COMPUTER NETWORKS

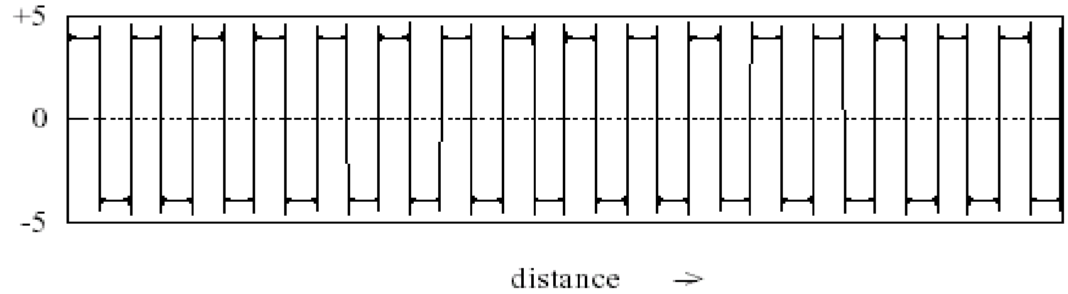
Chapter 02
The Physical Layer
Part 1

Chapter 2 The Physical Layer

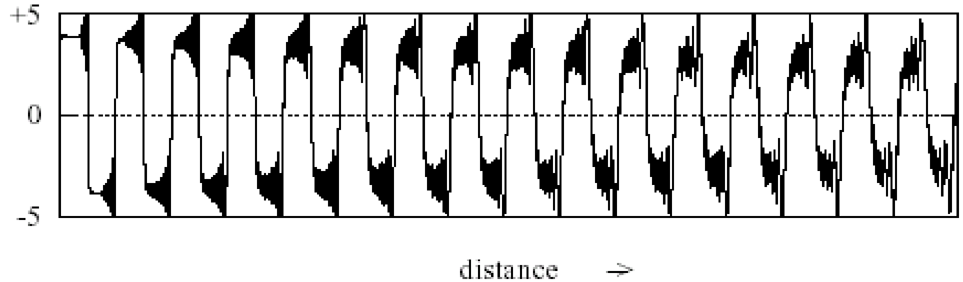
- **Essence:** Physical layer defines the mechanical, electrical, and functional timing interfaces to the network, provides the means to transmit bits from sender to receiver, that is, involves a lot on how to use (analog) signals for digital information.
- What will be talked about?
  - Theoretical analysis of data transmission
  - Transmission media (wires and no wires)
  - Three communication system: telephone, mobile phone, and cable television system

2.1 The Theoretical Basis for Data Communication

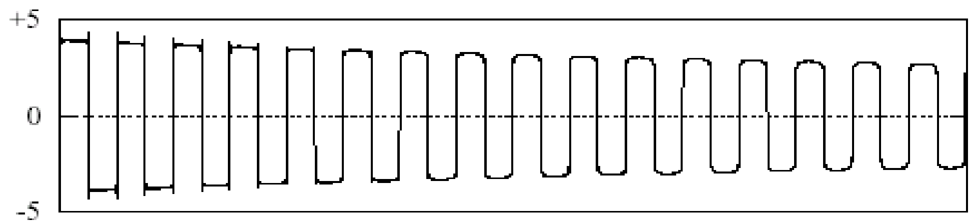
- We’re living in a digital world, meaning that we’d preferably want to send digital (i.e. two-valued) signals through wires.
- Wires are pretty much physical, meaning that Mother Nature will probably impose a few constraints here and there.
- **Observation:** Signals are not entirely transmitted through a wire as you would expect:



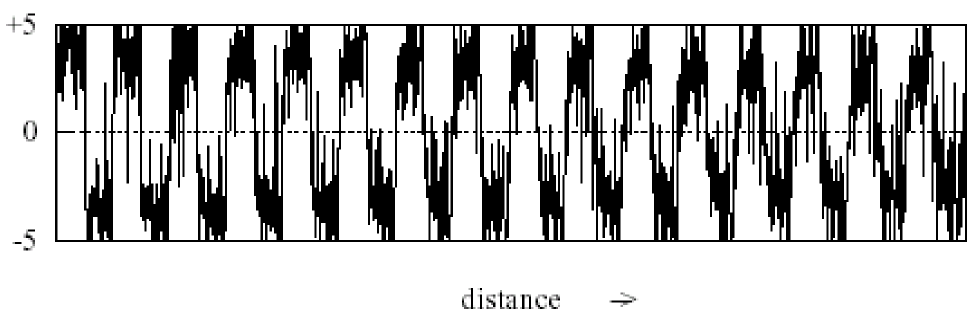
Effect of frequency-dependent **transmission delays**:



Effect of frequency-dependent **attenuation**:



Overall effect including **noise**:



- To understand what's going on, we need **Fourier Analysis**.
- A periodic function with period *T* (and frequency *f* = 1/*T*), *g*(*t*) can be written as:
  - Where $f = 1/T$ is the fundamental frequency, a_n and b_n are the sine and cosine amplitude of the *nth* harmonics (terms), and *c* is a constant.---Fourier Series

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

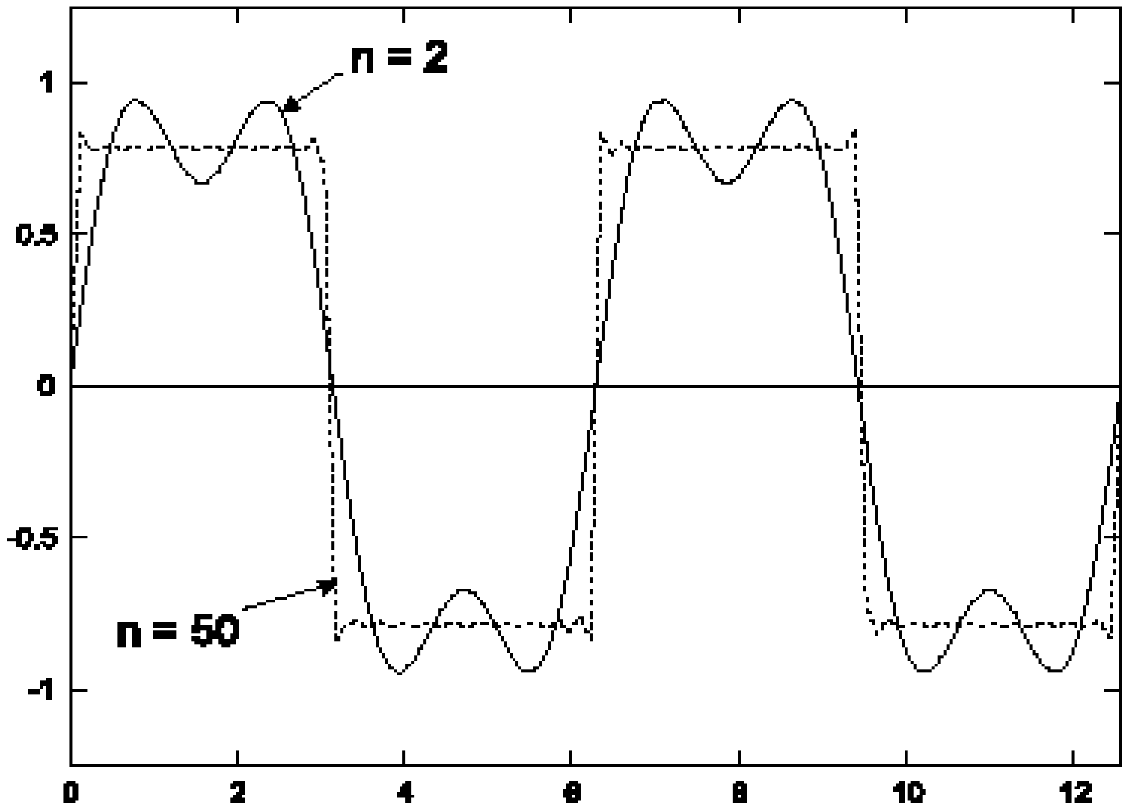
$$\int_0^T \sin(2\pi k f t)\sin(2\pi n f t)dt = \begin{cases} 0\ for\ k \neq n \\ T/2\ for\ k = n \end{cases}$$

$$a_n = \frac{2}{T}\int_0^T g(t)\sin(2\pi n f t)dt \qquad b_n = \frac{2}{T}\int_0^T g(t)\cos(2\pi n f t)dt$$

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

Example: $g(t) = \sum_{k=1}^{n} \frac{1}{2k-1} \sin[(2k-1)t]$

(n is the number of **harmonics** we take into account)



2.1.2 Bandwidth-Limited Signals

- **Example: 01100010,** 8 bit for ASCII “b”

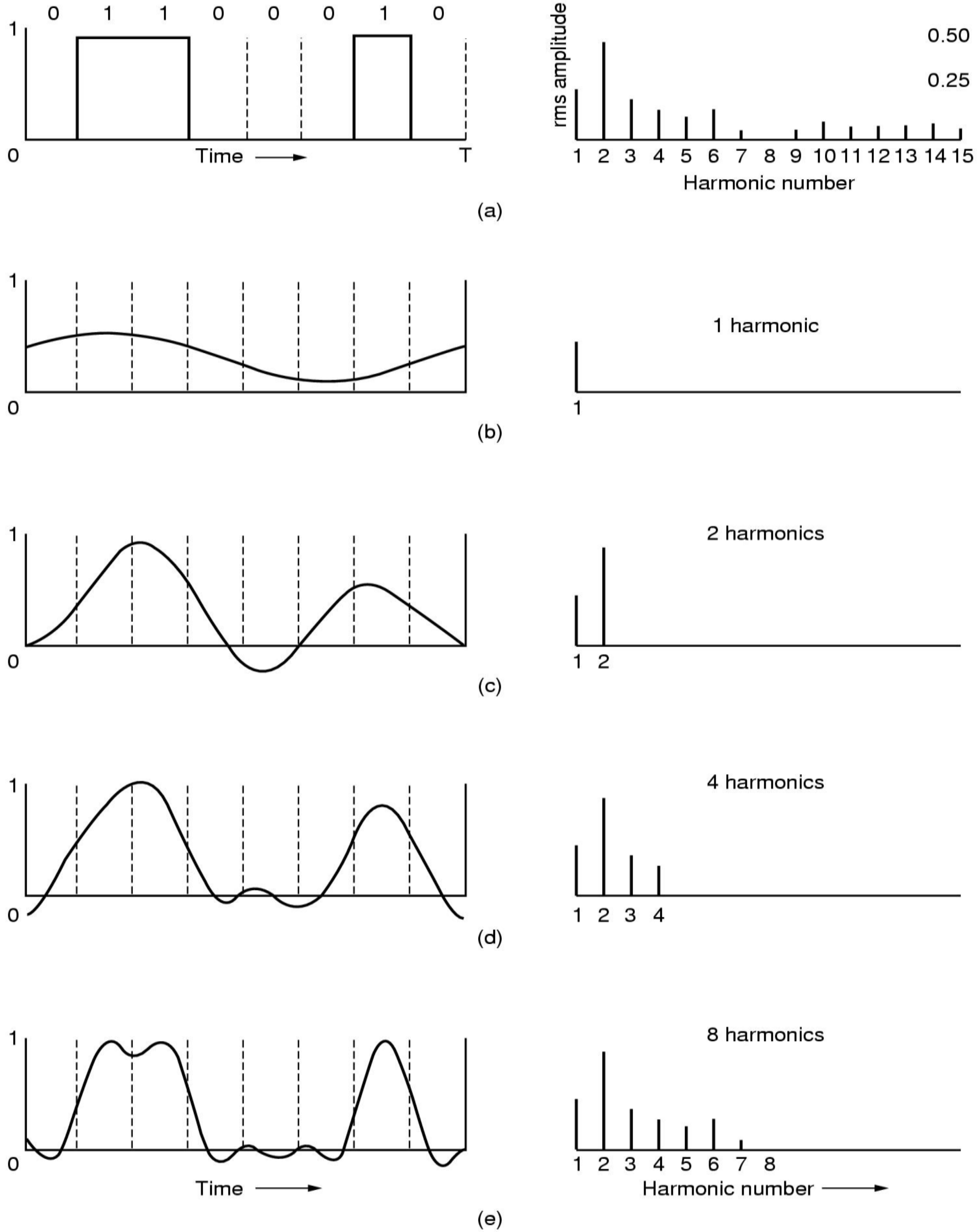
$a_n = 1/\pi n[\cos(\pi n/4) - \cos(3\pi n/4) + \cos(6\pi n/4) - \cos(7\pi n/4)]$

$b_n = 1/\pi n[\sin(3\pi n/4) - \sin(\pi n/4) + \sin(7\pi n/4) - \sin(6\pi n/4)]$

$c_n = 3/4$

The root mean square amplitudes is $(a_n^2 + b_n^2)^{1/2}$.

$$\sqrt{a_n^2 + b_n^2}$$



Note: root mean squares (on the right) reflect the dispersed energy at the given frequency.

Bandwidth

- What does this all mean?
  - Digital signal transmission can be thought of as being constructed as an infinite number of periodic analog signals.
  - The quality of transmission is frequency dependent, not all parts of the digital signal get through the wire as you would expect.
  - Digital signal transmission is subject to attenuation, distortion, etc. This is partly caused by disallowing high-frequency components to pass through. So the range of frequency or the number of bits of a transmission medium is called **bandwidth**.

- **Example:** (We are trying to transmit a single byte):
  - With a bit rate of b bits/sec, it takes 8/b seconds to send a byte.
  - The frequency $f1$ of the first harmonic is b/8 Hz
  - **Assumption:** We are using a simple encoding technique based on the fact that the line supports only two signal values.

bps	T(msec)	First harmonic (Hz)	# harmonics sent
300	26.67	37.5	80
600	13.33	75.0	40
1200	6.67	150.0	20
2400	3.33	300.0	10
4800	1.67	600.0	5
9600	0.83	1200.0	2
19200	0.42	2400.0	1
38400	0.21	4800.0	0

Bandwidth

- **Observation:** Most telephone carriers cut off the highest frequency at 3000 Hz, we can never transmit at a higher speed than 9600 bps (and without special encoding, it’s much lower)
- As a matter of fact, telephone line’s bandwidth is set at 4000Hz.

Improvement of Bandwidth

If there are four signal values available, we could encode 2 bits at a time:

00: 0 volt; 01: 2 volts; 10: 4 volts; 11: 6 volts

The number changes in a signal per second is called the **baud**.

Example: A 2400 bauds line (modem) can make a bit rate of 9600 bps provided it uses 16 (2^4) signal values:

S	bits	S	bits	S	bits	S	Bits
0	0000	4	0100	8	1000	12	1100
1	0001	5	0101	9	1001	13	1101
2	0010	6	0110	10	1010	14	1110
3	0011	7	0111	11	1011	15	1111

Baud-rate and Bit-rate

- What is baud rate:

The number changes in a signal per second is called the **baud rate, B=1/T**.

- What is bit rate:

The number of bits transmitted per second is called the **bit rate, bits per second, b/s or bps.**

- What is the relationship between bit rate and baud rate:

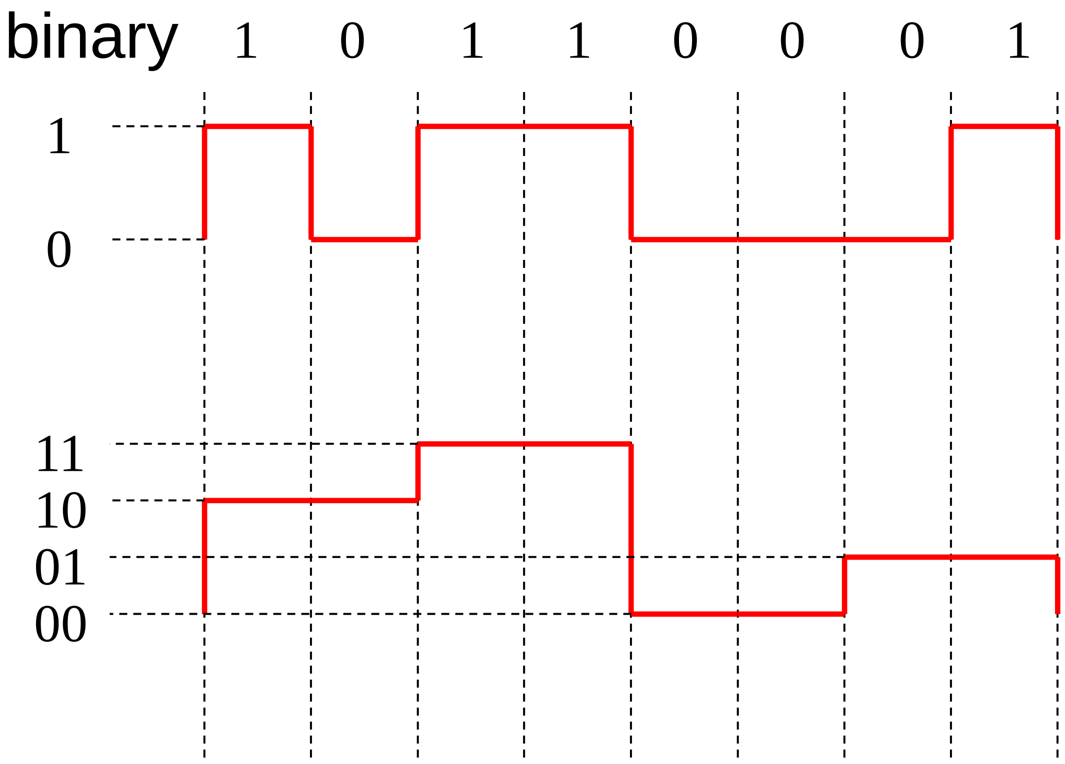
$$s = B * \log_2 v = 1/T * \log_2 v$$

where s is bit rate, B is baud rate, T is frequency period, v is number of signal values.

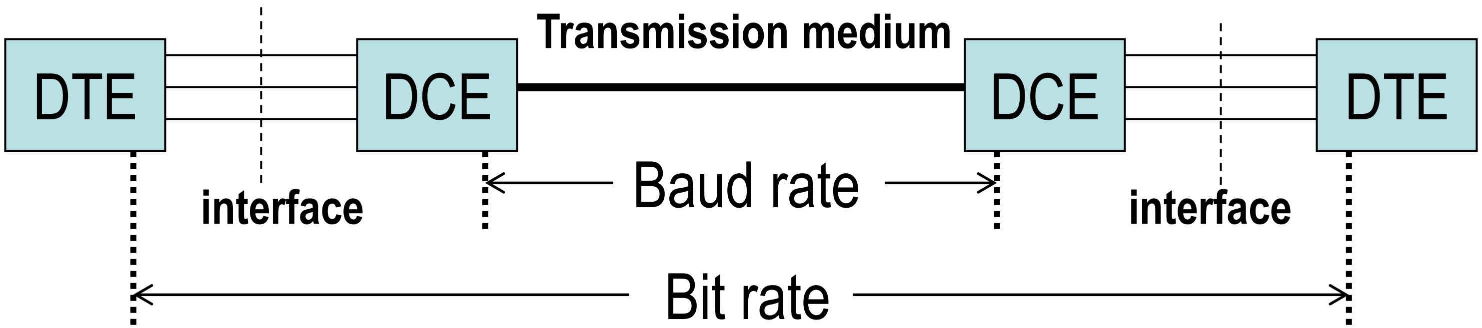
Ex: B=9600, v=2, s=9600 bps;

B=2400, v=16, s=9600 bps

Example for relationship between baud-rate and bit-rate



- Where do we talk about bit rate and baud rate?



2.1.3 The maximum data rate of a channel

- **Nyquist theory**

Nyquist showed that if the cut-off frequency is H Hz, the filtered signal can be reconstructed by making $2H$ samples. No more, no less. Consequence:

Maximum transmission rate = $2H \log_2 V$ bps (where V is the number of signal values)

This is for noiseless channels, say the maxim data rate of a 3-kHz noiseless channel is no more than 6000 bps, for binary transmission.

- **Shannon** showed that a *noisy* channel with a signal-to-noise ratio S/N, has a limit with respect to the bit rate:

Maximum transmission rate = $H \log_2 (1+S/N)$

In practice, we use dB(decibel) to represent signal-to-noise ratio in stead of S/N: $10\log_{10}(S/N)$ = ? dB

Example: A telephone line with H = 3000 and $10\log_{10}(S/N)=30\text{dB}$, can do no better than 30 kbps, no matter how you do your encoding (excluding compression). Here S/N is 1000, $\log_2 (1+S/N)$ is about 10.

2.2 Guided Transmission Media

- **Magnetic Media**

Never underestimate the bandwidth of a station wagon full of tapes hurtling down the highway

- Take a standard videotape that can carry about 200 gigabytes of data.
- A box of 60 x 60 x 60 cm can hold about 1000 tapes, which corresponds to 200TB, or 1600Tb.
- Sending such a box can be done within 24 hours, worldwide, 19Gbps; or 400Gbps within one hour.
- Costs: roughly $5000 to ship 200TB, 3 cents for 1GB
- **Question:** What is overlooked in this reasoning?
- **Answer: Delay**

Copper Wires

- **Twisted pair**

  Two insulated copper wires, twisted like a DNA string (reduces electrical interference). Often, twisted pairs go
  b at
  h

  F
  uns
  10B
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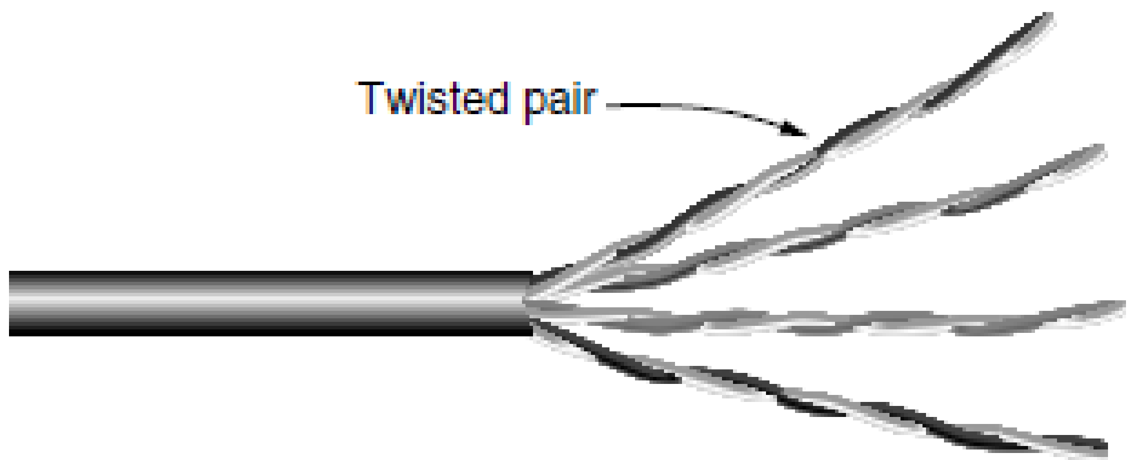
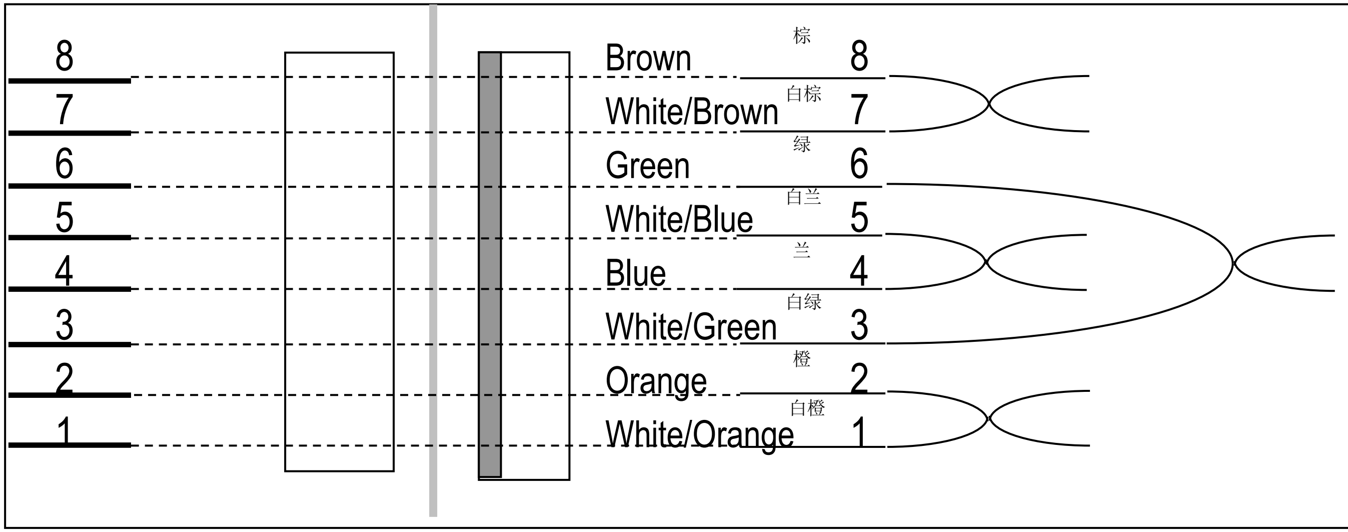


Figure 2-3. Category 5 UTP cable with four twisted pairs.

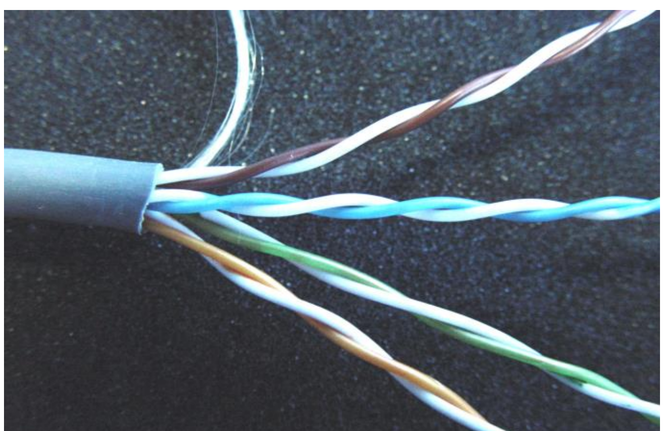
Category 5/Super Category 5

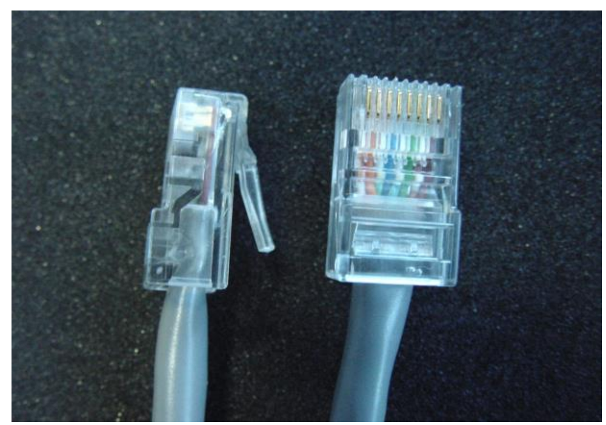
Category 6/7: for Gigabit transmission

- Connection standard: 568A/568B
  - 568B:



(a) (b)



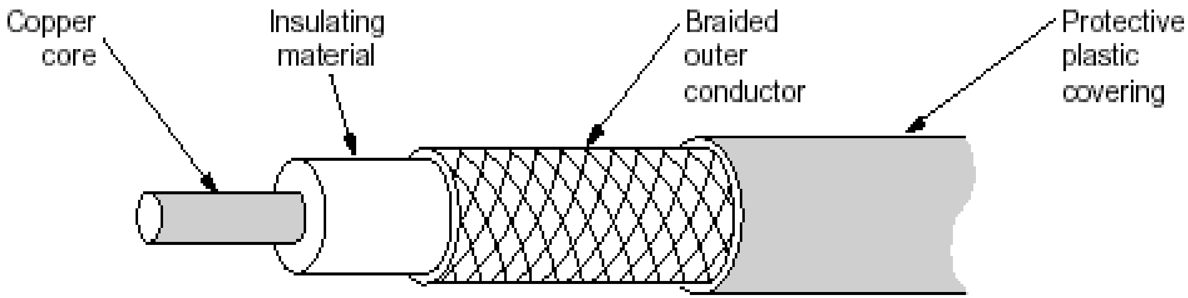


Link Terminology

- Full-duplex link
  - Used for transmission in both directions at once
  - e.g., use different twisted pairs for each direction
- Half-duplex link
  - Both directions, but not at the same time
  - e.g., senders take turns on a wireless channel
- Simplex link
  - Only one fixed direction at all times; not common

- **Coaxial Cable**

Exactly like the one you use for your TV Set:



- Baseband Coax
  50-ohm cable for digital transmission
  10Base-2, BNC, Thin-LAN, 185m/per segment
  10Base-5, AUI, Thick-LAN, 500m/ per segment
  At most 5 segments, up to 945m/2500m.
- Broadband Coax
  75-ohm cable for analog transmission, like cable TV.


2002 9 10


D-Link
Ethernet Transceiver
DE-850 Piercing Tap
2002 9 10


2002 9 10

Power Lines

- Household electrical wiring is another example of wires
  - Convenient to use, but horrible for sending data

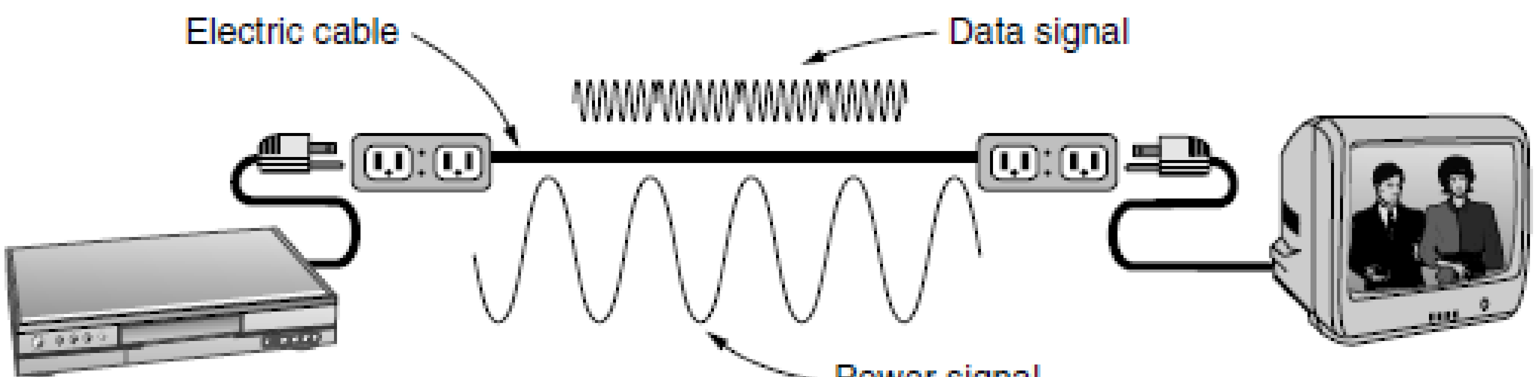
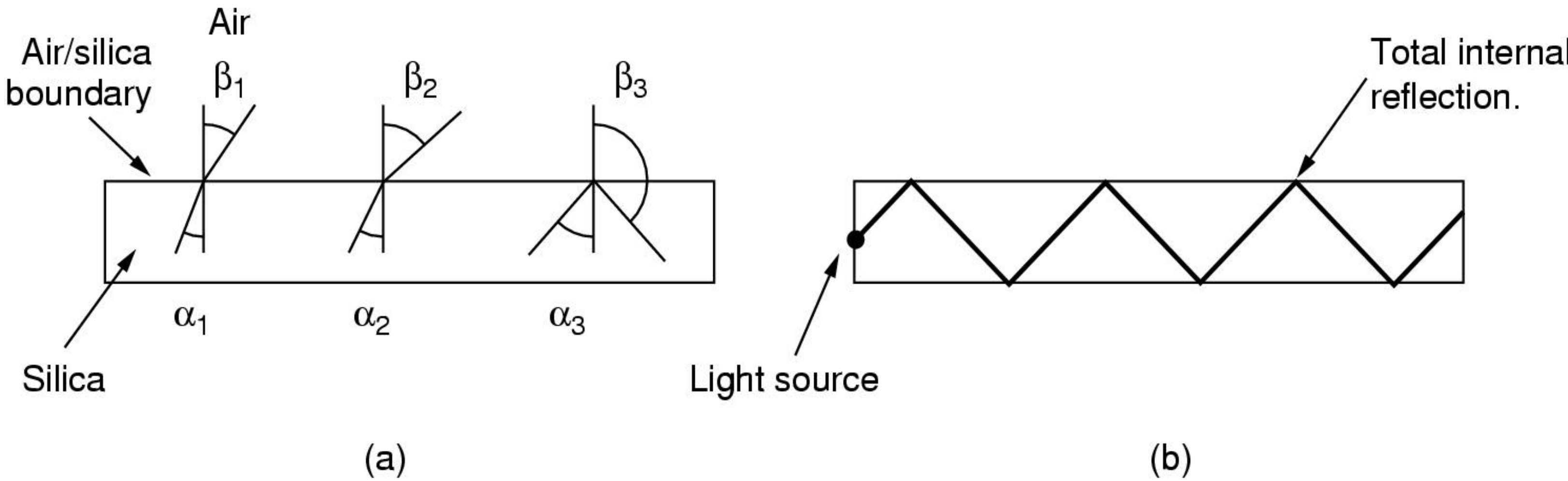


Figure 2-5. A network that uses household electrical wiring.

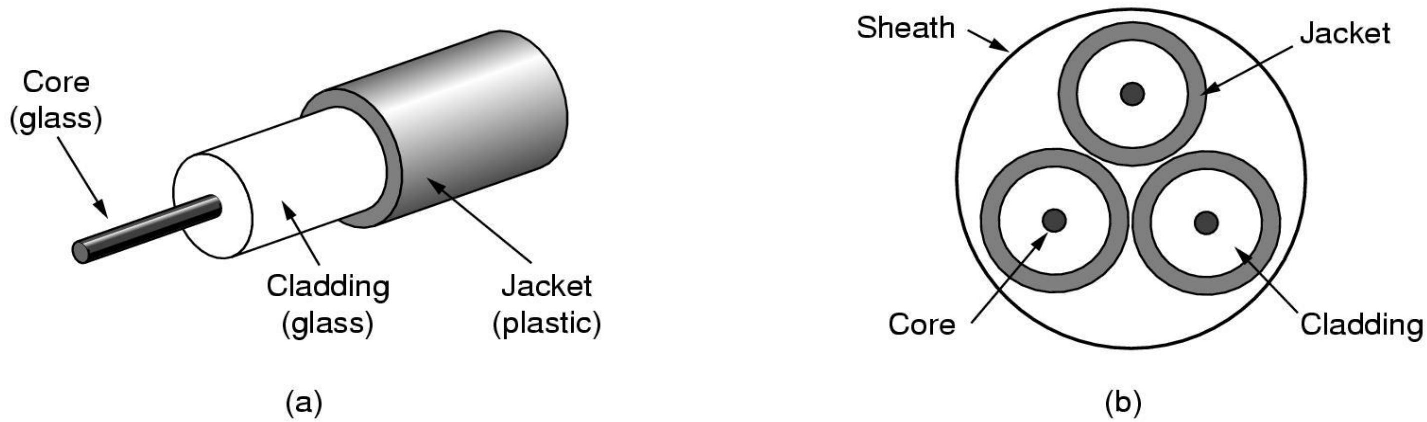
Fiber Optics

- **Principle:** Rather than using electrical signals, we use optical ones that are passed through optical fiber. Principal working is based on the refraction property of light:



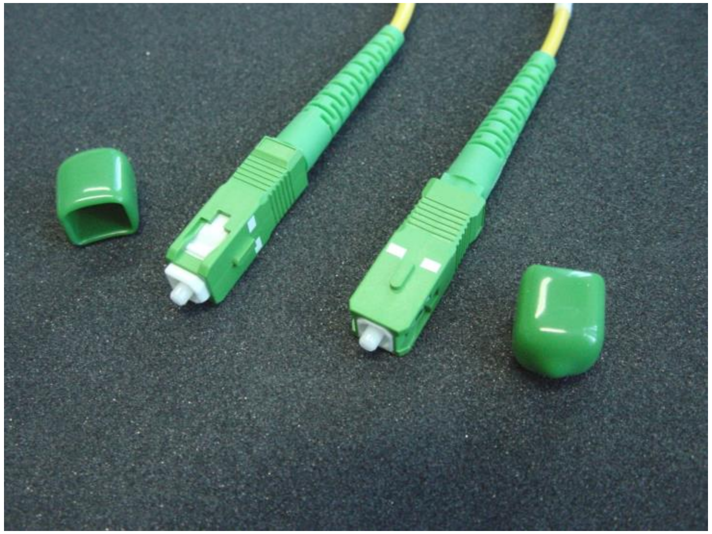
(a) Three examples of a light ray from inside a silica fiber impinging on the air/silica boundary at different angles. (b) Light trapped by total internal reflection.

As it turns out, attenuation is extremely well in optical fiber. This means that they can be used for long distances. In addition, the bandwidth is enormous.

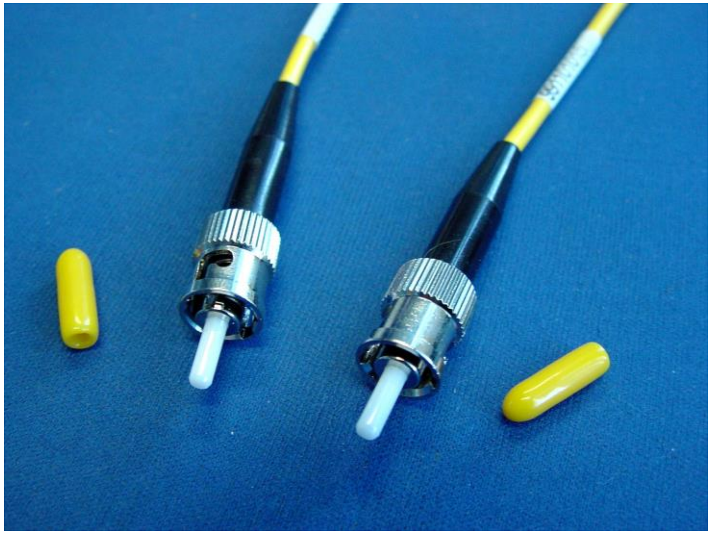


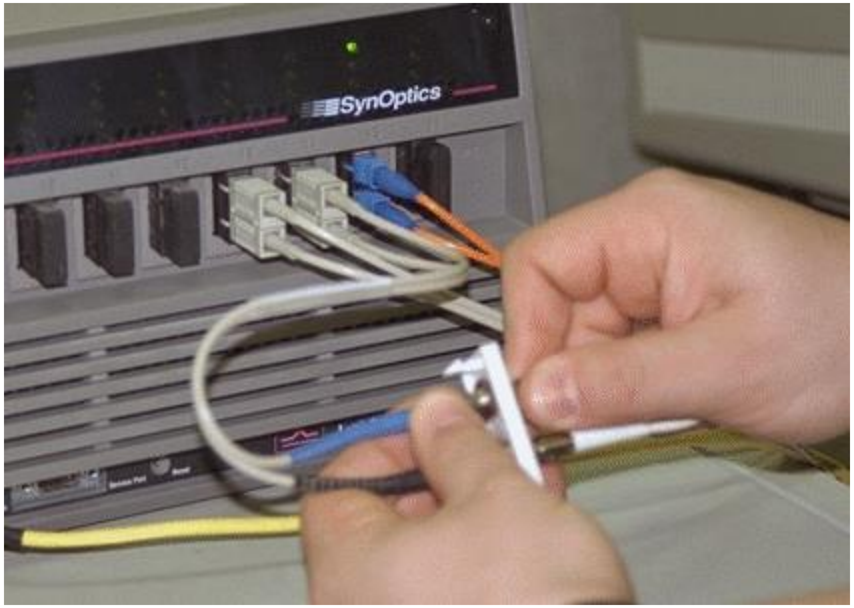
Item	LED	Semiconductor Laser
Data rate	Low	High
Mode	Multimode	Multimode or single mode
Distance	Short	Long
Lifetime	Long life	Short life
Temperature sensitivity	Minor	Substantial
Cost	Low cost	Expensive

SC：568A标准，方形，插入锁定



ST：插入锁定





光耦合器（ST）

- Attenuation in decibels = $10\log_{10}$(transmitted power/received power)

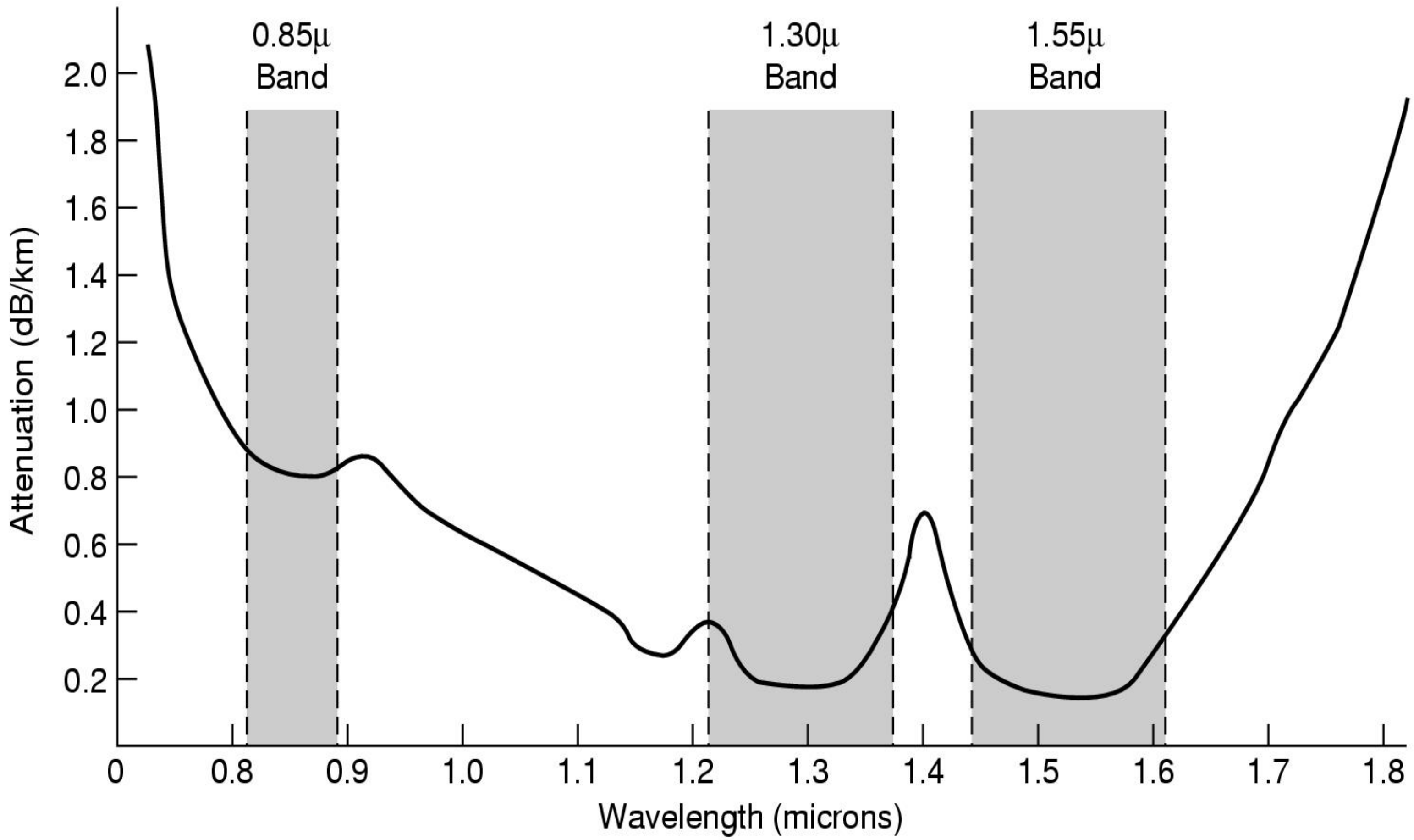
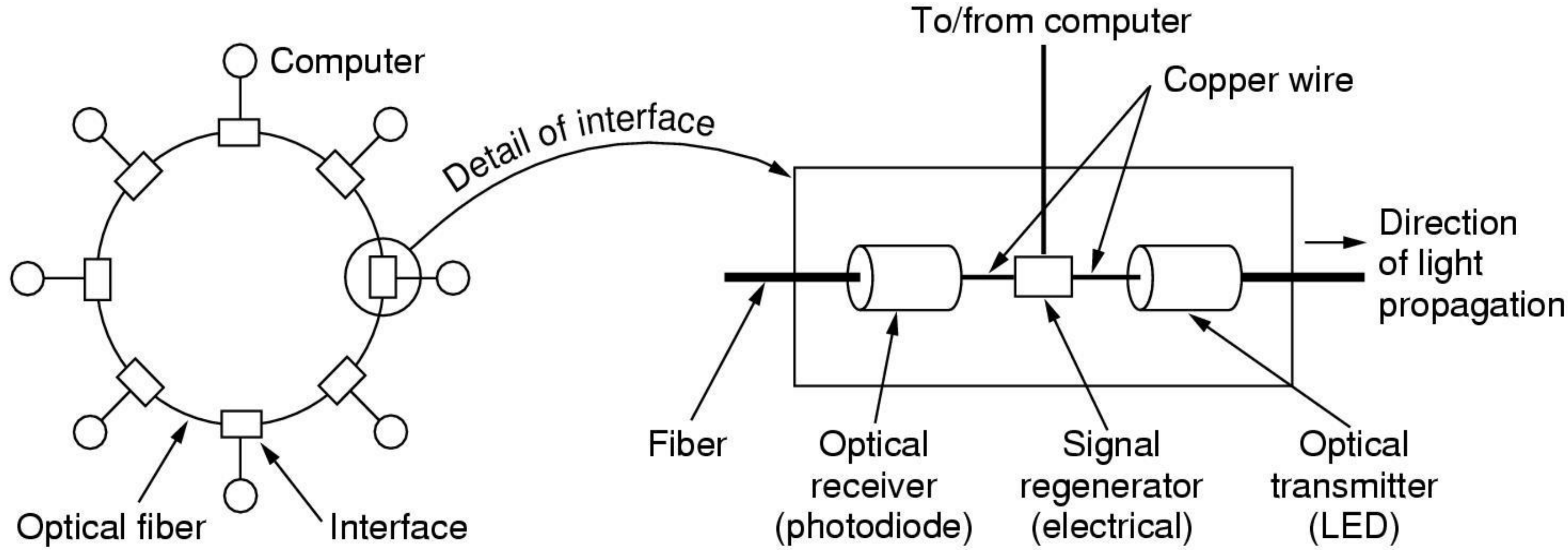
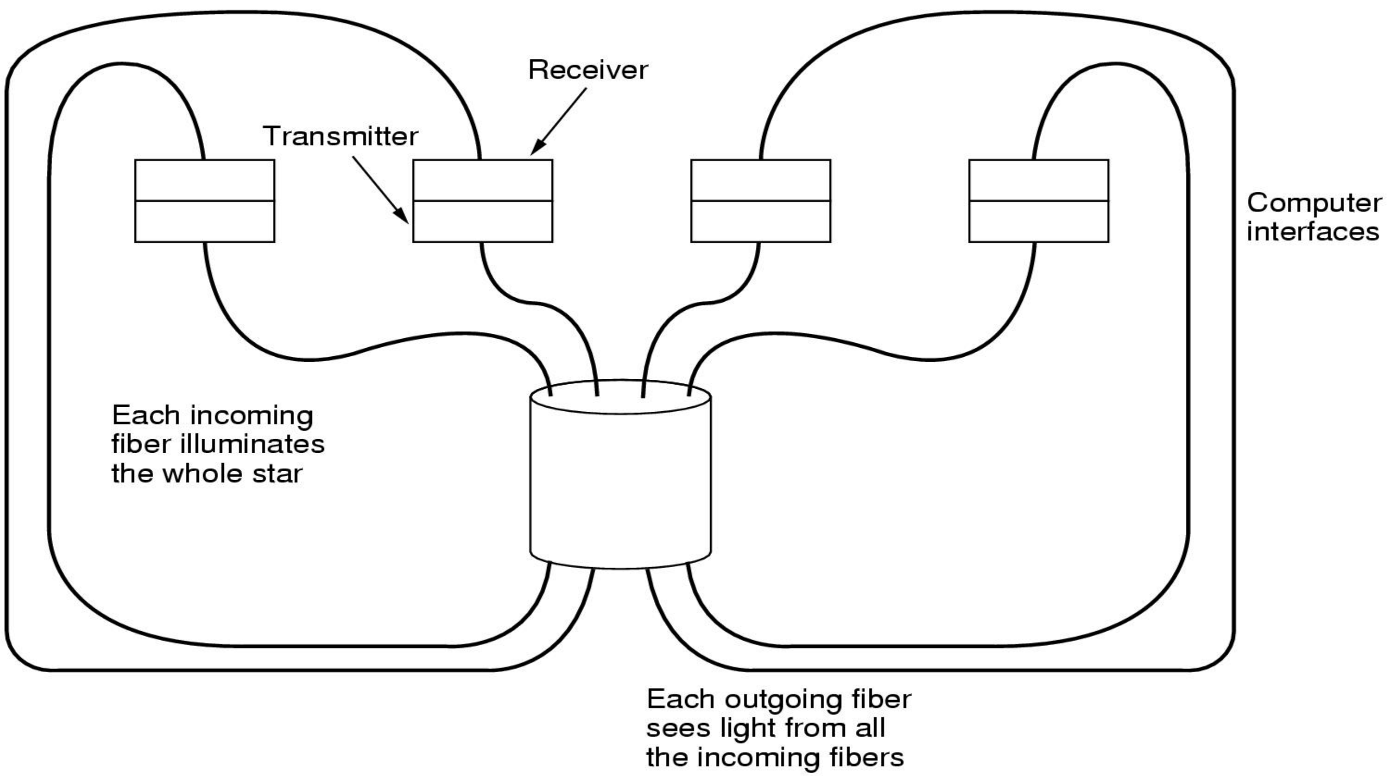


Fig. 2-6 Attenuation of light through fiber in the infrared region.

Fiber Connections

- **Observation:** An interface consists of a receiver (photodiode) which transforms light into electrical signals, and/or a transmitter (LED or laser-diode)
- **Passive interface:** A computer is directly connected to the optical fiber
- **Active interface:** There's an ordinary electrical repeater connected to two fiber segments and the computer:


Computer
Detail of interface
Optical fiber
Interface
To/from computer
Copper wire
Direction
of light
propagation
Fiber
Optical
receiver
(photodiode)
Signal
regenerator
(electrical)
Optical
transmitter
(LED)


Receiver
Transmitter
Computer
interfaces
Each incoming
fiber illuminates
the whole star
Each outgoing fiber
sees light from all
the incoming fibers

Optical Fiber vs. Copper Wire (1)

- **Bandwidth:** Fiber can support enormous bandwidths, exactly what we need with upcoming image-based applications (video-on-demand).
- **Attenuation:** Because the attenuation in fiber is less than in copper (can you imagine why?), we don't need to boost the signal as often. In practice, fiber requires an *active repeater* every 30 km, copper every 5 km.

Optical Fiber vs. Copper Wire (2)

- **External influences:** That’s right, no more interference from other cables, radios, power failures, etc. Cross-talk (you hearing another conversation) is out of the question.
- **Weight:** Fiber simply doesn’t weigh as much. Good for backbones, and the use of heavy maintenance equipment.

2.3 **Wireless Transmission**

- The electromagnetic spectrum

  Wireless Transmission is really great for all of us who can’t sit still, or feel they have to be on-line all the time (watch it – you may miss something). It’s also convenient when wiring is needed where it can’t be done, or isn’t really worth the trouble (jungles, islands, mountains).

The electromagnetic spectrum

- Wireless transmissions travel at the speed of light (c), uses a frequency (f) which has a wavelength (λ). The relation is that:

$$c = \lambda * f$$

c is a constant, approximately 3 x 10^8m/sec, that is theoretical in vacuum.

In practice, c is about 2 x 10^8m/sec either in fiber or copper.

That is 200m/μsec. (IMPORTANT!)

- The larger the wavelength is, the longer the distance it can travel without attenuation. Also, the dispersion of higher frequencies is much lower.

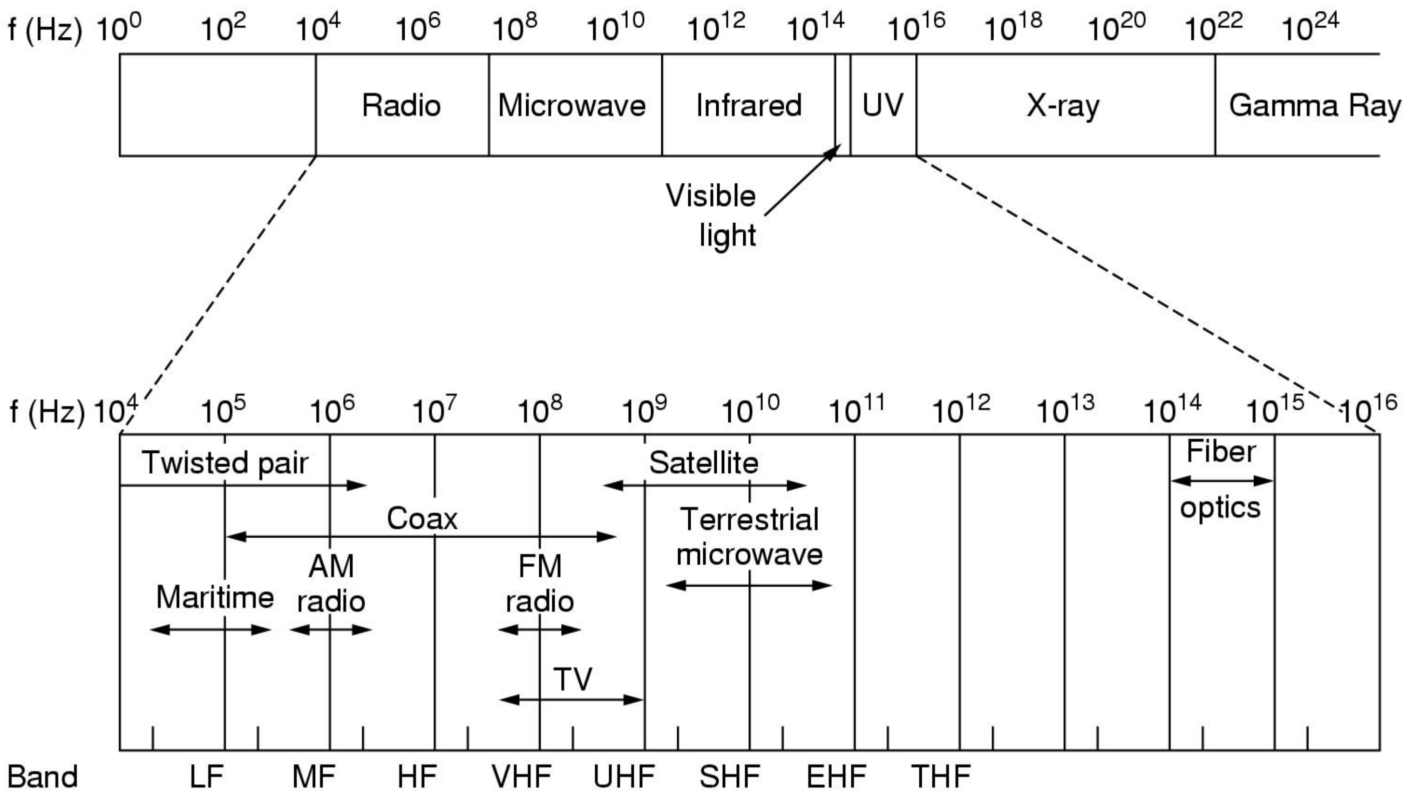


Fig. 2-11 The electromagnetic spectrum and its uses for communication

- **Note:** We can encode only a few bits per Hertz in the low frequency range, but much more in the higher ranges. This means that wireless transmission will generally have a much lower bandwidth (in practice: 1-2 Mbps).
- **Observation:** Fiber optics operate in the high frequency range, which explains the transmission rates of gigabits per second.
- If given the width of a wavelength band $\Delta\boldsymbol{\lambda}$, we can compute the corresponding frequency band Δf, and from that the data rate the band can produce.

$$c = \lambda \cdot f \Rightarrow \frac{df}{d\lambda} = -\frac{c}{\lambda^2} \Rightarrow \Delta f = -\frac{c \cdot \Delta\lambda}{\lambda^2}$$

- **Conclusion:** the wider the range, and the shorter the wavelength, the higher the bandwidth. Example: Fiber optics often work at $\lambda = 1.3 * 10^{-6}$ with $\Delta\lambda = 0.16 * 10^{-6}$ leading to 30THz bandwidth!
- In frequency hopping spread spectrum, the transmitter hops from frequency to frequency hundreds of times per second. In recent years, this technique has also been applied commercially—both 802.11 and Bluetooth use it.

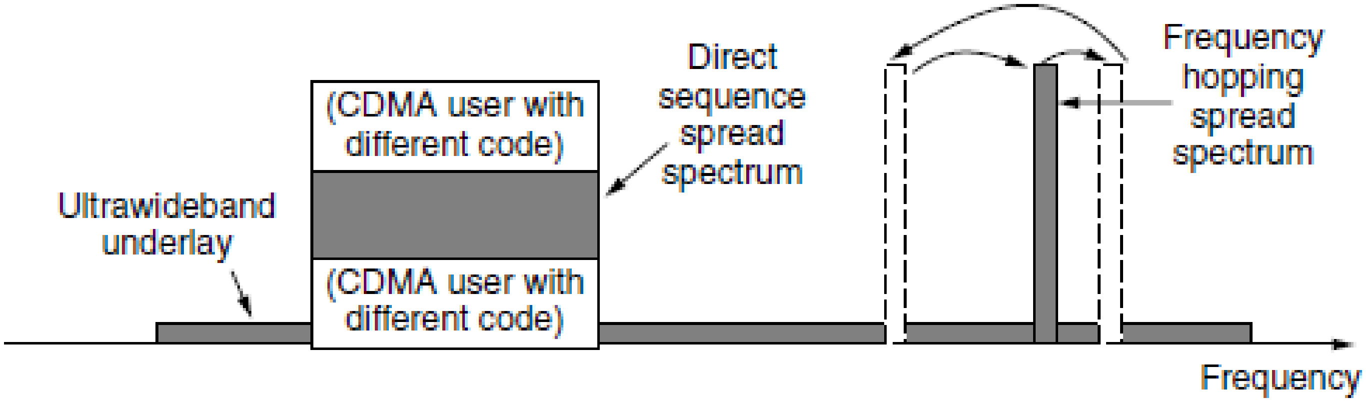


Figure 2-11. Spread spectrum and ultra-wideband (UWB) communication.

- **Observation:** Radio transmission (VLF–VHF) is extremely popular for its cheapness and range. Also, waves just go all over the place.

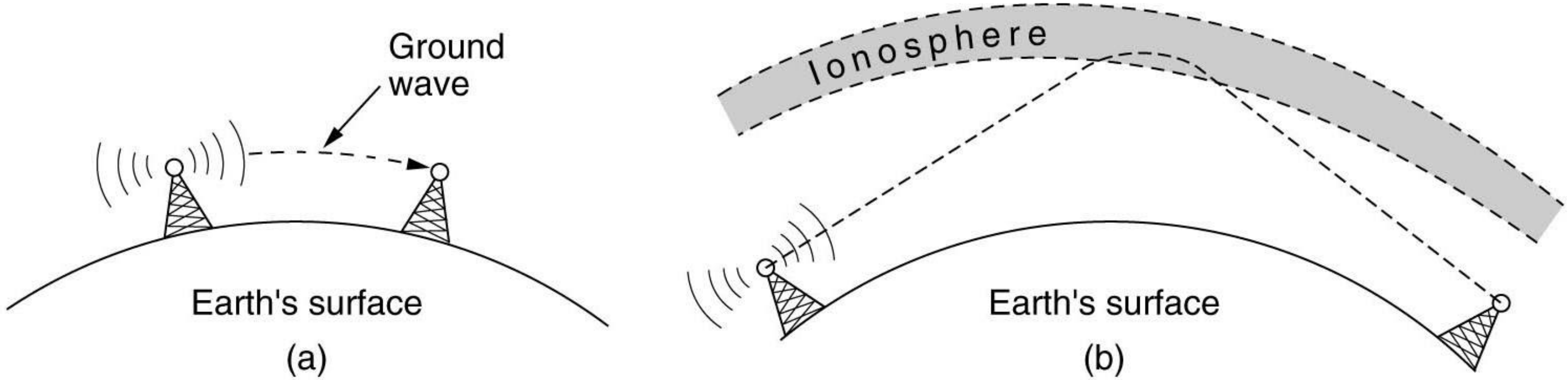


Fig. 2-12. (a) In the VLF, VF, and MF bands, radio waves follow the curvature of the earth. (b) In the HF they bounce off the ionosphere.

- **Observation:** Microwave transmission is also popular and is good for long distances, as long as it's directed.
- Problem is the density in the spectrum, requiring higher frequency ranges (which are hard for unguided transmissions)

Microwave Transmission

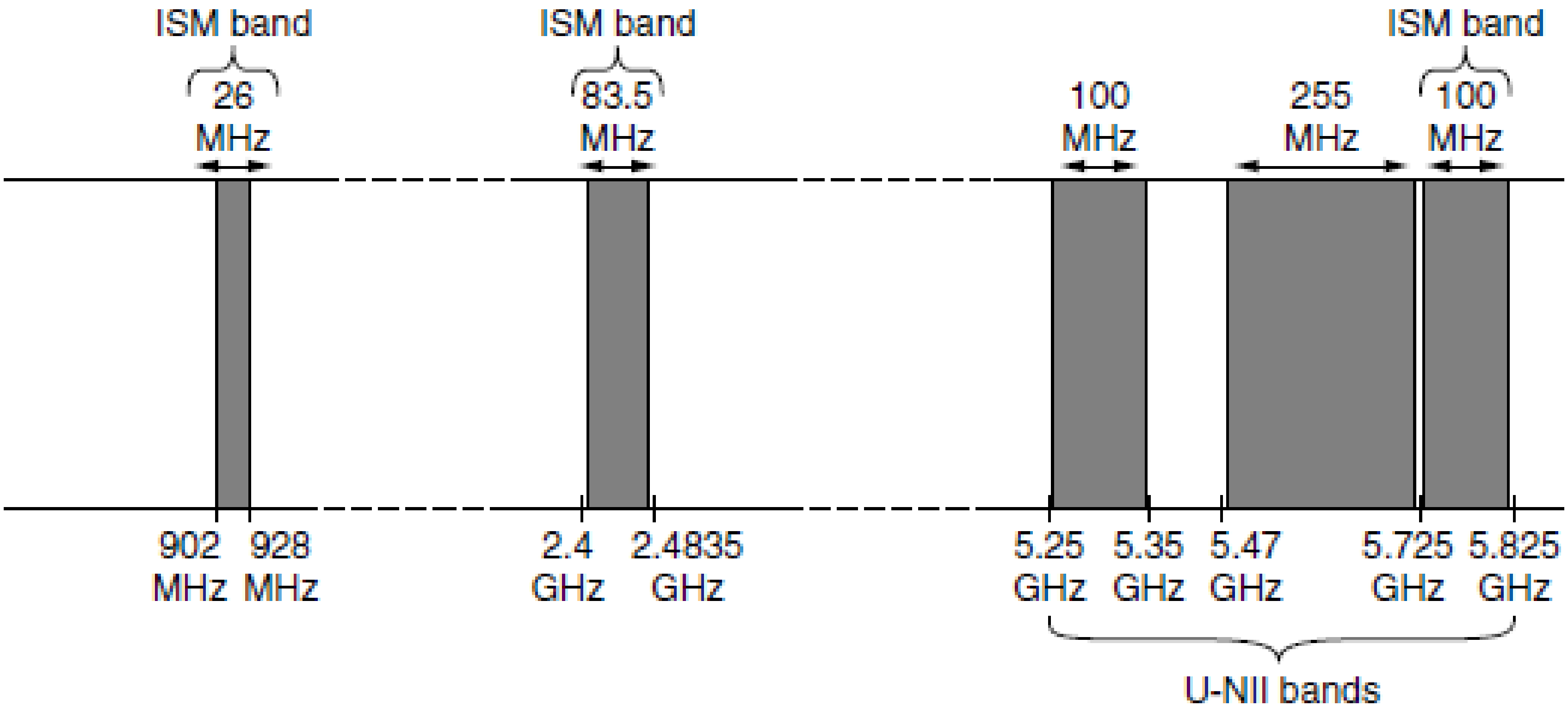


Figure 2-13. ISM and U-NII bands used in the United States by wireless devices.

for unlicensed usage: use spread spectrum techniques.

Infrared and Millimeter Waves

Light Wave Transmission

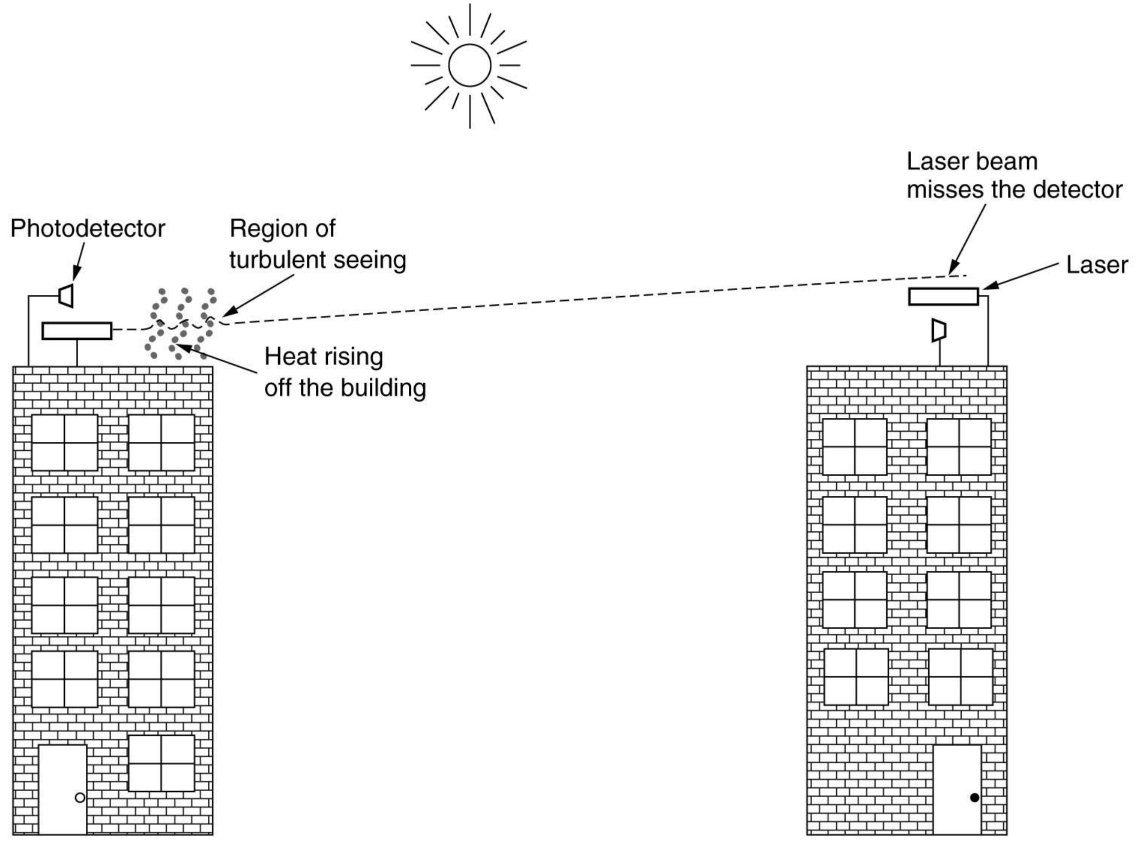


Fig. 2-14. Convection currents can interfere with laser communication systems. A bidirectional system, with two lasers, is pictured here.

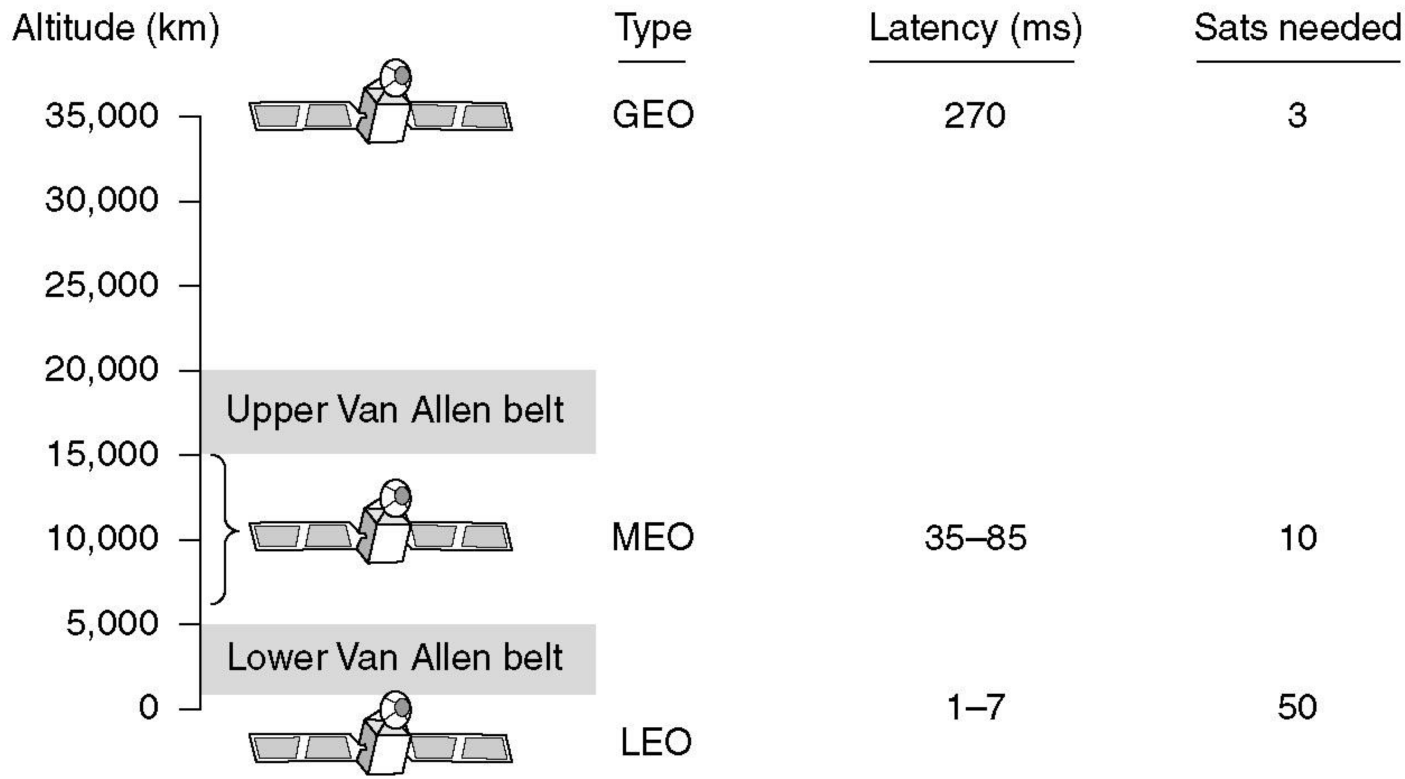
2.4 Communication Satellites

- Geostationary Satellites
- Medium-Earth Orbit Satellites
- Low-Earth Orbit Satellites
- Satellites versus Fiber

Satellites

- **Essence:** You direct a signal to something way up in the sky, and that reflects it back to earth.
- **Observation:** Reflection = receipt + amplification + sending back, possibly using a large dispersion so it can be received by many receivers on earth.
- **Issue:** Where to put the satellites (you should be able to direct your signal to them):
  - At 36,000 km height: they will move in sync with the rotation speed of the earth
  - At low-orbit, but then you will need to build a network of satellites for wide-area communication

Communication Satellites

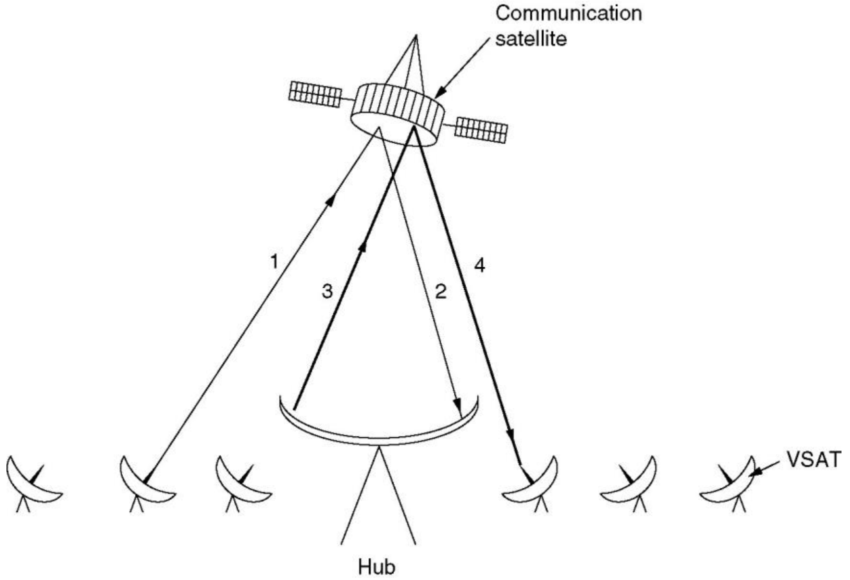


- Communication satellites and some of their properties, including altitude above the earth, round-trip delay time and number of satellites needed for global coverage.

The principal satellite bands

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

VSATs using a hub
VSAT: very small aperture terminals



Low-orbit Satellites

- **Essence:** We throw in a relatively large number of low-orbit satellites which jointly cover the surface of the earth; when you are

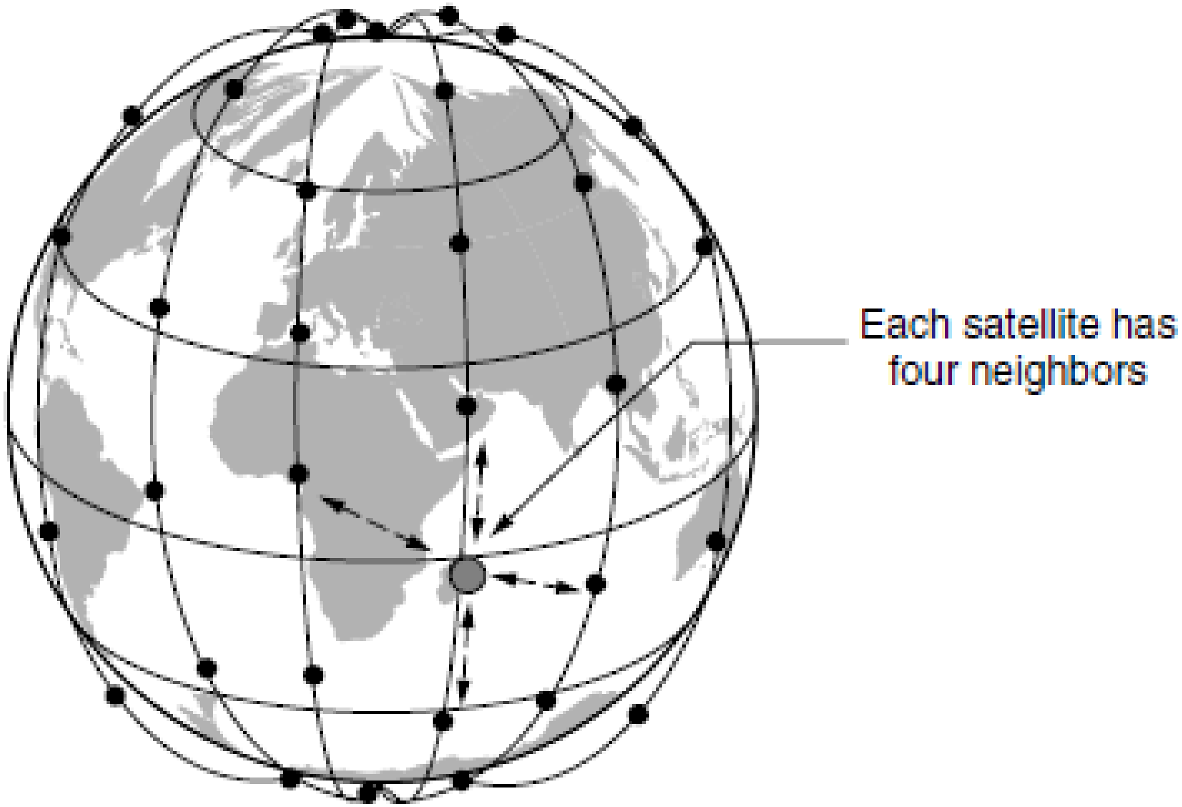
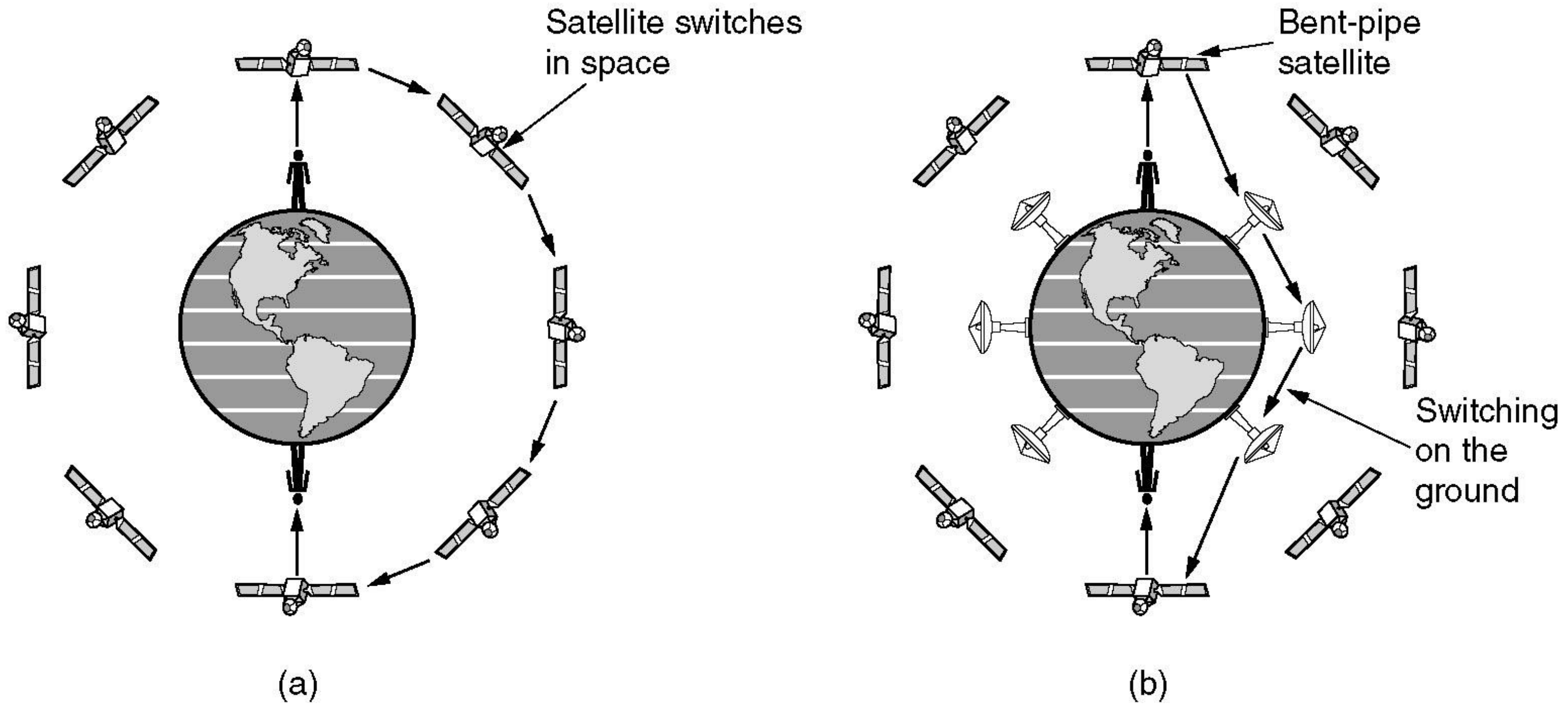


Figure 2-18. The Iridium satellites form six necklaces around the earth.

Globalstar



(a) Relaying in space. (b) Relaying on the ground.

Where (not) to use Satellites

- **Bandwidth:** Fiber wins, but not everyone has access to all the available bandwidth. Satellites may make it easier to transfer data anyway
- **Mobility and remote locations:** Satellites win, although it isn't clear whether simple cellular techniques may do just fine
- **Broadcasting:** Satellites win easily: broadcasting essentially comes for free
- **Fast and reliable:** Give credits to fiber: satellites are pretty bad due to inherent high latency (230 ms round-trip for geostationary satellites), and too much Mother Nature (rain!)

End of Chapter 2, Part 1