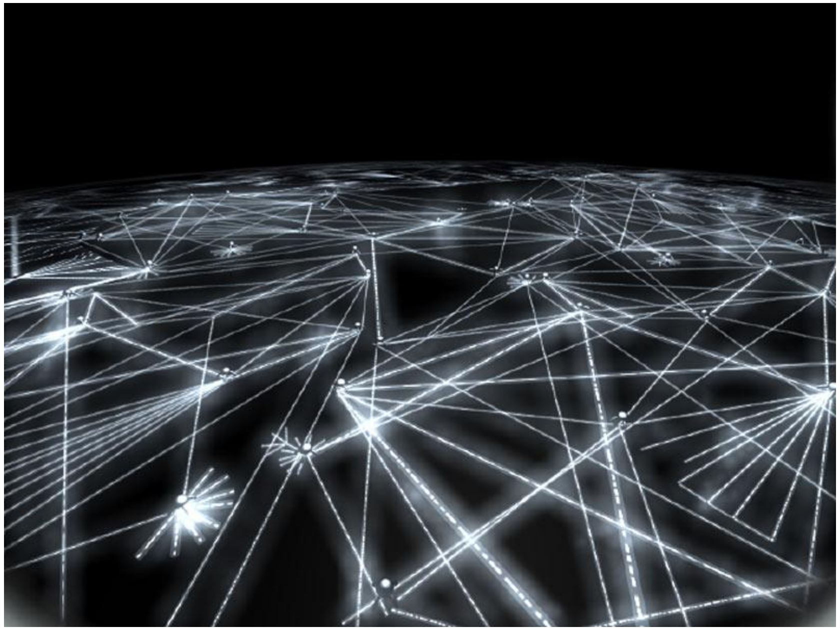
Optical Fiber Communication

Description
Components and system design for optical fiber communication.

Intended audience: BS students.

Time: Fri 2:00-5:00 pm
Location: Lab
Course Instructor: Me

E-mail: naeemiqbalch@gmail.com



From the movie
Warriors of the Net

Outline

Chapter No.	Chapter
1	Fiber Optic Communications Systems.
2	Optics Review.
3	Lightwave Fundamentals.
4	Integrated Optic Waveguides.
5	Optic Fiber Waveguides.
6	Optical Sources and Amplifiers.
7	Light Detectors.
8	Couplers and Connectors.
9	Distribution Networks and Fiber Components.
10	Modulation.
11	Noise and Detection.
12	System Design.

Course Content

Fibers:

Step-index fibers, graded-index fibers.
Fiber modes, single-mode fibers, multimode fibers.
Dispersion, mode coupling, and loss mechanics.
Glass materials, fiber fabrication, and characterization techniques.

Sources and Transmitters:

Light-emission processes in semiconductors.
Light-emitting diodes (LEDs).
Semiconductor lasers, (laser diodes: LDs).
Modulation response.
Source-fiber coupling.

(Image courtesy of Artem Visual Effects.)

Course Content: continued

Detectors and Receivers:

Photodetectors, receivers.
Receiver noise and sensitivity.

Optical Amplifiers

Erbium doped fiber amplifiers

Semiconductor optical amplifiers

Raman amplification

Systems:

System design: power budget and rise-time budget.
Single-Wavelength Fiber-Optic Networks (FDDI, SONET)
Wavelength-Division Multiplexing (WDM)

(Image courtesy of C.O.R.E. Digital Picture.)

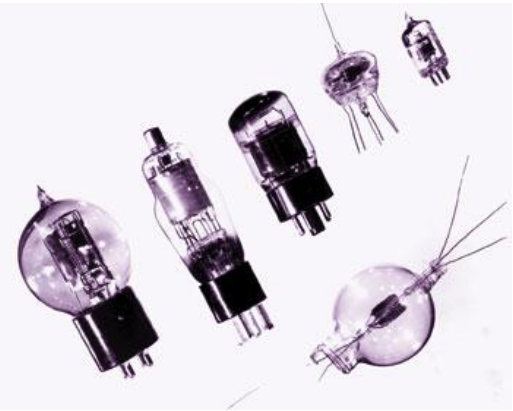
Historical Perspective

- Hand signals
- Smoke signals
- Lamps (traffic signals)
- 1960 Laser : A major breakthrough
- 1970 Fiber

A Short History of Optical Telecommunications

Circa 2500 B.C. Earliest known glass
Roman times-glass drawn into fibers
Venice Decorative Flowers made of glass fibers
1609-Galileo uses optical telescope
1626-Snell formulates law of refraction
1668-Newton invents reflection telescope
1840-Samuel Morse Invents Telegraph
1841-Daniel Colladon-Light guiding demonstrated
    in water jet
1870-Tyndall observes light guiding in a thin water jet
1873-Maxwell electromagnetic waves
1876-Elisha Gray and Alexander Bell Invent Telephone
1877-First Telephone Exchange
1880-Bell invents Photophone
1888-Hertz Confirms EM waves and relation to light
1880-1920 Glass rods used for illumination
1897-Rayleigh analyzes waveguide
1899-Marconi Radio Communication
1902-Marconi invention of radio detector
1910-1940 Vacuum Tubes invented and developed
1930-Lamb experiments with silica fiber
1931-Owens-Fiberglass
1936-1940 Communication using a waveguide

1876-Alexander Graham Bell

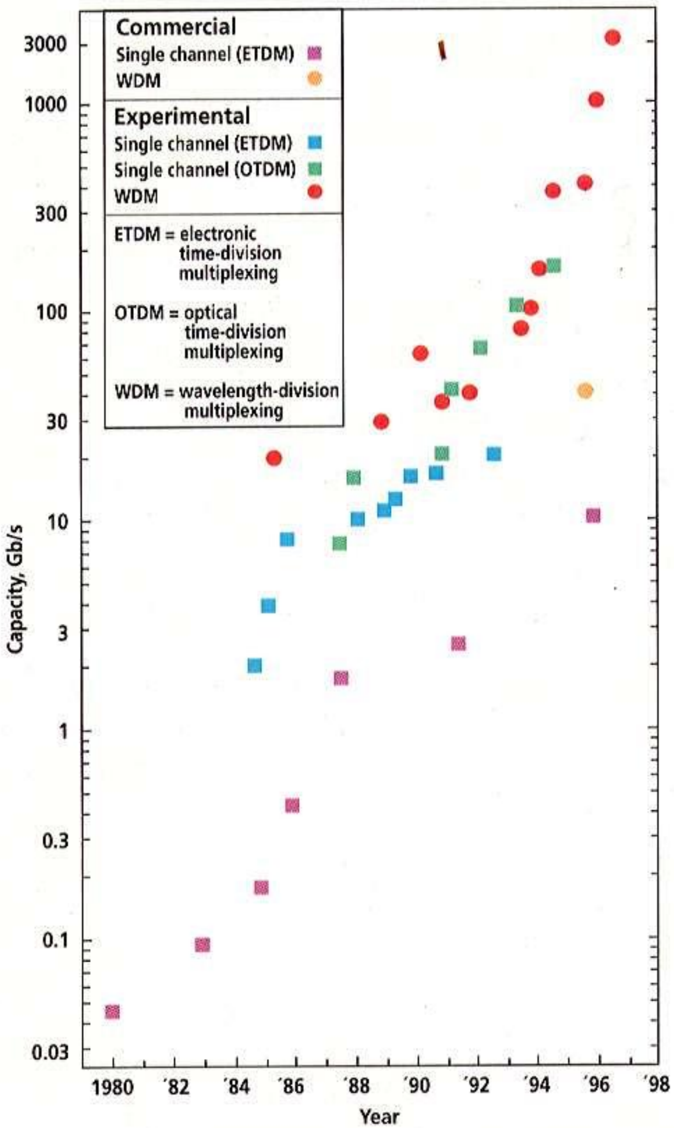


1970 I. Hayashi
Semiconductor Laser

1876 First commercial Telephone

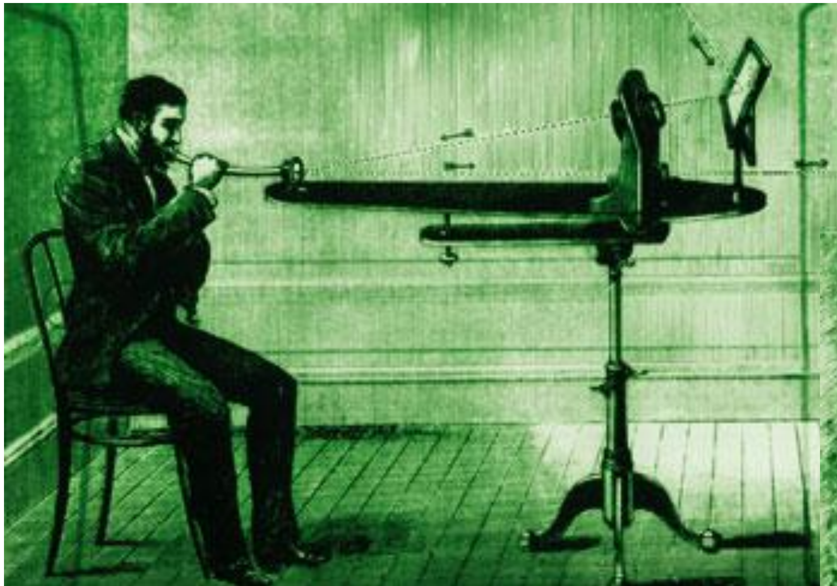
A Short History- Continued

1951-Heel, Hopkins, Kapany image transmission using fiber bundles
1957-First Endoscope used in patient
1958-Goubau et. al. Experiments with the lens guide
1958-59 Kapany creates optical fiber with cladding
1960-Ted Maiman demonstrates first laser in Ruby
1960-Javan et. al. invents HeNe laser
1962-4 Groups simultaneously make first semiconductor lasers
1961-66 Kao, Snitzer et al conceive of low loss single mode fiber communications and develop theory
1970-First room temp. CW semiconductor laser-Hayashi & Panish
April 1977-First fiber link with live telephone traffic-
GTE Long Beach 6 Mb/s
May 1977-First Bell system 45 mb/s links
GaAs lasers 850nm Multimode -2dB/km loss
Early 1980s-InGaAsP 1.3 µm Lasers
- 0.5 dB/km, lower dispersion-Single mode
Late 1980s-Single mode transmission at 1.55 µm -0.2 dB/km
1989-Erbium doped fiber amplifier
1 Q 1996-8 Channel WDM
4th Q 1996-16 Channel WDM
1Q 1998-40 Channel WDM
1998 Allwave fiber (Lucent Technologies)



Souce: Tingye Li, AT&T Research Laboratories; Alan E. Willner

Bells Photophone



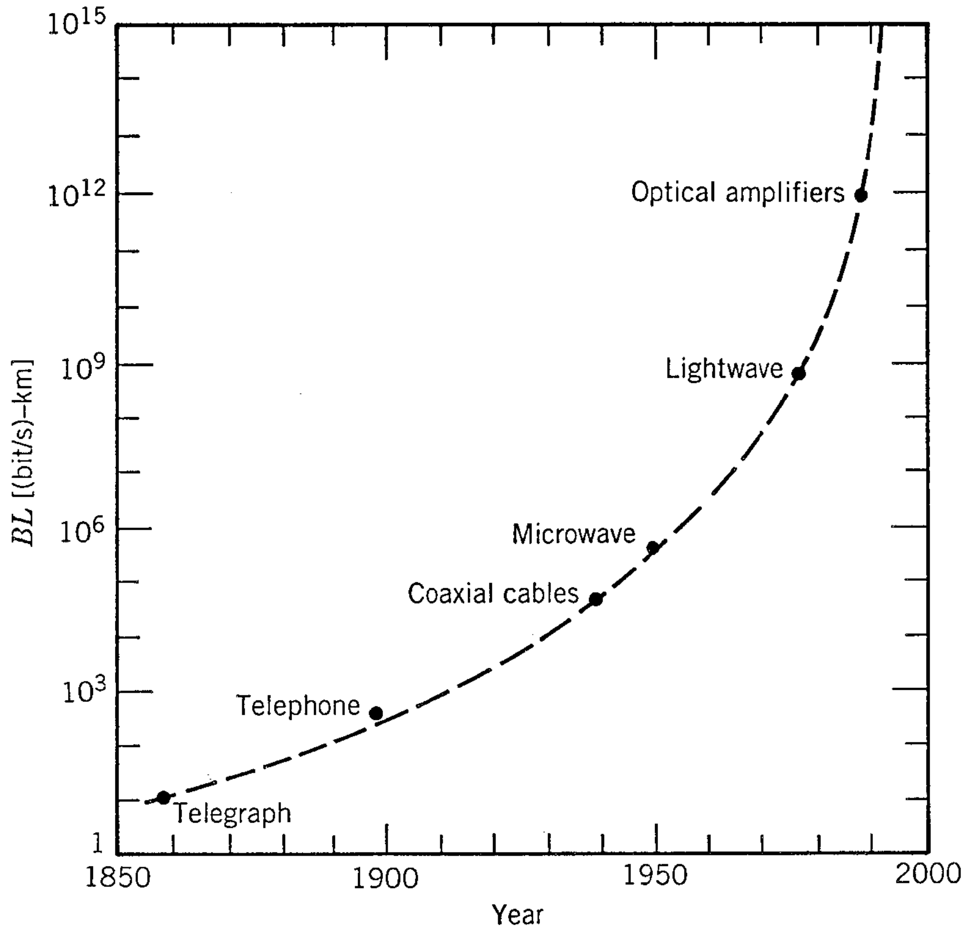
1880 - Photophone Transmitter

1880 - Photophone Receiver

“The ordinary man…will find a little difficulty in comprehending how sunbeams are to be used. Does Prof. Bell intend to connect Boston and Cambridge…with a line of sunbeams hung on telegraph posts, and, if so, what diameter are the sunbeams to be…?…will it be necessary to insulate them against the weather…?…until (the public) sees a man going through the streets with a coil of No. 12 sunbeams on his shoulder, and suspending them from pole to pole, there will be a general feeling that there is something about Prof. Bell’s photophone which places a tremendous strain on human credulity.”

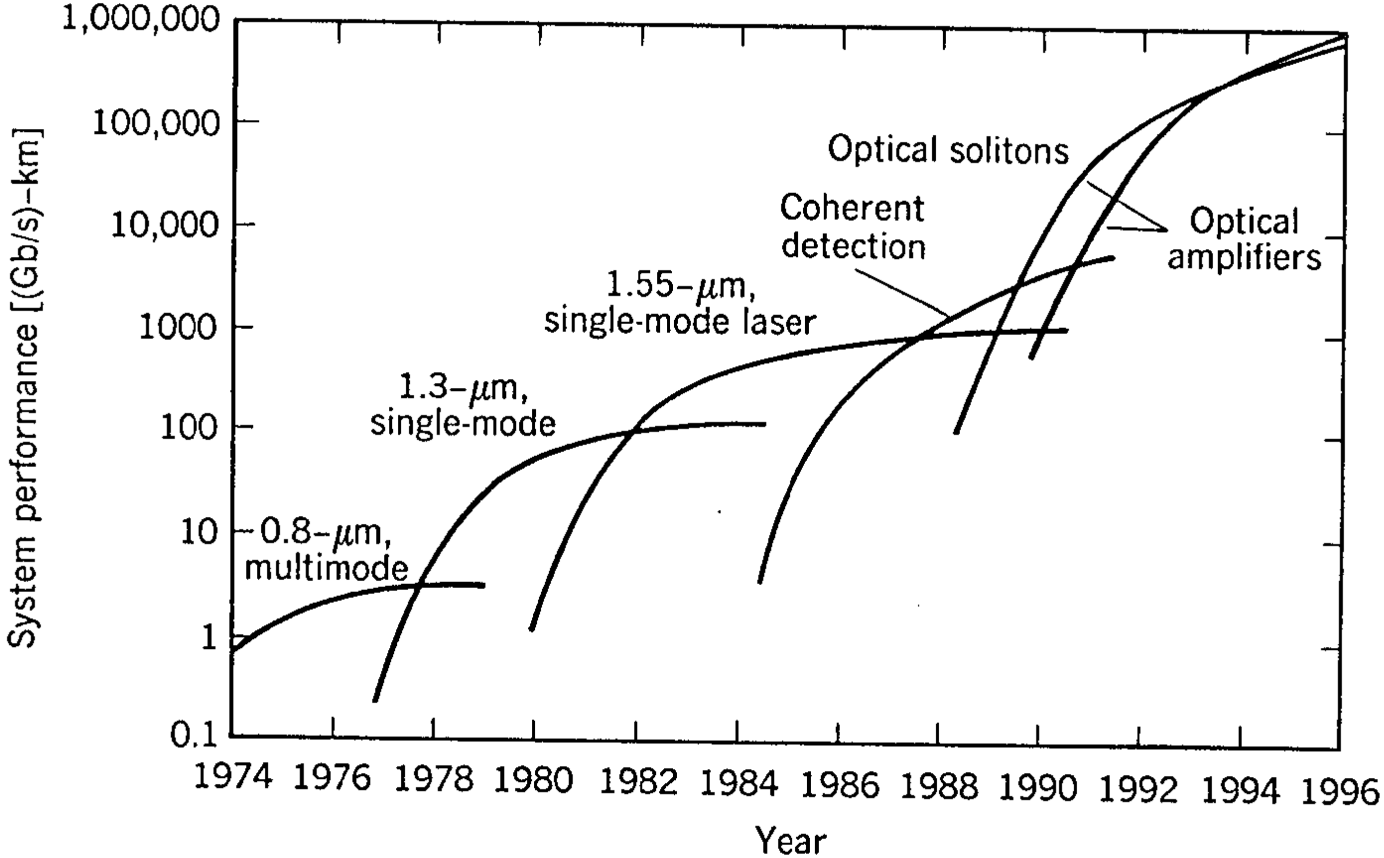
New York Times Editorial, 30 August 1880

Increase in Bitrate-Distance product



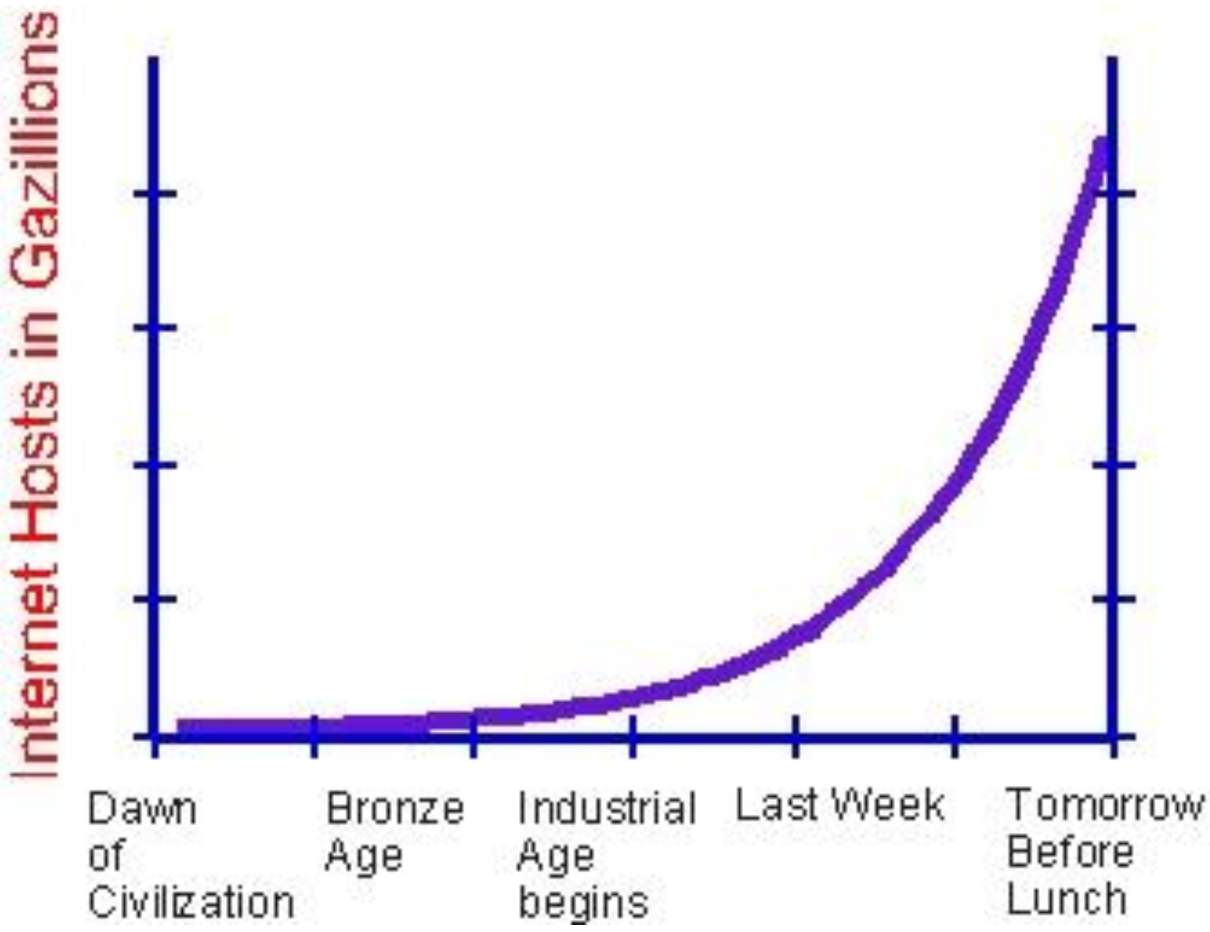
Agrawal-Fiber Optic Communications

Progress In Lightwave Communication Technology

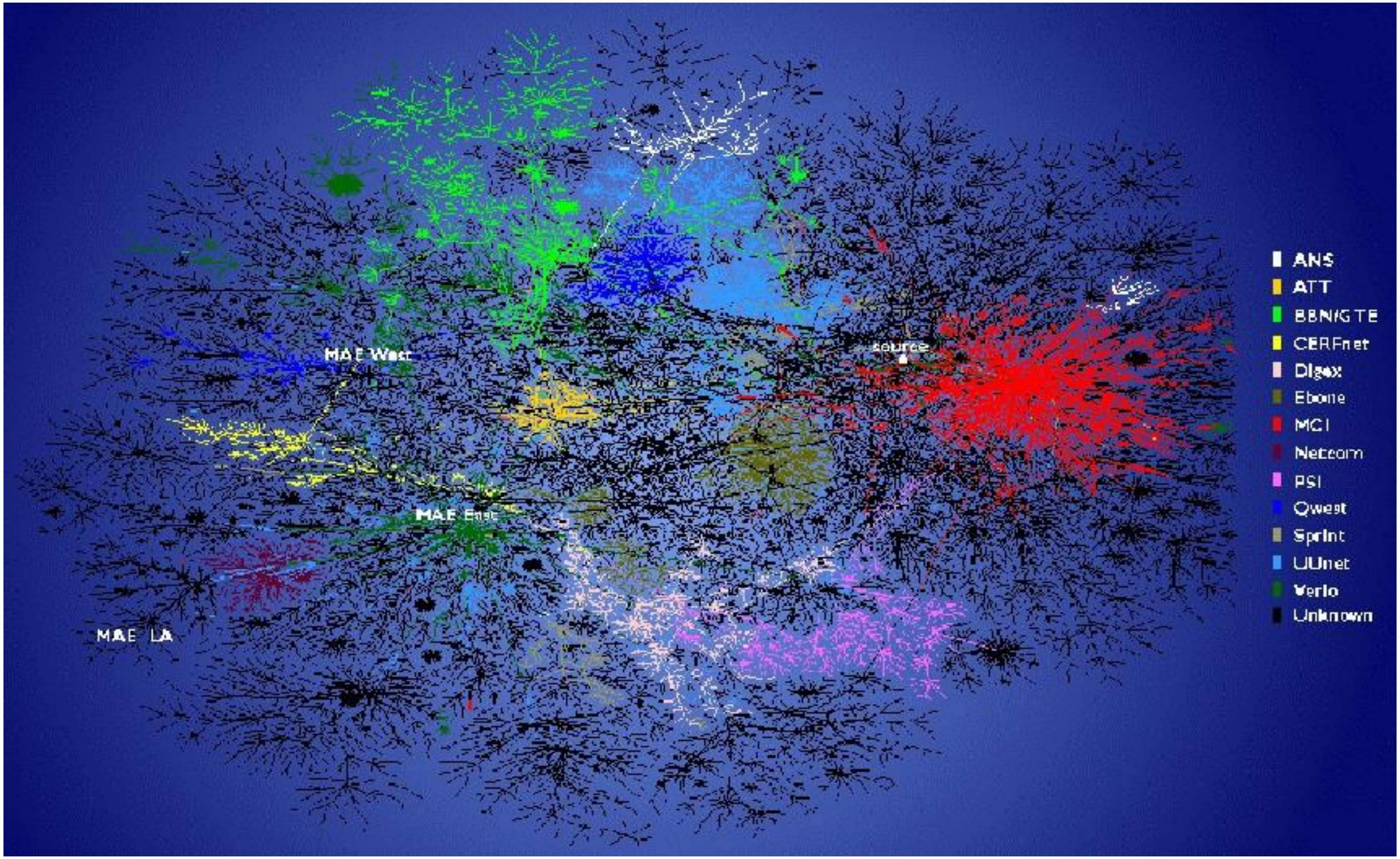


Growth of the Internet

Demand Driver for High Bandwidth Communications

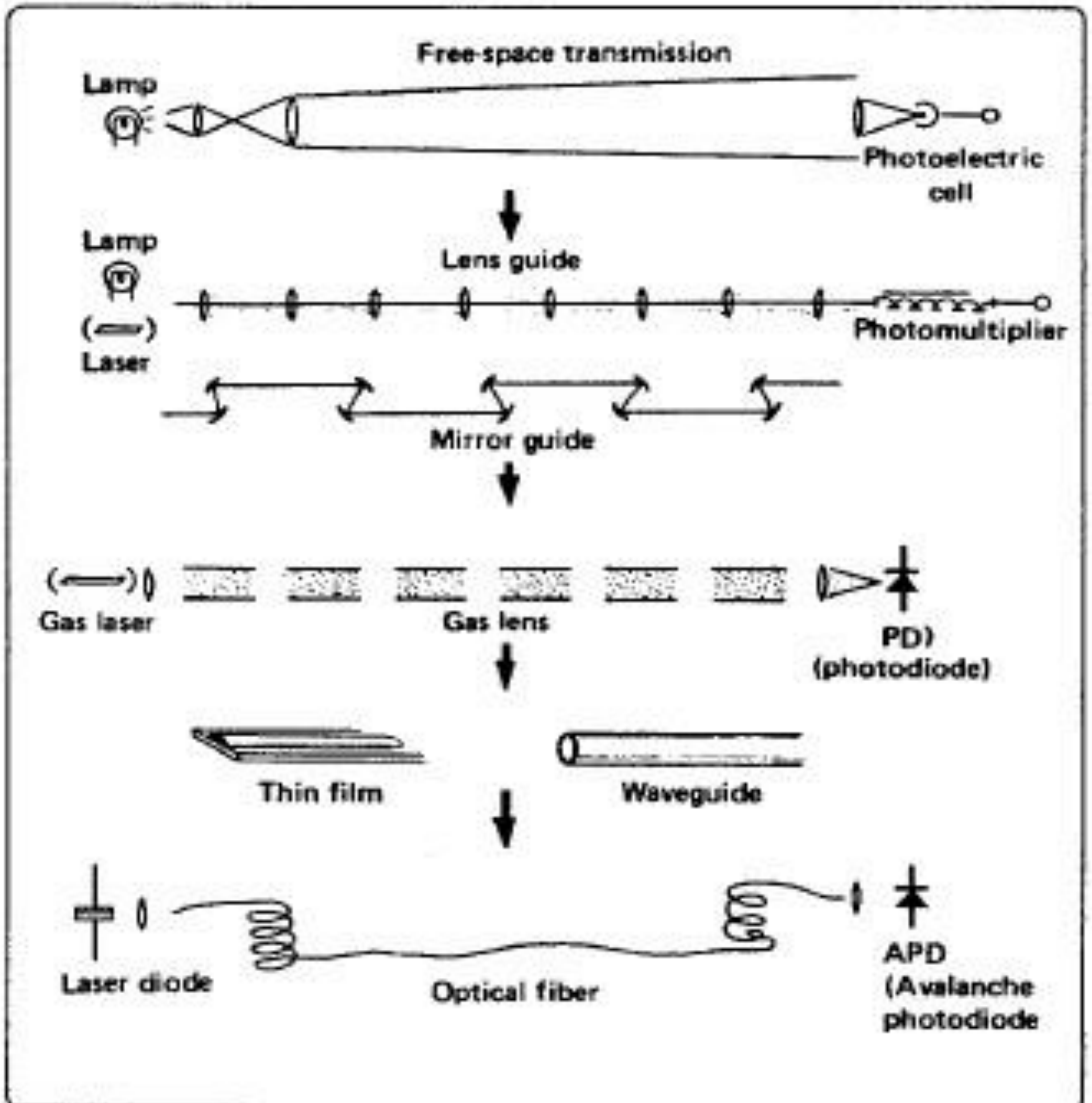


The Internet



From: www.caida.org

Approaches to Optical Communication



Why fiber?

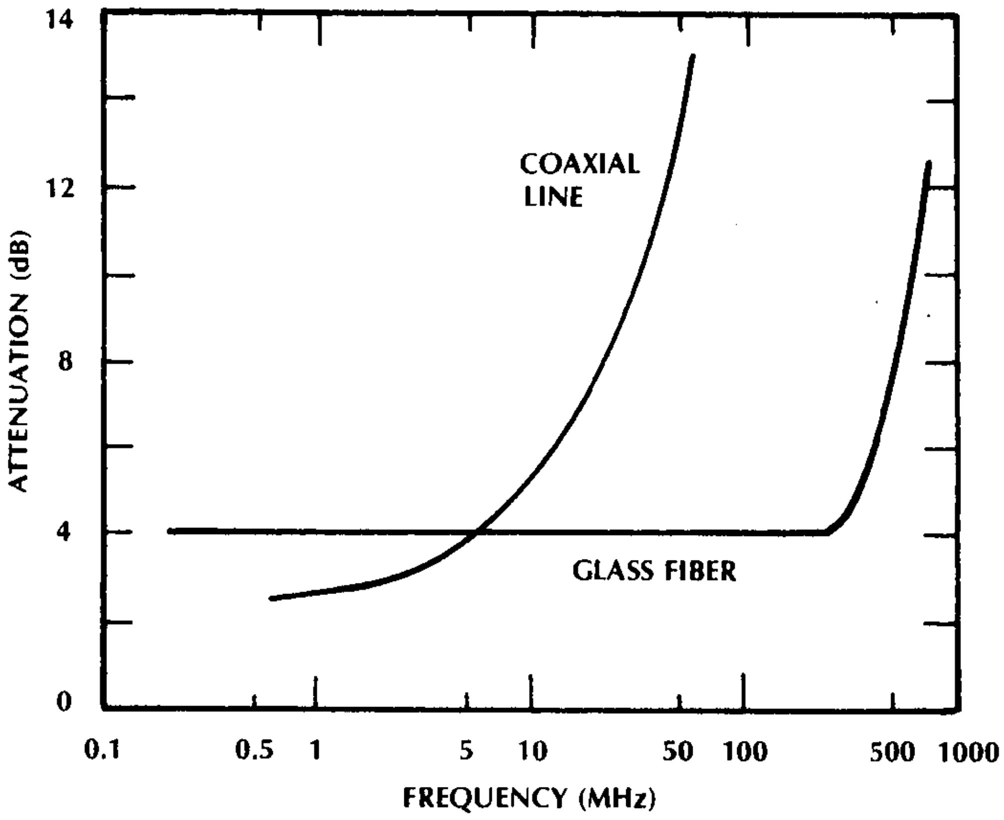
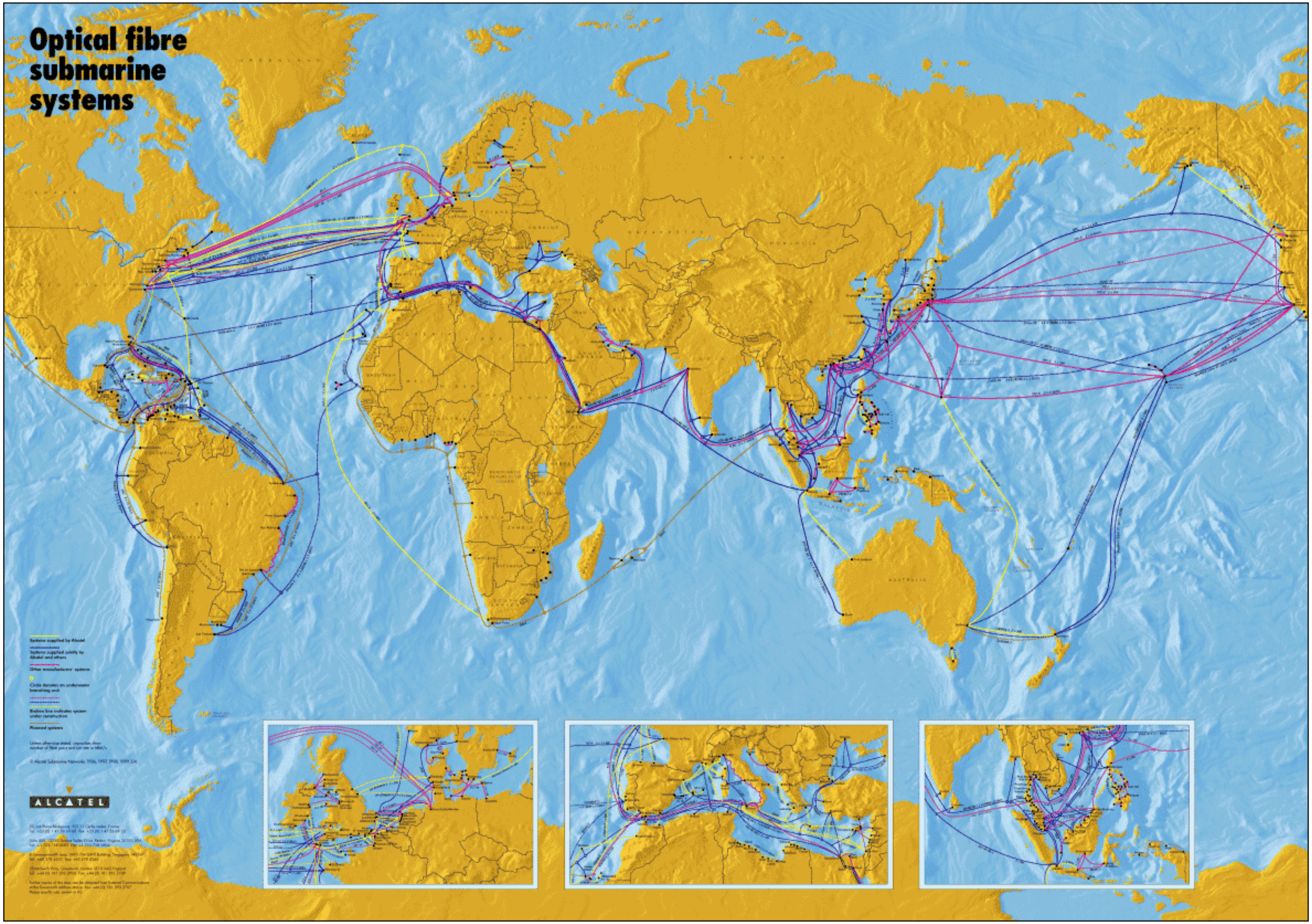


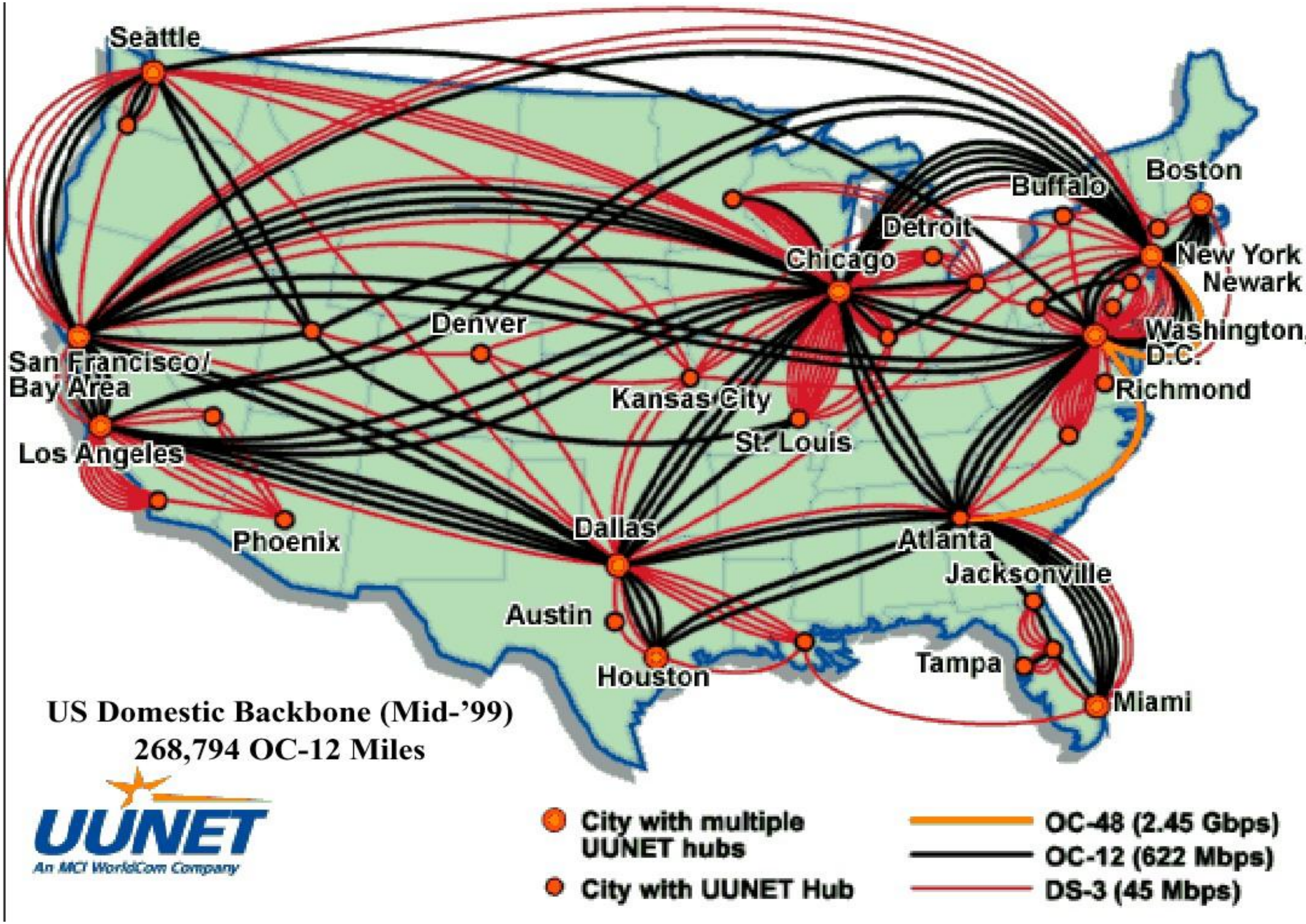
Figure 1-18 Effective attenuation of a 1-km length of coaxial line and glass fiber. The 3-dB bandwidth of the fiber is 500 MHz. (Coaxial line data from manufacturer's literature, Alpha Wire Corporation, Elizabeth, N.J.)

Global Undersea Fiber systems



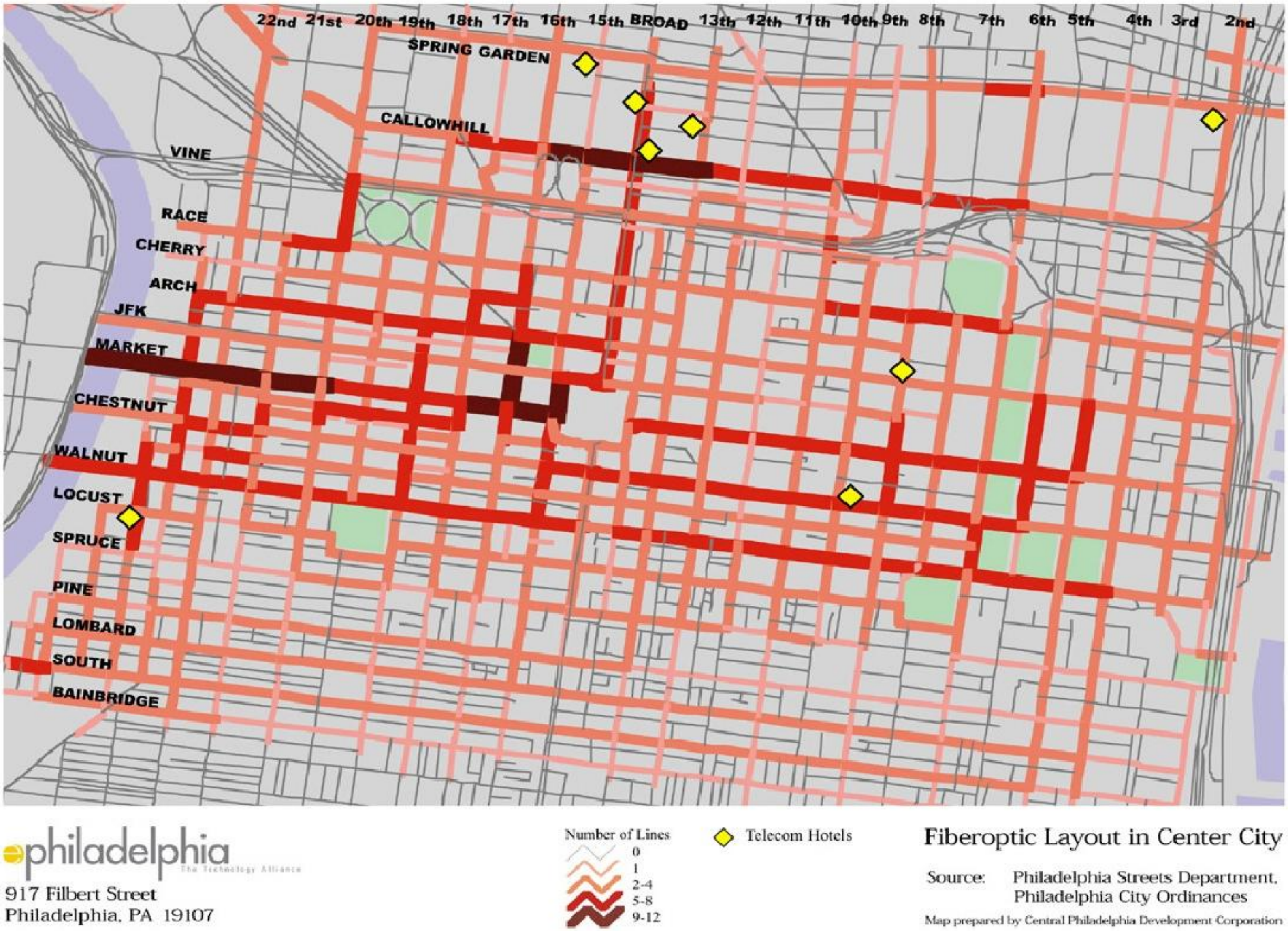
Installed Fiber in US

About 50,00 Route Miles Of Fiber Cable



US Domestic Backbone (Mid-'99)
268,794 OC-12 Miles

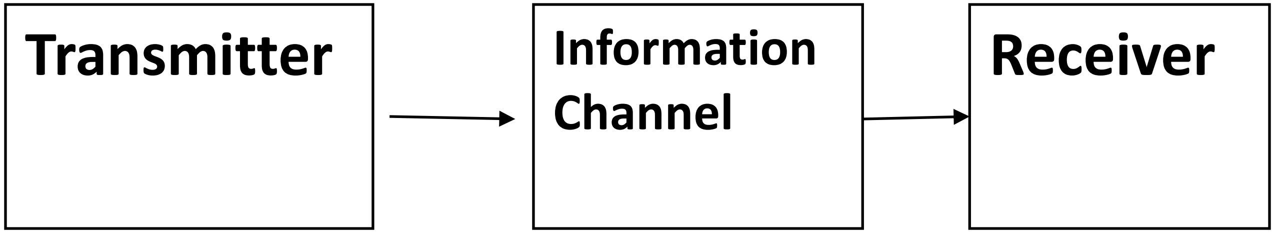
Example Metro network



Chapter 1

The Basic Communication System

- consists of a transmitter, a receiver, and an information channel
- At **transmitter** message is generated & put into suitable form for transfer over the information channel.
- The information travels from the transmitter to the receiver over this **channel**.
- Information channels can be divided into two categories: unguided channel and guided channel.
- At the **receiver** the message is extracted from the information channel and put into its final form.



The Basic Communication System

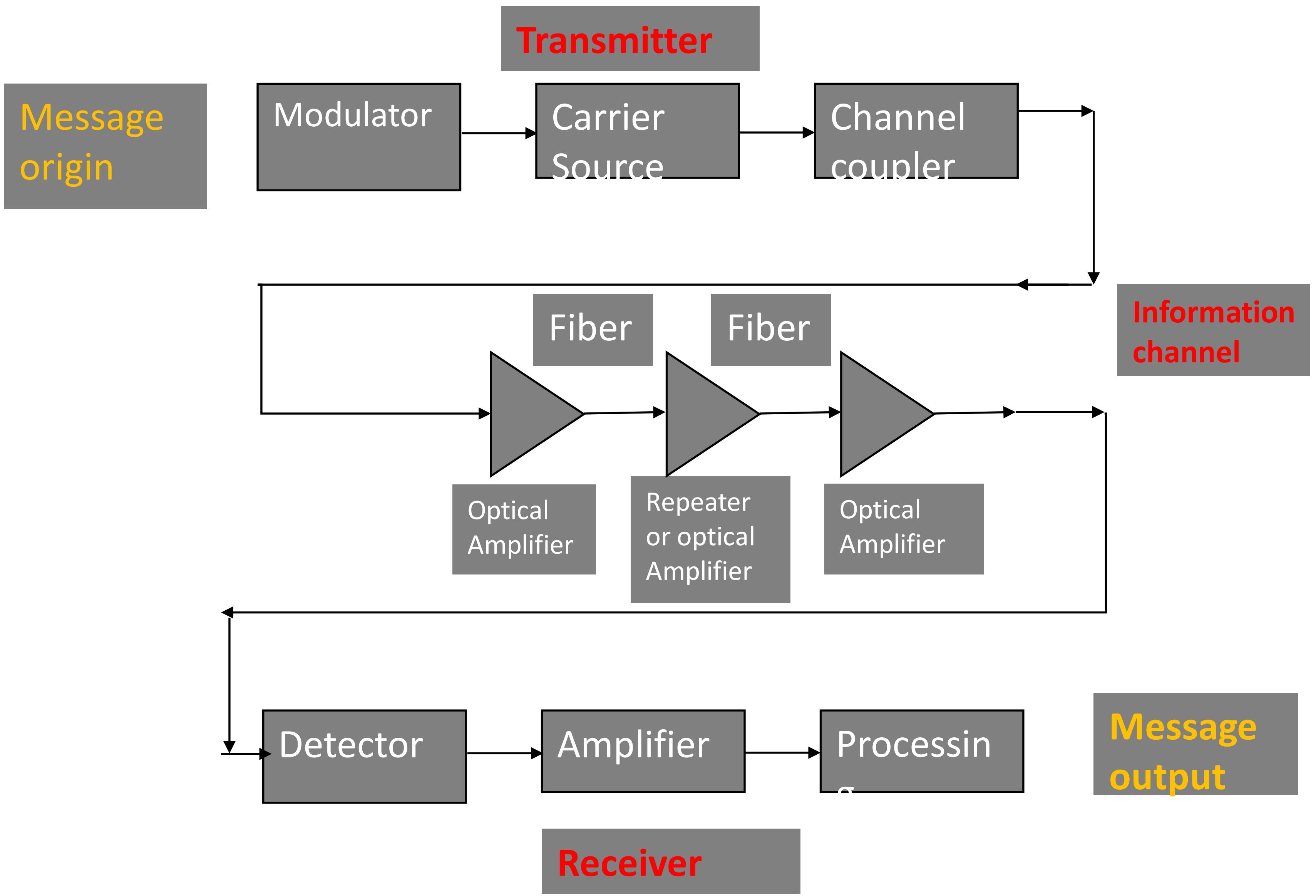
unguided channel

- The atmosphere over which waves can propagate.
- Systems include commercial radio and television broadcasts and microwave relay links.

Guided channels

- include a variety of conducting transmission structures.
  - two-wire line,
  - coaxial cable and
  - rectangular waveguide.
- Guided line cost more to manufacture, install and service than do atmospheric channels.
- advantage of privacy, no weather dependancy and the ability to convey message within, under and around physical structures.

Fiber Optic Communication System



Message Origin

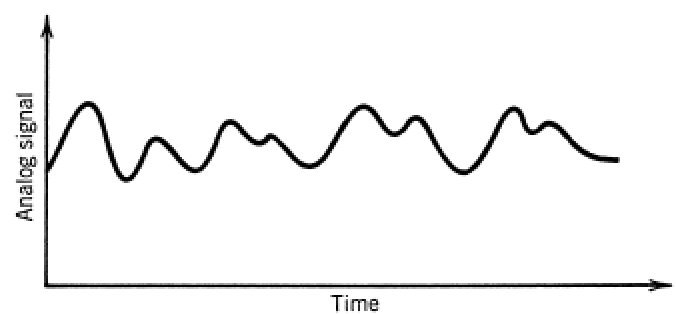
- Message origin may take several physical forms.
- A transducer that converts a no electrical message into an electrical signal.
  - E.g. microphones, video (TV) cameras converting sound waves, image into currents .
  - Data transfer between computers or parts the message is already in electrical form.
- when a fiber link comprises a portion of some larger system.
  - E.g. include fibers used in ground portion of a satellite system.
  - fibers used in relaying cable television signals.
- In any case, information must be in electrical form

Modulator

- The modulator has two main functions.
  1. converts the electrical message into the proper format.
  2. impresses this signal onto the wave generated by the carrier source.
- Two distinct categories of modulation
  - *analog* and
  - *digital.*

Analog Modulator

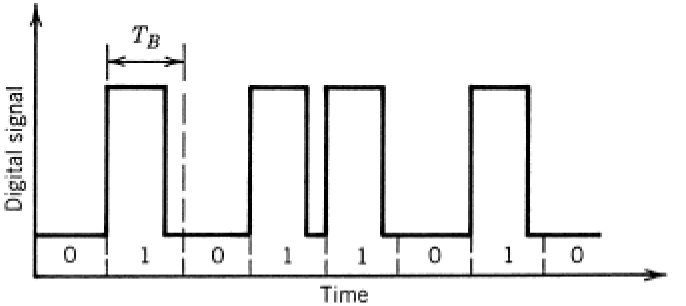
- An analog signal is continuous and reproduces the form of the original message quite faithfully.
  - sound wave containing a single tone
  - electrical current produced when a microphone picks up this wave has the same shape as the wave self.
- It may be appropriate to amplify this signal, so that the signal will be strong enough to drive the carrier source.



(a)

Digital modulation

- involves transmit information in discrete form.
- The signal is either on or off.
  - The *on* represents a digital 1 and
  - *off* state represents a digital 0.
  - These states the *binary digits* (or *bits)* of the digital system.
- The data rate is the no. of bits per sec (bps) transmitted.
- The sequence of on or pulses may be a coded version of an analog message.
- An analog-to-digital converter develops the digital sequence from the analog message.



Digital modulation

- The reverse process occurs at receiver, where the digital signal is return to its analog form.
- To impress a digital signal onto a carrier, the modulator need only turn the source on or off at the appropriate times.
- The ease of constructing digital modulate makes this format very attractive for fit systems.
- The choice of format must be made very early in the design of any system.

Carrier Source

- The carrier source generates the wave on which the information is transmitted called the *carrier.*
- It is produced by an electronic oscillator in radio-frequency communications systems.
- For fiber optic systems, a *laser diode* (LD) or a *light-emitting diode* (LED) is used, 2 devices can correctly be called optic oscillators.
- Ideally, they provide stable, single-frequency waves with sufficient power for long-distance propagation.
- Both differ technically but emit a range of frequencies & generally radiate only a few mill-watts of average power as receivers are so very sensitive.
- However, transmission losses continually decrease the power level and limits the length of communications link.

Carrier Source

- LEDs and laser diodes are small, light, and consume only moderate amounts of power.
- Both operate by passing current through them.
- It should be emphasized that the information being transmitted is contained in the variation of the optic power called *intensity modulation* (IM).

Carrier Source

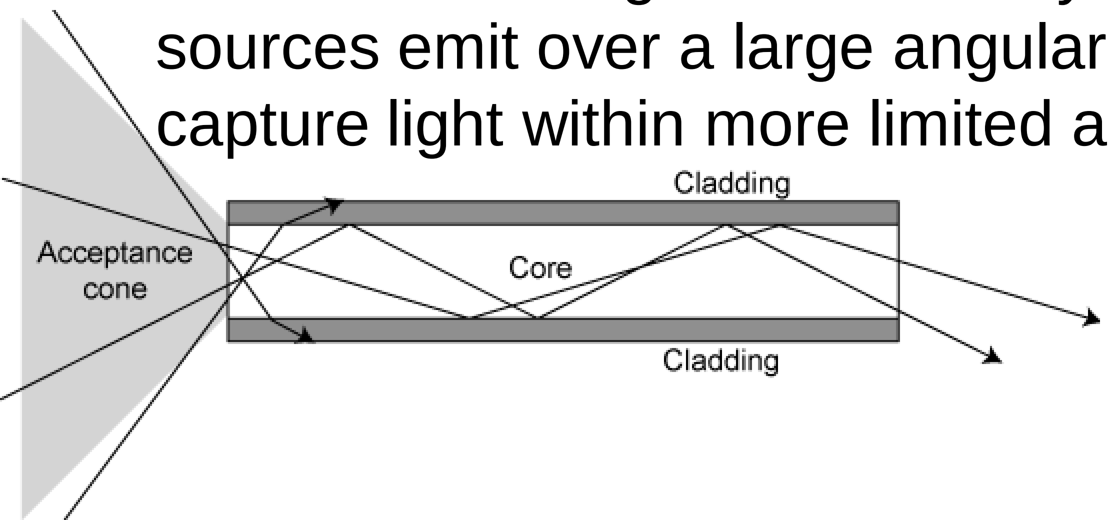
- DC. bias current, is added to the desired information signal, the modulating current for a digital system is always positive.
- Because a laser diode does not turn on until some threshold current is applied, the modulation current may include a DC. offset equal to this threshold value.
- The presence of a binary 1 drives the current beyond threshold and makes the diode emit light.
- A binary 0 leaves the current at threshold, where no radiation occurs.

Channel Coupler

- Coupler feeds power into the information channel.
- radio or television broadcasting, this element is antenna.
  - The antenna transfers the signals from the transmitter onto the information channel, in this case the atmosphere.
- guided system using wires, such as a telephone link,
  - the coupler need only be a simple con-nector for attaching the transmitter to the transmission line being used as the informa-tion channel.
- Atmospheric optic system,
  - the channel coupler is a lens used for collimating the light emitted by the source and directing this light toward the receiver.

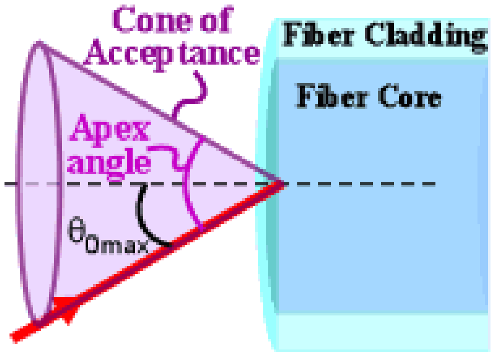
Channel Coupler

- Fiber system,
  - the coupler must efficiently transfer the modulated light beam from the source to the optic fiber.
- it is not easy to accomplish this without relatively large reductions in power.
- One difficulty arises because of the small size of conventional fibers, which have diameters of the order of 50 millionths of a meter.
- However, the large loss basically occurs because light sources emit over a large angular extent. Fibers can only capture light within more limited angles.



Channel Coupler

- The simplest type of coupler is shown. The light emitter is merely butted against the fiber.
- if the fiber is big enough to intercept all the light rays emitted by the source, the light will not be entirely collected because of the difference between the radiation and acceptance cone angles.
- More efficient, but also more complex, couplers can be constructed. It is an important part of the system because of the possibility of high losses.
- Numerical evaluation of expected efficiencies and the design of improved couplers are considered later



Information Channel

- path between the transmitter and receiver.
- a glass (or plastic) fiber is the channel.
- Desirable characteristics include low attenuation and large light-acceptance-cone angle particularly for transmission over long path.
- highly sensitive receivers are available, the power delivered to the receiver must be above some limiting value to obtain the desired message with clarity.

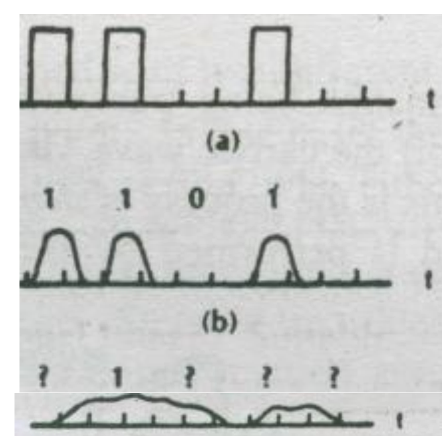
Information Channel

- Optical amplifiers boost the power levels of weak signals and are needed in very long links (hundreds and thousands of KM) to provide sufficient power to the receiver.
- Repeaters can be used only for digital systems to convert weak and distorted optical signals to electrical ones and then regenerate the original digital pulse trains for further transmission.
- propagation time is an important property that depends on the light frequency and on the path .

Information Channel

- A signal propagating along a fiber normally contains a range of optic frequencies and divides its power along several ray paths. This results in a distortion of the propagating signal.
- In a digital system, this distortion appears as a spreading and deforming of the on pulses

- spreading is so great that adjacent pulses begin to overlap and become unrecognizable as separate bits of information.



Information Channel

- To keep errors from occurring, pulses must be transmitted less frequently this, of course, limits the rate at which the pulses can be sent.
- The wave-velocity dependence on:
  - frequency
  - path
  - whether the modulation is digital or analog.
- The requirements for large light-acceptance angle and low signal distortion are contradictory, practical fibers represent a design compromise between these two qualities.

Information Channel

- In an atmospheric electronic communications system, an antenna collects the signal from the information channel and routes it to the rest of the receiver.
- In the fiber system, the output coupler merely directs the light emerging from the fiber onto the light detector.
- This light is radiated in a pattern identical to the fiber's acceptance cone.

Detector

- The information being transmitted must now be taken off the carrier wave. this is the process of *demodulating* the signal and is performed by the proper electronic circuit.
- In the fiber system, the optic wave is converted into an electric current by a photo detector.
- Semiconductor photodiodes of various designs are most commonly used. The current developed by these detectors is proportional to the power in the incident optic wave.
- Because the information is contained in the optic power variation, the detector output current contains this information.

Detector

- This current is a replica of that used to drive the carrier light source.
- The relationship between the signals at various points in the system is illustrated in Fig. 1-10 for an analog signal.
- The current generated by the transducer at the message origin is sketched in Fig. 1-10(a). This is the information signal we wish to transmit.
- The modulator adds a constant bias to this current [Fig. 1-10(b)] and applies the result to the light carrier.

Detector

- The carrier power waveform in Fig. 1-10(c) now contains the desired informa-tion.
- The signal is attenuated as it propagates through the fiber, as illustrated by the dimin-ished optic power shown in Fig. l-10(d).
- This figure is drawn assuming negligible waveform distortion owing to travel along the fiber. The detector converts the optic wave shape to elec-trical form, as shown in Fig. l-10(e).
- To complete the transmission, the detector output cur-rent is filtered to remove the constant bias and amplified if needed. The result, shown in Fig. l-10(f), is the desired information wave shape

Detector

- Important properties of photo detectors include:
  - small size
  - economy
  - long life
  - low power consumption
  - high sensitivity to optic signals
  - fast response to quick variations in the optic power.
- Fortunately, light detectors having these characteristics are readily available.

Signal Processor

- For analog transmission, the signal processor includes amplification and filtering of the signal..
- An ideal filter passes all frequencies contained in the transmitted information and rejects all others to improves the clarity of the intended transmission.
- Proper filtering maximizes the ratio of signal power to unwanted power.
- Random fluctuations in the received signal are referred to as *noise* it is present in all communications systems.

Signal Processor

- We will learn how to evaluate the amount of noise in a fiber system and how to design fiber systems to meet the *signal-to-noise ratio* (SNR) requirements for a given application.
- For a digital system, the processor may include decision circuits in addition to amplifiers and filters.
- The decision circuit decides if a binary 1 or 0 was received during the time slot of any individual bit.

Signal Processor

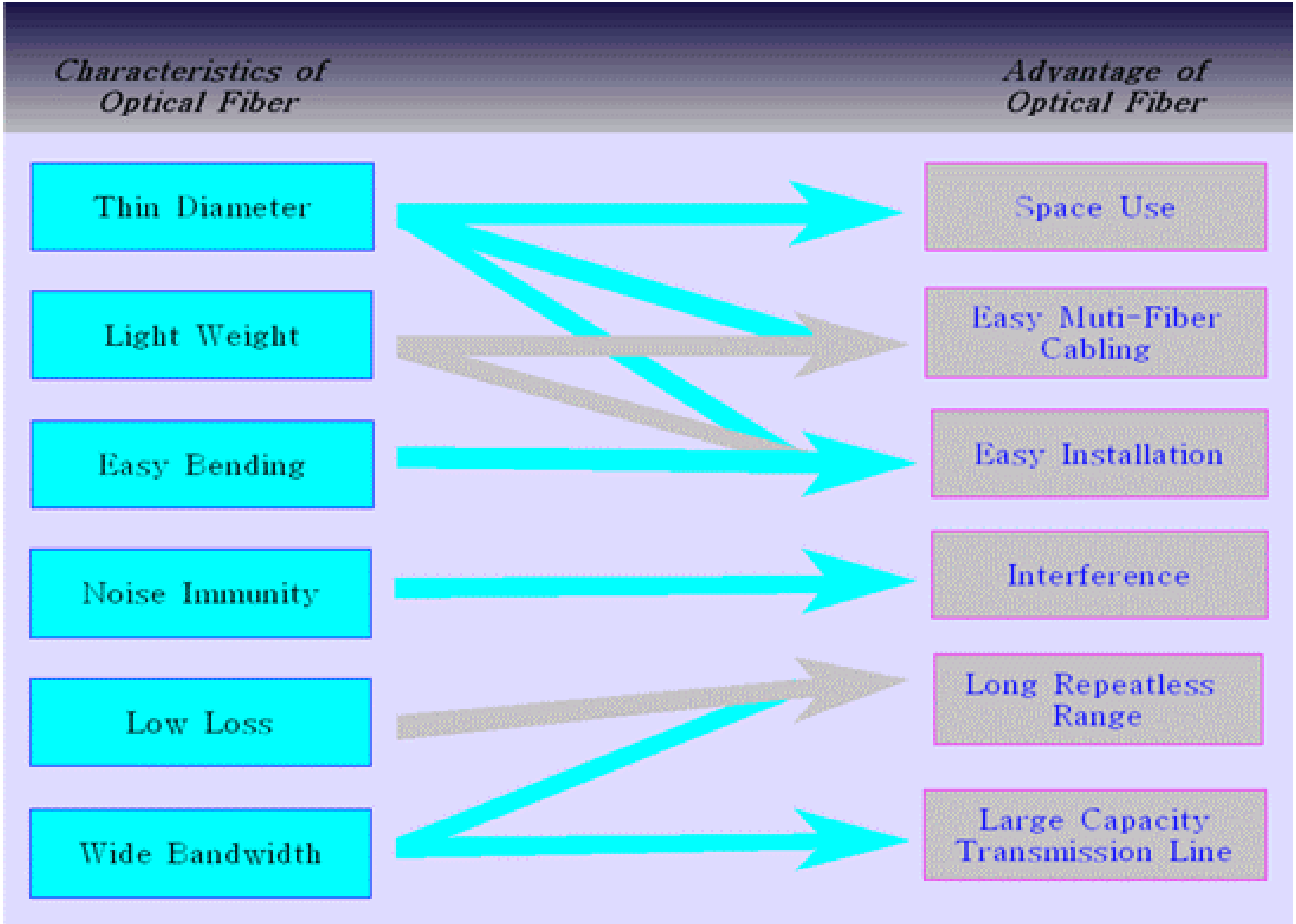
- Because of unavoidable noise, there will always be some probability of error in this process.
- The *bit-error rate* (BER) should be very small for quality communications.
- The digital signal processor must also decode the incoming sequence of Os and 1s if the original message was analog. This is done by a DAC converter, which re-creates the original electrical form of the information.
- If the communications were between machines, then the digital form might be suitable for use without digital-to-analog conversion.

Message Output

- If heard or viewed
  - Electrical signal -> sound wave or image
  - Transducers
    - Loud speaker
    - Cathode ray tube
- Directly Used
  - Electrical connector from the signal processor to succeeding system

ADVANTAGES OF OPTICAL FIBERS

1. VERY HIGH INFORMATION CARRING CAPACITY.
2. LESS ATTENUATION (order of 0.2 db/km)
3. SMALL IN DIAMETER AND SIZE & LIGHT WEIGHT
4. LOW COST AS COMPARED TO COPPER (as glass is made from sand..the raw material used to make OF is free….)
5. GREATER SAFETY AND IMMUNE TO EMI & RFI, MOISTURE & COROSSION
6. FLEXIBLE AND EASY TO INSTALL IN TIGHT CONDUICTS
7. ZERO RESALE VALUE (so theft is less)
8. IS DILECTRIC IN NATURE SO CAN BE LAID IN ELECTICALLY SENSITIVE SURROUNDINGS
9. DIFFICULT TO TAP FIBERS, SO SECURE
10. NO CROSS TALK AND DISTURBANCES


Characteristics of Optical Fiber
Advantage of Optical Fiber
Thin Diameter
Light Weight
Easy Bending
Noise Immunity
Low Loss
Wide Bandwidth
Space Use
Easy Muti-Fiber Cabling
Easy Installation
Interference
Long Repeatless Range
Large Capacity Transmission Line

DISADVANTAGES OF OPTICAL FIBERS…

1. The terminating equipment is still costly as compared to copper equipment.
2. Of is delicate so has to be handled carefully.
3. Last mile is still not totally fiberised due to costly subscriber premises equipment.
4. Communication is not totally in optical domain, so repeated electric – optical – electrical conversion is needed.
5. Optical amplifiers, splitters, MUX-DEMUX are still in development stages.
6. Tapping is not possible. Specialized equipment is needed to tap a fiber.
7. Optical fiber splicing is a specialized technique and needs expertly trained manpower.
8. The splicing and testing equipments are very expensive as compared to copper equipments.

ADVANTAGES OF FIBERS

- the advantages of optic fibers with few words of caution.
  - Fiber systems are not perfect.
  - They have technical and economic limitations.
- For any desired system the relative merits of guided channel versus unguided channel and metallic conductor versus fiber must be evaluated.

Desirable properties for evaluation.

- The basic material for glass fibers is silicon dioxide, which is plentiful.
- Some optic fibers are made of Transparent plastic, another readily available material.
- Costs Comparisons is most important consideration so must be done with care.
- Many fiber cables are cheaper than their wire equivalents.

Desirable properties for evaluation.

- Comparison on the basis of cost per unit of information transfer as fibers have greater information-carrying capacities than do metallic channels.
- Must include costs of installation, operation, and maintenance also.
- For long paths, fiber cables are cheaper to transport and easier to install than metal cables. As fibers are smaller and lighter.

properties to compare

Properties	Fiber	RG-19/U coaxial cable
Diameter inner	125 µm	
Diameter Outer	2.5 mm	28.4 mm
weight	6 kg/km	1110 kg/km
attenuation	5 dB/km	22.6 dB/km at 100-MHz signal

- Maintenance of fiber cables does differ.
- If a line is broken, **splices** or new connectors required that require more
- time and skill and expensive.

Strong and flexible

- Fibers and fiber cables have turned out to be surprisingly strong and flexible.
- Some fibers are so flexible that do not break by wrapped around curves of few cm radius.
- stored and transported tightly wrapped spools
- For a large radius bend, fibers, guide light with negligible loss.
- When a fiber is protected, in a plastic sheath, it is difficult to bend the cable in small radius
- The addition of a plastic sheath, steel rods and Kevlar(a synthetic polymer) the tensile strength transmission line increases.

Attenuation

- fibers available with very low transmission losses. Attenuation of 4 dB/km is typical of commercial glass fibers when operated at a wave-length around 0.82 *μm*.
- According to Fig. 1-14 this represents a transmission efficiency of 40% for a 1-km length.
- This degree of transparency could not be achieved before 1970.
- Now, fibers with losses of only a- few tenths of a dB/km are available for use around 1.3 *μm* and 1.55 *μm.*

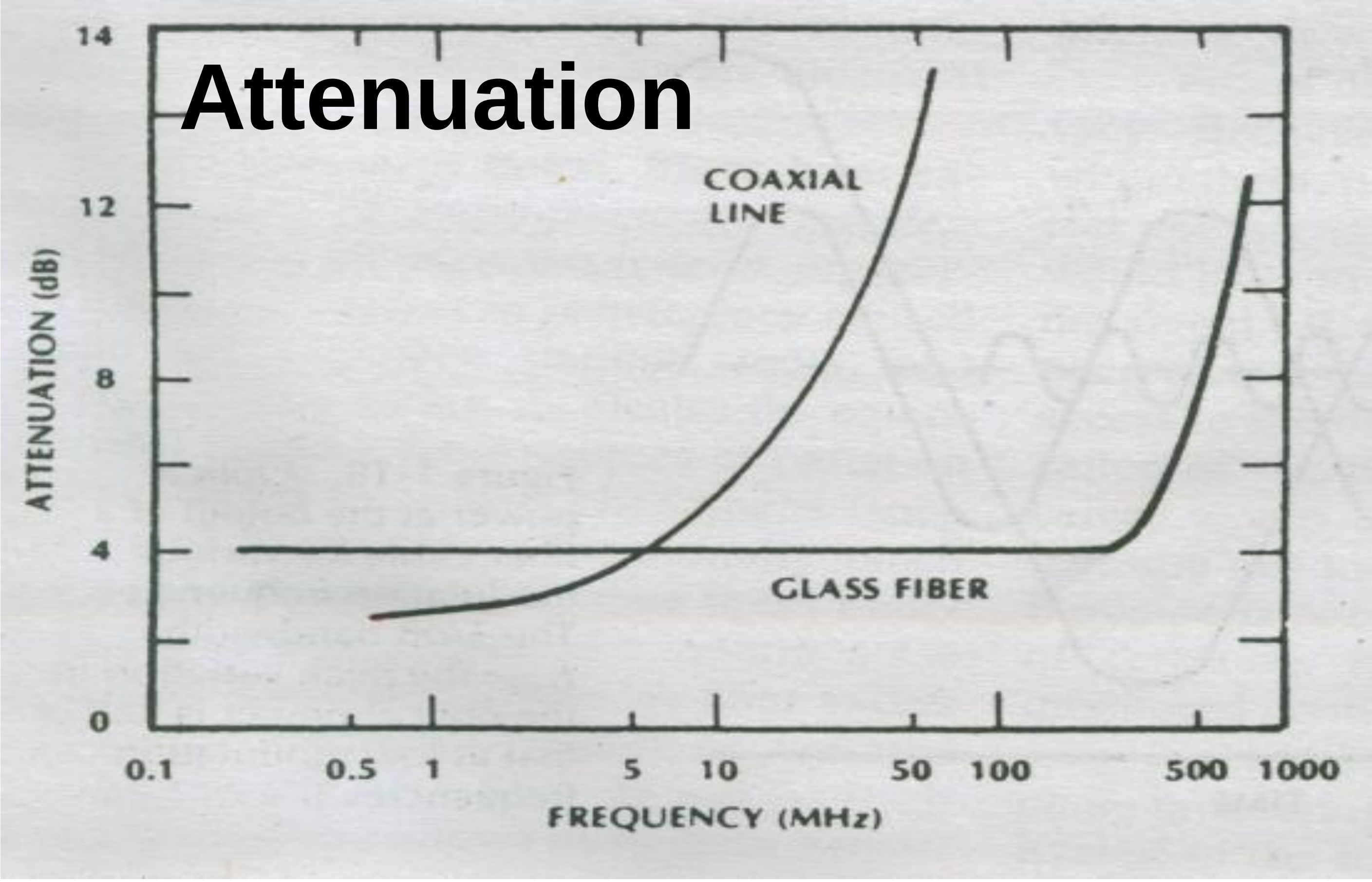
Attenuation

- Very long communications links can be constructed because of the availability of low-loss fibers.
- Amplifiers, needed to amplify weak signals, can be located at large intervals.
- The losses of wire transmission lines increase rapidly with frequency, as indicated in Fig. 1-18 for the RG-19/U coaxial cable.
- At high frequencies, link lengths and amplifier spacing would be significantly smaller for wire systems than for fiber systems.

Attenuation

- One of the most important advantages of fibers is their ability to carry large amounts of information and to do so in either digital or analog form.
- For example, a single fiber of the type developed for telephone service can propagate data at the T3 rate, 44.7 Mbps.
- This fiber transmits 672 voice channels. Fibers with even greater capacities are available.
- Although pulse spreading (see Fig. 1-8) limits the maximum rate, fiber capabilities meet the requirements of most data-handling sys-tems and exceed the capabilities of conducting cables.

Attenuation



- Figure 1-18
- Effective attenuation of a 1-km length of coaxial line and glass fiber.
- The 3-dB bandwidth of the fiber is 500 MHz. (Coaxial line data from manufacturer's literature,

Dramatic comparison (wires)

- The metal cable with 900 twisted pairs, diameter is 70 mm. Each carries 24 voice channels (T1 rate), so the cable capacity is 21,600 calls.
- 1 fiber cable for telephone has a 12.7-mm diameter and contains 144 fibers, each operating at the T3 rate (672 channels), so total capacity of 96,768 calls.
- fiber cable has 4.5 times capacity than wire cable & cross-sectional area that is 30 times less.

Protection

- Optic fibers are insulators (not conductors).
- No electric currents flow through them.
- optic wave within fiber is trapped, so none leaks outs to interfere with signals. Conversely, light cannot couple into the fiber from outside.
- fiber is well protected from interference and coupling with other communications .
- fibers have excellent rejection of :
  - *radiofrequency interference* (RFI) and of
  - *electromagnetic interference* (EMI).

EMI Rejection

- EMI includes diff sources of radiation & other possibilities (lightning, sparking).
- these undesired signals increase the system noise level beyond acceptable limit .
- fiber excels at rejecting externally caused background noise.
- The ability of a fiber to isolate itself from its environment allows to pack numerous fibers to transmit many channels along a single path.
- No crosstalk occurs.

insulation

- As fibers are insulators, they don’t pickup, propagate electromagnetic pulses (EMP) caused by nuclear explosions (millions volt induction)
- The voltage pulse can travel many miles & destroy the electronics at the end of the path.
- In an environment in which high-voltage lines are present, a wire communications link could possibly short-circuit the lines by falling across them, causing considerable damage.
- Sparking could ignite combustible gases in the area, problem disappears with fibers.

Repair

- No need for a common ground between a fiber transmitter and receiver.
- It is possible to repair the fiber while the system is on without the possibility of short circuiting the electronics at the transmitter or receiver.
- This problem might occur when repairing a metallic cable.

Security, privacy and training

- fibers do not radiate the energy within them, it is difficult for an intruder to detect the signal. If the fiber is physically violated to obtain the signal, power reaching the receiver drops & is detected.
- Electronic communications systems include processing at both ends of information channel.
- Fiber systems require similar processing & allows incorporation of fibers into systems originally conceived for wire transmission .
- It is even possible to make an optic system transparent to the user.

Security, privacy and training

- Users simply supply electrical inputs and receive electrical outputs, just as they do for all-electronic systems.
- No extra training is required for persons.
- Corrosion caused by water or chemicals is less severe for glass .
- However, water must not penetrate the glass.
- For submerged applications, fibers are encapsulated within cables, which protect them from the water

Extreme Temperatures

- Glass fibers can withstand extreme temperatures (800 C) before deteriorating.
- Plastic cable sheathing can melt, leaving the fiber unprotected
- Fiber cables with an operating range of -25° to + 65°C are commercially available .
- Large temperature variations also cause expansions and contractions that upset the critical alignments required for low-loss connections.

Connection

- Fibers are available in long lengths, reducing need for numerous splices. A common length is 1 km (several km possible)
- Less splice less cost and losses
- Expensive Metal connectors with precision (loss < 1 dB)
- Inexpensive plastic connectors (loss >2 dB)
- permanently splicing fibers is possible.

Frequency and Period

- The frequency unit, the hertz, is equivalent to one cycle of oscillation per second .
- The time between successive peaks of an oscillation is called the period and is given by the reciprocal of the wave frequency.
- If f is the wave frequency and T is its period then
  - $T=1/f$.

Sampling

- When analog signals are transmitted digitally, the bit rate depends on the
  1. rate at which the analog signal is sampled
  2. the coding scheme.

- Why the standard 4-kHz telephone channel is sampled 8000 times a second?

- According to the sampling theorem, an analog signal can be accurately transmitted if sampled at a rate of at least twice the highest frequency contained in that signal. For this reason the standard 4-kHz telephone channel is sampled 8000 times a second.
  – 8 bits/sample -> 64 Kbps

APPLICATIONS OF OPTICAL FIBERS…

1. LONG DISTANCE COMMUNICATION BACKBONES
2. INTER-EXCHANGE JUNCTIONS
3. VIDEO TRANSMISSION
4. BROADBAND SERVICES
5. COMPUTER DATA COMMUNICATION (LAN, WAN etc..)
6. HIGHT EMI AREAS
7. MILITARY APPLICATION
8. NON-COMMUNICATION APPLICATIONS (sensors etc…)

Telephone links

- transmit messages with frequencies up to 4000 Hz, normal speech is contained < than this value.
- Messages are intelligible and individual voices are quite recognizable with this bandwidth.
- A channel with a larger bandwidth would reproduce sounds with higher quality, but this is not necessary in practical telephone circuits.
- Bandwidth reductions below 4 kHz are possible if some degradation in speech quality is al-lowable.
- For voice-transmission examples we assume the 4-kHz bandwidth for commercial telephone
- The range up to 4 kHz is called the *baseband* of the voice message.

Commercial AM

- (Amplitude modulation) broadcasting stations transmit messages from 100 to 5000 Hz.
- The AM format requires a bandwidth of twice the highest modulation frequency, so stations have 10-kHz bandwidths, separated by 10 kHz.
- High-quality music reproduction requires transmission of modulating frequencies up to 15 kHz.
- FM *(frequency modulation)* broadcasting stations transmit information between 50^and 15,000 Hz.
- The FM format requires a 200-kHz bandwidth to accomplish this result.

Video signals

- Additional bandwidth is require for video signals.
- Commercial television channels have a 6-MHz bandwidth(both the picture and the sound).
- The highest video frequency actually transmitted is near 4.2 MHz.
- The range of frequencies occupied by the TV signal (up to 6 -MHz) is the baseband of the television message.
- When analog signals are transmitted digitally, the bit rate depends on the rate at which the analog signal is sampled and the coding scheme.

Video signals

- According to the *sampling theorem,* an analog signal can be accurately transmitted if sampled at a rate of at least twice the highest frequency contained in that signal.
- standard 4-kHz telephone channel is sampled 8000 times a second.
- The coding procedure uses 8 bits to describe the amplitude of each sample, so that a total of 64,000 bps are transmitted for a single telephone message.
- By sending pulses at a rate higher than 64 kbps, several messages can be simultaneously transmitted.

Video signals

- The different messages are combined *(multiplexed)* onto a single information channel by interleaving their data bits at the transmitter.
- The messages are separated *(de-multiplexed)* at the receiver.