The Physical Layer

Chapter 2

Theoretical Basis for Data Communication

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

Fourier Analysis

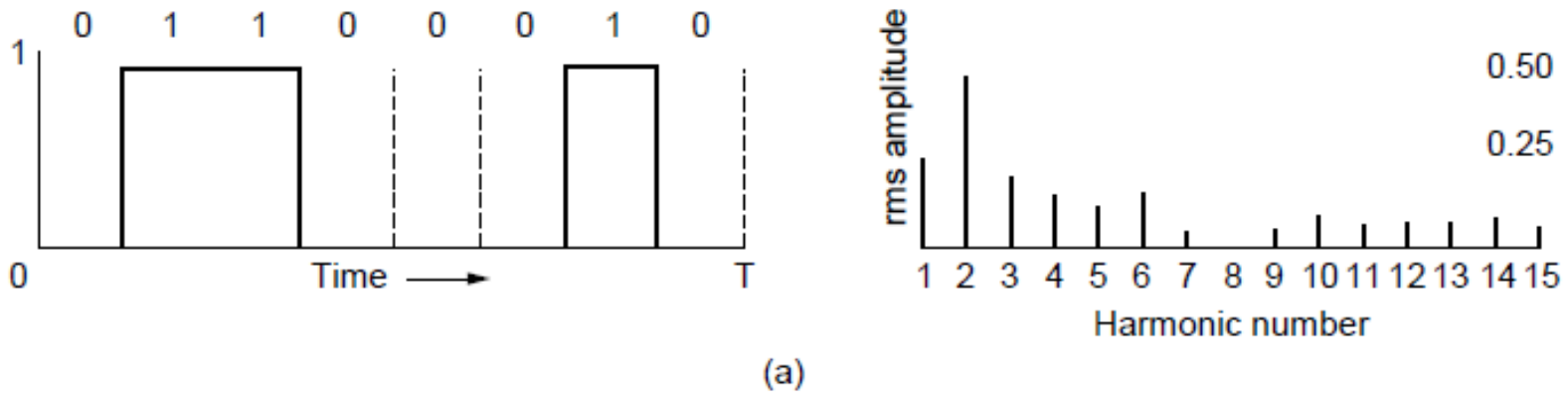
- We model the behavior of variation of voltage or current with mathematical functions
- Fourier series is used

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

- Function reconstructed with

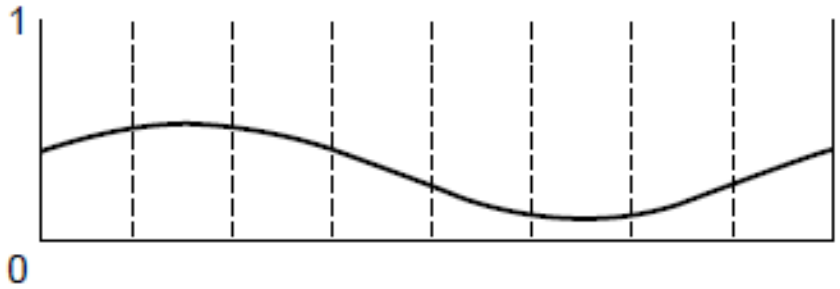
$$a_n = \frac{2}{T}\int_0^T g(t)\sin(2\pi nft)\,dt \qquad b_n = \frac{2}{T}\int_0^T g(t)\cos(2\pi nft)\,dt \qquad c = \frac{2}{T}\int_0^T g(t)\,dt$$

Bandwidth-Limited Signals (1)

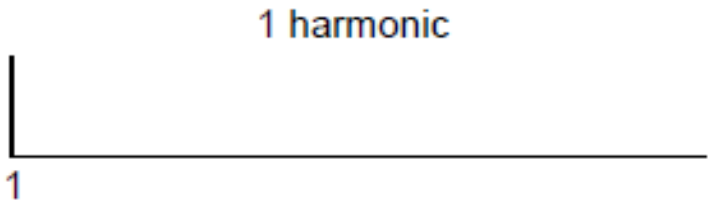


A binary signal and its root-mean-square Fourier amplitudes.

Bandwidth-Limited Signals (2)

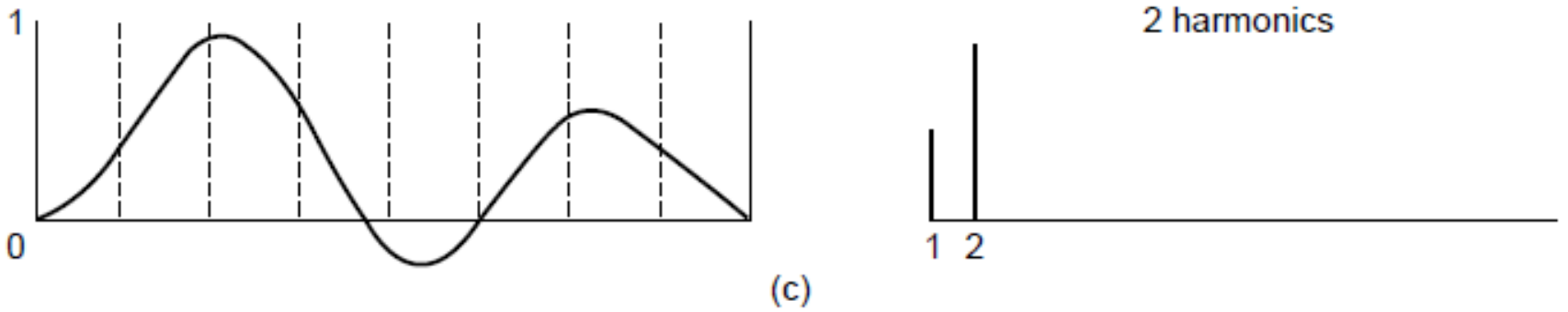


(b)



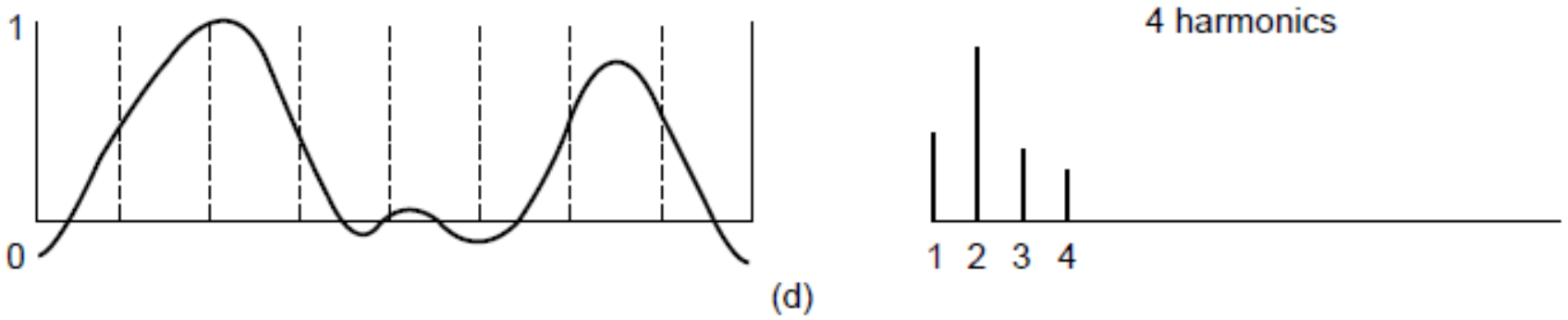
(b)-(e) Successive approximations to the original signal.

Bandwidth-Limited Signals (3)



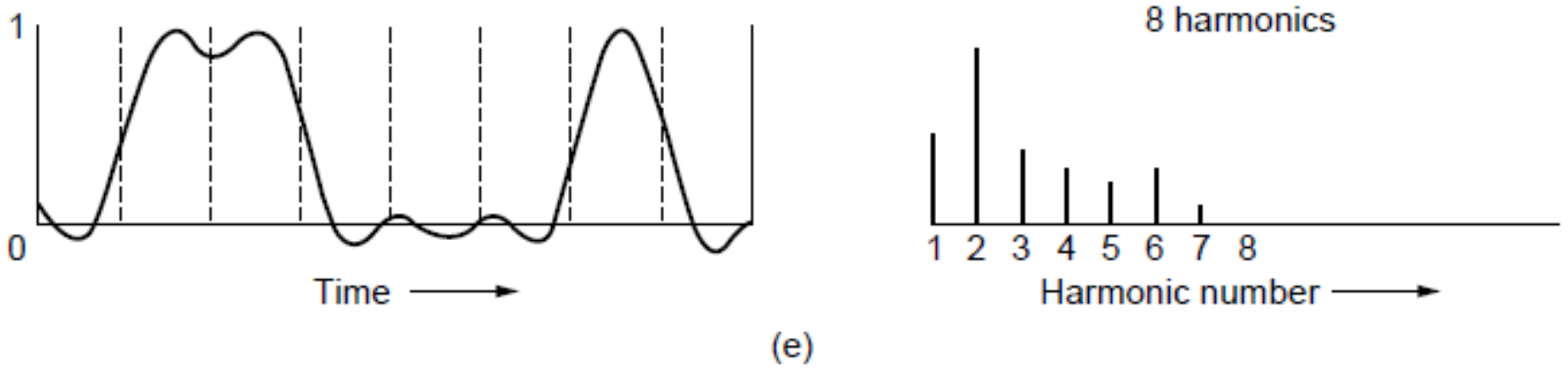
(b)-(e) Successive approximations to the original signal.

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's theorem

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

- Shannon's formula for capacity of a noisy channel

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

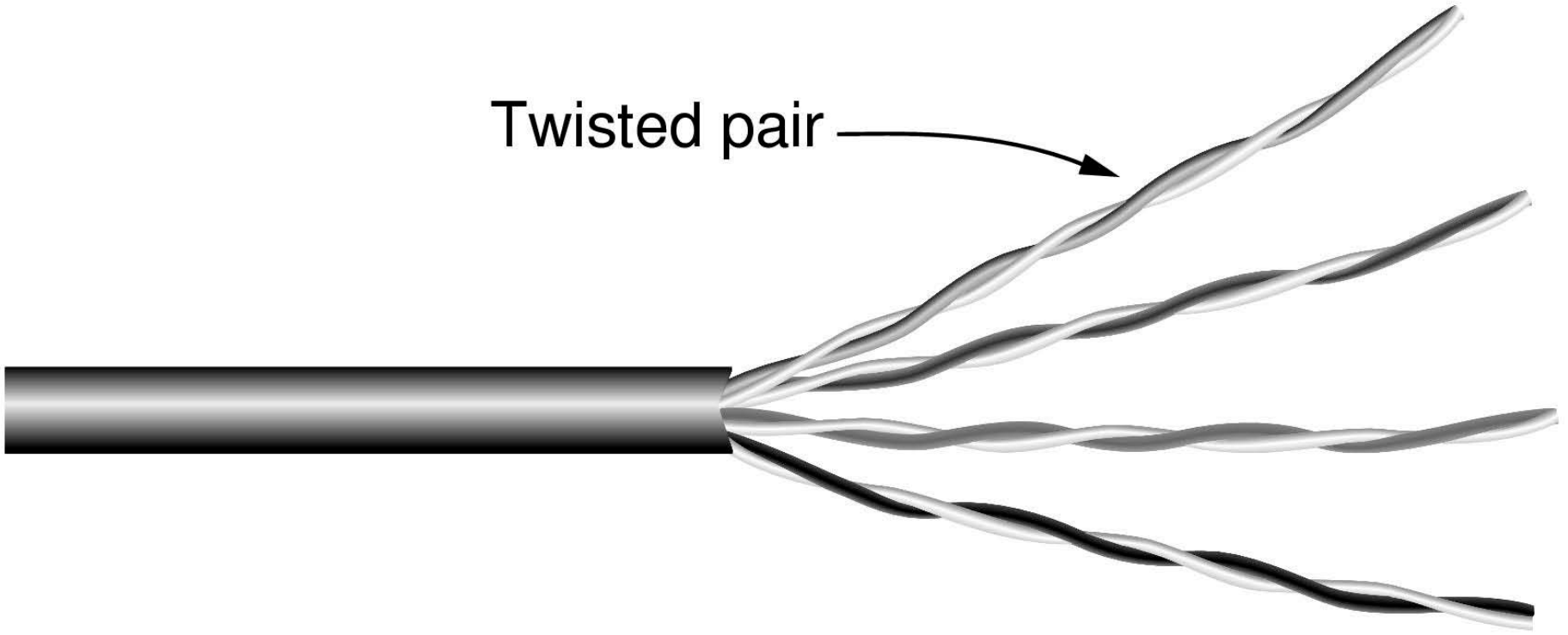
Guided Transmission Media

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

Magnetic Media

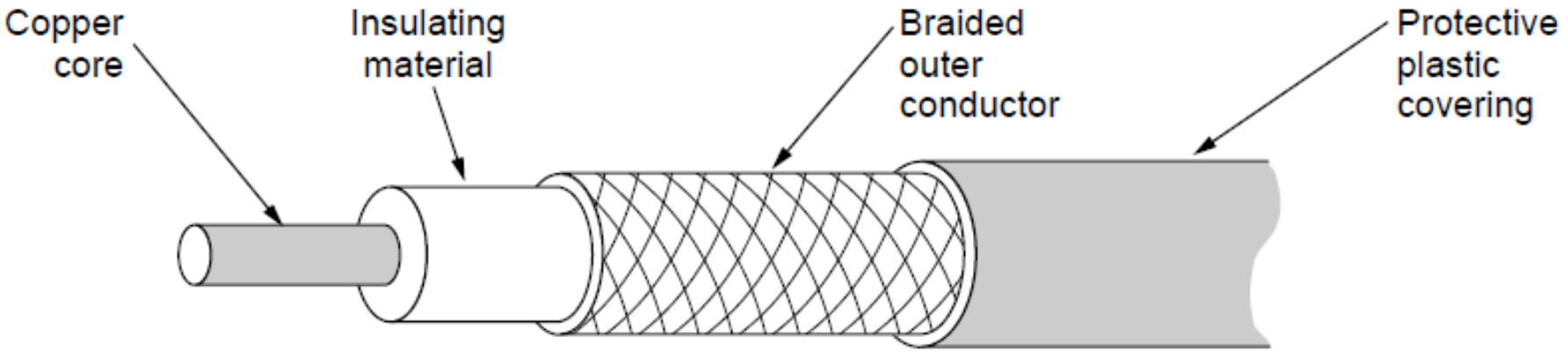
- Write data onto magnetic media
  - Disks
  - Tapes
- Data transmission speed
  - Never underestimate the bandwidth of a station wagon full of tapes hurtling down the highway.

Twisted Pairs



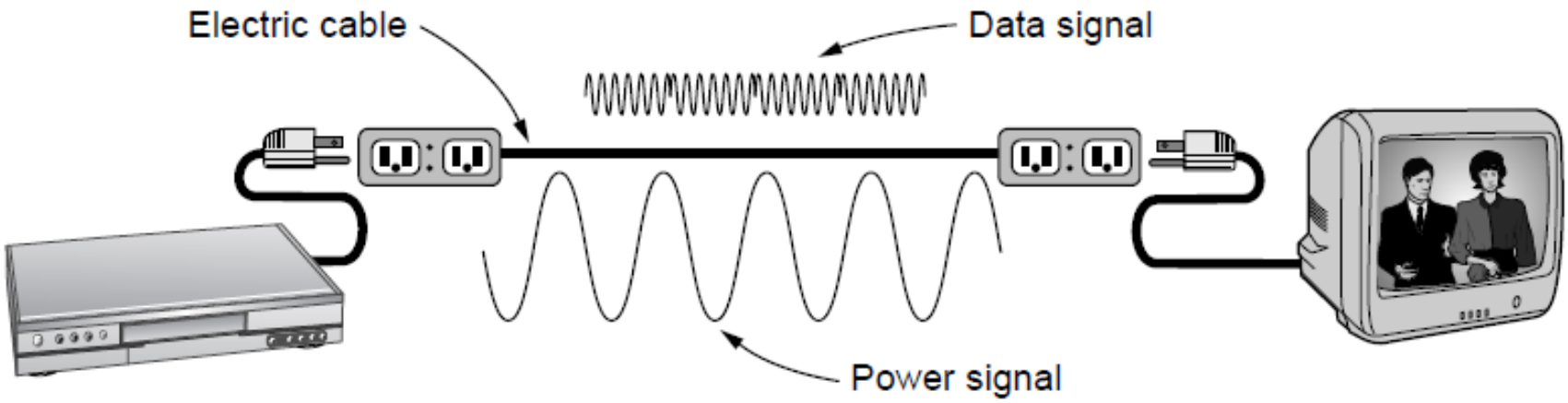
Category 5 UTP cable with four twisted pairs

Coaxial Cable



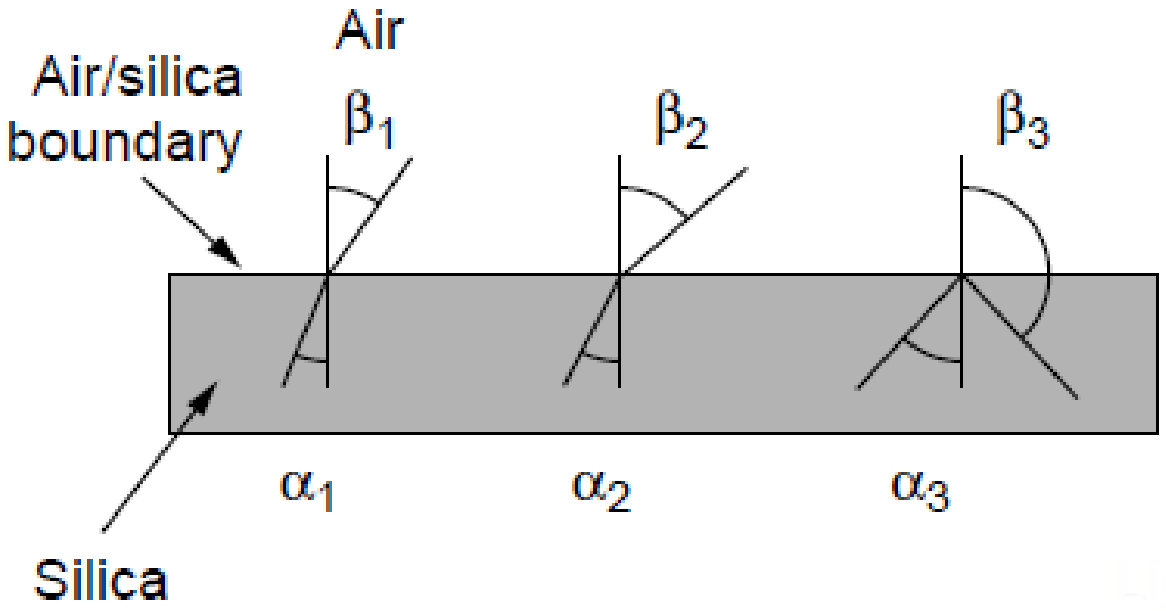
A coaxial cable

Power Lines



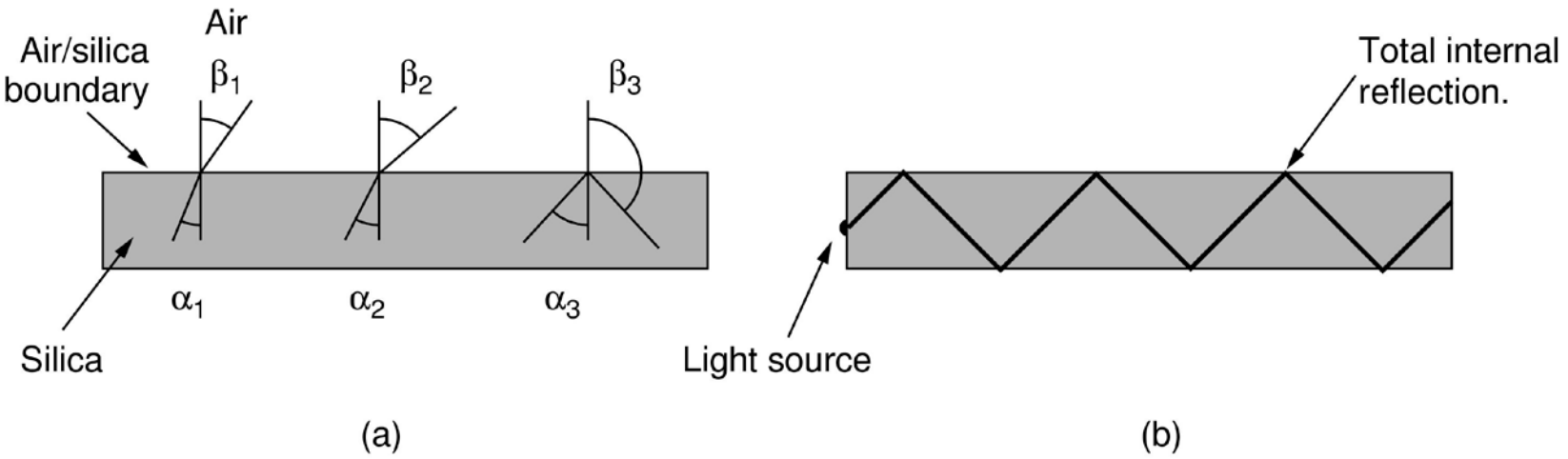
A network that uses household electrical wiring.

Fiber Optics (1)



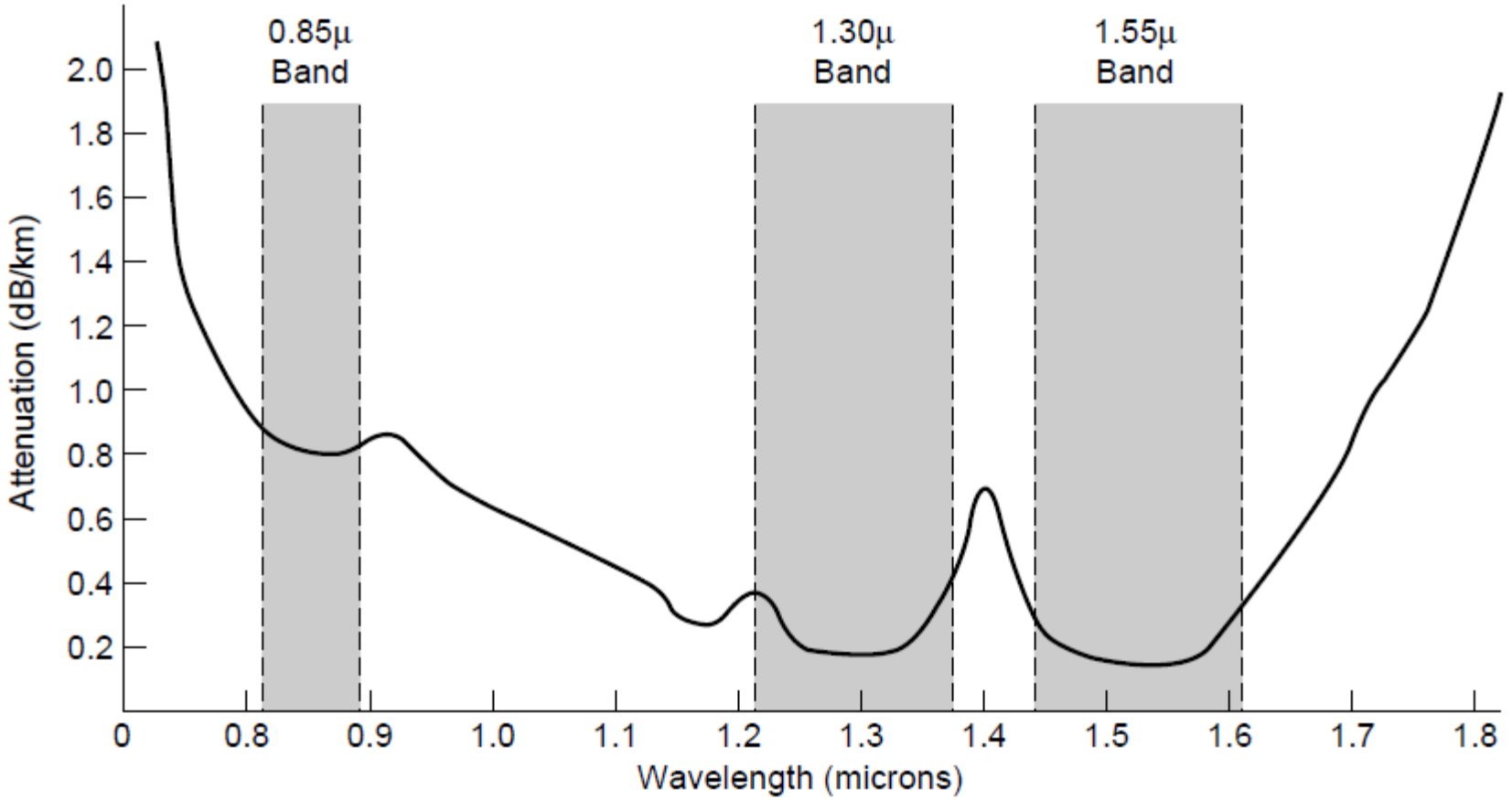
Three examples of a light ray from inside a silica fiber impinging on the air/silica boundary at different angles.

Fiber Optics (2)



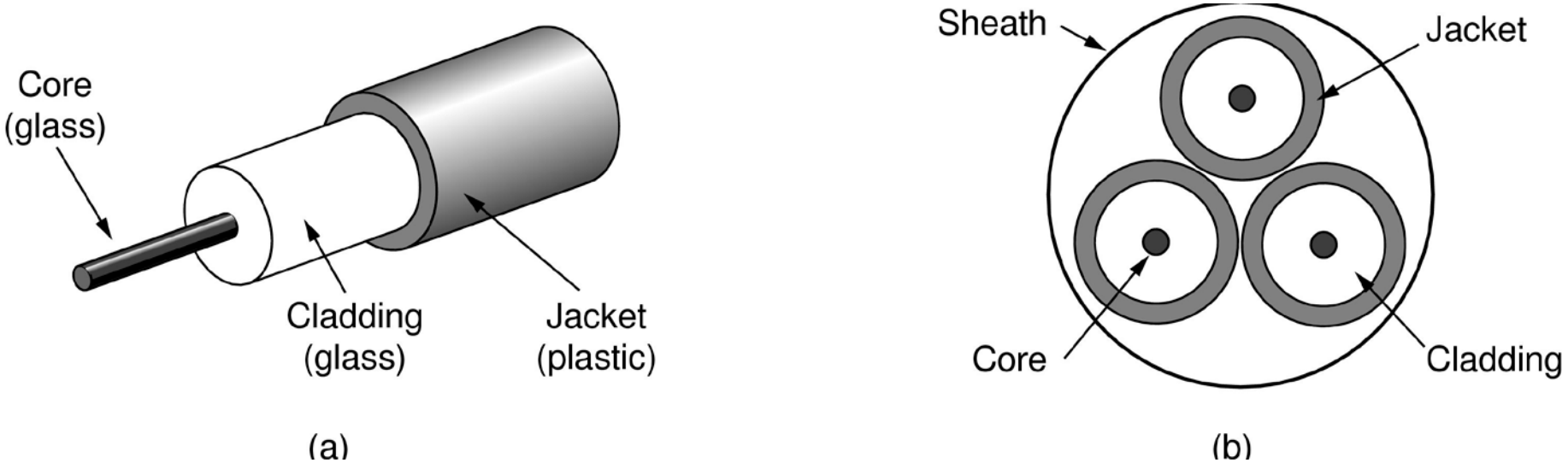
Light trapped by total internal reflection.

Transmission of Light Through Fiber



Attenuation of light through fiber
in the infrared region

Fiber Cables (1)



Views of a fiber cable

Fiber Cables (2)

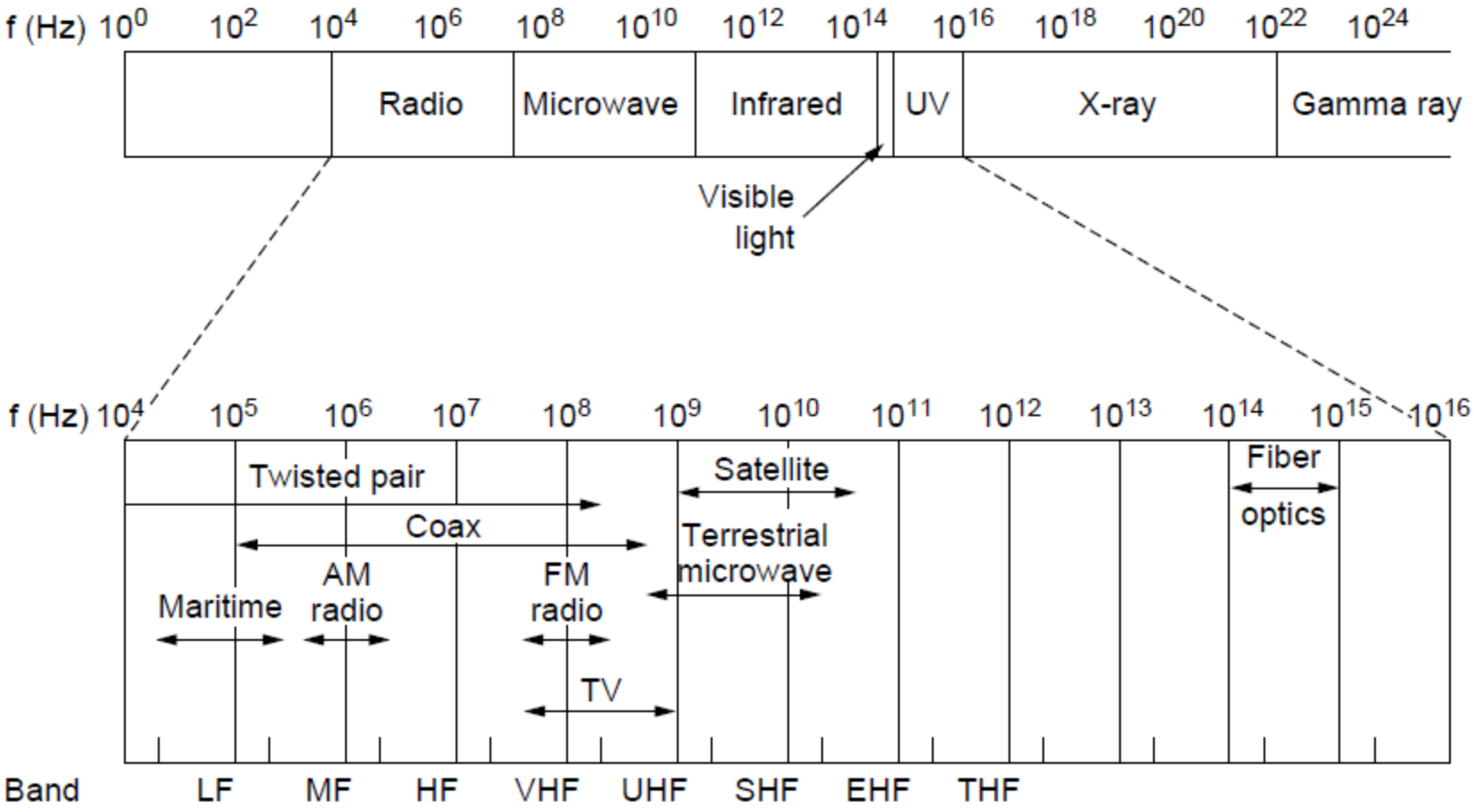
Item	LED	Semiconductor laser
Data rate	Low	High
Fiber type	Multi-mode	Multi-mode or single-mode
Distance	Short	Long
Lifetime	Long life	Short life
Temperature sensitivity	Minor	Substantial
Cost	Low cost	Expensive

A comparison of semiconductor diodes and LEDs as light sources

Wireless Transmission

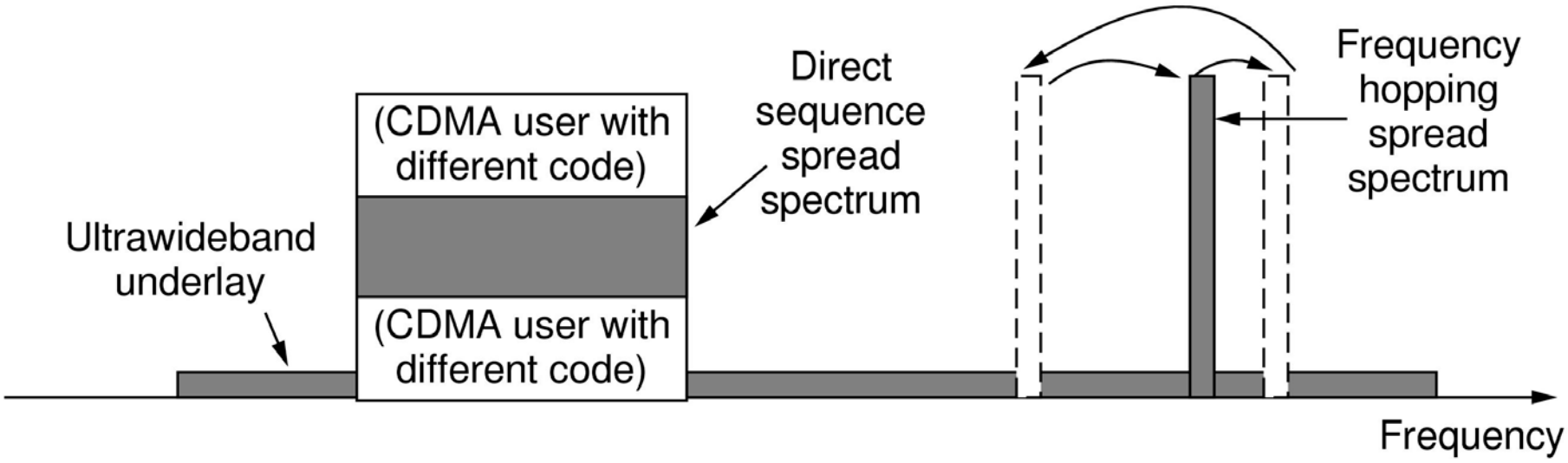
- The Electromagnetic Spectrum
- Radio Transmission
- Microwave Transmission
- Infrared Transmission
- Light Transmission

The Electromagnetic Spectrum (1)



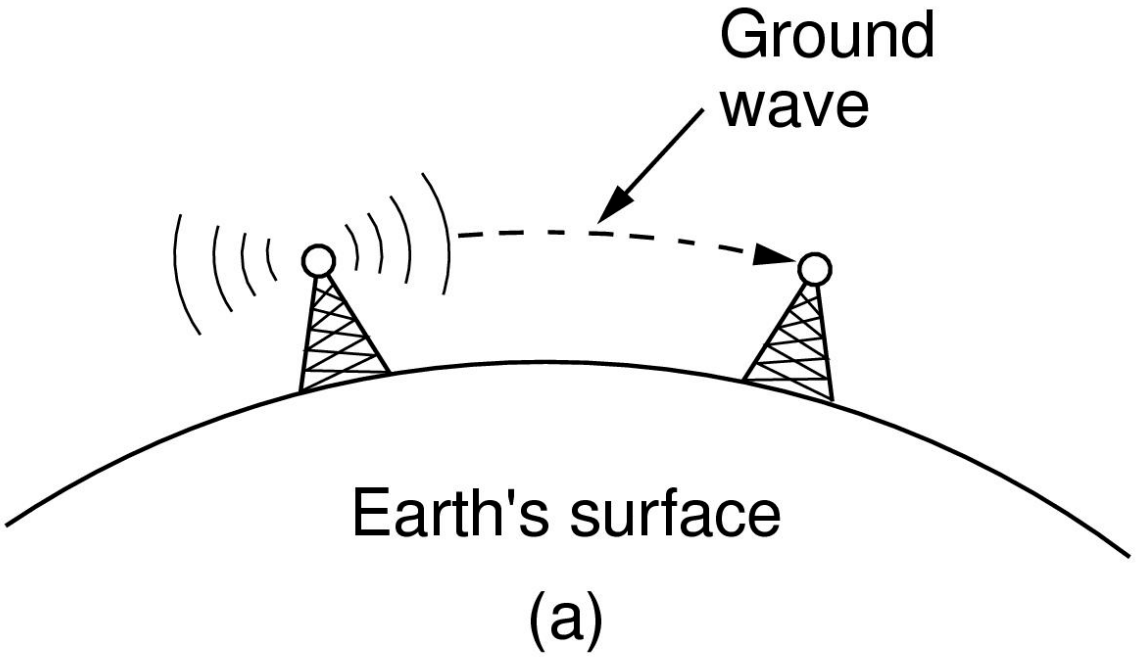
The electromagnetic spectrum and its uses for communication

The Electromagnetic Spectrum (2)



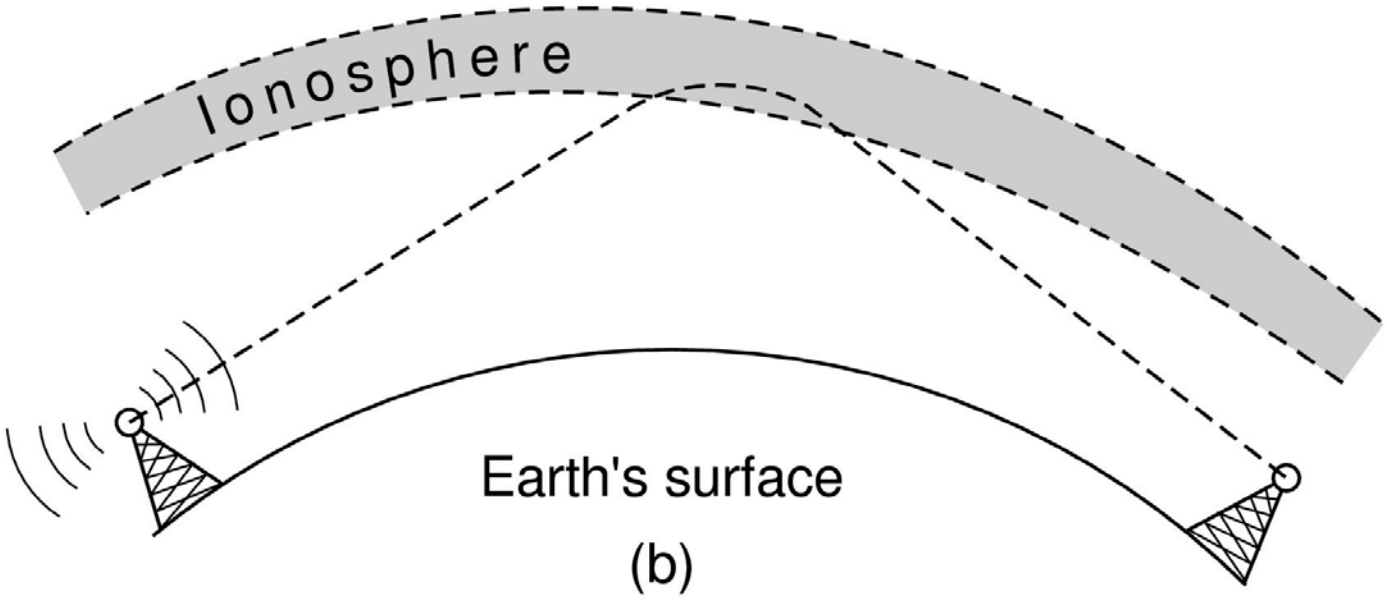
Spread spectrum and ultra-wideband (UWB) communication

Radio Transmission (1)



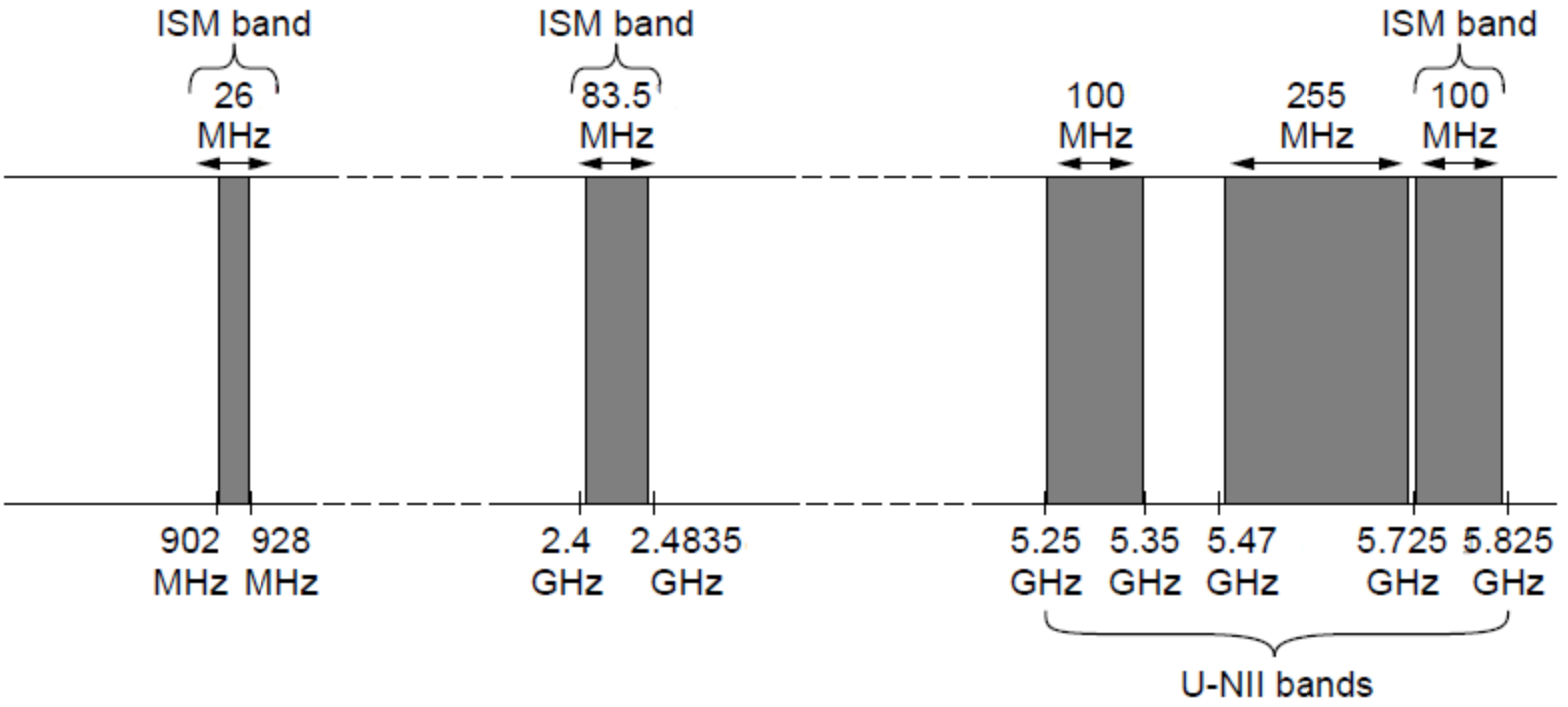
In the VLF, LF, and MF bands, radio waves follow the curvature of the earth

Radio Transmission (2)



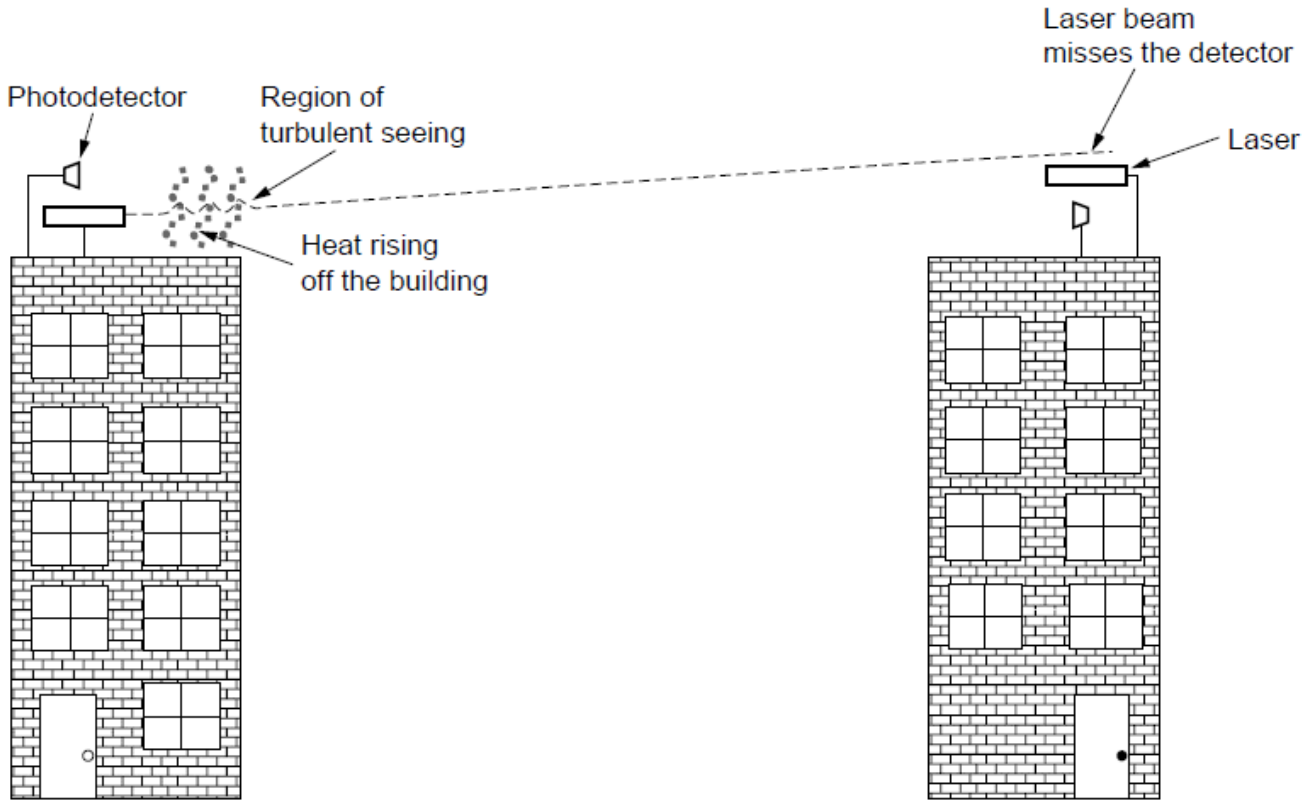
In the HF band, they bounce off the ionosphere.

The Politics of the Electromagnetic Spectrum



ISM and U-NII bands used in the United States by wireless devices

Light Transmission

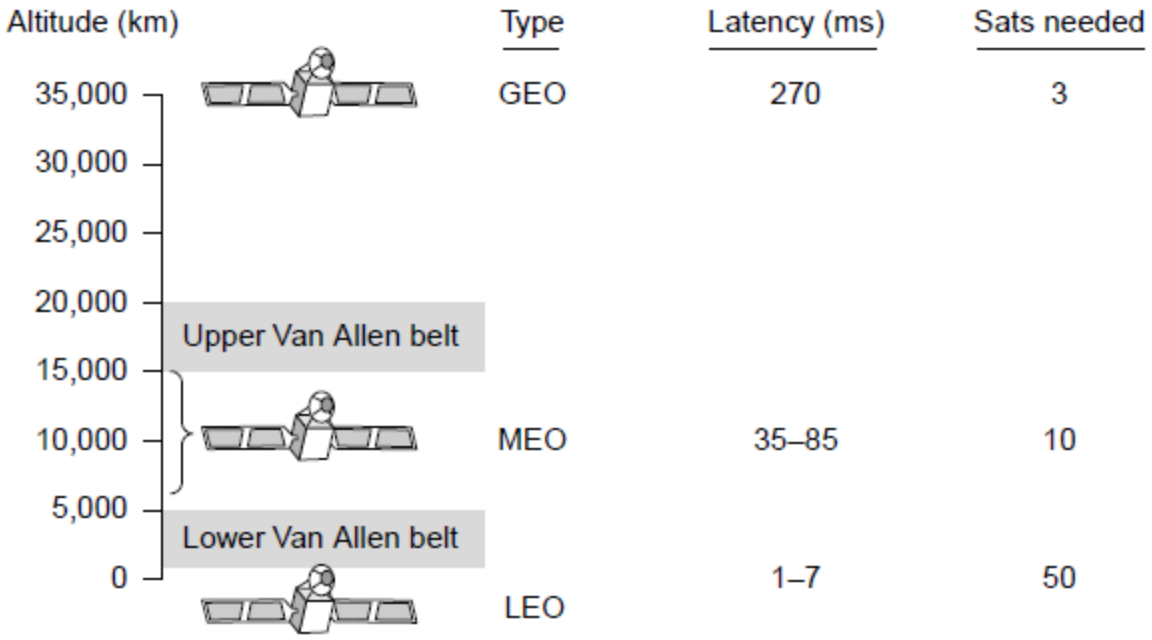


Convection currents can interfere with laser communication systems. A bidirectional system with two lasers is pictured here.

Communication Satellites

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

Communication Satellites



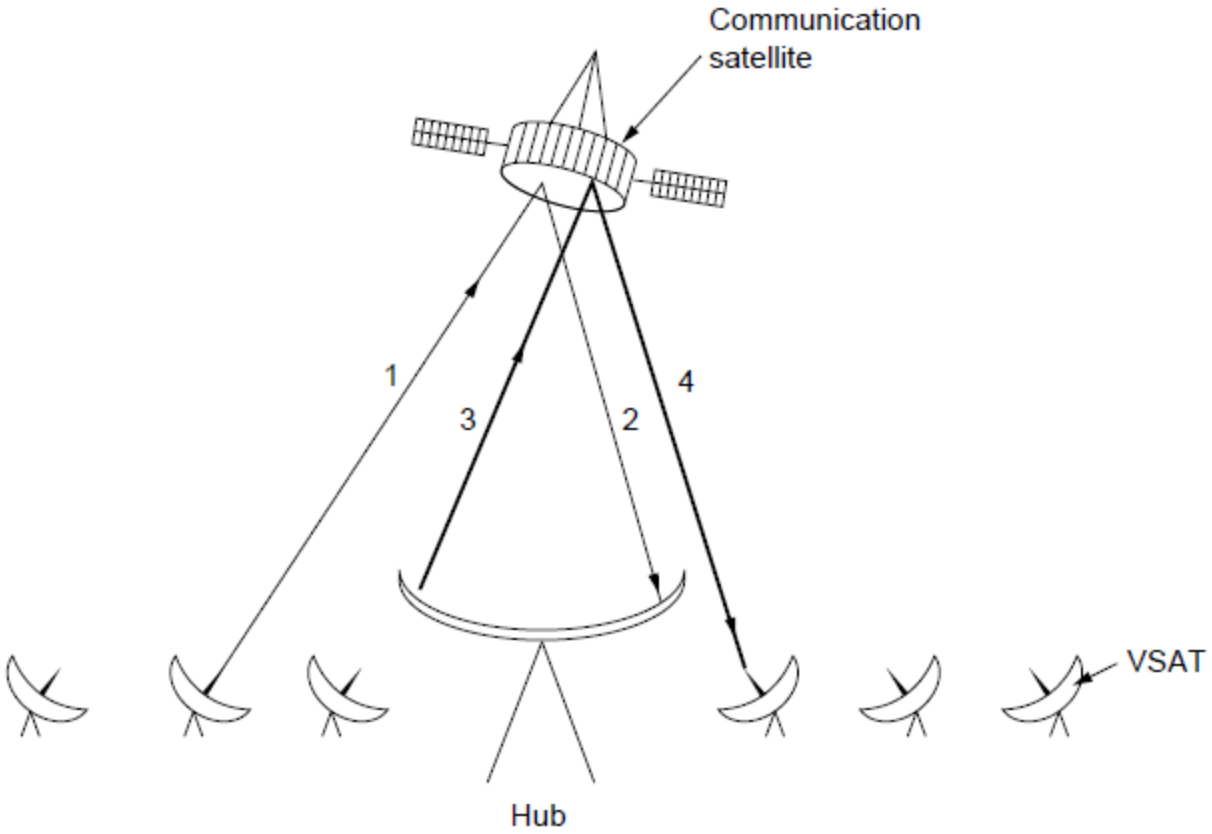
Communication satellites, some properties, including: altitude above earth, round-trip delay time, number of satellites for global coverage.

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

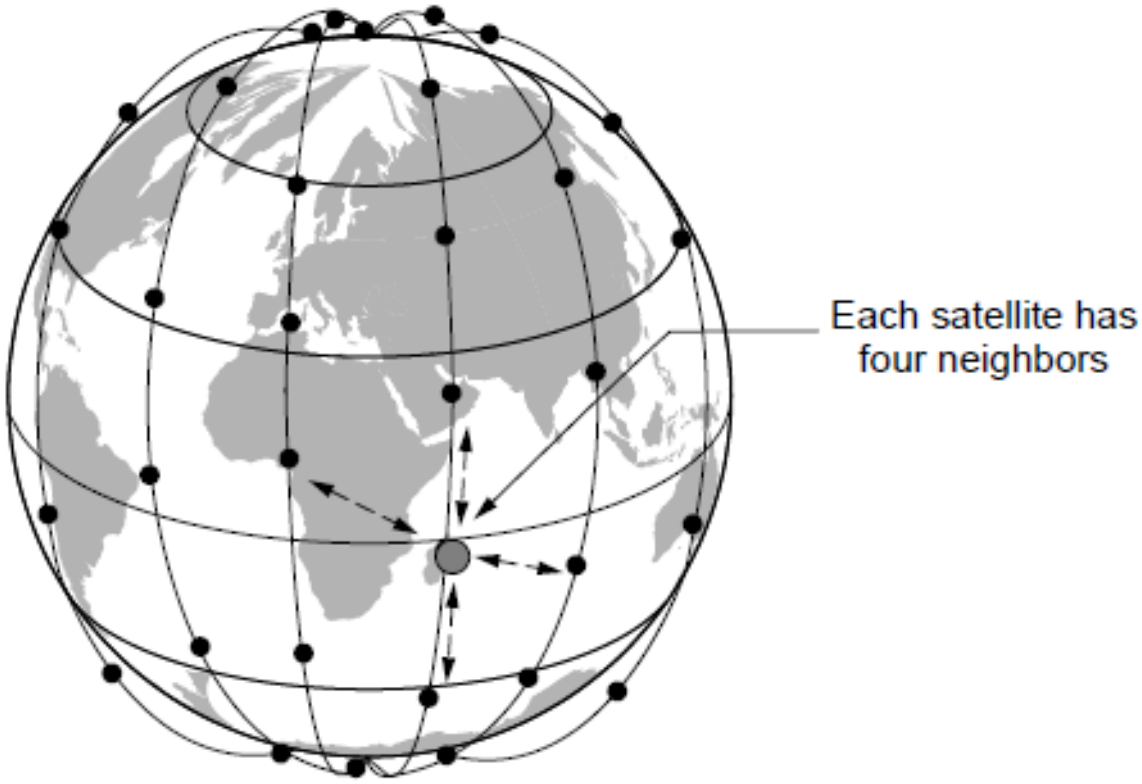
The principal satellite bands

Geostationary Satellites (2)



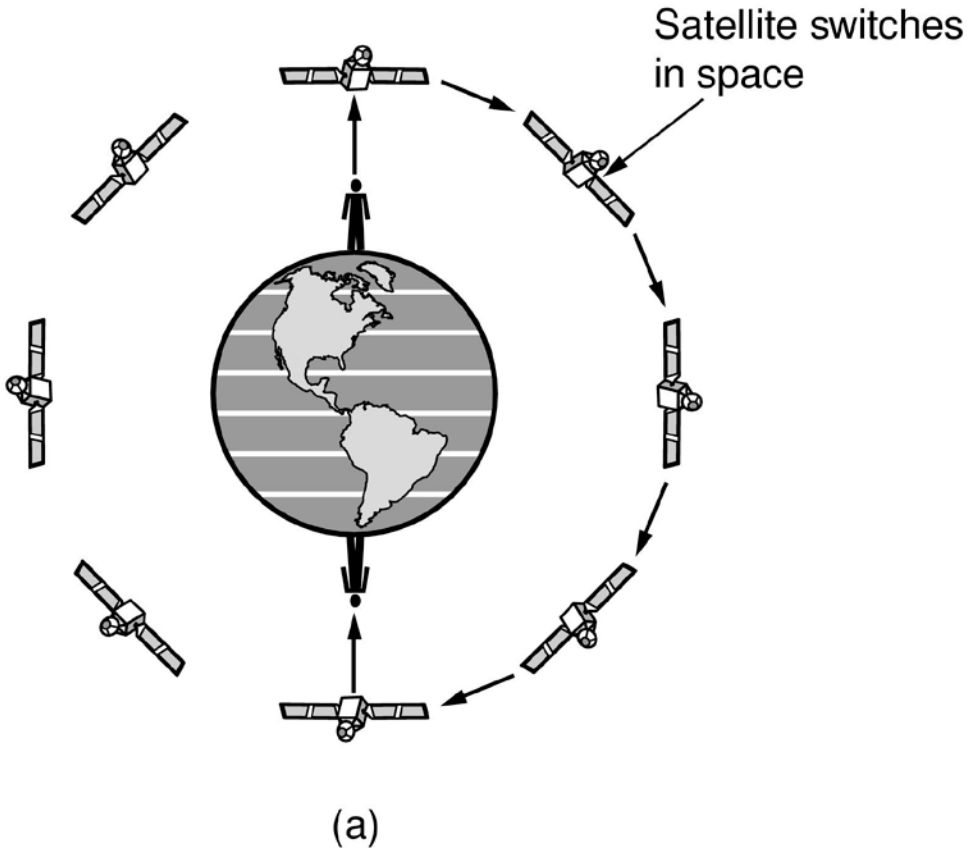
VSATs using a hub.

Low-Earth Orbit Satellites (1)



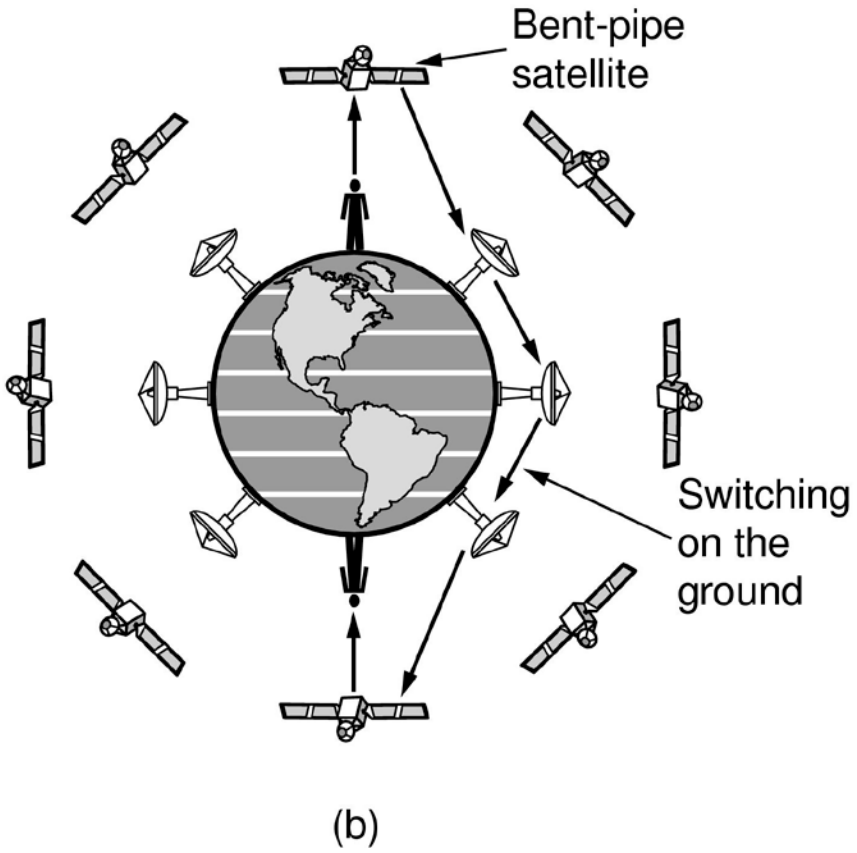
The Iridium satellites form six necklaces around the earth.

Low-Earth Orbit Satellites (2)



Relaying in space.

Low-Earth Orbit Satellites (3)

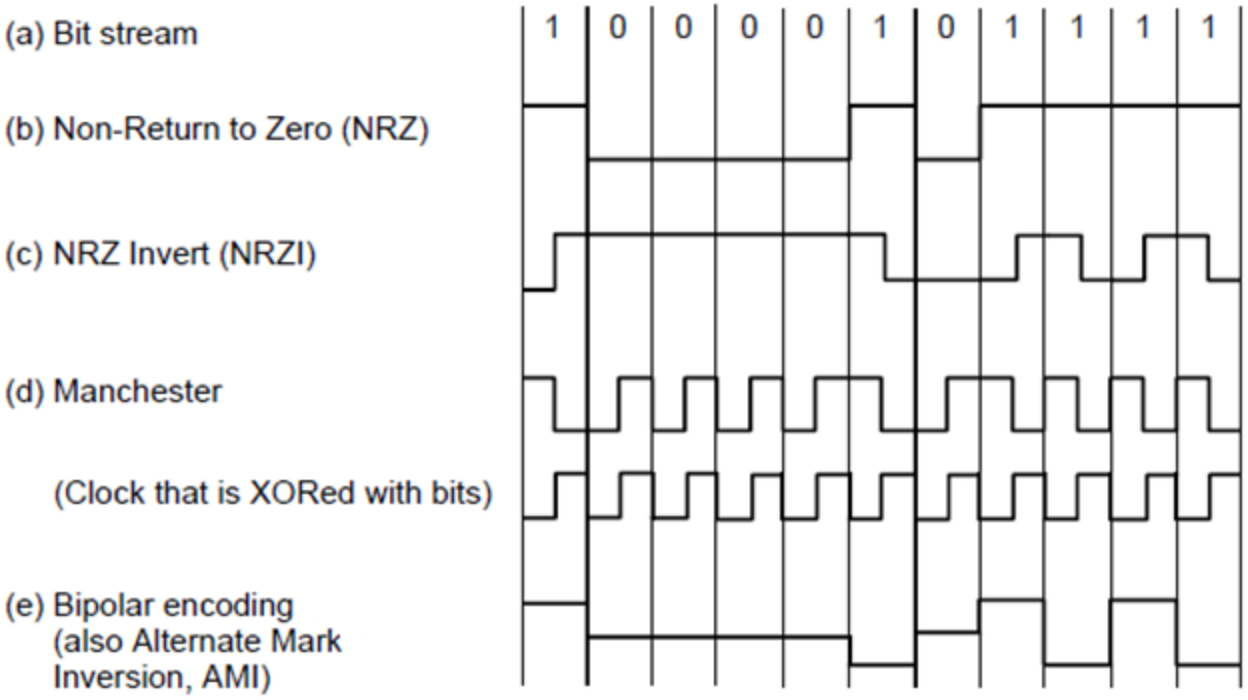


Relaying on the ground

Digital Modulation and Multiplexing

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

Baseband Transmission



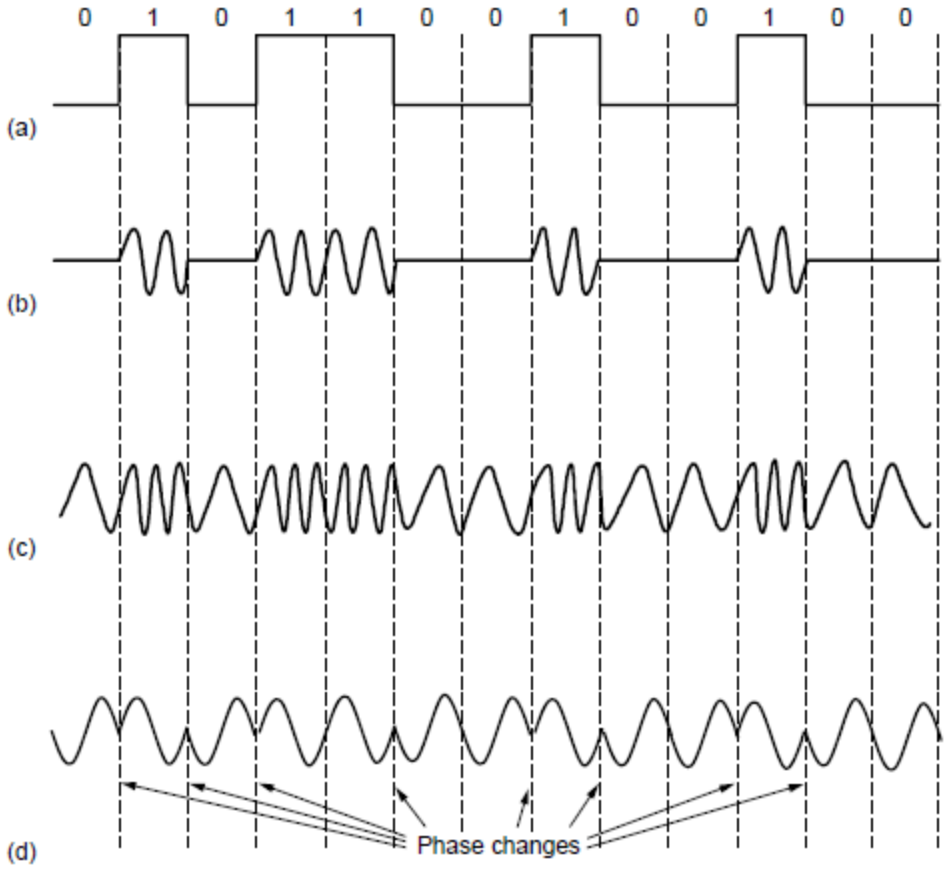
Line codes: (a) Bits, (b) NRZ, (c) NRZI, (d) Manchester, (e) Bipolar or AMI.

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

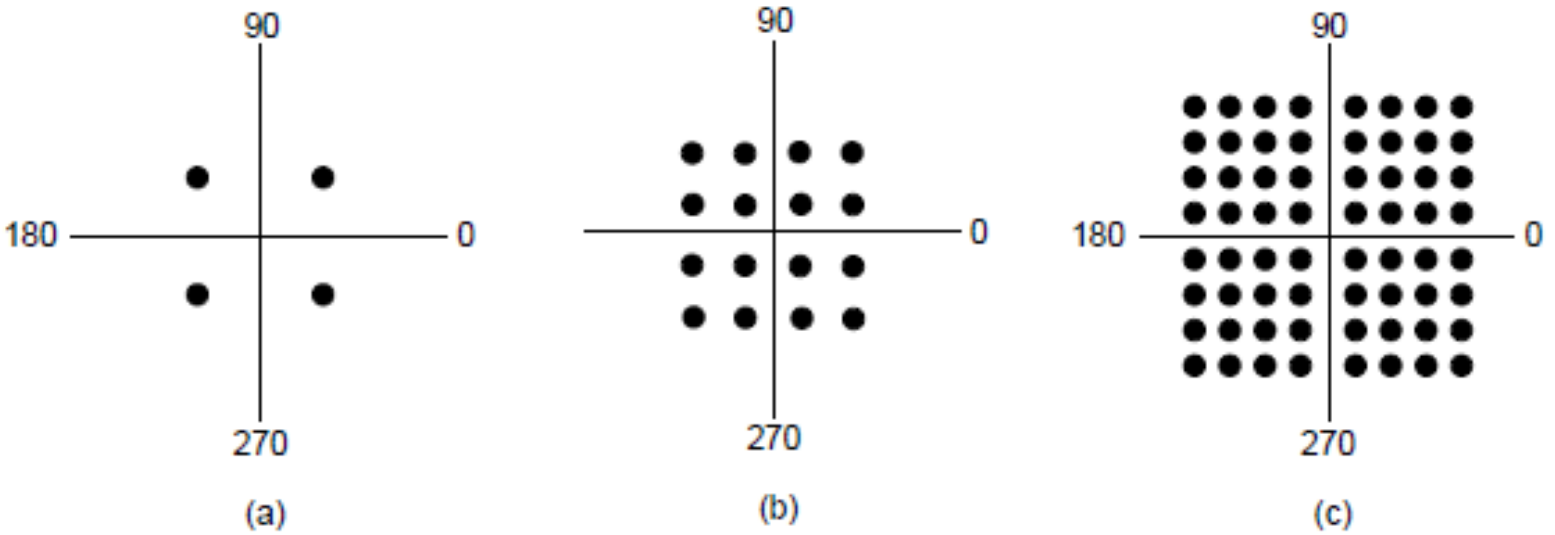
4B/5B mapping.

Passband Transmission (1)



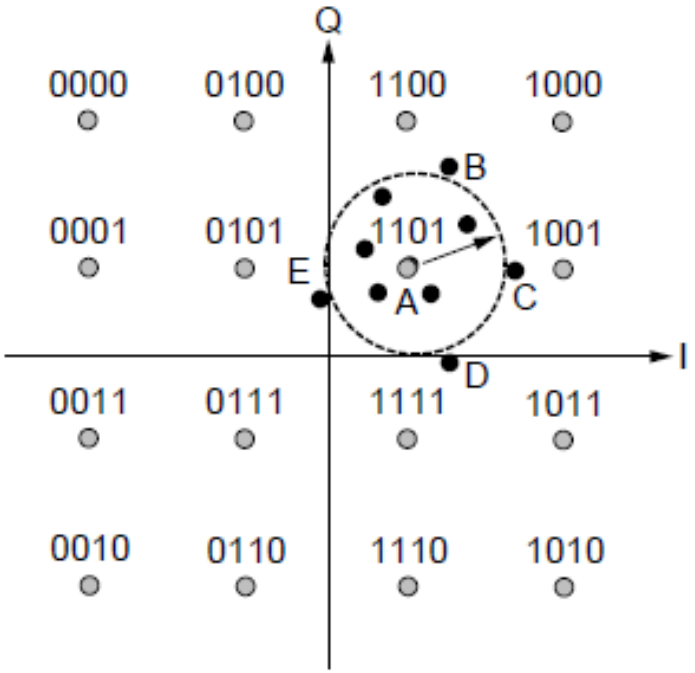
(a) A binary signal. (b) Amplitude shift keying. (c) Frequency shift keying. (d) Phase shift keying.

Passband Transmission (2)



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

Frequency Division Multiplexing (1)

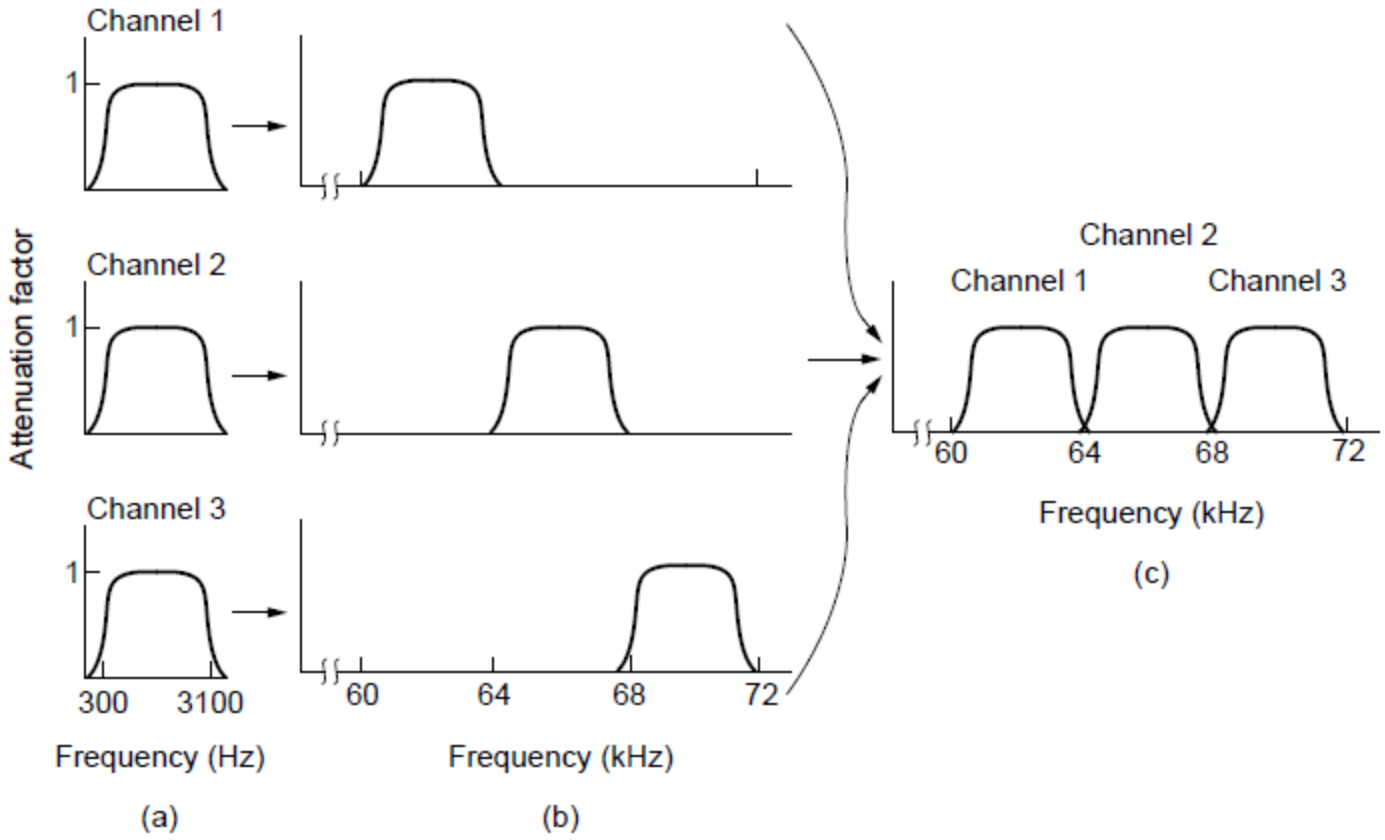


When 1101 is sent:

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

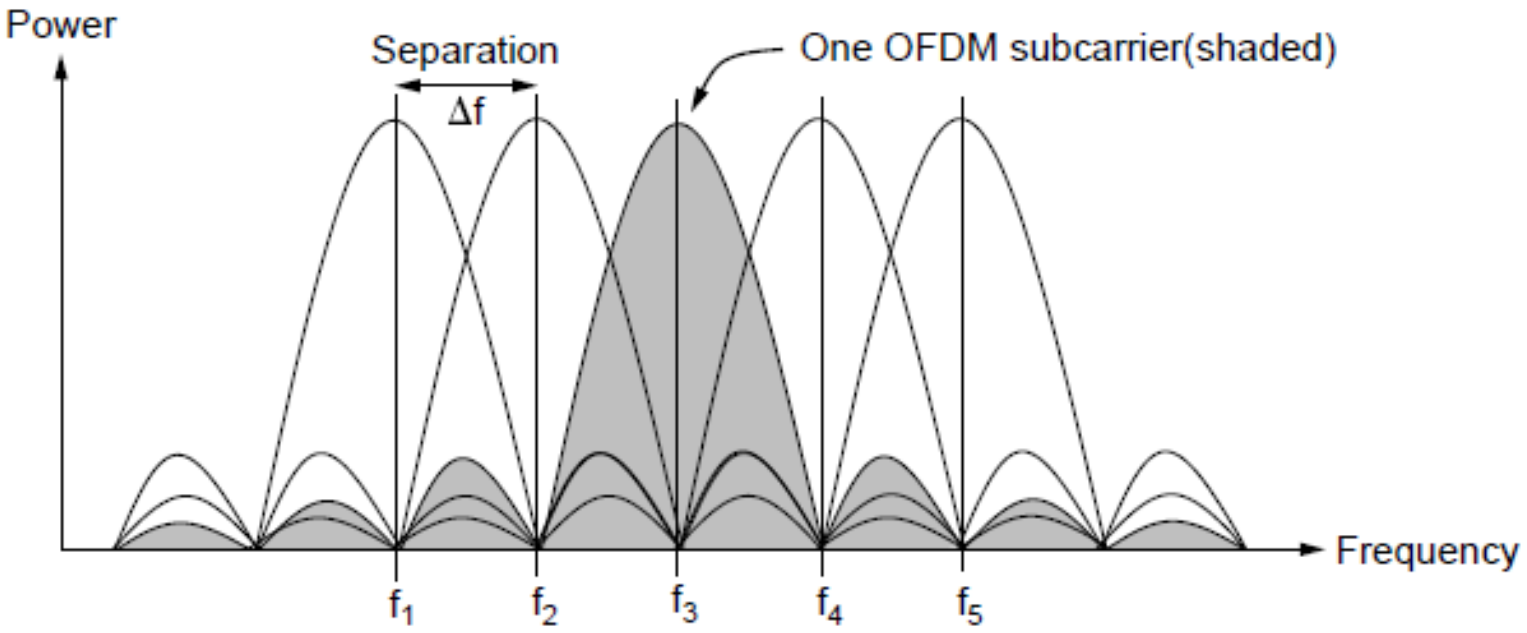
Gray-coded QAM-16.

Frequency Division Multiplexing (2)



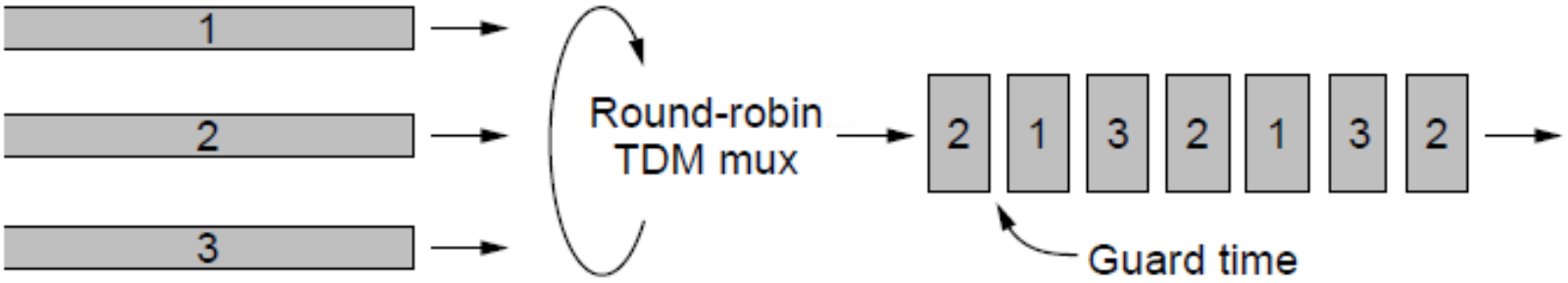
Frequency division multiplexing. (a) The original bandwidths. (b) The bandwidths raised in frequency. (c) The multiplexed channel.

Frequency Division Multiplexing (3)



Orthogonal frequency division multiplexing (OFDM).

Time Division Multiplexing



Time Division Multiplexing (TDM).

Code Division Multiplexing (1)

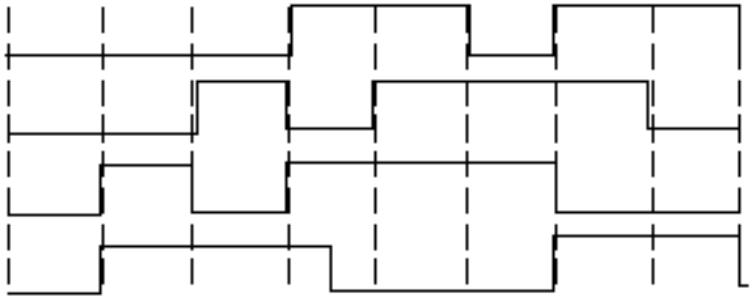
A = (–1 –1 –1 +1 +1 –1 +1 +1)

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)

$S_1 = C = (-1\ +1\ -1\ +1\ +1\ +1\ -1\ -1)$

$S_2 = B+C = (-2\ \ 0\ \ 0\ \ 0\ +2\ +2\ \ 0\ -2)$

$S_3 = A+\overline{B} = (\ 0\ \ 0\ -2\ +2\ \ 0\ -2\ \ 0\ +2)$

$S_4 = A+\overline{B}+C = (-1\ +1\ -3\ +3\ +1\ -1\ -1\ +1)$

$S_5 = A+B+\overline{C}+D = (-4\ \ 0\ -2\ \ 0\ +2\ \ 0\ +2\ -2)$

$S_6 = A+B+\overline{C}+D = (-2\ -2\ \ 0\ -2\ \ 0\ -2\ +4\ \ 0)$

(c)

$S_1 \bullet C = [1+1-1+1+1+1-1-1]/8 = 1$

$S_2 \bullet C = [2+0+0+0+2+2+0+2]/8 = 1$

$S_3 \bullet C = [0+0+2+2+0-2+0-2]/8 = 0$

$S_4 \bullet C = [1+1+3+3+1-1+1-1]/8 = 1$

$S_5 \bullet C = [4+0+2+0+2+0-2+2]/8 = 1$

$S_6 \bullet C = [2-2+0-2+0-2-4+0]/8 = -1$

(d)

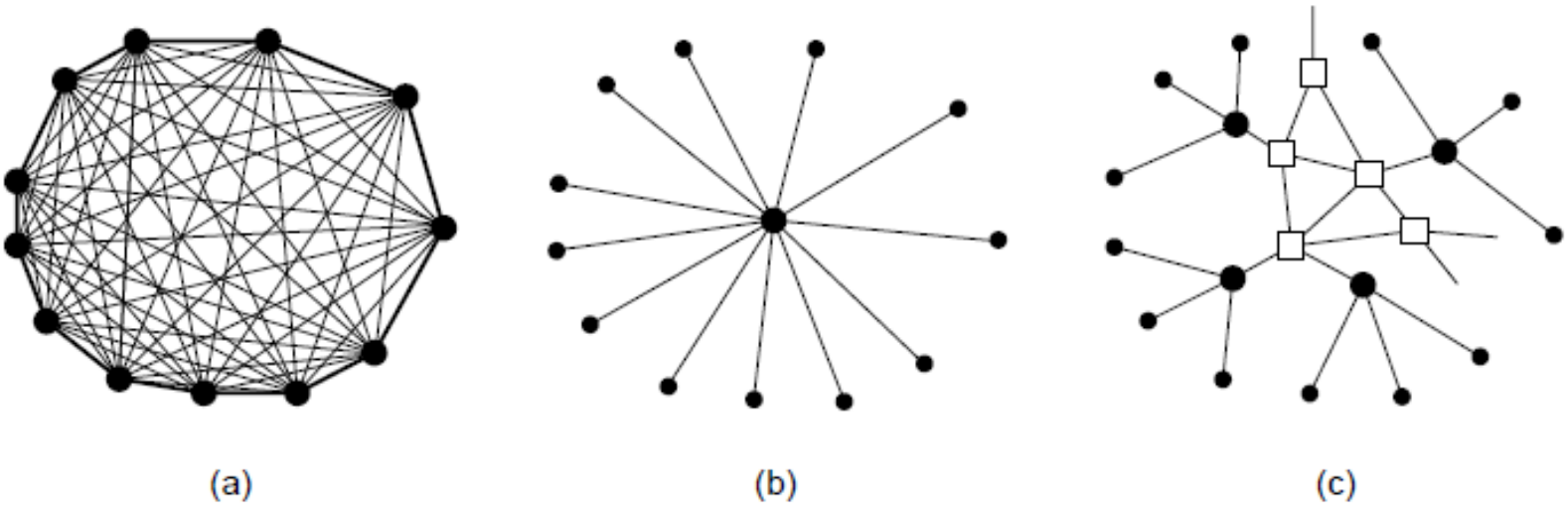
(a) Six examples of transmissions.

(b) Recovery of station C's

The Public Switched Telephone Network

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

Structure of the Telephone System (1)

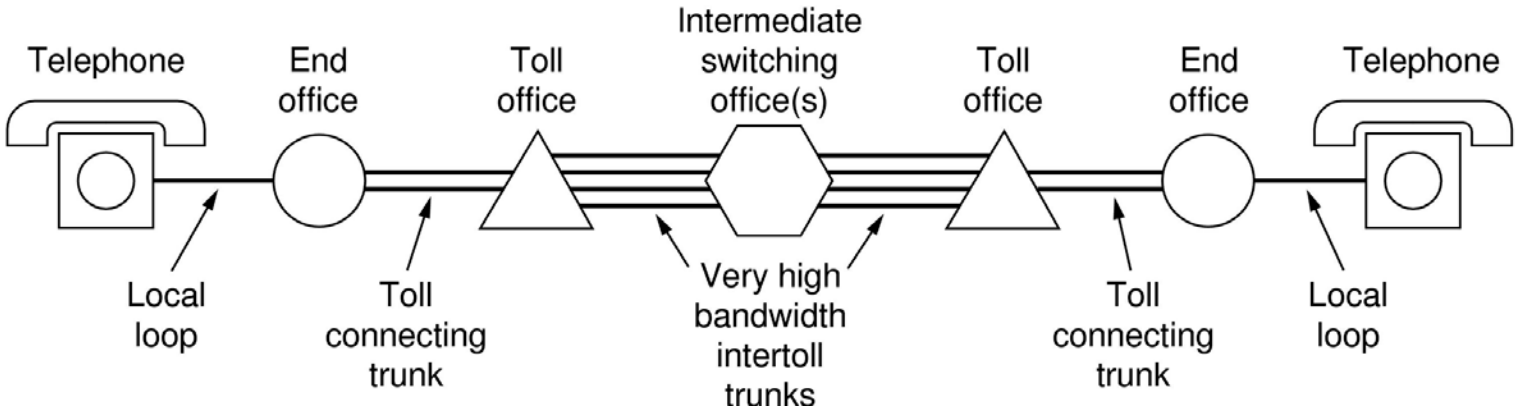


(a) Fully interconnected network.

(b) Centralized switch.

(c) Two-level hierarchy.

Structure of the Telephone System (2)



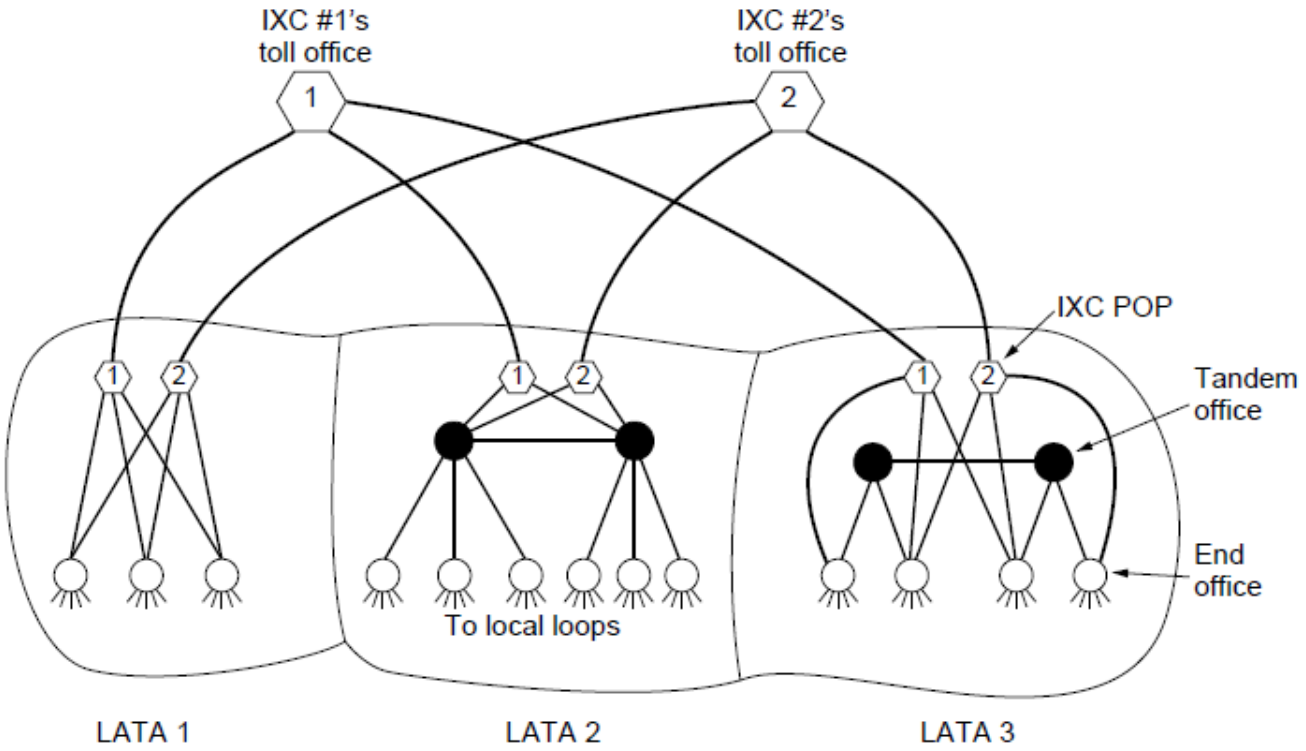
A typical circuit route for a long-distance call.

Structure of the Telephone System (3)

Major Components

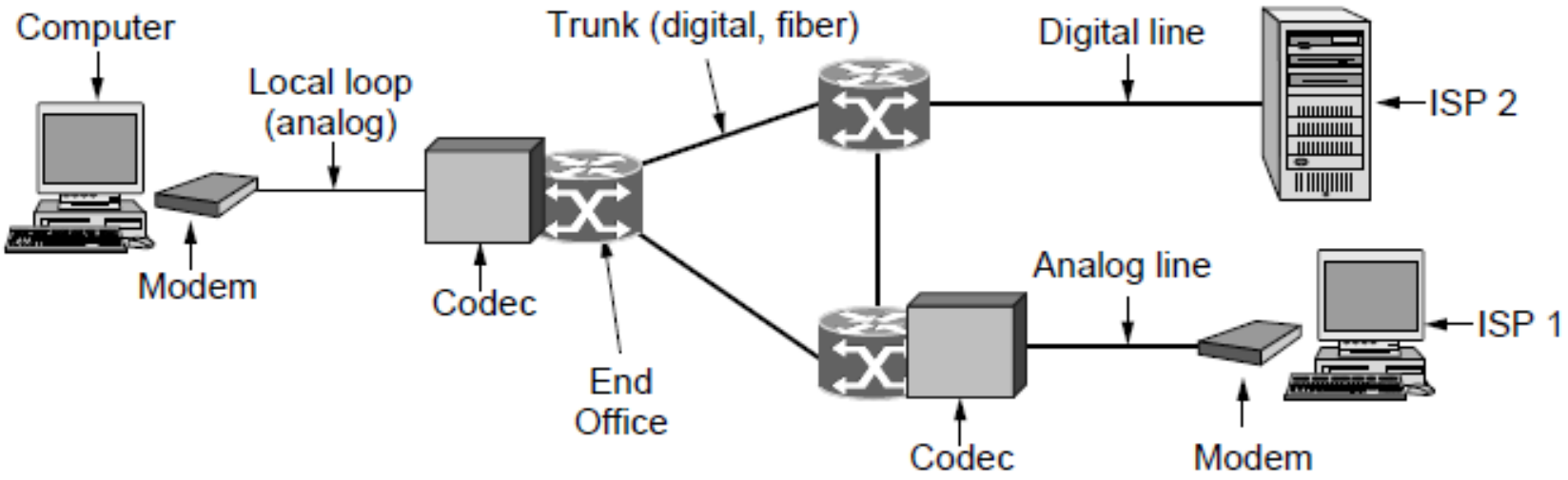
1. Local loops analog twisted pairs to houses, businesses).
2. Trunks (digital fiber optic links between switching offices).
3. Switching offices (calls are moved from one trunk to another).

The Politics of Telephones



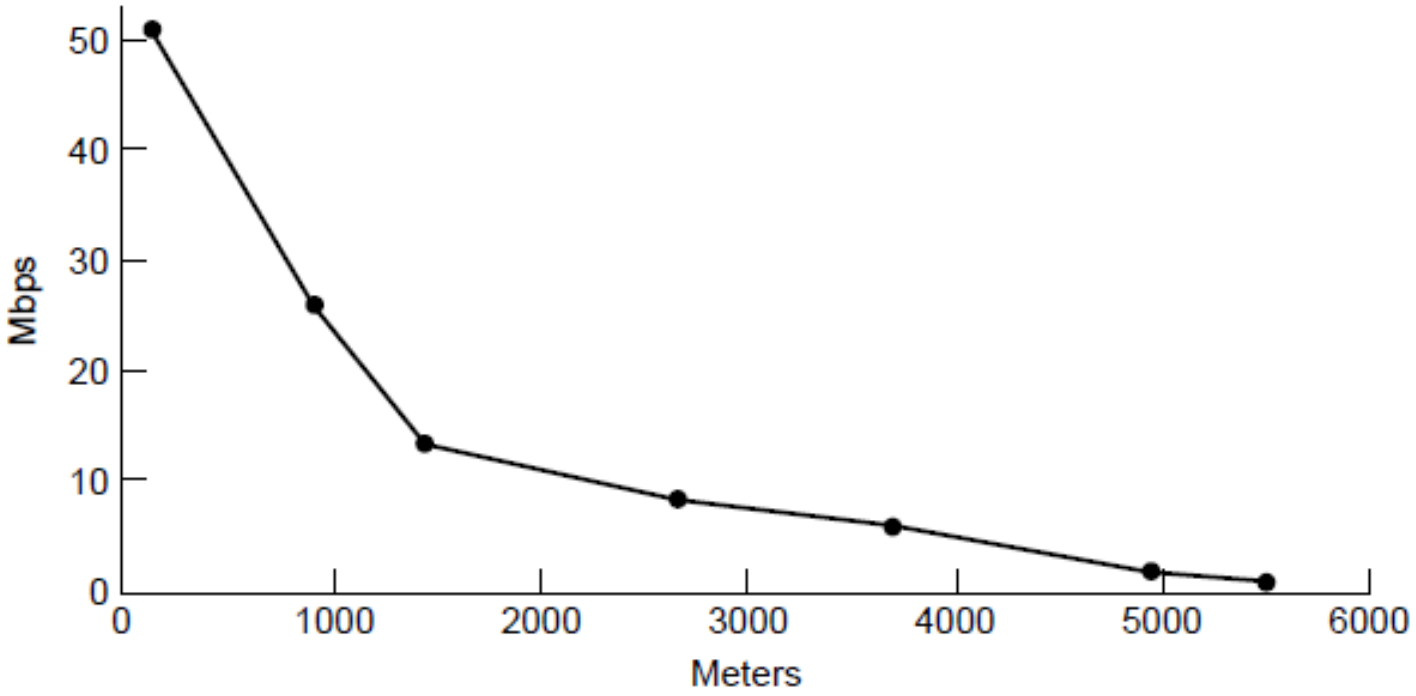
The relationship of LATAs, LECs, and IXCs. Circles are LEC switching offices. Hexagons belong to IXC whose number is in it.

Telephone Modems



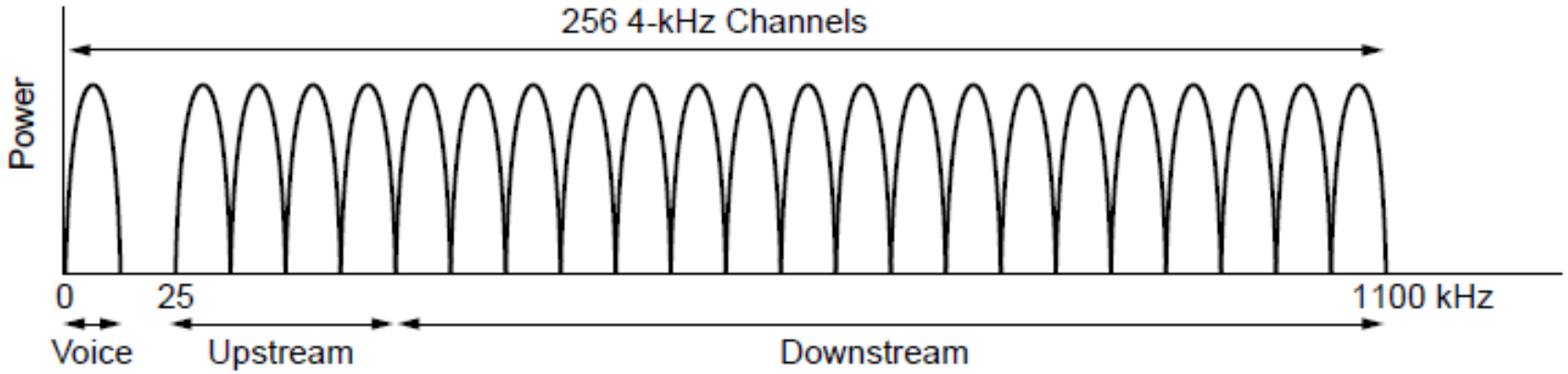
Use of both analog and digital transmission for computer -to-computer call. Conversion done by modems and codecs.

Digital Subscriber Lines (1)



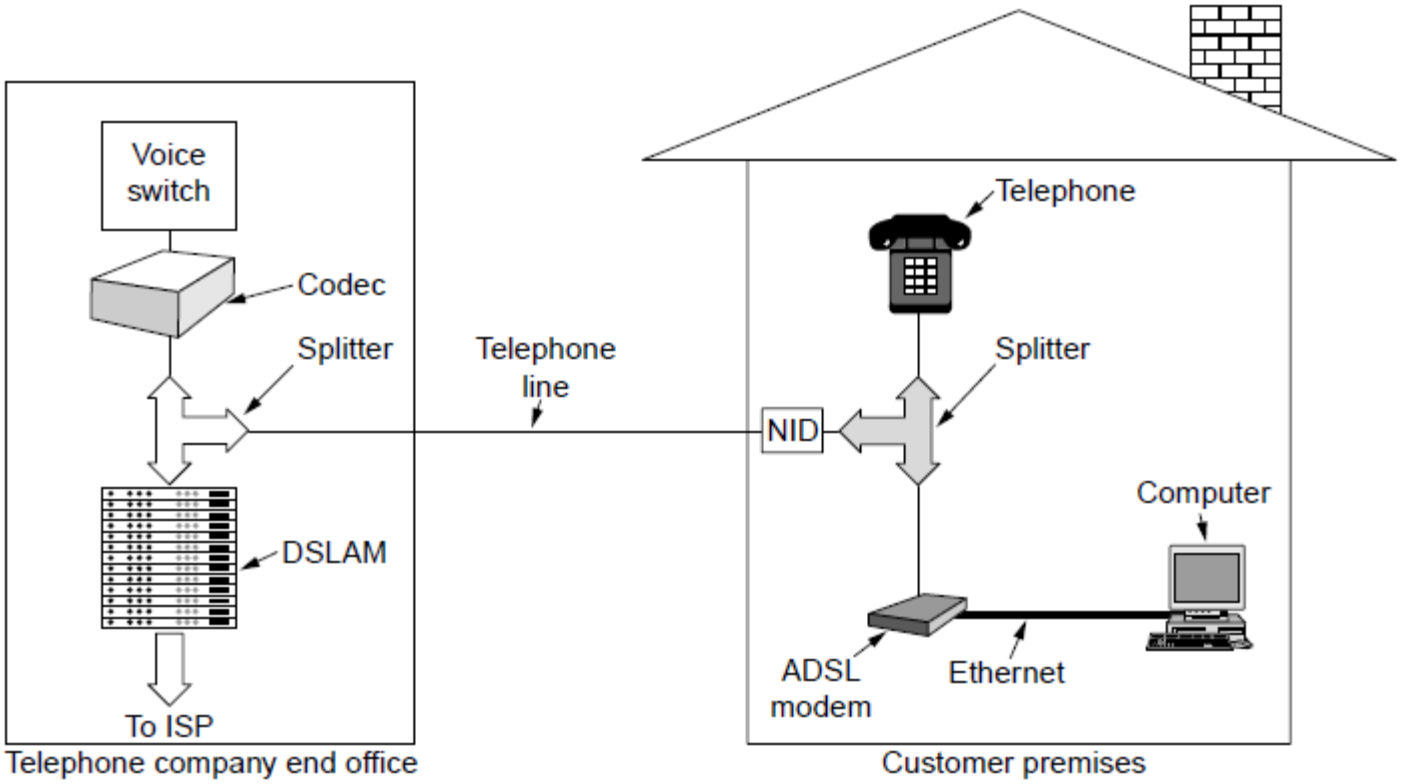
Bandwidth versus distance over Category 3 UTP for DSL.

Digital Subscriber Lines (2)



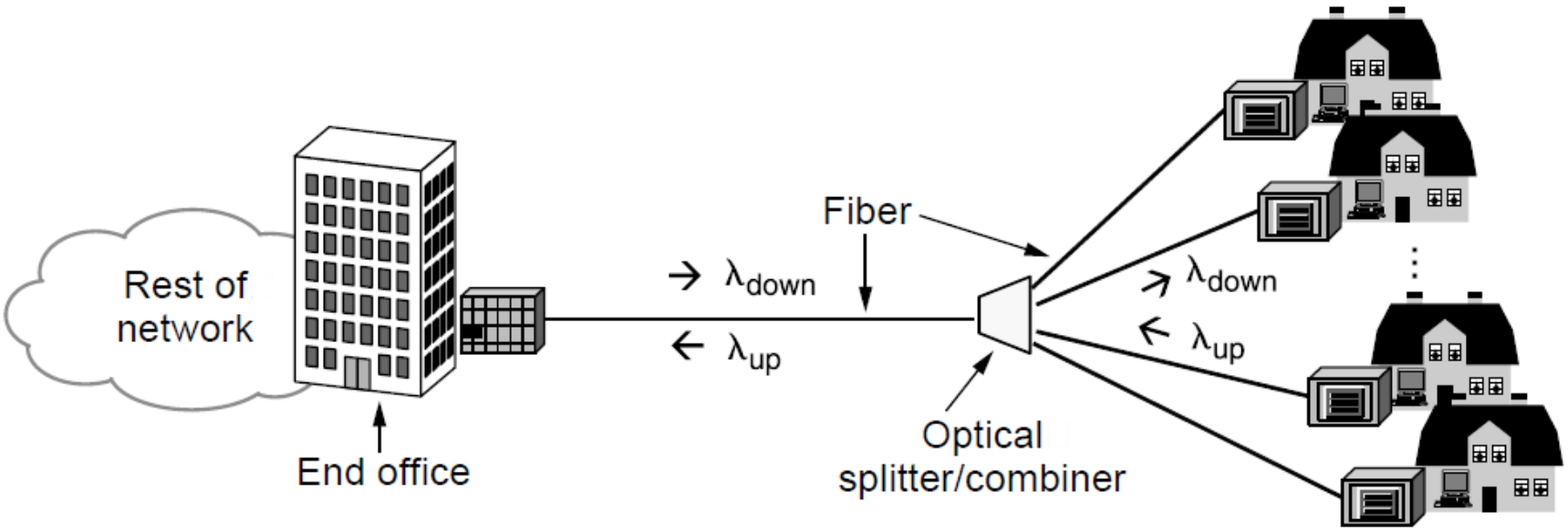
Operation of ADSL using discrete multitone modulation.

Digital Subscriber Lines (3)



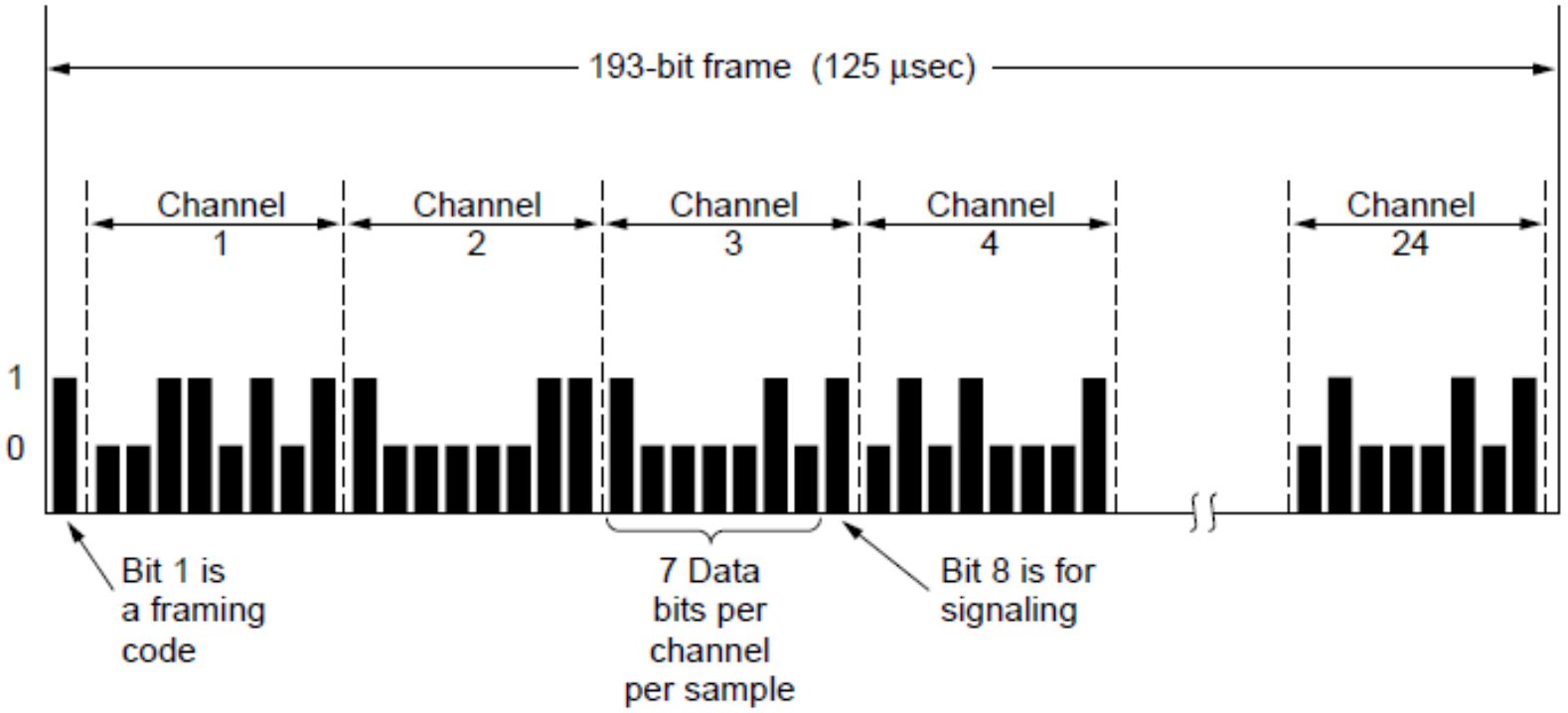
A typical ADSL equipment configuration.

Fiber To The Home



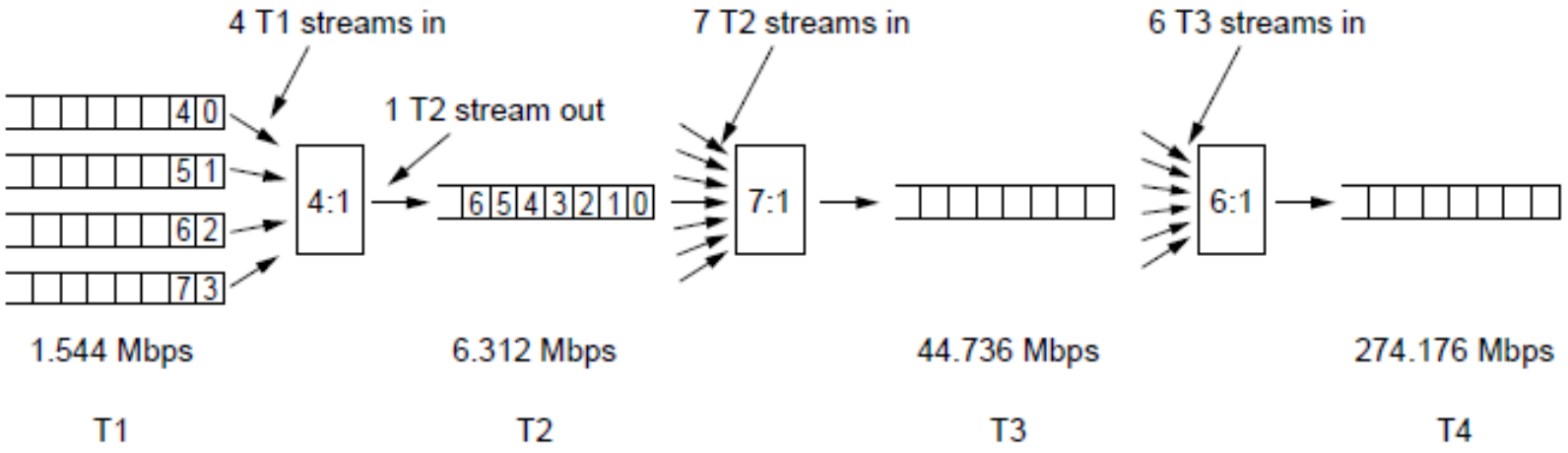
Passive optical network for Fiber To The Home.

Time Division Multiplexing (1)



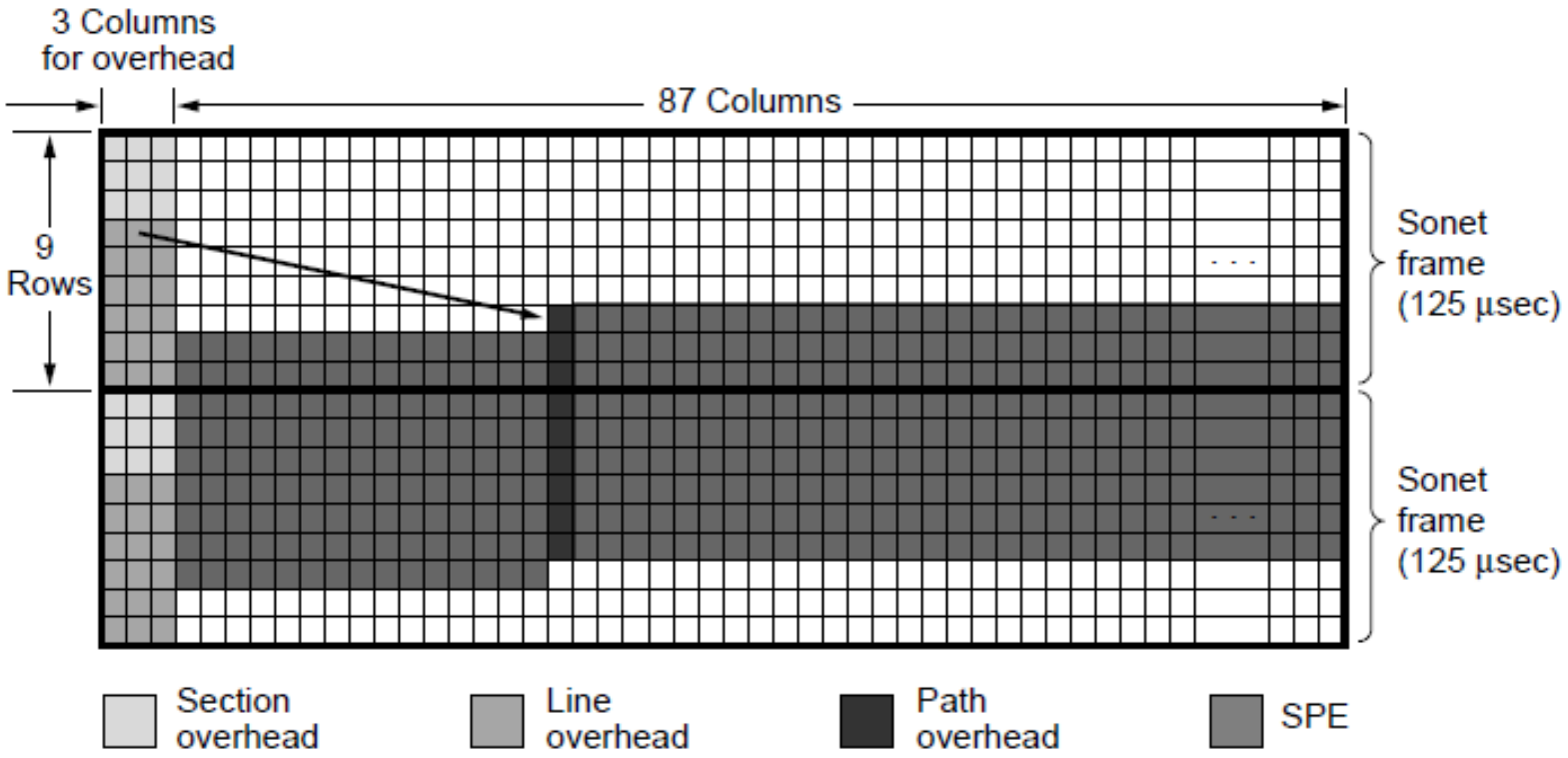
The T1 carrier (1.544 Mbps).

Time Division Multiplexing (2)



Multiplexing T1 streams into higher carriers

SONET/SDH (1)



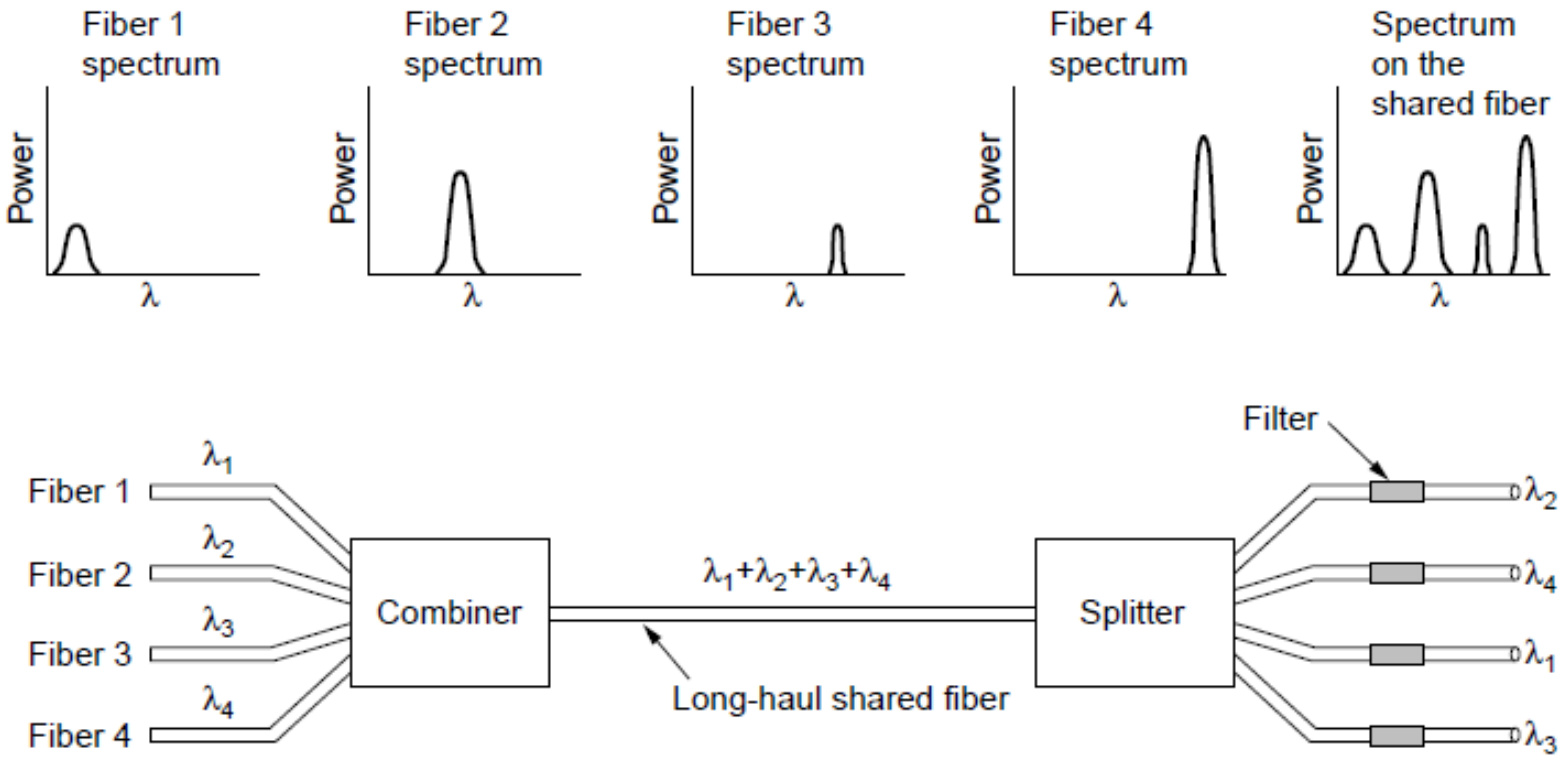
Two back-to-back SONET frames.

SONET/SDH (2)

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

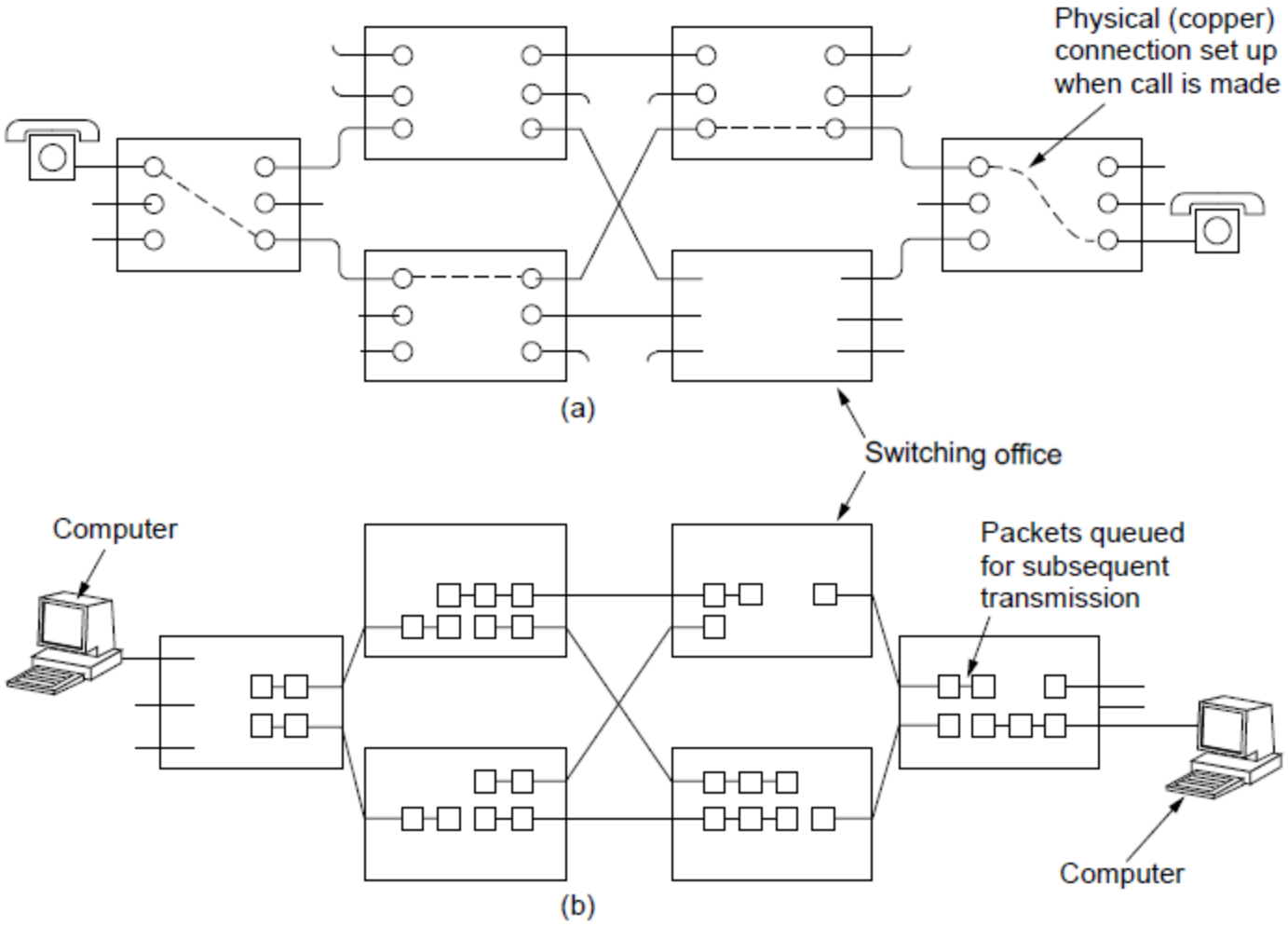
SONET and SDH multiplex rates.

Wavelength Division Multiplexing



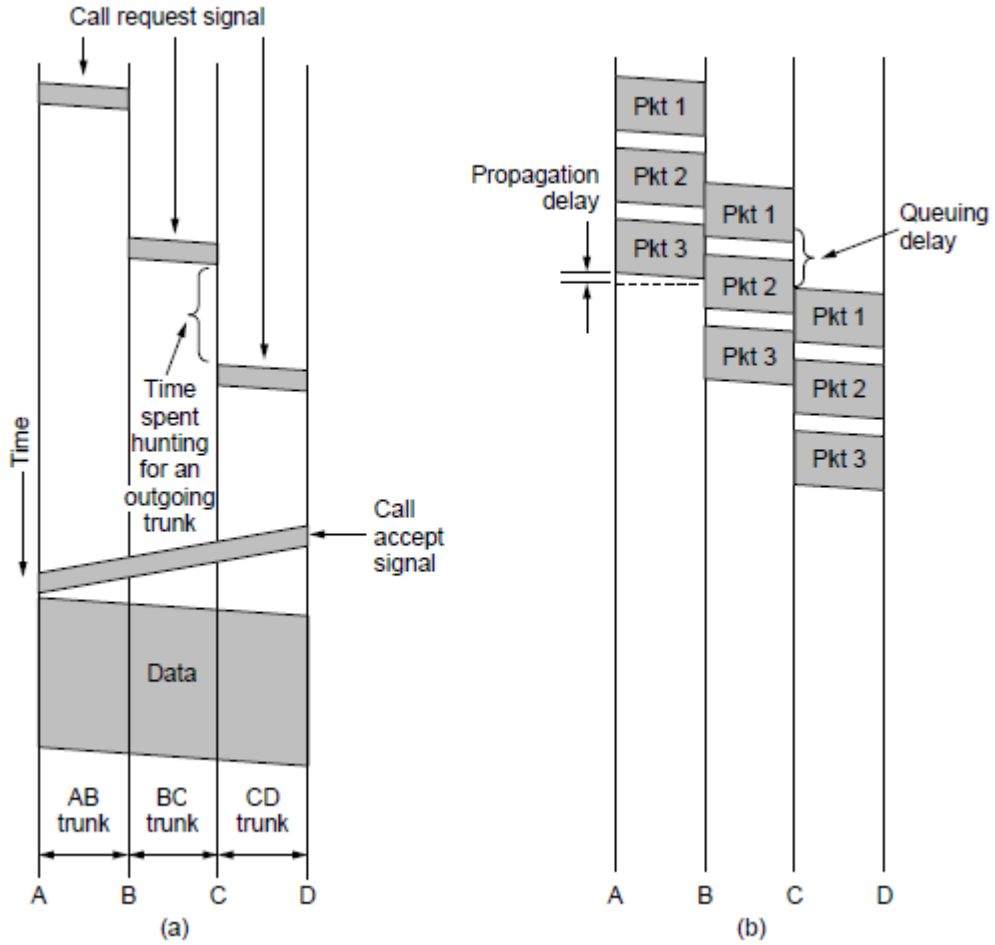
Wavelength division multiplexing

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)

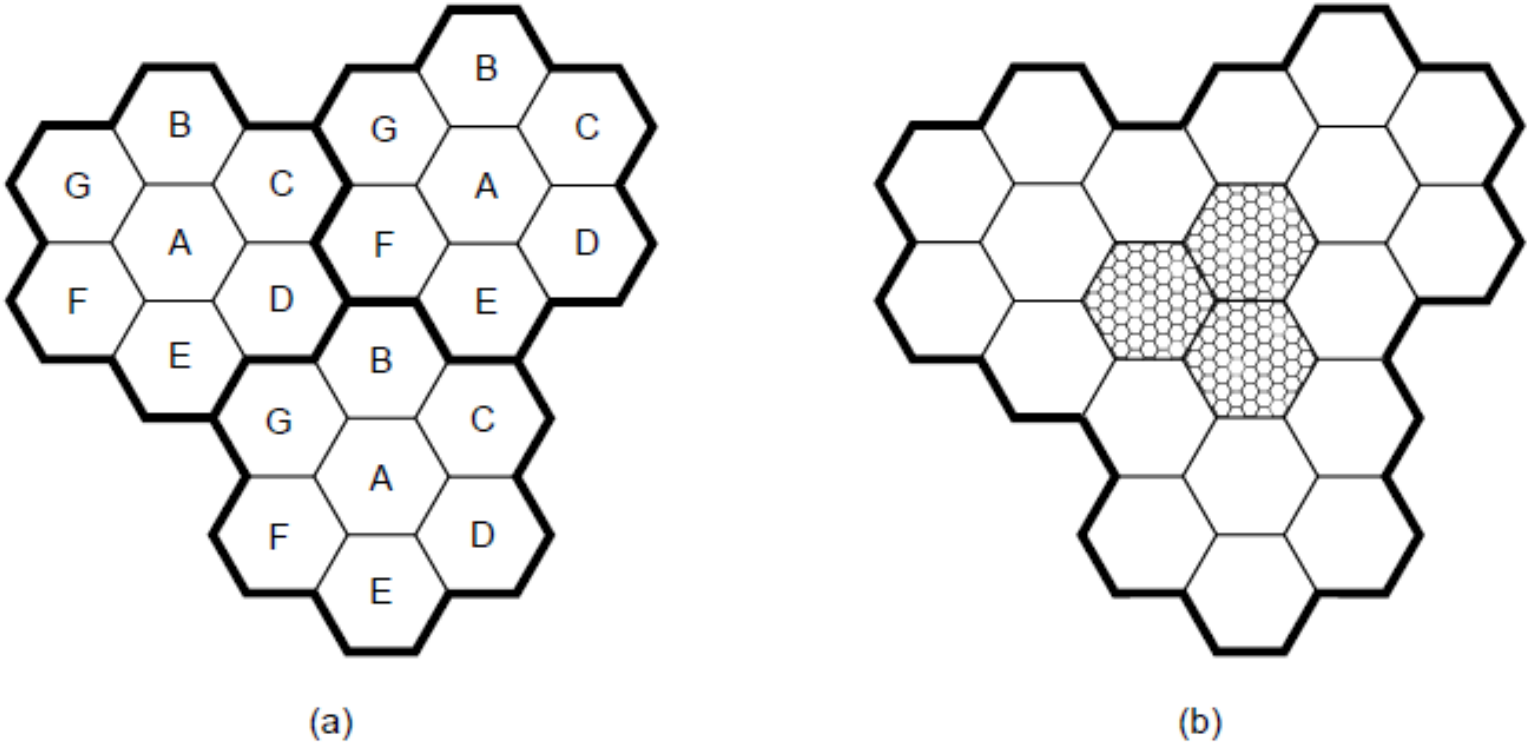
Item	Circuit switched	Packet switched
Call setup	Required	Not needed
Dedicated physical path	Yes	No
Each packet follows the same route	Yes	No
Packets arrive in order	Yes	No
Is a switch crash fatal	Yes	No
Bandwidth available	Fixed	Dynamic
Time of possible congestion	At setup time	On every packet
Potentially 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

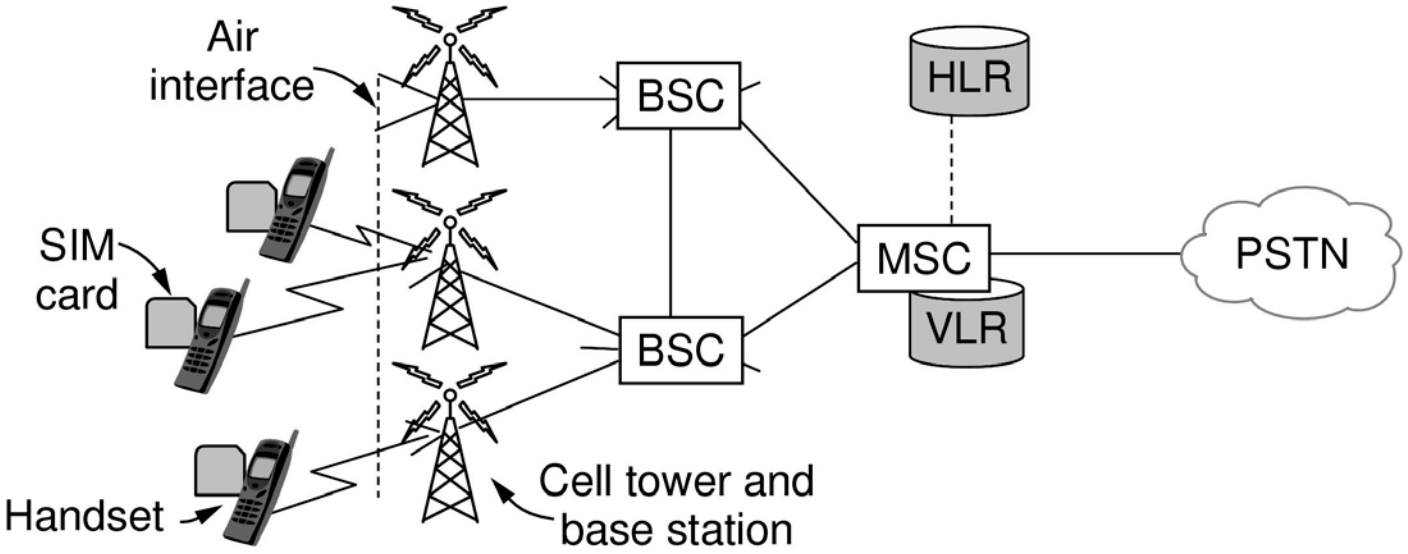
- First-Generation (1G) Mobile Phones Analog Voice
- Second-Generation (2G) Mobile Phones Digital Voice
- Third-Generation (3G) Mobile Phones Digital Voice + Data

Advanced Mobile Phone System



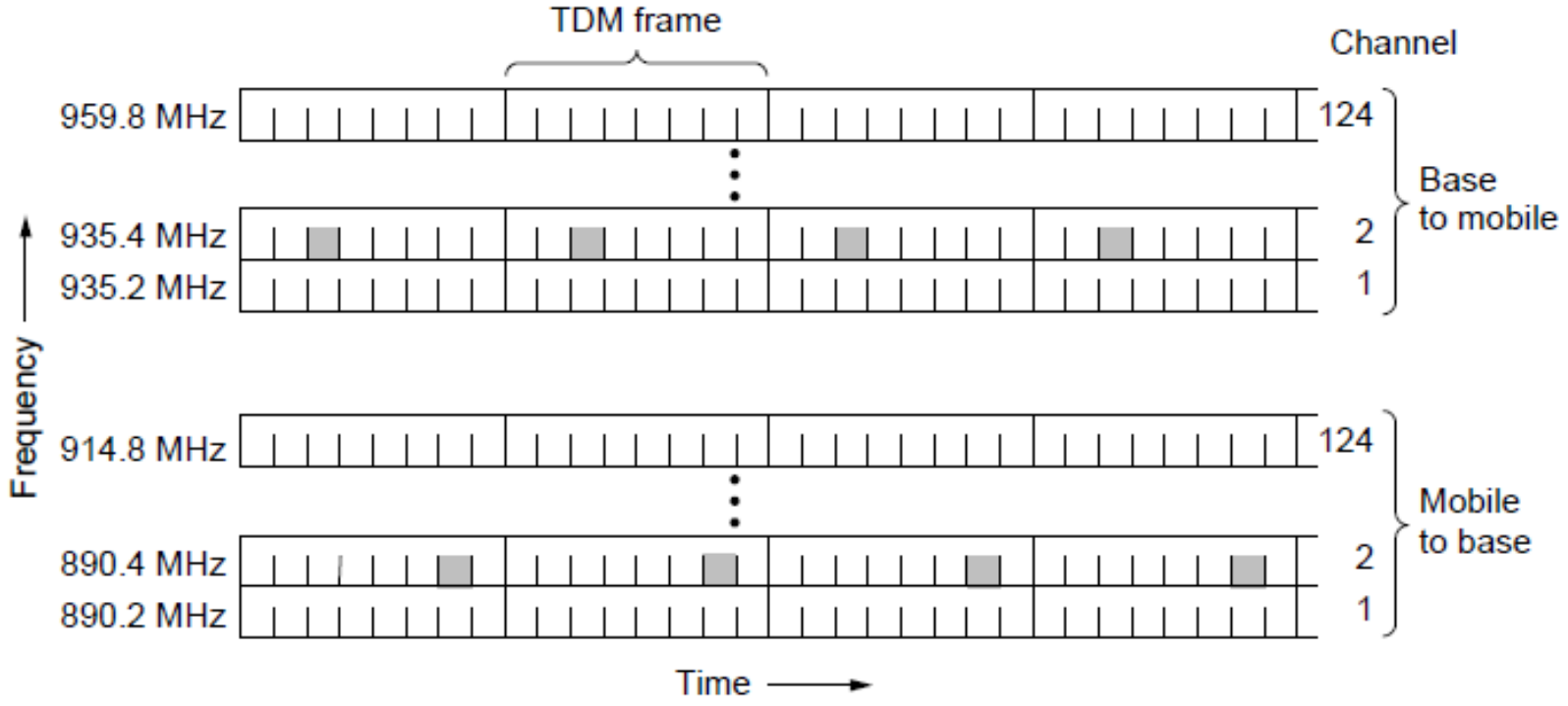
(a) Frequencies are not reused in adjacent cells.
(b) To add more users, smaller cells can be used.

GSM—The Global System for Mobile Communications (1)



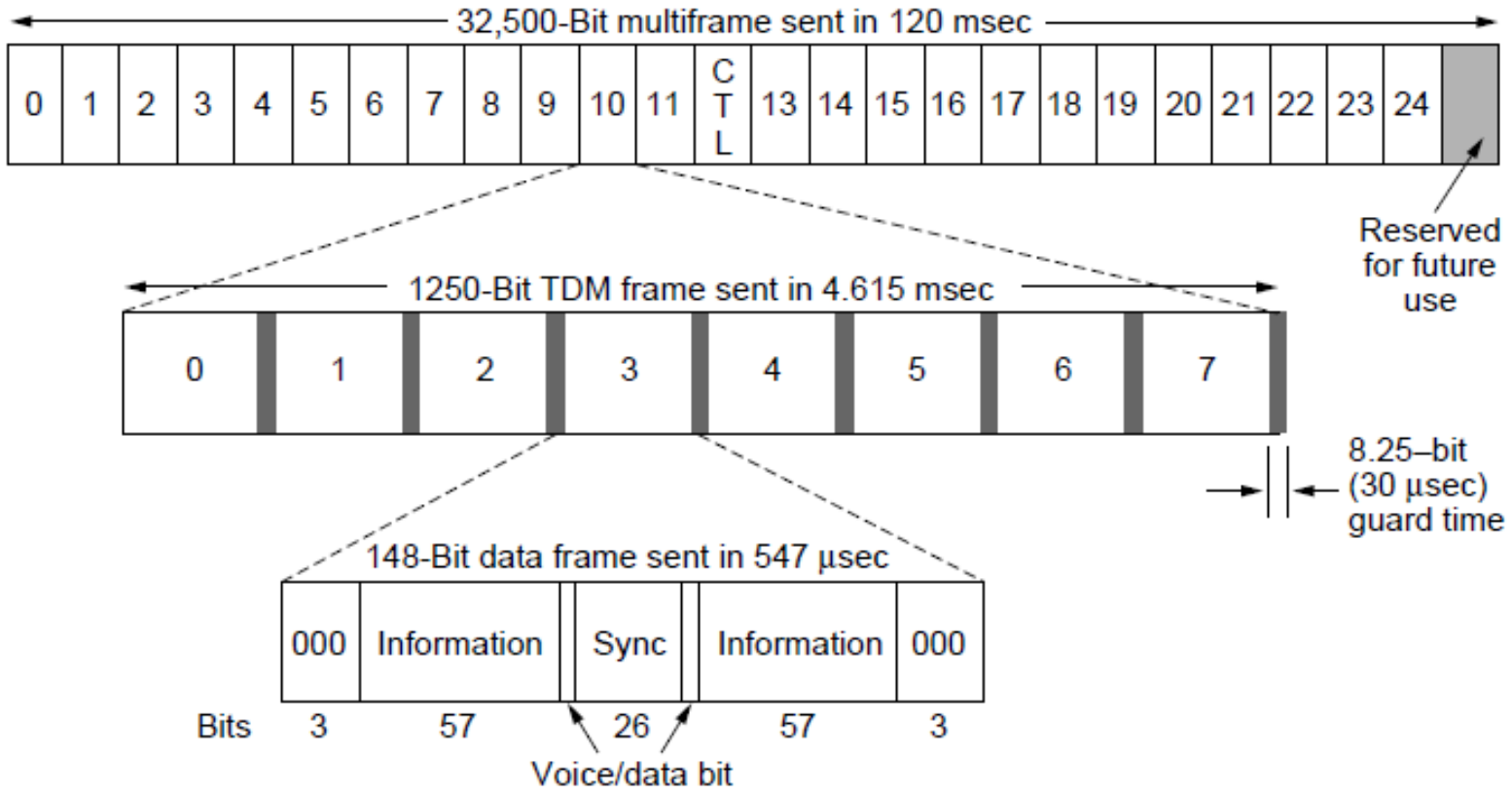
GSM mobile network architecture.

GSM—The Global System for Mobile Communications (2)



GSM uses 124 frequency channels, each of which uses an eight-slot TDM system.

GSM—The Global System for Mobile Communications (3)



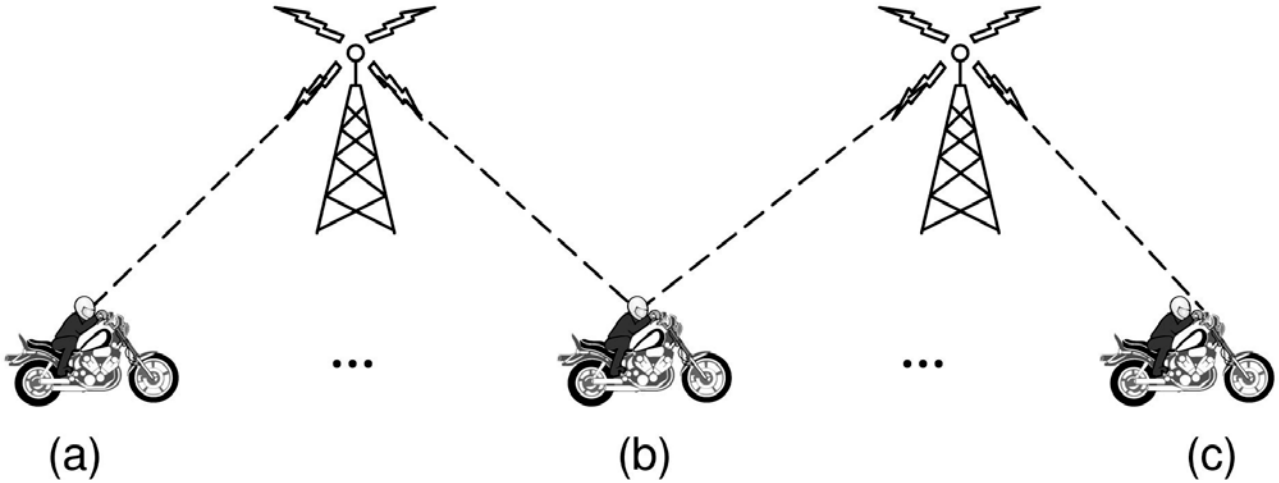
A portion of the GSM framing structure.

Digital Voice and Data (1)

Basic services intend by IMT-2000 network

- High-quality voice transmission.
- Messaging (replacing email, fax, SMS, chat).
- Multimedia (music, videos, films, television).
- Internet access (Web surfing, incl. audio, video).

Digital Voice and Data (2)

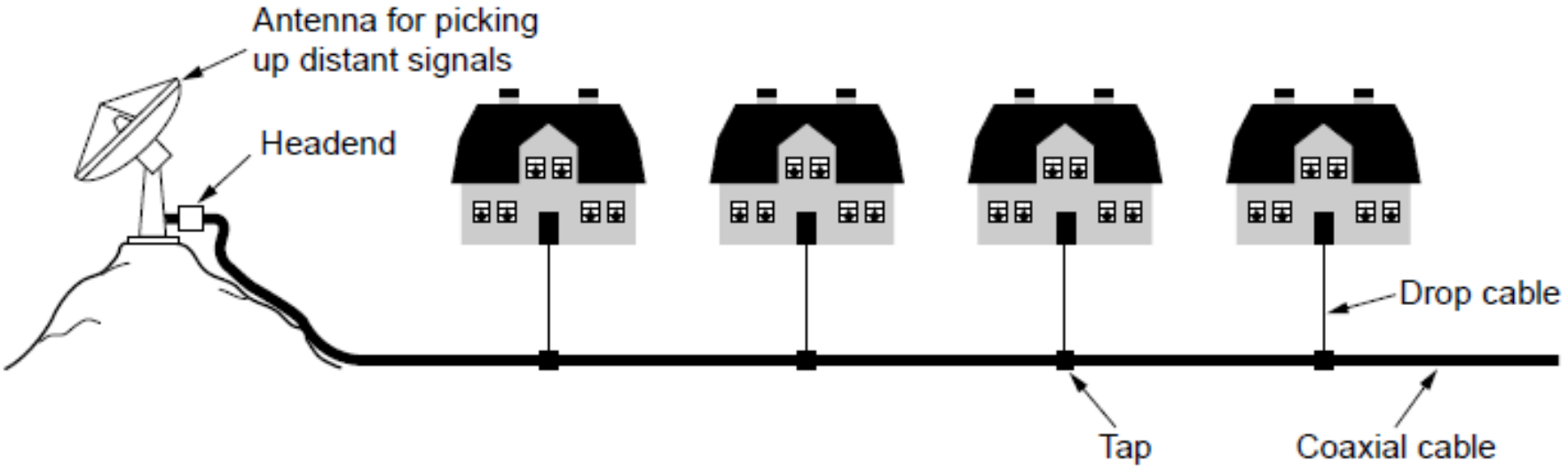


Soft handoff (a) before, (b) during, and (c) after.

Cable Television

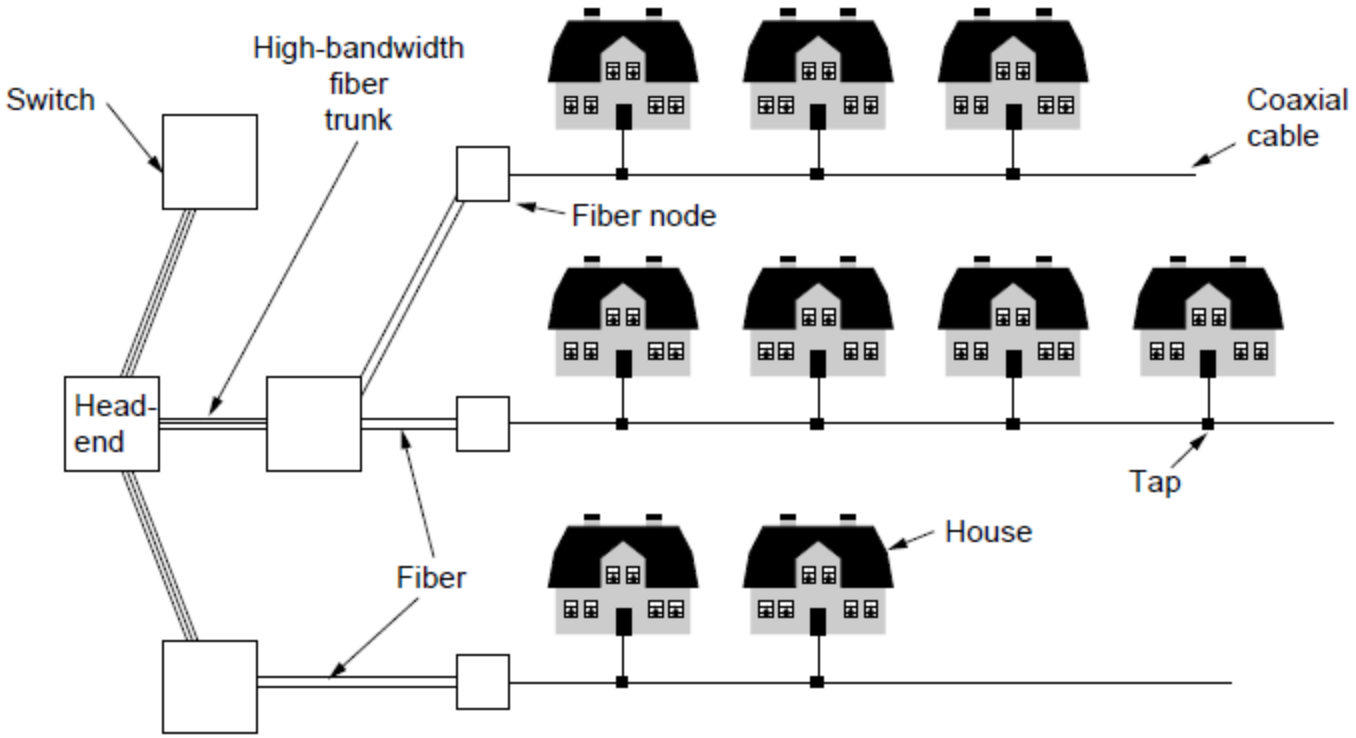
- Community antenna television
- Internet over cable
- Spectrum allocation
- Cable modems
- ADSL versus cable

Community Antenna Television



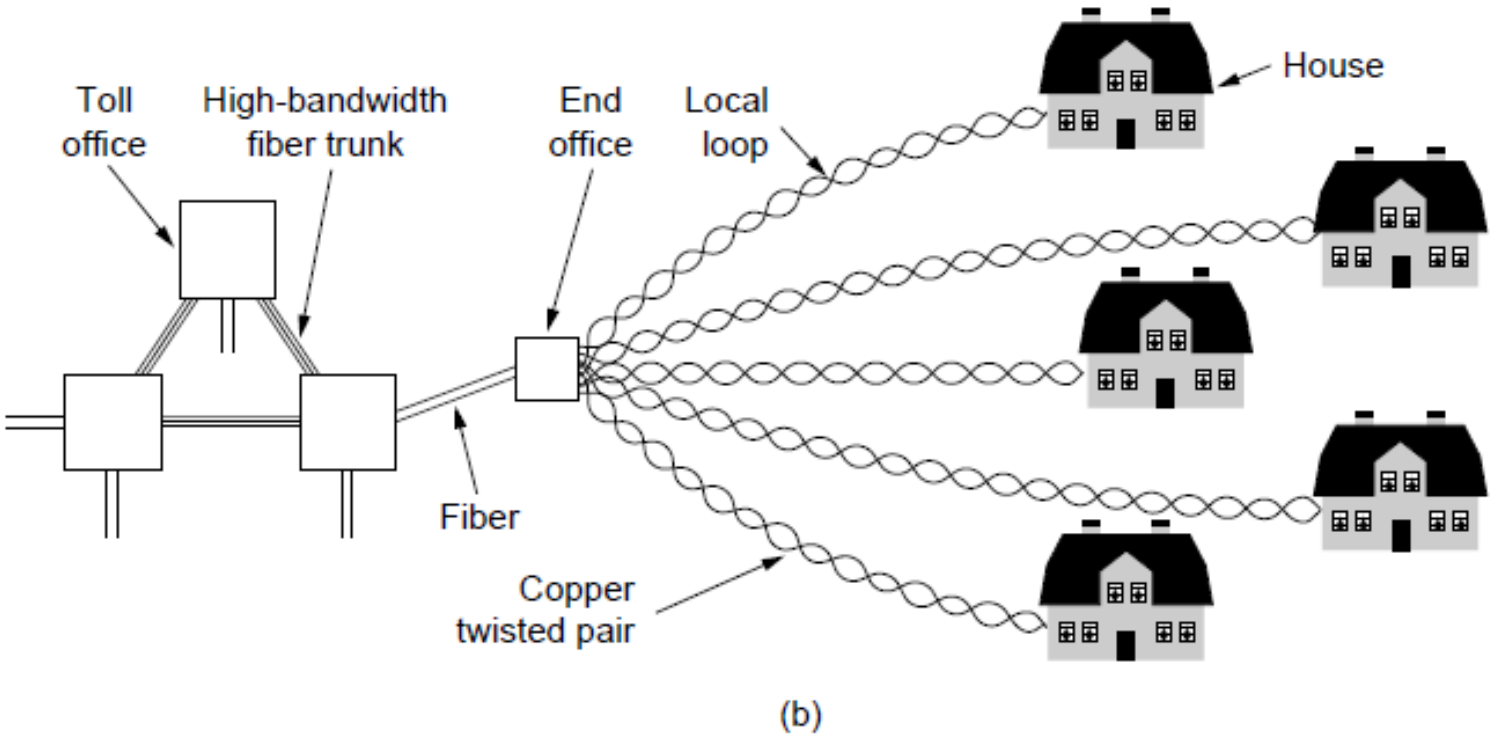
An early cable television system

Internet over Cable (1)



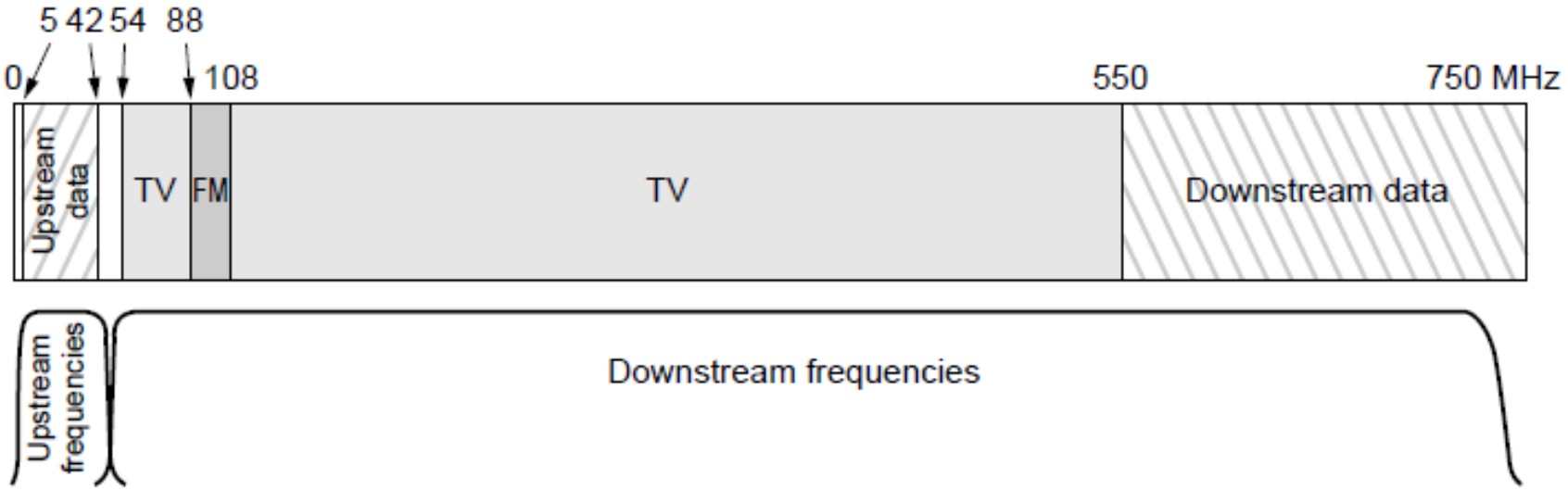
Cable television

Internet over Cable (2)



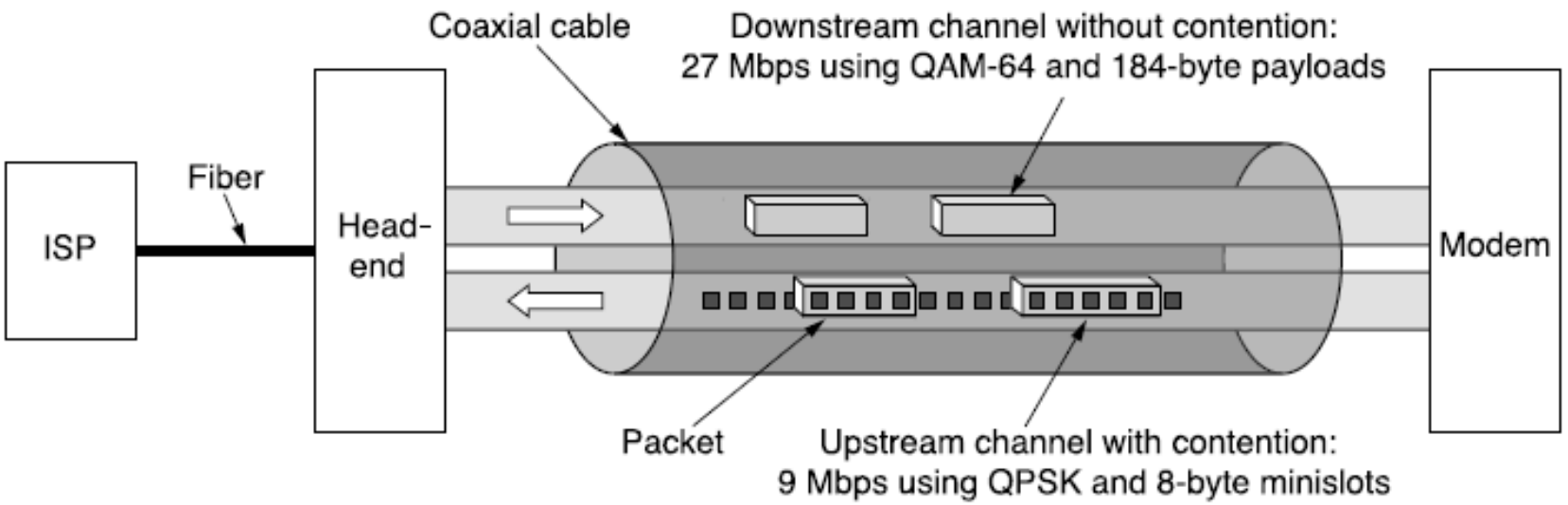
The fixed telephone system.

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