PHOTONIC COMMUNICATIONS

Photonic networking (10a)

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- **Optics** is an old subject involving the generation, propagation & detection of light.
- Three major developments are responsible for rejuvenation of optics & its application in modern technology:

  1- Invention of Laser

  2- Fabrication of low-loss Optical Fiber - OF

  3- Development of Semiconductor Optical Devices

- As a result, new disciplines have emerged & new terms describing them have come into use, such as:
- **Electro-Optics:** is generally reserved for optical devices in which electrical effects play a role, such as lasers, electro-optic modulators & switches.

- **Optoelectronics:** refers to devices & systems that are essentially electronics but involve lights, such as LED, liquid crystal displays & array photodetectors.
- **Quantum Electronics**: is used in connection with devices & systems that rely on the interaction of light with matter, such as lasers & nonlinear optical devices.
- **Quantum Optics**: Studies quantum & coherence properties of light.
- **Lightwave Technology**: describes systems & devices that are used in optical communication & signal processing.
- **Photonics**: in analogy with electronics, involves the control of photons in free space and matter.

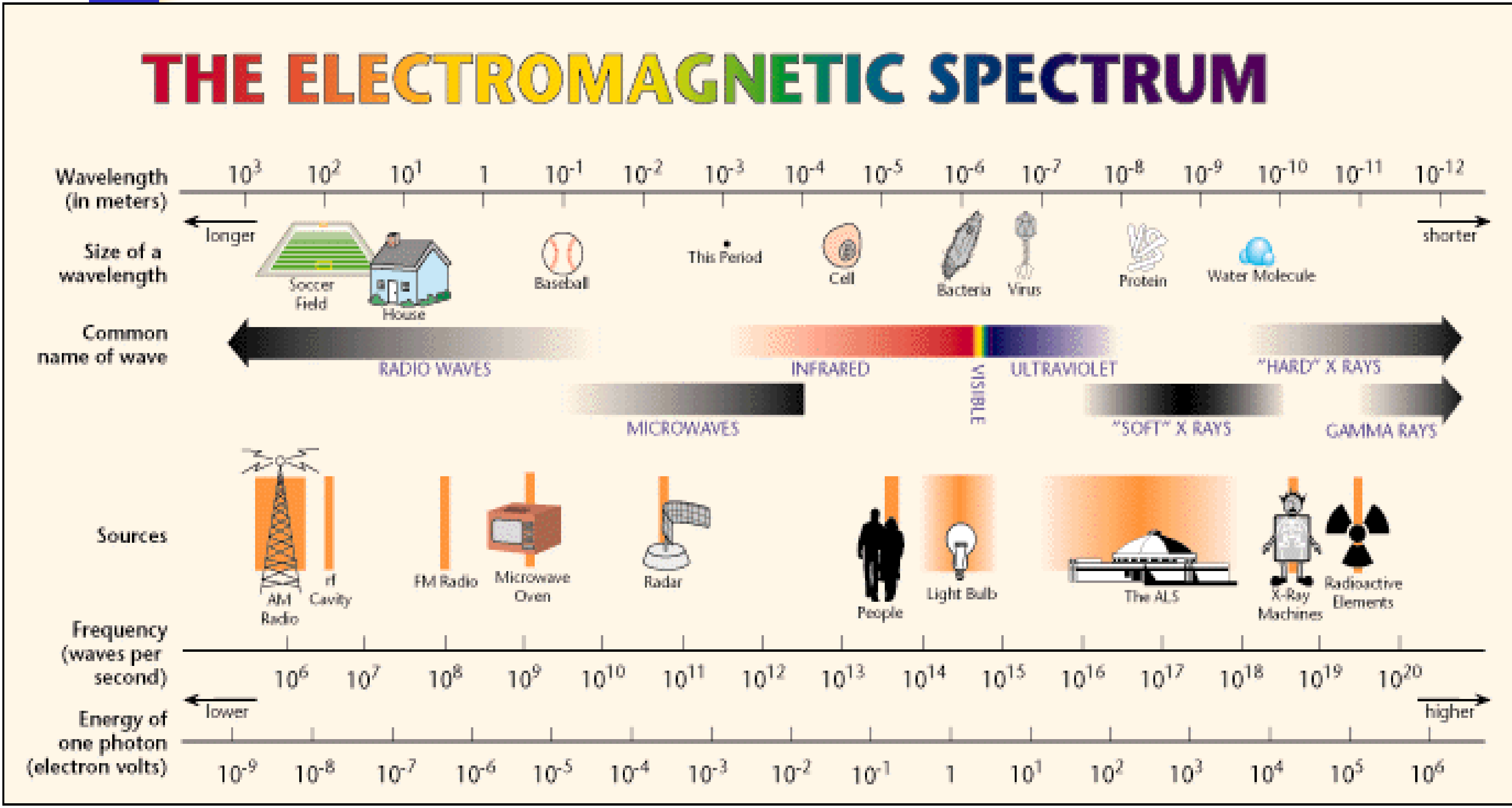
- **Photonics** reflects the importance of the photon nature of light. **Photonics & electronics** clearly overlap since electrons often control the flow of photons & conversely, photons control the flow of electrons.
- **The scope of Photonics**

  1- Generation of Light (Coherent & Incoherent)

  2- Transmission of Light (Through free space **-FSO**, Fibers **-OF**, Imaging systems, Waveguides, …)

  3- Processing of Light Signals (Modulation, Switching, Amplification, Frequency conversion, …)

  4- Detection of Light (Coherent & Incoherent)
- **Photonic Communications:** describes the applications of photonic technology in communication devices & systems, such as transmitters, transmission media, receivers & signal processors, etc.



THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
lower
higher
Energy of one photon (electron volts)
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 1 10^1 10^2 10^3 10^4 10^5 10^6

Photonic Communications Advantages

- **Extremely wide bandwidth- BW:** high carrier frequency (a wavelength of 1552.5 nm corresponds to a center frequency of 193.1 THz!) & consequently orders of magnitude increase in available transmission bandwidth & larger information capacity.
- **OF** have **small size & light weight**.
- **OF** are **immune to electromagnetic interference** (high voltage transmission lines, radar systems, power electronic systems, airborne systems, …)
- **Lack of EMI cross talk** between channels
- Availability of **very low loss OF** (0.25 to 0.3 dB/km), high performance active & passive photonic components such as tunable lasers, very sensitive **PD**, couplers, filters,
- **Low cost systems for high data rates** in excess of several Gbit/s.

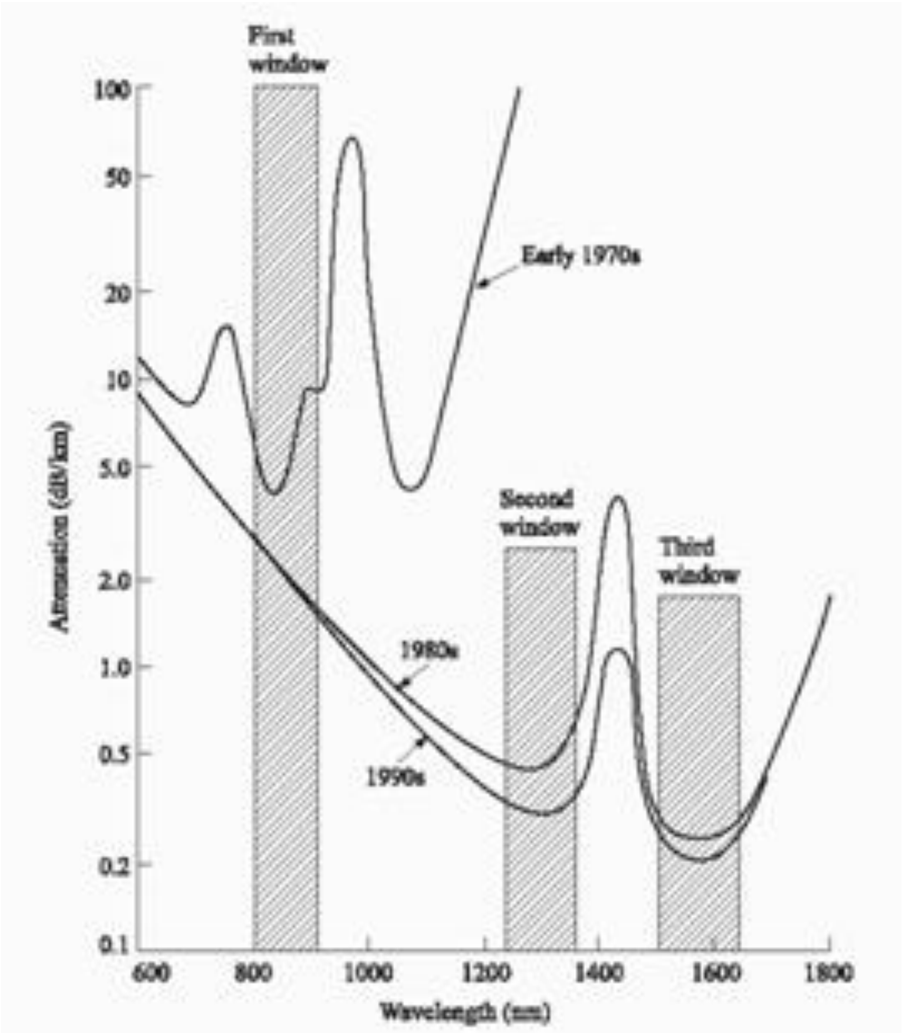
Photonic Communications Advantages

BW demands

Type & applications	Format	Uncompressed	Compressed
Voice, digital telegraphy	4 kHz voice	64 kbps	16-32 kbps
Audio	16-24 kHz	512-748 kbps	32-384 kbps (MPEG, MP3)
Video conferencing	176 144 or 352 288 frames @ 10-30 frames/s	2-35.6 Mbps	64 kbps-1.544 Mbps (H.261 coding)
Data transfer, E-commerce,Video entertainment			1-10 Mbps
Full-motion broadcast video	720 480frames @ 30 frames/s	249 Mbps	2-6Mbps (MPEG-2)
HDTV	1920 1080 frames@ 30 frames /s	1.6 Gbps	19-38 Mbps (MPEG-2)

Evolution of Fiber Optic Systems

- **1950s**: Imaging applications of **OF** in medicine & non-destructive testing, lighting, **FOS**
- **1960s:** Research on lowering the **OF** loss for telecom. applications.
- **1970s**: Development of low loss **OF**, semiconductor light sources **-LD** & **PD** – **PIN**, **APD**
- **1980s: SM OF** (**OC-3** to **OC-48**) over repeater spacings of 40 km.
- **1990s**: Optical amplifiers (e.g. **EDFA**), **WDM** (Wavelength Division Multiplexing) toward **Dense-WDM -DWDM**.



Optical Fiber communications, 3rd ed.,G.Keiser, McGrawHill, 2000

System Design Choices: Photodetector, Optical Source, Fibers

- **Photodetectors:** Compared to APD, PINs are less expensive and more stable with temperature. However PINs have lower sensitivity.
- **Optical Sources**

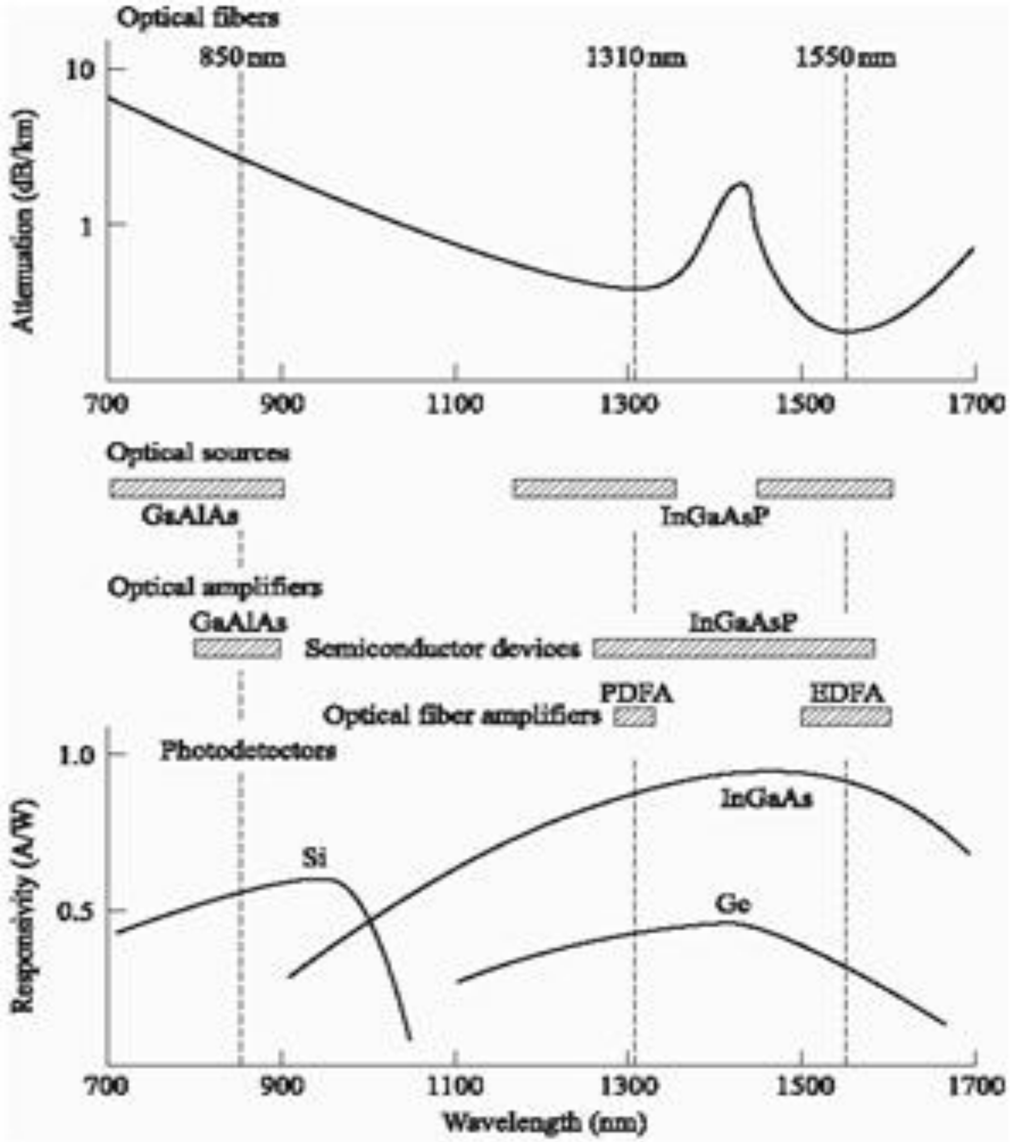
  1- LEDs: 150 (Mb/s).km @ 800-900 nm and larger than 1.5 (Gb/s).km @ 1330 nm

  2- InGaAsP lasers: 25 (Gb/s).km @ 1330 nm and ideally around 500 (Gb/s).km @ 1550 nm. 10-15 dB more power. However more costly and more complex circuitry.
- **Fiber**

  1- Single-mode fibers - SM OF are often used with lasers or edge-emitting LEDs.

  2- Multi-mode fibers – MM OF are normally used with LEDs. NA and should be optimized for any particular application.

Operating of OFs, optical sources, OFAs and PDs in 3 different optical windows



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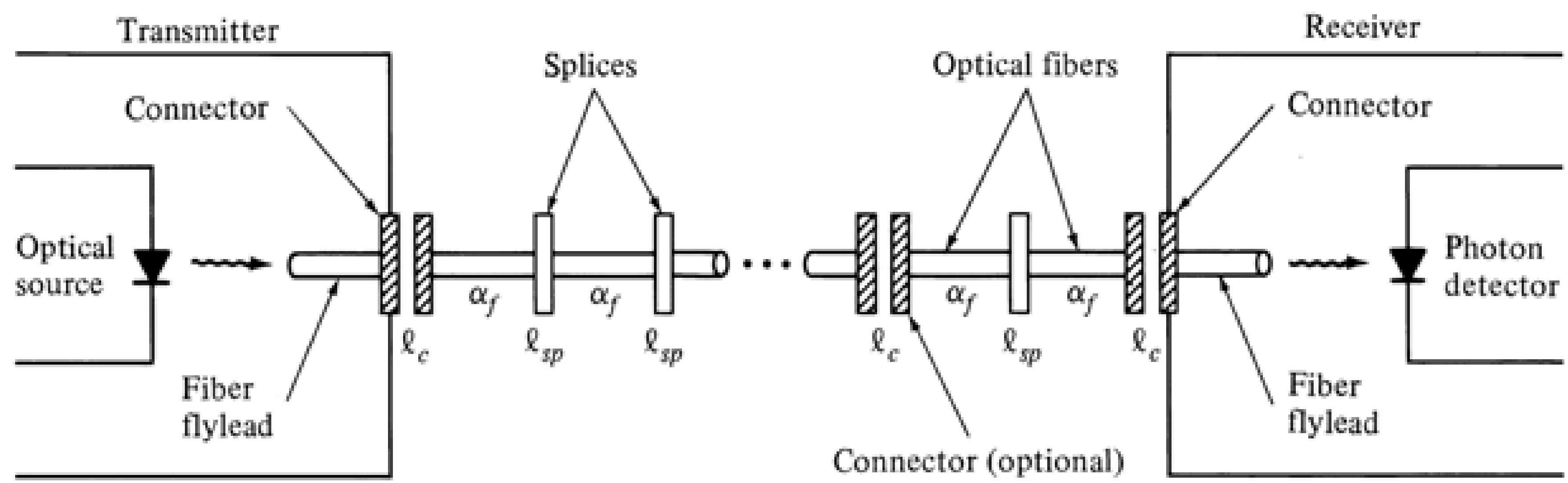
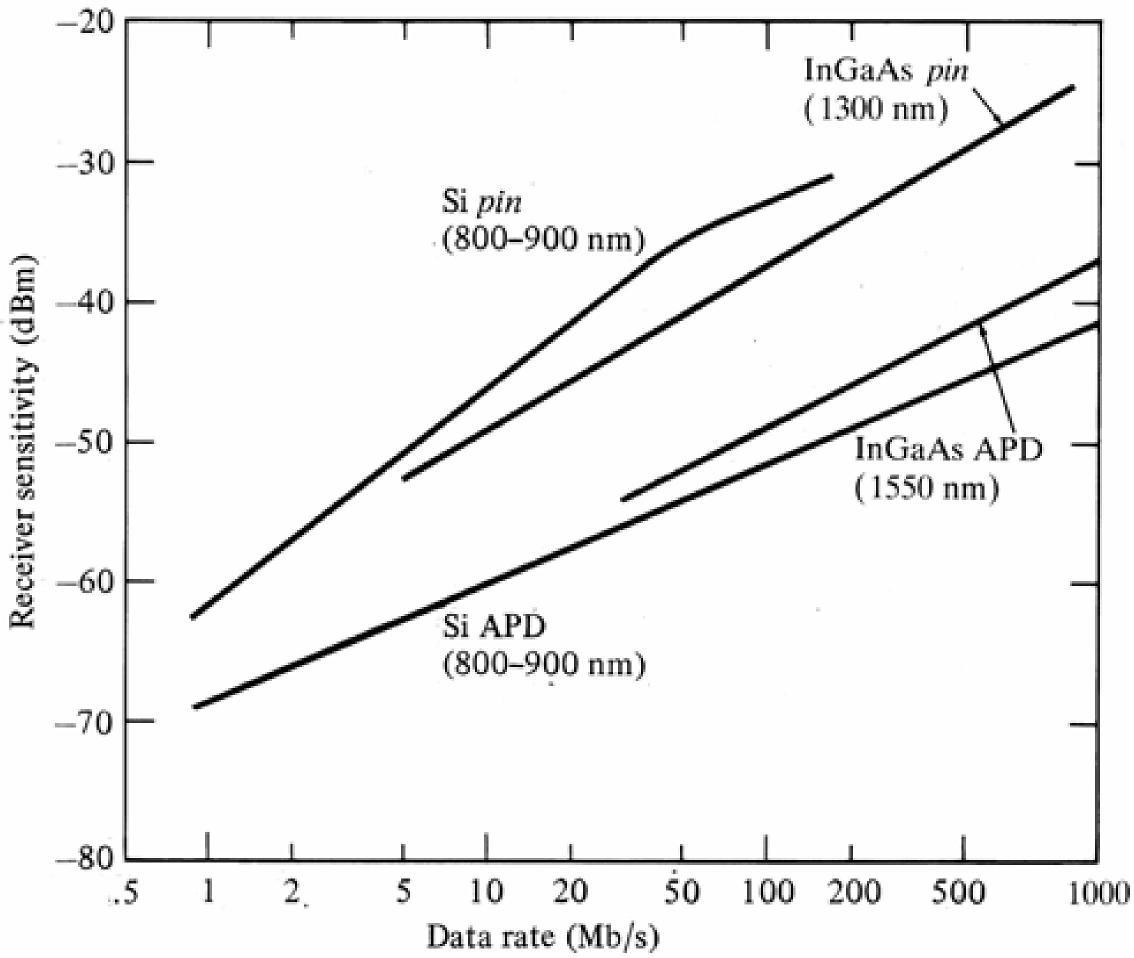
Link Power/Loss Analysis



$$P_T[dB] = P_s[dBm] - P_R[dBm]$$

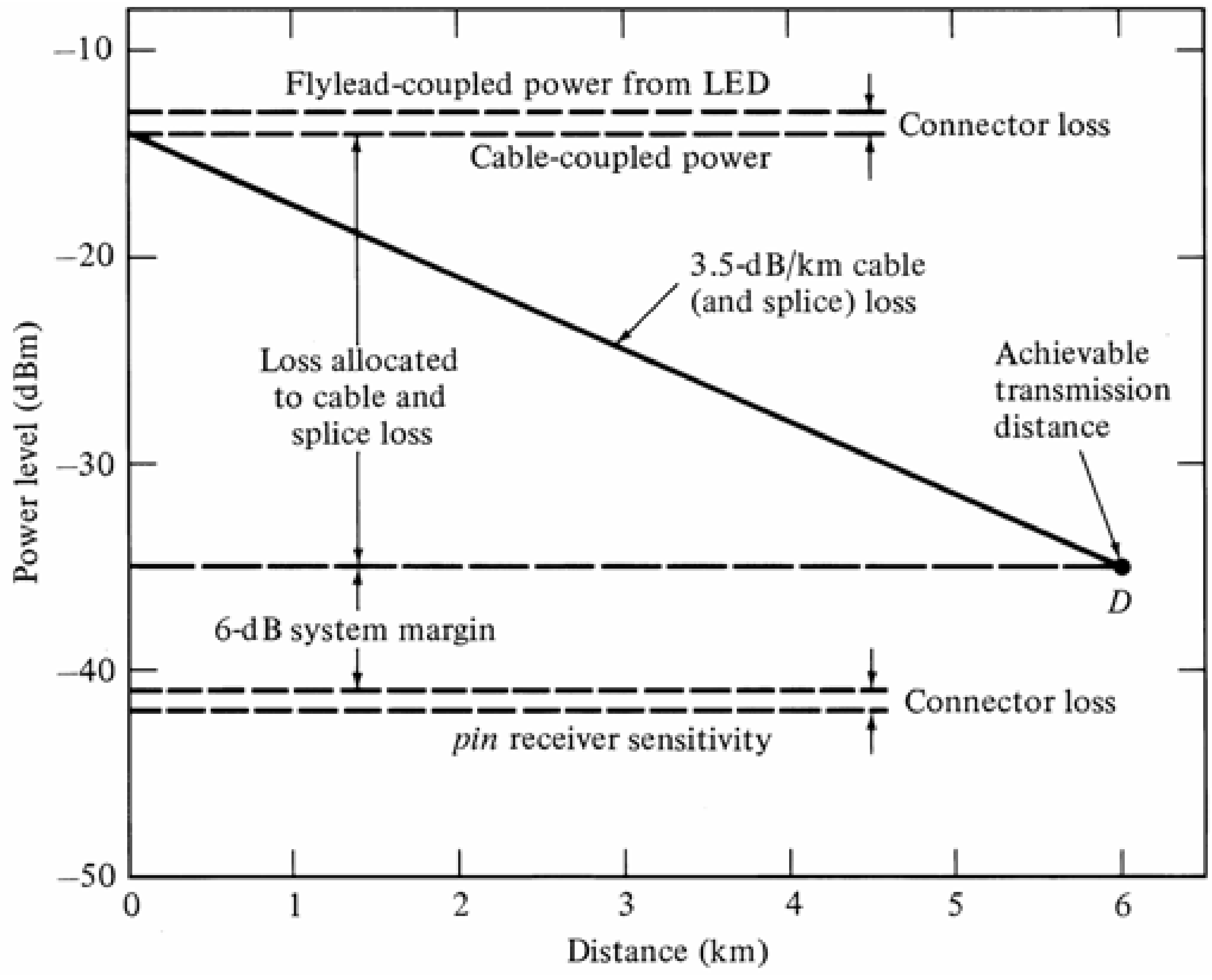
$$P_T = 2l_c[dB] + \alpha_f[dB/km] \times L[km] + \text{System Margin}$$

Receiver Sensitivities vs. Bit Rate



The Si PIN & APD and InGaAsP PIN plots for BER= 10^{-9} .
The InGaAs APD plot is for BER= 10^{-11} .

Link Loss Budget Example 1



Link Power Budget Table Example 2

Example 2:

SONET OC-48

2.5 Gb/s link

Transmitter: 3dBm @ 1550 nm;

Receiver: InGaAs APD with -32 dBm sensitivity @ 2.5 Gb/s;

Fiber: 60 km long with o.3 dB/km attenuation; jumper cable loss 3 dB each, connector loss of 1 dB each.

Component/loss parameter	Output/sensitivity/ loss	Power margin (dB)
Laser output	3 dBm	
APD Sensitivity @ 2.5 Gb/s	-32 dBm	
Allowed loss	3-(-32) dBm	35
Source connector loss	1 dB	34
Jumper+Connector loss	3+1 dB	30
Cable attenuation	18 dB	12
Jumper+Connector loss	3+1 dB	8
Receiver Connector loss	1 dB	7(final margin)

Dispersion Analysis (Rise-Time Budget)

$$t_{sys} = [t_{tx}{}^2 + t_{\mathrm{mod}}{}^2 + t_{GVD}{}^2 + t_{rx}{}^2]^{1/2}$$

$$= \left[t_{tx}{}^2 + \left(\frac{440 L^q}{B_0} \right)^2 + D^2 \sigma_\lambda{}^2 L^2 + \left(\frac{350}{B_{rx}} \right)^2 \right]^{1/2}$$

$t_{tx}[ns]$: transmitter rise time $\quad t_{rx}[ns]$: receiver rise time $\quad t_{\mathrm{mod}}[n]$: modal dispersion

$B_{rx}[MHz]$:3dB Electrical BW $\quad L[km]$:Length of the fiber $\quad B_0[MHz]$:BW of the 1 km of the fiber;

$q \approx 0.7$ $\quad t_{GVD}$[ns]: rise-time due to group velocity dispersion

$D[ns/(km.nm)]$:Dispersion $\quad \sigma_\lambda$[nm]: Spectral width of the source

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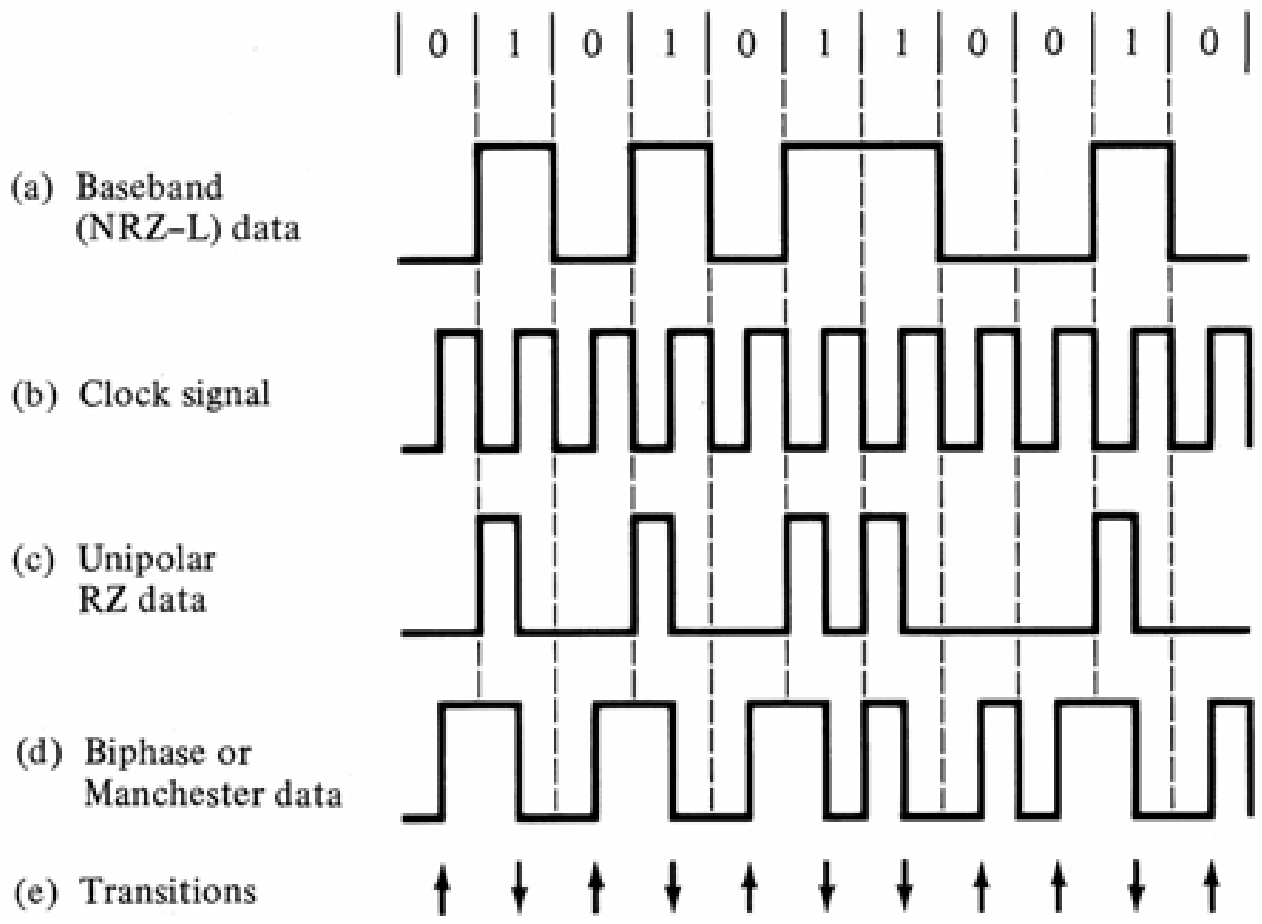
Two-level Binary Channel Codes



System rise-Time & Information Rate

In digital transmission system, the system rise-time limits the bit rate of the system according to the following criteria:

$$t_{sys} < 70\% \text{ of NRZ bit period}$$

$$t_{sys} < 35\% \text{ of RZ bit period}$$

Example

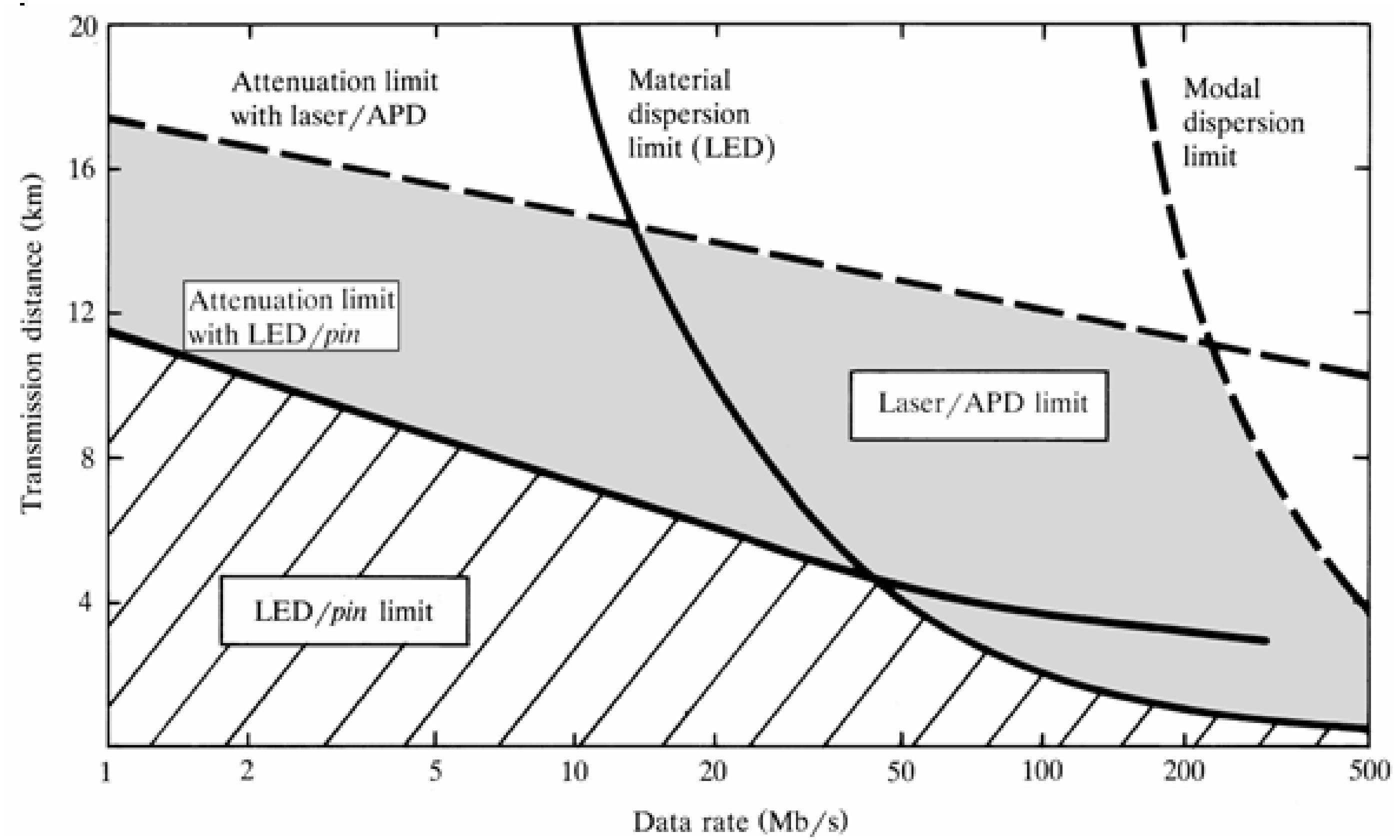
- Laser Tx has a rise-time of 25 ps at 1550 nm and spectral width of 0.1 nm
- Length of fiber is 60 km with dispersion 2 ps/(nm.km)
- The InGaAs APD has a 2.5 GHz BW
- The rise-time budget (required) of the system for NRZ signaling is 0.28 ns whereas the total rise-time due to components is 0.14 ns
- The system is designed for 20 Mb/s

Transmission Distance for MM-OF

Example

- NRZ signaling,
- Source/detector:
  800-900 nm LED/PIN or AlGaAs laser/APD combinations;
- LED output=-13 dBm;
  Fiber loss=3.5 dB/km;
  Fiber bandwidth 800 MHz.km;
  q=0.7; 1-dB connector/coupling loss at each end;
  6 dB system margin,
  Material dispersion ins 0.07 ns/(km.nm);
  Spectral width for LED=50 nm.
- Laser λ=850 nm,
  Spectral width=1 nm;
  Laser ouput=0 dBm,
  Laser system margin=8 dB;

Transmission Distance for MM-OF

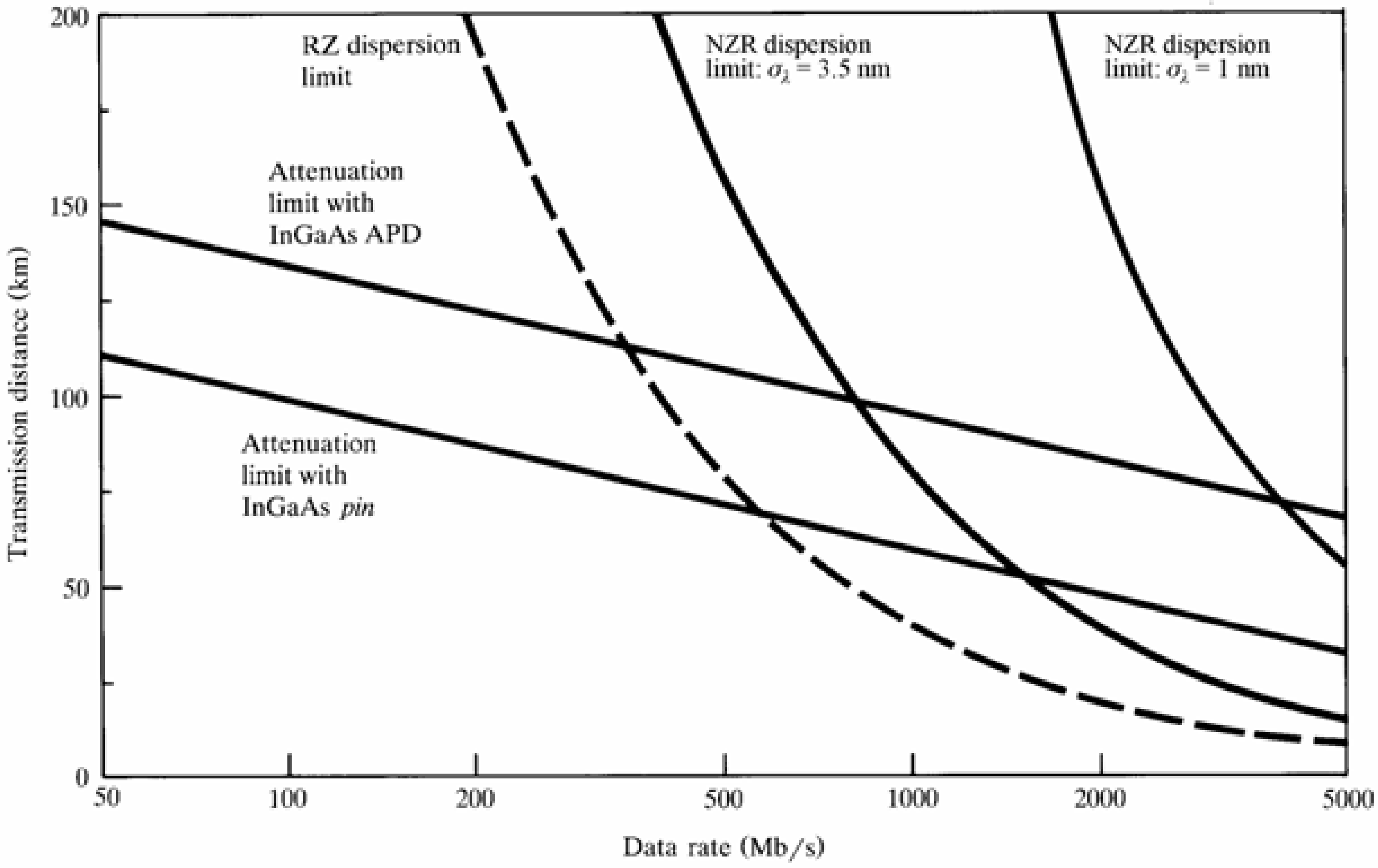


Transmission Distance for a SM OF

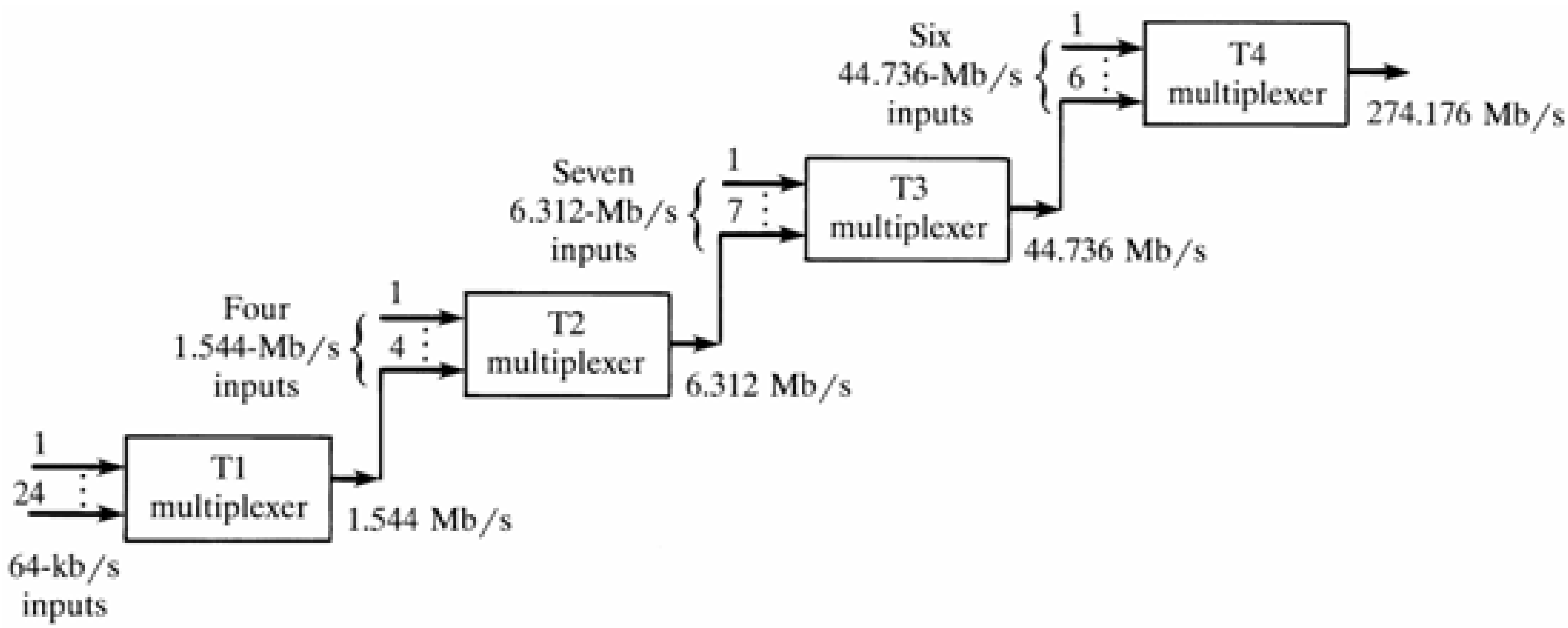
Example

- Communication at 1550 nm;
  no modal dispersion;
- Source: Laser;
- Receiver: InGaAs-APD (11.5 log *B* -71.0 dBm);
  PIN (11.5log *B*-60.5 dBm);
- Fiber loss =0.3 dB/km;
  D=2.5 ps/(km.nm);
- Laser spectral width 1 and 3.5 nm;
- Laser output 0 dBm;
- Laser system margin=8 dB;

Transmission Distance for a SM OF



- Digital link consisting of **Time-Division-Multiplexing (TDM)** of 64 kbps voice channels (early 1980).



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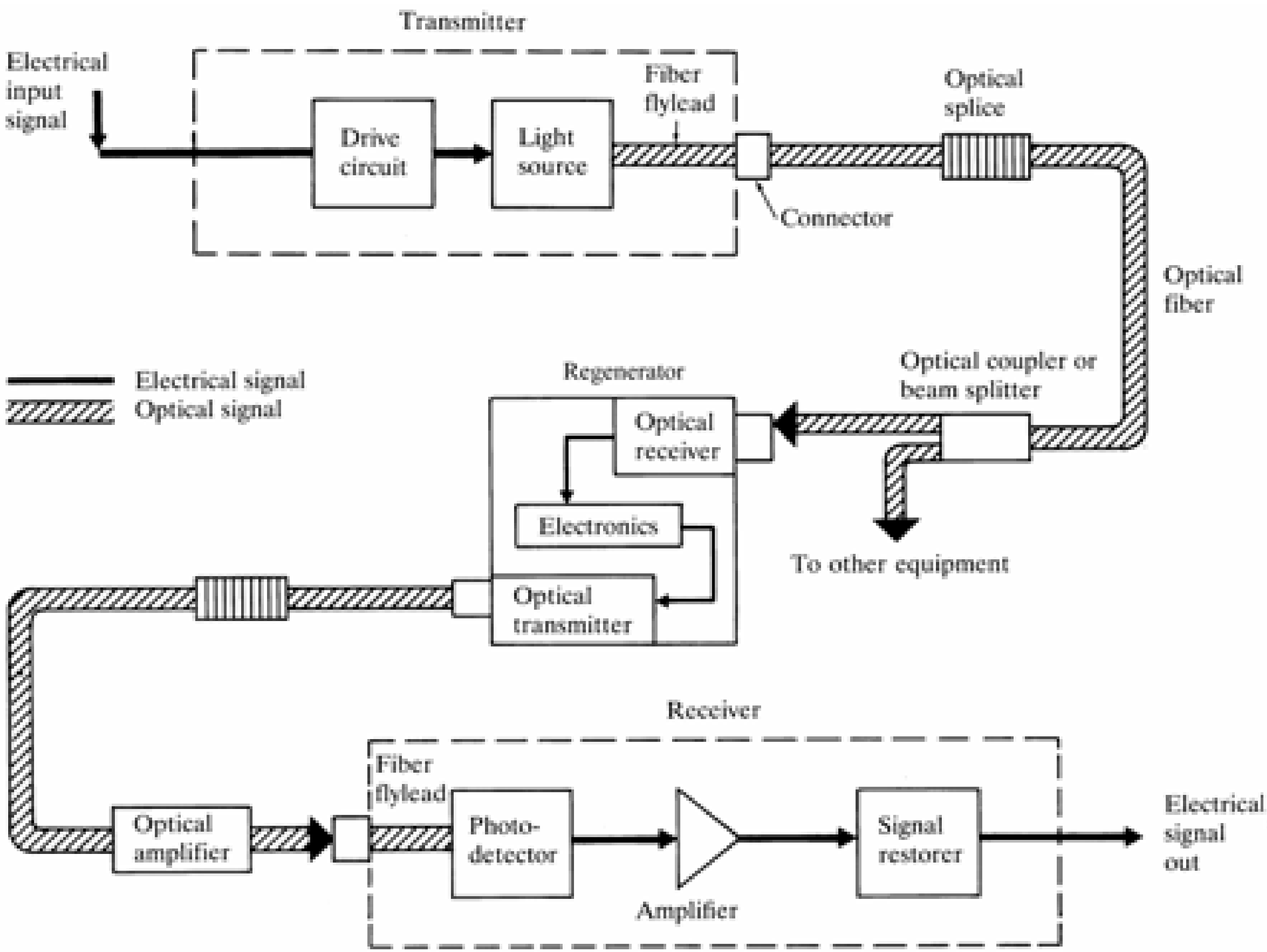
SONET & SDH Standards

- **SONET (Synchronous Optical NETwork)** is the network standard used in north America & **SDH (Synchronous Digital Hierarchy)** is used in other parts of the world. These define a synchronous frame structure for sending multiplexed digital traffic over **OF** trunk lines.
- The basic building block of **SONET** is called **STS-1** (**Synchronous Transport Signal**) with 51.84 Mbps data rate. Higher-rate **SONET** signals are obtained by byte-interleaving *N* **STS-1** frames, which are scramble & converted to an **Optical Carrier Level *N* (OC-N)** signal.
- 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.

SONET & SDH Transmission Rates

SONET level	Electrical level	Line rate (Mb/s)	SDH equivalent
OC-1	STS-1	51.84	-
OC-3	STS-3	155.52	STM-1
OC-12	STS-12	622.08	STM-4
OC-24	STS-24	1244.16	STM-8
OC-48	STS-48	2488.32	STM-16
OC-96	STS-96	4976.64	STM-32
OC-192	STS-192	9953.28	STM-64

Typical Components of a Photonic Communication Link



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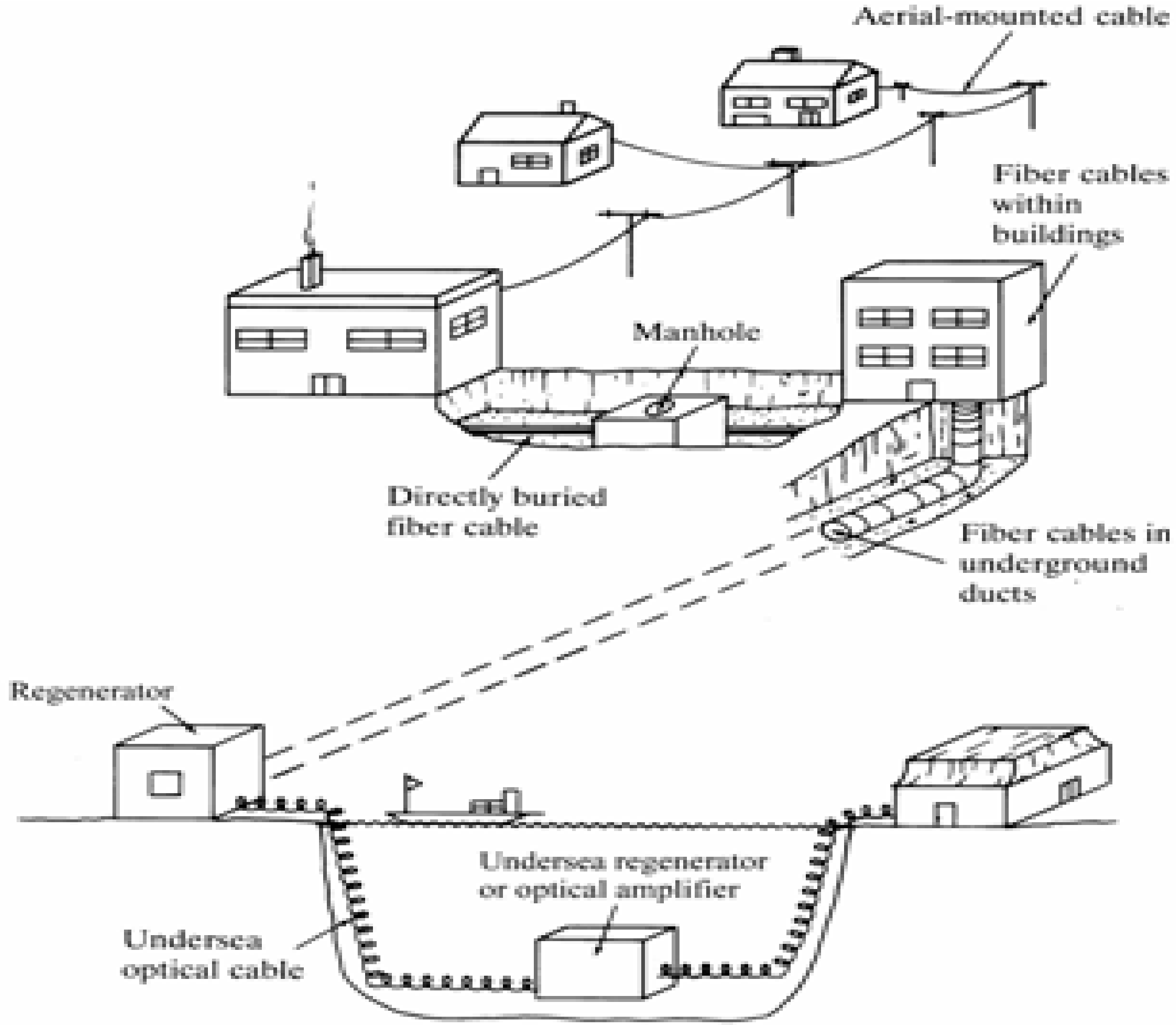
Photonic Communication Link Installation



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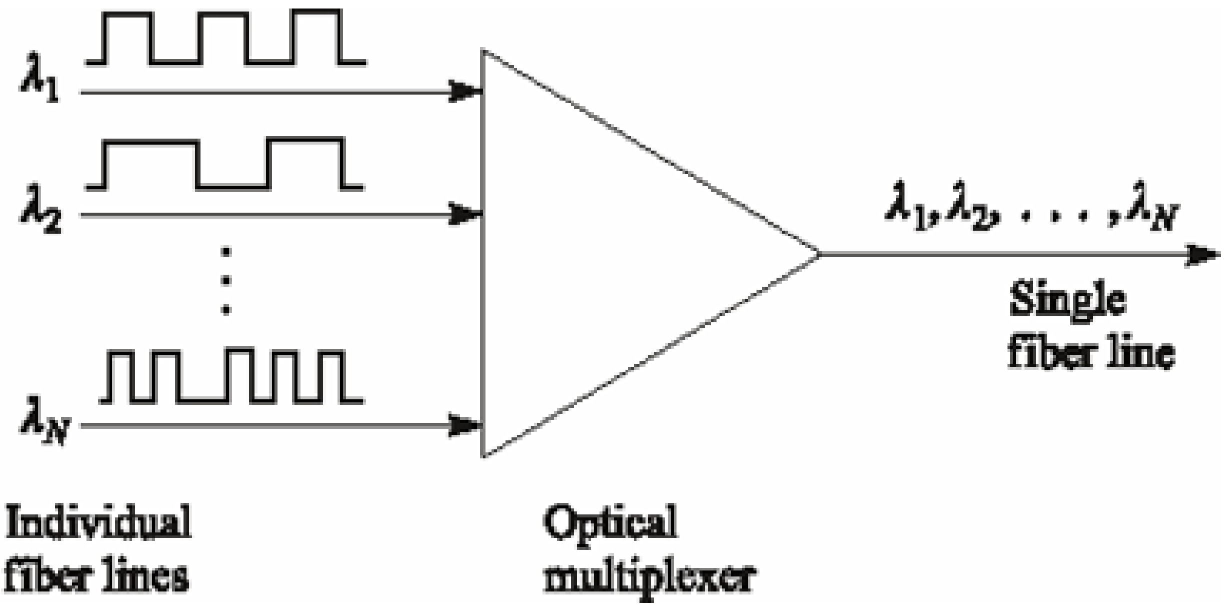
WDM Concept



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SONET/SDH Network Concept

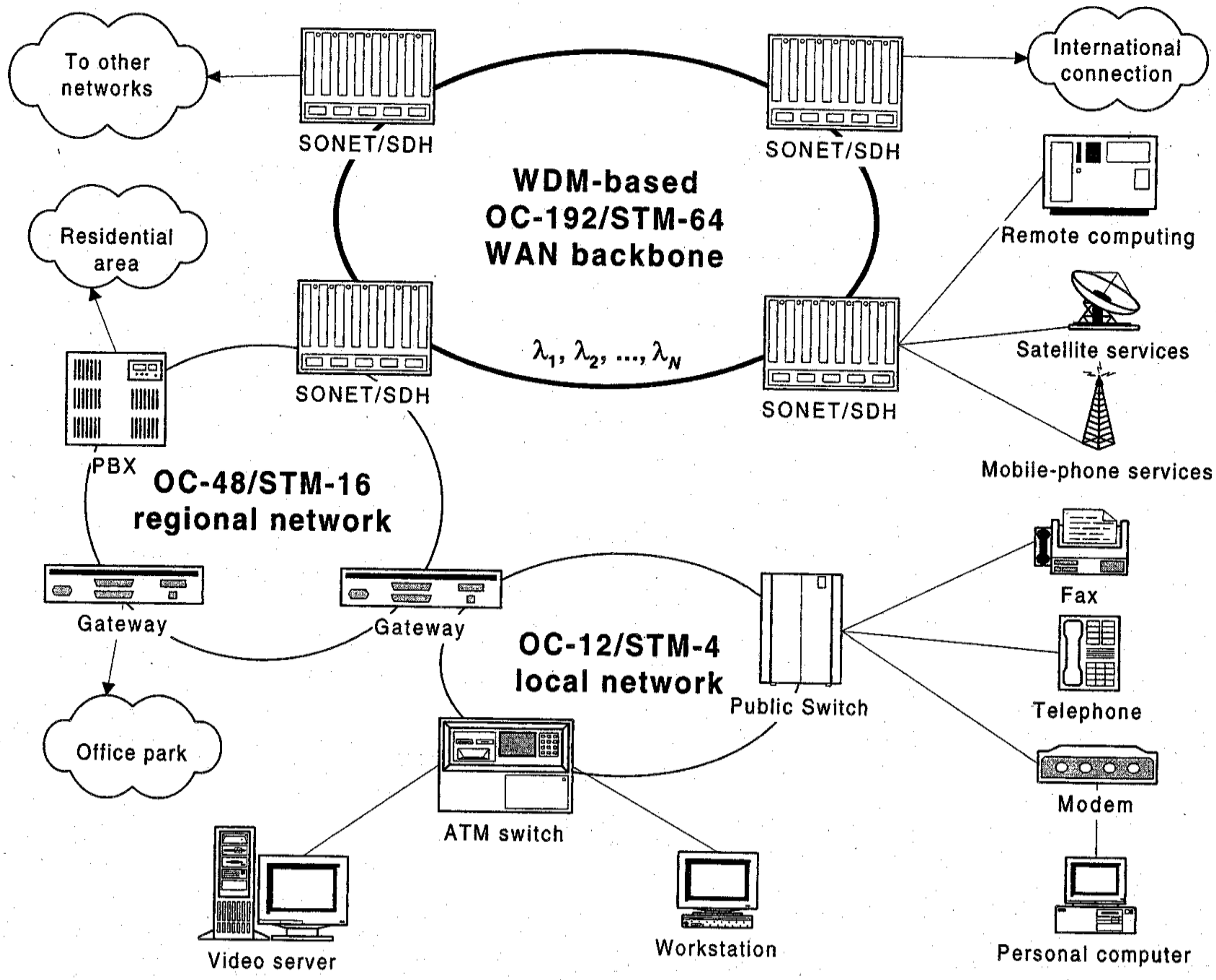

FIGURE 1-9
Conceptual SONET/SDH optical transport network connecting local, metropolitan, and wide-area communications elements.

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