CSMC 417

Computer Networks

Prof. Ashok K Agrawala

Set 3

The Physical Layer

The Theoretical Basis for Data Communication

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

Fourier Analysis

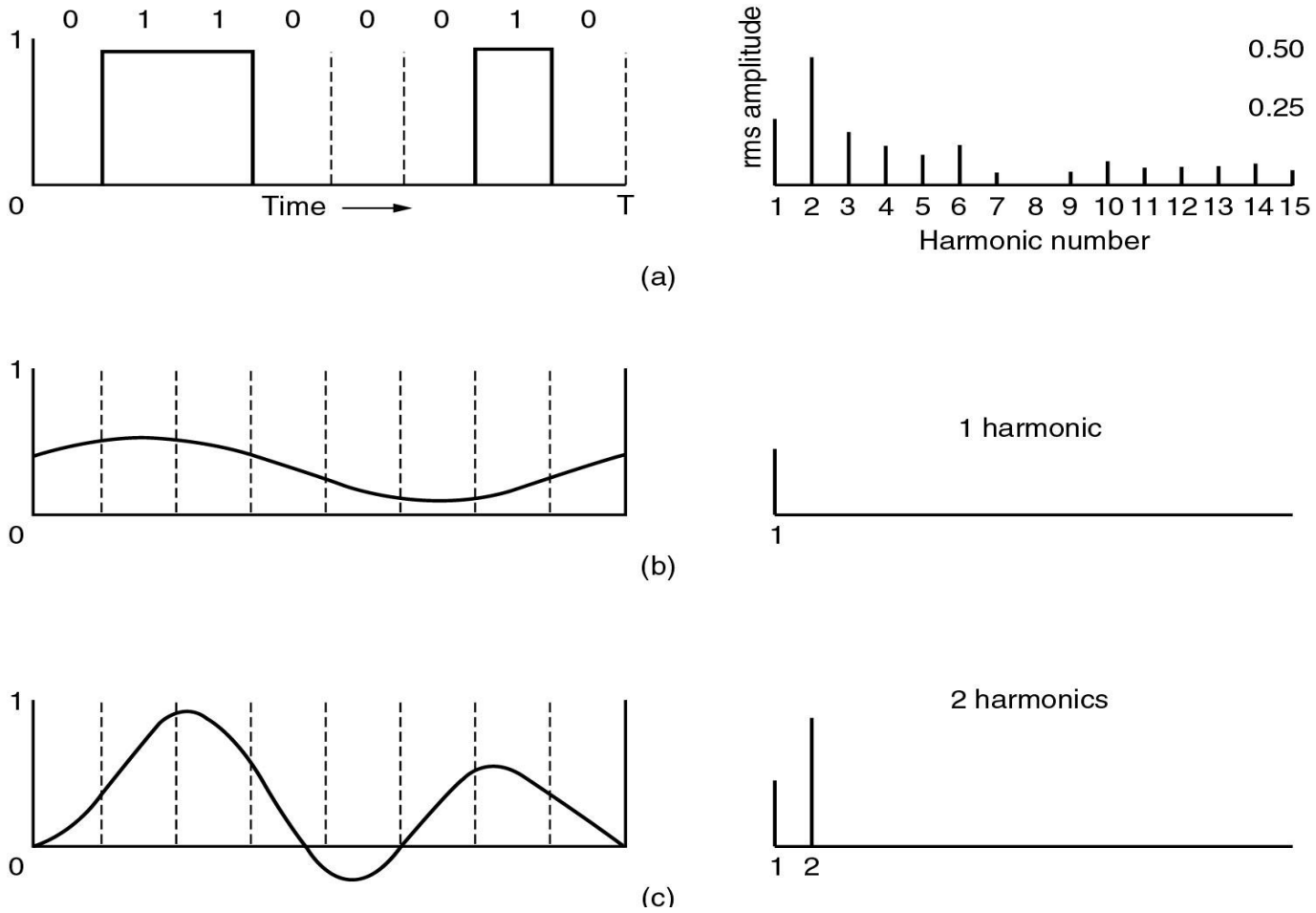
- We model the behavior of variation of voltage or current with mathematical functions
- Fourier series is used

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

- Function reconstructed with

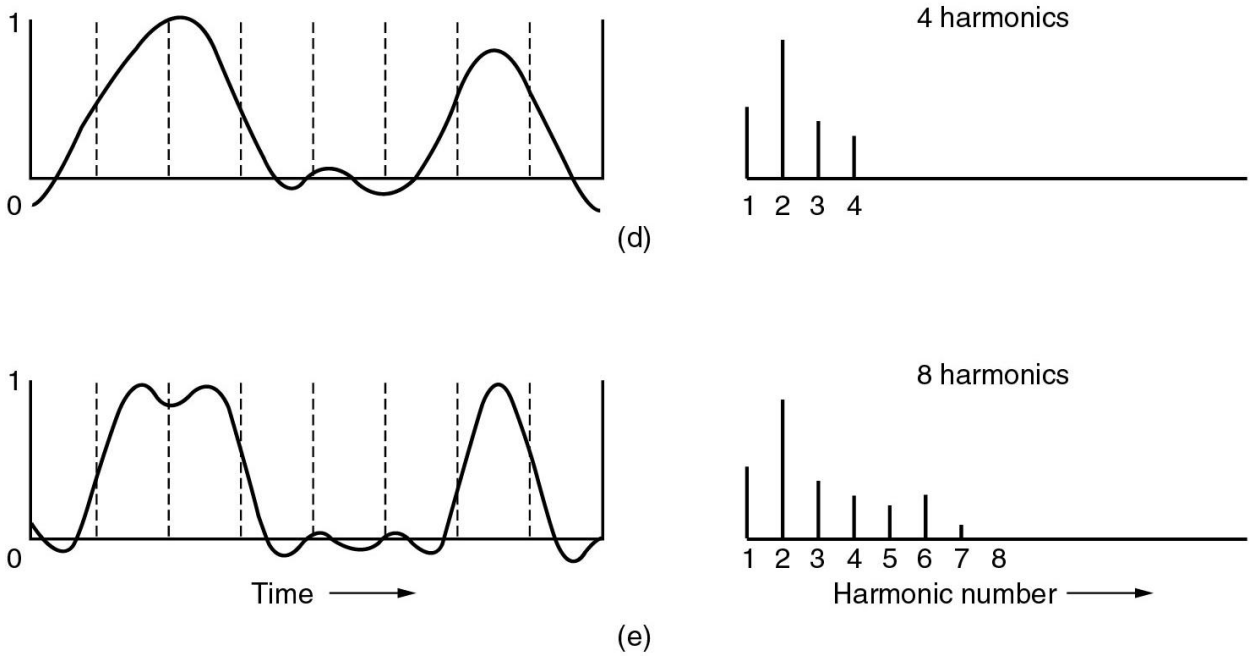
$$a_n = \frac{2}{T}\int_0^T g(t)\sin(2\pi nft)\,dt \qquad b_n = \frac{2}{T}\int_0^T g(t)\cos(2\pi nft)\,dt \qquad c = \frac{2}{T}\int_0^T g(t)\,dt$$

Bandwidth-Limited Signals



A binary signal and its root-mean-square Fourier amplitudes.
(b) – (c) Successive approximations to the original signal.

Bandwidth-Limited Signals (2)



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

Bandwidth-Limited Signals (3)

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

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 Data

- Magnetic Media
- Twisted Pair
- Coaxial Cable
- 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.

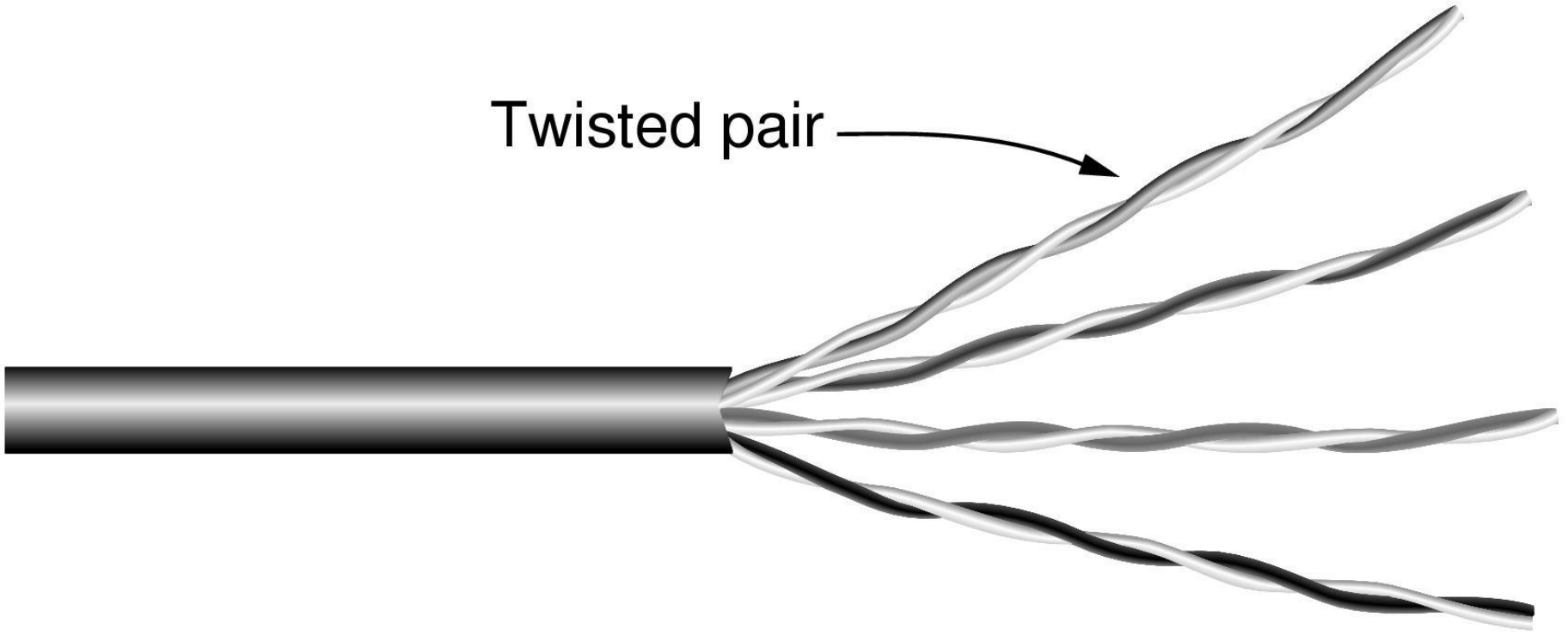
Twisted Pair

(a)

(b)

(a) Category 3 UTP.
(b) Category 5 UTP.

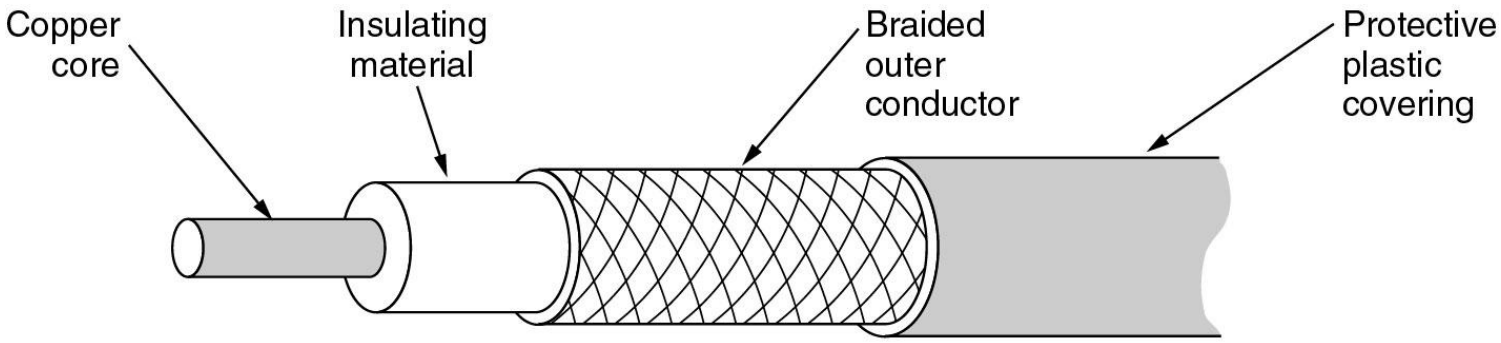
Twisted Pairs



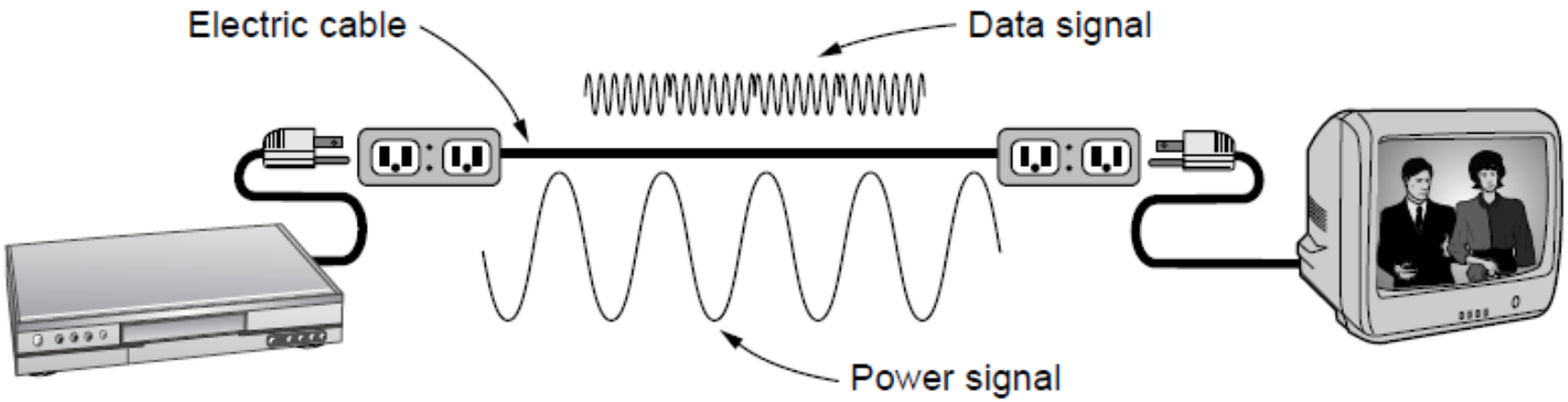
Category 5 UTP cable with four twisted pairs

Coaxial Cable

A coaxial cable.

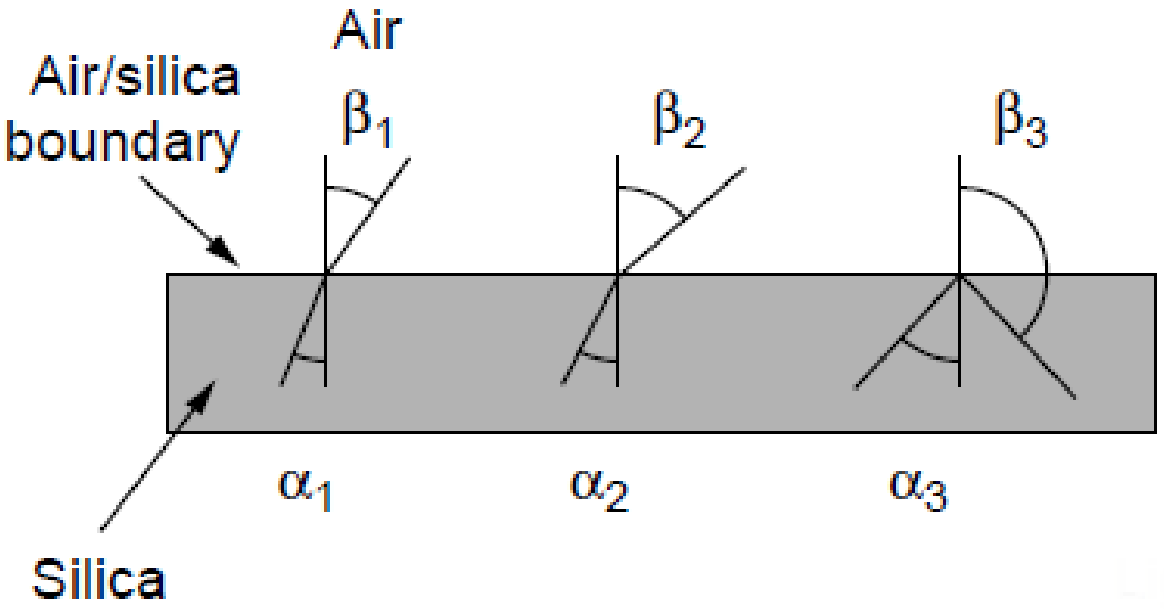


Power Lines



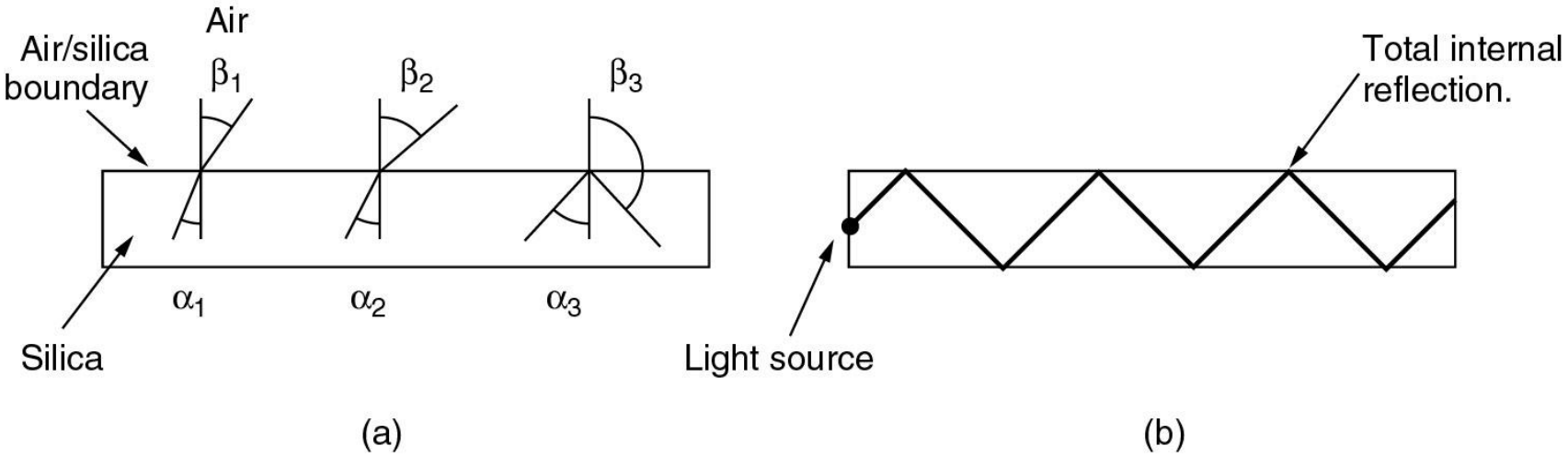
A network that uses household electrical wiring.

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

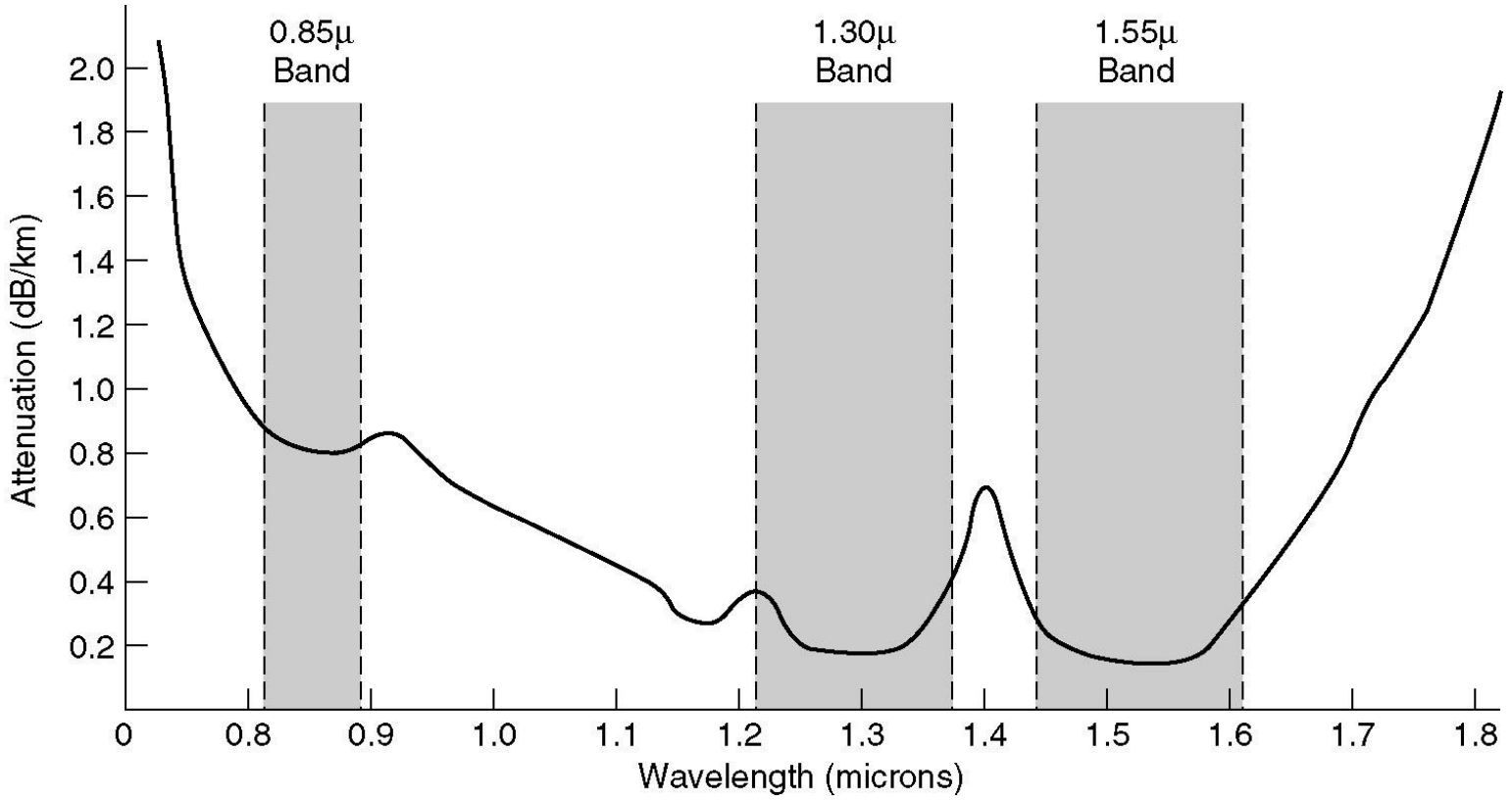


(a) Three examples of a light ray from inside a silica fiber impinging on the air/silica boundary at different angles.

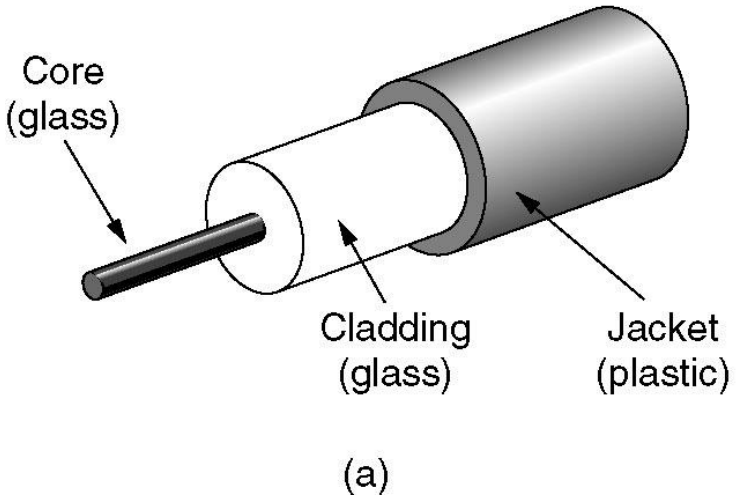
(b) Light trapped by total internal reflection.

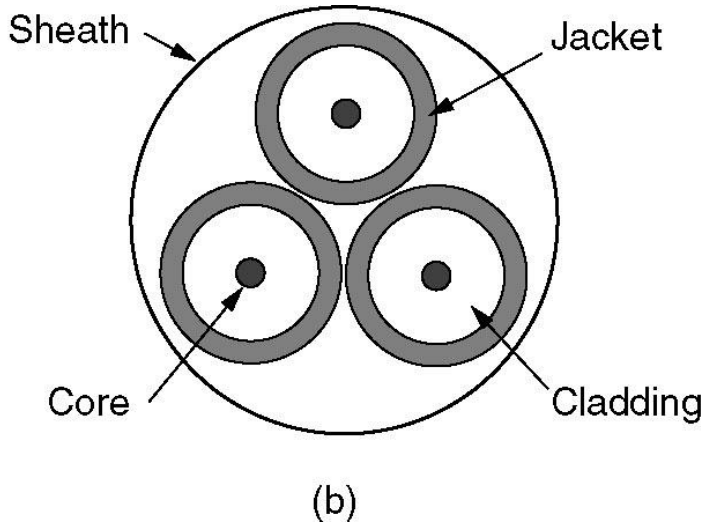
Transmission of Light through Fiber

Attenuation of light through fiber in the infrared region.



Fiber Cables





(a) Side view of a single fiber.

(b) End view of a sheath with three fibers.

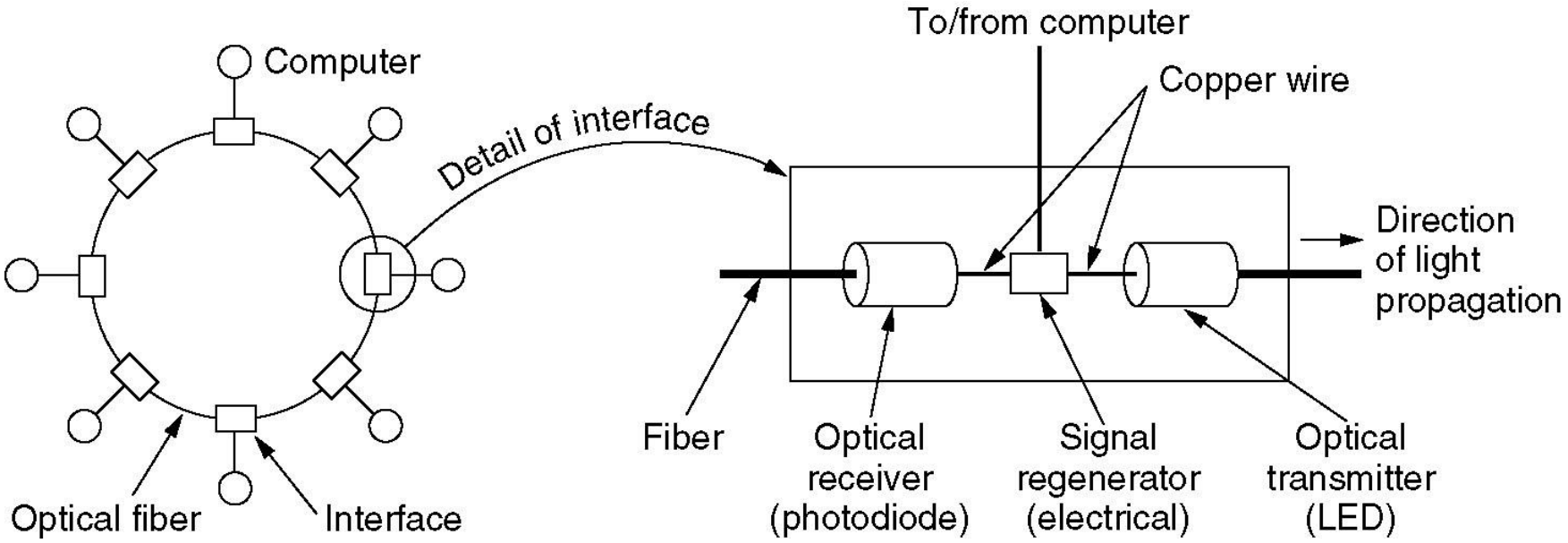
Fiber Cables (2)

A comparison of semiconductor diodes and LEDs as light sources.

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

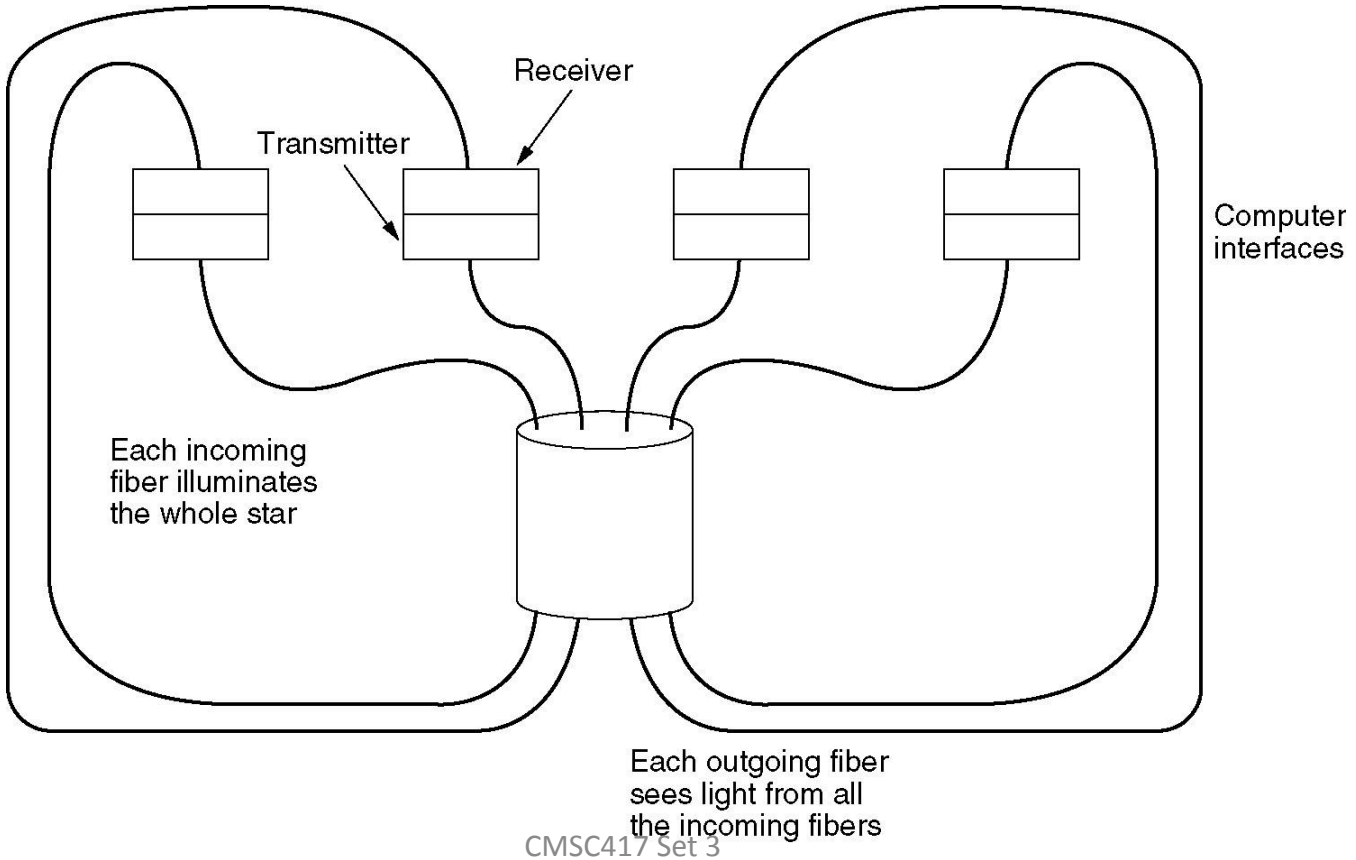
Fiber Optic Networks

A fiber optic ring with active repeaters.



Fiber Optic Networks (2)

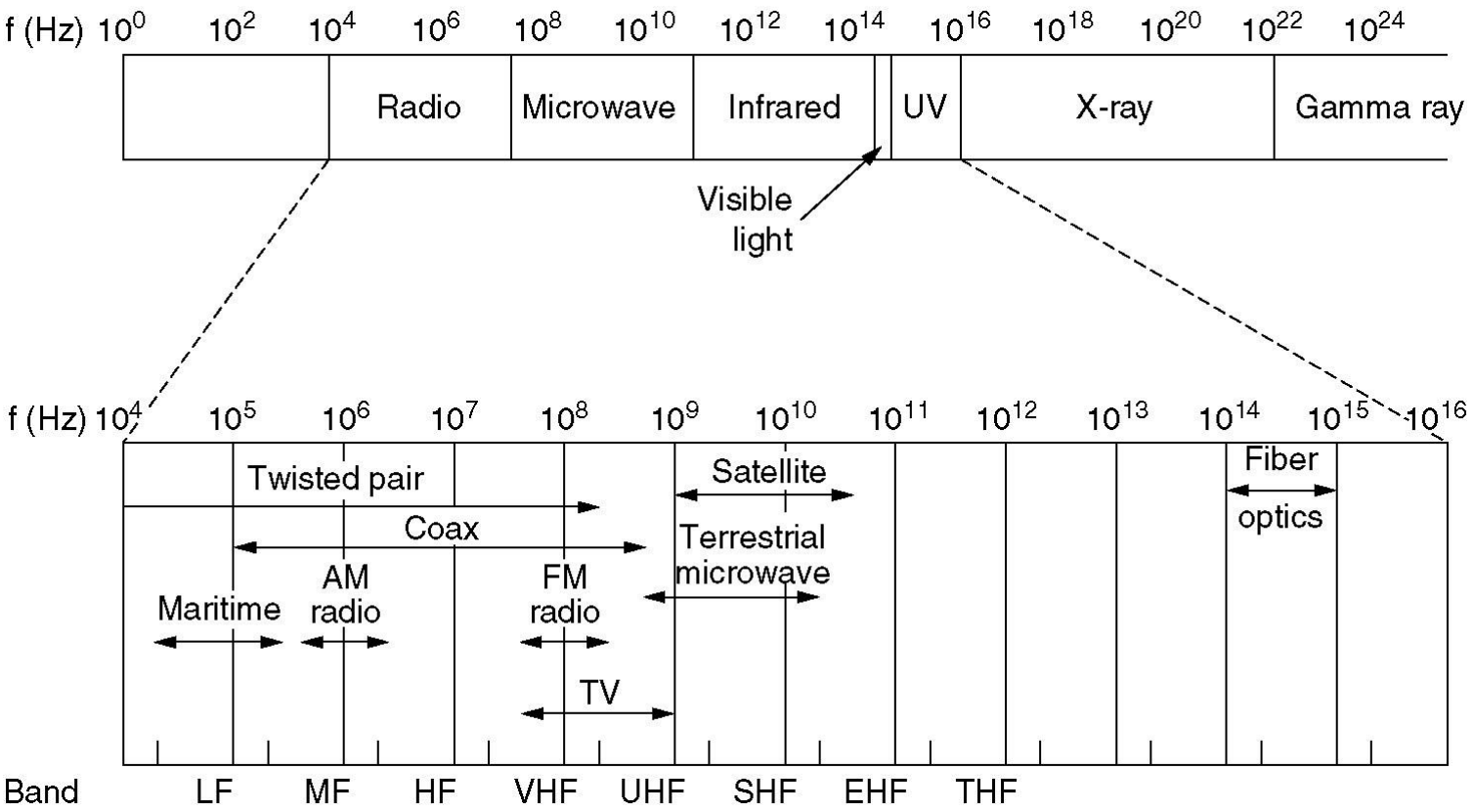
A passive star connection in a fiber optics network.



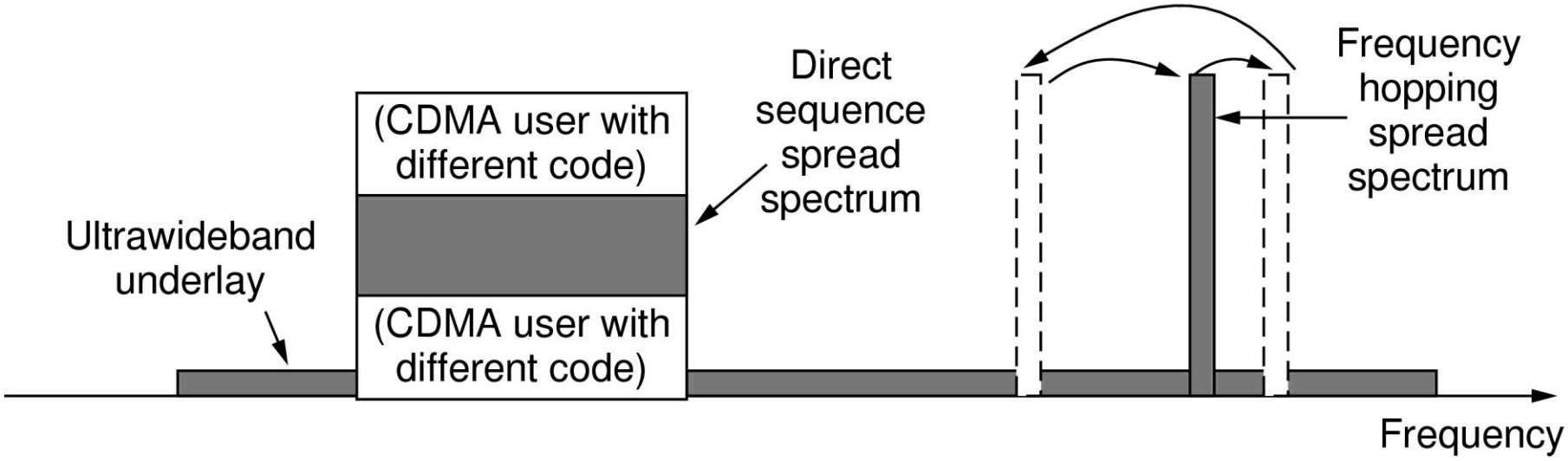
Wireless Transmission

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

The Electromagnetic Spectrum

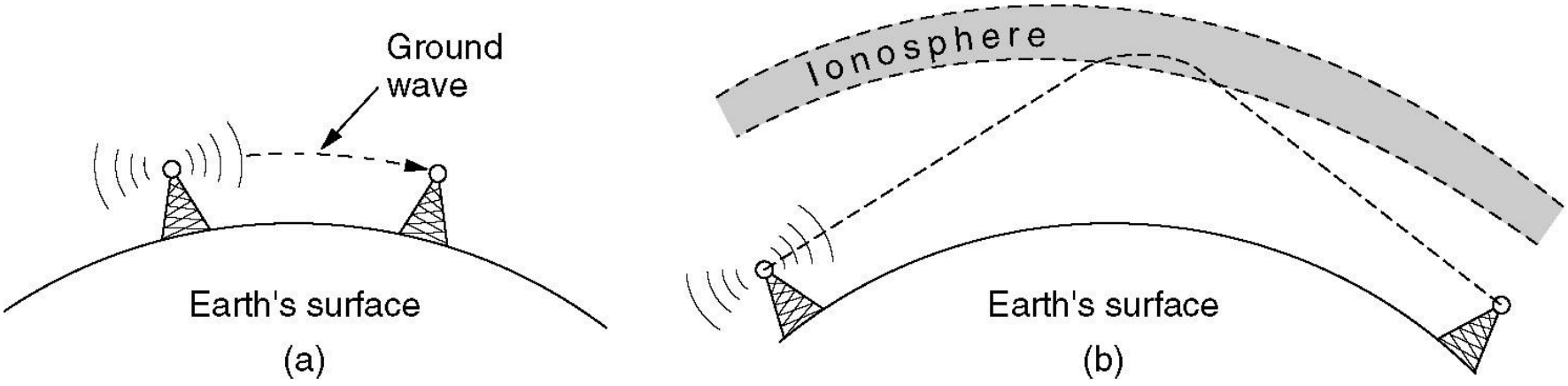


The Electromagnetic Spectrum (2)



Spread spectrum and ultra-wideband (UWB) communication

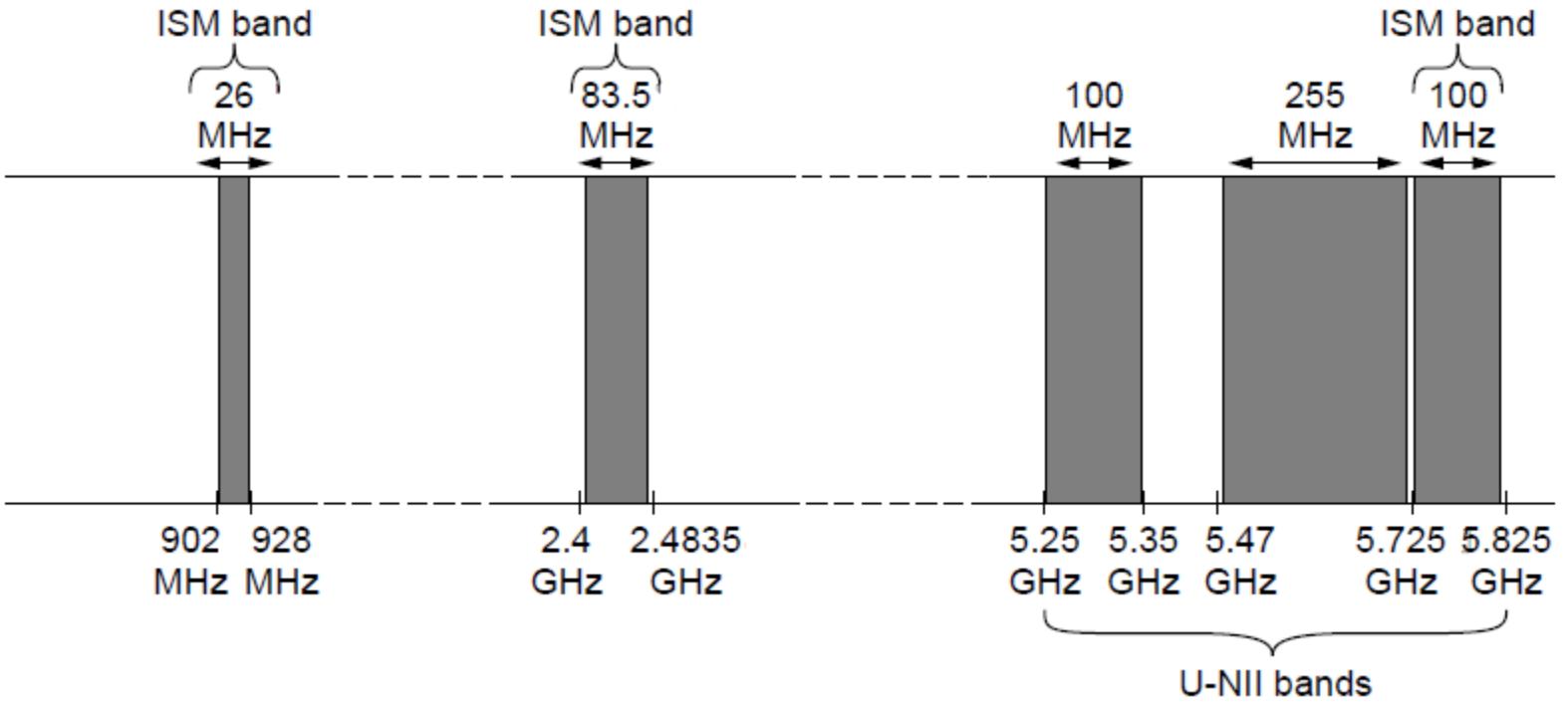
Radio Transmission



(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.

The Politics of the Electromagnetic Spectrum

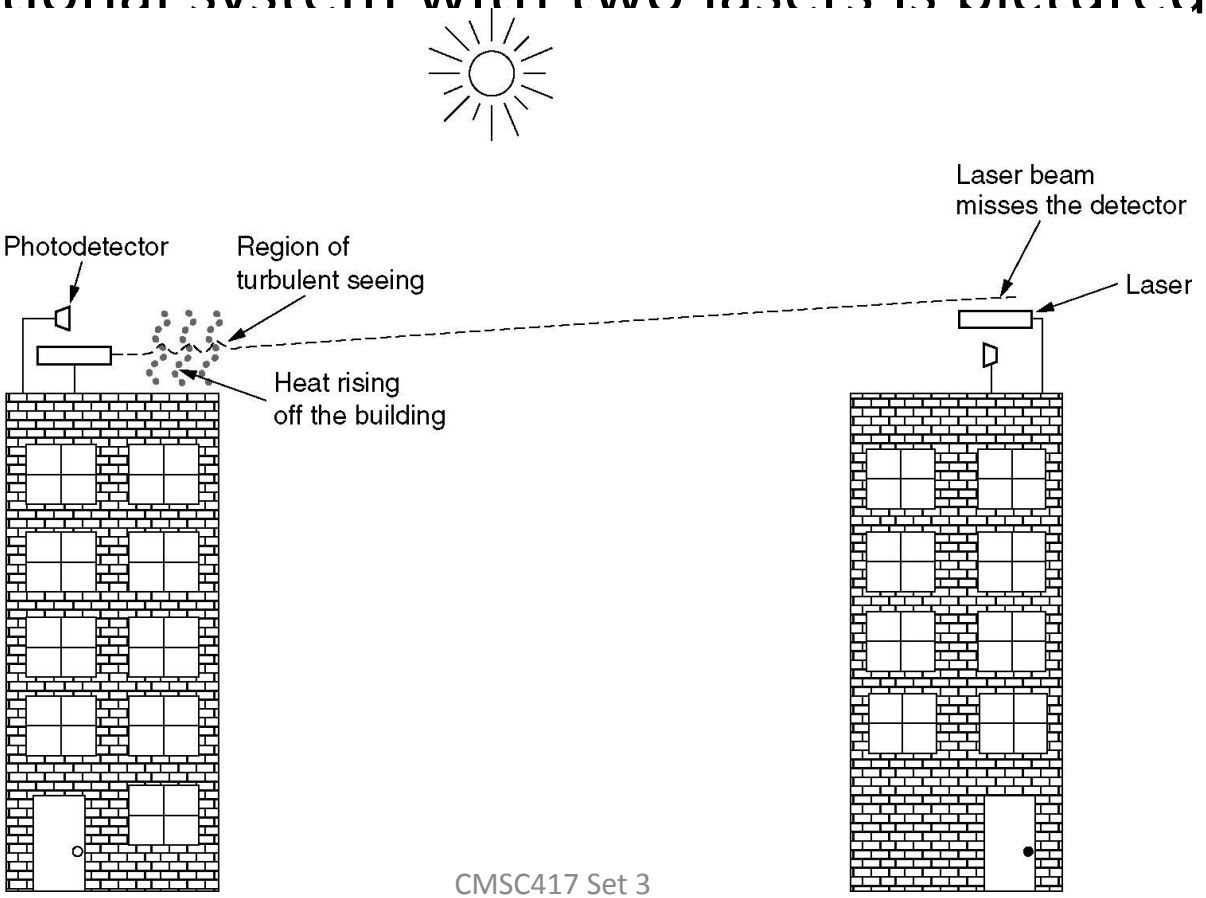


ISM and U-NII bands used in the United States by wireless devices

Lightwave Transmission

Convection currents can interfere with laser communication systems.

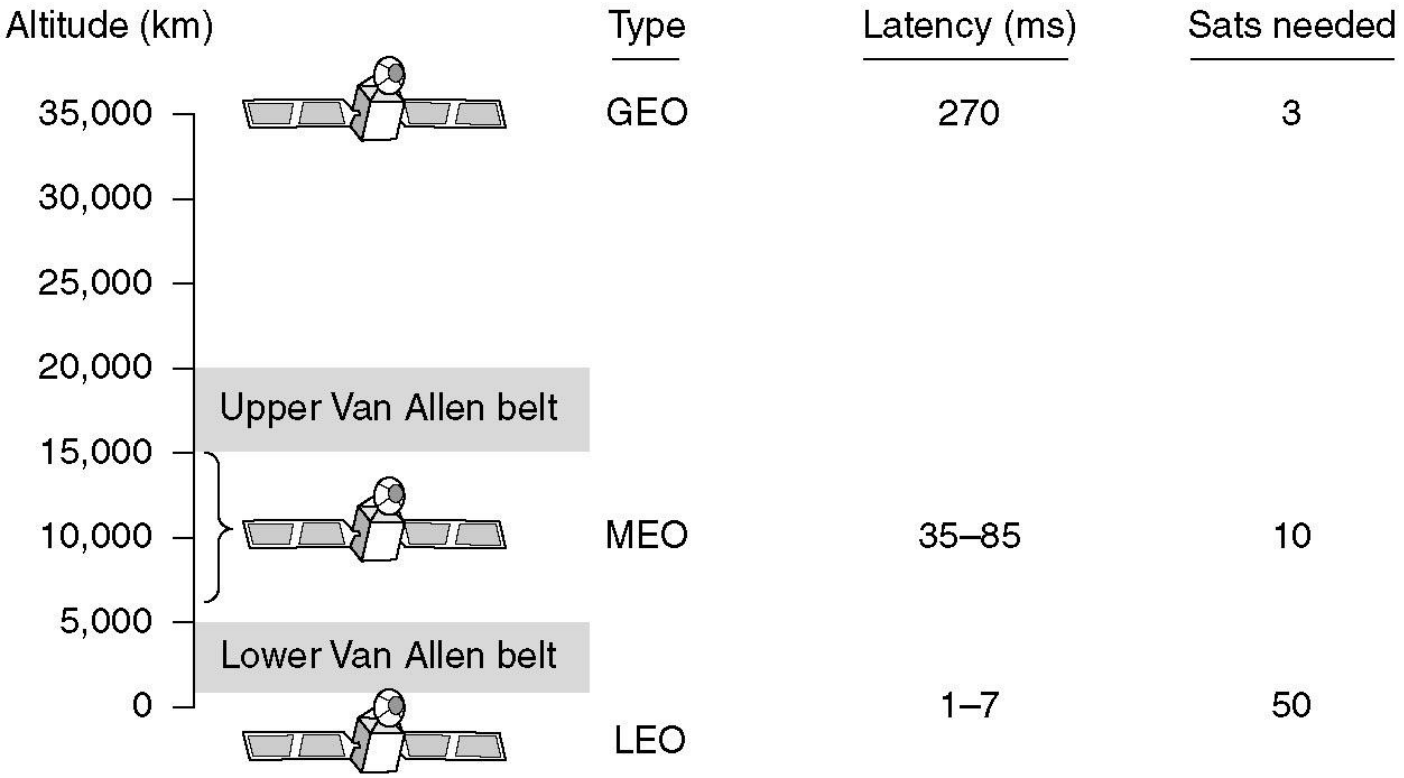
A bidirectional system with two lasers is pictured here.



Communication Satellites

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

Communication Satellites



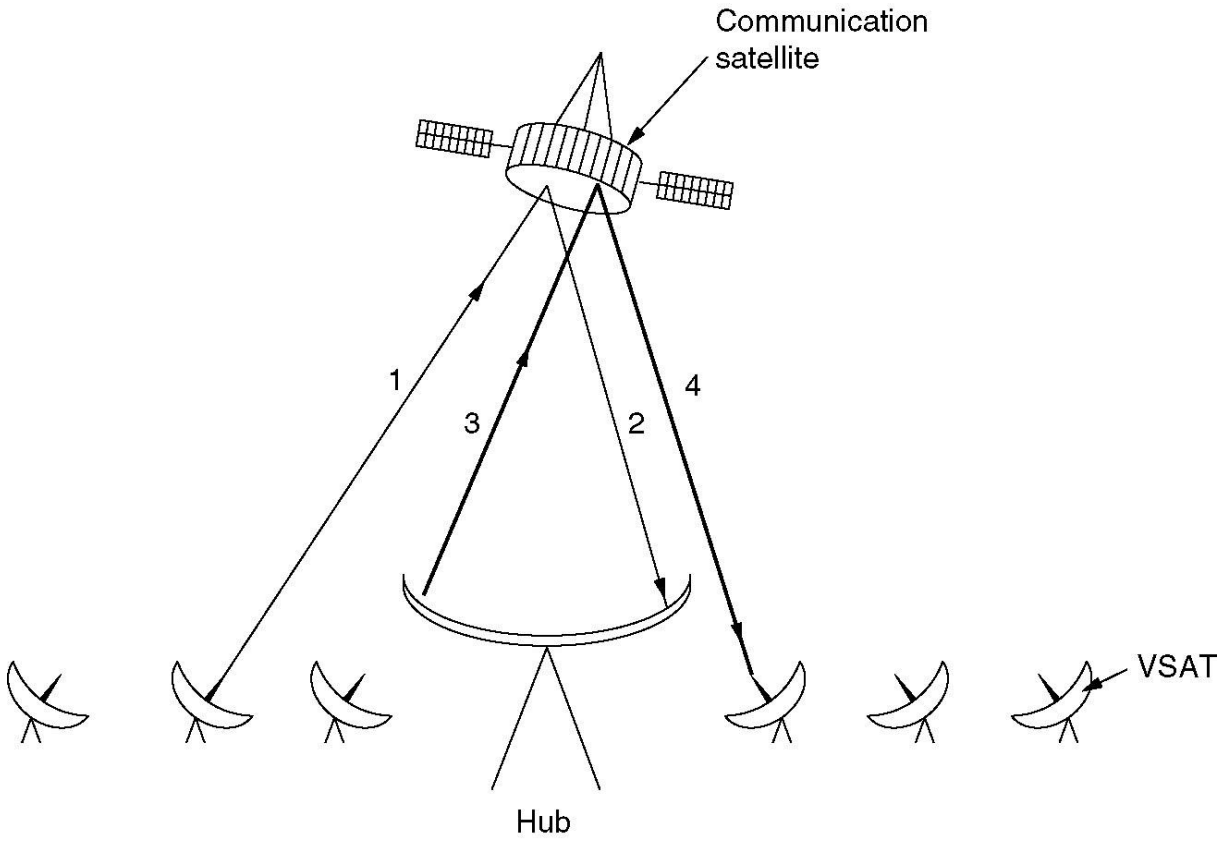
Communication satellites and some of their properties, including altitude above the earth, round-trip delay time and number of satellites needed for global coverage.

Communication Satellites (2)

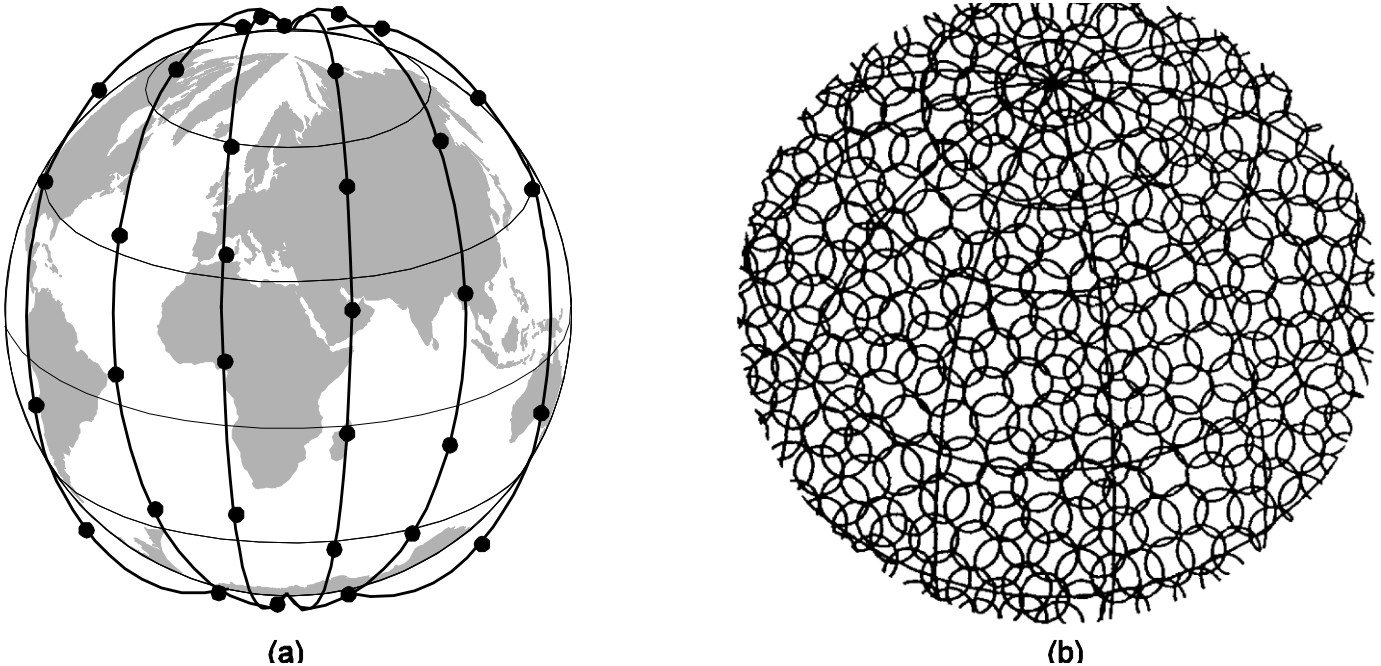
The principal satellite bands.

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

Communication Satellites (3)



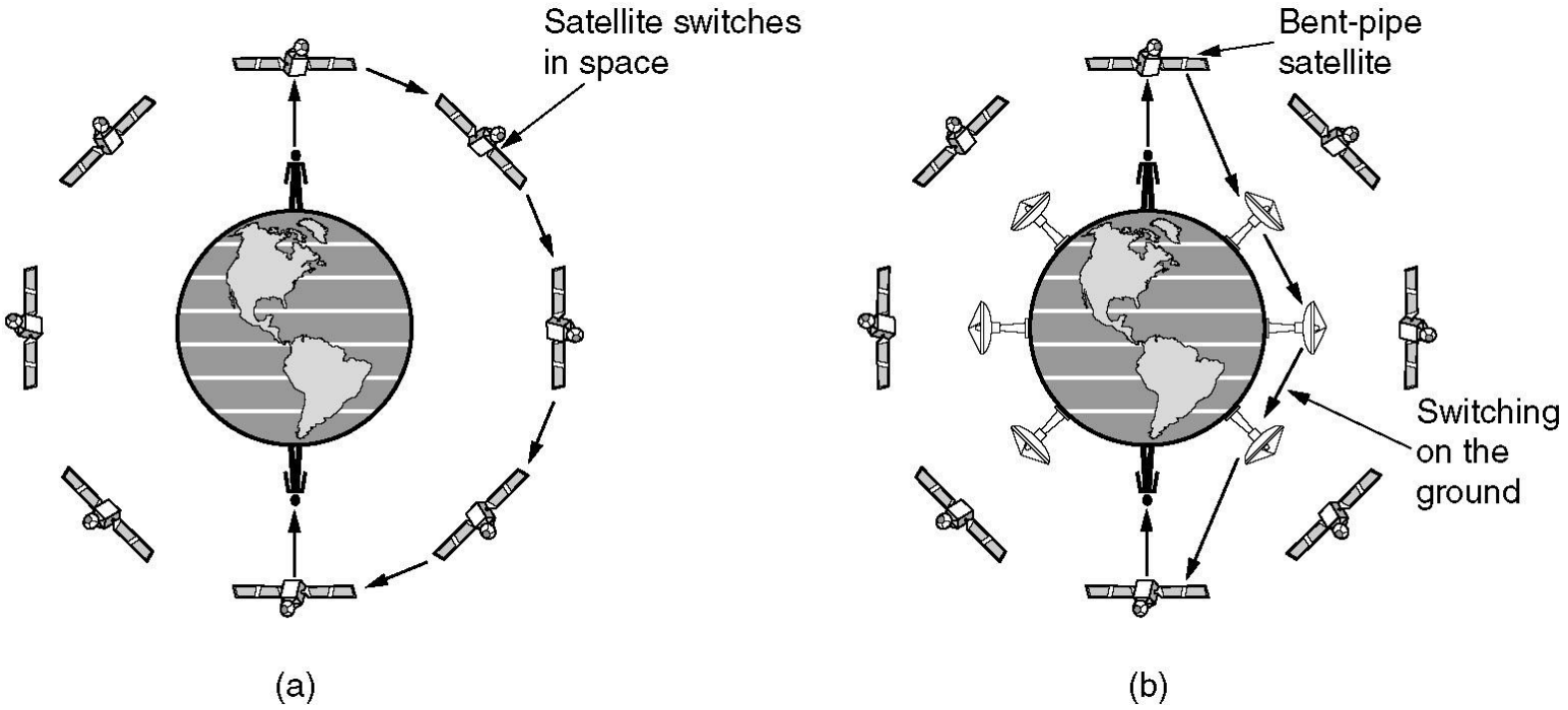
Low-Earth Orbit Satellites
Iridium



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

(b) 1628 moving cells cover the earth.

Globalstar



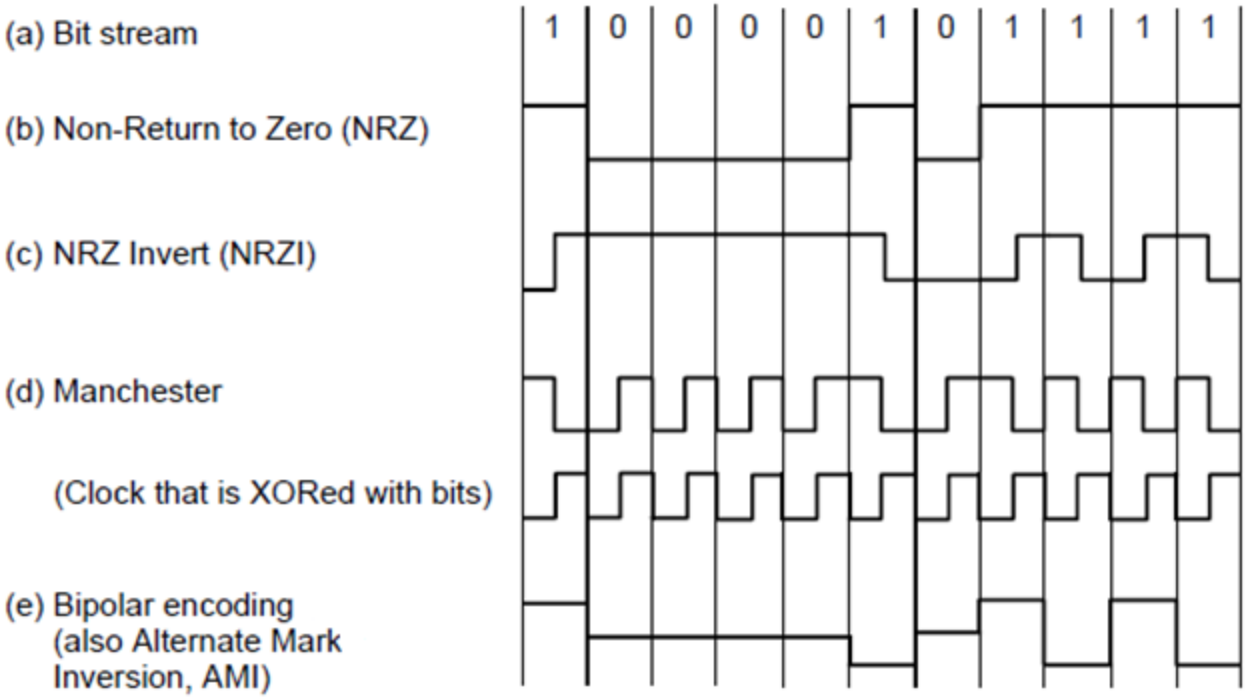
(a) Relaying in space.

(b) Relaying on the ground.

Digital Modulation and Multiplexing

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

Baseband Transmission



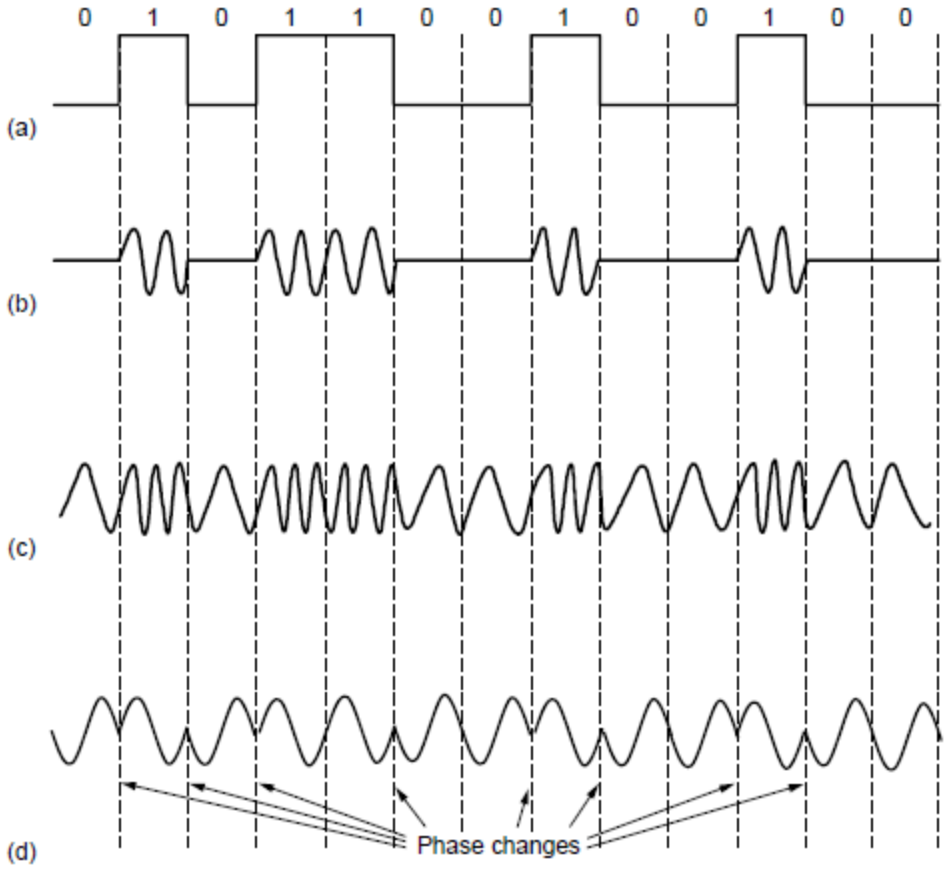
Line codes: (a) Bits, (b) NRZ, (c) NRZI, (d) Manchester, (e) Bipolar or AMI.

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

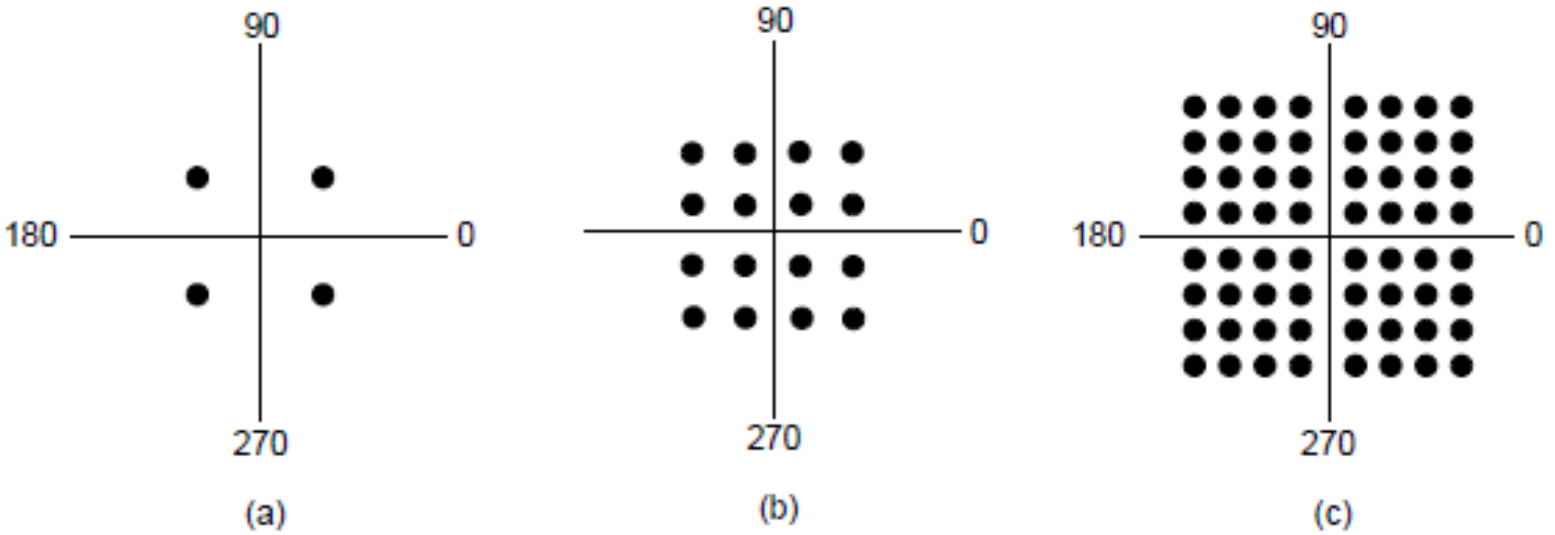
4B/5B mapping.

Passband Transmission (1)



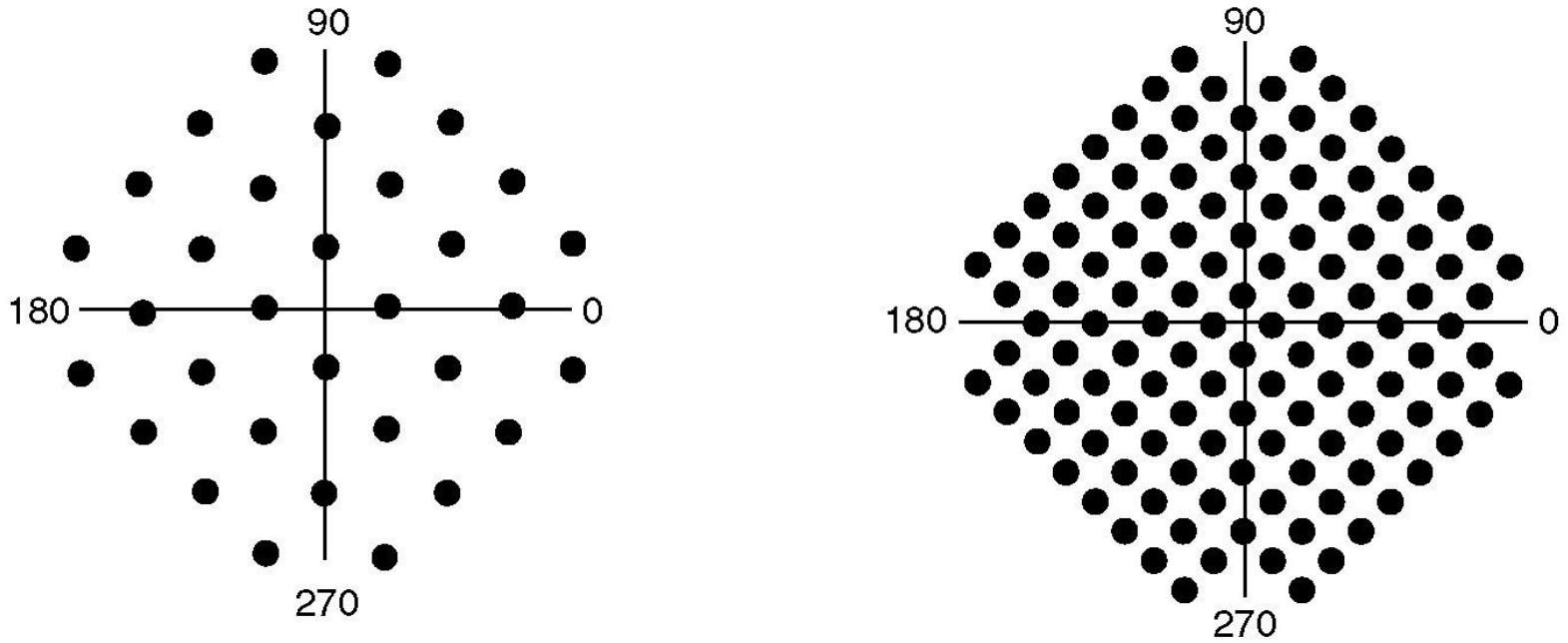
(a) A binary signal. (b) Amplitude shift keying. (c) Frequency shift keying. (d) Phase shift keying.

Passband Transmission (2)



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

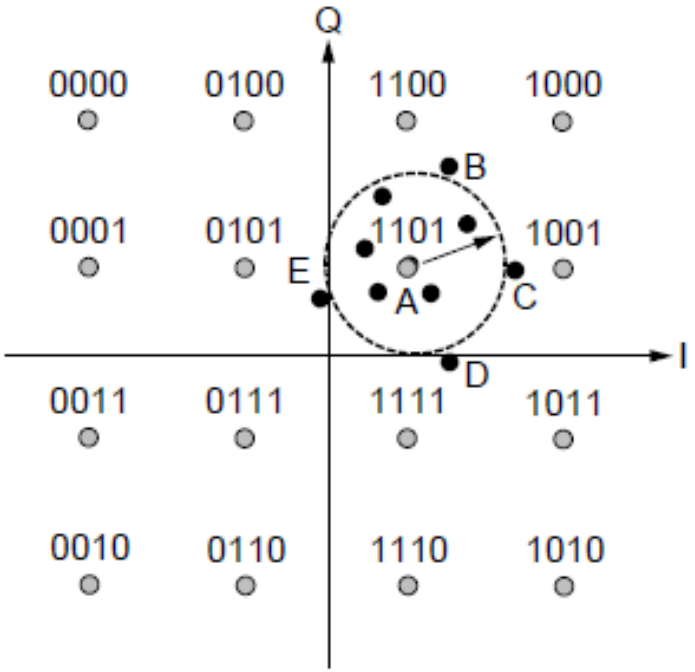
Modems (3)



(a) V.32 for 9600 bps.

(b) V32 bis for 14,400 bps.

Frequency Division Multiplexing (1)

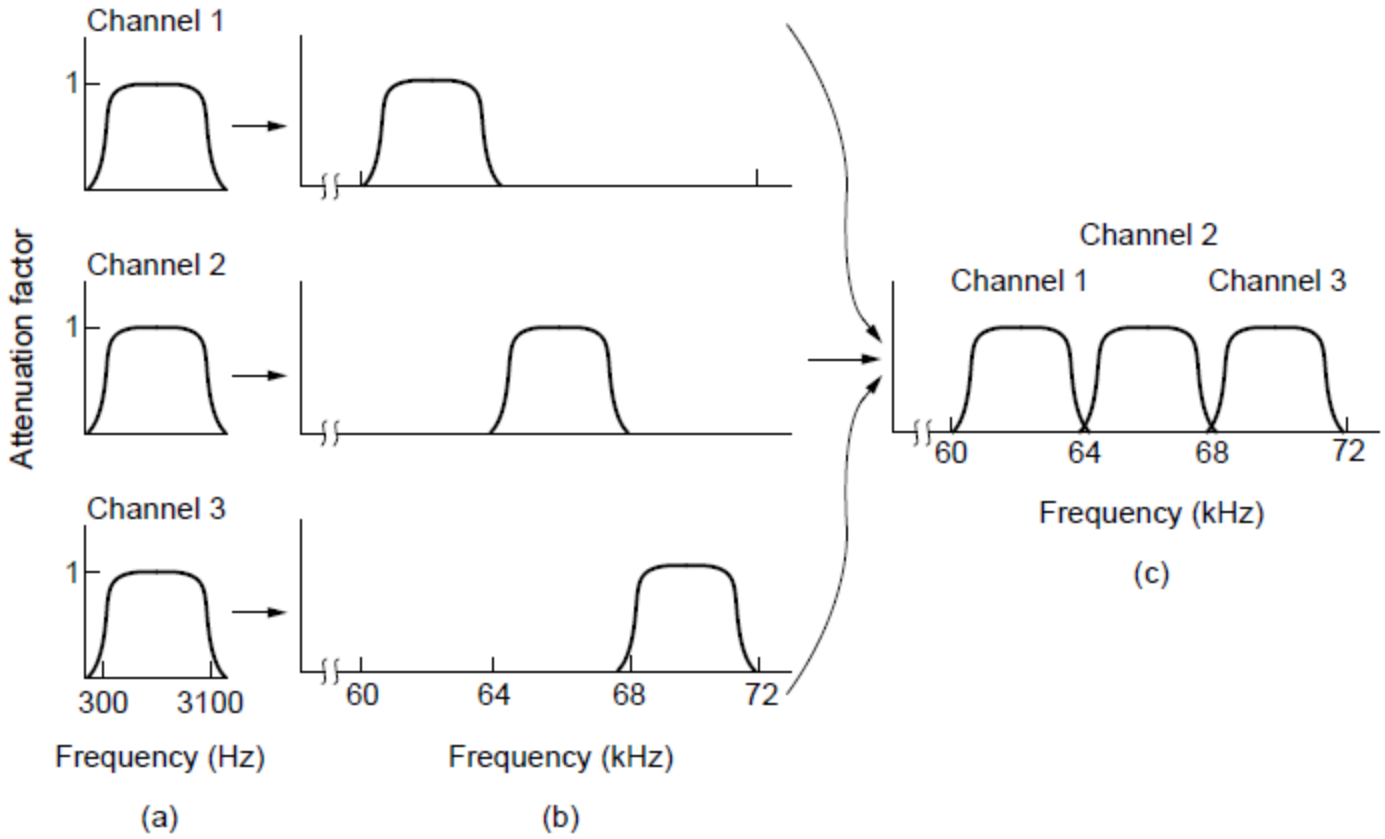


When 1101 is sent:

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

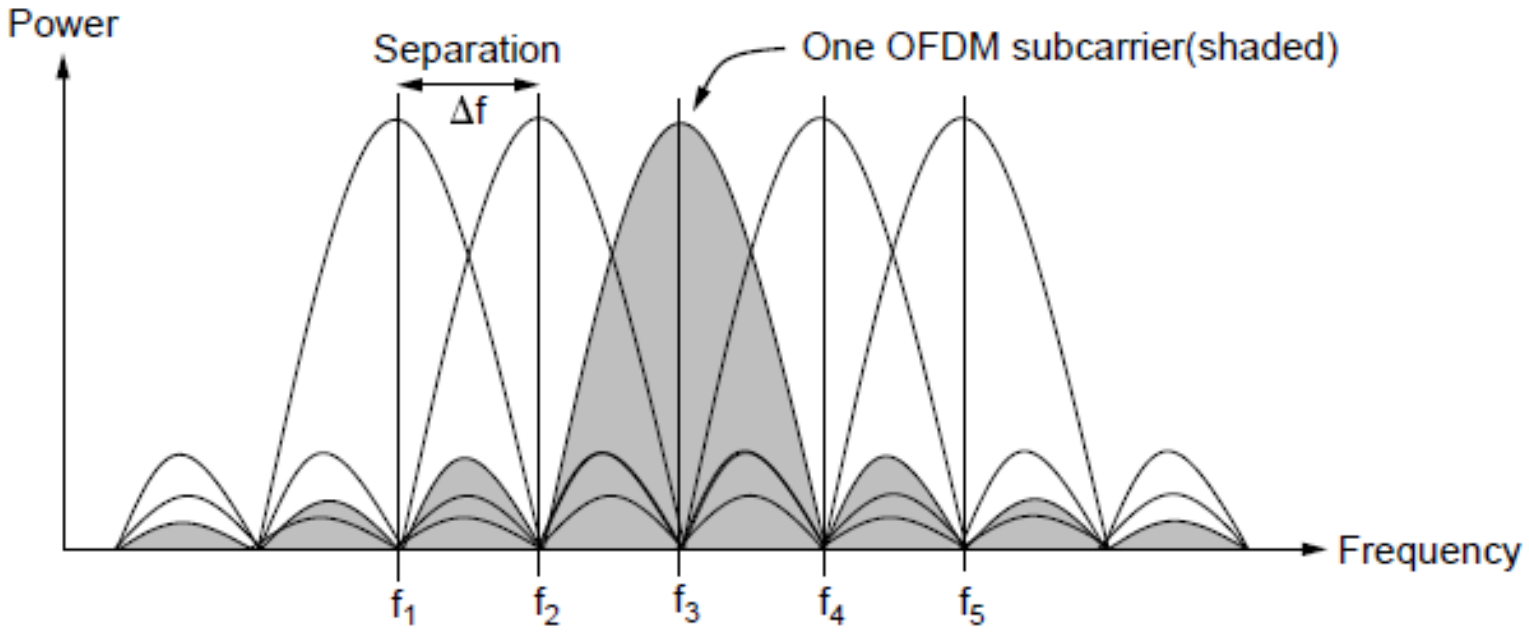
Gray-coded QAM-16.

Frequency Division Multiplexing (2)



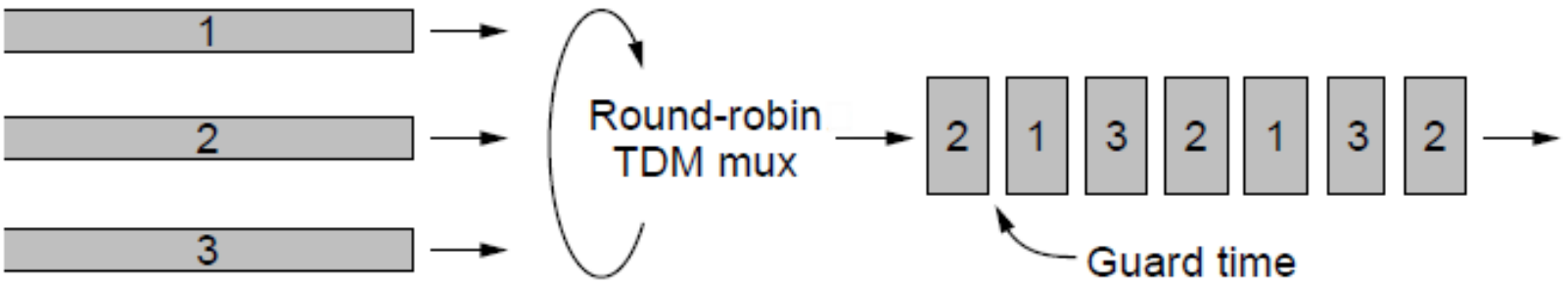
Frequency division multiplexing. (a) The original bandwidths. (b) The bandwidths raised in frequency. (c) The multiplexed channel.

Frequency Division Multiplexing (3)



Orthogonal frequency division multiplexing (OFDM).

Time Division Multiplexing



Time Division Multiplexing (TDM).

Code Division Multiplexing (1)

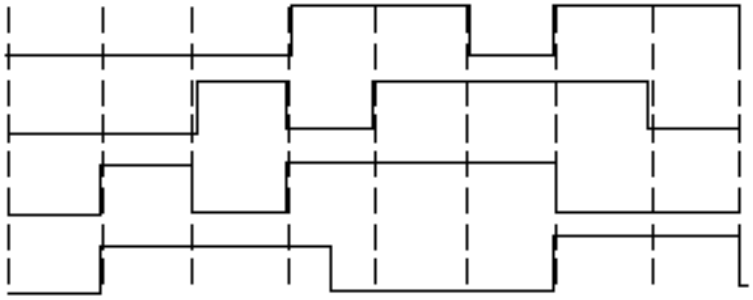
A = (–1 –1 –1 +1 +1 –1 +1 +1)

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)

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

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

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

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

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

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

(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)

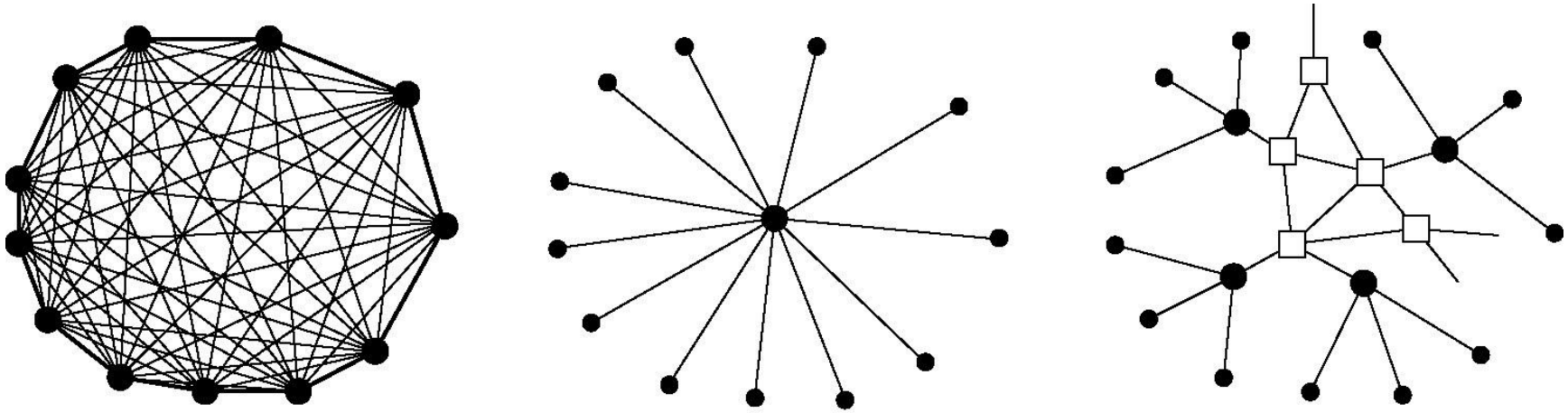
(a) Six examples of transmissions.

(b) Recovery of station C's

Public Switched Telephone System

- Structure of the Telephone System
- The Politics of Telephones
- The Local Loop: Modems, ADSL and Wireless
- Trunks and Multiplexing
- Switching

Structure of the Telephone System



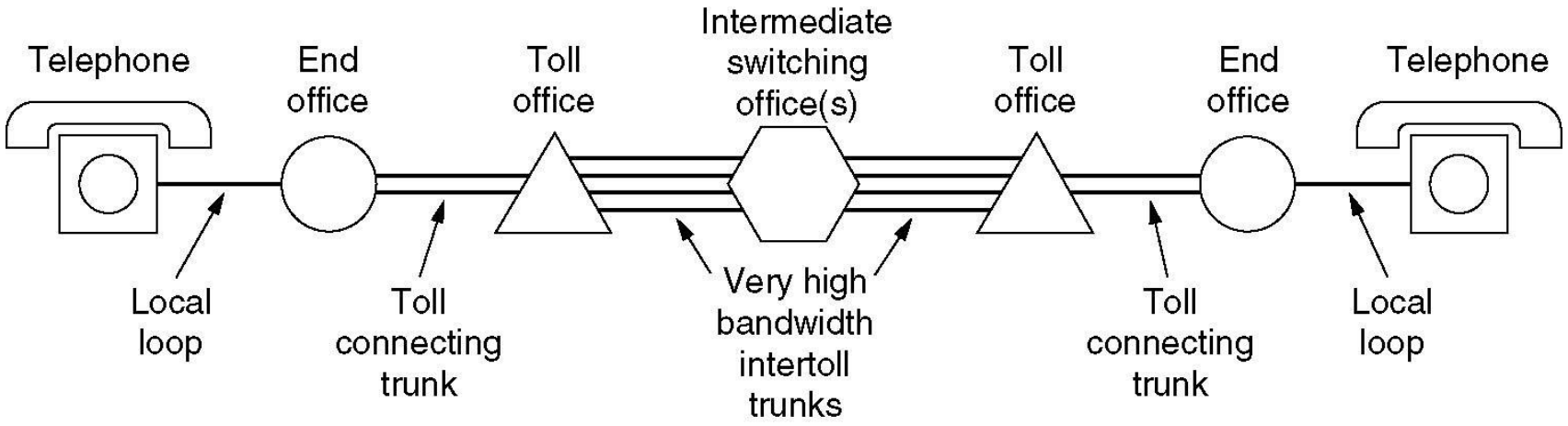
(a) Fully-interconnected network.

(b) Centralized switch.

(c) Two-level hierarchy.

Structure of the Telephone System (2)

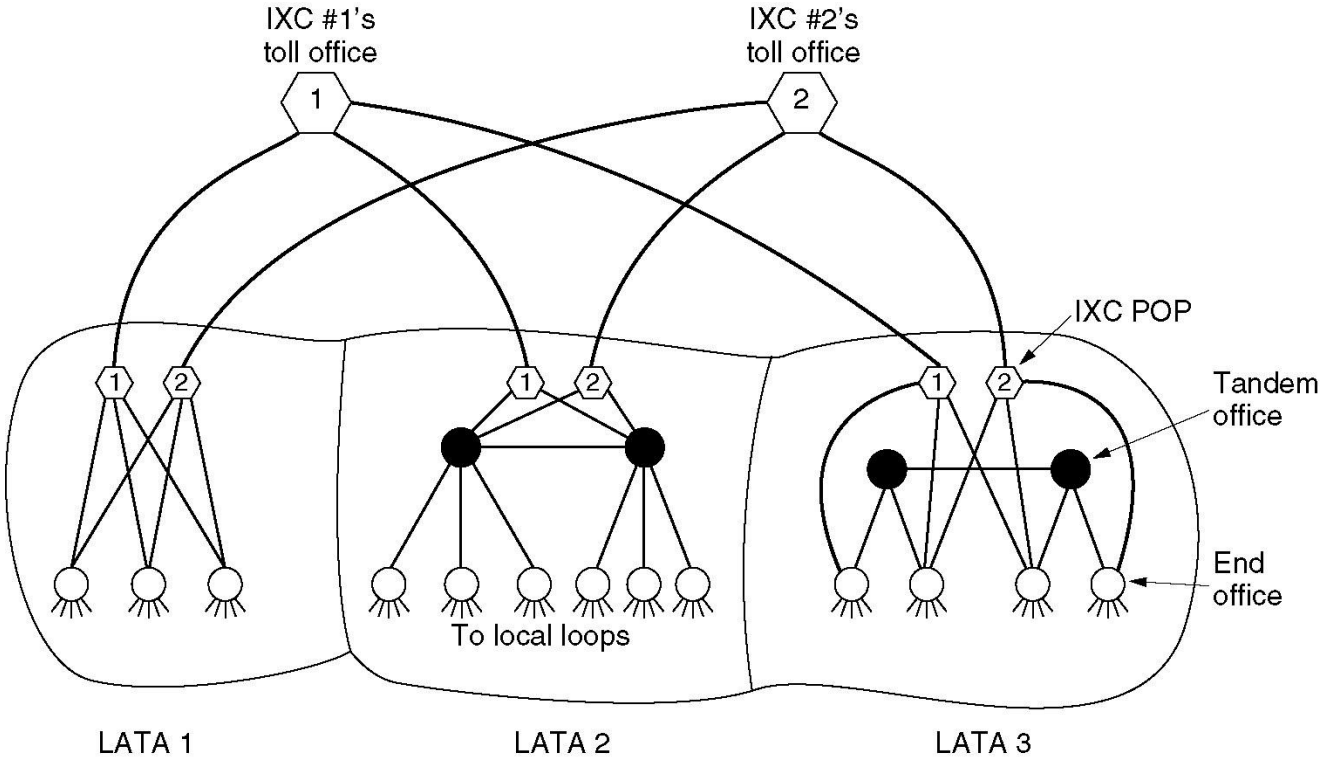
A typical circuit route for a medium-distance call.



Major Components of the Telephone System

- Local loops
  - Analog twisted pairs going to houses and businesses
- Trunks
  - Digital fiber optics connecting the switching offices
- Switching offices
  - Where calls are moved from one trunk to another

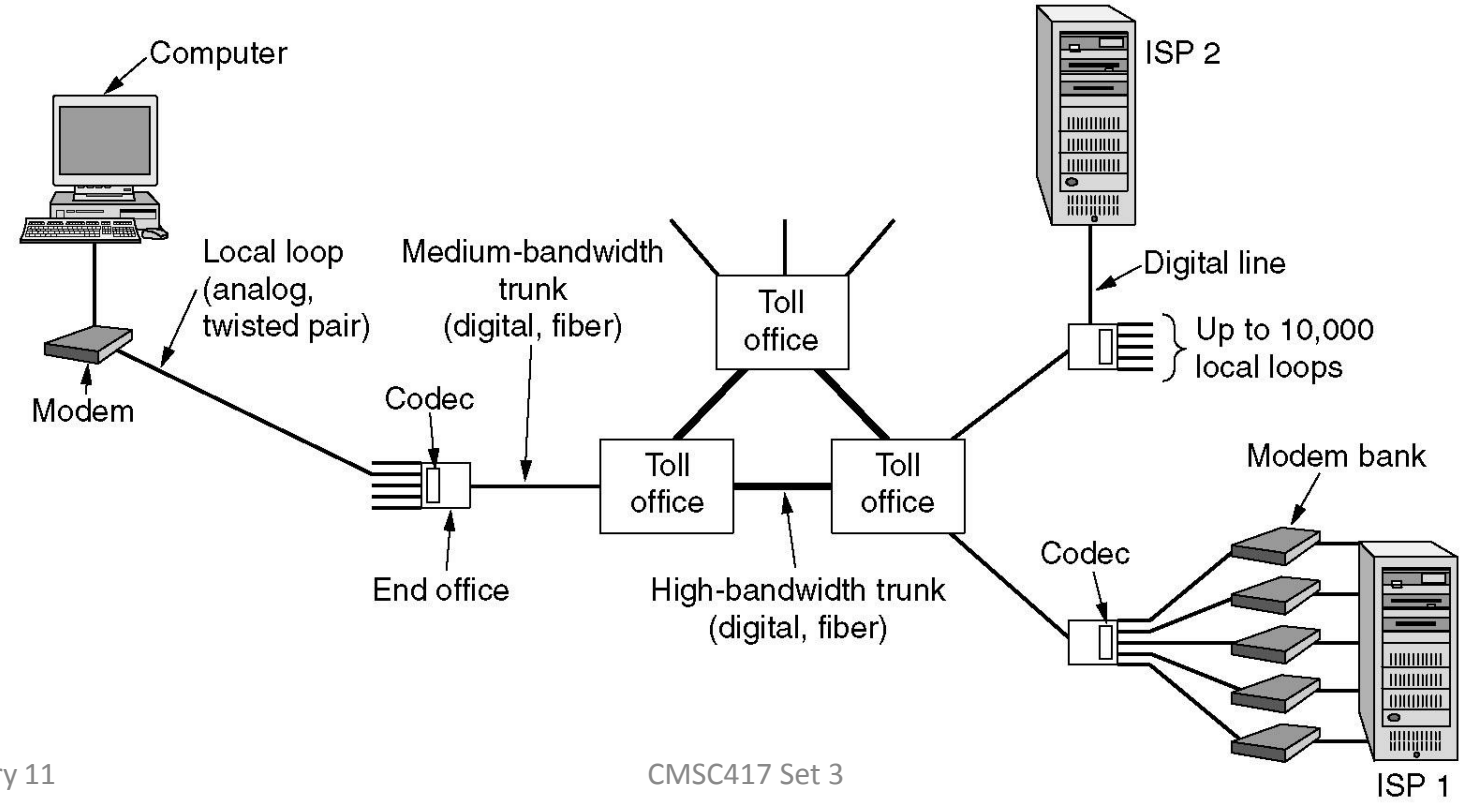
The Politics of Telephones



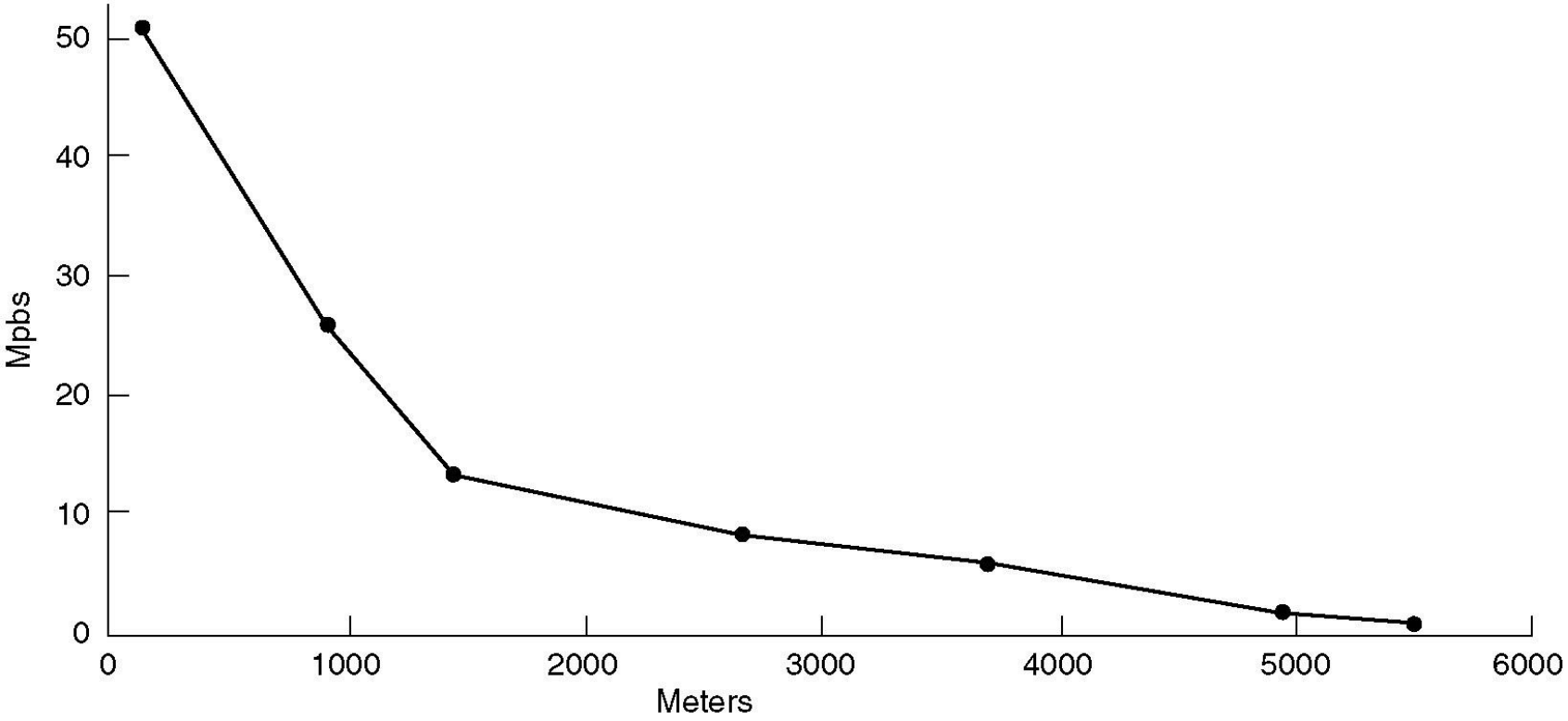
The relationship of LATAs, LECs, and IXCs. All the circles are LEC switching offices. Each hexagon belongs to the IXC whose number is on it.

The Local Loop: Modems, ADSL, and Wireless

The use of both analog and digital transmissions for a computer to computer call. Conversion is done by the modems and codecs.

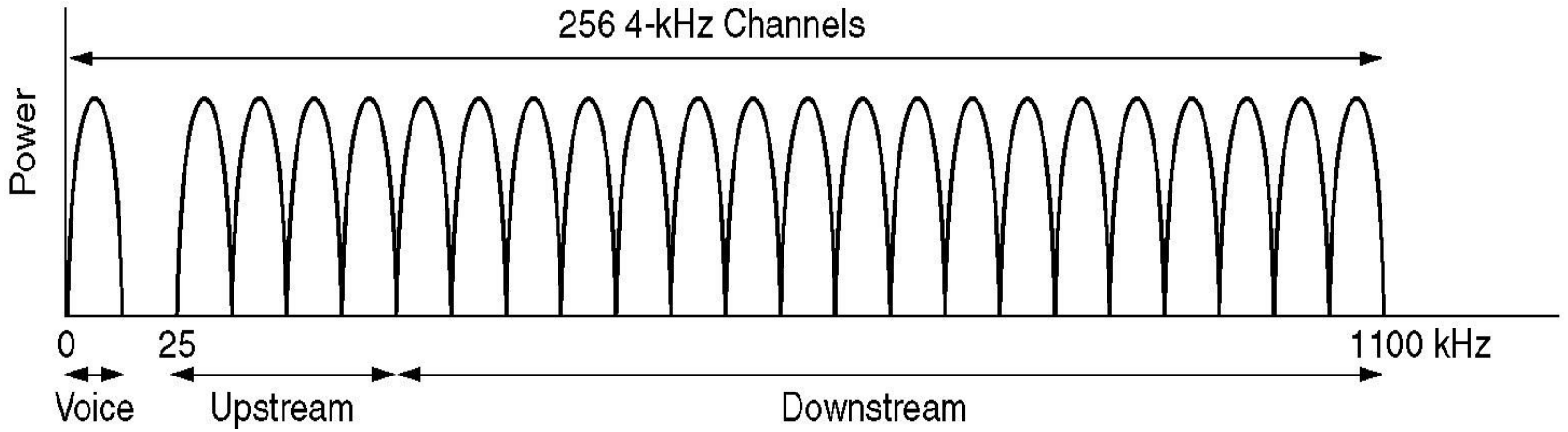


Digital Subscriber Lines

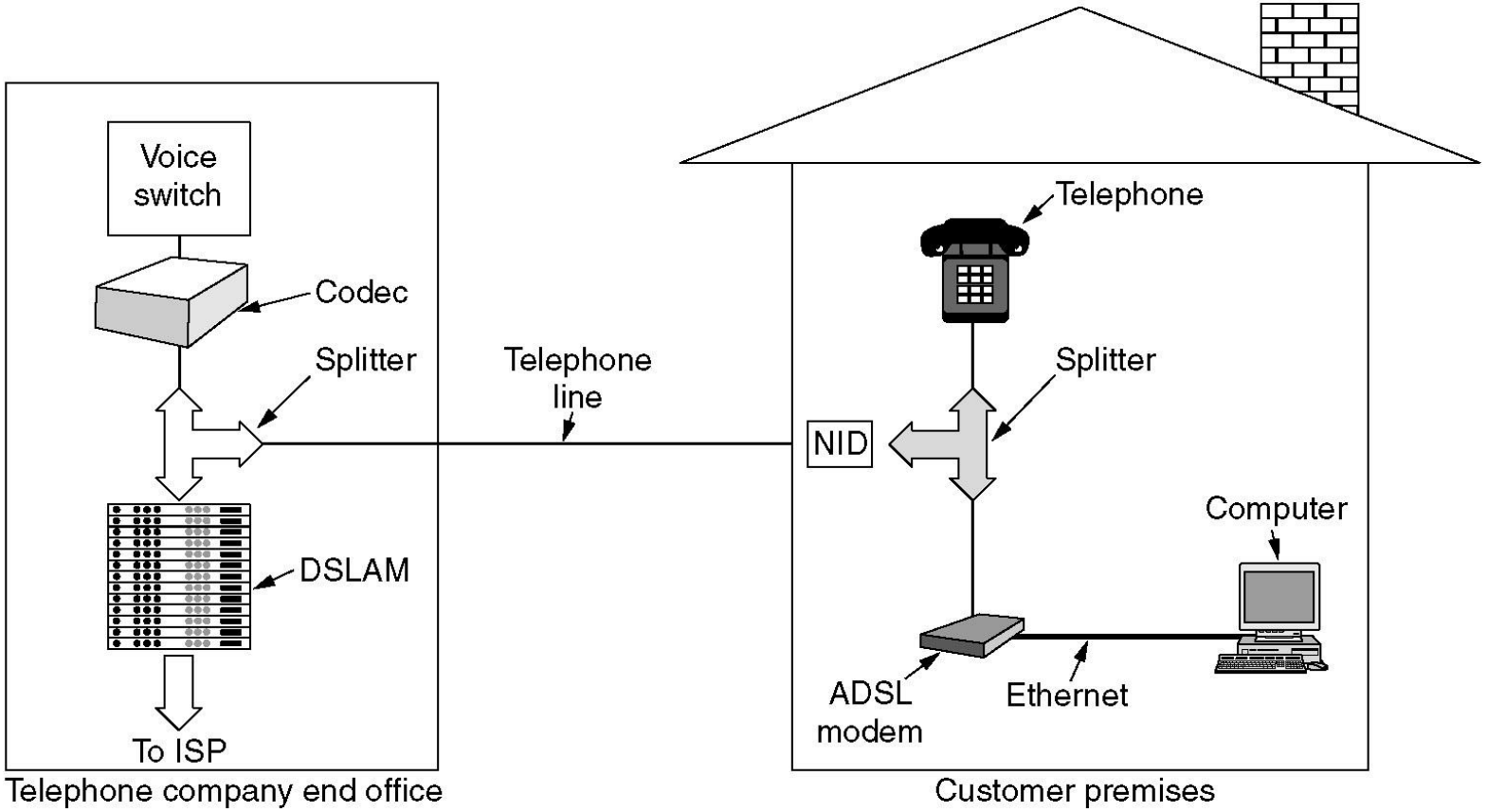


Digital Subscriber Lines (2)

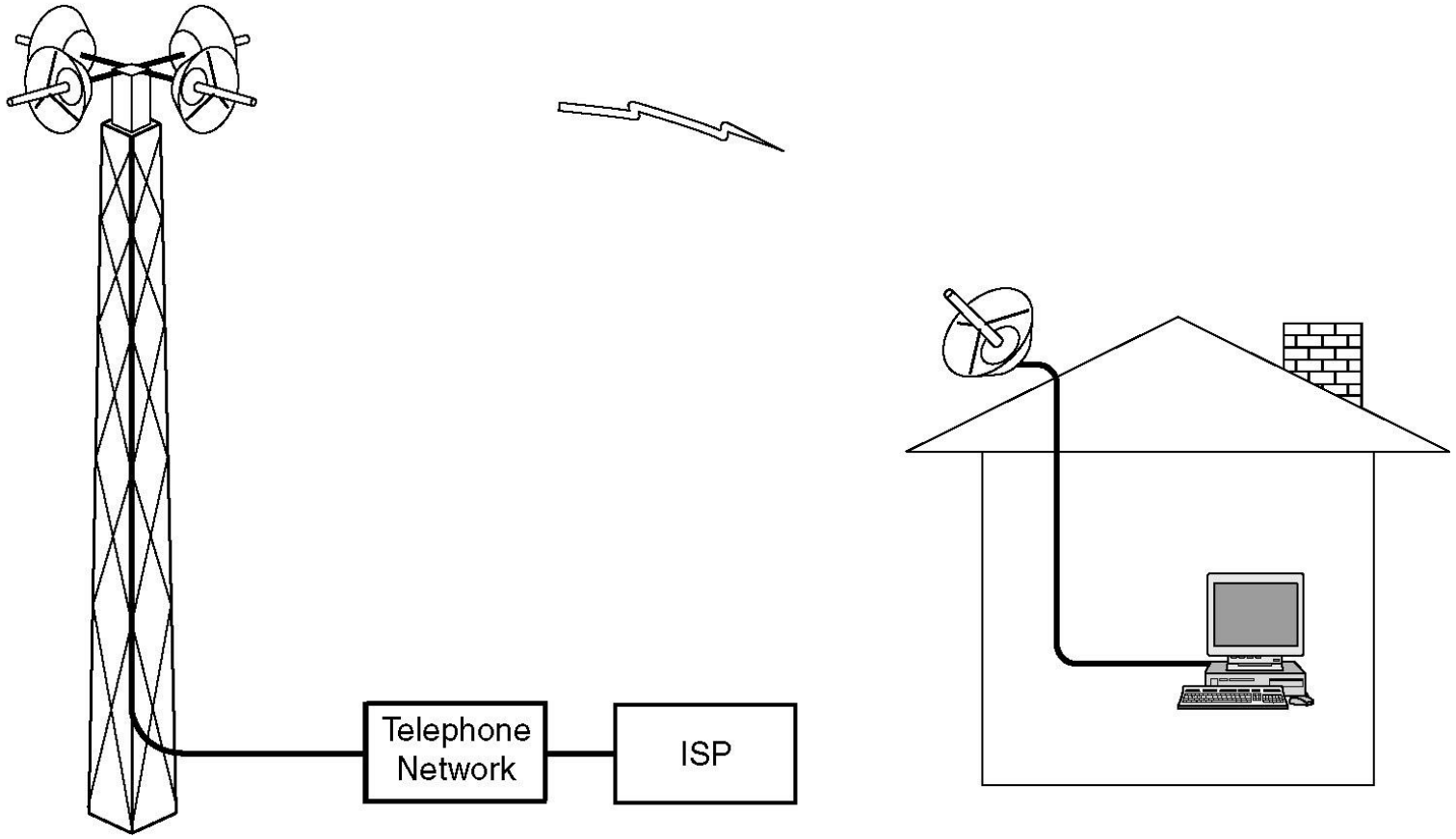
Operation of ADSL using discrete multitone



Digital Subscriber Lines (3)

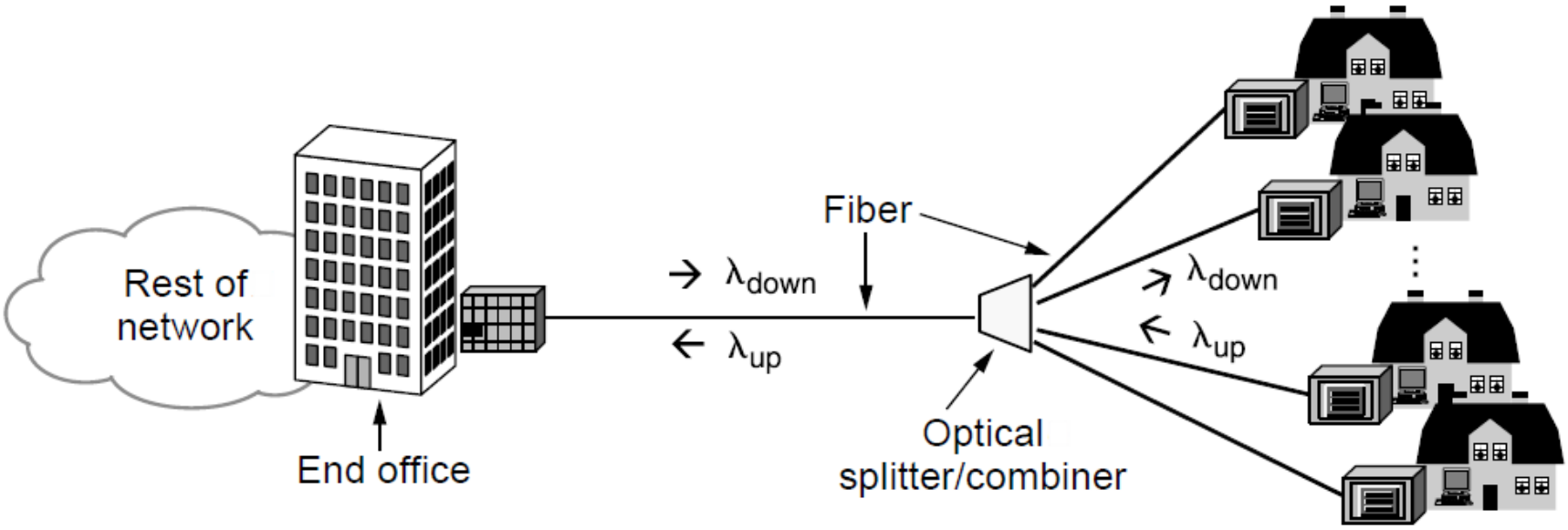


Wireless Local Loops



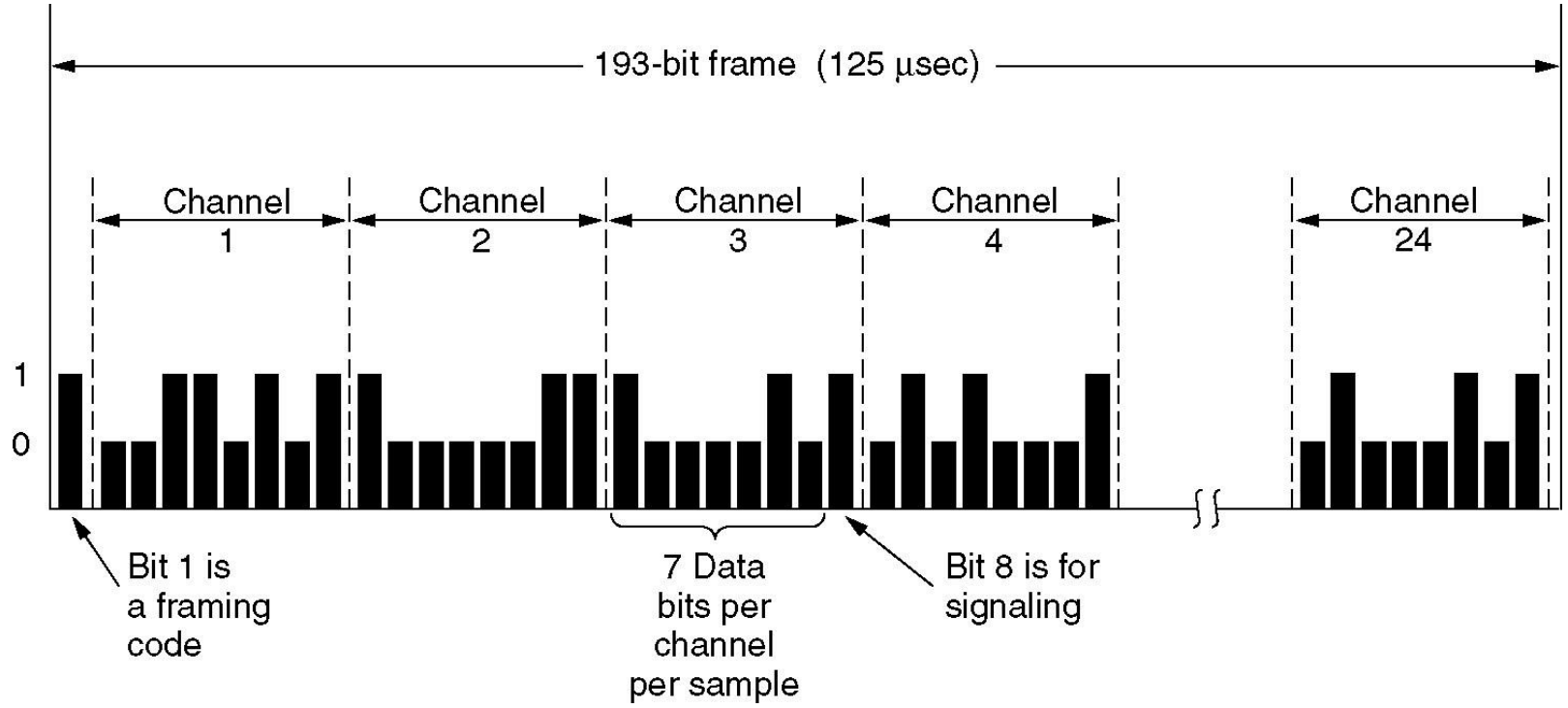
Architecture of an LMDS system.

Fiber To The Home



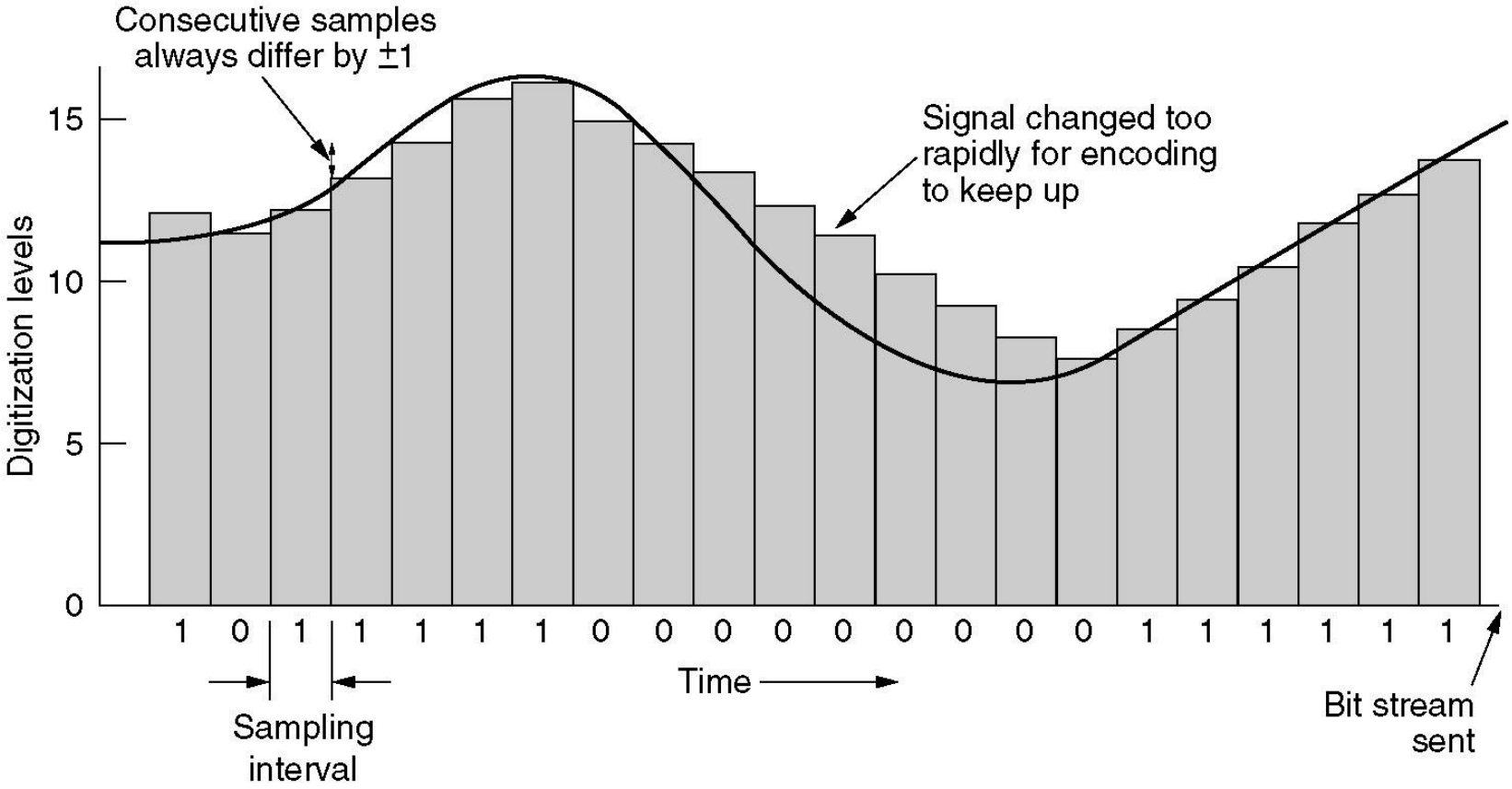
Passive optical network for Fiber To The Home.

Time Division Multiplexing



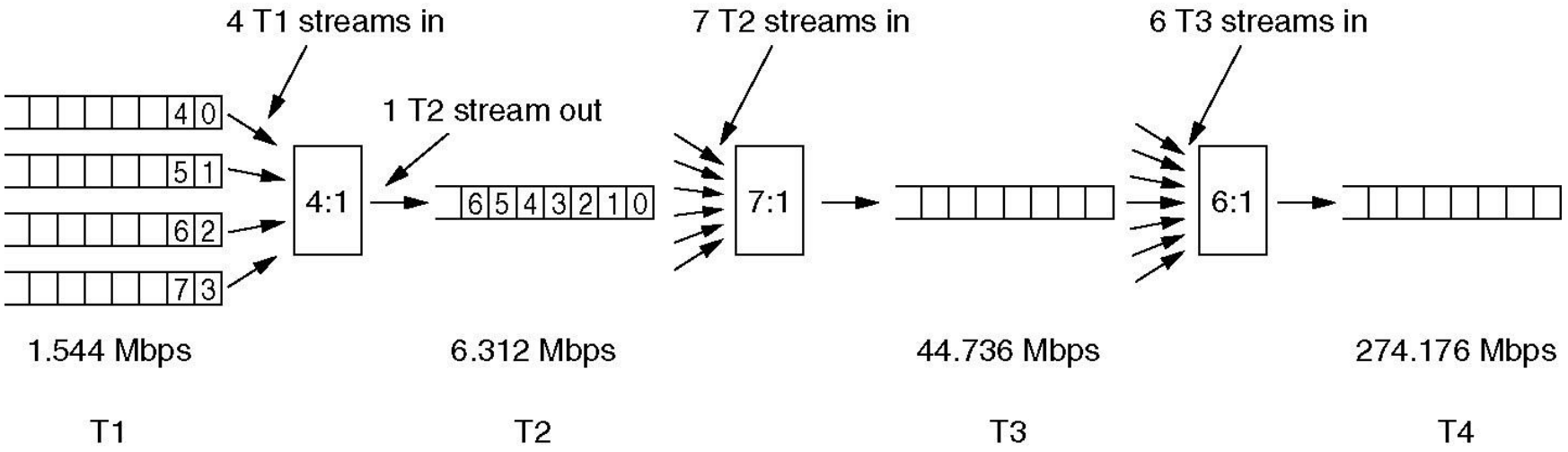
The T1 carrier (1.544 Mbps).

Time Division Multiplexing (2)

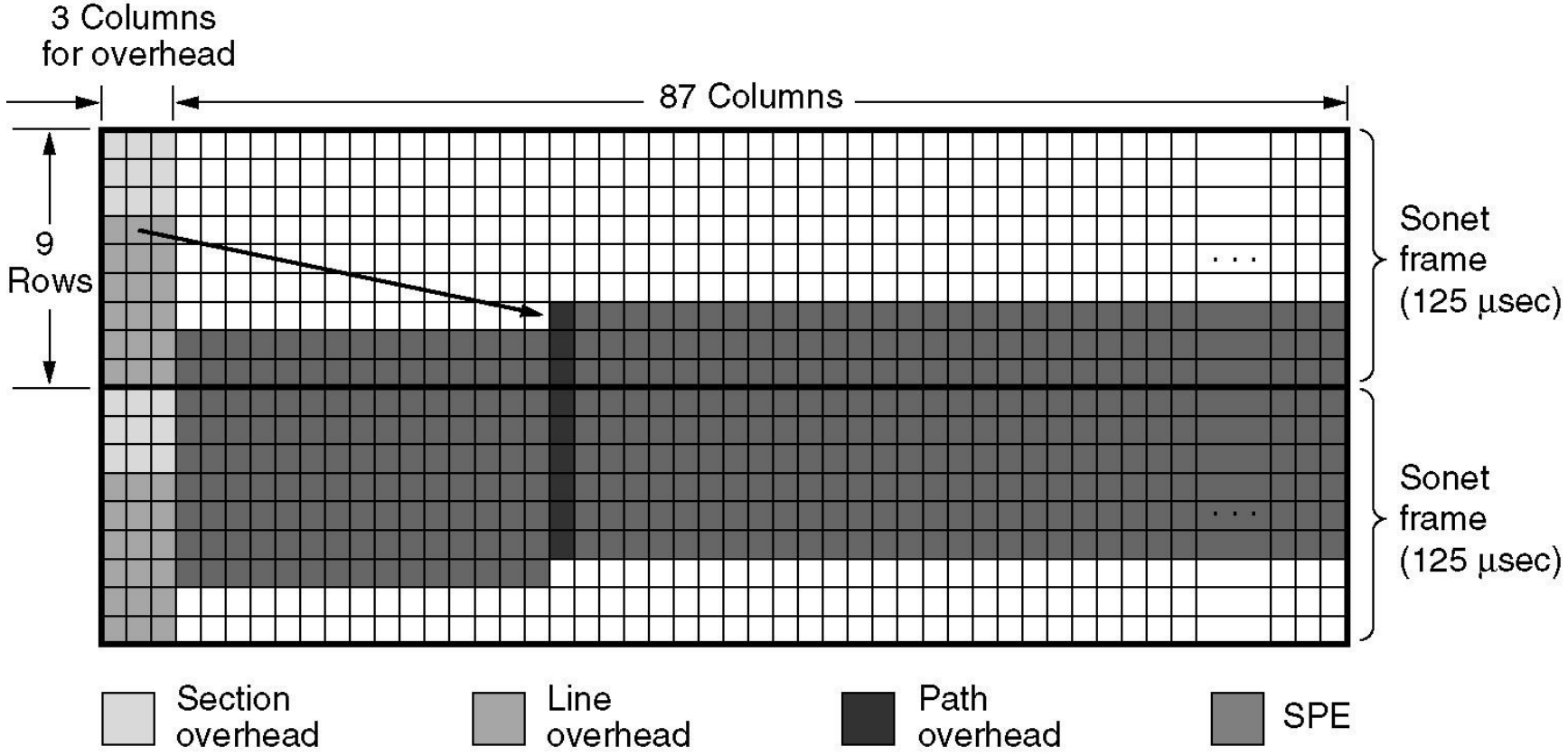


Time Division Multiplexing (3)

Multiplexing T1 streams into higher carriers.



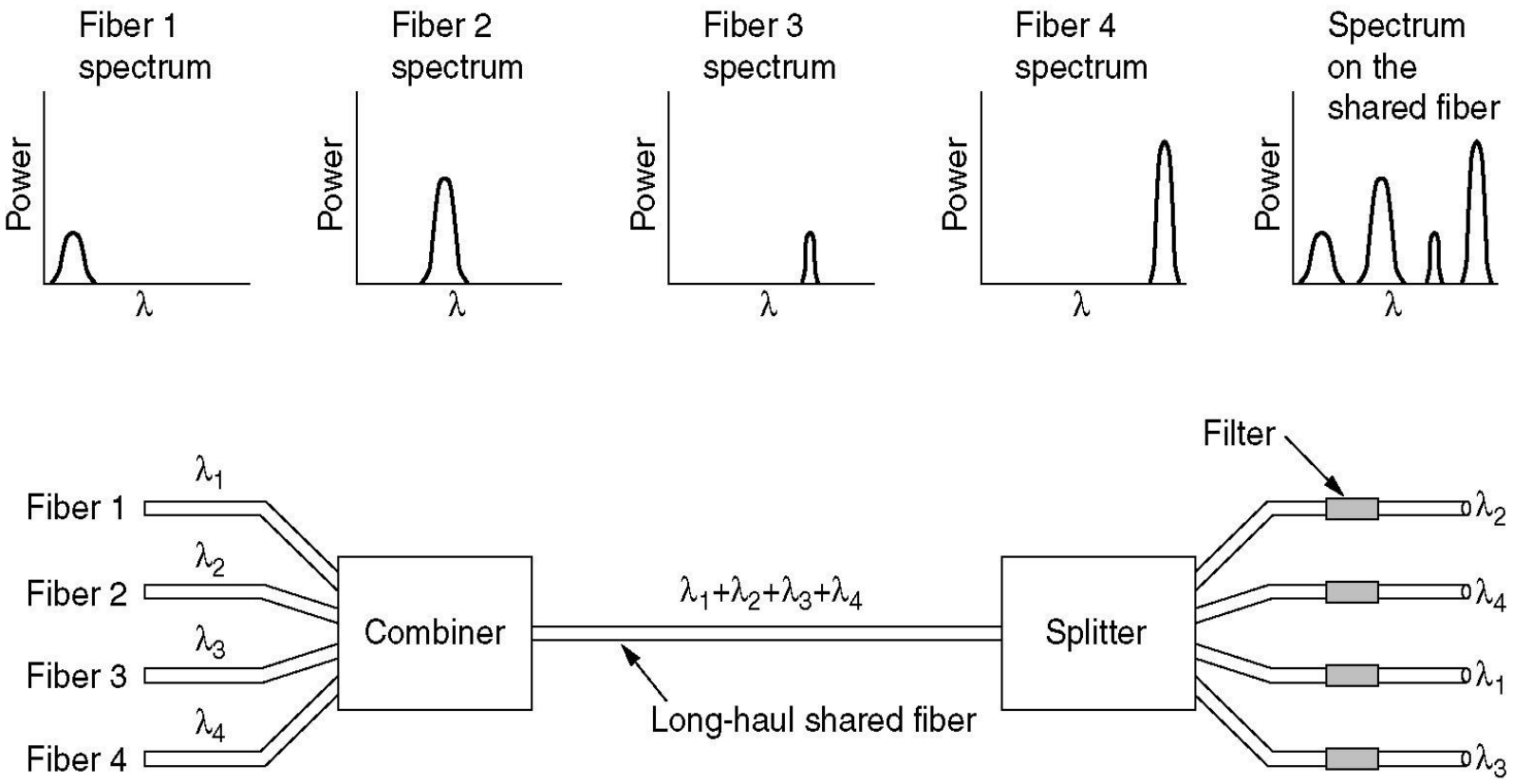
Time Division Multiplexing (4)



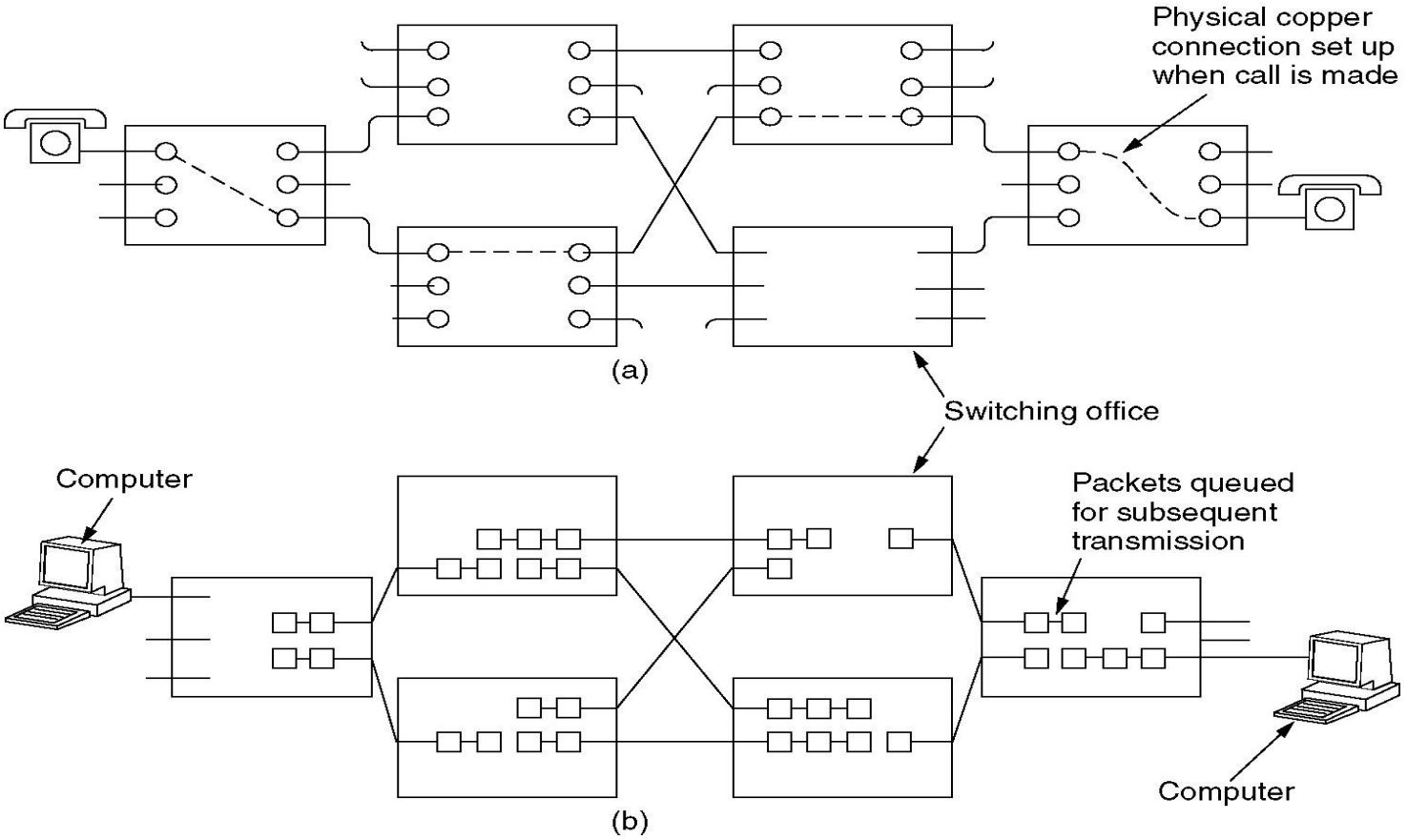
Time Division Multiplexing (5)

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-9	OC-9	STM-3	466.56	451.008	445.824
STS-12	OC-12	STM-4	622.08	601.344	594.432
STS-18	OC-18	STM-6	933.12	902.016	891.648
STS-24	OC-24	STM-8	1244.16	1202.688	1188.864
STS-36	OC-36	STM-12	1866.24	1804.032	1783.296
STS-48	OC-48	STM-16	2488.32	2405.376	2377.728
STS-192	OC-192	STM-64	9953.28	9621.504	9510.912

Wavelength Division Multiplexing



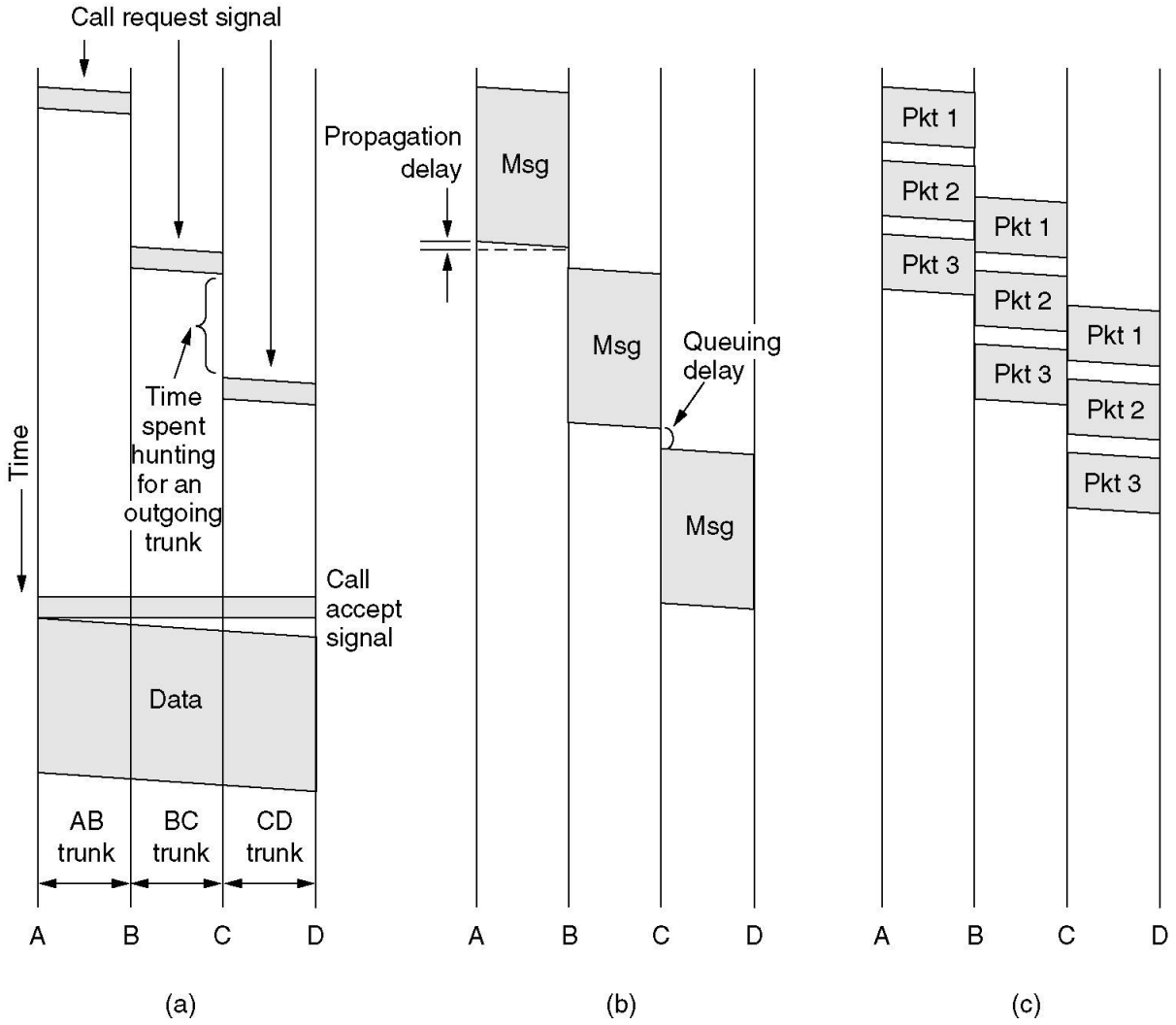
Circuit Switching



(a) Circuit switching.

(b) Packet switching.

Message Switching



(a) Circuit switching (b) Message switching (c) Packet switching

Packet Switching

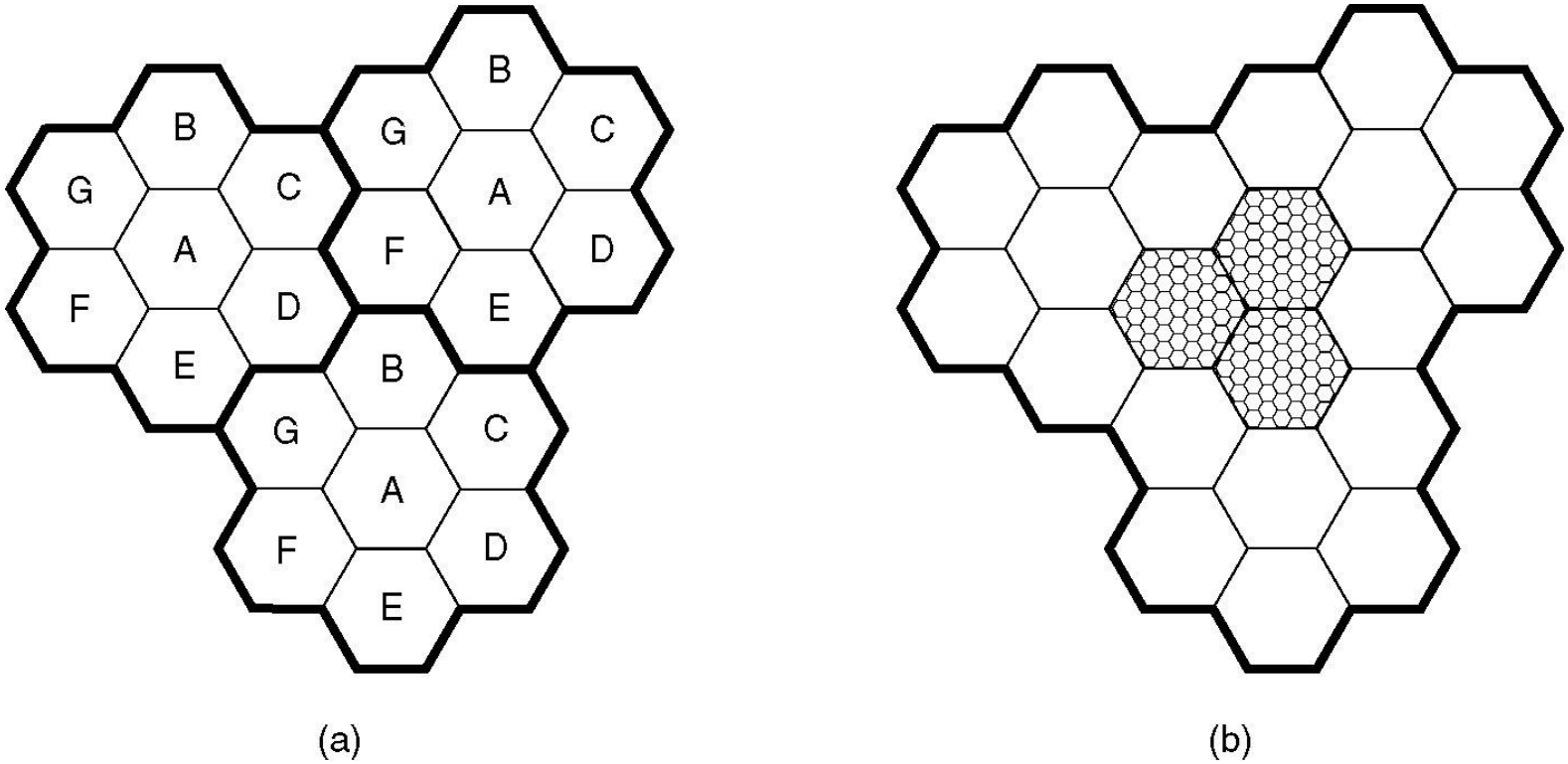
Item	Circuit-switched	Packet-switched
Call setup	Required	Not needed
Dedicated physical path	Yes	No
Each packet follows the same route	Yes	No
Packets arrive in order	Yes	No
Is a switch crash fatal	Yes	No
Bandwidth available	Fixed	Dynamic
When can congestion occur	At setup time	On every packet
Potentially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

A comparison of circuit switched and packet-switched networks.

The Mobile Telephone System

- First-Generation Mobile Phones: Analog Voice
- Second-Generation Mobile Phones: Digital Voice
- Third-Generation Mobile Phones: Digital Voice and Data

Advanced Mobile Phone System



(a) Frequencies are not reused in adjacent cells.

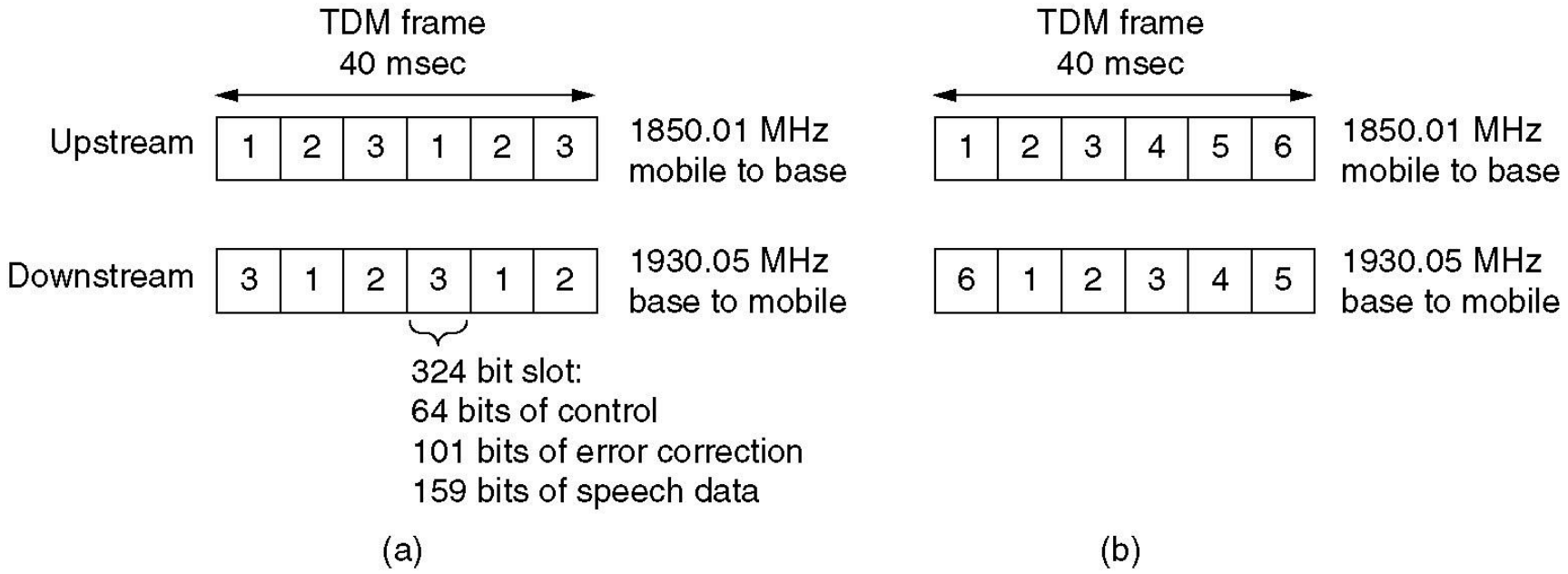
(b) To add more users, smaller cells can be used.

Channel Categories

The 832 channels are divided into four categories:

- Control (base to mobile) to manage the system
- 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

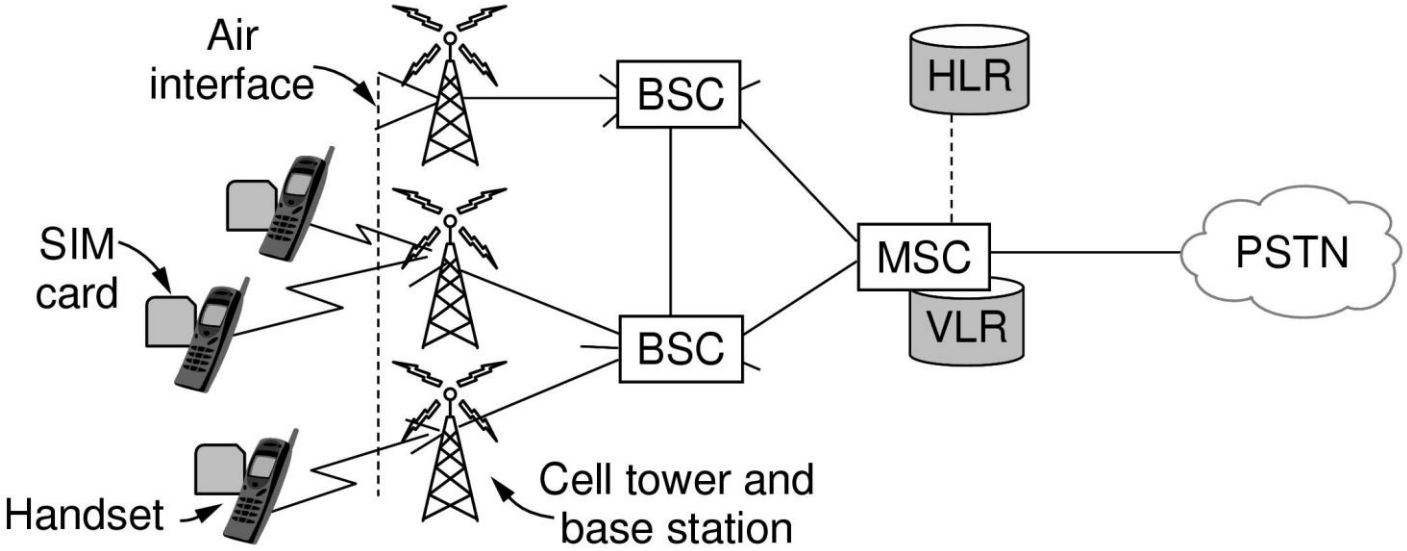
D-AMPS
Digital Advanced Mobile Phone System



(a) A D-AMPS channel with three users.

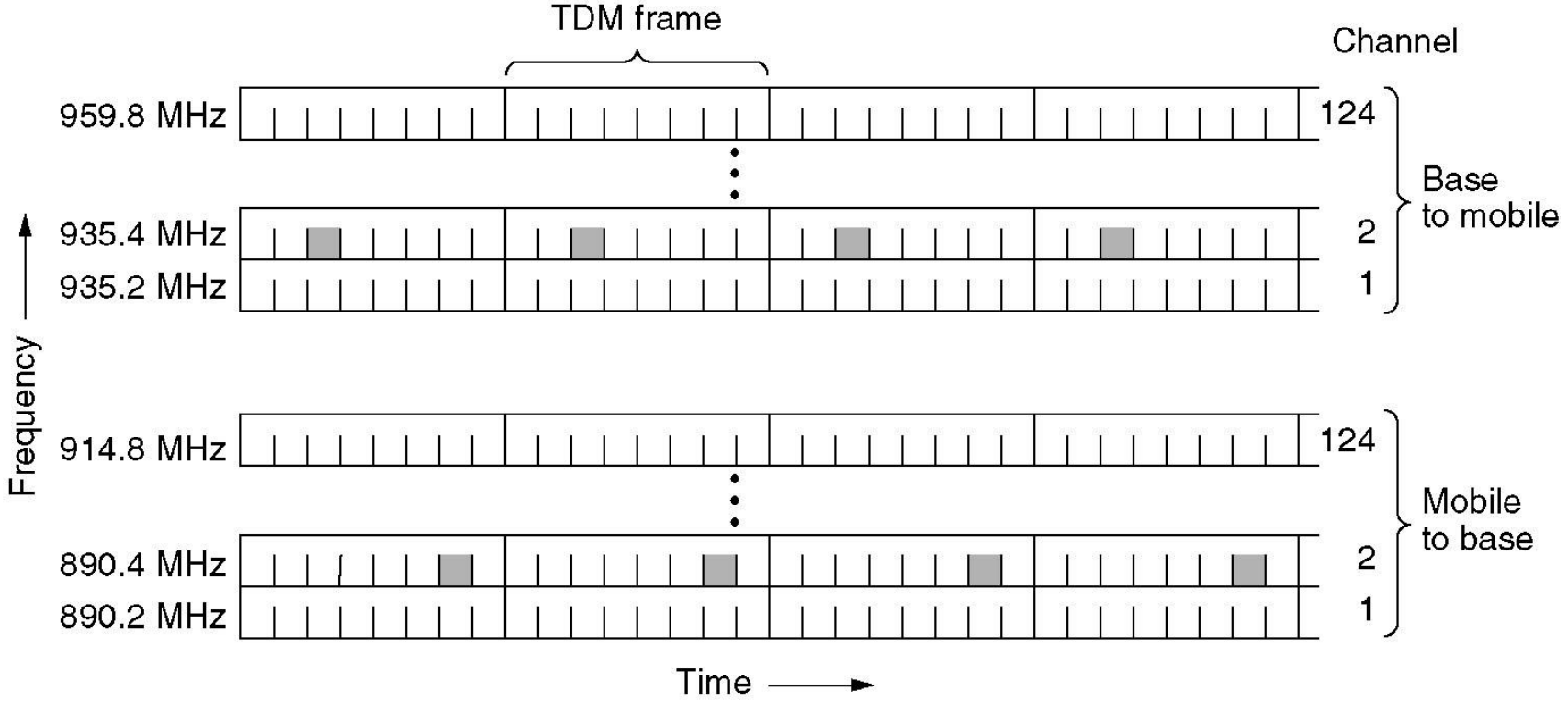
(b) A D-AMPS channel with six users.

GSM—The Global System for Mobile Communications (1)



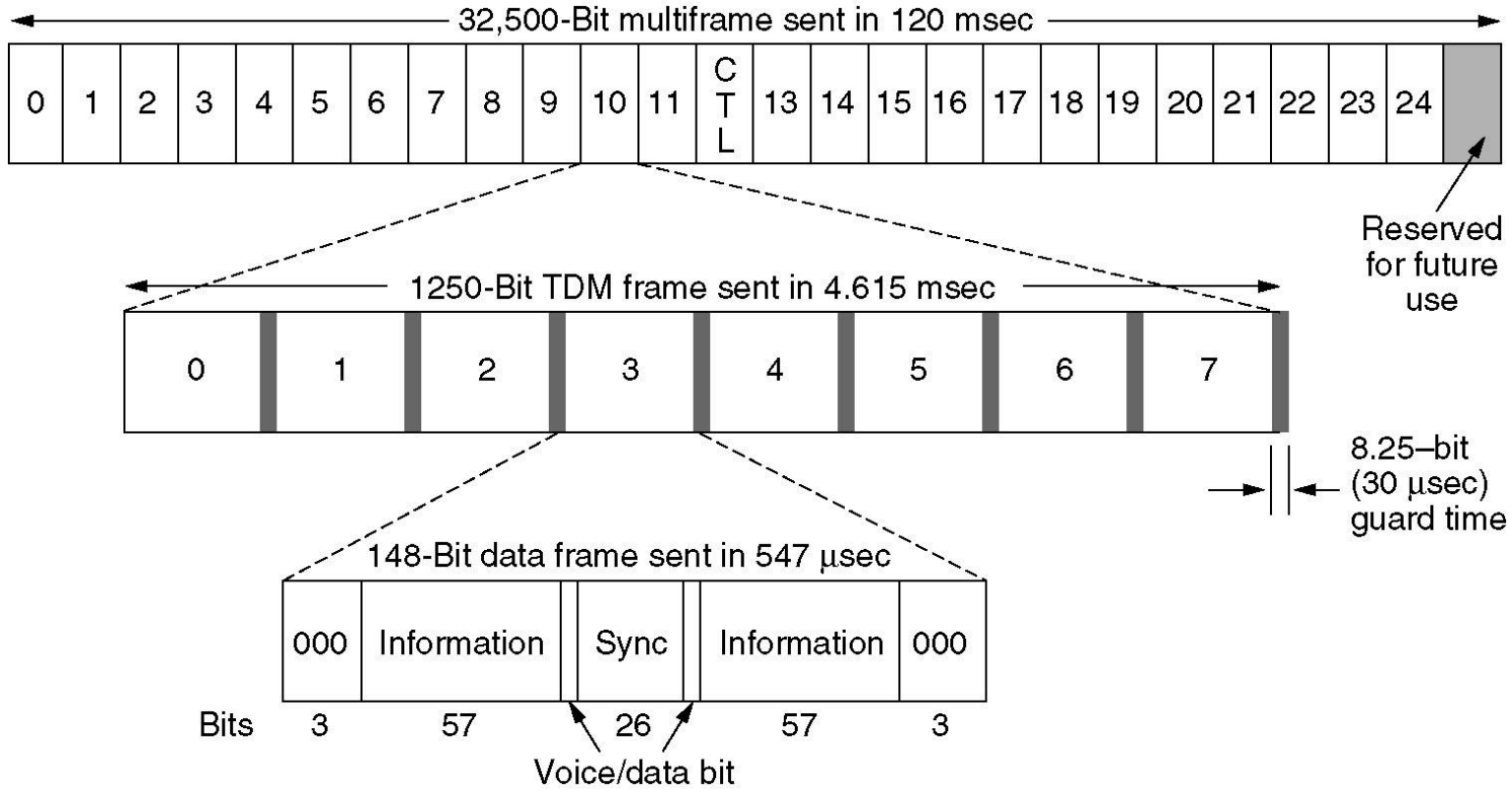
GSM mobile network architecture.

GSM
Global System for Mobile Communications



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

GSM (2)


32,500-Bit multiframe sent in 120 msec
0 1 2 3 4 5 6 7 8 9 10 11 CTL 13 14 15 16 17 18 19 20 21 22 23 24
Reserved for future use
1250-Bit TDM frame sent in 4.615 msec
0 1 2 3 4 5 6 7
8.25–bit (30 μsec) guard time
148-Bit data frame sent in 547 μsec
000 Information Sync Information 000
Bits 3 57 26 57 3
Voice/data bit

CDMA – Code Division Multiple Access

A: 0 0 0 1 1 0 1 1
B: 0 0 1 0 1 1 1 0
C: 0 1 0 1 1 1 0 0
D: 0 1 0 0 0 0 1 0

(a)

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)

(b)

Six examples:

– – 1 –	**C**	$S_1 = (-1 +1 -1 +1 +1 +1 -1 -1)$
– 1 1 –	**B** + $\overline{\mathbf{C}}$	$S_2 = (-2 \ 0 \ 0 \ 0 +2 +2 \ 0 -2)$
1 0 – –	**A** + $\overline{\mathbf{B}}$	$S_3 = (\ 0 \ 0 -2 +2 \ 0 -2 \ 0 +2)$
1 0 1 –	**A** + **B** + **C**	$S_4 = (-1 +1 -3 +3 +1 -1 -1 +1)$
1 1 1 1	**A** + **B** + **C** + **D**	$S_5 = (-4 \ 0 -2 \ 0 +2 \ 0 +2 -2)$
1 1 0 1	**A** + **B** + $\overline{\mathbf{C}}$ + **D**	$S_6 = (-2 -2 \ 0 -2 \ 0 -2 +4 \ 0)$

(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)

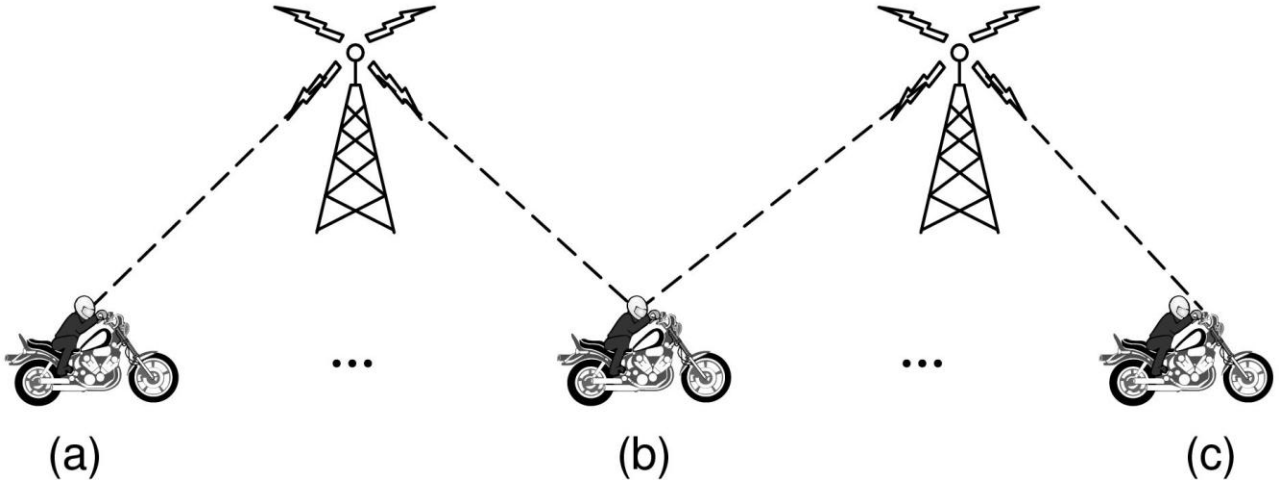
(a) Binary chip sequences for four stations
(b) Bipolar chip sequences
(c) Six examples of transmissions
(d) Recovery of station C's signal

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.)

Digital Voice and Data (2)



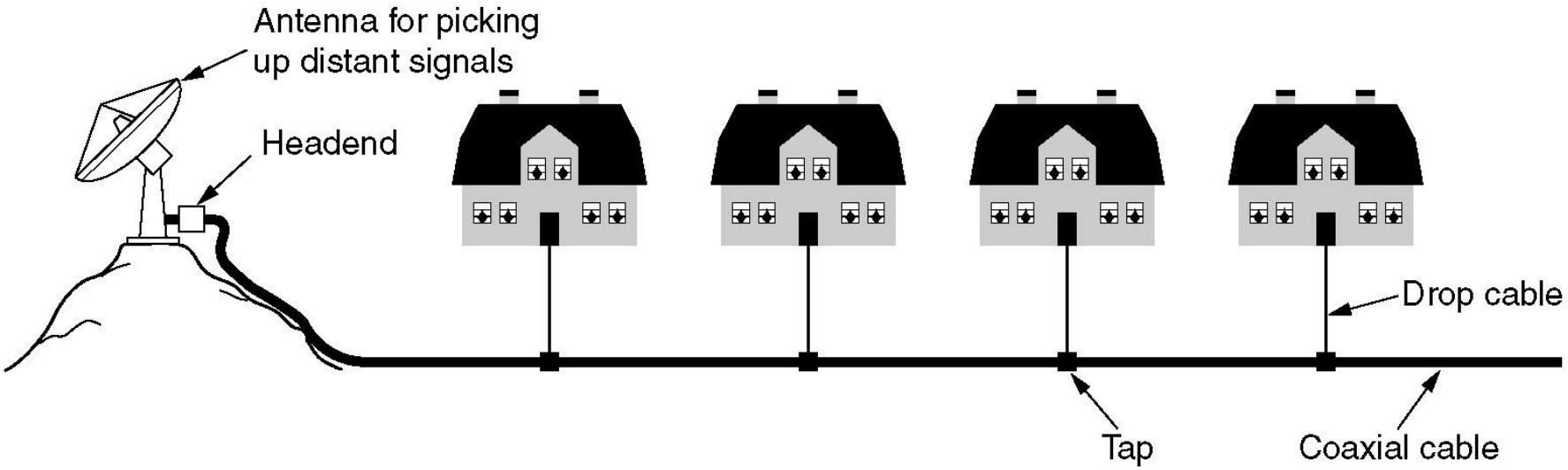
Soft handoff (a) before, (b) during, and (c) after.

Cable Television

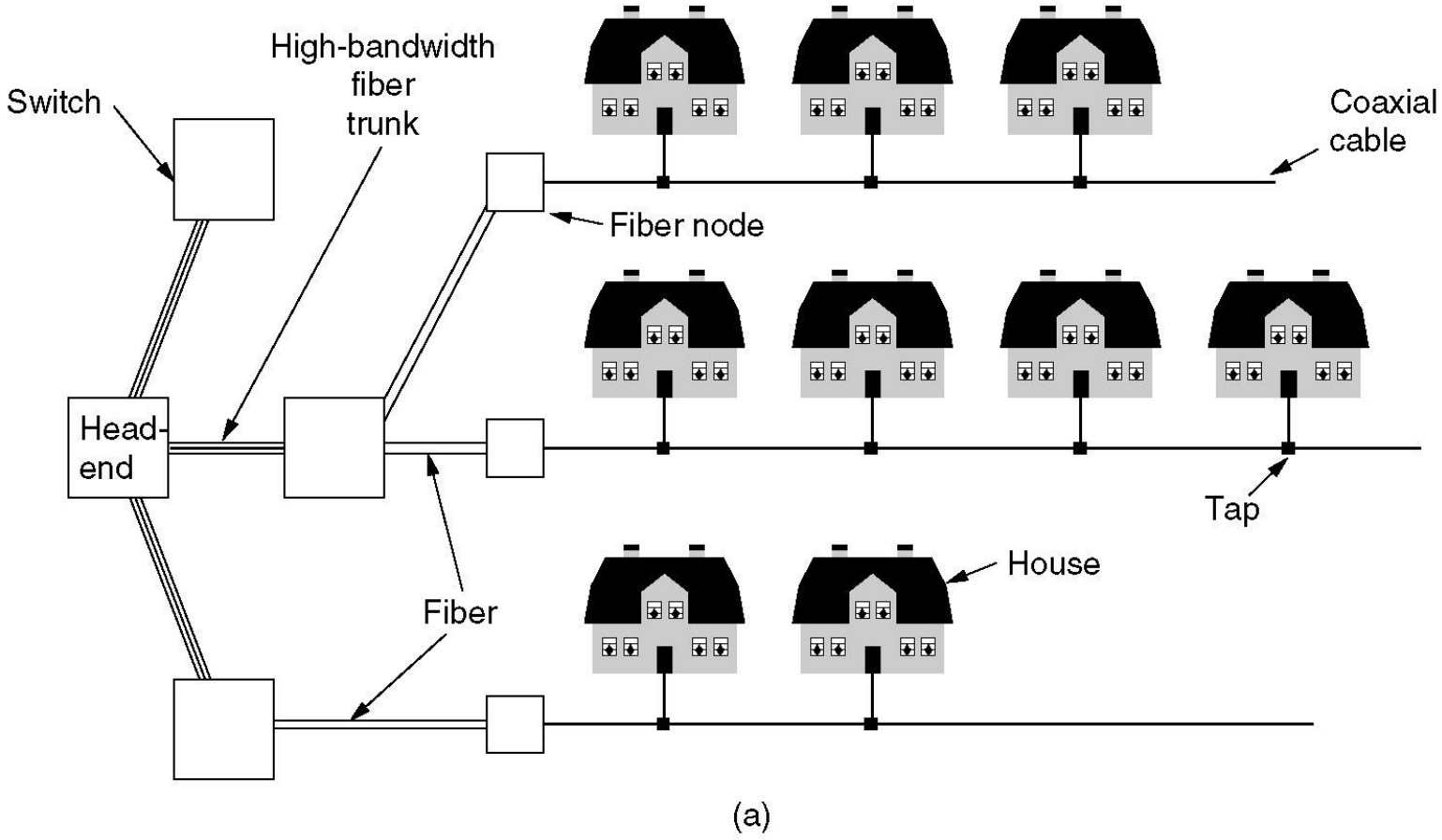
- Community Antenna Television
- Internet over Cable
- Spectrum Allocation
- Cable Modems
- ADSL versus Cable

Community Antenna Television

An early cable television system.

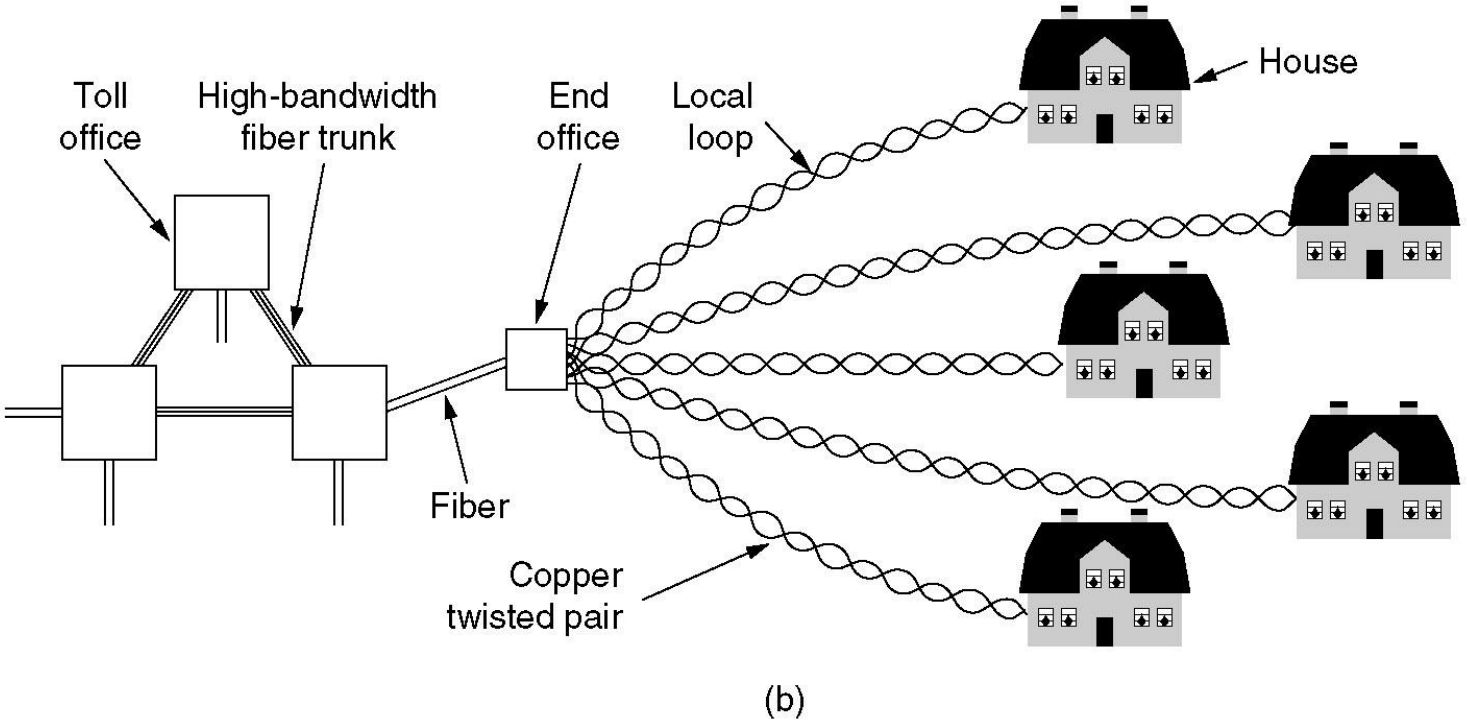


Internet over Cable



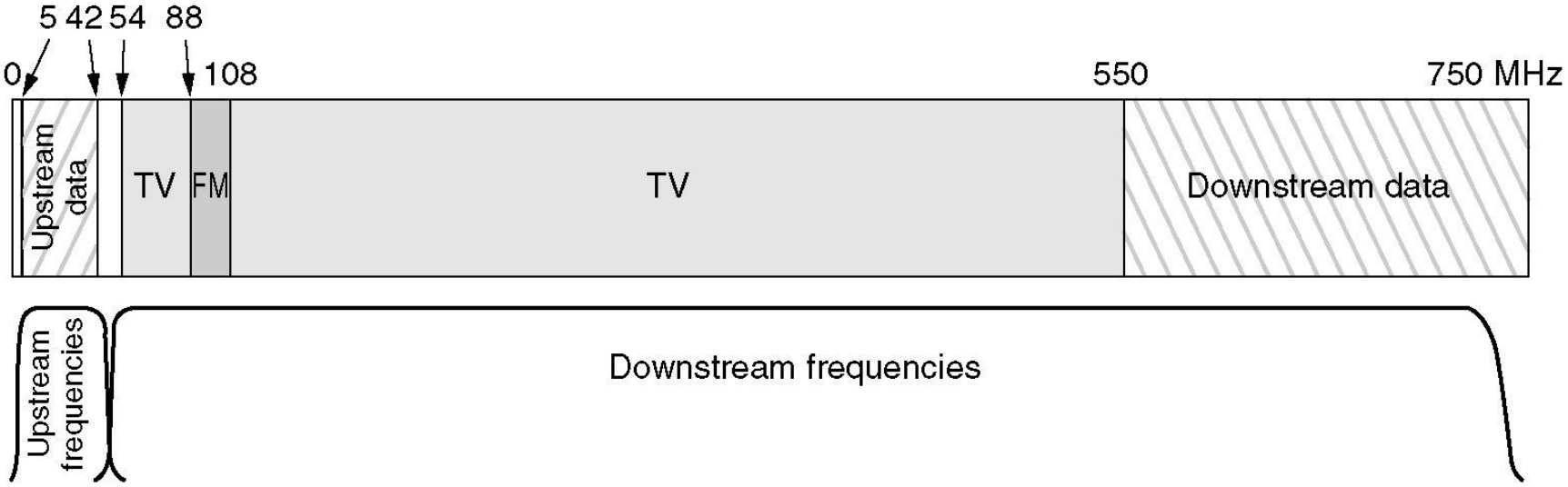
Cable television

Internet over Cable (2)



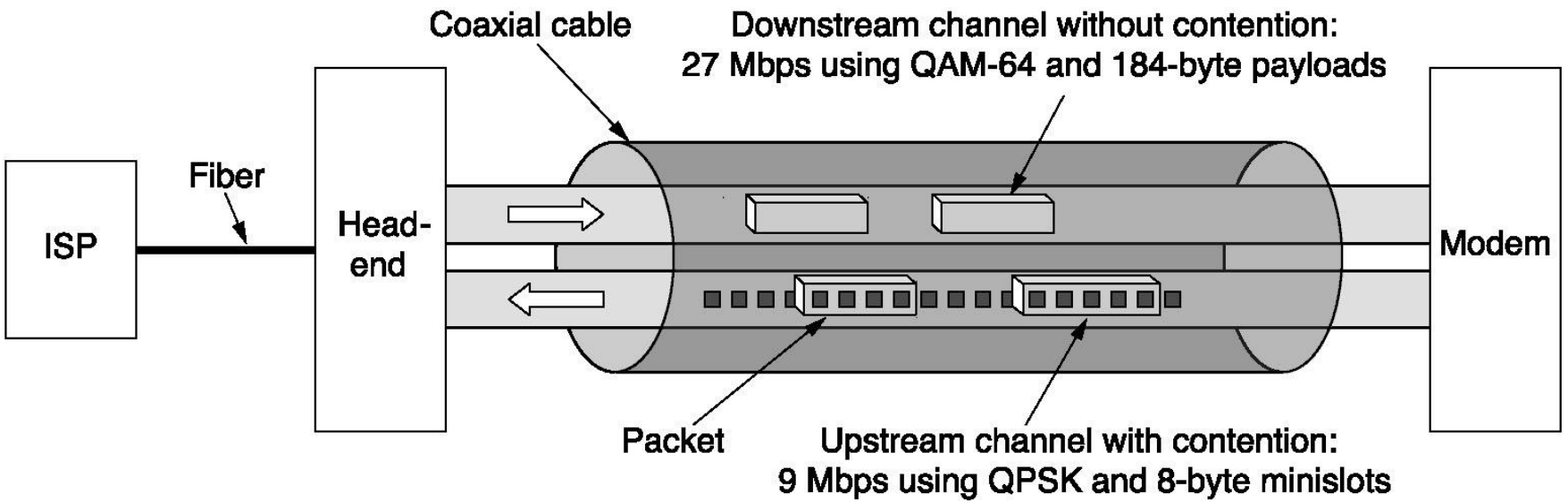
The fixed telephone system.

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.