trace that optical signal passes between the source and destination without experiencing any opto-electrical-opto (O-E-O) conversion.
- In general, the lightwave paths differ in lengths and in the information capacity that is carried along.



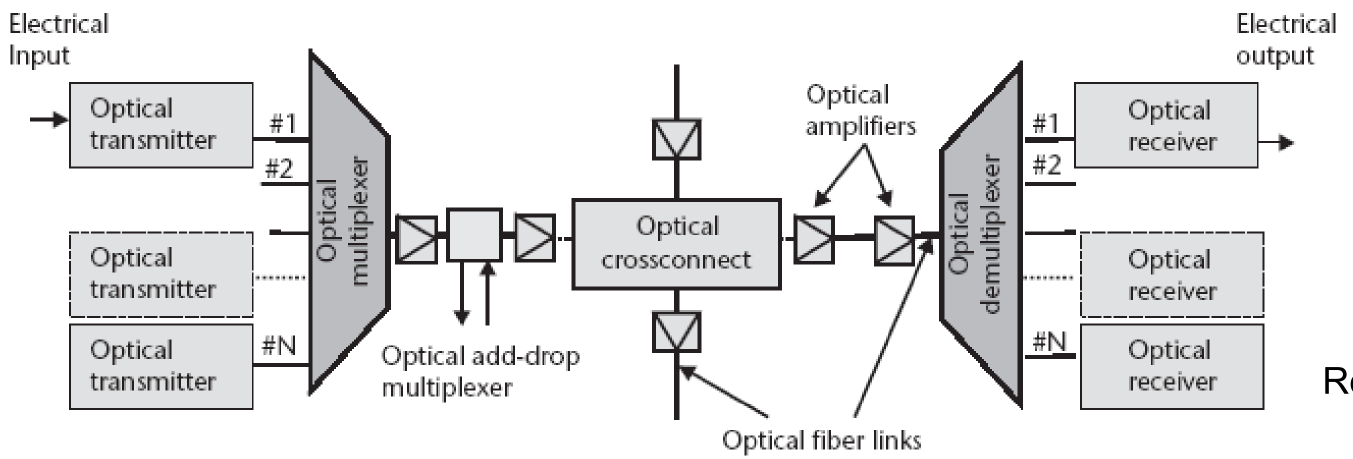
Ref. [3]

- The lightwave path can be considered as bandwidth wrapper for lower speed transmission channels, which form virtual circuit services.
- In such cases the time division multiplexing (TDM) technique is applied to aggregate the bandwidth of virtual circuits before it is wrapped in the lightwave path.
- Multiplexing of virtual circuits:
  – Fixed multiplexing (each circuits receives a guaranteed amount of the bandwidth-*a bandwidth pipe*)
  – Statistical multiplexing (in packet-switching the data content is divided into data packets, which can be handled independently)
- The fixed multiplexing of virtual circuits is defined by SONET/SDH standards.
- Bit-rates of different bandwidth channels:

TDM/Synchronous Bandwidth Channels	*Bit-rate*	*Data/Asynchronous Bandwidth channels*	*Bit-rate*
DS-1	1.544 Mb/s	10-BaseT Ethernet	10 Mb/s
E-1	2.048 Mb/s	100-BaseT Ethernet	100 Mb/s
OC-1	51.84 Mb/s	FDDI	100 Mb/s
OC-3=STM-1	155.52 Mb/s	ESCON	200 Mb/s
		Fiber Channel-I	200 Mb/s
OC-12=STM-4	602.08 Mb/s	Fiber Channel-II	400 Mb/s
		Fiber Channel-III	800 Mb/s
OC-48=STM-16	2.488 Gb/s	Gb Ethernet	1 Gb/s
OC-192=STM-64	9.953 Gb/s	10Gb Ethernet	10 Gb/s
OC-768=STM-256	39.813 Gb/s	40Gb Ethernet	40 Gb/s

Optical transmission systems

- The simplest optical transmission system is a point-to-point connection that utilizes a single optical wavelength, which propagates through an optical fiber.
- The upgrade of this topology is deployment of the wavelength division multiplexing (WDM) technology, where multiple optical wavelengths are combined to travel over the same physical route.



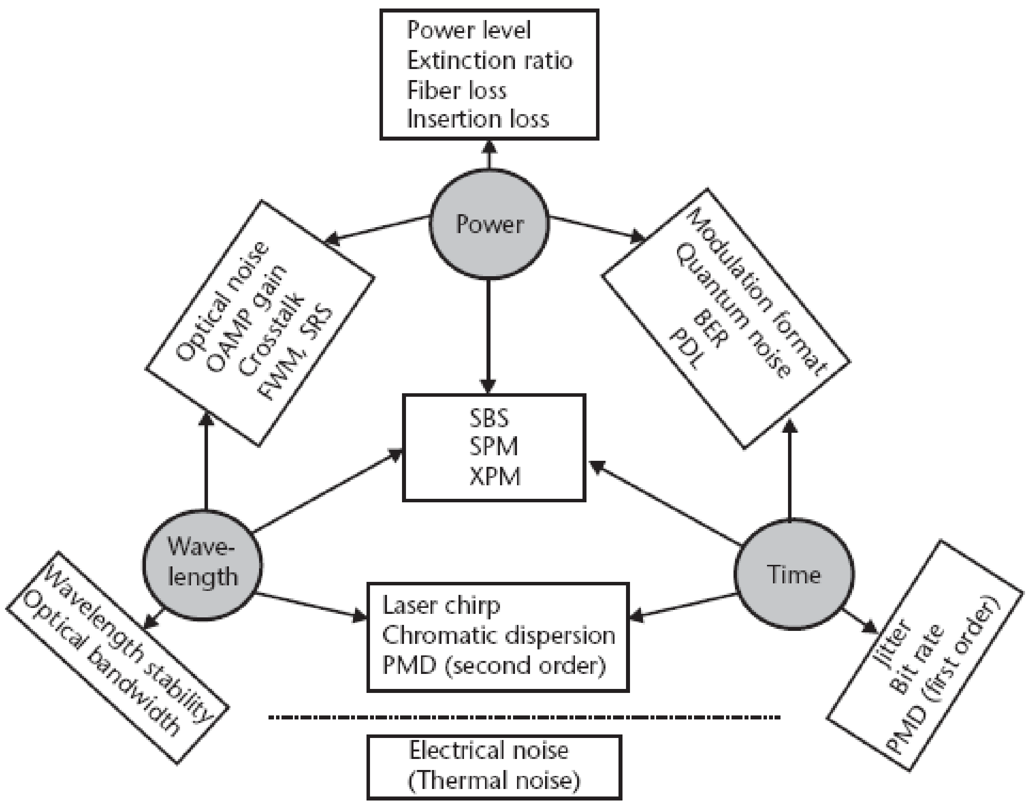
Ref. [3]

Classification of optical transmission systems

- *Transmission length*: very short reach (hundreds of meters), short reach (several kilometers), long reach (tens and hundreds of kilometers), ultra-long reach (thousands of kilometers)
- *Bit rate*: low-speeds (tens of MB/s), medium-speed (hundreds MB/s), high-speed (Gb/s)
- *Application perspective*: power budget limited (loss limited) and bandwidth (transmission speed) limited

Major parameters related to optical transmission

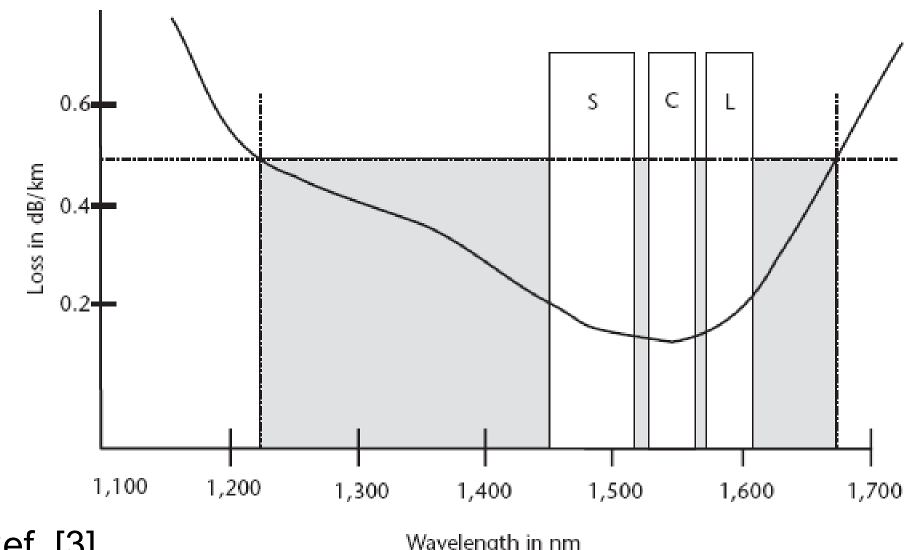
- The ultimate goal of optical signal transmission is usually defined as achieving the pre-specified bit error rate (BER) between two end users or between two intermediate points.
- Optical transmission system needs to be properly engineered in order to provide stable and reliable operation during its lifetime, which includes the management of key engineering parameters.



Ref. [3]

Optical fiber bandwidth

- Optical fiber is the central point of an optical signal transmission.
- It offers wider available bandwidth, lower signal attenuation, and smaller signal distortions compared to other wired physical media.
- The total bandwidth is approximately 400 nm, or around 50 THz, if it is related to the wavelength region with fiber attenuation bellow 0.5 dB/km.
- The usable optical bandwidth is commonly split into several wavelength bands.
- The bands around the minimum attenuation point, usually referred to as C and L bands, are the most suitable for high channel count DWDM transmission.
- The wavelength region around 1300 nm is less favorable for optical signal transmission because signal attenuation is higher than attenuation in S, C, and L bands. On the other hand it is quite usable for CATV signals, and CWDM technique can easily be employed.



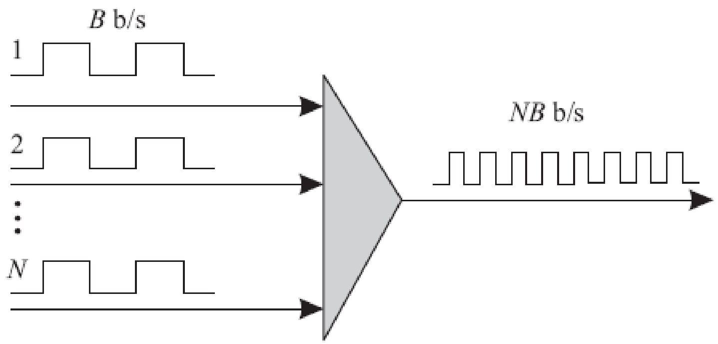
Ref. [3]

Band	Descriptor	Wavelength range (nm)
O-band	Original	1260 to 1360
E-band	Extended	1360 to 1460
S-band	Short	1460 to 1530
C-band	Conventional	1530 to 1565
L-band	Long	1565 to 1625
U-band	Ultra-long	1625 to 1675

Ref. [2]

Multiplexing Techniques

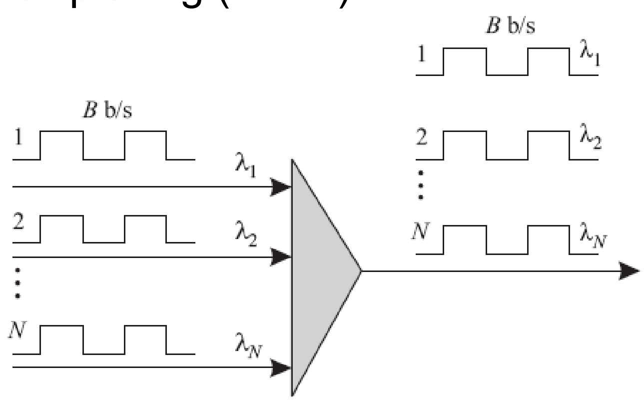
- Time-division multiplexing (TDM) or optical TDM (OTDM):



TDM or OTDM mux

Ref. [2]

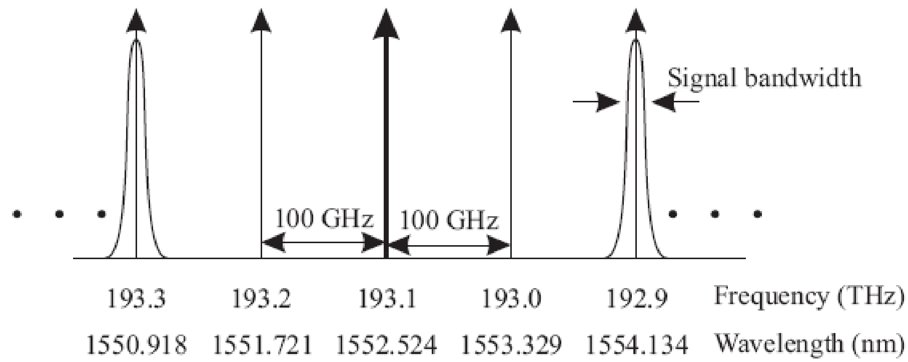
- Wavelength division multiplexing (WDM):



Ref. [2]

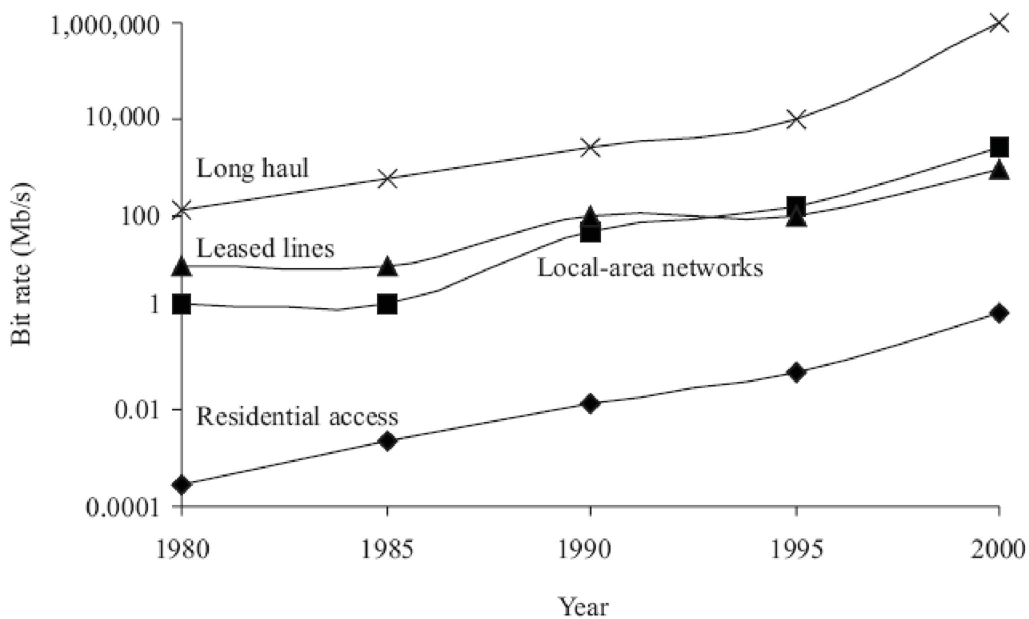
- Other multiplexing techniques:
  – Code division multiplexing (CDM)
  – Sub-carrier multiplexing (SCM)

100 GHz ITU Frequency grid



Ref. [2]

Bandwidth growth



Ref. [2]

Modulation Techniques

- A monochromatic electromagnetic wave, which is used as a signal carrier, can be represented through its electric field:

$$\boldsymbol{E}(t) = \boldsymbol{p}A\cos(\omega t + \varphi)$$

$A -$ the wave amplitude

$\omega -$ the frequency

$\varphi -$ the phase

$\boldsymbol{p} -$ the polarization orientation

- Each of this parameters can be utilized to carry information:
  - Amplitude modulation (AM)/Amplitude shift keying (ASK)
  - Frequency modulation (FM)/Frequency shift keying (FSK)
  - Phase modulation (PM)/Phase shift keying (PSK)
  - Polarization modulation (PoM)/Polarization shift keying (PolSK)
- The power of an optical signal is proportional to the square of its electric field amplitude. The *intensity modulation* can be performed if the power of optical signal is changed in accordance with the modulation signal. The modulation is referred to *on-off keying* (OOK) if information signal is in digital form. The OOK scheme is commonly used in practice.

KEY OPTICAL COMPONENTS

- Semiconductor Light Sources
  - Light-emitting diodes (LEDs)
  - Semiconductor lasers: Fabry-Perrot, distributed feedback (DFB), distributed Bragg reflector (DBR), vertical cavity surface emitting (VCSEL), tunable lasers (external cavity laser, mutilaser chip, three-section tunable)
- Optical Modulators
  - Direct optical modulation
  - External modulation: Mach-Zehnder modulator, Electro-absorption modulator
- Optical Fibers
  - Multimode
  - Single-mode
- Optical Amplifiers
  - SOA, EDFA, Raman amplifiers
  - Applications: boost amplifiers, in-line amplifiers, preamplifiers
- Photodiodes: PIN, APD, MSM photodetectors
- Optical components
  - Optical isolators, optical circulators, and optical filters
  - Optical couplers, optical switches, and optical multiplexers/demultiplexers

Signal Impairments

Fiber loss:
- Material absorption
  - intrinsic (ultraviolet, infrared),
  - extrinsic (water vapor, Fe, Cu, Co, Ni, Mn, Cr, dopants: GeO_2, P_2O_5, B_2O_3)
- Rayleigh scattering and
- Waveguide imperfections (Mie scattering, bending losses, etc.)

Insertion loss

Dispersion:
- Intermodal (multimode)
- Chromatic:
  - -material
  - -waveguide
- PMD, PDL

Fiber nonlinearities:
- Scattering effects (SBS, SRS)
- Kerr nonlinearities (SPM, XPM, FWM)

Noise

- Transmitter: Laser intensity noise, mode partition noise, laser phase noise
- Optical cable (fiber and splicing): modal noise, reflection-induced noise
- Optical amplifier # 1: spontaneous emission
- Optical amplifier # 2: amplified spontaneous emission (ASE)
- Optical receiver (photodiode): thermal noise, quantum noise

ENABLING TECHNOLOGIES

- Related to the components:
  - Amplifiers
  - Compensators
  - Modulators
- Related to the method:
  - Advanced modulation formats
  - Constrained (modulation or line) coding
  - Advanced detection schemes (MLSD, BCJR, coherent detection, …)
  - Forward error correction (RS codes, concatenated RS codes, turbo-product, and LDPC codes)

References

1. G. P. Agrawal, *Fiber-Optic Communication Systems*, Third Ed., John Wiley & Sons, Inc., 2002.
2. R. Ramaswami and K. Sivarajan, *Optical Networks: A Practical Perspective*, Second Ed., Morgan Kaufman, 2002.
3. M. Cvijetic, *Optical Transmission Systems Engineering*, Artech House, Inc., 2004.