# The Physical Layer

Chapter 2

# Theoretical Basis for Data Communication

*Information transmitted on wires by varying some physical property such as voltage or current.*

- Fourier analysis
- Bandwidth-limited signals
- Maximum data rate of a channel

# Fourier Analysis

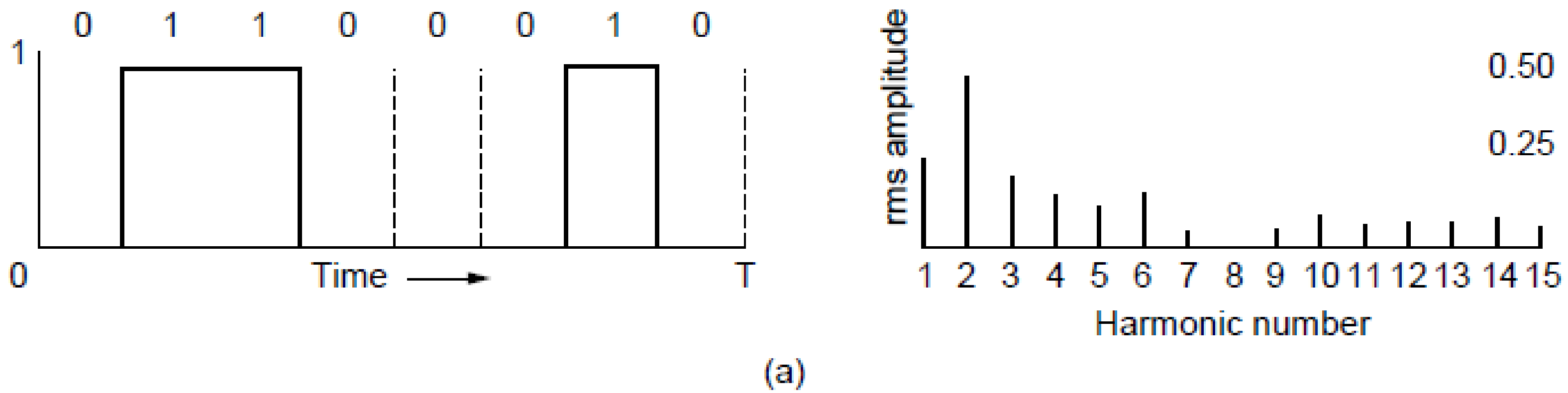
- Fourier proved that any reasonably behaved periodic function can be constructed as the sum of a (possibly infinite) number of sines and cosines

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

- Function reconstructed with

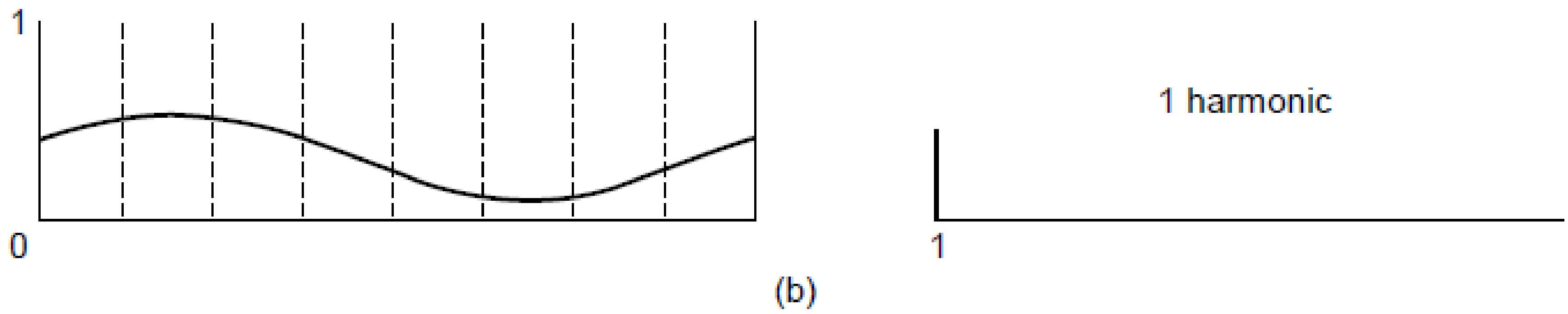
$$a_n = \frac{2}{T}\int_0^T g(t)\sin(2\pi nft)\,dt \qquad b_n = \frac{2}{T}\int_0^T g(t)\cos(2\pi nft)\,dt \qquad c = \frac{2}{T}\int_0^T g(t)\,dt$$

# Bandwidth-Limited Signals (1)



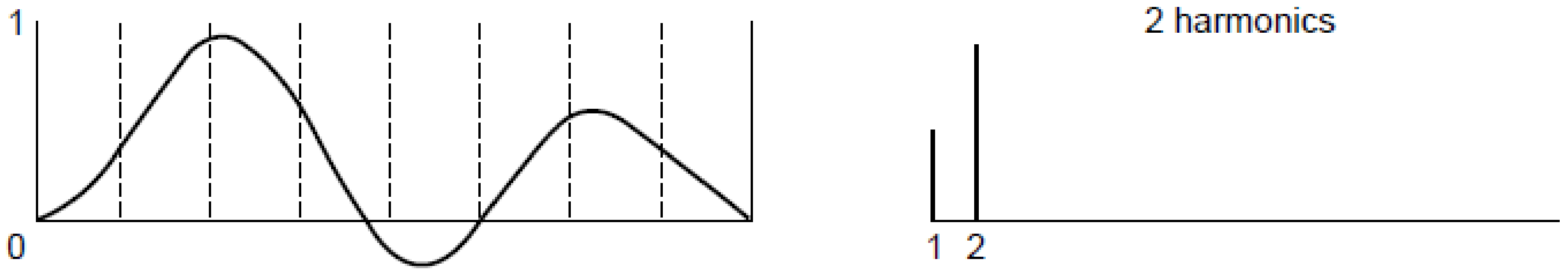

A binary signal and its root-mean-square Fourier amplitudes.

# Bandwidth-Limited Signals (2)




(b)-(e) Successive approximations to the original signal.

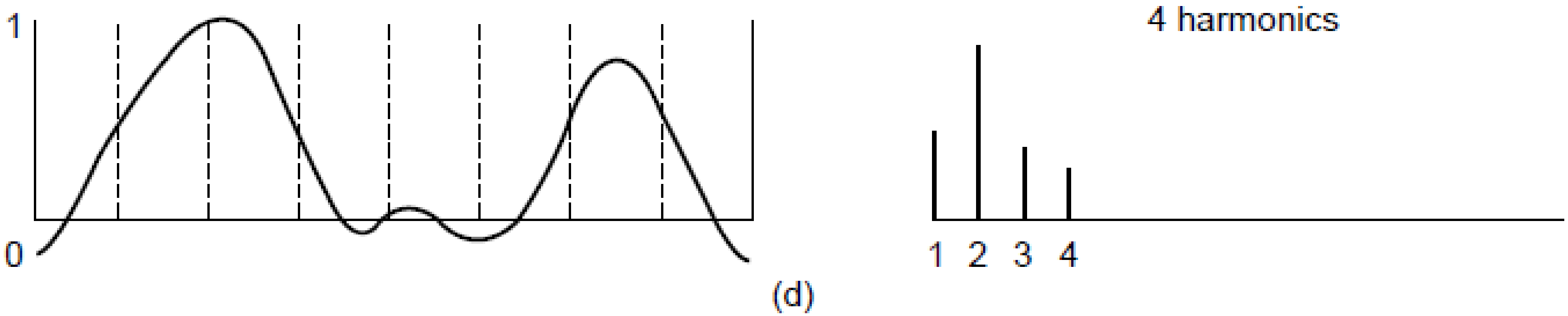
# Bandwidth-Limited Signals (3)



(c)

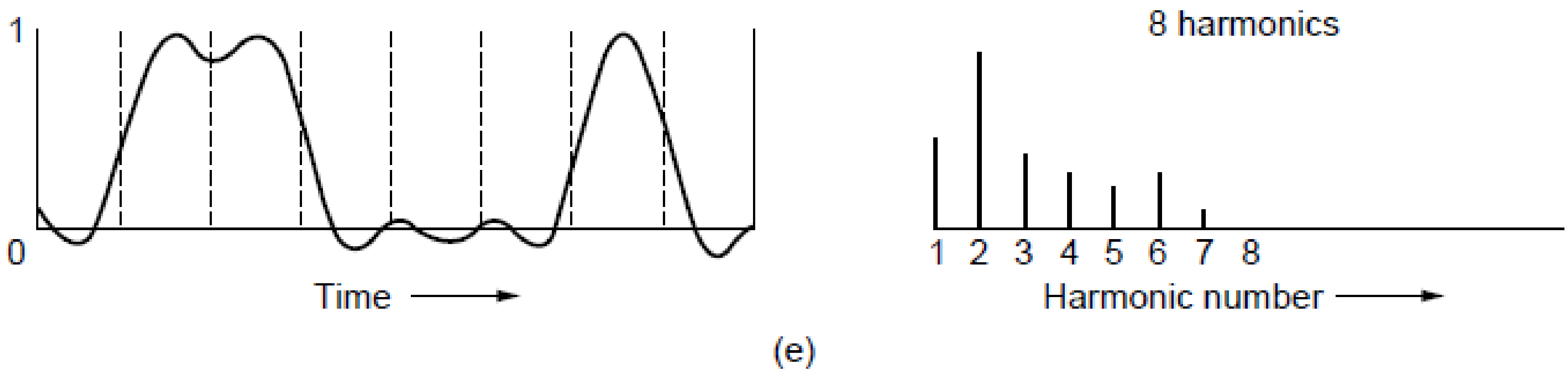
(b)-(e) Successive approximations to the original signal.

# Bandwidth-Limited Signals (4)




(b)-(e) Successive approximations to the original signal.

# Bandwidth-Limited Signals (5)




(b)-(e) Successive approximations
to the original signal.

# Bandwidth-Limited Signals (6)

| 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 for our example.

# The Maximum Data Rate of a Channel

- Nyquist proved that if an arbitrary signal has been run through a low-pass filter of bandwidth B, the filtered signal can be completely reconstructed by making only 2B (exactly) samples per second. Sampling the line faster pointless.
- Nyquist's theorem

$$\text{maximum data rate} = 2B\log_2 V \text{ bits/sec}$$

B: Bandwidth

V: Discrete Voltage Levels

# Shannon's Formula

- Shannon's formula for capacity of a noisy channel

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

S/N: Signal to Noise Ratio,

Expressed in Decibels (dB): $10\log_{10}(S/N)$

# Guided Transmission Media

- Magnetic media
- Twisted pairs
- Coaxial cable
- Power lines
- Fiber optics

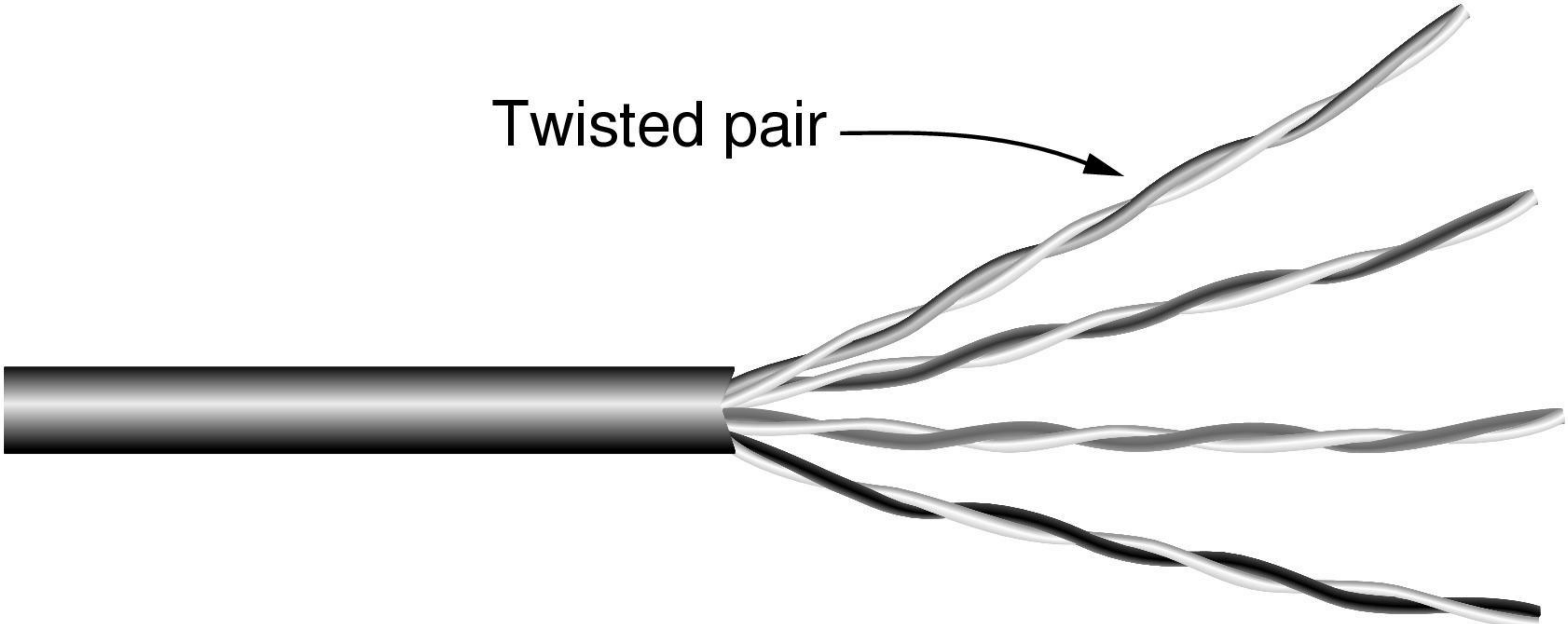
# Magnetic Media

- Write data onto magnetic media
  - Disks
  - Tapes
- Data transmission speed
  - Never underestimate the bandwidth of a station wagon full of tapes hurtling down the highway.

# Twisted Pair

- Two parallel lines are constitute a fine antena. When the wires are twisted, the waves from different twists cancel out, so the wire radiated less efficiently.
- Most common application is the telephone system.
- The bandwidth depends on the thickness of the wire and the distance traveled. Several megabits/sec can be achieved for a few kilometers in many cases.

# Twisted Pairs




Category 5 UTP cable with four twisted pairs

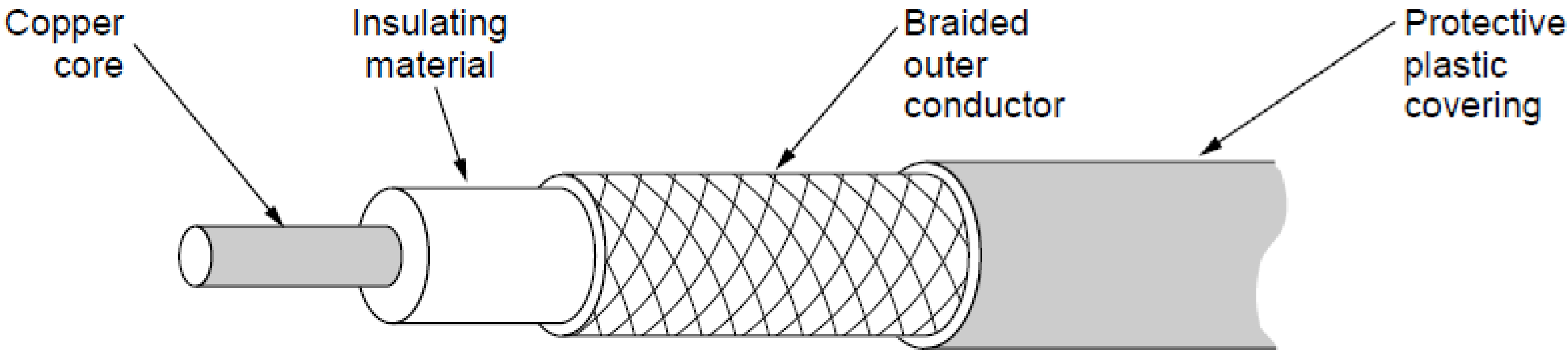
# Twisted Pair

- LAN standards may use twisted pairs differently. For example 100-Mbps Ethernet uses two pairs, one pair for each direction.
- To reach higher speeds, 1-Gbps Ethernet uses all four pairs in both directions simultaneously.
- Cat 5 cables have more twists per meter than Category 3 cables. More twists result in less crosstalk and a better signal quality over longer distances.
- Some cables in Category 6 and above are rated for signals of 500 MHz and can support the 10-Gbps links.

# Some terminology for link directions

- Full duplex
- Half-Duplex
- Simplex

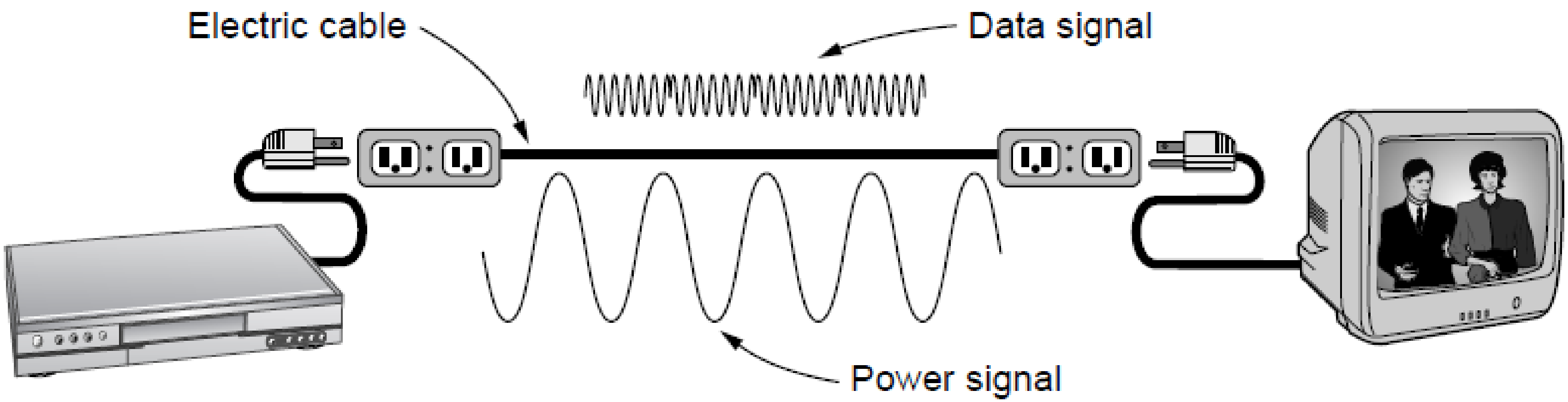
# Coaxial Cable




A coaxial cable

It has better shielding and greater bandwidth than unshilded twisted pairs. They have bandwidth of a few GHz for long distance lines (today replaced by optical fiber lines).

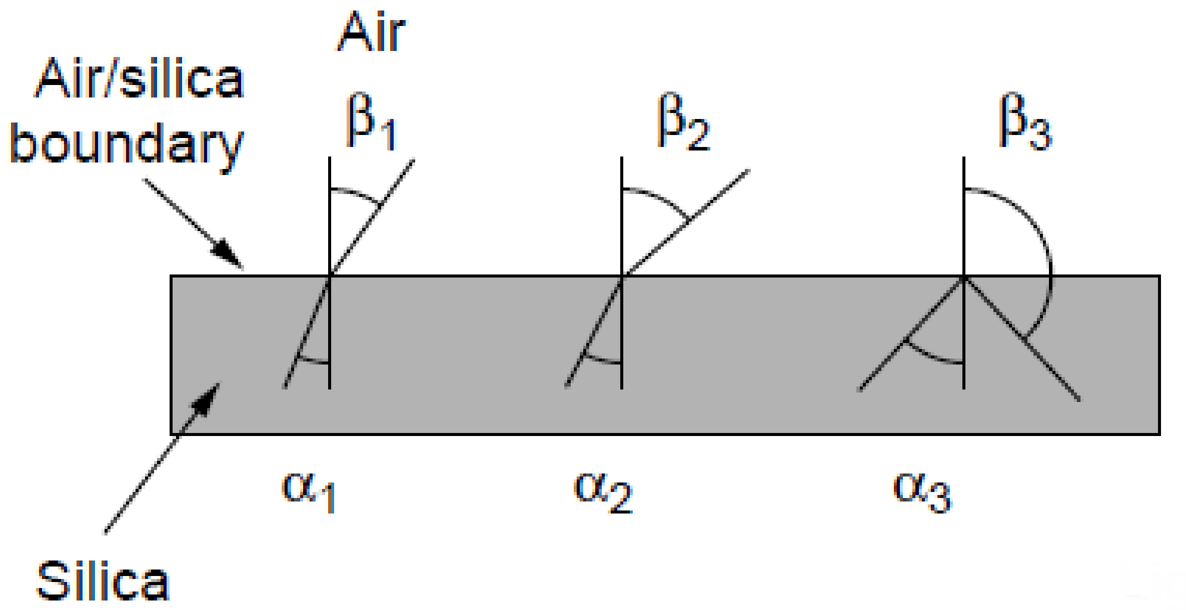
# Power Lines




A network that uses household electrical wiring.

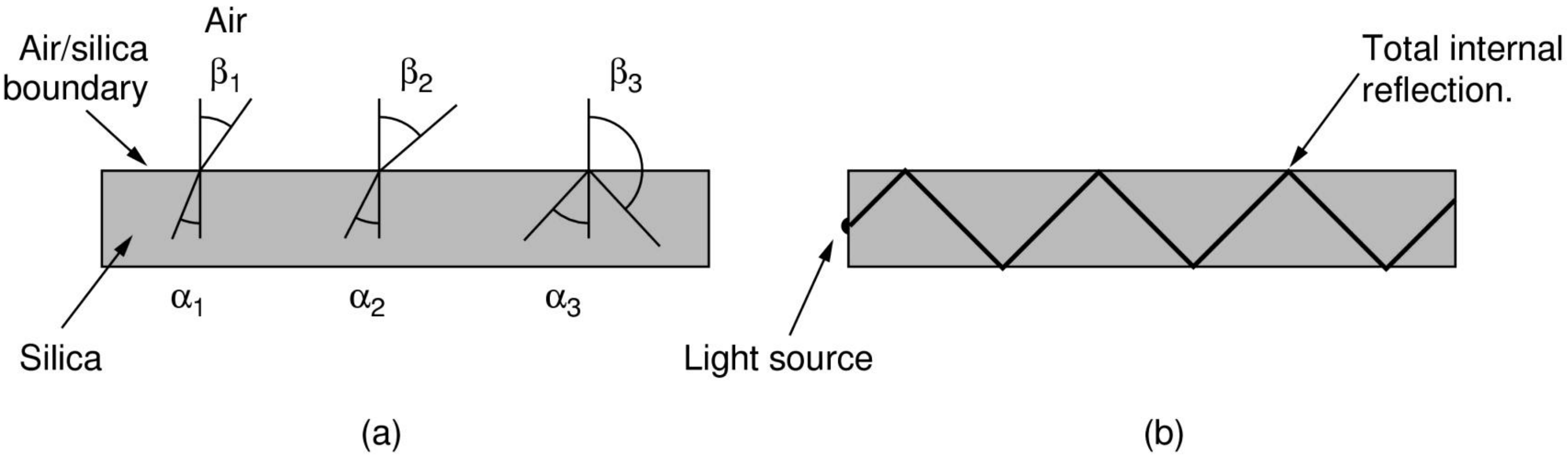
It has been used by electricity companies for metering for years, as weel in the home to control devices.
The data signal is superimposed on the low-frequency power signal as both signals use the wiring at the same time.
The electrical properties of the wiring may chance from house to house and change as appliances are turned on and off.
Practical to send at least 100 Mbps over typical electrical wiring.

# Fiber Optics (1)




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

# Fiber Optics (2)

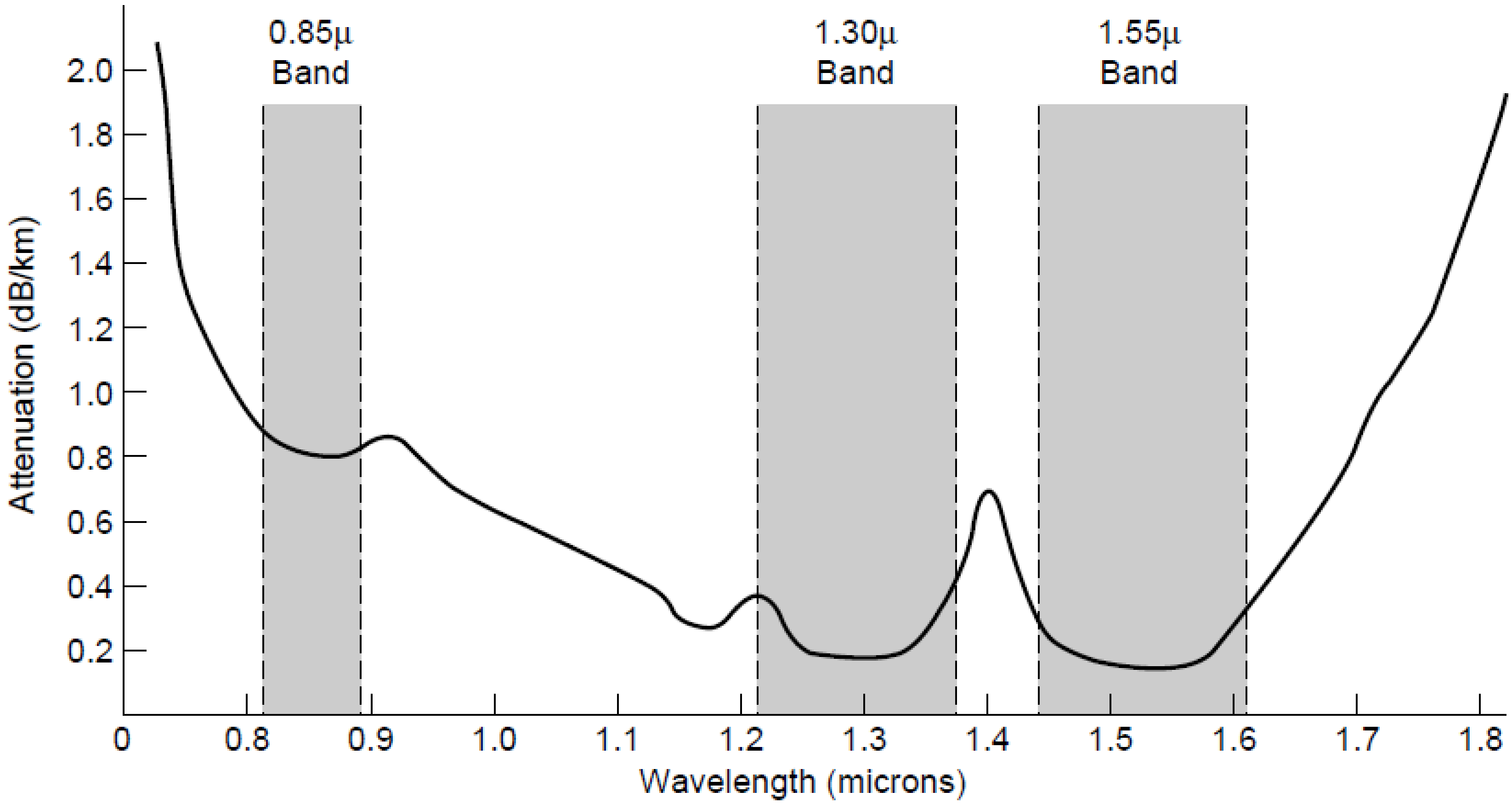



Light trapped by total internal reflection.

# Fiber Optics (3)

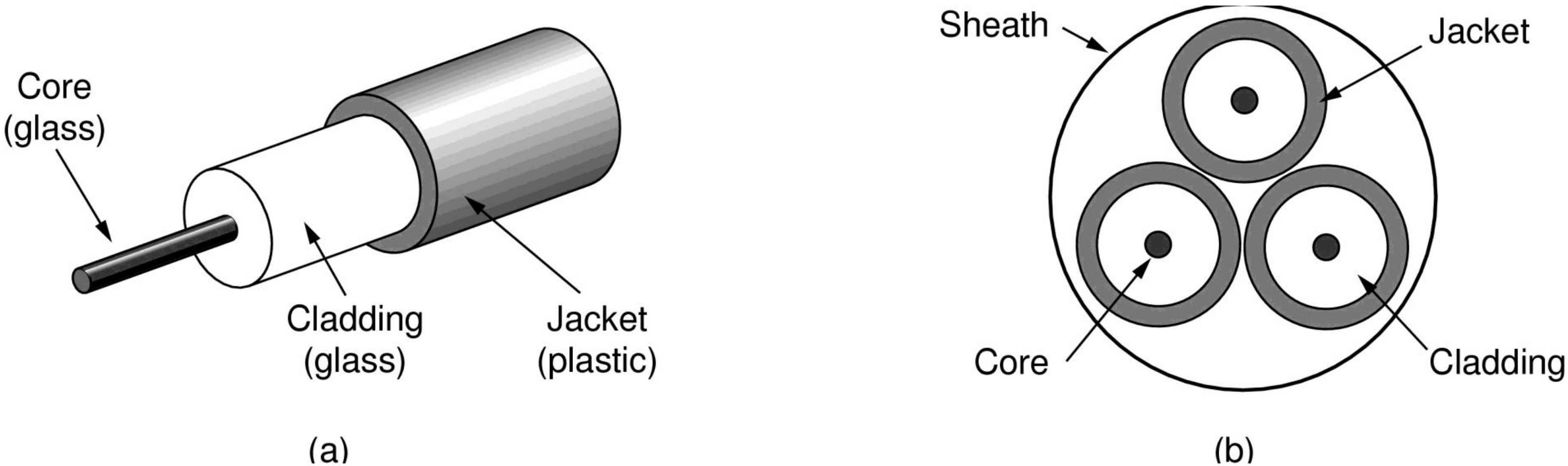
- Single-mode fiber (light can propagate only in a straight line) vs multi-mode fibers.
- 100 Gbps for 100 km without amplification and with very small error rate.

# Transmission of Light Through Fiber




Attenuation of light through fiber
in the infrared region

# Fiber Cables (4)




Views of a fiber cable

In multi-mode fibers, the core is typically 50 microns, 8 to 10microns in single-mode fibbers.

# Fiber Cables (5)

| Item | LED | Semiconductor laser |
| --- | --- | --- |
| Data rate | Low | High |
| Fiber type | Multi-mode | Multi-mode 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

# Wireless Transmission

- The Electromagnetic Spectrum
- Radio Transmission
- Microwave Transmission
- Infrared Transmission
- Light Transmission

# A Fundamental Relation

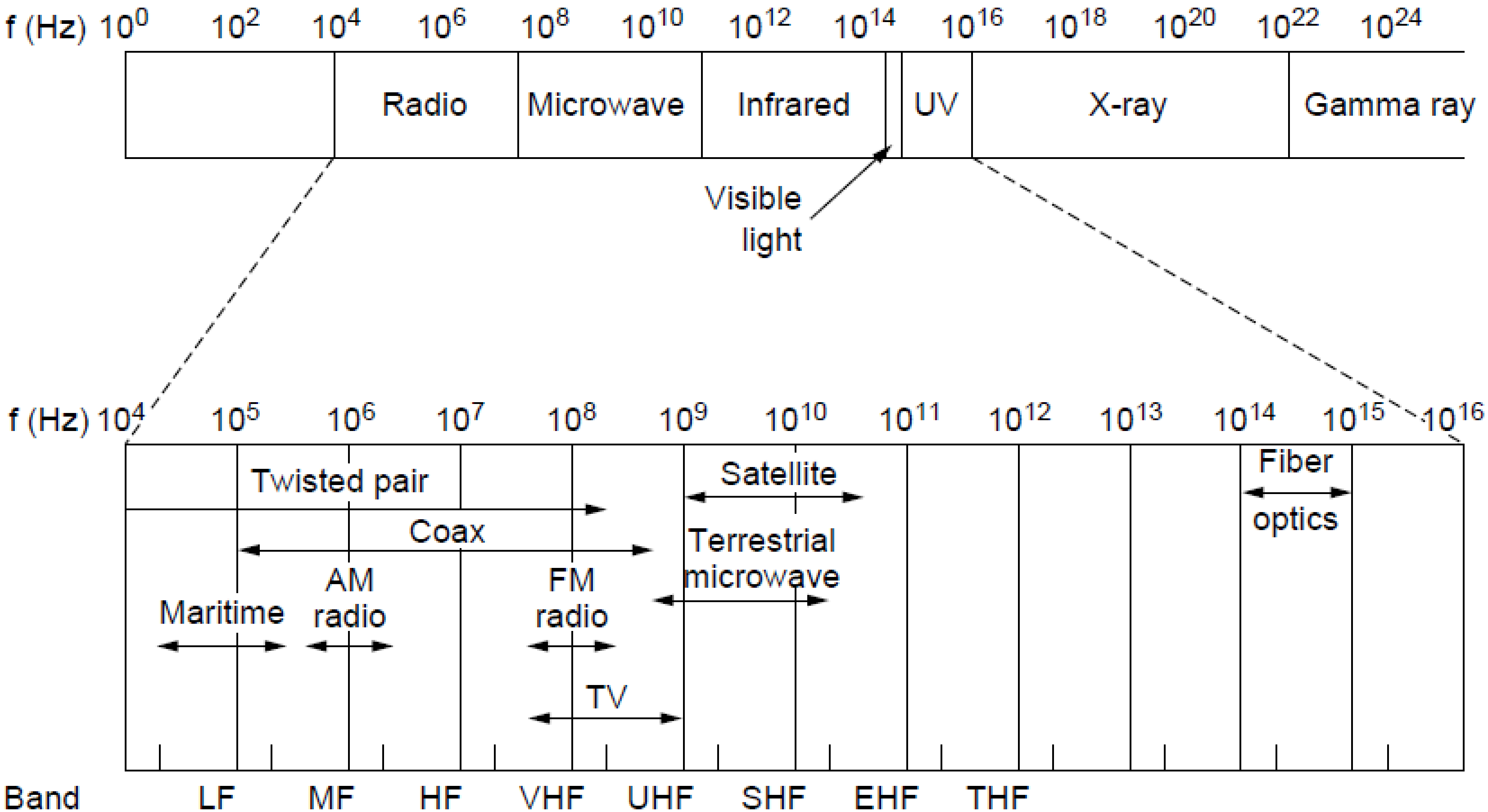
$$\lambda f = c$$

$\lambda$:wavelength (the distance between two consequtive maxima or minima)

f: frequency

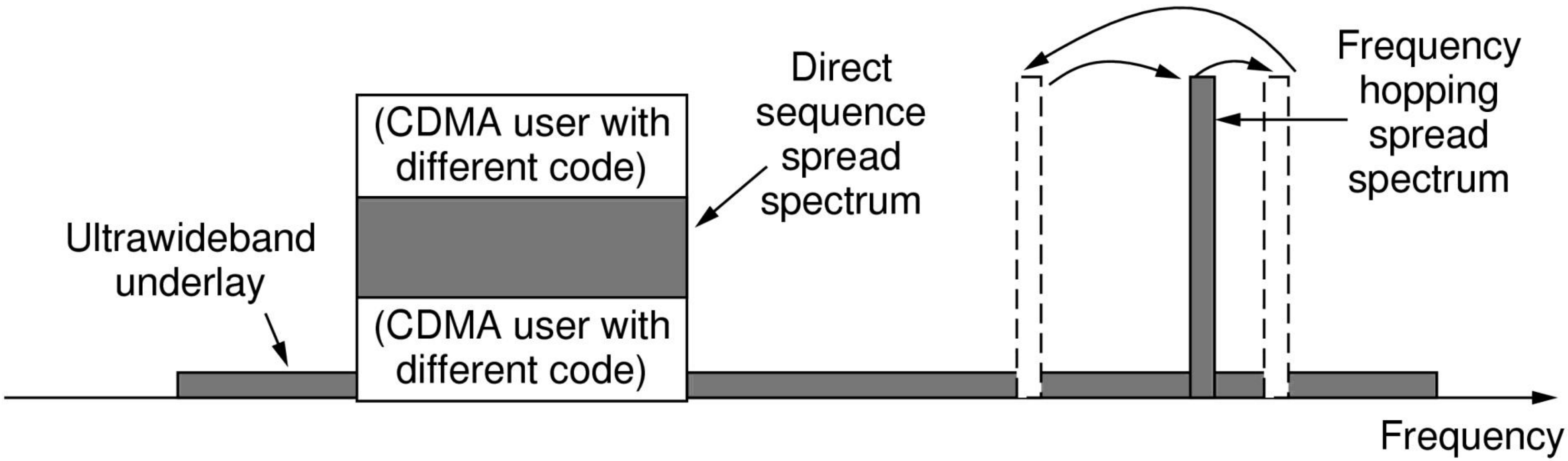
c:speed of light in vacuum, nearly $3 \times 10^{8}$ m/sec

# The Electromagnetic Spectrum (1)



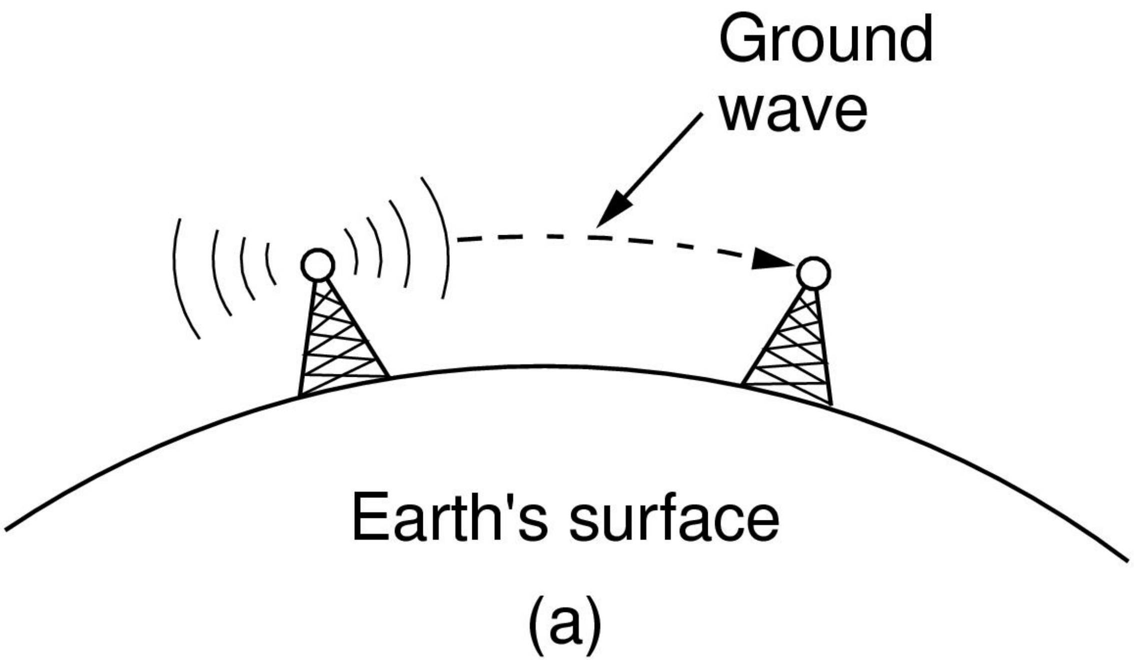

The electromagnetic spectrum and its uses for communication

# The Electromagnetic Spectrum (2)



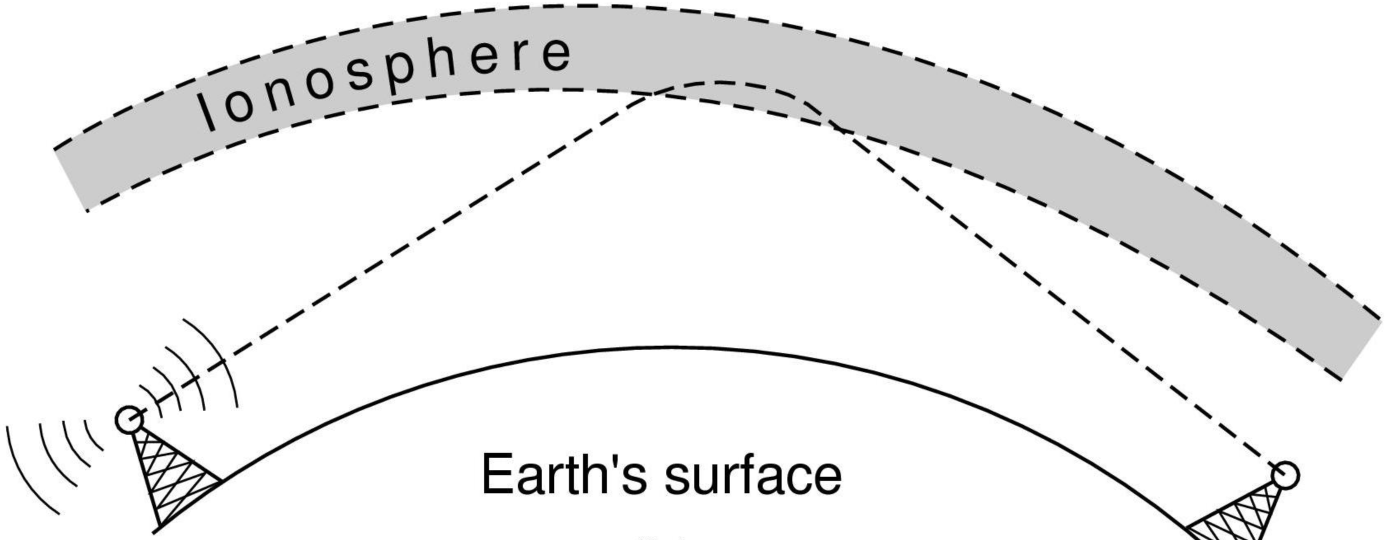

Spread spectrum and ultra-wideband (UWB) communication

# Radio Transmission (1)




In the VLF, LF, and MF bands, radio waves follow the curvature of the earth

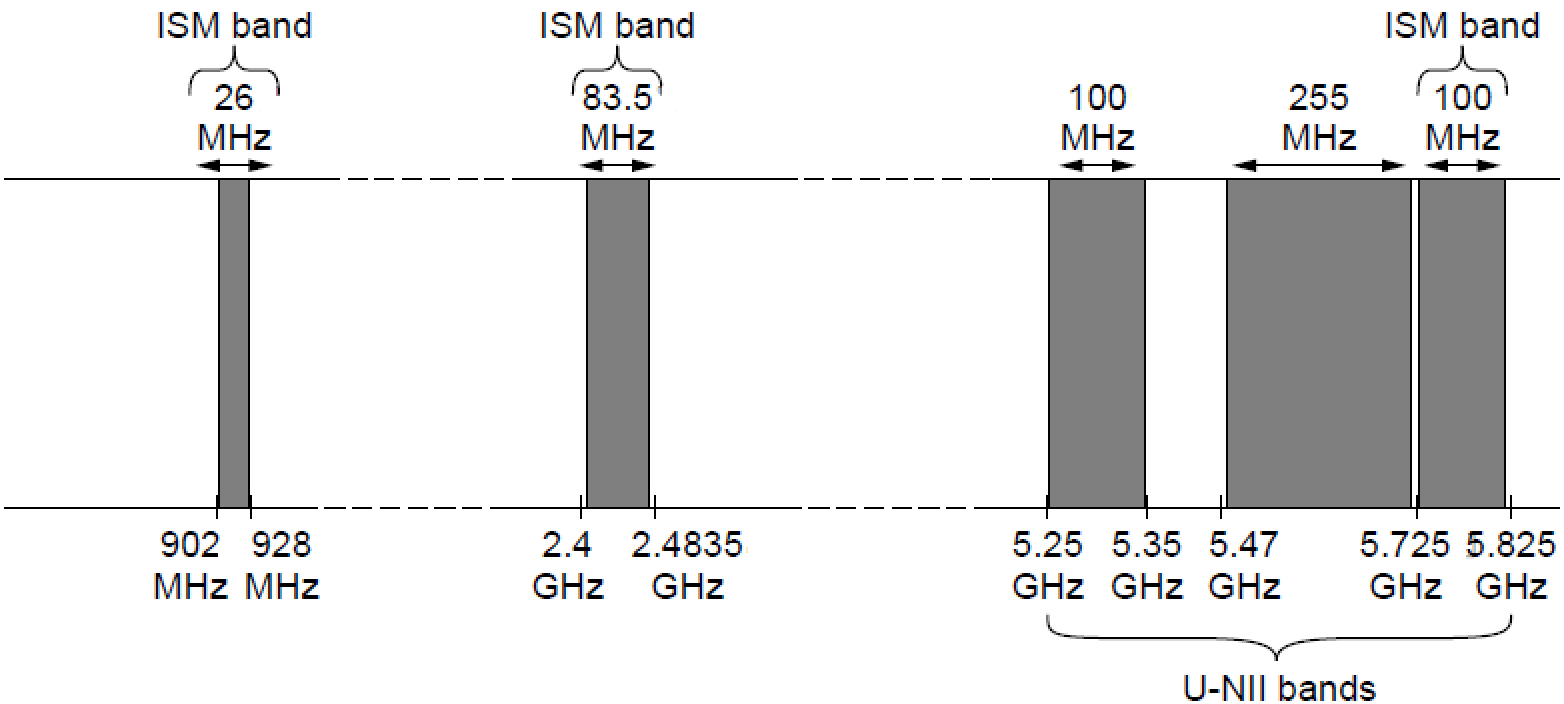
# Radio Transmission (2)



(b)

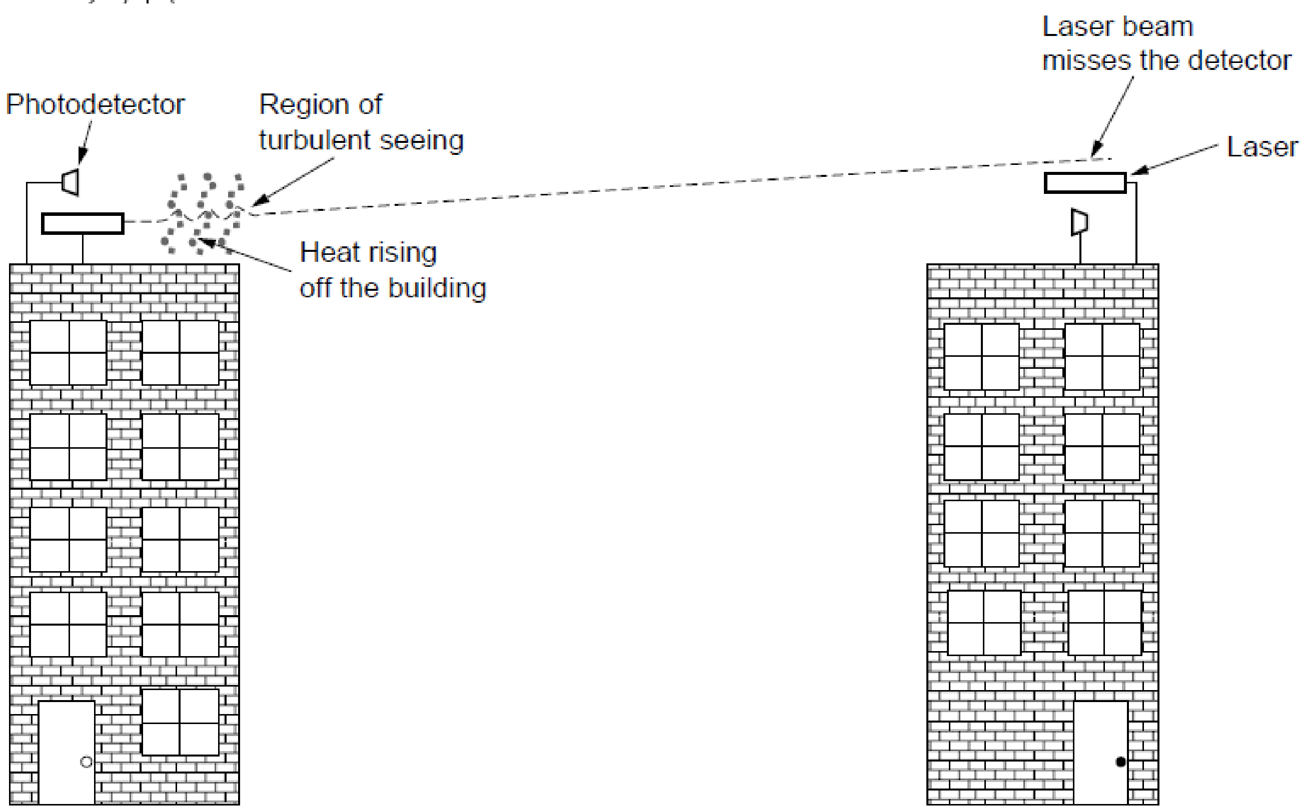
In the HF band, they bounce off the ionosphere.

# The Politics of the Electromagnetic Spectrum




ISM (Industrial, Scientific, Medical) and U-NII (Unlicensed National Infrastructure) bands used in the United States by wireless devices

# Light Transmission



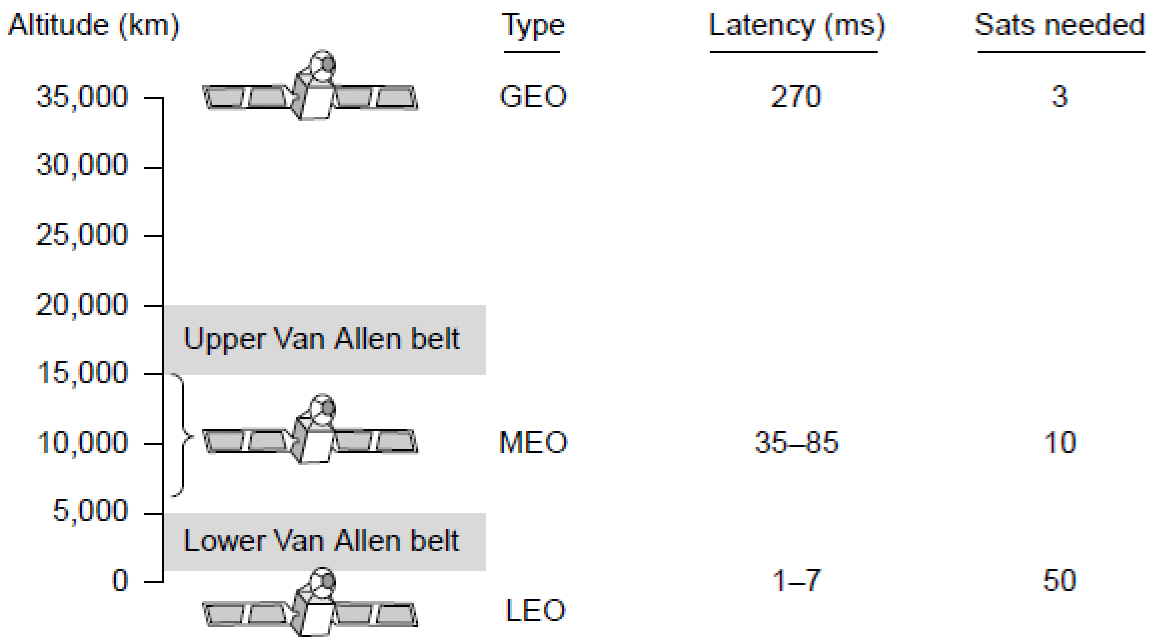

Convection currents can interfere with laser communication systems. A bidirectional system with two lasers is pictured here.

# Communication Satellites

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

Big microwave repeaters in the sky.
Transponders are responsible to listen to some portion of the spectrum, amplify the incoming signal and send it at another frequency to avoid interference.
Footprint is important.

# Communication Satellites



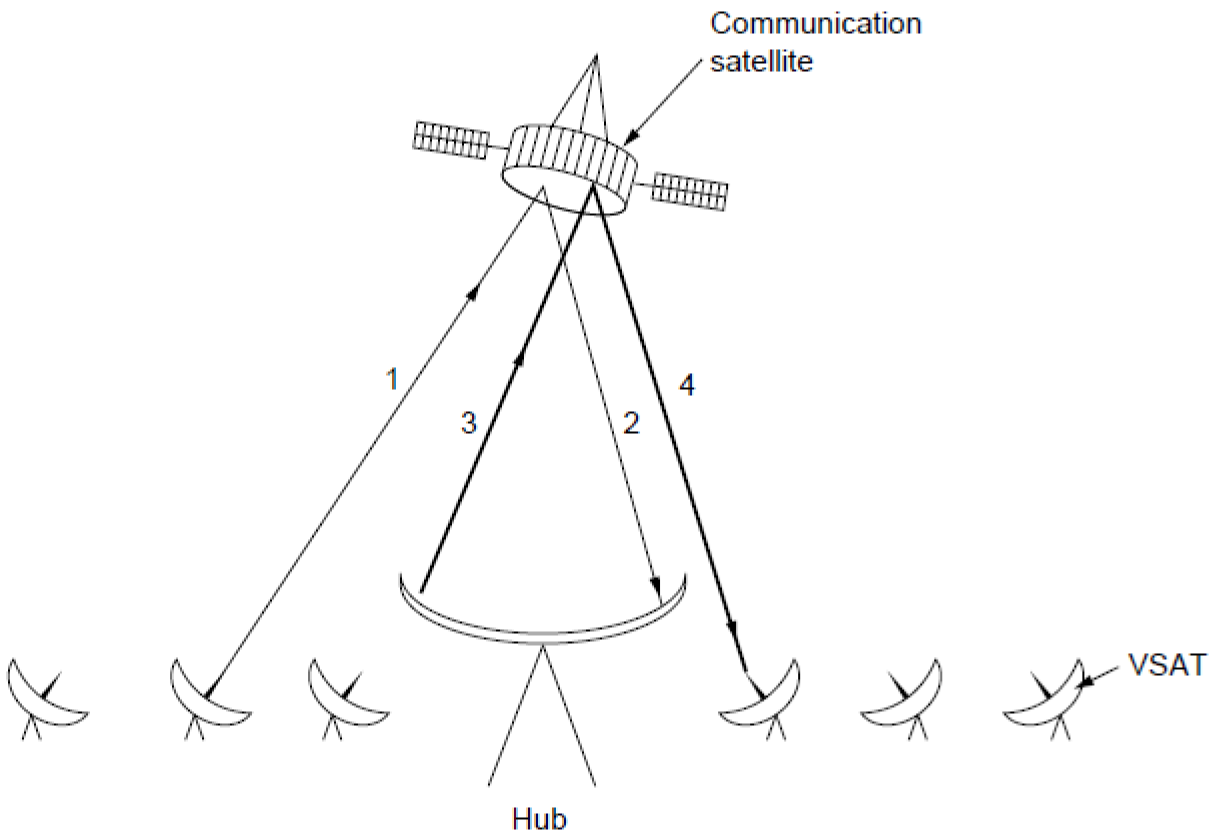

Communication satellites, some properties, including: altitude above earth, round-trip delay time, number of satellites for global coverage.

# Geostationary Satellites (1)

| 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 |

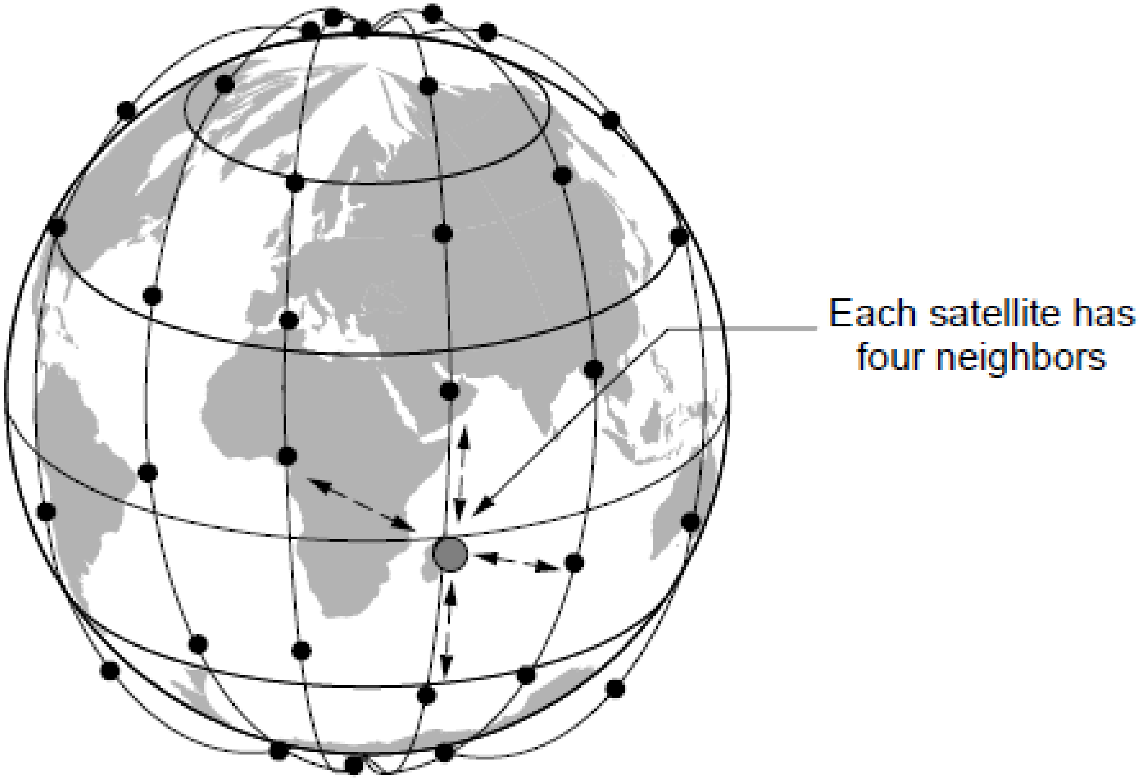
The principal satellite bands

# Geostationary Satellites (2)



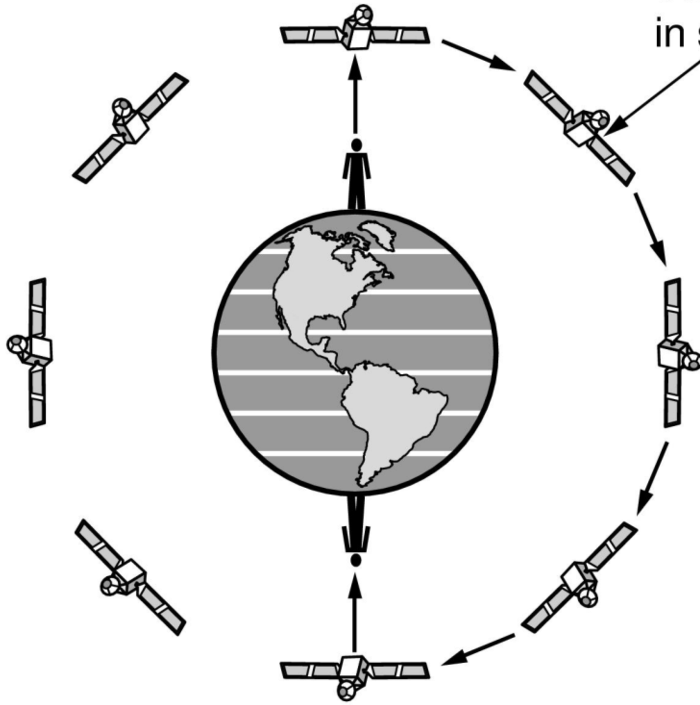

VSATs using a hub.

# Low-Earth Orbit Satellites (1)




The Iridium satellites form six necklaces around the earth.

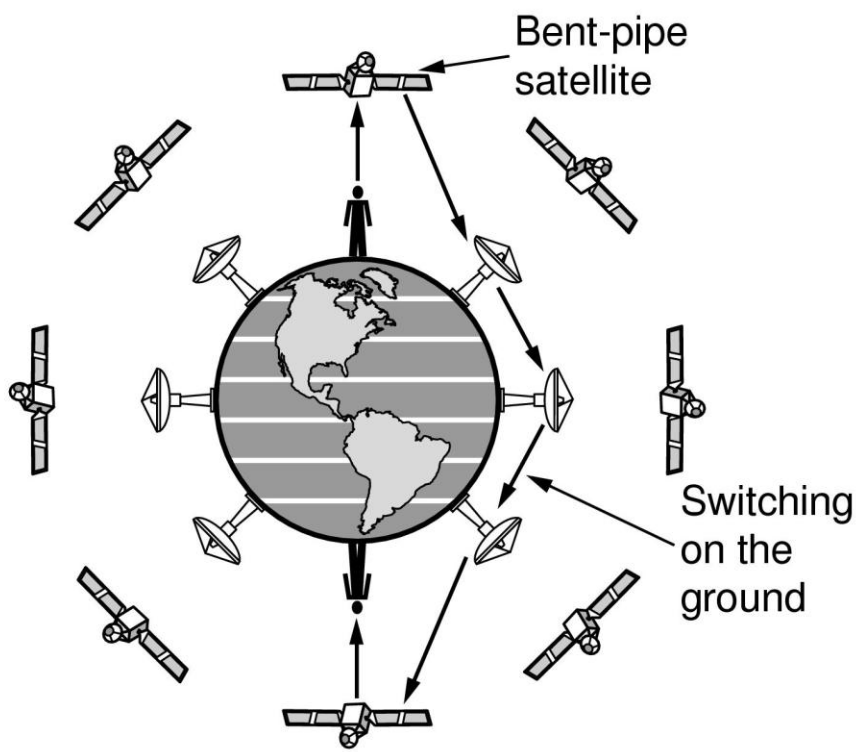
# Low-Earth Orbit Satellites (2)




(a)

Relaying in space.

# Low-Earth Orbit Satellites (3)



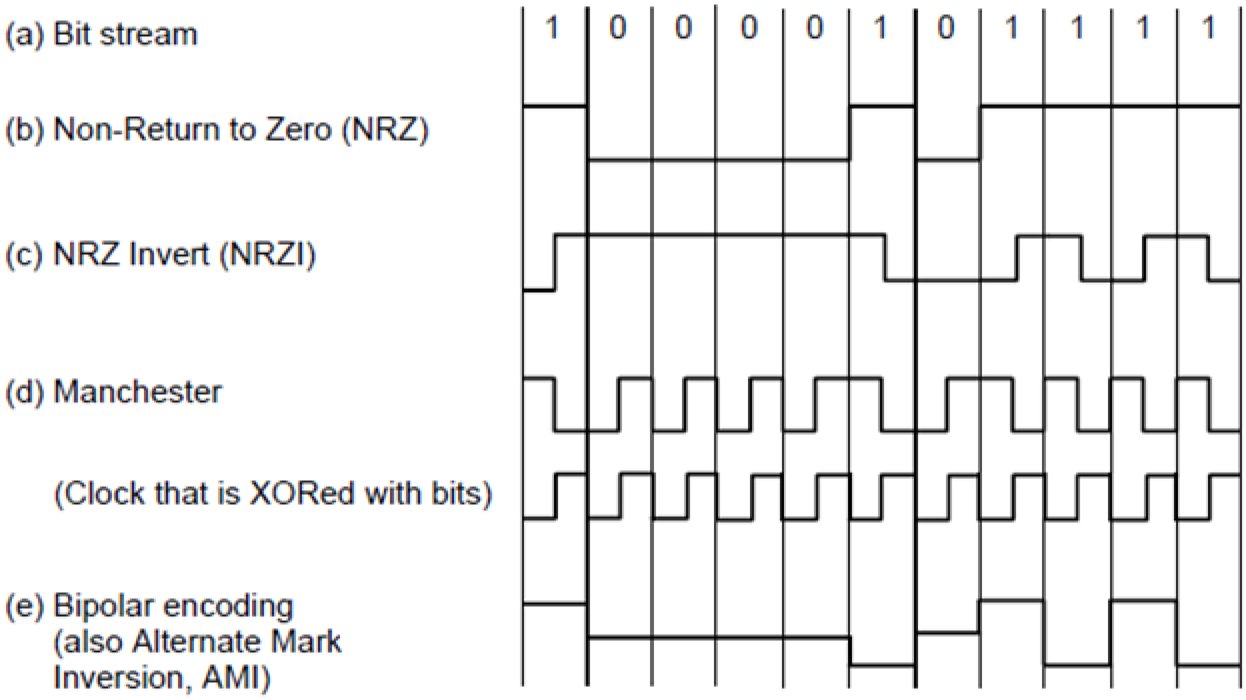

(b)

Relaying on the ground

# Digital Modulation and Multiplexing

- Baseband Transmission
- Passband Transmission
- Frequency Division Multiplexing
- Time Division Multiplexing
- Code Division Multiplexing

# Baseband Transmission




Line codes: (a) Bits, (b) NRZ, (c) NRZI, (d) Manchester, (e) Bipolar or AMI.

- Baud rate = symbol rate, *the rate at which the signal changes*
- Bit rate = symbol rate * number of bits per symbol
- 4 voltage levels represent 2 bits.

# Clock Recovery

- Long run of 1s and 0s cause problems
- How to synch the clocks
- Separate clock line
- Manchester encoding
- Non Return to Zero Invert (solves the problem of long run of 1s)
- 4B/5B mapping

# Clock Recovery

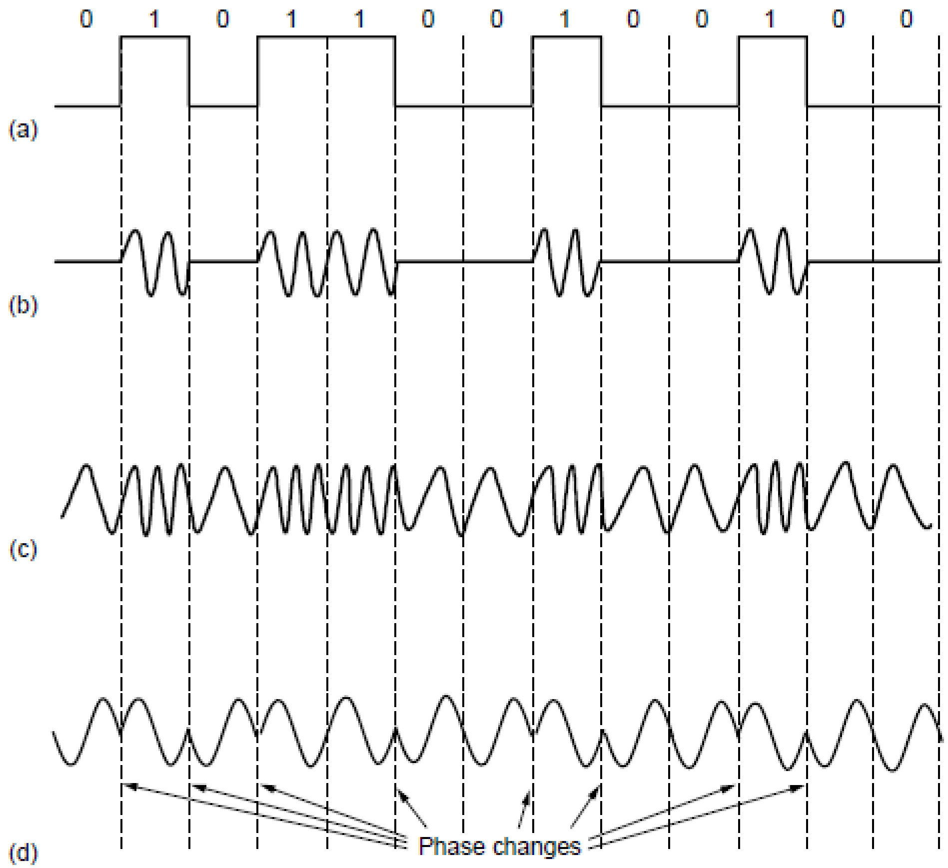
| Data (4B) | Codeword (5B) | Data (4B) | Codeword (5B) |
|---|---|---|---|
| 0000 | 11110 | 1000 | 10010 |
| 0001 | 01001 | 1001 | 10011 |
| 0010 | 10100 | 1010 | 10110 |
| 0011 | 10101 | 1011 | 10111 |
| 0100 | 01010 | 1100 | 11010 |
| 0101 | 01011 | 1101 | 11011 |
| 0110 | 01110 | 1110 | 11100 |
| 0111 | 01111 | 1111 | 11101 |

4B/5B mapping.

# Scrambler

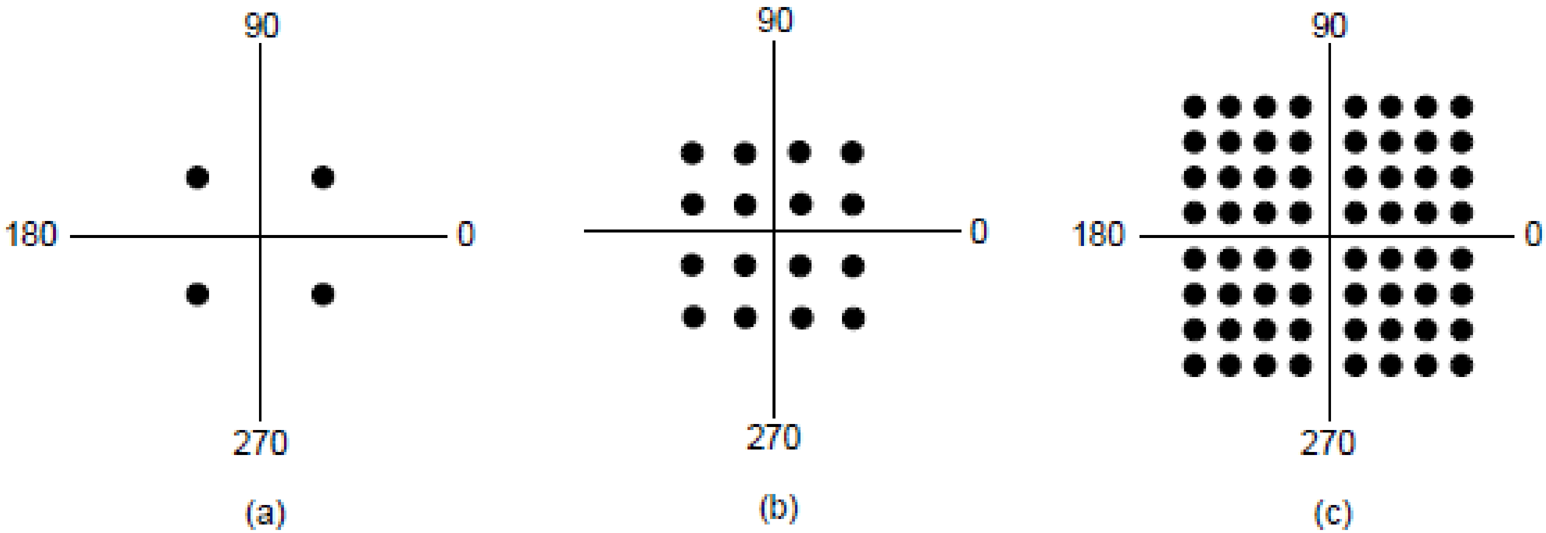
- Scrambler works by XORing the data with a pseudorandom sequence before it is trnasmitted.
- The receiver then XORs the incoming bits with the same pseudorandom sequence to recover the real data.

# Passband Transmission (1)




(a) A binary signal. (b) Amplitude shift keying.
(c) Frequency shift keying. (d) Phase shift keying.

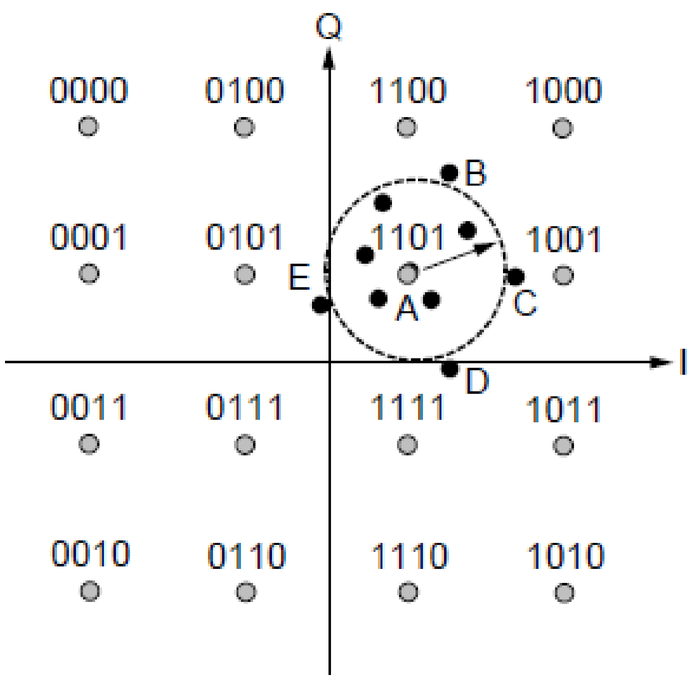
# Passband Transmission (2)




(a) QPSK. (b) QAM-16. (c) QAM-64.

QPSK: Quadrature Phase Shift Keying, QAM: Quadrature Amplitude Modulation

# Frequency Division Multiplexing (1)

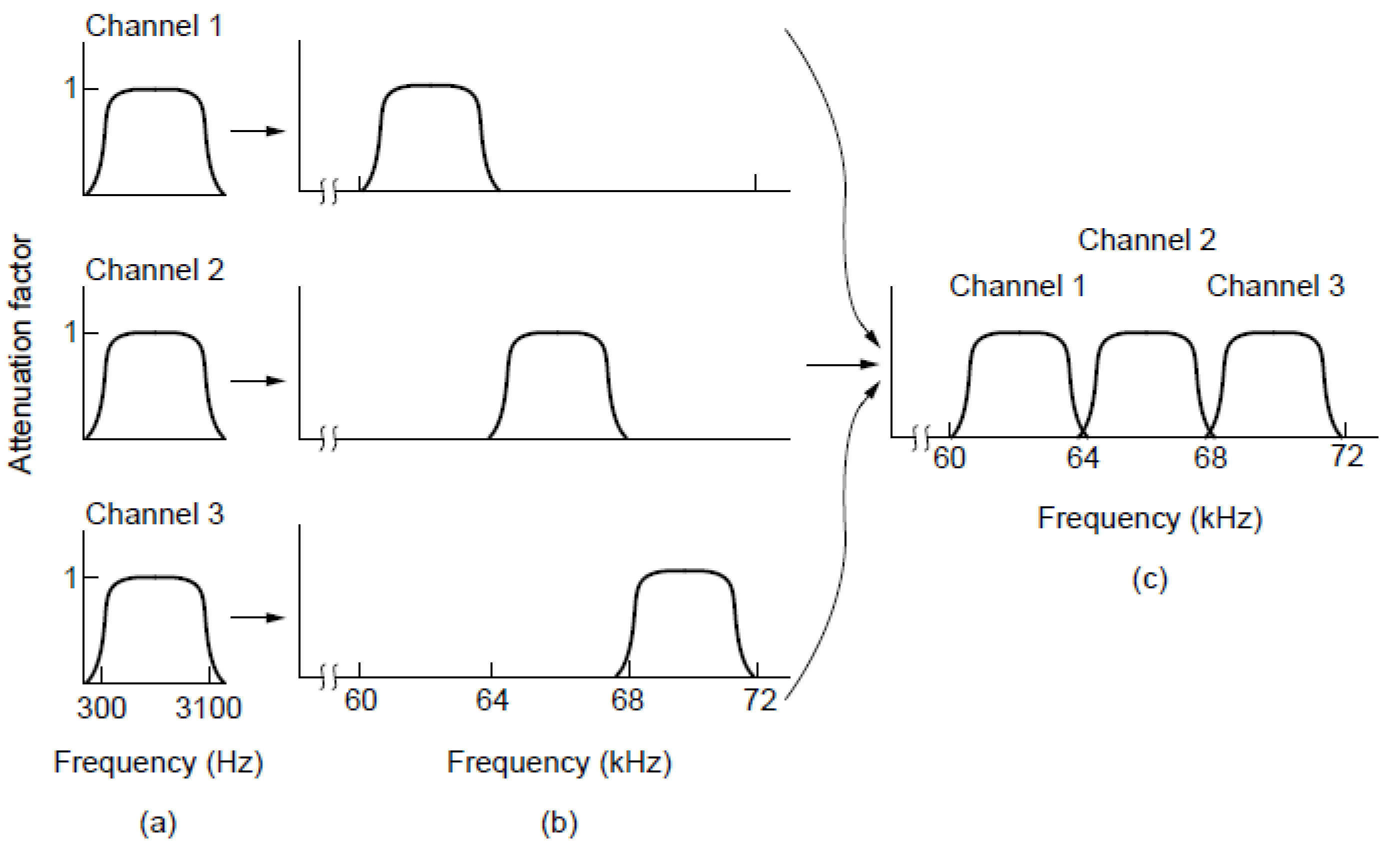



When 1101 is sent:

| Point | Decodes as | Bit errors |
|---|---|---|
| A | 1101 | 0 |
| B | 1100 | 1 |
| C | 1001 | 1 |
| D | 1111 | 1 |
| E | 0101 | 1 |

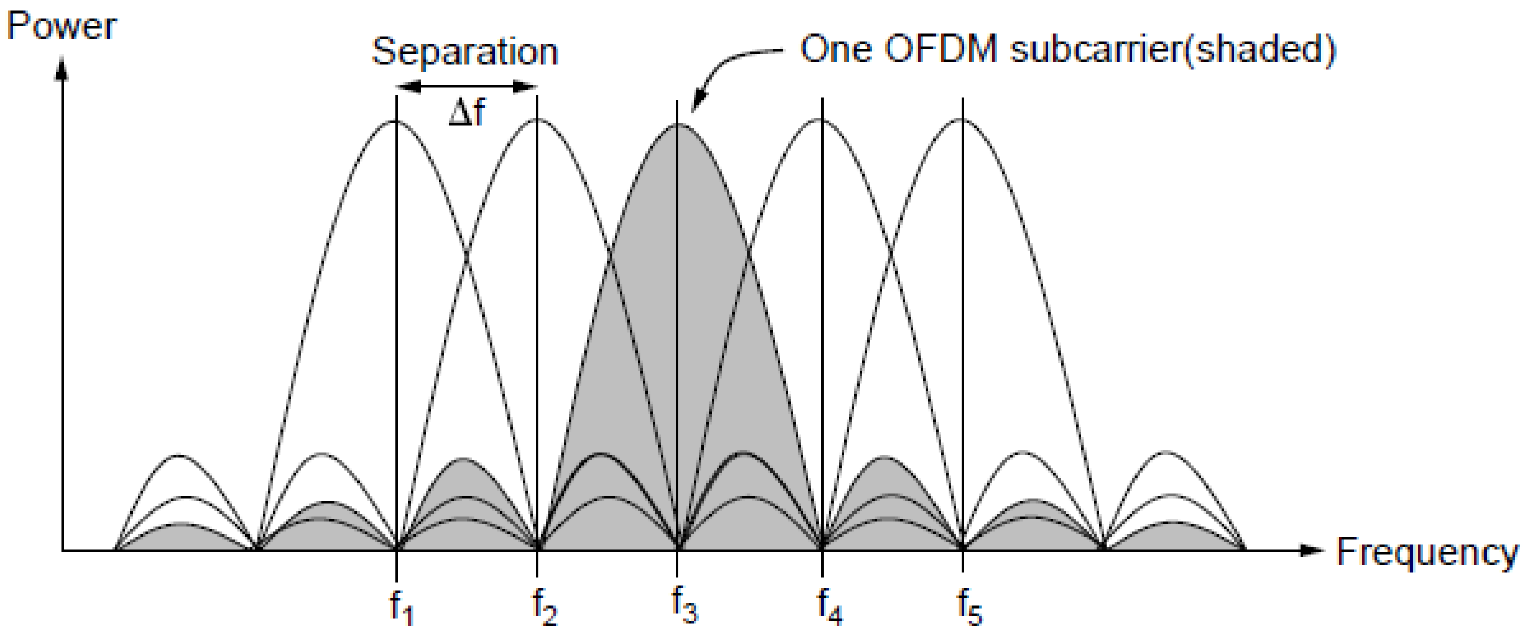
Gray-coded QAM-16.

# Frequency Division Multiplexing (2)



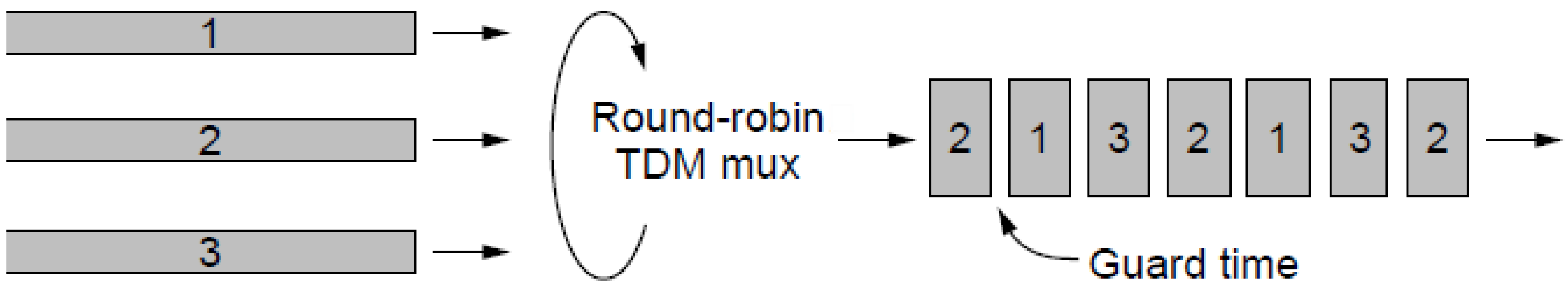

Frequency division multiplexing. (a) The original bandwidths.
(b) The bandwidths raised in frequency.
(c) The multiplexed channel.

# Frequency Division Multiplexing (3)




Orthogonal frequency division multiplexing (OFDM).

# Time Division Multiplexing




Time Division Multiplexing (TDM).

# Code Division Multiplexing (1)

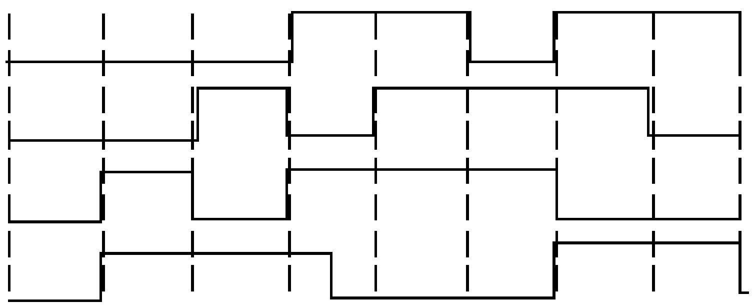
A = (−1 −1 −1 +1 +1 −1 +1 +1)

B = (−1 −1 +1 −1 +1 +1 +1 −1)

C = (−1 +1 −1 +1 +1 +1 −1 −1)

D = (−1 +1 −1 −1 −1 −1 +1 −1)

(a)



(b)

(a) Chip sequences for four stations.

(b) Signals the sequences represent

# Code Division Multiplexing (2)

$$
\begin{array}{llll}
S_1 = C & = (-1\ +1\ -1\ +1\ +1\ +1\ -1\ -1) & S_1 \bullet C = [1+1-1+1+1+1-1-1]/8 = 1 \\
S_2 = B+C & = (-2\ \ 0\ \ 0\ \ 0\ +2\ +2\ \ 0\ -2) & S_2 \bullet C = [2+0+0+0+2+2+0+2]/8 = 1 \\
S_3 = A+\overline{B} & = (\ 0\ \ 0\ -2\ +2\ \ 0\ -2\ \ 0\ +2) & S_3 \bullet C = [0+0+2+2+0-2+0-2]/8 = 0 \\
S_4 = A+\overline{B}+C & = (-1\ +1\ -3\ +3\ +1\ -1\ -1\ +1) & S_4 \bullet C = [1+1+3+3+1-1+1-1]/8 = 1 \\
S_5 = A+B+C+D & = (-4\ \ 0\ -2\ \ 0\ +2\ \ 0\ +2\ -2) & S_5 \bullet C = [4+0+2+0+2+0-2+2]/8 = 1 \\
S_6 = A+B+\overline{C}+D & = (-2\ -2\ \ 0\ -2\ \ 0\ -2\ +4\ \ 0) & S_6 \bullet C = [2-2+0-2+0-2-4+0]/8 = -1
\end{array}
$$

(c) (d)

(a) Six examples of transmissions.

(b) Recovery of station C's

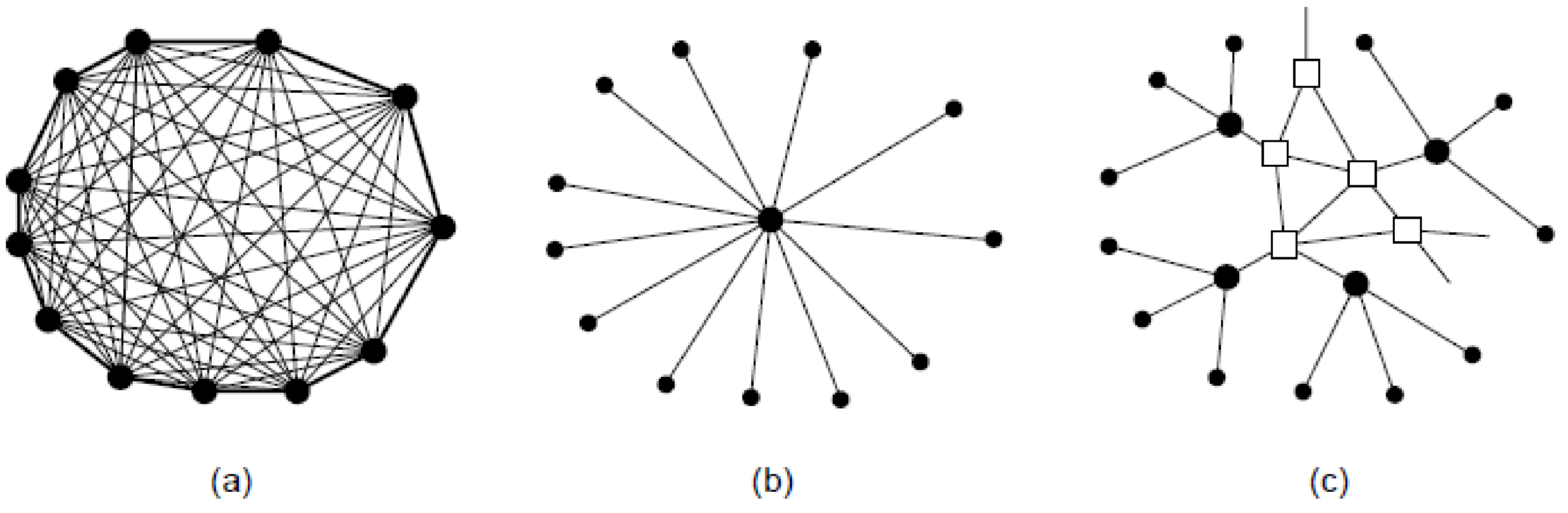
# The Public Switched Telephone Network (PSTN)

- Structure of the telephone system
- Politics of telephones
- Local loop: modems, ADSL, and fiber
- Trunks and multiplexing
- Switching

# Structure of the Telephone System

- Alexander Graham Bell patented the telephone in 1876 just a few hours before his rival Elisha Gray.
- Initial market was for the sale of telephones which were sold in pairs. The customers connected them with a wire.
- Within a year, the cities were covered with wires passing over trees and houses.
- Bell formed the first the  Bell Telephone Company which opened the first switching office in 1878.

# Structure of the Telephone System




(a) Fully interconnected network.

(b) Centralized switch.

(c) Two-level hierarchy.

# Structure of the Telephone System

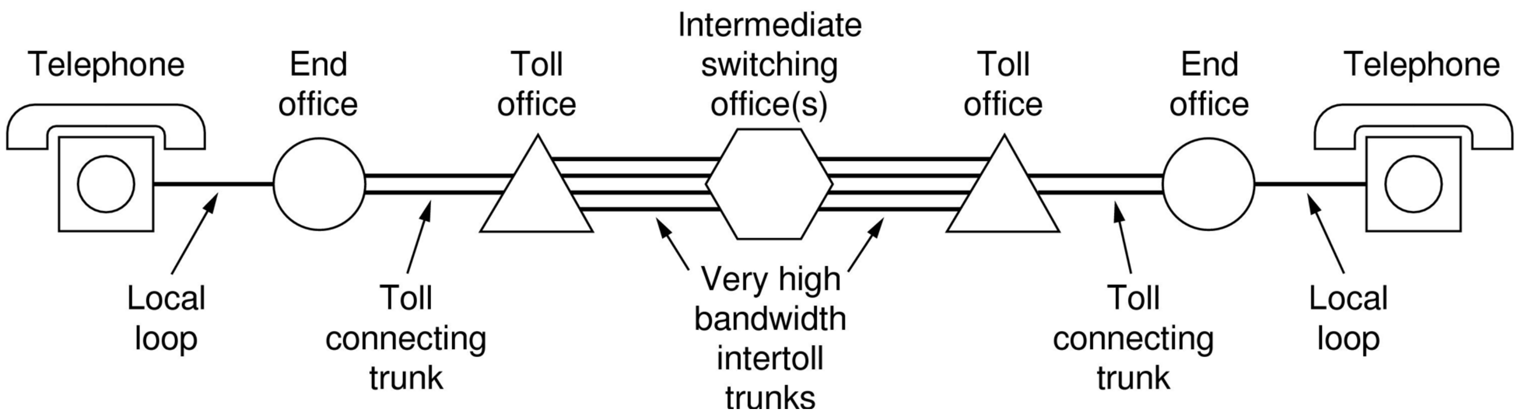
By 1880 three major parts of a telephone system were in place:

1)The switcing offices,

2)The wires between the end users and the switching offices,

3)Long distance connections between the switching offices.

# Structure of the Telephone System




A typical circuit route for a long-distance call.

# Structure of the Telephone System

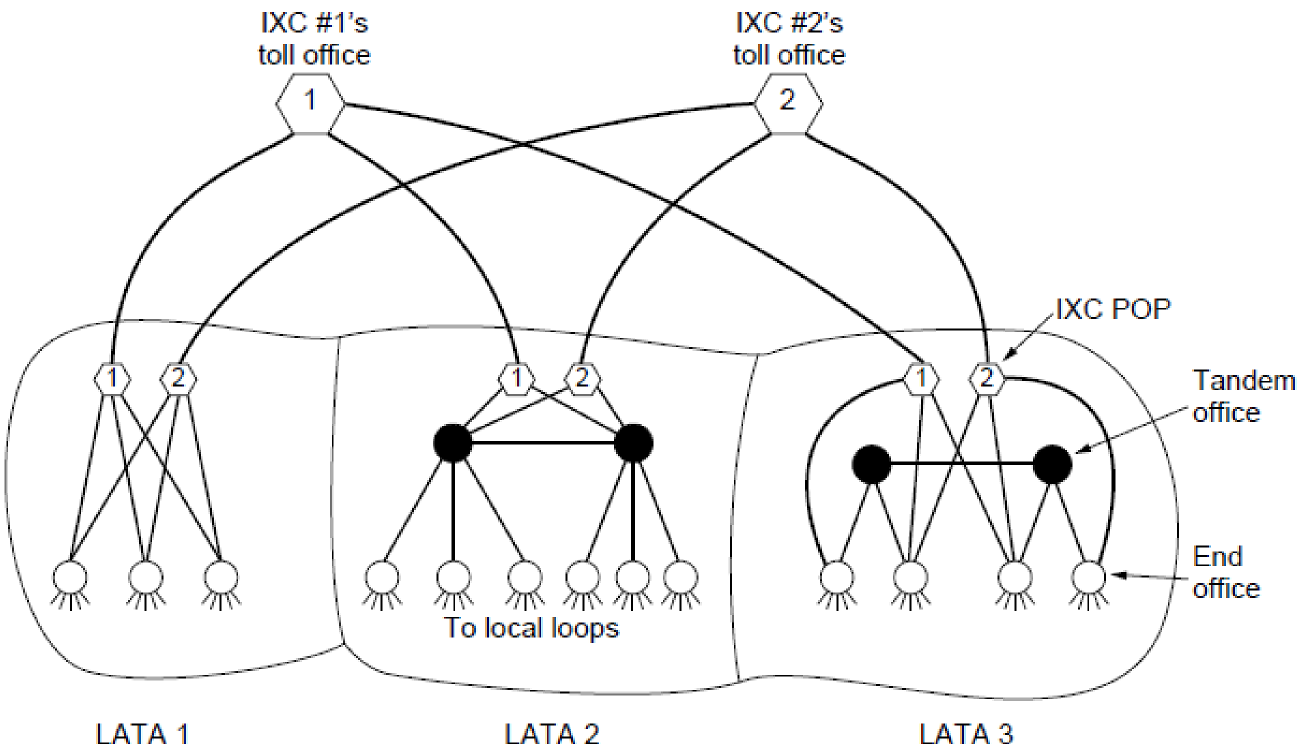
- Prior to the breakup of AT&T in 1984, the US telephone system used hierarchical routing to find a path, going to higher levels until there was a switching office in common.
- This was replaced with more practical non hierarchical routing.

# Structure of the Telephone System

## Major Components

1. Local loops (analog twisted pairs to houses, businesses).
2. Trunks (digital fiber optic links between switching offices).
3. Switching offices (calls are moved from one trunk to another).

# The Politics of Telephones

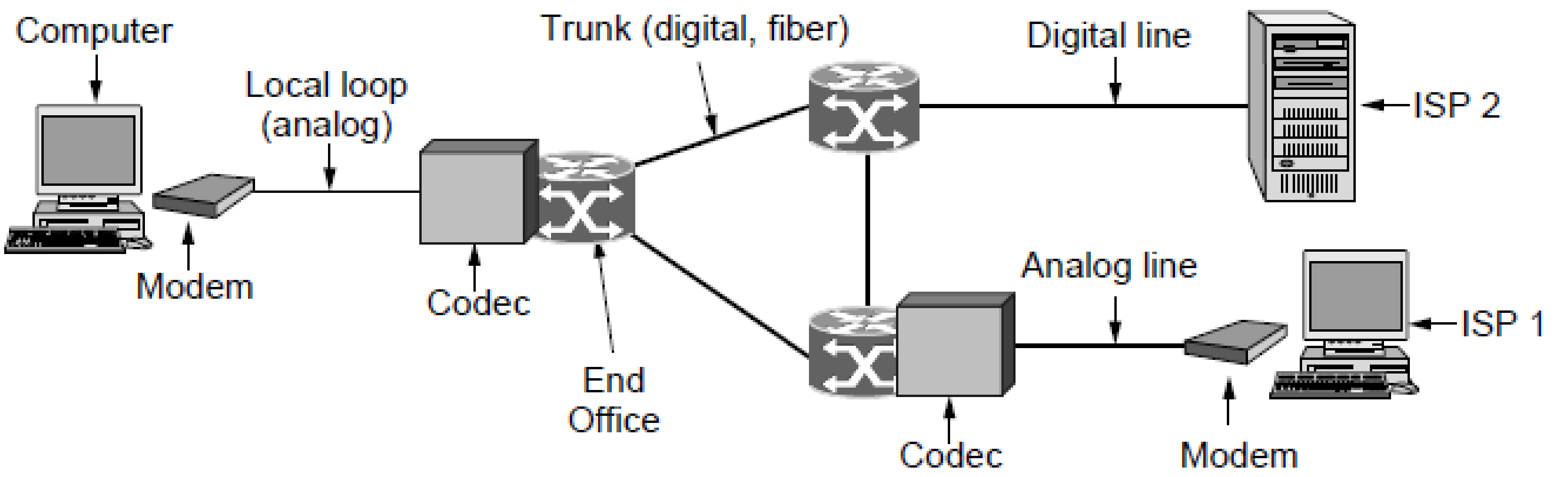



The relationship of LATAs (local access and transport areas), LECs (local exchange carriers), and IXCs(interexchange carriers). Circles are LEC switching offices. Hexagons belong to IXC whose number is in it. POP (point of presence)

# The Politics of Telephones

- In 1984 AT&T was broken into smaller companies. Inter-LATA traffic was handled by different kind of company, an IXC.
- In 1995, cable tv companies, local telephone companies, long distance companies, and mobile operators were allowed to enter one another's bussiness.
- In 1996, local number portability was allowed.

# Telephone Modems (ModulatorDemodulator)




Use of both analog and digital transmission for computer -to-computer call. Conversion done by modems and codecs.

# Telephone Modems

- Nyquist theorem tells a perfect 3000-Hz line cannot sends symbols faster than 6000 baud (in practice 2400-signals/sec or 2400 baud).
- By using 4 phases QPSK achieves 4800 bps.
- V.32 modem standard uses 32 constellation points and achieve 9600 bps (4 data bits+1 checkbit)
- V.34bis standard achieves 14 databits/symbol at 2400 baud, means 33 600 bps.

# Telephone Modems

- The reason behind 56-kbps modems:

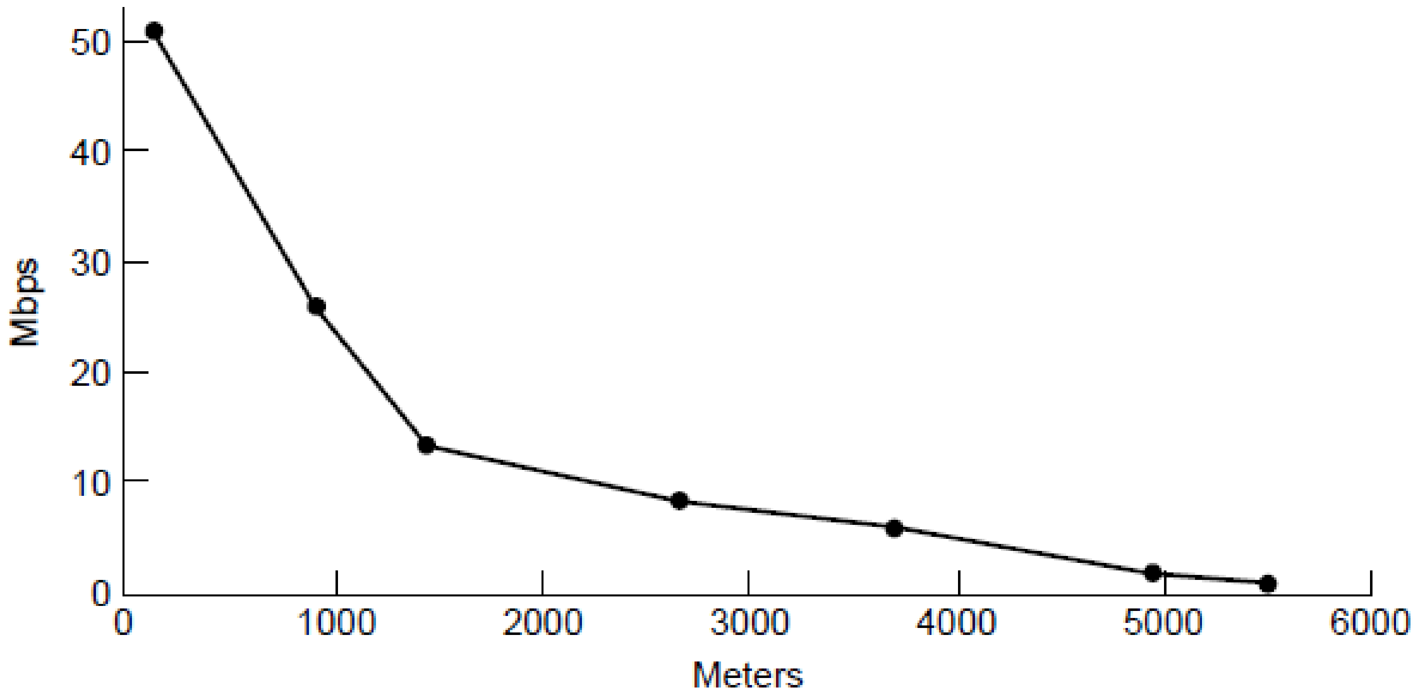
  - Each telephone channel is 4000 Hz with the guard bands.

  - Number of samples per sec is 8 000

  - Number of bits per sample is 8 (in US 7 data+1 control, in Europe 8 data)

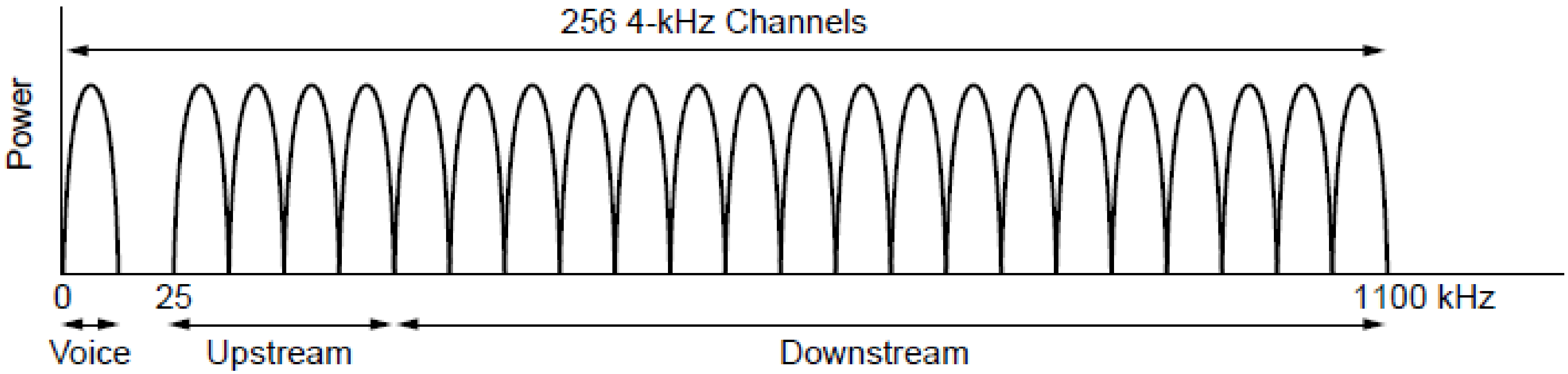
  - Hence 56 kbps in US and 64 kbps in Europe. For the standard 56kbps was chosen.

# Digital Subscriber Lines (1)



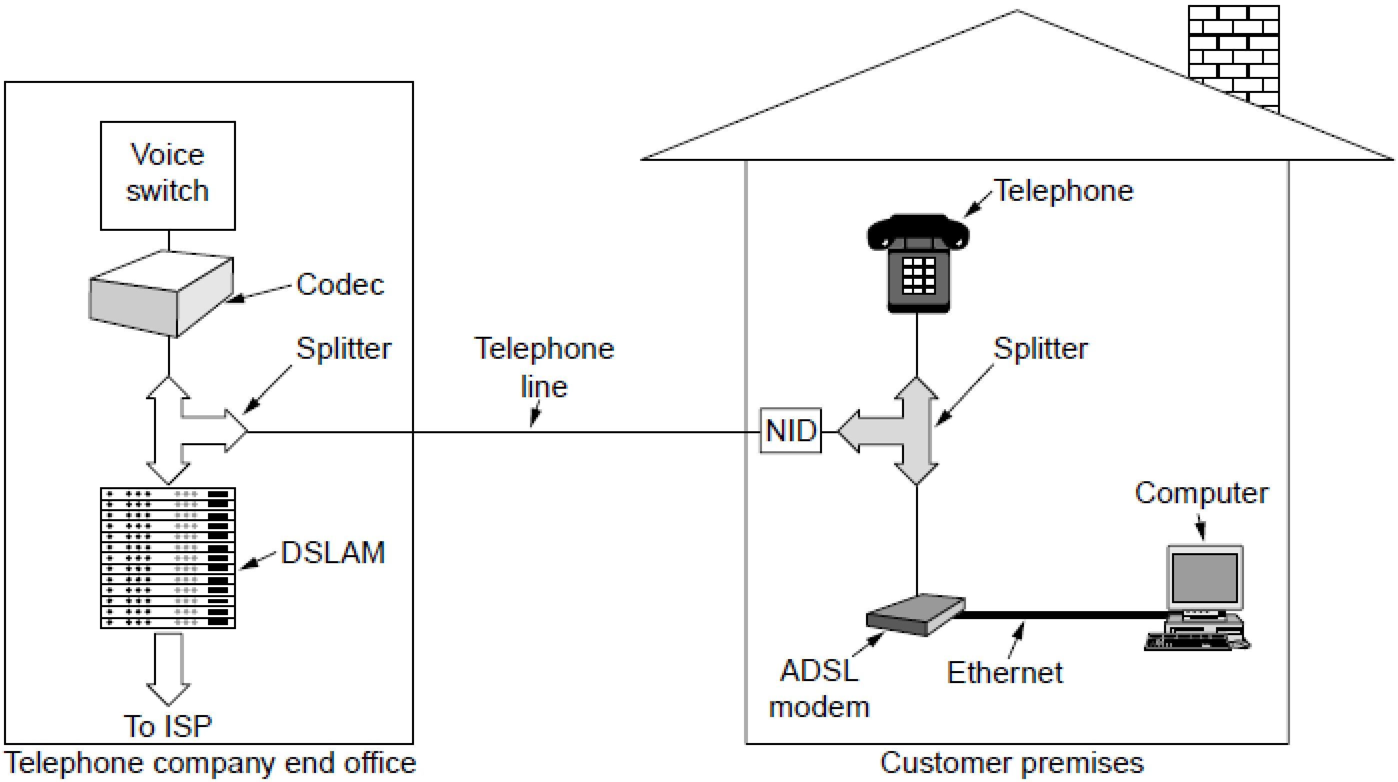

Bandwidth versus distance over Category 3 UTP for DSL (Digital Subscriber Line).

# Digital Subscriber Lines (2)



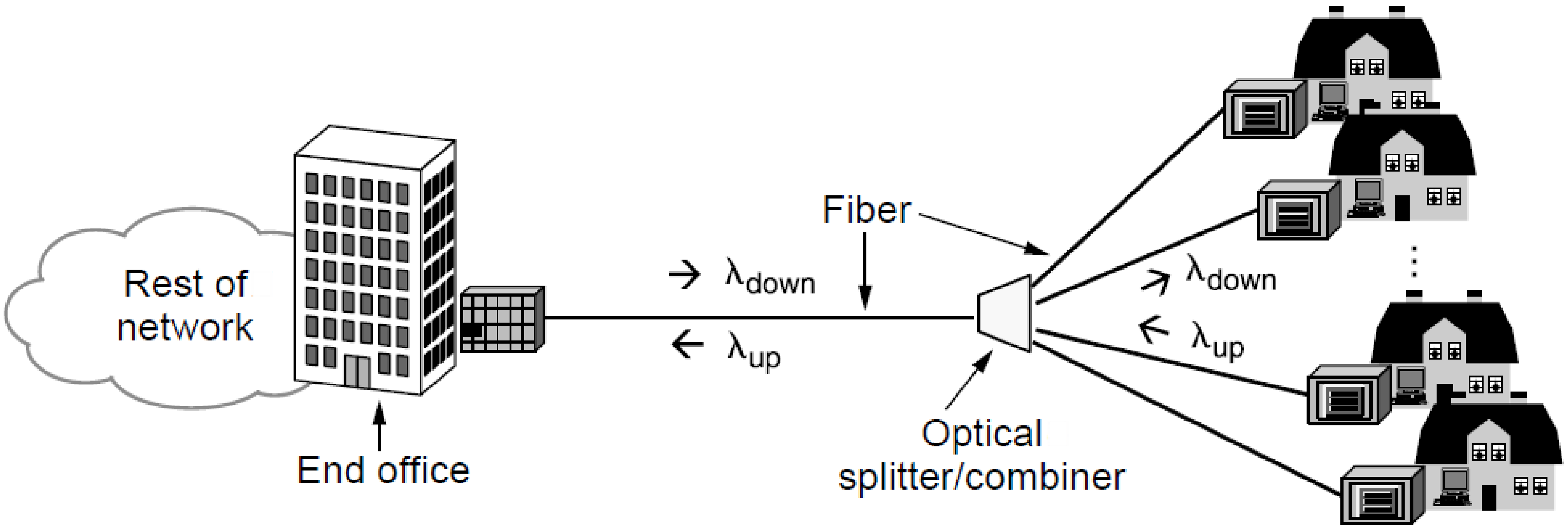

Operation of ADSL using discrete multitone modulation.

# Digital Subscriber Lines (3)




A typical ADSL equipment configuration.

# Fiber To The Home



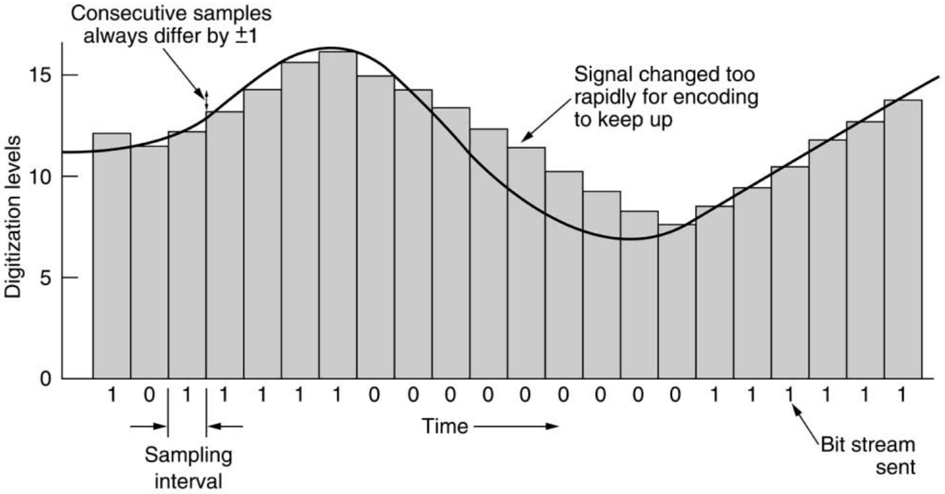

Passive optical network (PON) for Fiber To The Home.

# Fiber To The Home

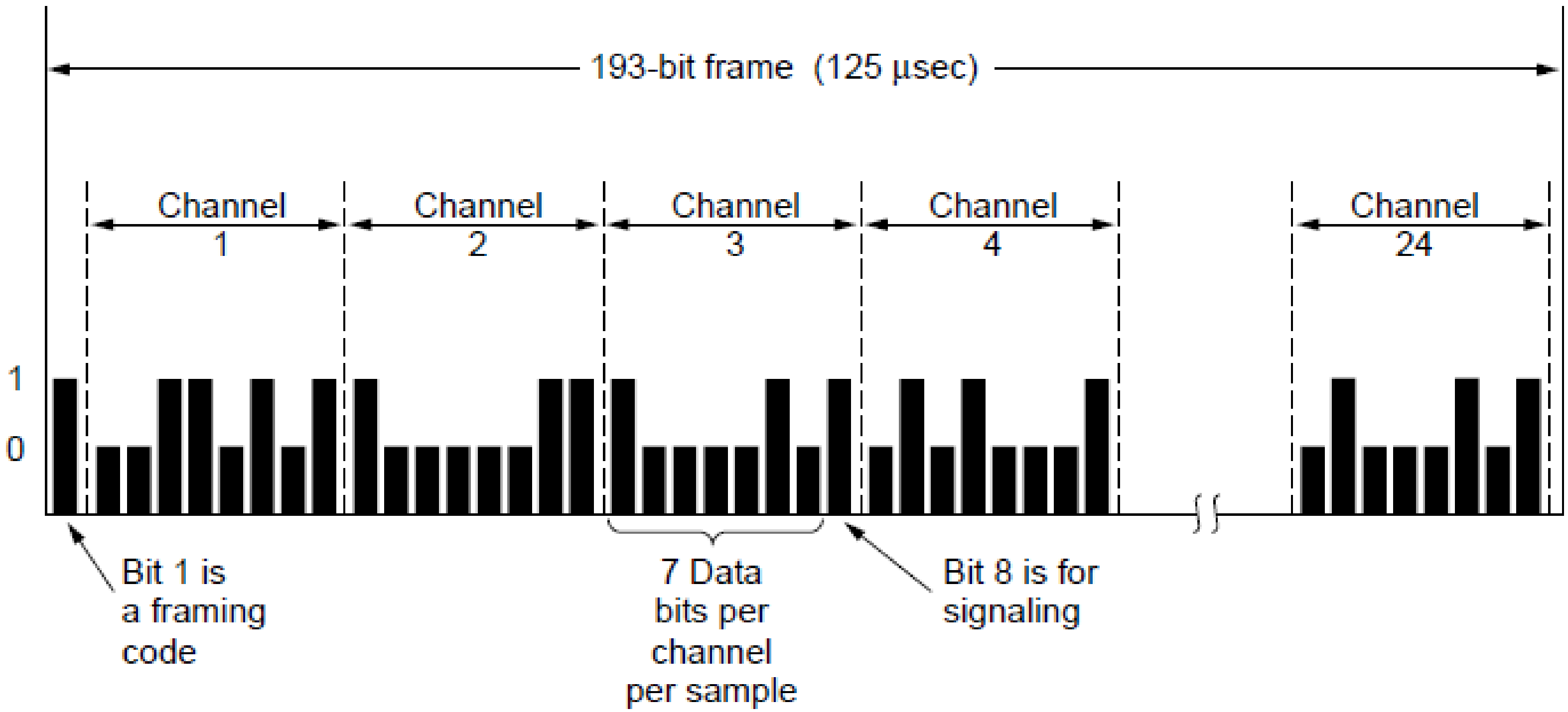
- Passive means no powered equipment is required to amplify or otherwise process signals.
- PONs can provide higher data rates to users over the distances of up to 20 km.
- GPON- Gigabit-capable PON and EPON- Ethernet PONs are the two spandards.

# Digitizing Voice Signals

- Pulse Code Modulation (PCM)
  - Consider 4000-Hz voice channels, 8000 samples
  - 125 μsec/sample, 8 bits per sample-64 kbps
- Differential PCM

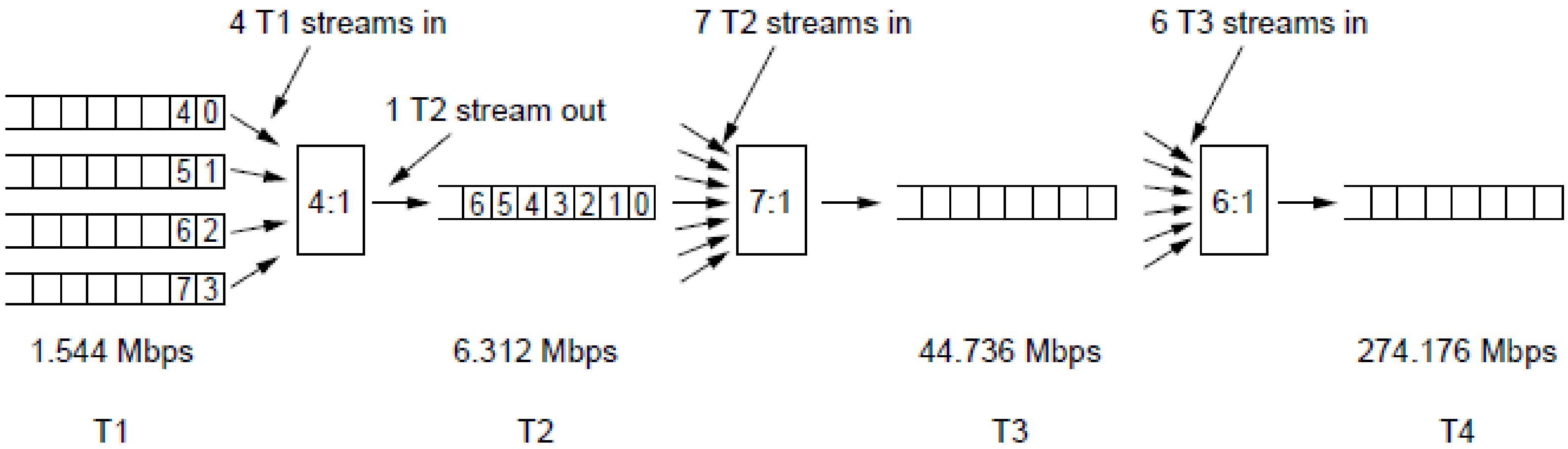


# Time Division Multiplexing




The T1 carrier (1.544 Mbps).

# Time Division Multiplexing




Multiplexing T1 streams into higher carriers

# Time Division Multiplexing (Signaling)

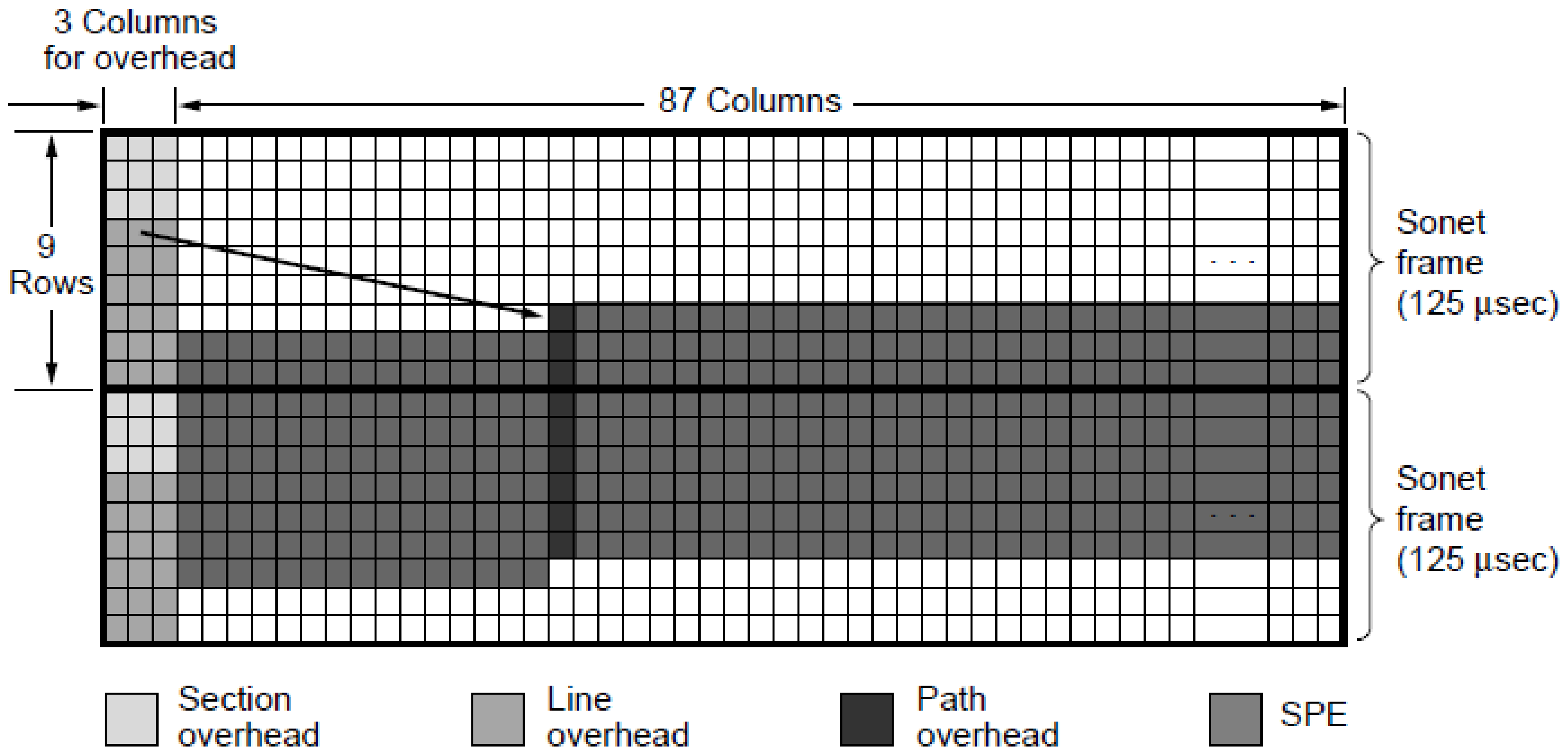
- The T1 format has several variations.

  - signalling information is **in-band**: some of data bits used for signaling. Also called **robbed-bit signaling**.

  -signalling information is **out-of-band**:one of the 24 channels is reserved for signaling.

- Outside North America and Japan, the 2 048-Mbps E1 carrier is used instead of T1 carrying 32 8-bit data samples packed into the basic 125-microsec frame.

# SONET/SDH (1)-SKIP



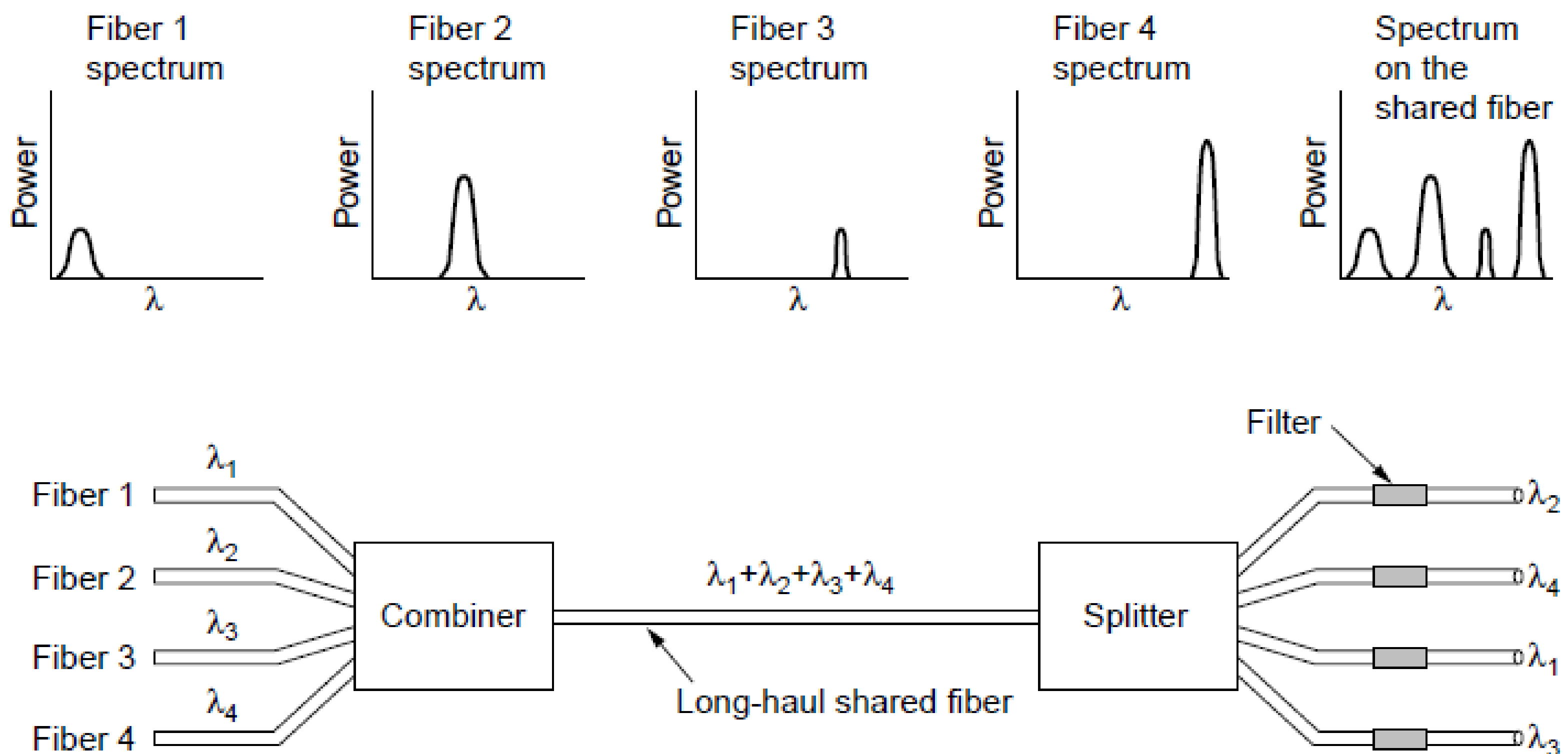

Two back-to-back SONET frames.

# SONET/SDH (2)-SKIP

| SONET | | SDH | Data rate (Mbps) | | |
|---|---|---|---|---|---|
| Electrical | Optical | Optical | Gross | SPE | User |
| STS-1 | OC-1 | | 51.84 | 50.112 | 49.536 |
| STS-3 | OC-3 | STM-1 | 155.52 | 150.336 | 148.608 |
| STS-12 | OC-12 | STM-4 | 622.08 | 601.344 | 594.432 |
| STS-48 | OC-48 | STM-16 | 2488.32 | 2405.376 | 2377.728 |
| STS-192 | OC-192 | STM-64 | 9953.28 | 9621.504 | 9510.912 |
| STS-768 | OC-768 | STM-256 | 39813.12 | 38486.016 | 38043.648 |

SONET and SDH multiplex rates.

# Wavelength Division Multiplexing

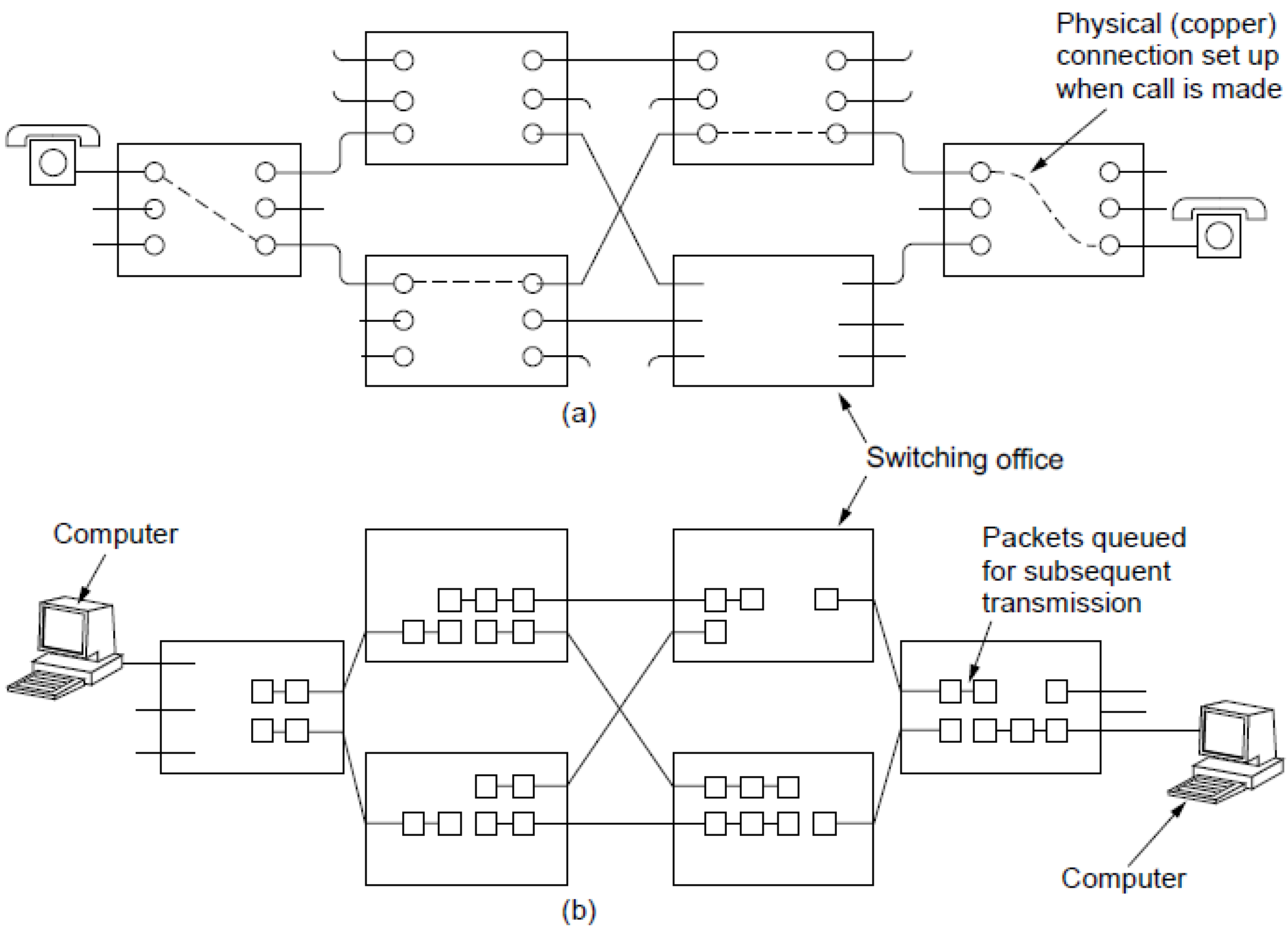



Wavelength division multiplexing

# Switching

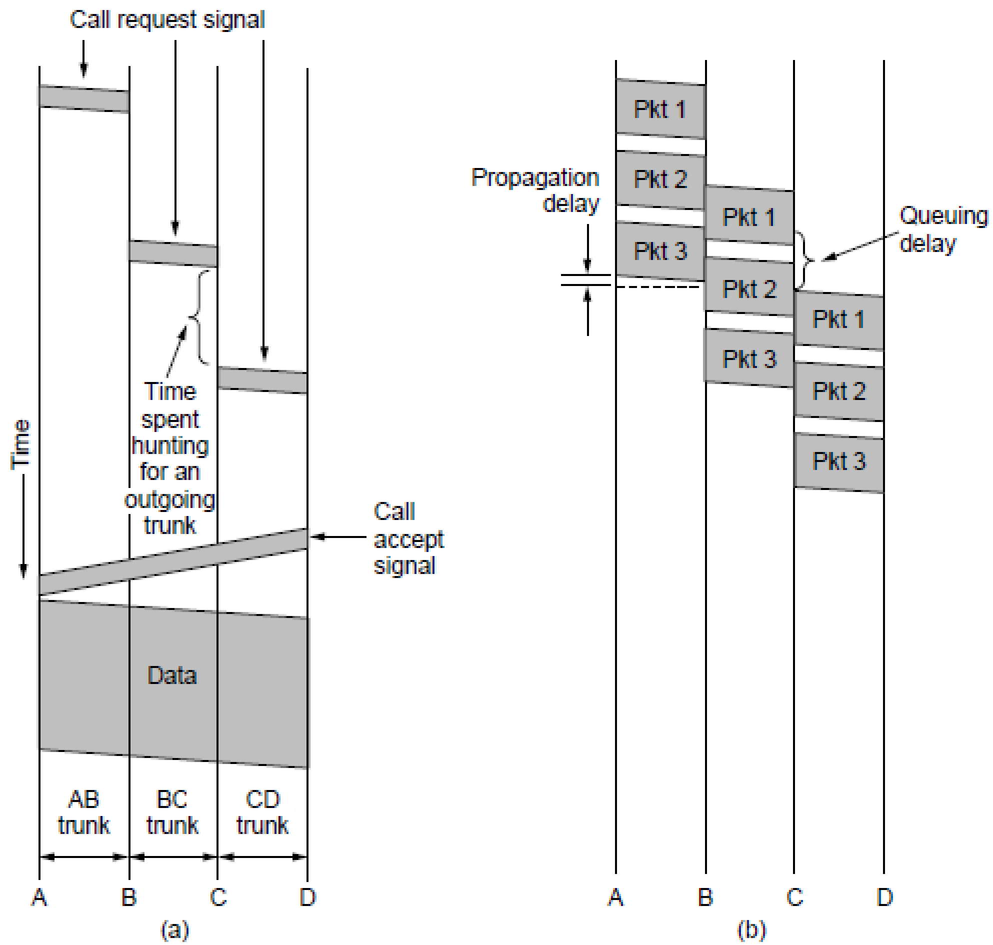
- Circuit switching
- Packet switching

# Circuit Switching/Packet Switching (1)




(a) Circuit switching. (b) Packet switching.

# Circuit Switching/Packet Switching (2)




Timing of events in (a) circuit switching, (b) packet switching

# Circuit Switching/Packet Switching (3)

| Item | Circuit switched | Packet switched |
|---|---|---|
| Call setup | Required | Not needed |
| Dedicated physical path | Yes | No |
| Each packet follows the same route | Yes | No |
| Packets arrive in order | Yes | No |
| Is a switch crash fatal | Yes | No |
| Bandwidth available | Fixed | Dynamic |
| Time of possible congestion | At setup time | On every packet |
| Potentially wasted bandwidth | Yes | No |
| Store-and-forward transmission | No | Yes |
| Charging | Per minute | Per packet |

A comparison of circuit-switched and packet-switched networks.

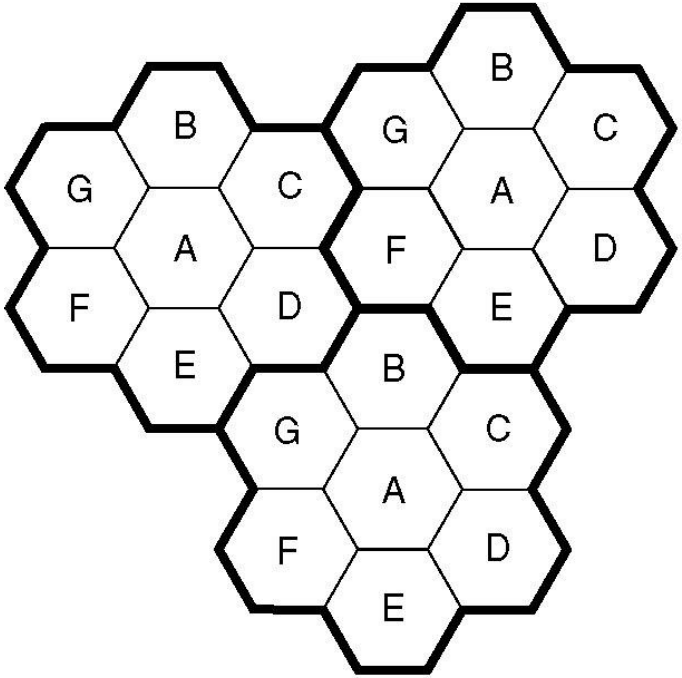
# Mobile Telephone System

- First-Generation (1G) Mobile Phones Analog Voice
- Second-Generation (2G) Mobile Phones Digital Voice
- Third-Generation (3G) Mobile Phones Digital Voice + Data

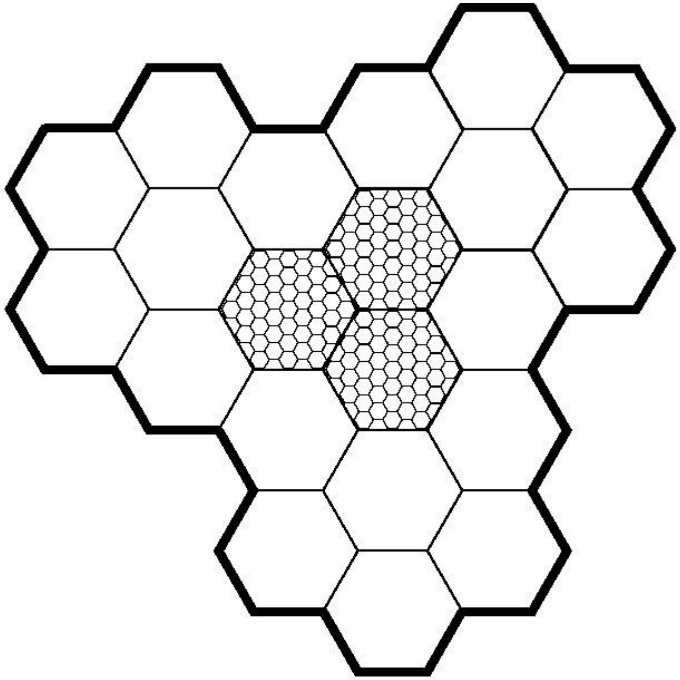
# First generation Mobile Phones

- Push-to-talk late 1950s: Wireless radiophones. One transmitter. Single channel.
- IMTS (Improved Mobile Telephone System), 1960s: One transmitter on hilltop. 23 channels.
- AMPS (Advanced Mobile Phone System), by Bell Labs,1982:
  - Cells, microcells=>Frequency reuse=>Increased capacity
  - Base stations
  - MSC(Mobile Switching Center) or MTSO(Mobile Telephone Switching Office)
  - Changing base stations: Handoff (takes about 300 msec, channel assignment by MSC)

# Advanced Mobile Phone System (hexagon based modeling)




(a)



(b)

(a) Frequencies are not reused in adjacent cells.

(b) To add more users, smaller cells (microcells) can be used.

# Channel Categories (AMPS)

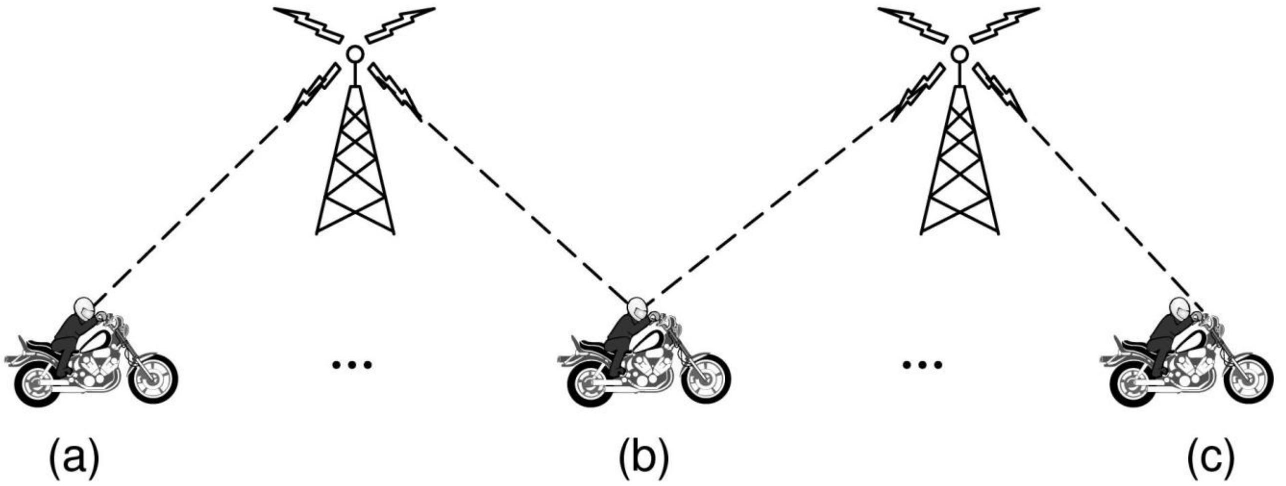
- 832 full-duplex channels, 832 simplex pairs, each 30 kHz wide
  - (824-849Mhz) upstream
  - (869-894Mhz) downstream.
- Four categories:
  - Control (base to mobile) to manage the system (Location registration)
  - Paging (base to mobile) to alert users to calls for them
  - Access (bidirectional) for call setup and channel assignment
  - Data (bidirectional) for voice, fax, or data

# AMPS Communication

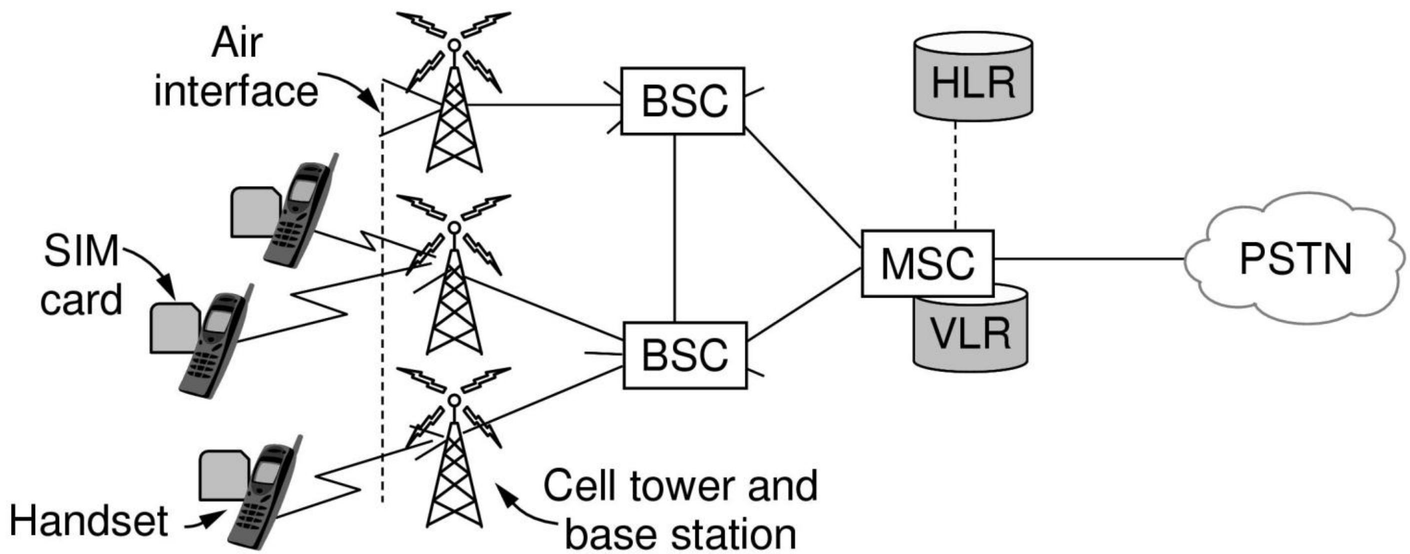
- Mobile phone broadcasts serial and tel. No.
- Base station tells its MTSO, which records and informs home MTSO of location
- Call:
  - Caller transmits its id and callee phone no.
  - Base station informs caller’s MTSO which allocates channel, caller switches to this channel.
  - Callee is found via its home MTSO
  - Callee’s current MTSO allocates channel and callee switches to this channel.

# AMPS, HandOff

- MSC manages it without help from the mobile devices



# GSM—The Global System for Mobile Communications (1)

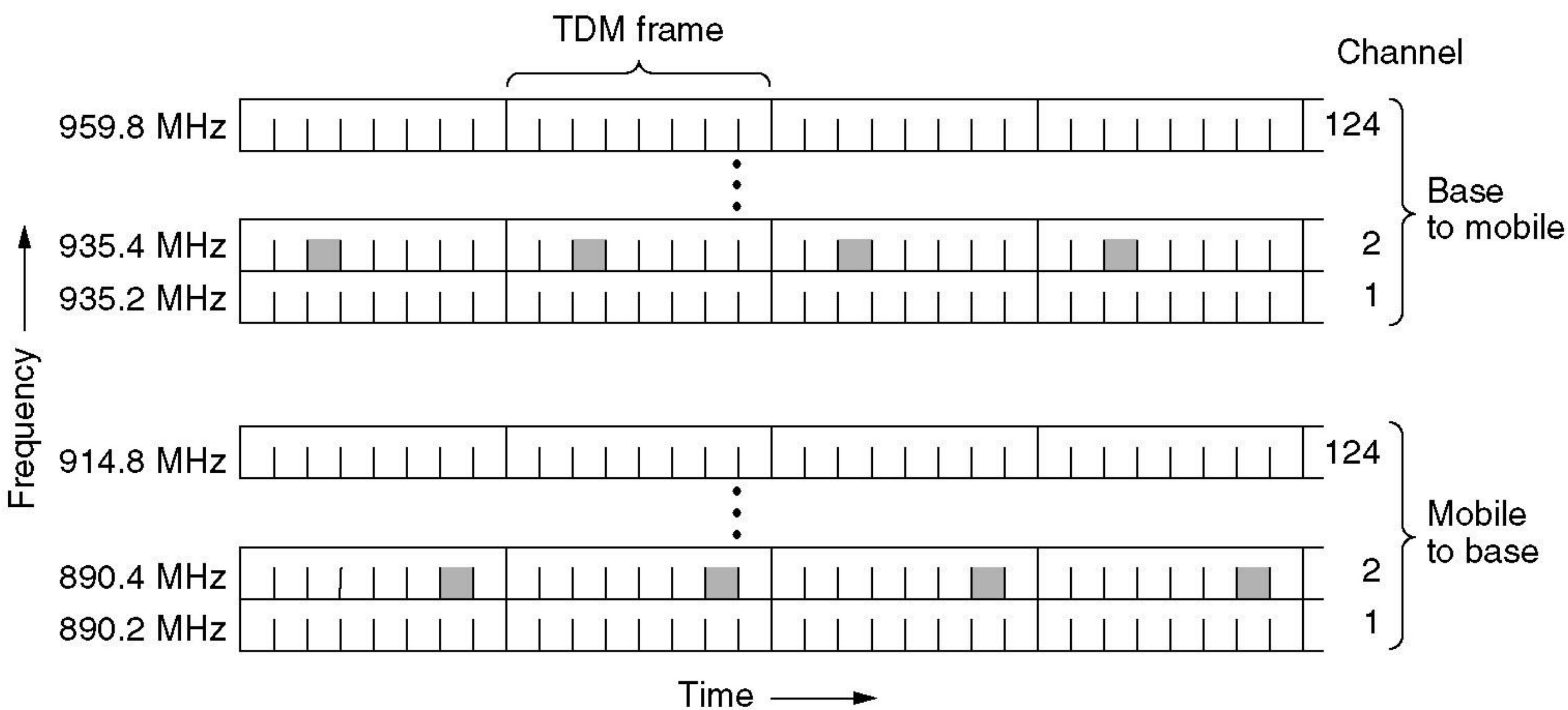



BCS:base station controller, HLR: home location register, VLR:visitor location register

GSM mobile network architecture.

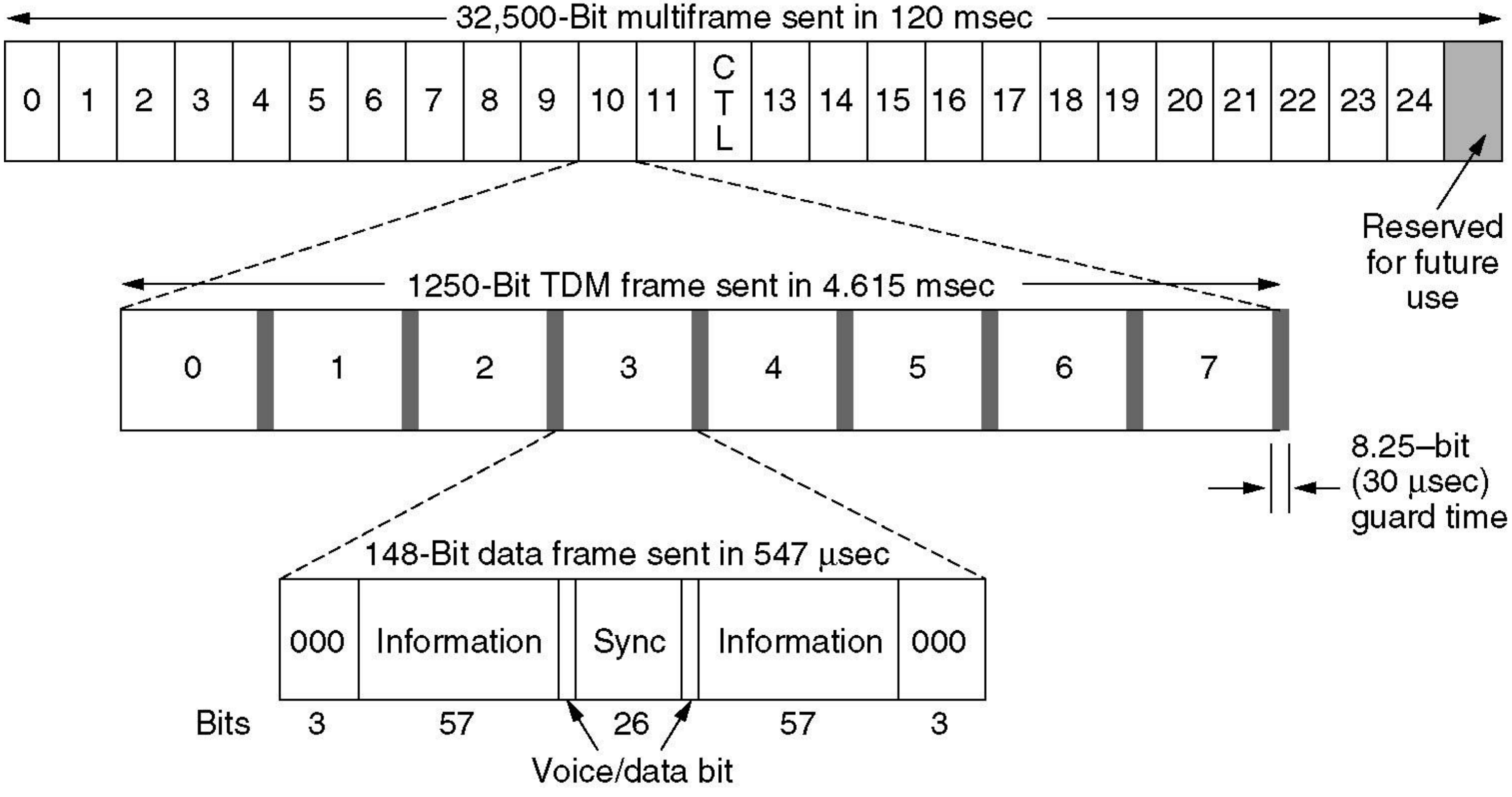
# GSM
# Global System for Mobile Communications

GSM uses 124 pairs of simplex frequency channels, each of which uses an eight-slot



# GSM (2)

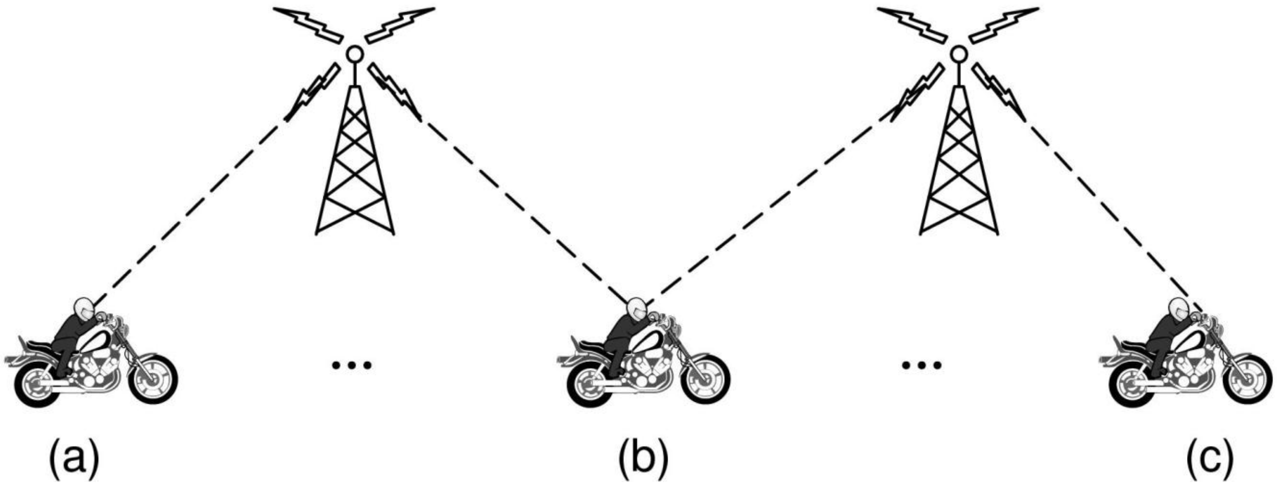
A portion of the GSM framing structure.



# GSM, HandOff

- The mobile measures the signal quality to other nearby base station.
- This information is sent to the BSC.
- The BSC can use it to determine when a mobile is leaving one cell and entering another so it can perform the handoff.
- This is called MAHO (Mobile Assisted HandOff).

# GSM, Handoff



# Third-Generation Mobile Phones: Digital Voice and Data

Basic services an IMT-2000 network should provide

- High-quality voice transmission
- Messaging (replace e-mail, fax, SMS, chat, etc.)
- Multimedia (music, videos, films, TV, etc.)
- Internet access (web surfing, w/multimedia.)
- Videoconferencing, group game playing

# Third-Generation Mobile Phones

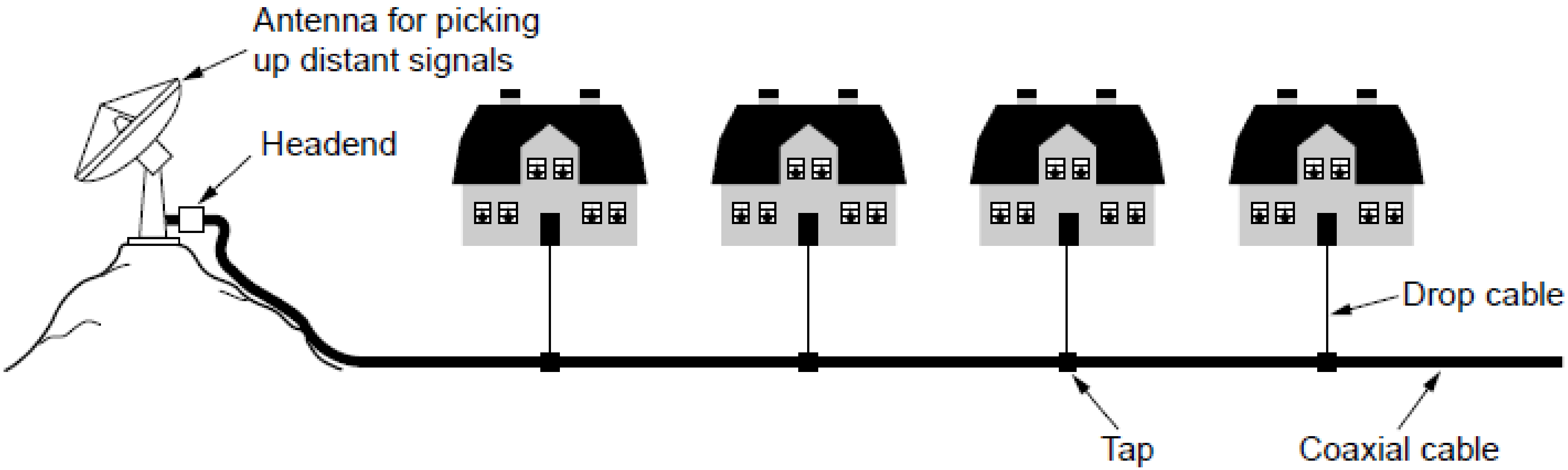
- UMTS (W-CDMA):
  - Ericsson
  - Direct sequence spread spectrum
  - UMTS to GSM handoff possible
- CDMA2000:
  - Qualcomm
  - Direct sequence spread spectrum
  - Backward compatible with 2. generation CDMA system (IS-95)
- GPRS (General Packet Radio Service)
  - Overlay packet network on top of GSM.
  - Send and receive IP packets.
  - Pay per packet transfer
- EDGE/EGPRS Enhanced Data rates for GSM Evolution-2.5G)
  - 48 kbps for each timeslot and upto 8 timeslots

UP TO HERE...

# Cable Television

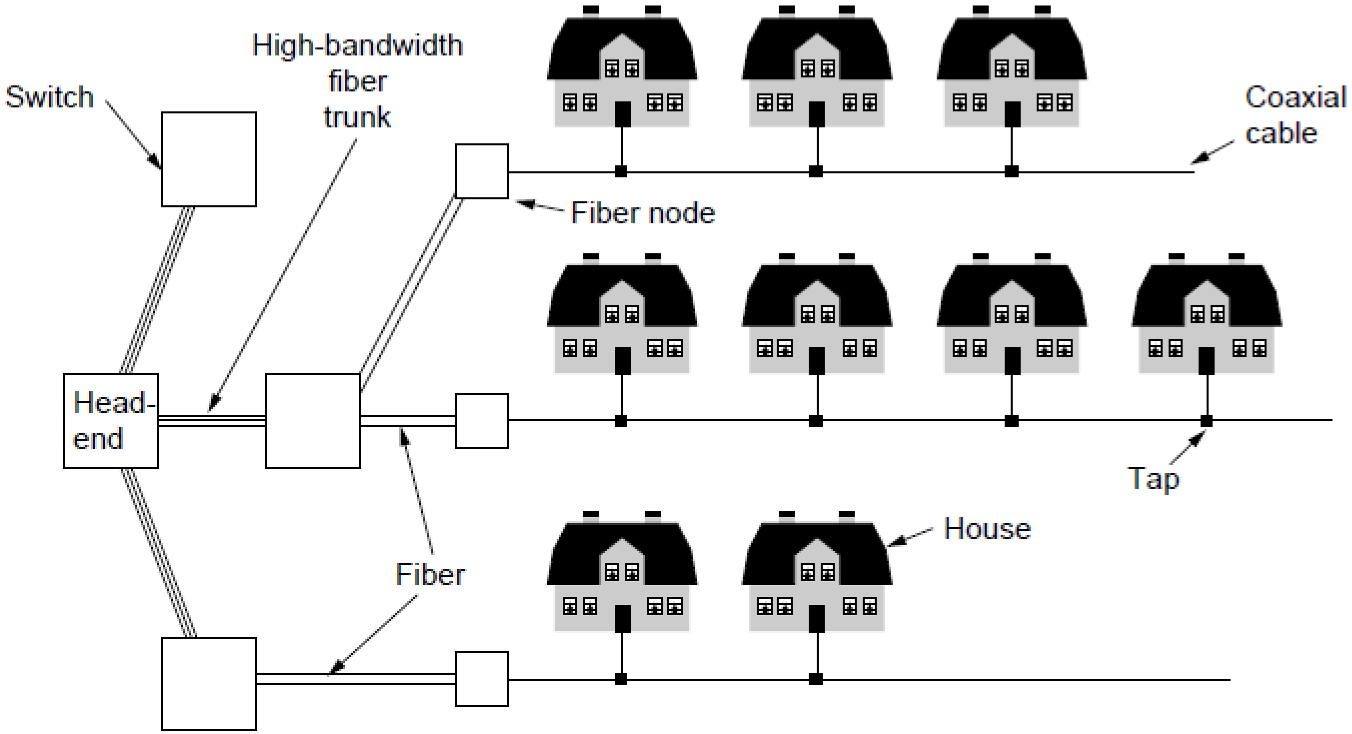
- Community antenna television
- Internet over cable
- Spectrum allocation
- Cable modems
- ADSL versus cable

# Community Antenna Television



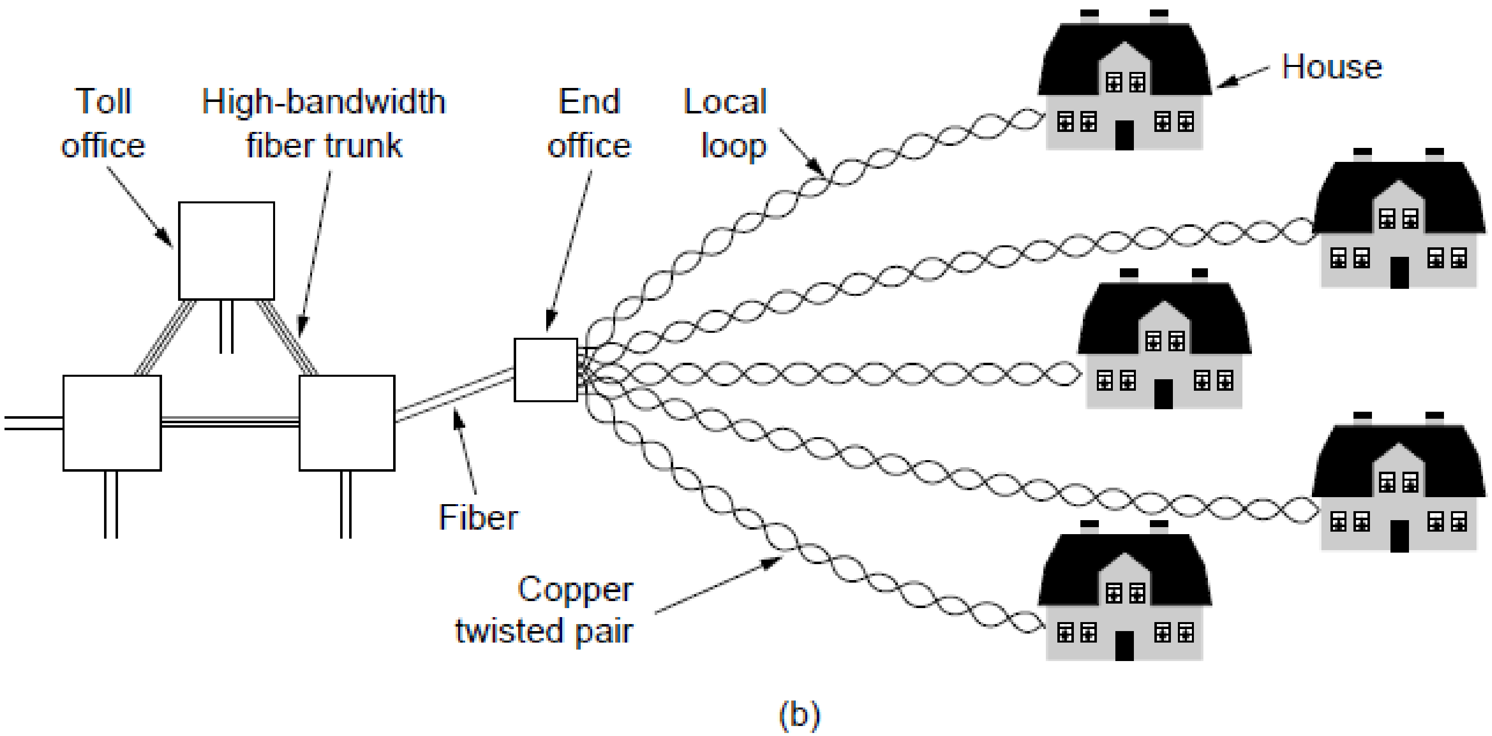

An early cable television system

# Internet over Cable (1)



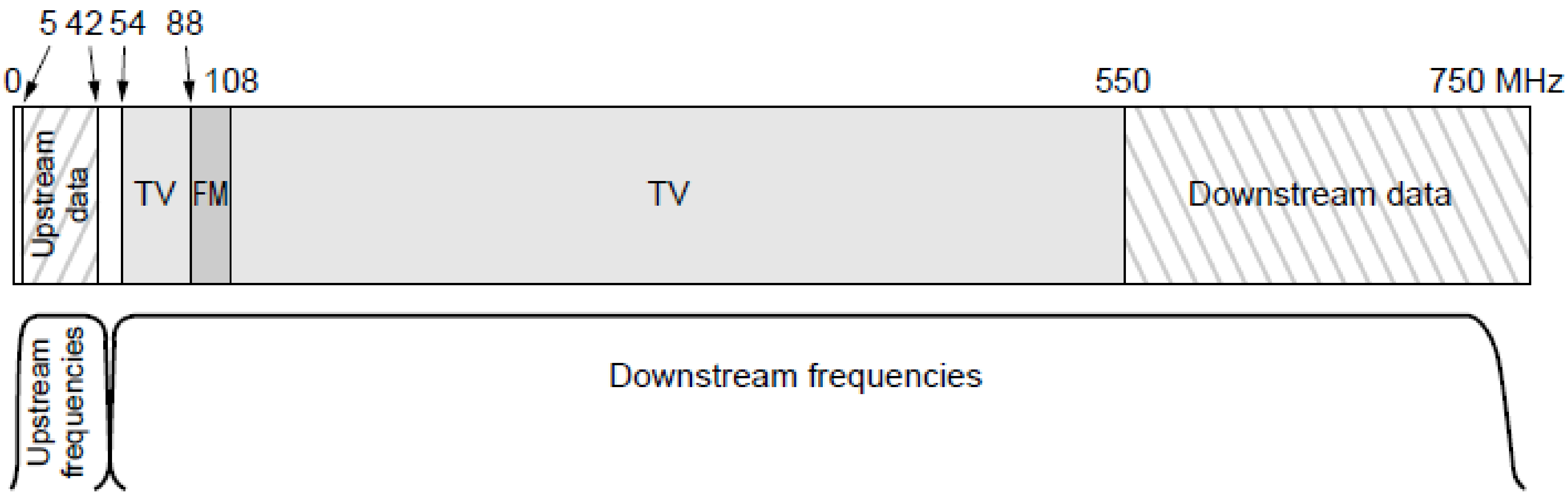

Cable television

# Internet over Cable (2)



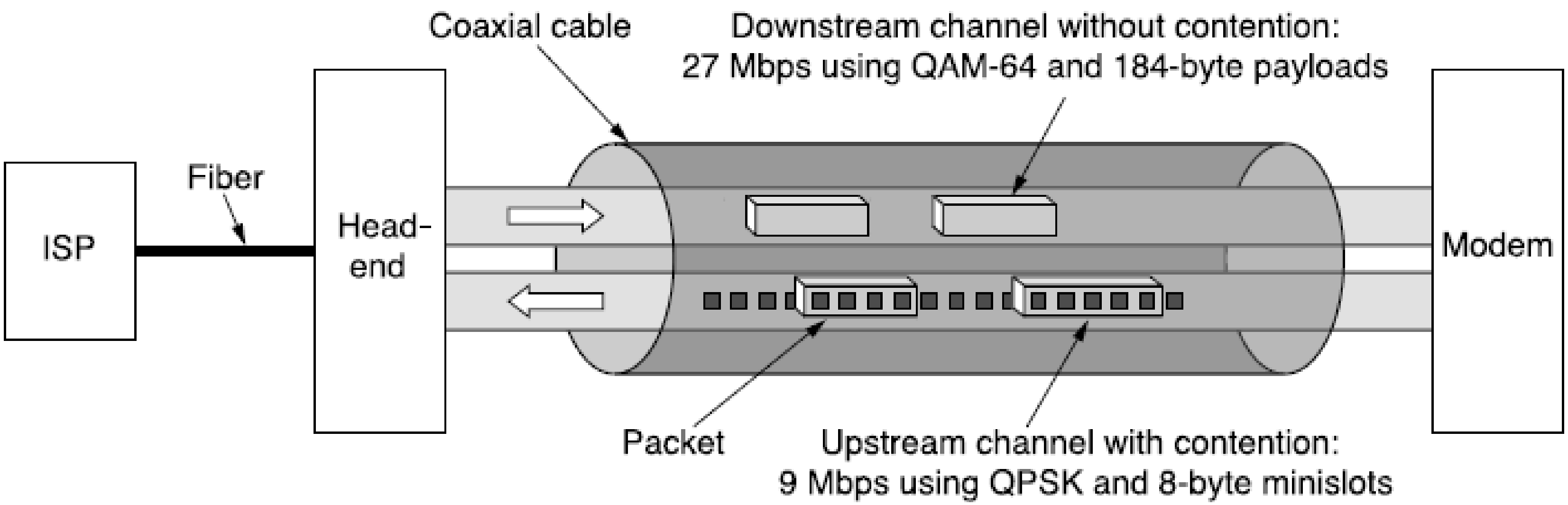

The fixed telephone system.

# Spectrum Allocation




Frequency allocation in a typical cable TV system used for Internet access.

# Cable Modems




Typical details of the upstream and downstream channels in North America.

End

Chapter 2