Chapter 2

(Week 3)

The Physical Layer

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The Purpose of the Physical Layer

- THE PURPOSE OF THE PHYSICAL LAYER IS TO TRANSPORT A RAW BIT STREAM FROM ONE MACHINE TO ANOTHER

5	Application layer
4	Transport layer
3	Network layer
2	Data link layer
1	Physical layer

The Hybrid Model of Computer Network

Physical Layer's Functions (1/2)

The Physical Layer is concerned with transmitting raw bits over a communication channel. The typical questions here are:

a) How many volts should be used to represent a 1 and a 0;

b) How many nanoseconds a bit lasts;

c) Whether transmission may proceed simultaneously in both directions;

Physical Layer's Functions (2/2)

d) How the initial connection is established and how it is torn down when both sides are finished;

e) How many pins the network connector has and what each pin is used for;

The design issues here largely deal with mechanical, electrical, and timing interfaces of the network.

The physical transmission medium, which lies below the physical layer, is also studied in scope of physical layer.

The Theoretical Basis for Data Communication (2/1)

- Information can be transmitted on wires by varying some physical property such as voltage or current.

- By representing the value of this voltage or current as a single-valued function of time, f(t), we can model the behavior of the signal and analyze it mathematically.

The Theoretical Basis for Data Communication (2/2)

- Fourier Analysis
- Bandwidth-Limited Signals
- Maximum Data Rate of a Channel

Fourier Analysis (1/3)

- Any periodic function, g(t), with period T can be constructed by summing a (possibly infinite) number of sines and cosines:

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$

$f = \frac{1}{T}$ is the fundamental frequency; c is a constant;

a_n and b_n are the sine and cosine amplitudes of the nth harmonics.

Such decomposition is called a Fourier series.

Fourier Analysis (2/3)

- From the Fourier series, the function can be reconstructed;
- That is, if the period, T, is known and the amplitudes are given, the original function of time can be found by performing the sums of $g(t)$.
- A data signal that has a finite duration can be handled by just imagining that it repeats the entire pattern over and over forever (i.e., the interval from T to $2T$ is the same as from 0 to T, etc.)

Fourier Analysis (3/3)

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$

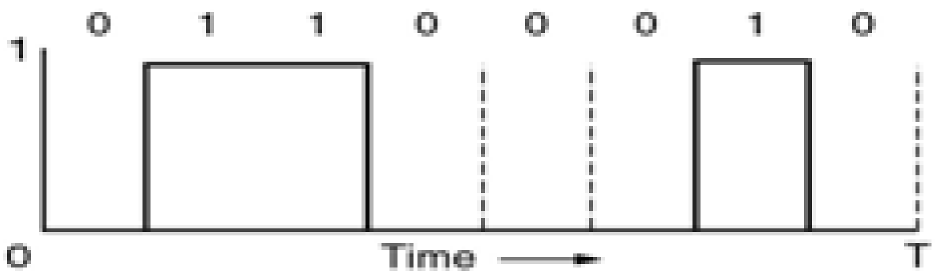
$$a_n = \frac{2}{T}\int_0^T g(t)\sin(2\pi nft)\,dt$$

$$b_n = \frac{2}{T}\int_0^T g(t)\cos(2\pi nft)\,dt$$

$$c = \frac{2}{T}\int_0^T g(t)\,dt$$

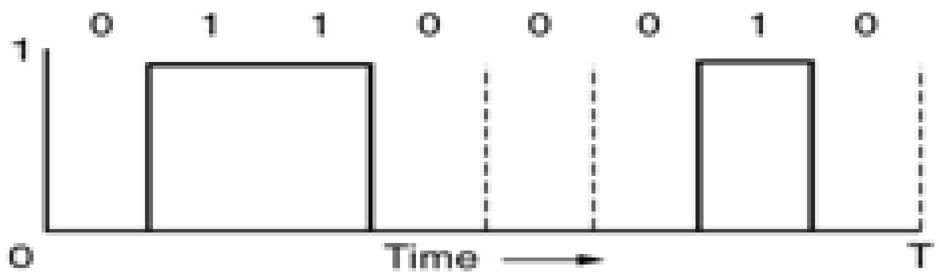
Bandwidth-Limited Signals (1/8)

- Let us consider the relation of the Fourier Series with data communication.
- Let us consider how to transmit the ASCII character “b”, which can be encoded in an 8-bit: 01100010.



This signal is the voltage output by the transmitting computer

Bandwidth-Limited Signals (2/8)



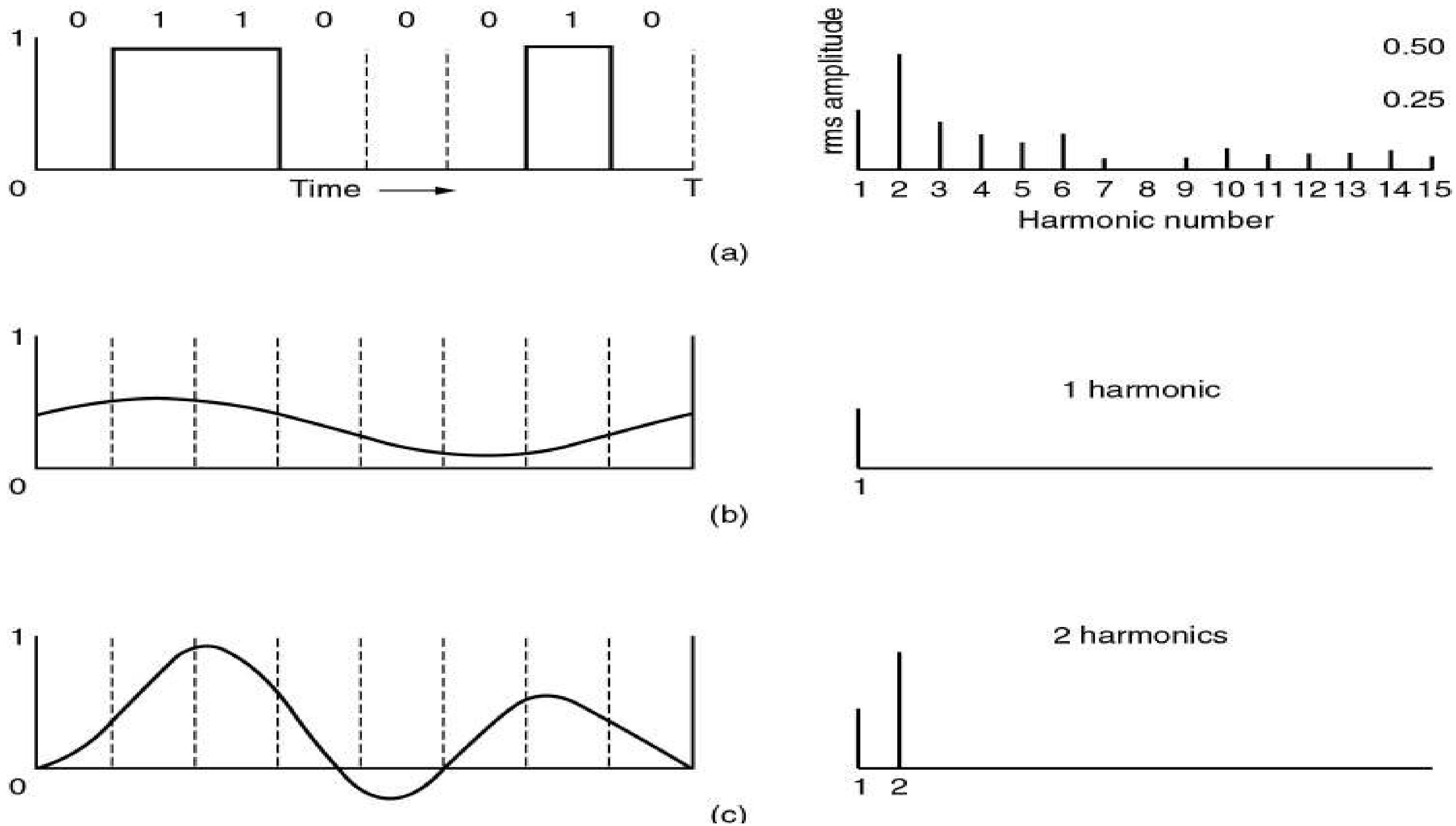
The Fourier analysis of this signal is the voltage output by the transmitting computer gives the following coefficients:

$$a_n = \frac{1}{\pi n}\left[\cos(\pi n/4) - \cos(3\pi n/4) + \cos(6\pi n/4) - \cos(7\pi n/4)\right]$$

$$b_n = \frac{1}{\pi n}\left[\sin(3\pi n/4) - \sin(\pi n/4) + \sin(7\pi n/4) - \sin(6\pi n/4)\right]$$

$$c = 3/4$$

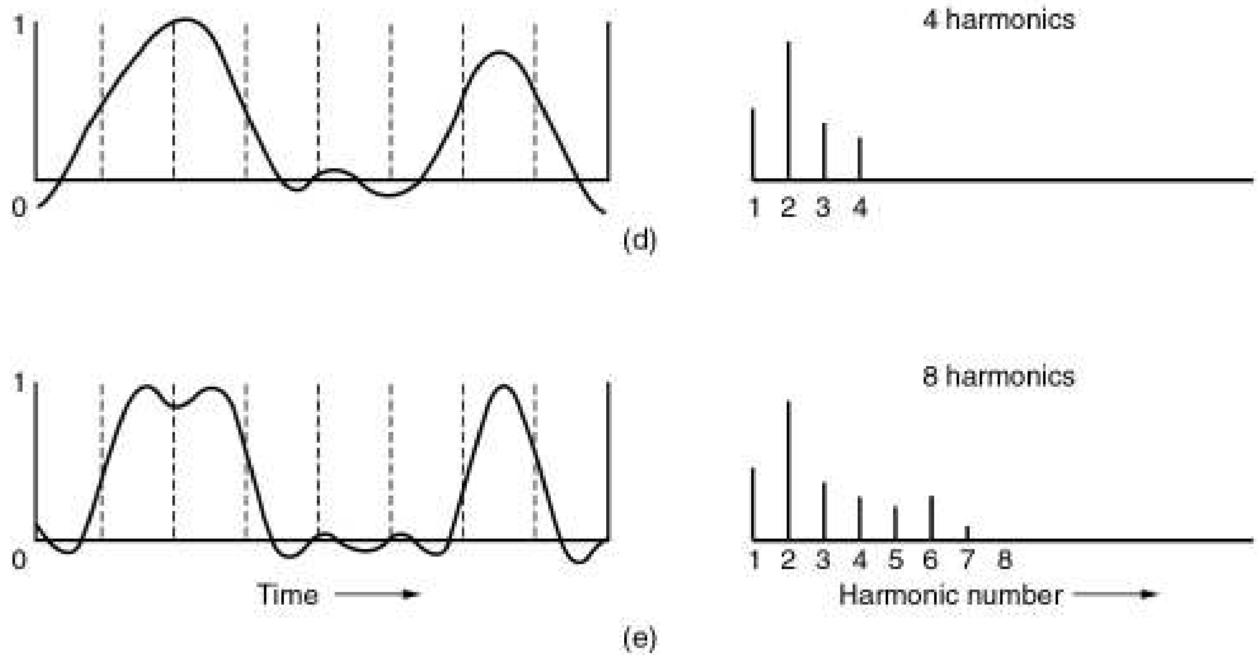
Bandwidth-Limited Signals (3/8)



(a) A binary signal and its root-mean-square Fourier amplitudes.

(b) – (c) Successive approximations to the original signal.

Bandwidth-Limited Signals (4/8)



(d) – (e) Successive approximations to the original signal.

Bandwidth-Limited Signals (5/8)

- This figure shows the Root-Mean-Square amplitudes for the first few terms. $\sqrt{a_n^2 + b_n^2}$
- These values are proportional to the energy transmitted at the corresponding frequency.

Bandwidth-Limited Signals (6/8)

- Usually, the amplitudes are transmitted undiminished from 0 up to some frequency f_c .

  All amplitudes above this cutoff frequency are transmitted attenuated.
- The range of frequencies transmitted without being strongly attenuated is called the bandwidth.
- Bandwidth is a physical property of the transmission medium and usually depends on the construction, thickness, and length of the medium.

Bandwidth-Limited Signals (7/8)

- Assume that a bit rate is *b bits/sec*.
- Then the time required to send 8 bits (for example) 1 bit at a time is *T=8/b sec*.
- So frequency of the first harmonic is *f=1/T=b/8 Hz.*
- An ordinary telephone line, often called a voice-grade line, has an artificially-introduced cutoff frequency just above *3000 Hz*.
- This restriction means that the number of the highest harmonic passed through is roughly 3000/(b/8) or 24,000/b.

Bandwidth-Limited Signals (8/8)

Bps	T (msec)	First harmonic (Hz)	# Harmonics sent
300	26.67	37.5	80
600	13.33	75	40
1200	6.67	150	20
2400	3.33	300	10
4800	1.67	600	5
9600	0.83	1200	2
19200	0.42	2400	1
38400	0.21	4800	0

Relation between data rate and harmonics.

Maximum Data Rate of a Channel (1/3)

- Nyquist Theorem: If an arbitrary signal has been run through a low-pass filter of bandwidth *H*, the filtered signal can be completely reconstructed by making only *2H* (exact) samples per second.

maximum data rate $= 2H \log_2 V$ bits/sec

V is discrete levels of signal, for binary signal *V=2*.

- For example, a noiseless *3-kHz* channel can transmit binary signals at a maximal rate *6000bps*.

Maximum Data Rate of a Channel (2/3)

- There is always random (thermal) noise present due to the motion of the molecules in the system.
- The amount of noise is measured by the ratio of the signal power to the noise power, called the signal-to-noise-ratio, or S/N.
- Usually, the ratio itself is not quoted; instead, the quantity $10 \log_{10} S/N$ is given.
- These units are called decibels (dB)
- An S/N ratio of 10 is 10 dB, a ratio of 100 is 20dB.

Maximum Data Rate of a Channel (3/3)

- Shannon Theorem: The maximum data rate of a noisy channel whose bandwidth is *H* Hz, and whose signal-to-noise ratio is *S/N*, is given by:

$$\text{maximum number of bits/sec} = H \log_2 (1 + S/N)$$

- For example, a channel of 3000 Hz bandwidth with a signal to thermal noise ratio of 30 dB can never transmit much more than 30,000 bps.

Transmission Media

- Various physical media can be used for the actual transmission.
- Each one has its own niche in terms of bandwidth, delay, cost, and ease of installation and maintenance.
- There are two groups of transmission media:

1) Guided media (copper wire, fiber optics, etc.)

2) Unguided media or wireless (terrestrial radio, lasers through the air, satellite, etc.)

- This material will provide background information on the key transmission technologies used in modern networks.

Guided Transmission Data

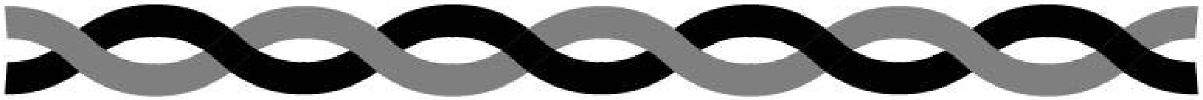
- Magnetic Media
- Twisted Pair
- Coaxial Cable
- Fiber Optics

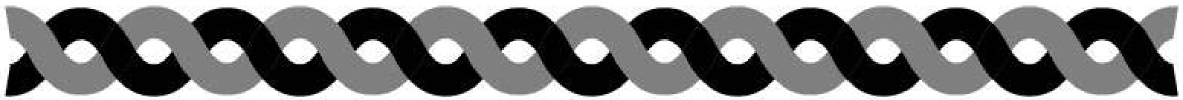
Magnetic Media

- Magnetic tape;
- Removable media (e.g., recordable DVDs);
- More cost effective, especially for applications in which high bandwidth or cost per bit transported is the key factor.

Twisted Pair (1/2)

A twisted pair consists of two insulated copper wires, typically about 1 mm thick.


(a)


(b)

(a) Category 3 UTP.

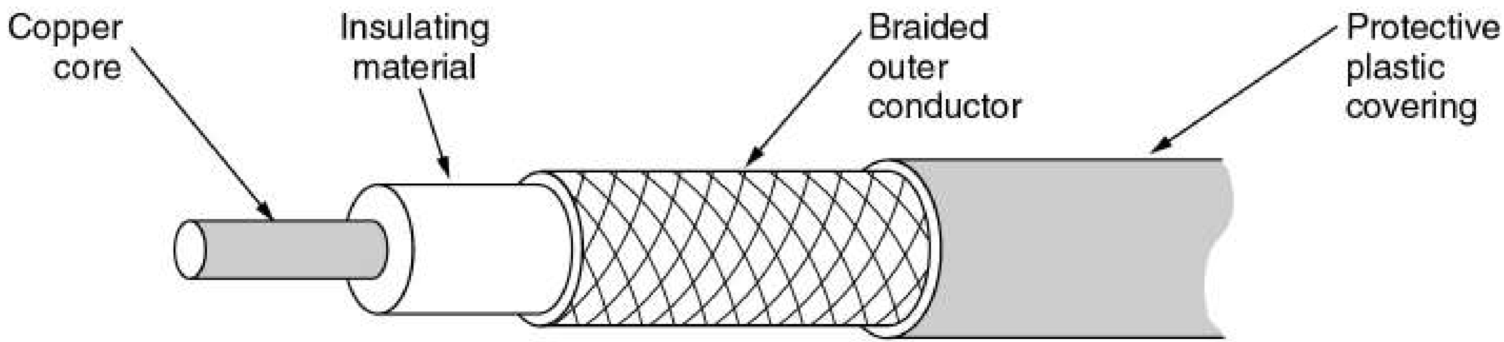
(b) Category 5 UTP.

Twisted Pair (2/2)

- Twisted pairs can run several kilometers without amplification, but for longer distances, repeaters are needed.
- Twisted pairs can be used for transmitting either analog or digital signals.
- The bandwidth depends on the thickness of the wire and the distance traveled, but several megabits/sec can be achieved for a few kilometers in many cases.

Coaxial Cable

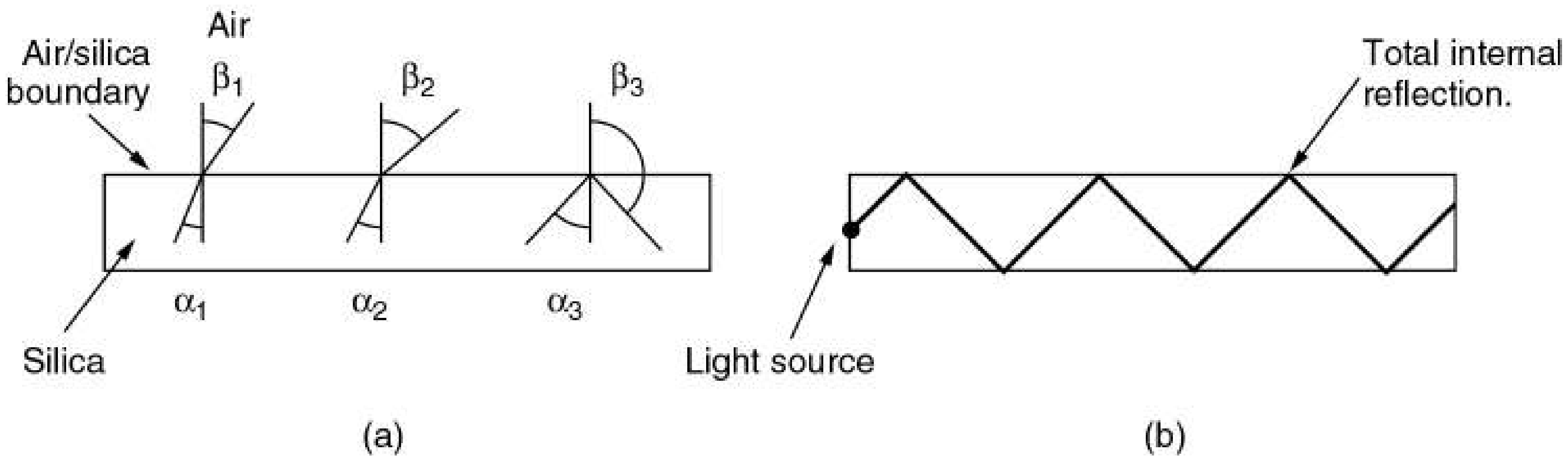
- A coaxial cable has better shielding than twisted pairs, so it can span longer distance at higher speeds.
- The bandwidth depends on the cable quality, length, and signal-to-noise ratio of the data signal.



A coaxial cable: Modern cables have a bandwidth of close to 1 GHz.

Fiber Optics (1/2)

An optical transmission system has three key components: the light source, the transmission medium, and the detector.



(a) Three examples of a light ray from inside a silica fiber impinging on the air/silica boundary at different angles.

(b) Light trapped by total internal reflection.

Fiber Optics (2/2)

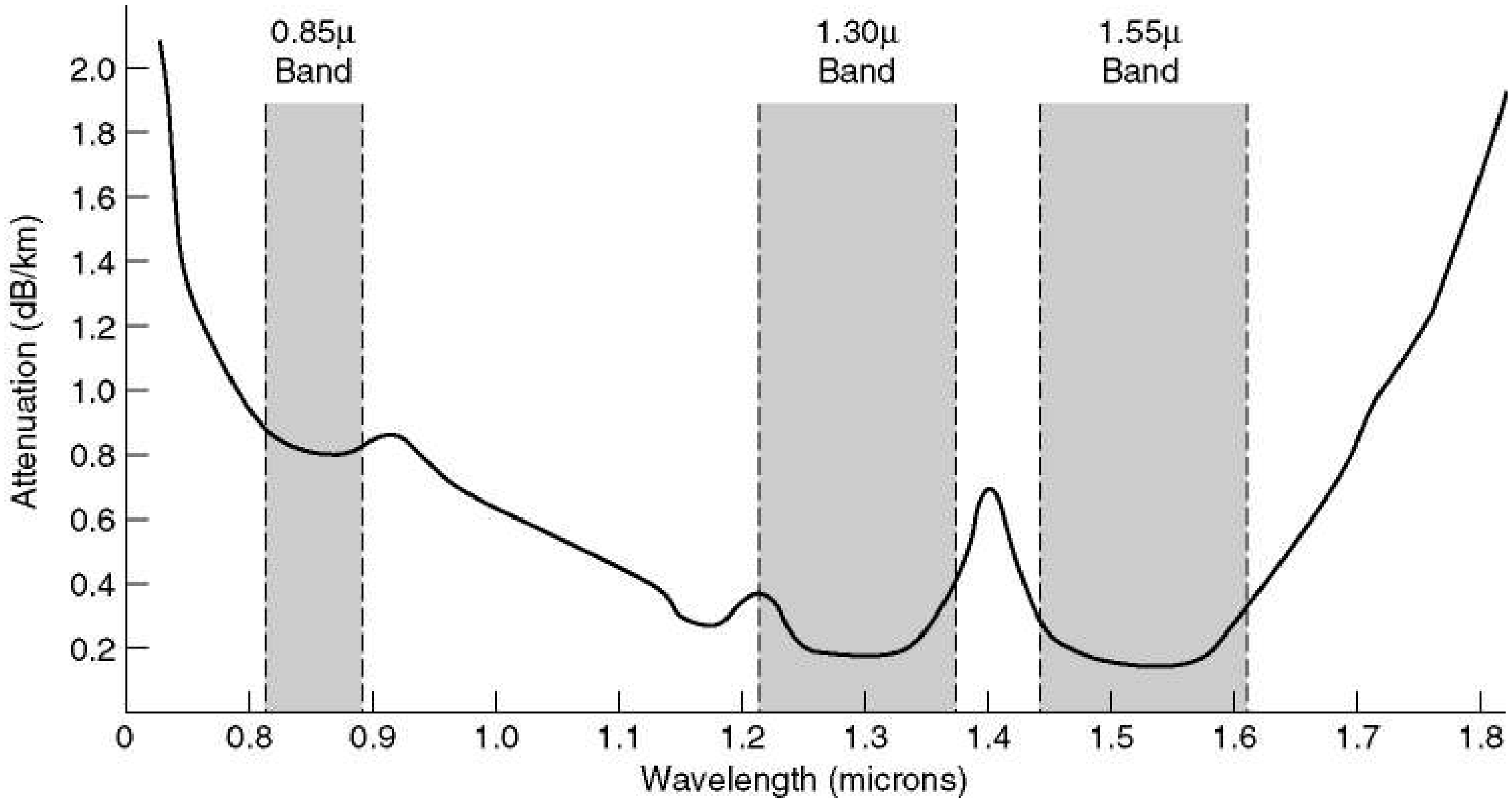
- Multimode Fiber.
- Singlemode Fiber.
- Singlemode fibers are more expensive but are widely used for longer distance.
- Currently available single mode fibers can transmit data at 50 Gbps for 100 km without amplification.

Transmission of Light through Fiber (1/3)

- The attenuation of light through glass depends on the wavelength of the light (as well as on some physical properties of the glass).
- The attenuation in decibels is given by the formula:

$$Attenuation\_in\_decibels = 10\log_{10}\frac{transmitted\_power}{received\_power}$$

Transmission of Light through Fiber (2/3)



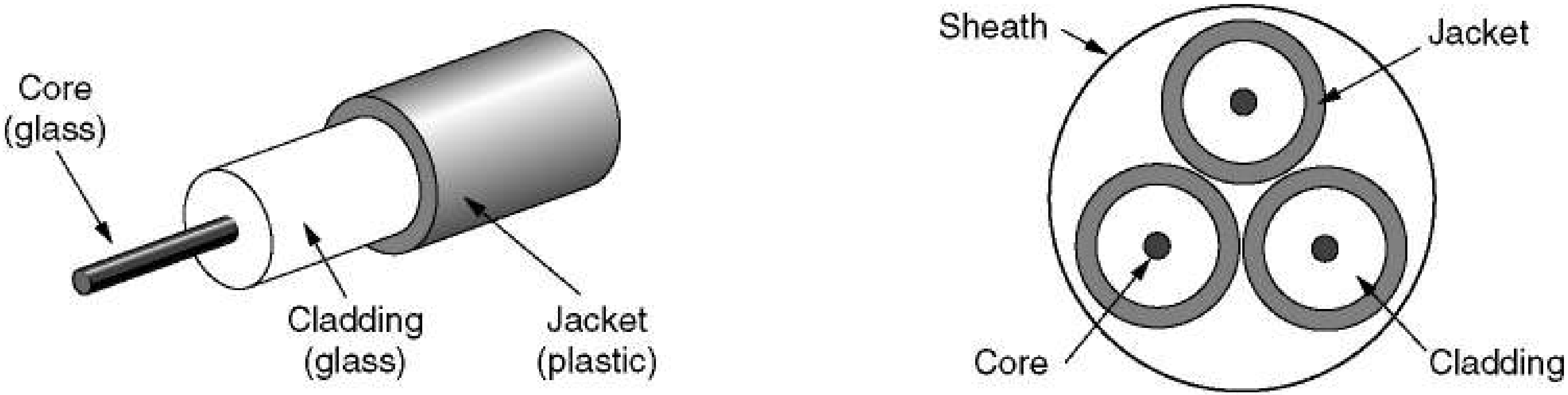
Attenuation of light through fiber in the infrared region.

Transmission of Light through Fiber (3/3)

- Three wavelength bands are used for optical communication.
- They are centered at 0.85, 1.30, and 1.55 microns, respectively.
- The last two have good attenuation properties (less than 5 percent loss per kilometer).
- All three bands are 25.000 to 30.000 GHz.

Fiber Cables (1/3)

Fiber optic cables are similar to coax, except without the braid.



(a) (b)

(a) Side view of a single fiber: the core is 8 to 10 microns in diameter.

(b) End view of a sheath with three fibers: the core is typically 50 microns in diameter.

Fiber Cables (2/3)

- Fibers can be connected in three different ways.
- First, they can terminate in connectors and be plugged into fiber sockets. Connectors lose about 10 to 20 percent of the light, but they make it easy to reconfigure systems.
- Second, they can be spliced mechanically. Mechanical splices take trained personnel about 5 minutes and result in a 10 percent light loss.
- Third, two pieces of fiber can be fused (melted) to form a solid connection. A small amount of attenuation occurs.

Fiber Cables (3/3)

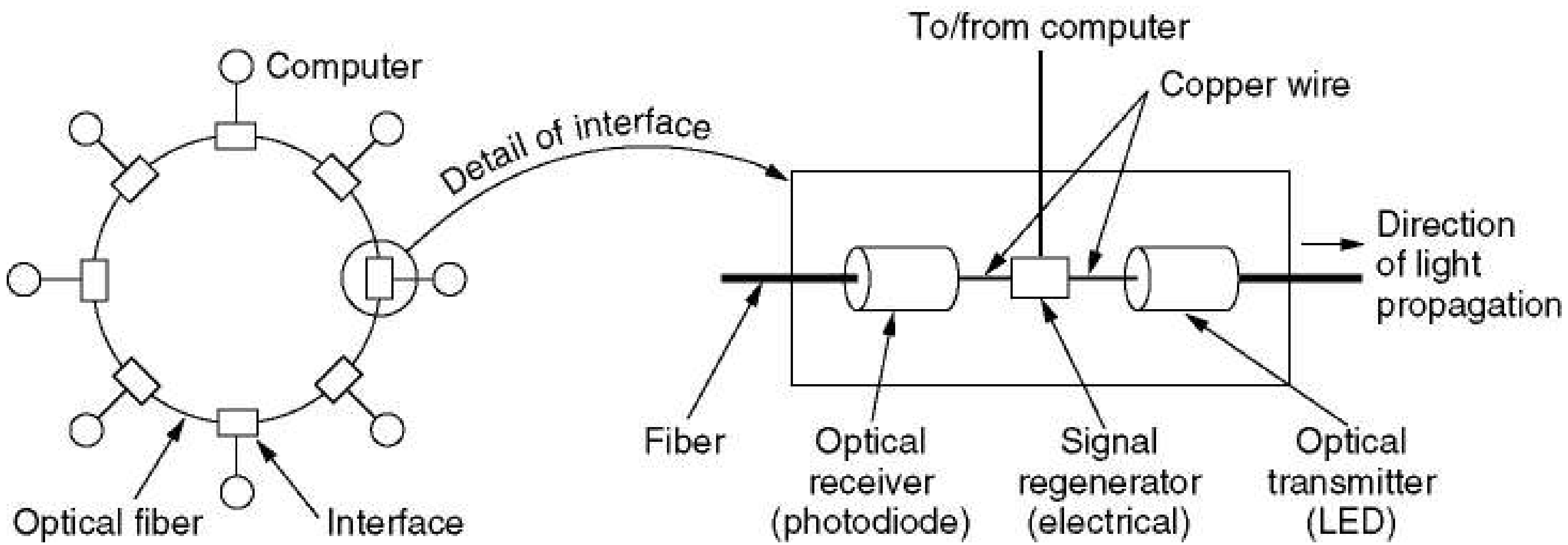
Item	LED	Semiconductor laser
Data rate	Low	High
Fiber type	Multimode	Multimode or single mode
Distance	Short	Long
Lifetime	Long life	Short life
Temperature sensitivity	Minor	Substantial
Cost	Low cost	Expensive

A comparison of semiconductor diodes and LEDs as light sources.

- The receiving end of an optical fiber consists of a photodiode, which gives off an electrical pulse when struck by light.
- The typical response time of a photodiode is 1 nsec., which limits data rates to about 1 Gbps.

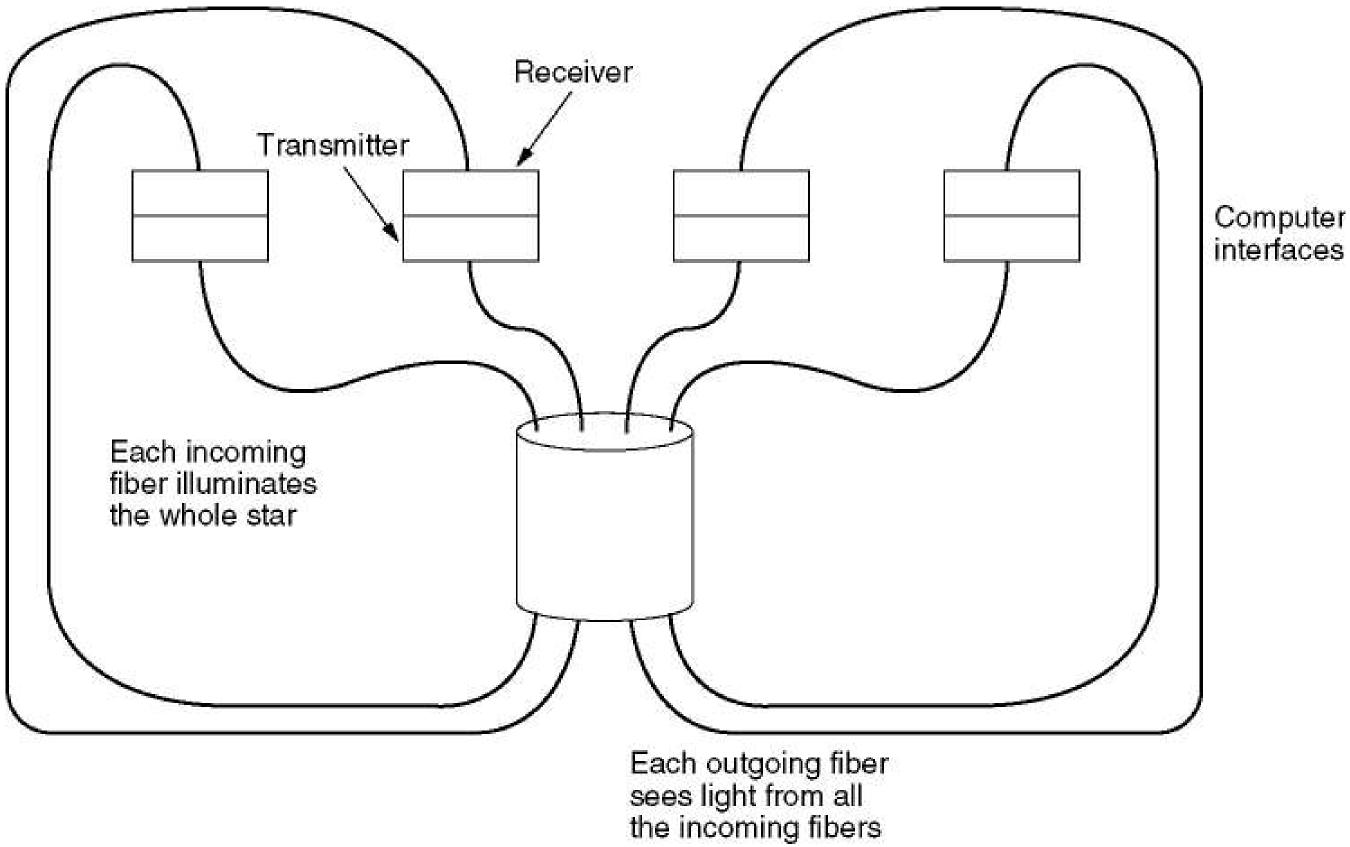
Fiber Optic Networks

Fiber optics can be used for LANs as well as for long-haul transmissions.



A fiber optic ring with active repeaters.

Fiber Optic Networks (2)



A passive star connection in a fiber optics network.

Wireless Transmission (1/4)

- Some users need to be on-line all the time.
- For these users, wireless communication is the answer.
- The future holds only two kinds of communication:

a) Fiber;

b) Wireless.

- All fixed (i.e., nonmobile) computers, telephones, faxes, and so on will use fiber, and all mobile ones will use wireless.

Wireless Transmission (2/4)

- The principle of the wireless communication:

-When electrons move, they create electromagnetic waves that can propagate through space (even in a vacuum).

-The number of oscillations per second of a wave is called its frequency, *f*, and is measured in *Hz*.

-The distance between two consecutive maxima (or minima) is called the wavelength – λ *(lambda)*.

Wireless Transmission (3/4)

- The principle of the wireless communication (Cont).

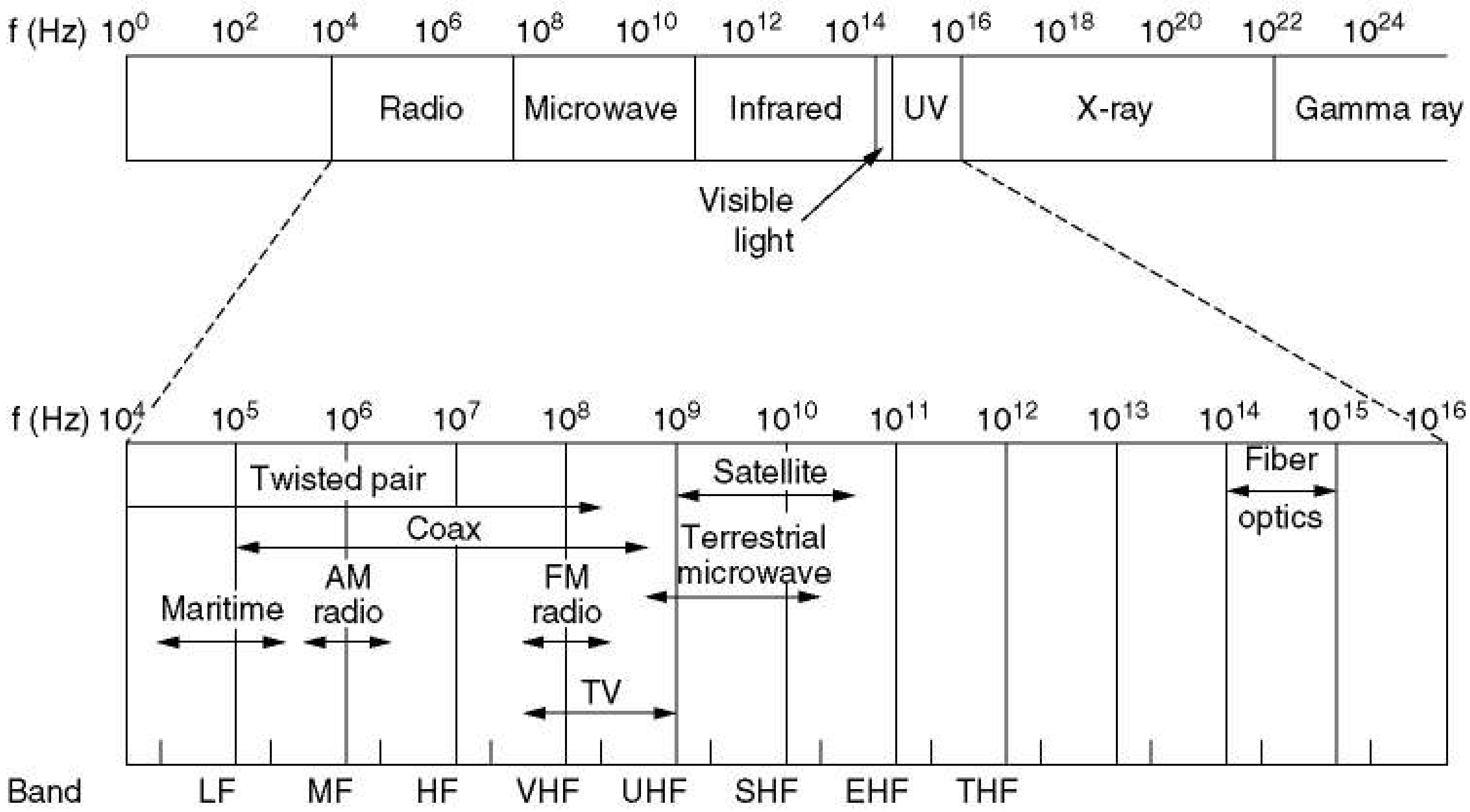
-When an antenna of the appropriate size is attached to an electrical circuit, the electromagnetic waves can be broadcast efficiently and received by a receiver some distance away.

-All wireless communication is based on this principle.

Wireless Transmission (4/4)

- The Electromagnetic Spectrum
- Radio Transmission
- Microwave Transmission
- Infrared and Millimeter Waves
- Lightwave Transmission

The Electromagnetic Spectrum (1/6)



The electromagnetic spectrum and its uses for communication.

The Electromagnetic Spectrum (2/6)

- The “radio, microwave, infrared, and visible light portions of the spectrum can of the spectrum can all be used for transmitting information by modulating the amplitude, frequency, or phase of waves.
- Ultraviolet light, X-rays, and gamma rays would be even better, due to their higher frequencies, but they are hard to produce and modulate, do not propagate well through buildings, and are dangerous to living things.

The Electromagnetic Spectrum (3/6)

- The amount of information that an electromagnetic wave can carry is related to its bandwidth.
- With current technology, it is possible to encode a few bits per Herts at low frequencies, but often as many as 8 at high frequencies, so a coaxial cable with a 750 MHz bandwidth can carry several gigabits/sec.

The Electromagnetic Spectrum (4/6)

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

∇f is the corresponding frequency band

c is speed of light.

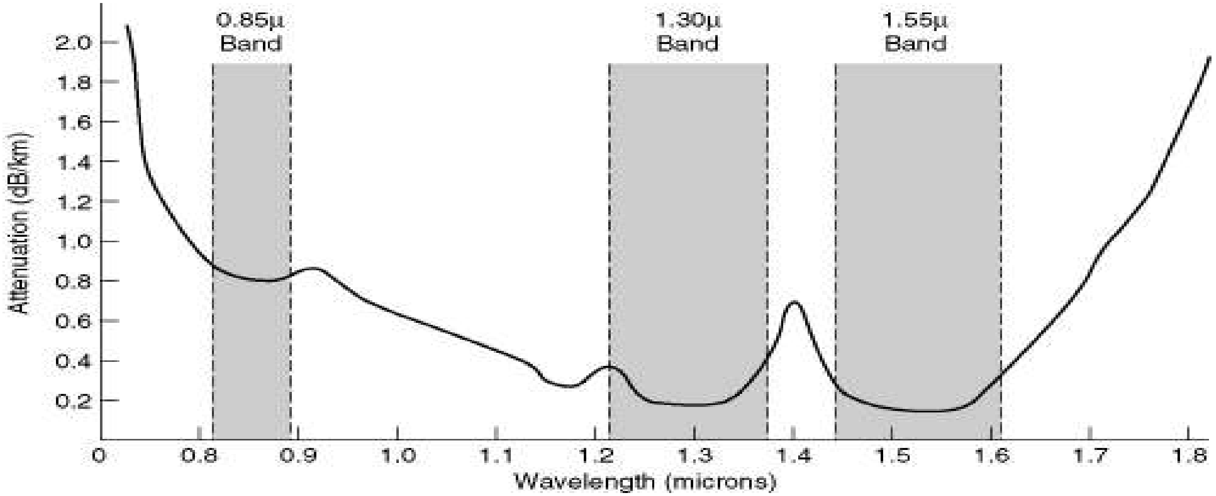
$\nabla\lambda$ is the width of a wavelength band.

λ is the wavelength

As we see the wider the band, the higher the data rate.

The Electromagnetic Spectrum (5/6)

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



Example: Consider the 1.30-micron band.

Here we have $\lambda = 1.3x10^{-6}$ and $\nabla\lambda = 0.17x10^{-6}$

So, ∇f is about 30 THz.

At, say, 8 bits/Hz, we get 240 Tbps.

The Electromagnetic Spectrum (6/6)

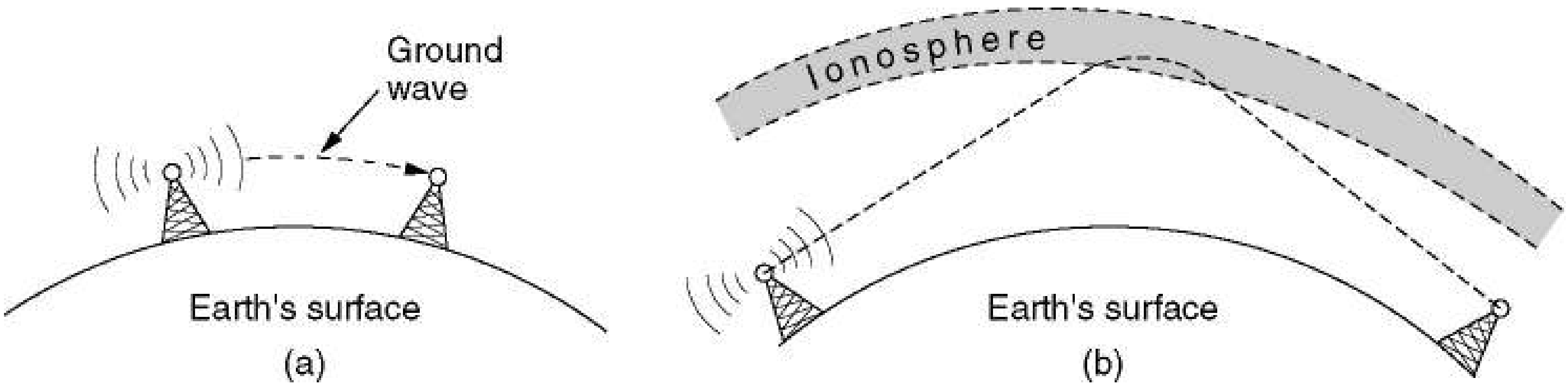
- Most transmissions use a narrow frequency band (i.e., $\nabla f / f$ << 1) to get best reception (many watts/Hz);
- However, in some cases, a wide band is used.

a) Frequency hopping spread spectrum;

b) Direct sequence spread spectrum.

Radio Transmission

Radio waves are easy to generate, can travel long distance, can penetrate buildings and omnidirectional.



(a) In the VLF, LF, and MF bands, radio waves follow the curvature of the earth.

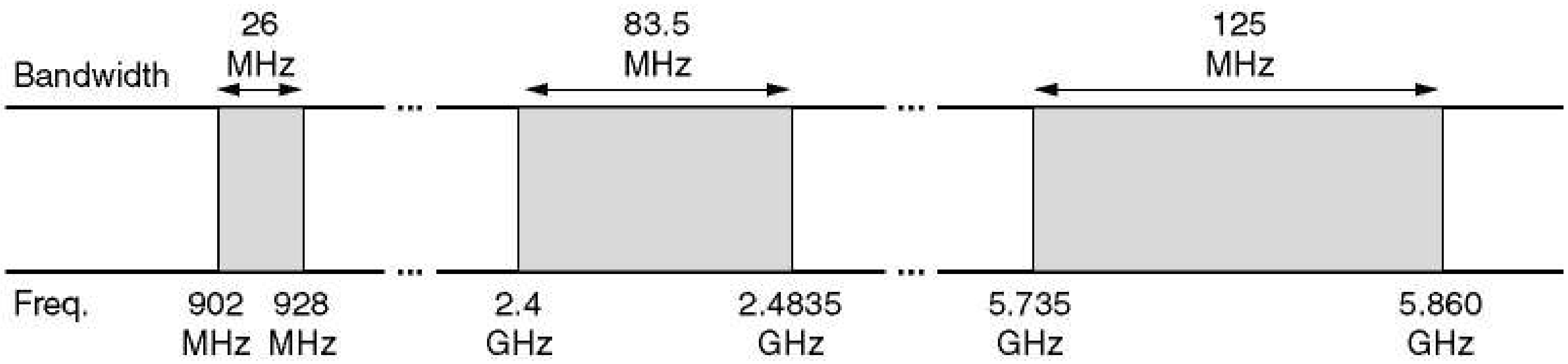
(b) In the HF band, they bounce off the ionosphere.

Microwave Transmission

- Above 100 MHz, the waves travel in nearly straight lines and can therefore be narrowly focused.
- Since the microwaves travel in a straight line, if the towers are too far apart, the earth will get in the way. Consequently, repeaters are needed periodically.
- Microwave communication is widely used for long-distance telephone communication, mobile phone, television distribution, etc.

Politics of the Electromagnetic Spectrum

National governments allocate spectrum for AM and FM radio, television, and mobile phone, as well as for telephone companies, police, maritime, navigation, military, government, and many other competing users.

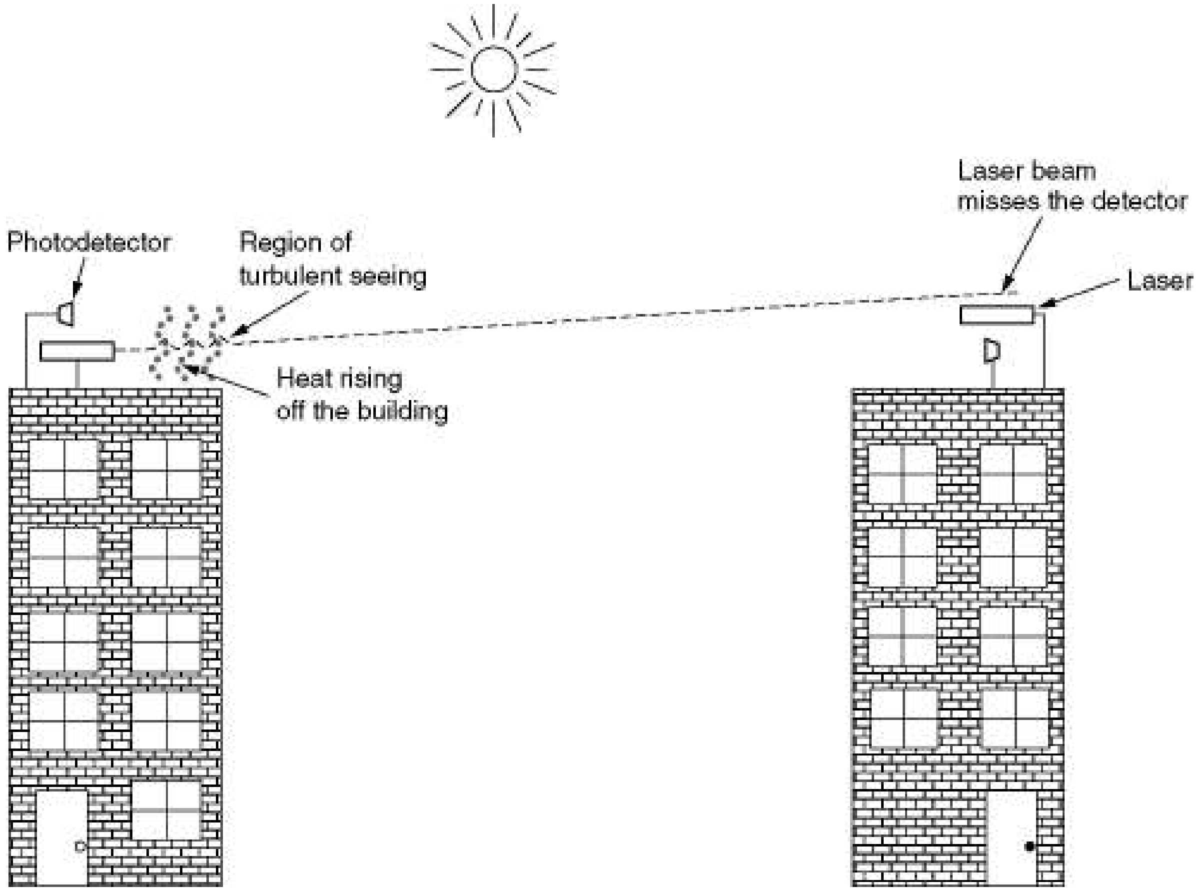


The ISM (Industrial, Scientific, Medical) bands in the United States.

Infrared and Millimeter Waves

- They are used for short-range communication.
- The remote controls used on televisions, VCRs, and steres all use infrared communication
- The infrared waves do not pass through solid walls.

Lightwave Transmission



Convection currents can interfere with laser communication systems.
A bidirectional system with two lasers is pictured here.

Communication Satellites (1/4)

- Communication satellite is a big microwave repeater in the sky.
- Communication satellite contains several transponders, each of which listens to some portion of the spectrum, amplifies the incoming signal, and then rebroadcast it at another frequency to avoid interference with the incoming signal.

Communication Satellites (2/4)

- The downward beams can be broad, covering a substantial fractions of the earth's surface, or narrow, covering an area only hundreds of kilometers in diameter.
- This mode of operation is known as a bent pipe.

Communication Satellites (3/4)

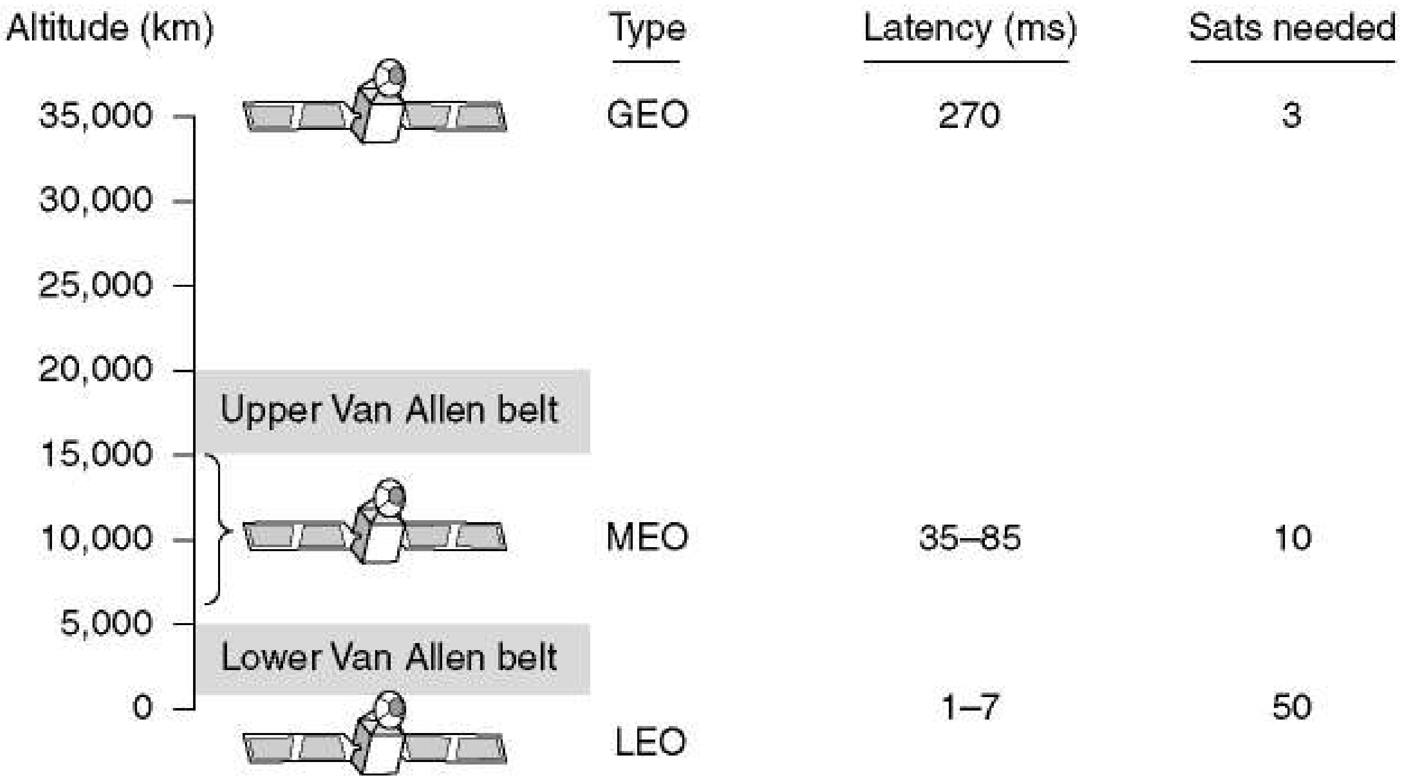
- According to Kepler's law, the orbital period of a satellite varies as the radius of the orbit to the 3/2 power.
- The higher the satellite, the longer the period.
- Near the surface of the earth, the period is about 90 minutes.
- At an altitude of about 35.800 km, the period is 24 hours
- At an altitude of about 384.000 km, the period is about 1 month.

Communication Satellites (4/4)

- Geostationary-Earth Orbit (GEO) Satellites
- Medium-Earth Orbit (MEO) Satellites
- Low-Earth Orbit (LEO) Satellites
- Satellites versus Fiber

- Geostationary satellites include the orbits, solar panels, radio frequencies and launch procedures.

Communication Satellites (1)



Communication satellites and some of their properties, including altitude above the earth, round-trip delay time and number of satellites needed for global coverage.

Geostationary Satellites (1/3)

Band	Downlink	Uplink	Bandwidth	Problems
L	1.5 GHz	1.6 GHz	15 MHz	Low bandwidth; crowded
S	1.9 GHz	2.2 GHz	70 MHz	Low bandwidth; crowded
C	4.0 GHz	6.0 GHz	500 MHz	Terrestrial interference
Ku	11 GHz	14 GHz	500 MHz	Rain
Ka	20 GHz	30 GHz	3500 MHz	Rain, equipment cost

The principal satellite bands.

C band – Commercial satellite traffic

L and S bands – International agreement (2000)

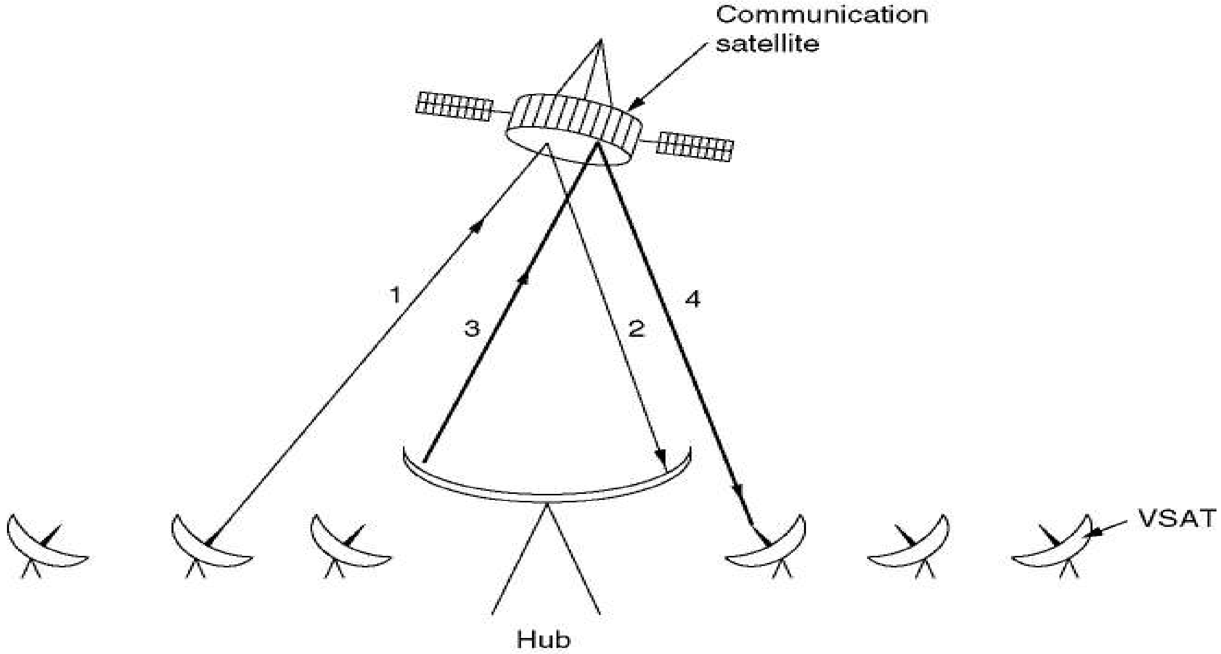
Ku (under) band – Commercial telecommunication carriers

Ka (above) band - Commercial satellite traffic

Geostationary Satellites (2/3)

- A modern satellite has around 40 transponders, each with an 80-MHz bandwidth.
- The first geostationary satellites covered about 1/3 of the earth's surface, called footprint.
- With the enormous decline in the price, size, and power requirements of microelectronics, footprints can be focused on a small geographical area.
- VSATs (Very Small Aperture Terminals) are low cost microstations. They have 1-meter or smaller antennas (versus 10 m for a standard GEO antenna) and can put out about 1 watt of power.

Geostationary Satellites (3/3)



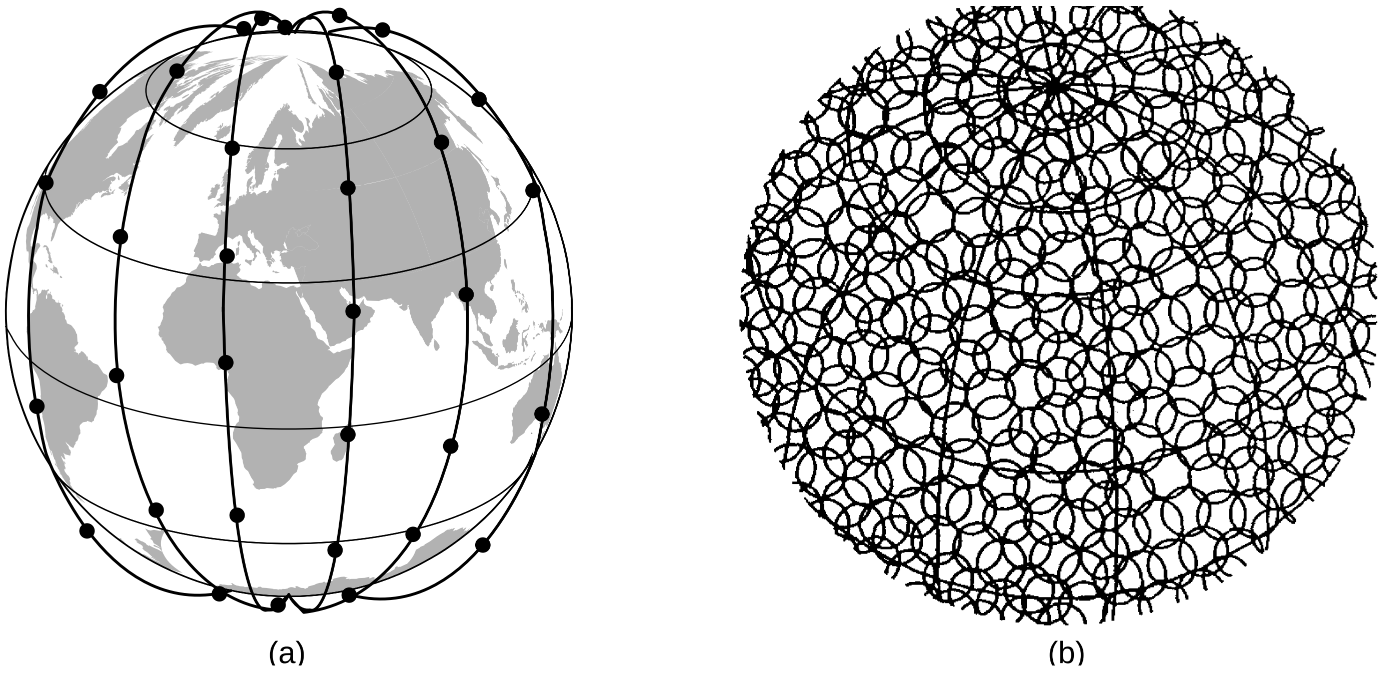
VSATs (Very Small Aperture Terminals) using a hub.

The microstations do not have enough power to communicate directly with another (via the satellite, of course). Instead, a special ground station, the hub, with a large, high-gain antenna is needed to relay traffic between VSATs.

Medium-Earth Orbit (MEO) Satellites

- MEO satellites are placed at much lower amplitudes.
- Currently, MEO satellites are not used for telecommunications.
- The 24 GPS (Global Positioning System) sattelite orbiting at about 18,000 km are examples of MEO Sattelites.

Low-Earth Orbit Satellites Iridium (Voice Communication)



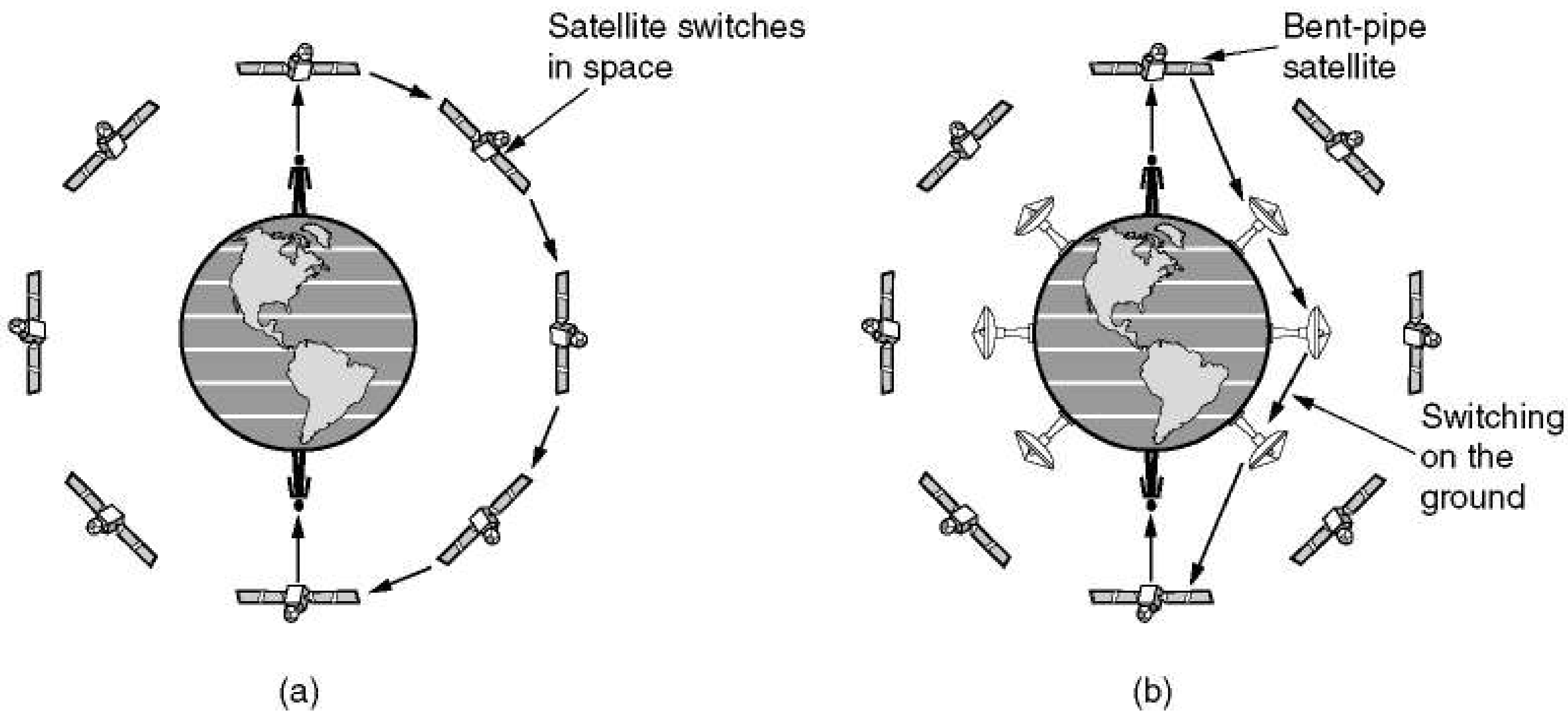
(a) The Iridium satellites from six necklaces around the earth.

(b) 1628 moving cells cover the earth.

Iridium is the element number 77

Dysprosium is the element number 66

Globalstar
(Voice Communication)



(a) Relaying in space.

(b) Relaying on the ground.

Teledesic (Internet Services)

- Teledesic is targeted at bandwidth-hungry Internet users all over the world.
- An uplink is about 100 Mbps
- A downlink is about 720 Mbps
- Teledesic uses a small, fixed, VSAT-type antenna.