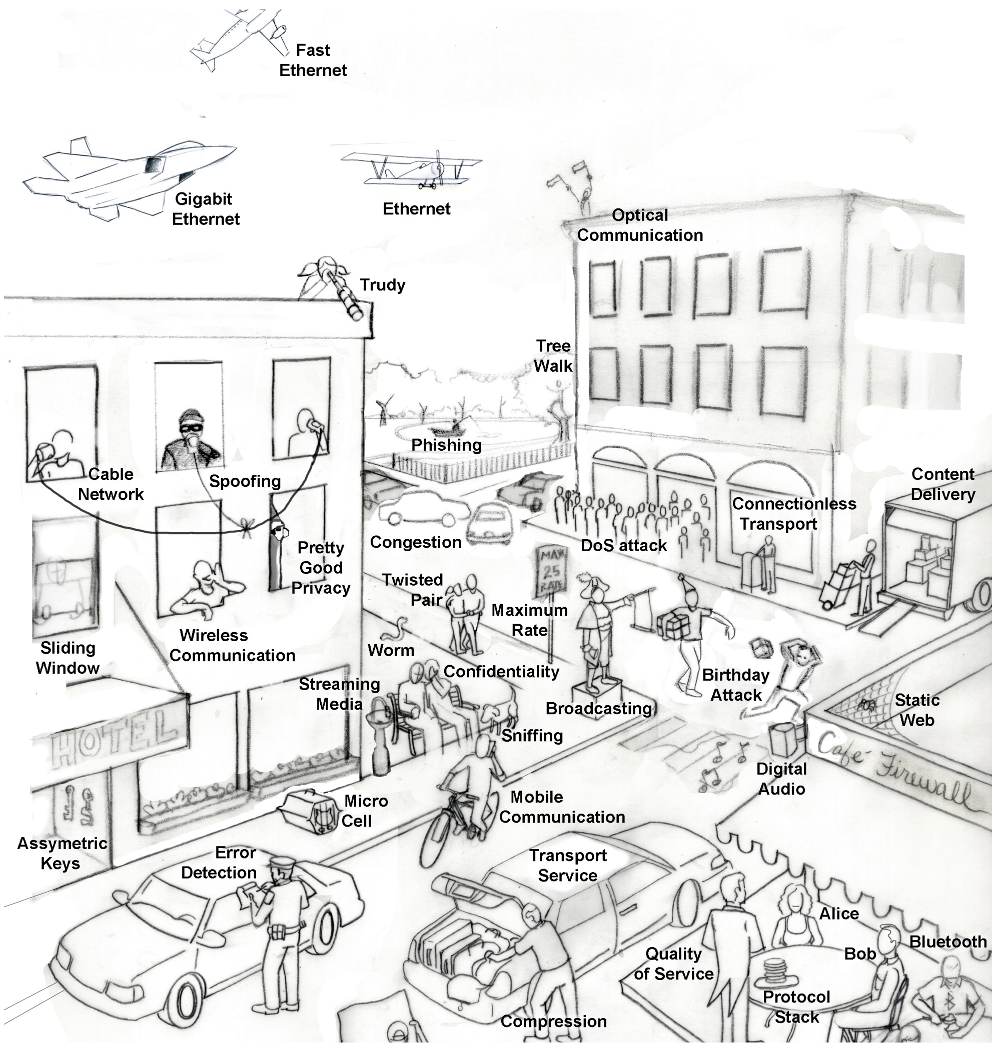
Computer Networking

Sixth edition



Chapter 2

The Physical Layer

Let There Be Light!

(and all the other wavelengths)

$$\nabla \bullet E = \rho/\varepsilon$$

$$\nabla \bullet B = 0$$

$$\nabla \times E = -\partial B/ \partial t$$

$$\nabla \times B = -\mu J + \mu\varepsilon\partial E/ \partial t$$

Maxwell's Equations

James Clerk Maxwell (1831 -1879)

Basically invented Modern Physics

"In this class, I hope you will learn not merely results, or formulae applicable to cases that that may possibly occur in our practice afterwards, but the principles on which those formulae depend, and without which the formulae are mere mental rubbish.

I know the tendency of the human mind is to do anything rather than think. But mental labor is not thought, and those who have with labor acquired the habit of application often find it much easier to get up a formula than to master a principle."

– James Clerk Maxwell (1860)
Inaugural Address, Kings College
London

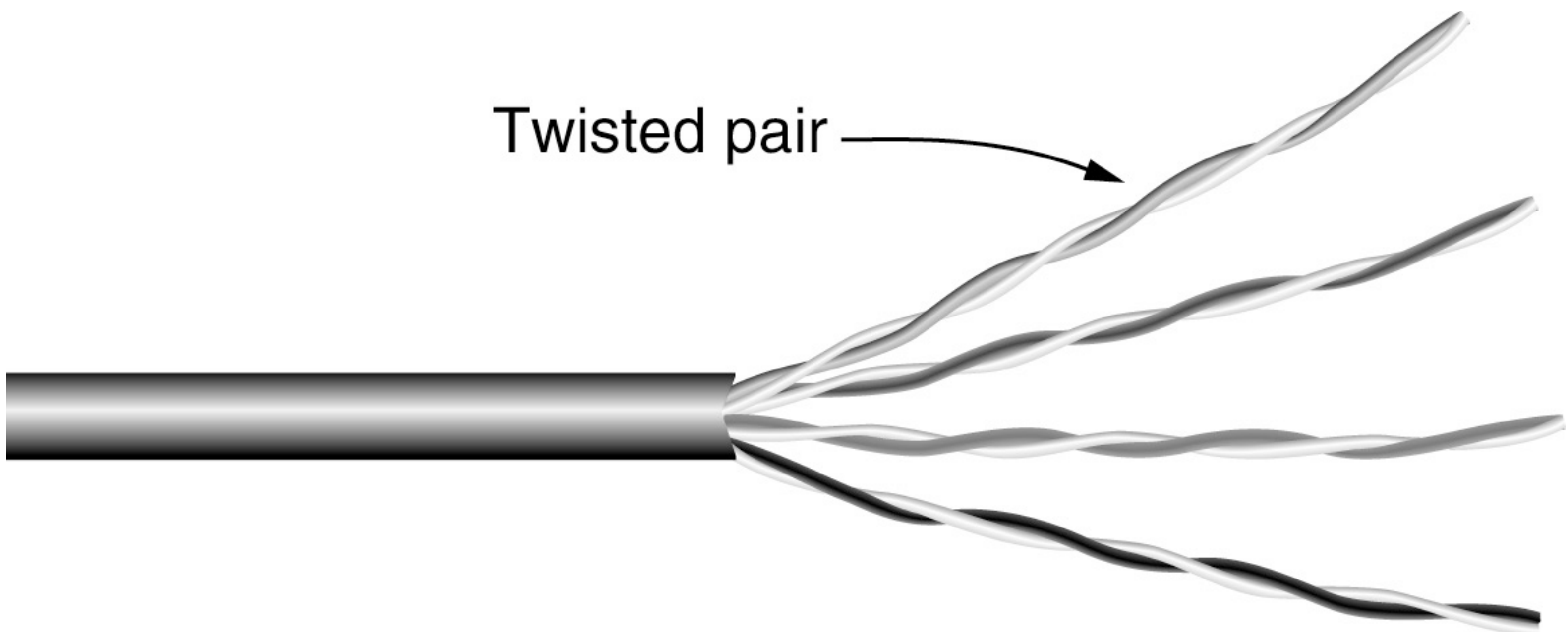
Guided Transmission Media

- Guided transmission media
  - Persistent storage
  - Twisted pairs
  - Coaxial cable
  - Power lines
  - Fiber optics

Persistent Storage

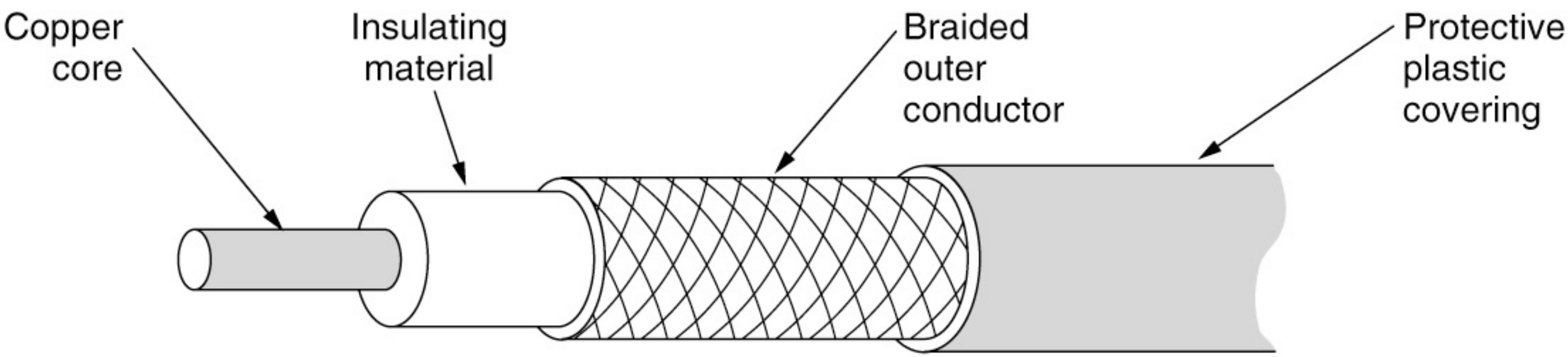
- Consists of magnetic or solid-state storage
- Common way to transport data
  - Write to persistent storage
  - Physically transport the tape or disks to the destination machine
  - Read data back again
- Cost effective for applications where a high data rate or cost per bit transported is the key factor
- Never underestimate the data rate of a station wagon full of tapes hurtling down the highway

Twisted Pairs



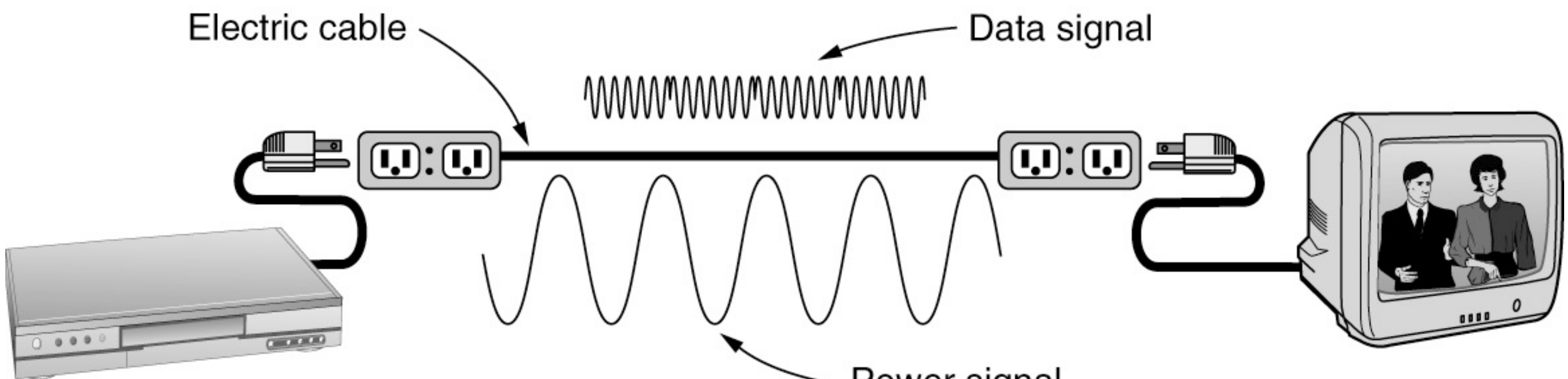
A category 5e twisted pair consists of two insulated wires gently twisted together. Four such pairs are typically grouped in a plastic sheath to protect the wires and keep them together.

Coaxial Cable



A coaxial cable consists of a stiff copper wire as the core, surrounded by an insulating material. The insulator is encased by a cylindrical conductor, often as a closely woven braided mesh. The outer conductor is covered in a protective plastic sheath.

Power Lines



Using power lines for networking is simple. In this case, a TV and a receiver are plugged into the wall, which must be done anyway because they need power. Then they can send and receive movies over the electrical wiring.

Fiber Optics (1 of 7)

- Allows essentially infinite bandwidth
- Must consider costs
  - For installation over the last mile and to move bits
- Uses
  - Long-haul transmission in network backbones
  - High-speed LANs
  - High-speed Internet access
- Key components
  - Light source, transmission medium, and detector
- Transmission system uses physics

Fiber Optics (2 of 7)

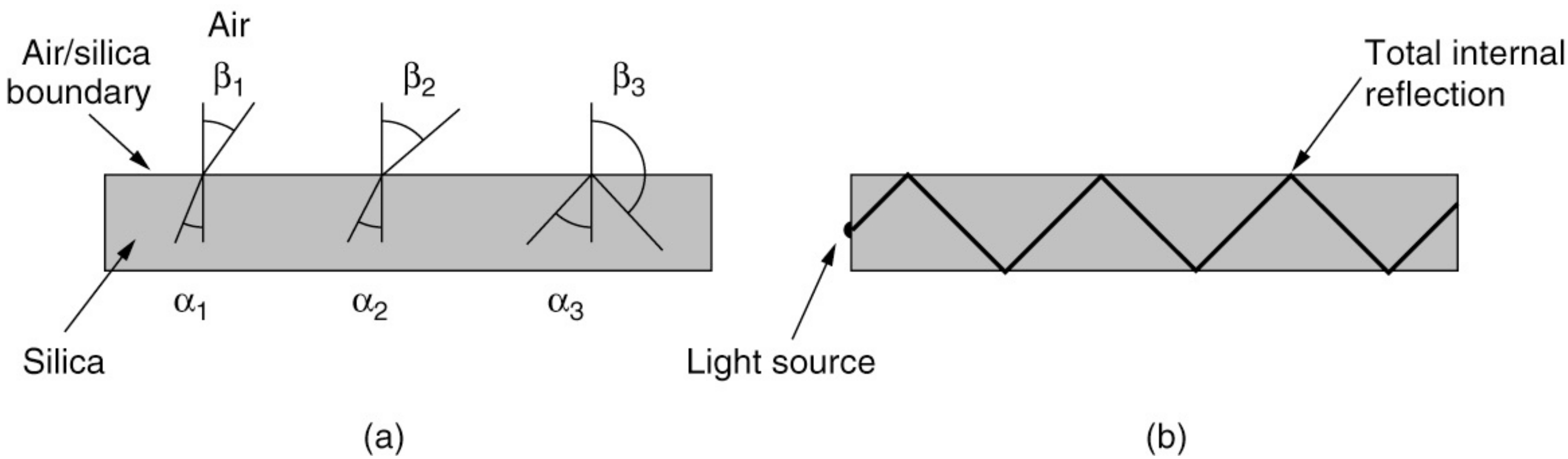
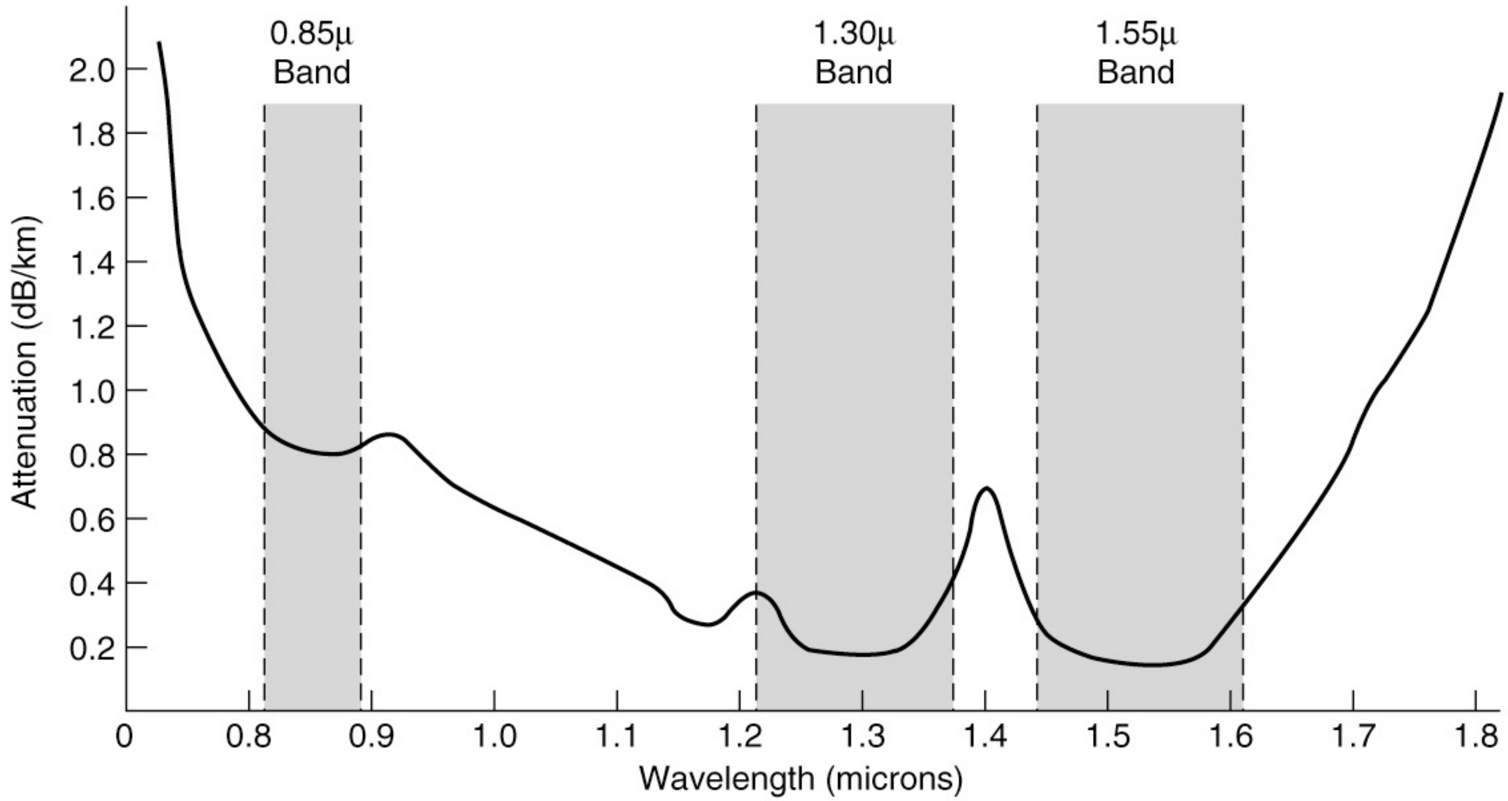


Figure (a) illustrates a light ray inside a silica fiber impinging on the air/silica boundary at different angles. Figure (b) illustrates light trapped by total internal reflection.

Fiber Optics (3 of 7)

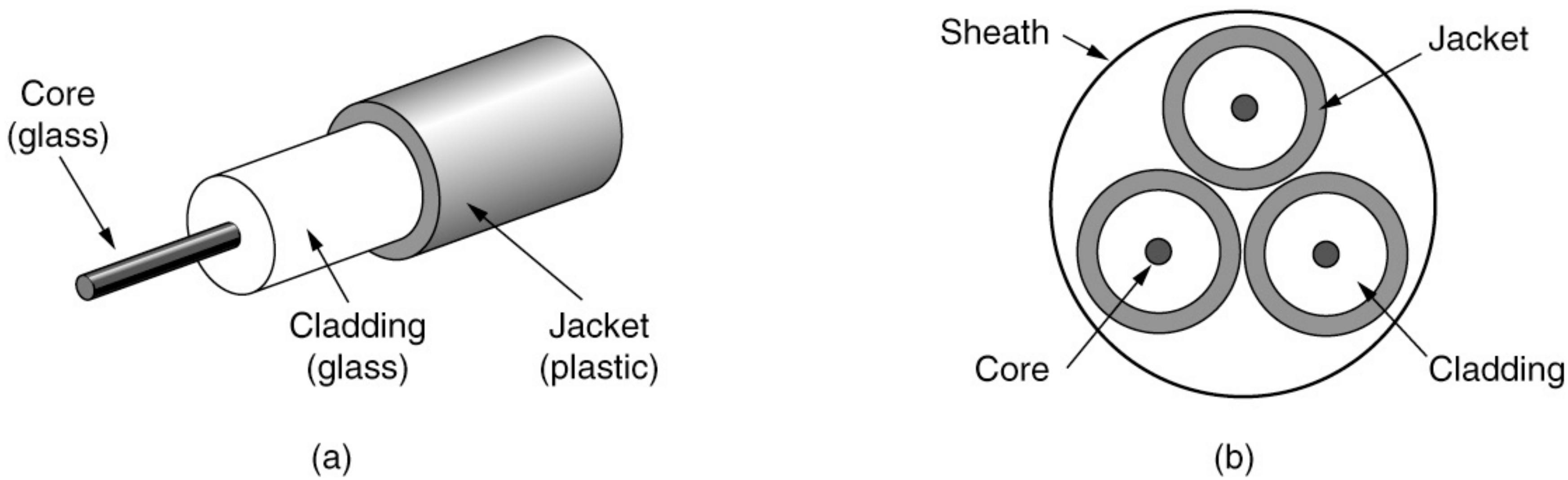
- Transmission of light through fiber
  - Attenuation of light through glass
    - Dependent on the wavelength of the light
    - Defined as the ratio of input to output signal power
- Fiber cables
  - Similar to coax, except without the braid
- Two kinds of signaling light sources
  - LEDs (Light Emitting Diodes)
  - Semiconductor lasers
    - Light Amplification by Stimulated Emission of Radiation

Fiber Optics (4 of 7)



Attenuation of light through fiber in the infrared region is measured in units of decibels (dB) per linear kilometer of fiber.

Fiber Optics (5 of 7)



Views of a fiber cable

Fiber Optics (6 of 7)

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.

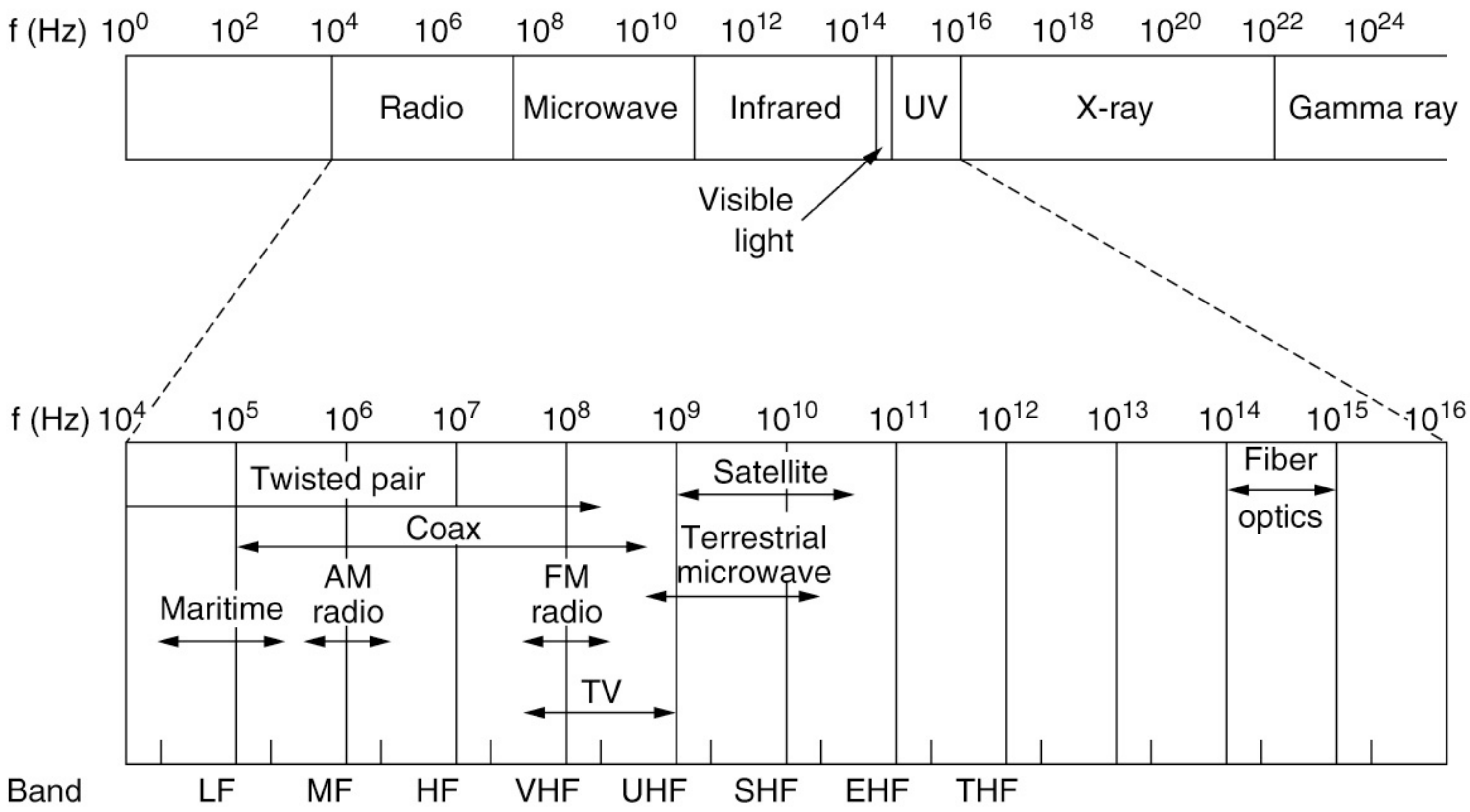
Fiber Optics (7 of 7)

- Fiber advantages over copper
  - Handles higher bandwidth
  - Not affected by power surges, electromagnetic interference, power failures, corrosive chemicals
  - Thin and lightweight
  - Do not leak light
  - Difficult to tap
- Fiber disadvantage
  - Less familiar technology that requires specific engineering skills
  - Fibers damaged easily by being bent too much

Wireless Transmission

- The electromagnetic spectrum
  - Modulate wave amplitude, frequency, or phase
- Frequency hopping spread spectrum
  - Transmitter hops from frequency to frequency hundreds of times per second
- Direct sequence spread spectrum
  - Code sequence spreads data signal over wider frequency band
- Ultra-wideband communication
  - Communication sends a series of low-energy rapid pulses, varying their carrier frequencies to communicate information

The Electromagnetic Spectrum

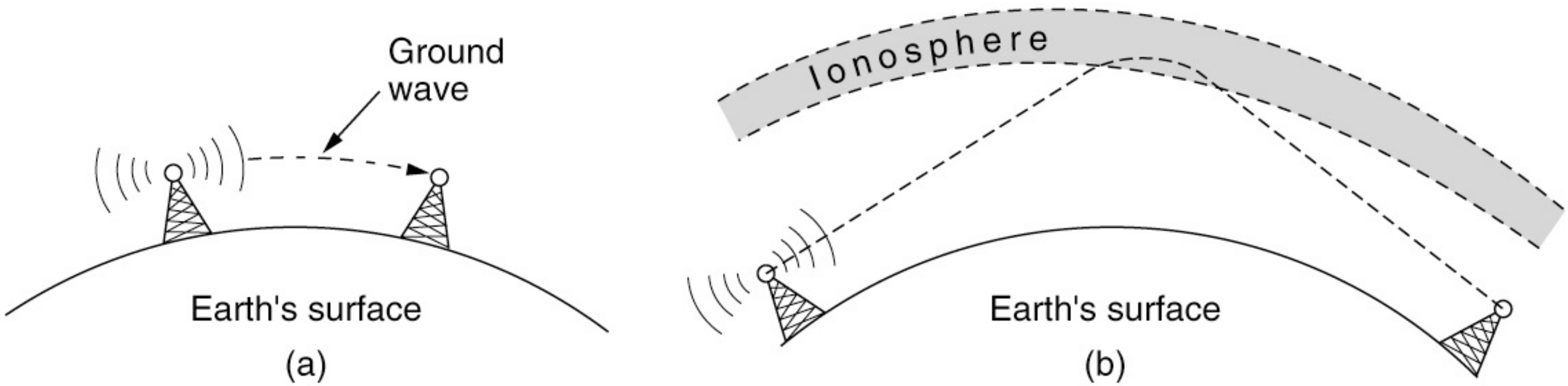


The electromagnetic spectrum and its uses for communication.

Using the Spectrum for Transmission

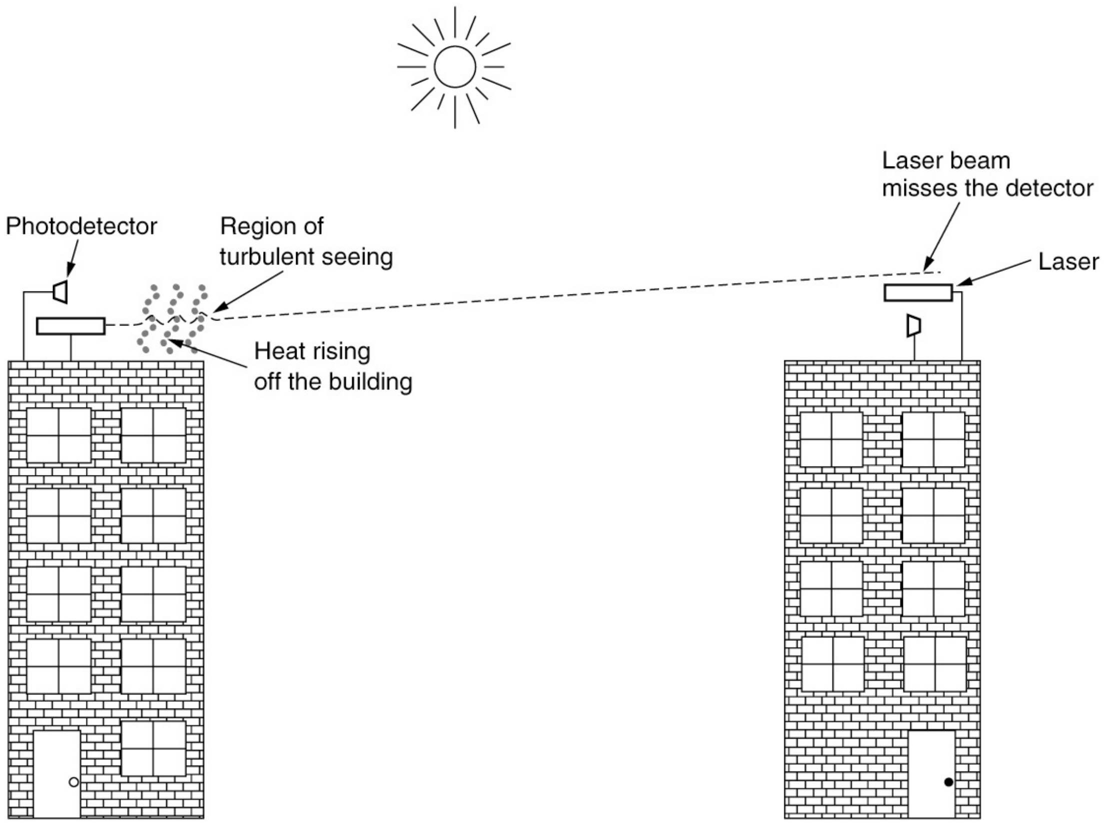
- Radio transmission
  - Omnidirectional waves, easy to generate, travel long distances, penetrate buildings
- Microwave transmission
  - Directional waves requiring repeaters, do not penetrate buildings
- Infrared transmission
  - Unguided waves used for short-range communication, relatively directional, cheap, easy to build, do not penetrate solid walls
- Light transmission
  - Unguided optical communication

Radio Transmission



In the VLF, LF, and MF bands, radio waves follow the curvature of the earth. In the HF band, they bounce off the ionosphere.

Light Transmission



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

From Waveforms to Bits

- The theoretical basis for data communication
  - Fourier analysis
  - Bandwidth-limited signals
- The maximum data rate of a channel
  - We often say ‘bandwidth’ when we mean ‘data rate.’
    - We should be more careful.
- Digital modulation
- Multiplexing

Fourier Analysis

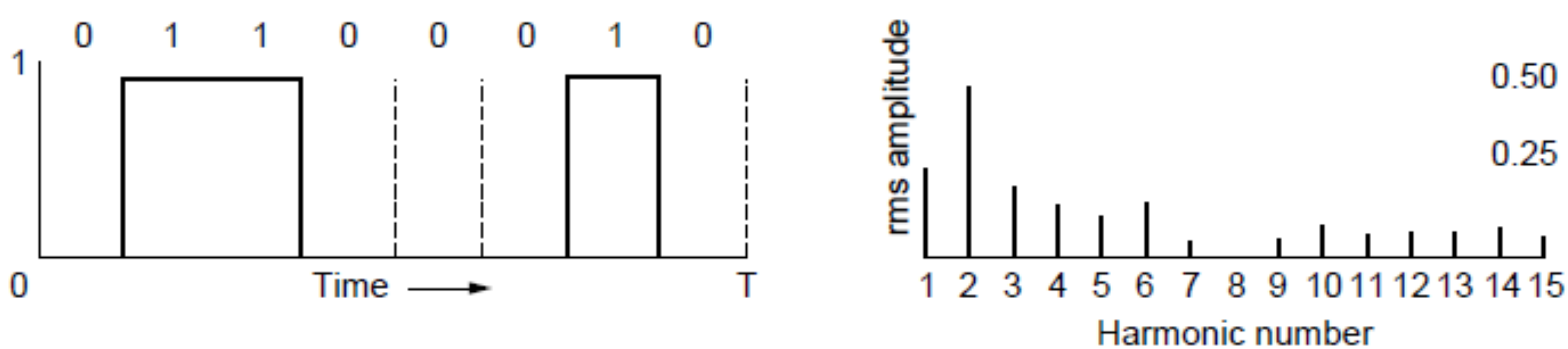
- We model the behavior of variation of voltage or current with mathematical functions
- Fourier series is used

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

- Function reconstructed with

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

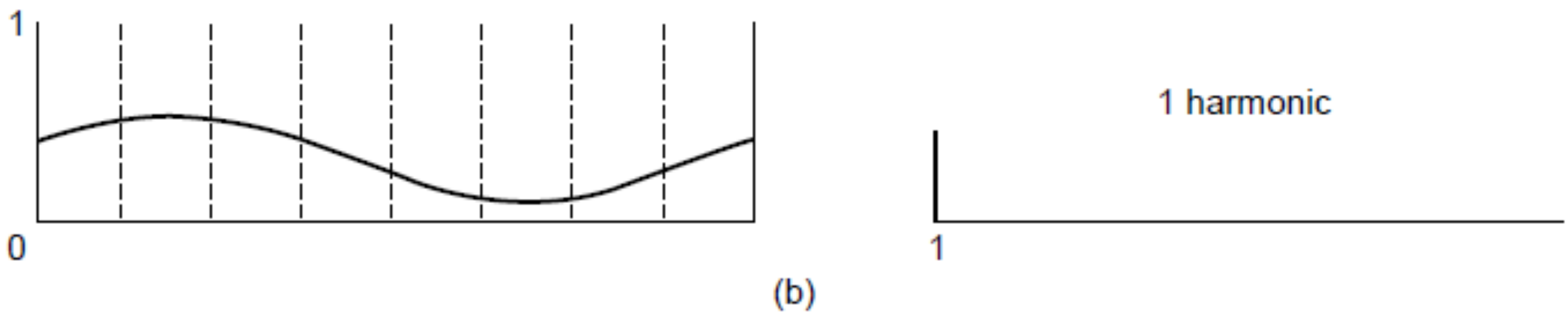
Bandwidth-Limited Signals (1 of 6)



(a)

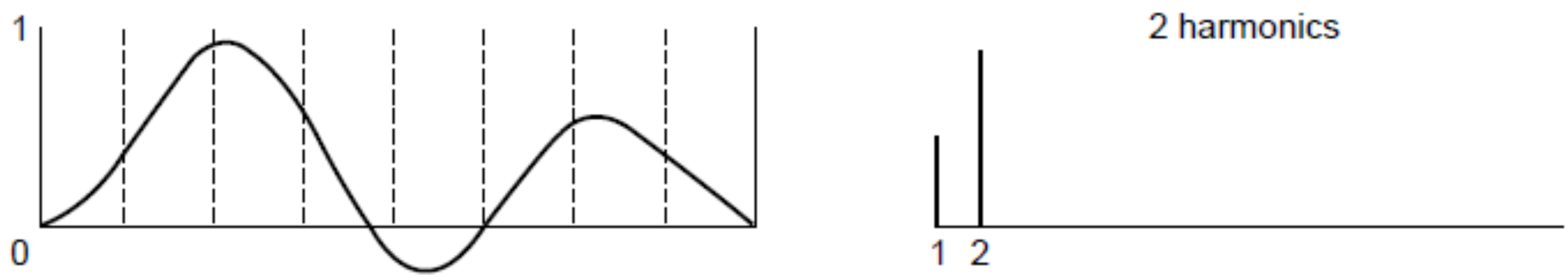
A binary signal and its root-mean-square Fourier amplitudes.

Bandwidth-Limited Signals (2 of 6)



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

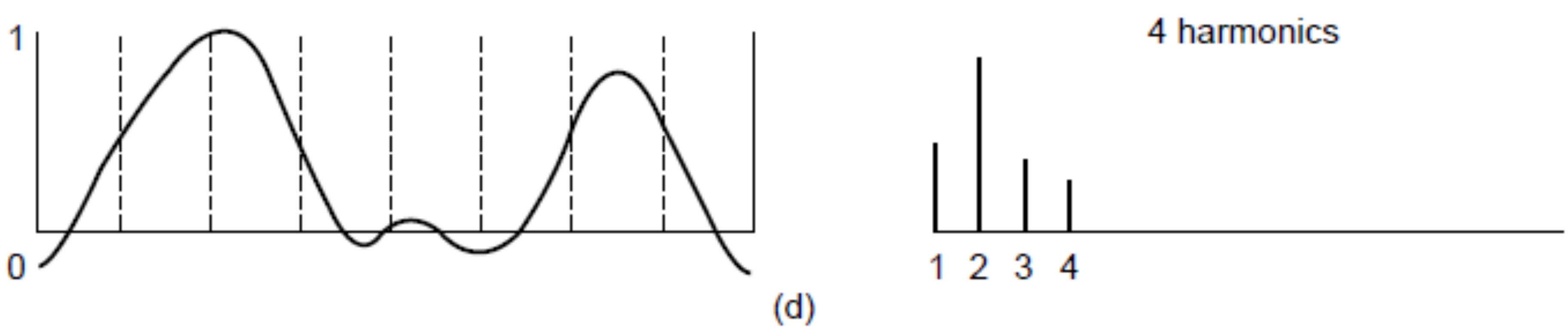
Bandwidth-Limited Signals (3 of 6)



(c)

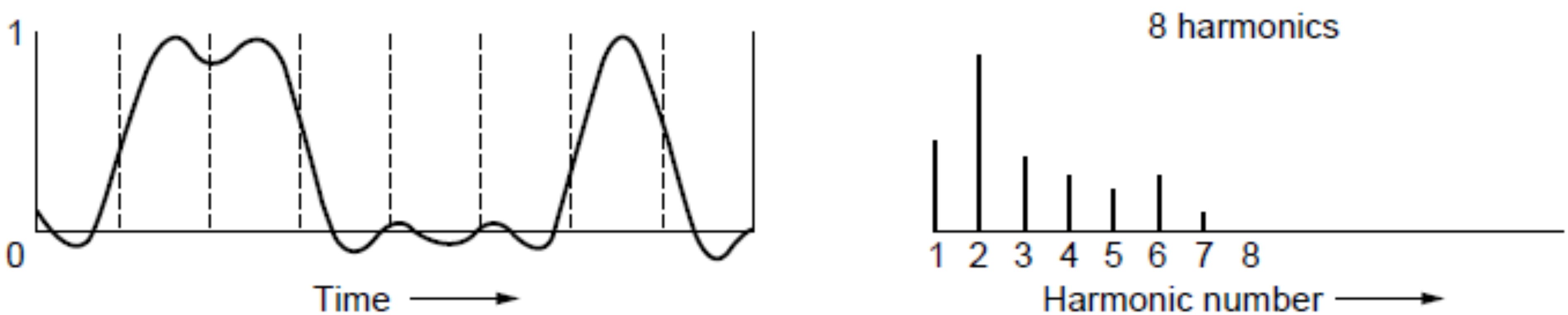
(b)-(e) Successive approximations to the original signal.

Bandwidth-Limited Signals (4 of 6)



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

Bandwidth-Limited Signals (5 of 6)



(e)

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

Bandwidth-Limited Signals (6 of 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

The relation between data rate and harmonics for our example.

The Maximum Data Rate of a Channel

- Nyquist's theorem

  Maximum data rate = $2B\log_2 V$ bits/sec

- Shannon's formula for capacity of a noisy channel

  Maximum data rate = $B\log_2 (1 + S/N)$*bits/sec*

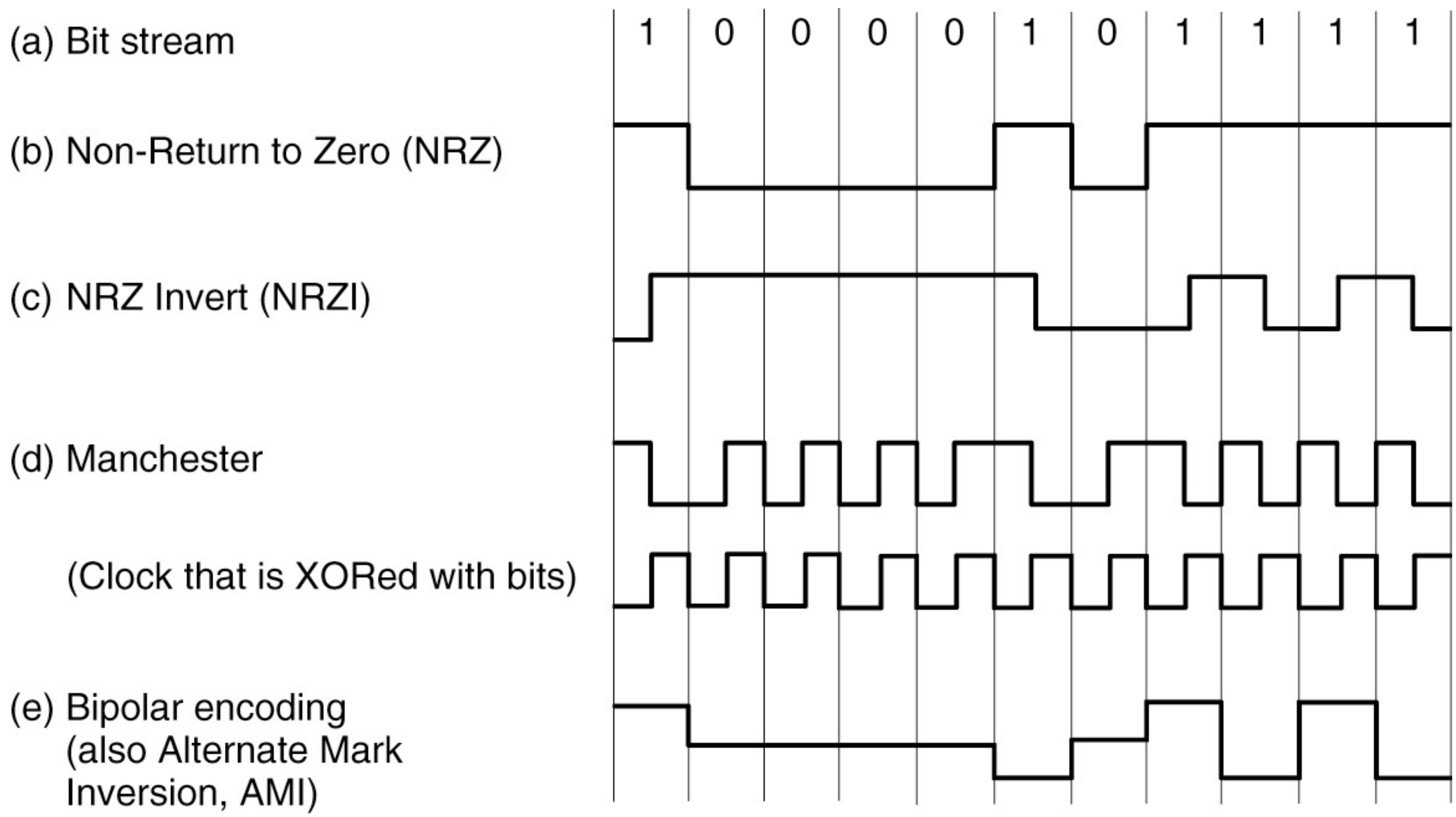
Making Bits

- The number of samples/second is the **baud rate.** One **symbol** is sent for each baud.
  - If a 2400 baud line uses 0 volts for 0 and 1 volt for a 1, then there is one bit per symbol or the 2400 bits/sec.
  - If it does 4 voltage levels, then that is 2 bits per symbol or 4800 bits/sec.
- Modulation uses combinations of amplitude, frequency and phase to increase the number of bits per symbol and hence the bit rate.

Digital Modulation

- Baseband transmission
- Bandwidth efficiency
- Clock recovery
- Balanced signals
- Passband transmission

Baseband Transmission



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

Bandwidth Efficiency

- Bandwidth is often a limited resource
- Solution
  - Use more than two signaling levels
  - By using four voltages we can send 2 bits at once as a single symbol
  - Design works as long as the signal at the receiver is sufficiently strong to distinguish the four levels
  - Signal rate change is half the bit rate, so the needed bandwidth has been reduced

Clock Recovery

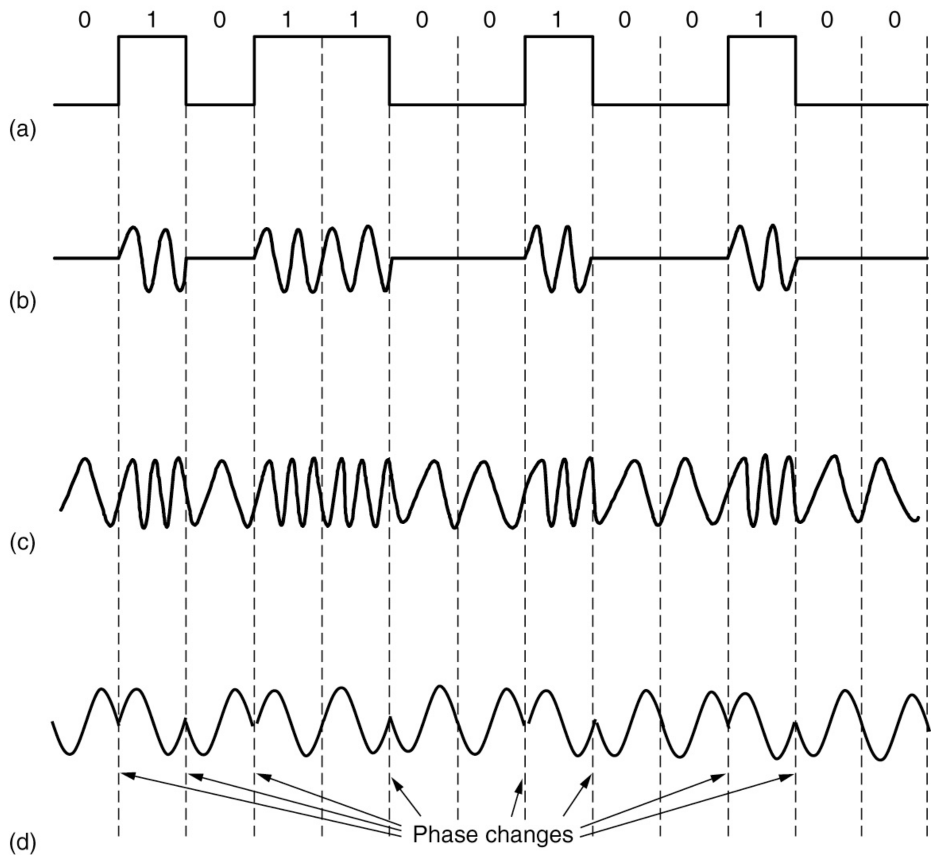
Data (4B)	Codeword (5B)	Data (4B)	Codeword (5B)
0000	11110	1000	10010
0001	01001	1001	10011
0010	10100	1010	10110
0011	10101	1011	10111
0100	01010	1100	11010
0101	01011	1101	11011
0110	01110	1110	11100
0111	01111	1111	11101

4B/5B mapping.

Balanced Signals

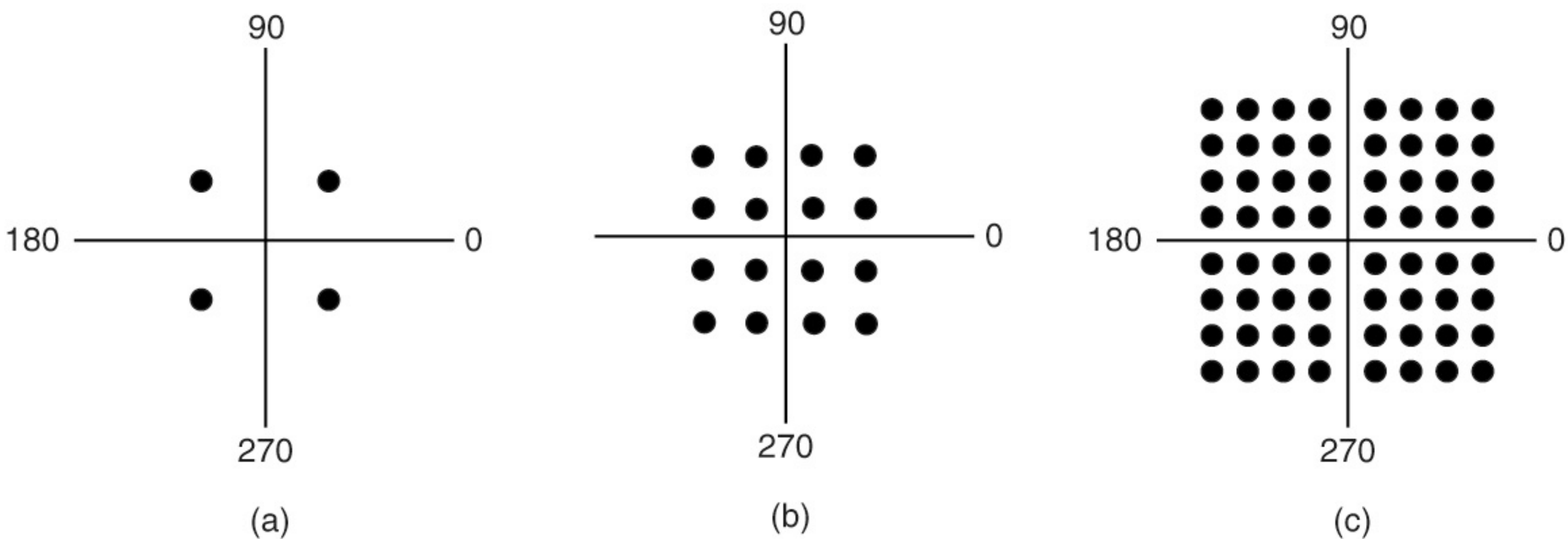
- Balanced signals
  - Signals having as much positive voltage as negative voltage even over short periods of time
  - They average to zero (they have no DC electrical component)
- Balancing helps to provide transitions for clock recovery
- Provides a simple way to calibrate receivers
- Straightforward way to construct a balanced code
  - Use two voltage levels to represent a logical 1 and a logical zero
  - Scheme is called is called bipolar encoding
  - Bipolar encoding adds a voltage level to achieve balance

Passband Transmission (1 of 3)



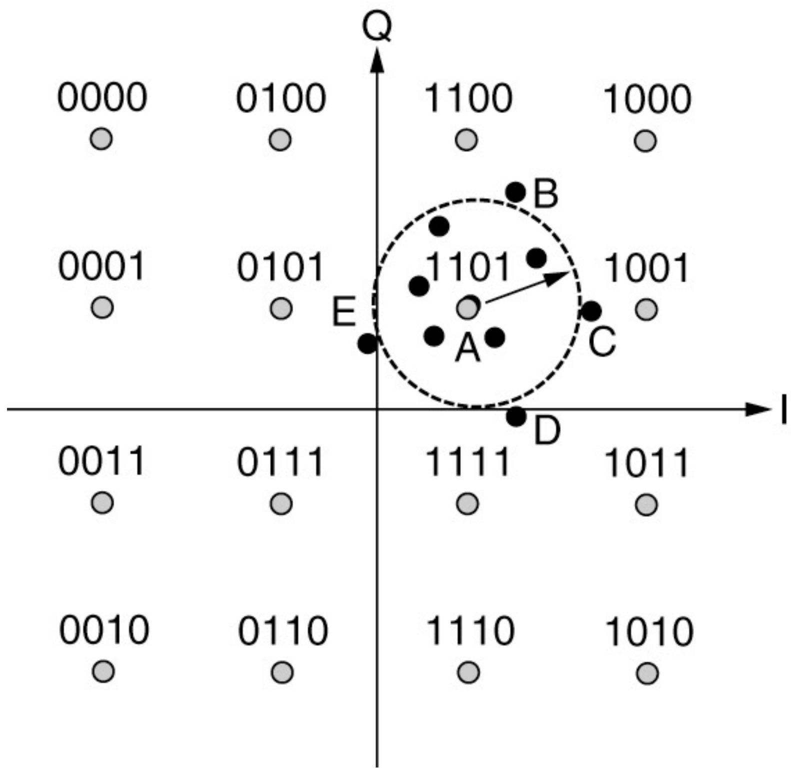
(a) A binary signal. (b) Amplitude shift keying. (c) Frequency shift keying. (d) Phase shift keying.

Passband Transmission (2 of 3)



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

Passband Transmission (3 of 3)



When 1101 is sent:

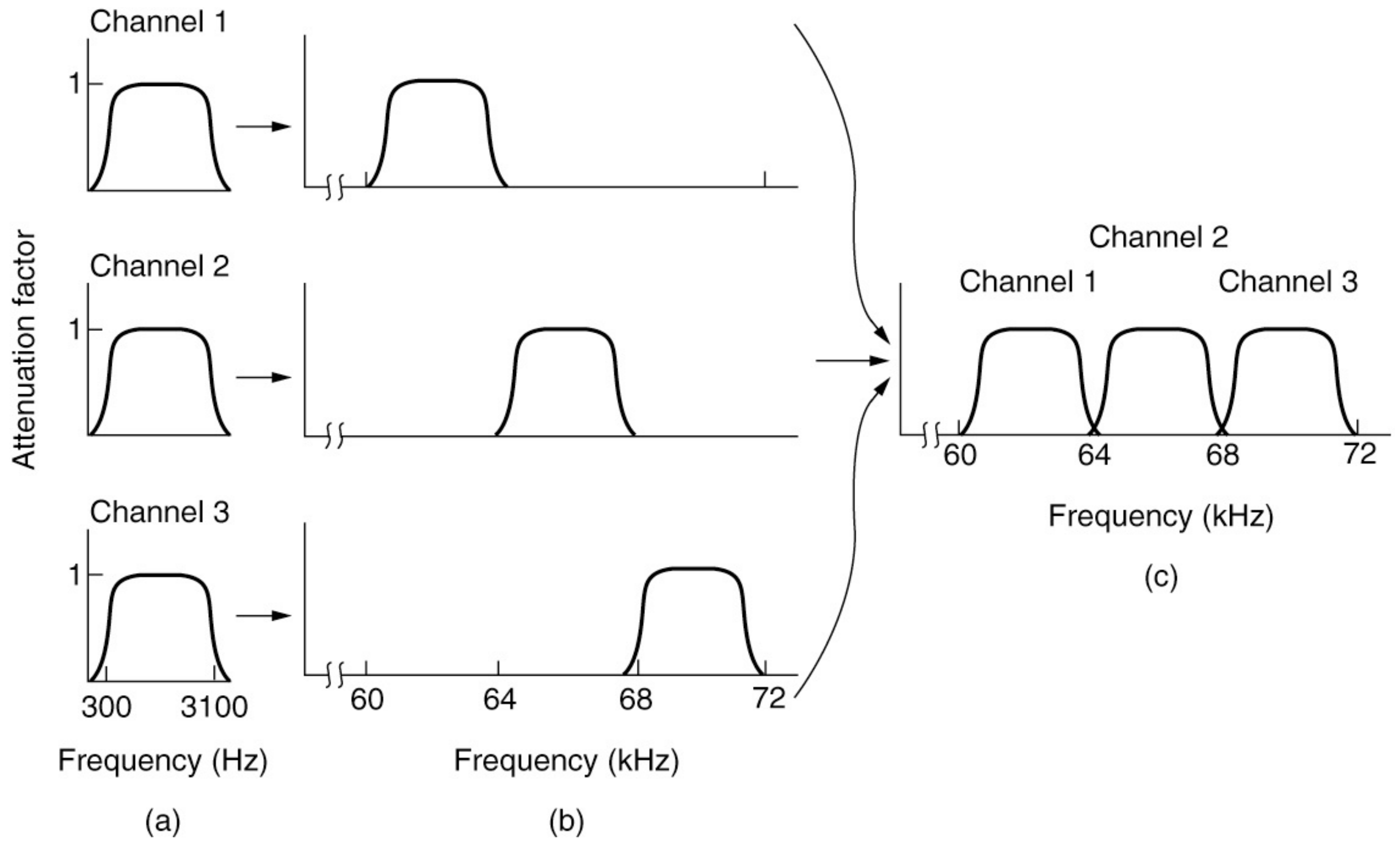
Point	Decodes as	Bit errors
A	1101	0
B	1100	1
C	1001	1
D	1111	1
E	0101	1

Gray-coded QAM-16

Multiplexing

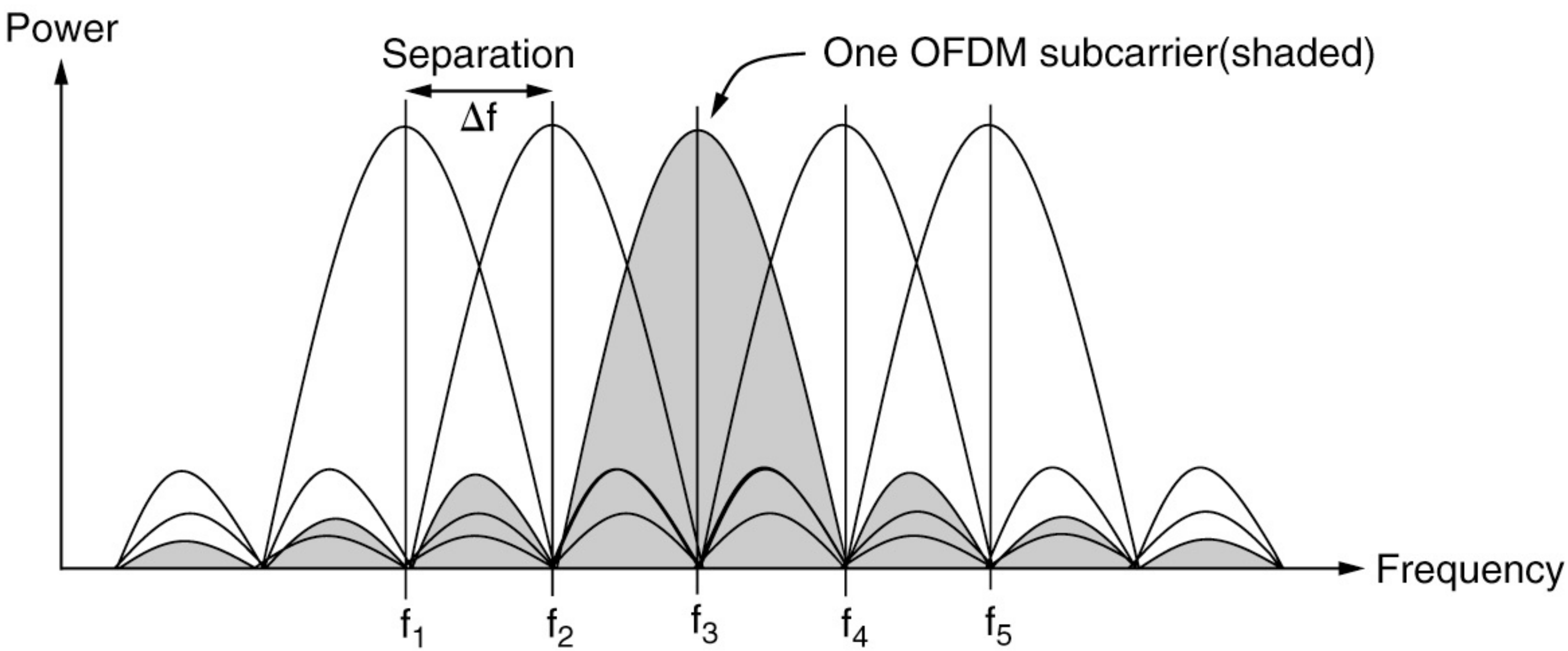
- Frequency Division Multiplexing
- Time Division Multiplexing
- Code Division Multiplexing
- Wavelength Division Multiplexing

Frequency Division Multiplexing (1 of 2)



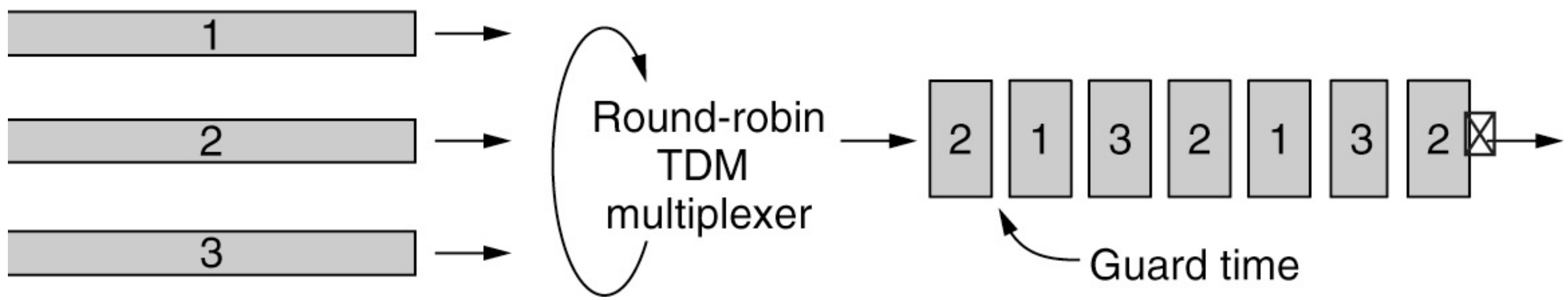
(a) The original bandwidths. (b) The bandwidths raised in frequency. (c) The multiplexed channel.

Frequency Division Multiplexing (2 of 2)



Orthogonal frequency division multiplexing (OFDM).

Time Division Multiplexing



Time Division Multiplexing (TDM)

Code Division Multiplexing

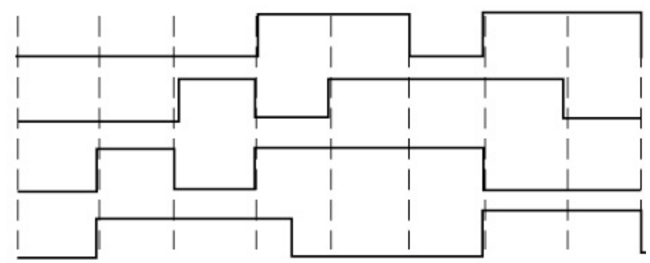
$A = (-1\ -1\ -1\ +1\ +1\ -1\ +1\ +1)$

$B = (-1\ -1\ +1\ -1\ +1\ +1\ +1\ -1)$

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

$D = (-1\ +1\ -1\ -1\ -1\ -1\ +1\ -1)$

(a)



(b)

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

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

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

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

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

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

(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) Chip sequences for four stations. (b) Signals the sequences represent. (c) Six examples of transmissions. (d) Recovery of station C's signal.

What's a Dot Product?

The Dot Product is an operation on two vectors that yields a scalar.

Take two vectors **A** and **B**, where $(a_1, a_2, \ldots a_n)$ and $(b_1, b_2, \ldots b_n)$

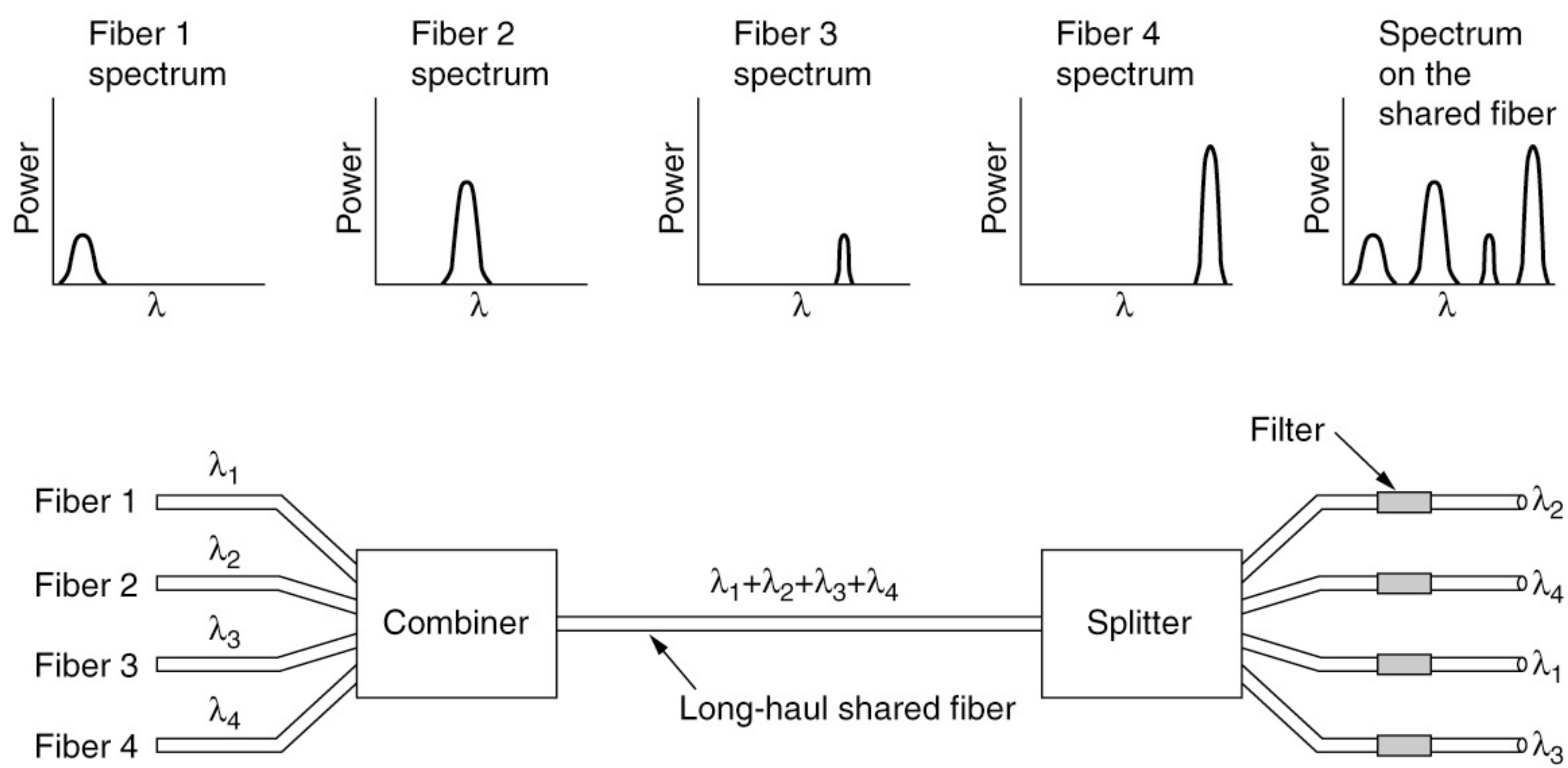
$$\mathbf{A} \bullet \mathbf{B} = \sum a_i b_i = |\mathbf{A}|\,|\mathbf{B}| \cos\theta$$

Therefore, when the vectors are parallel $\cos\theta = 1$ and $\mathbf{A} \bullet \mathbf{B} = |\mathbf{A}|\,|\mathbf{B}|$

Or if the vectors are perpendicular $\cos\theta = 0$ and $\mathbf{A} \bullet \mathbf{B} = 0$

With waves, this can be very useful.

Wavelength Division Multiplexing

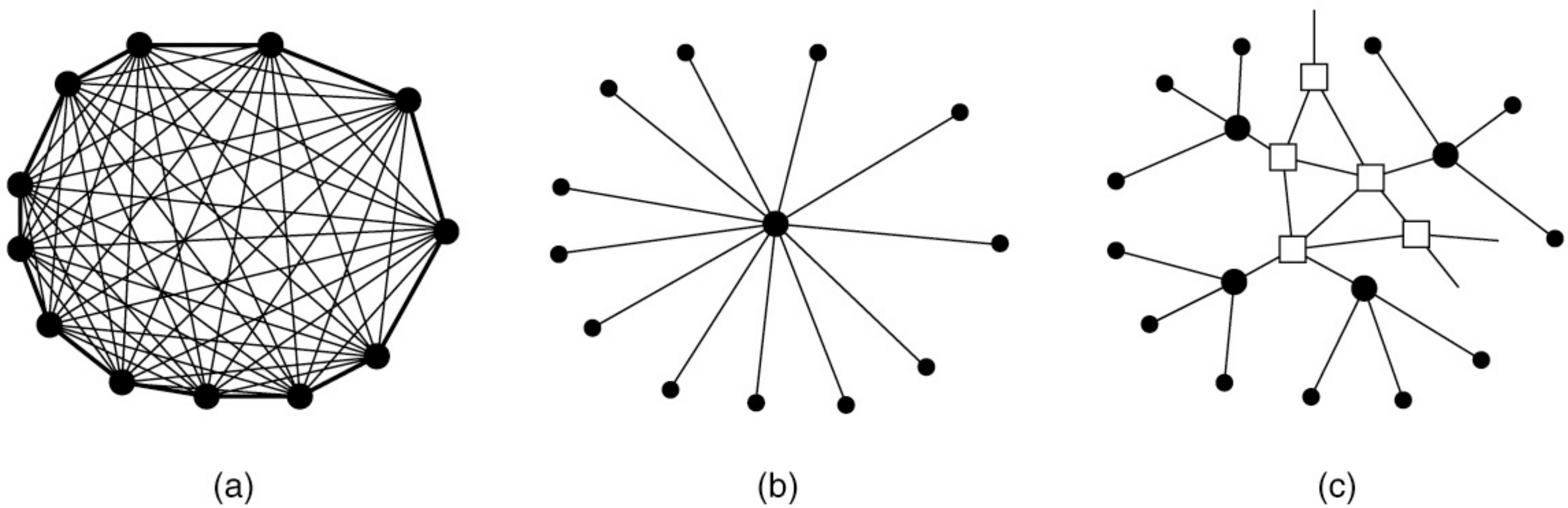


Wavelength division multiplexing

The Public Switched Telephone Network

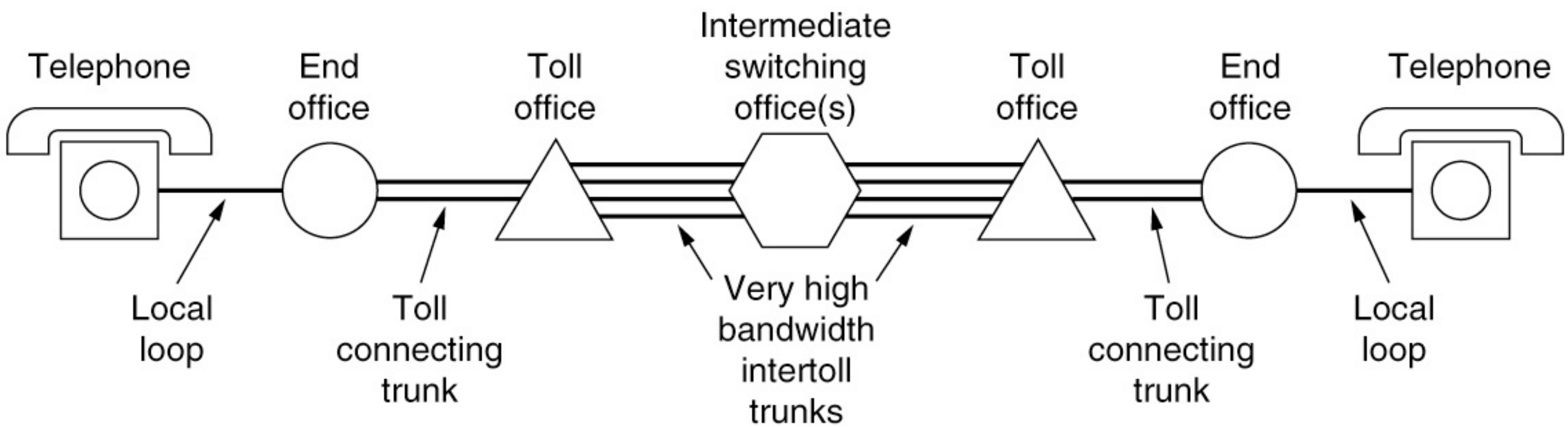
- Structure of the Telephone System
- The Local Loop: Telephone Modems, ADSL, and Fiber
  - Telephone modems

Structure of the Telephone System (1 of 2)



(a) Fully interconnected network. (b) Centralized switch. (c) Two-level hierarchy.

Structure of the Telephone System (2 of 2)

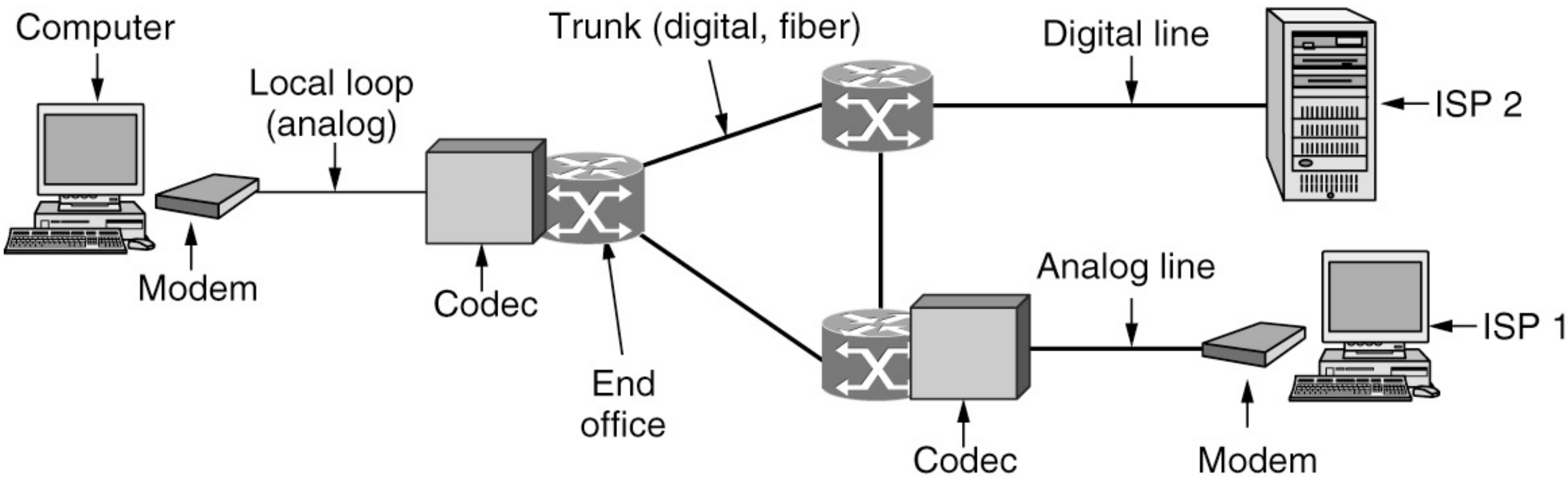


A typical circuit route for a long-distance call.

The Local Loop: Telephone Modems, ADSL, and Fiber

- Telephone Modems
- Digital Subscriber Lines (DSL)
- Fiber To The X (FTTX)

Telephone Modems (1 of 2)



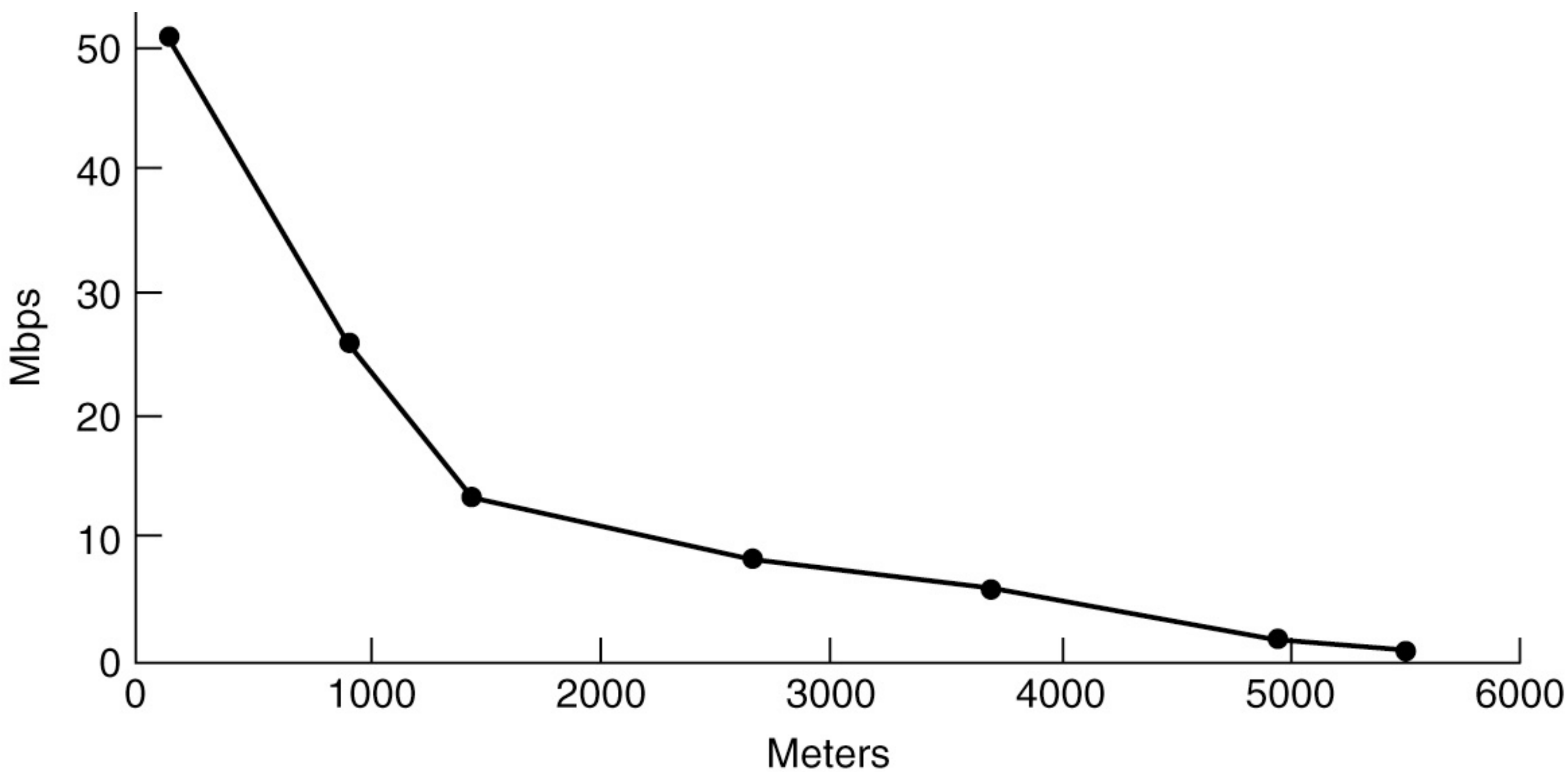
The use of both analog and digital transmission for a computer-to-computer call. Conversion is done by the modems and codecs.

Telephone Modems (2 of 2)

Modem standard	Baud	Bits/symbol	Bps
V.32	2400	4	9600
V.32 bis	2400	6	14,400
V.34	2400	12	28,800
V.34 bis	2400	14	33,600

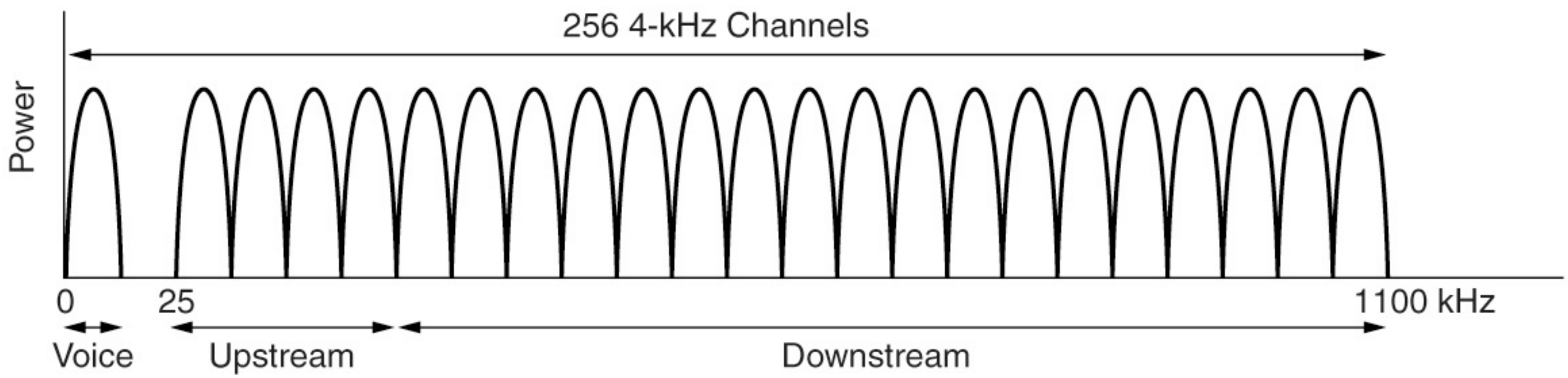
Some modem standards and their bit rate.

Digital Subscriber Lines (DSL) (1 of 3)



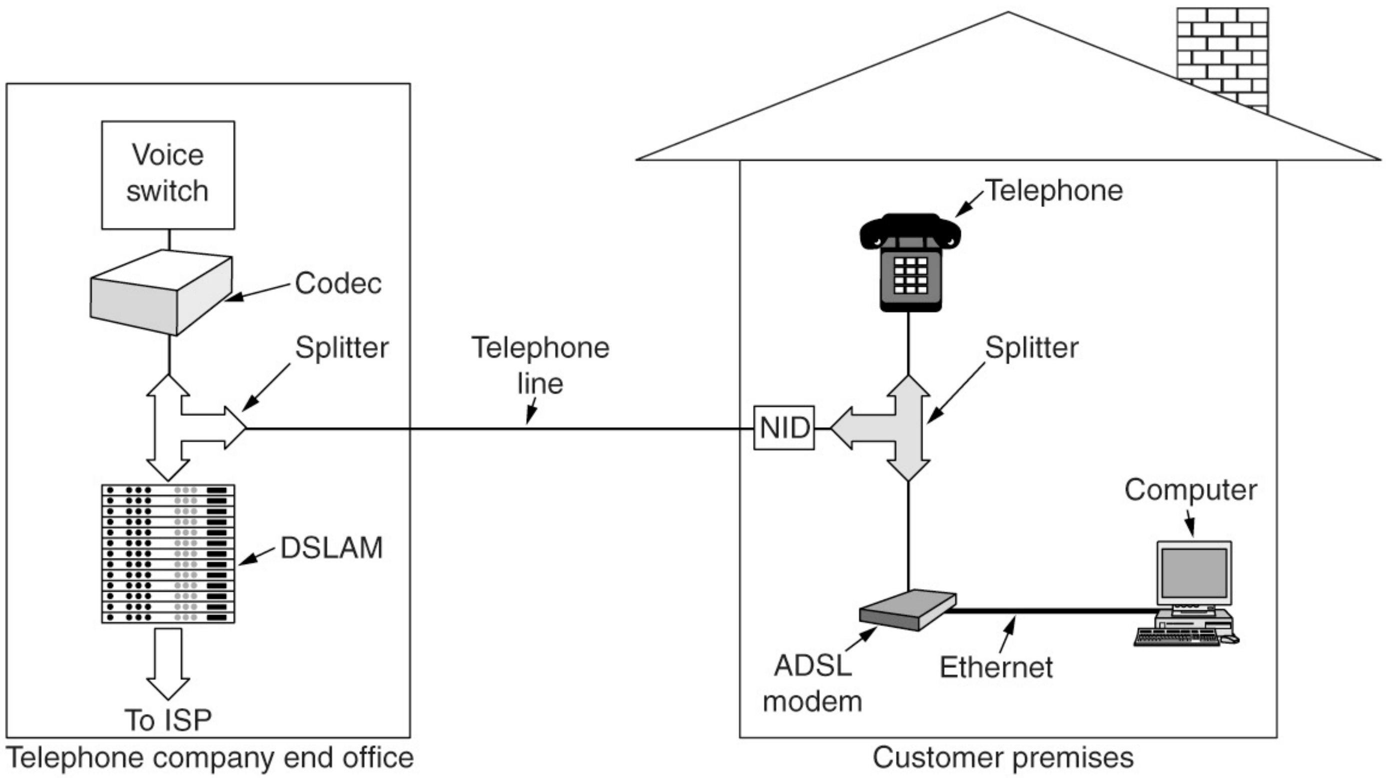
Bandwidth versus distance over Category 3 UTP for DSL.

Digital Subscriber Lines (DSL) (2 of 3)



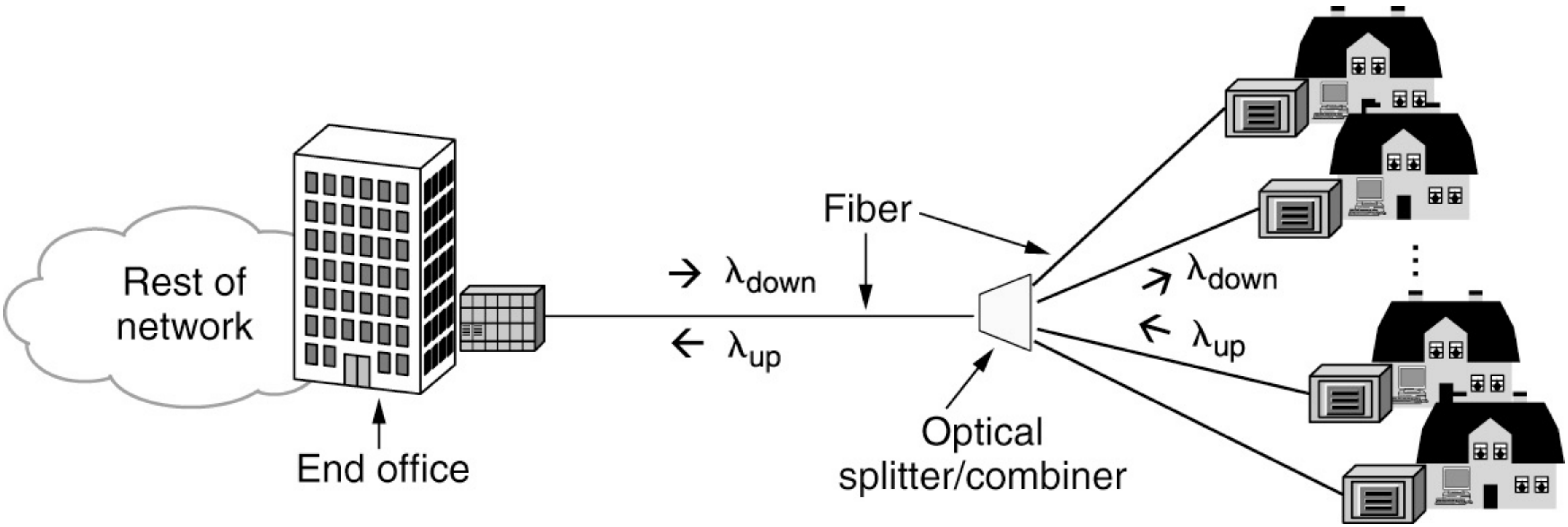
Operation of ADSL using discrete multitone modulation.

Digital Subscriber Lines (DSL) (3 of 3)



A typical ADSL equipment configuration.

Fiber To The X (FTTX)



Passive optical network for Fiber To The Home.

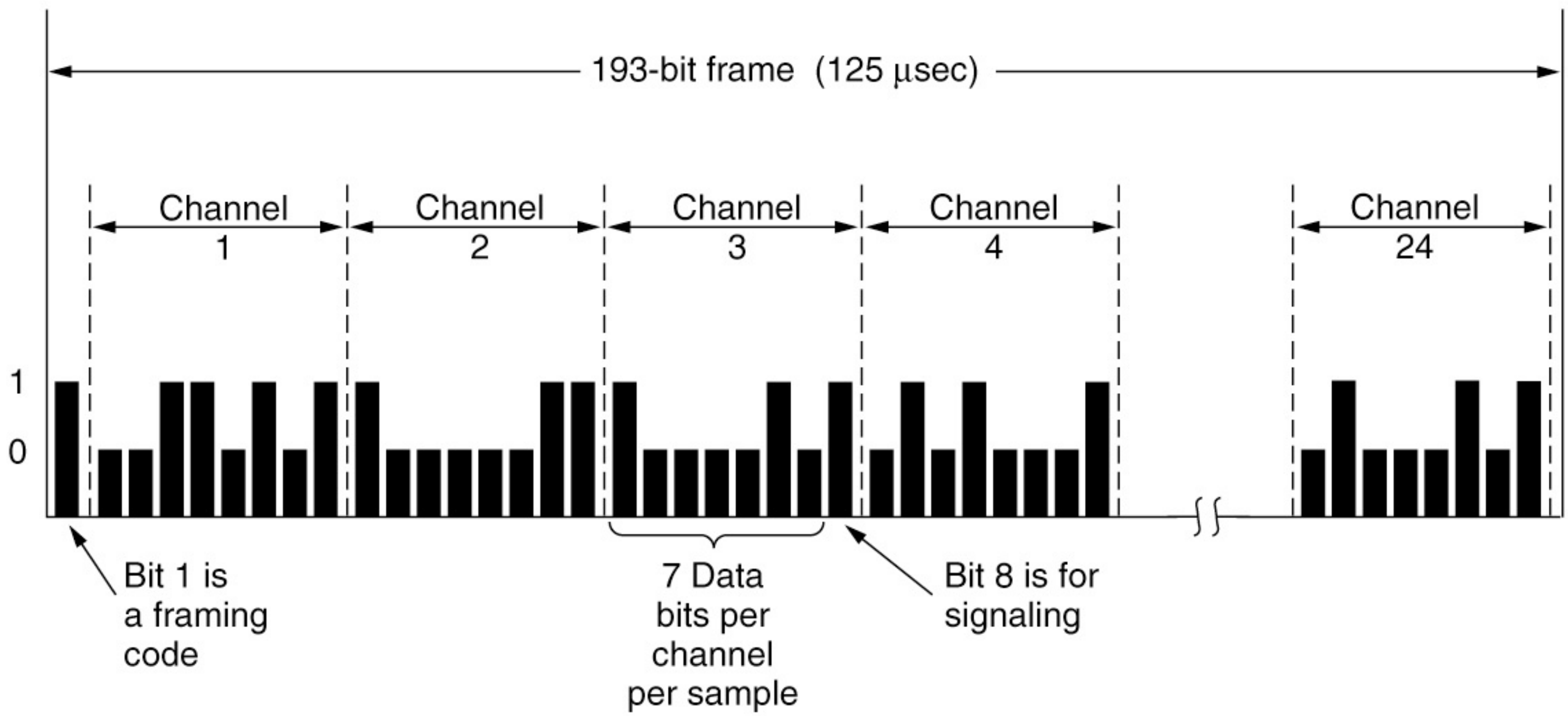
Trunks and Multiplexing

- Digitizing Voice Signals
- T-Carrier: Multiplexing Digital Signals on the Phone Network
- Multiplexing Optical Networks: SONET/SDH

Digitizing Voice Signals

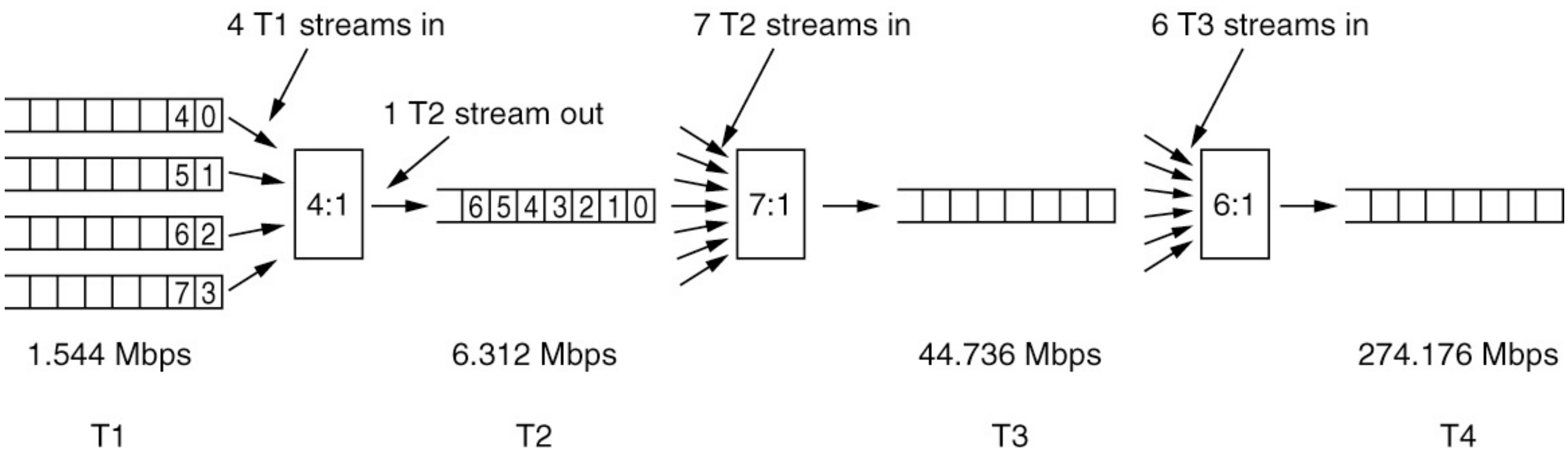
- TDM technique in widespread use today
  - Conversion from analog to digital in the end office is needed
  - Use a codec to digitize analog signals
  - PCM (Pulse Code Modulation) technique used
  - Each sample of the amplitude of the signal is quantized to an 8-bit number
  - Two versions of quantization are used: μ-law and A-law
  - Companding
    - Compressing the dynamic range of the signal before it is (evenly) quantized
    - Expanding it when the analog signal is recreated
  - Analog signal recreated from the quantized samples by playing them out (and smoothing them) over time

T-Carrier: Multiplexing Digital Signals on the Phone Network (1 of 2)



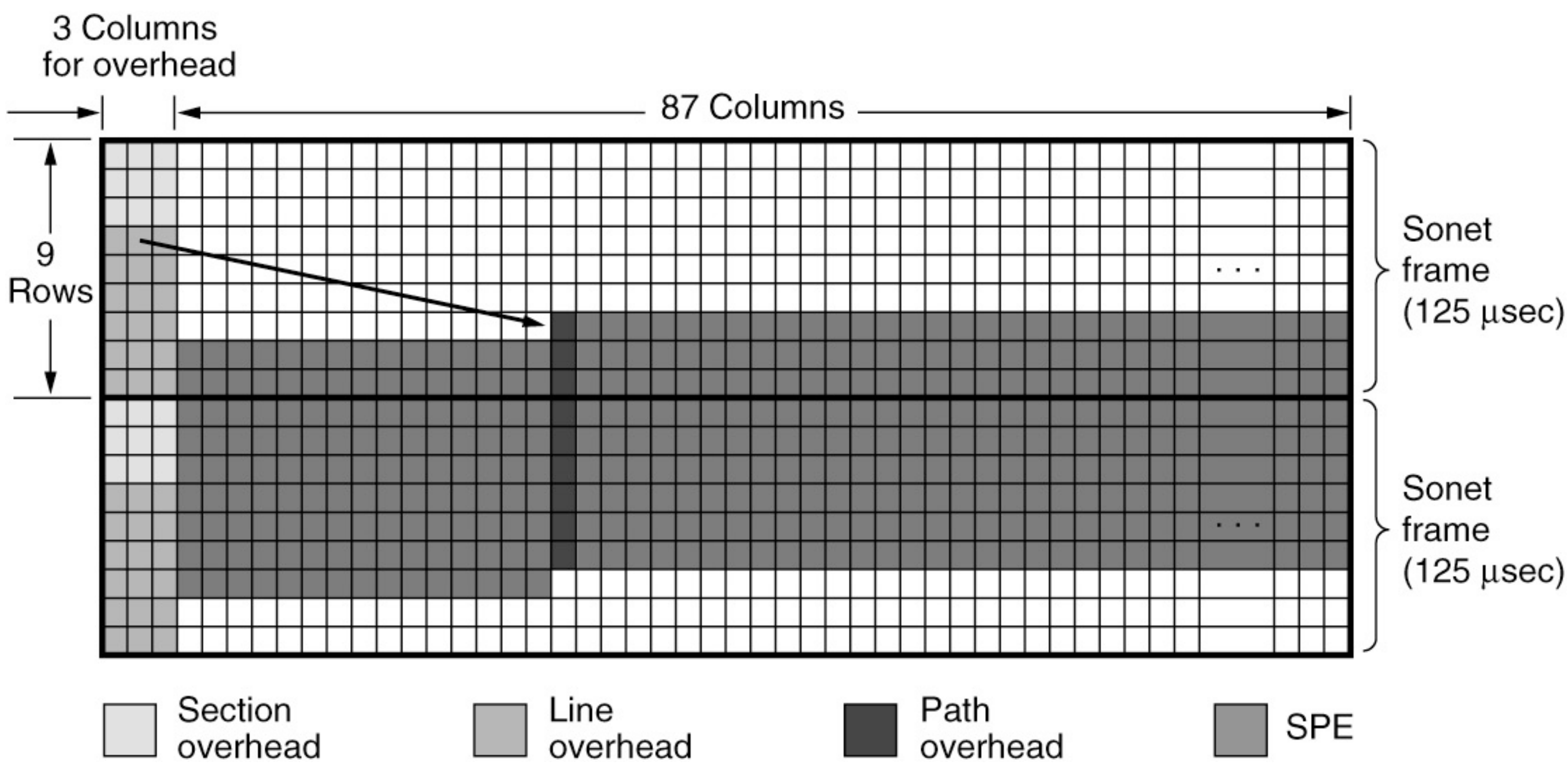
The T1 carrier (1.544 Mbps).

T-Carrier: Multiplexing Digital Signals on the Phone Network (2 of 2)



Multiplexing T1 streams into higher carriers.

Multiplexing Optical Networks: SONET/SDH (1 of 2)



Two back-to-back SONET frames.

Multiplexing Optical Networks: SONET/SDH (2 of 2)

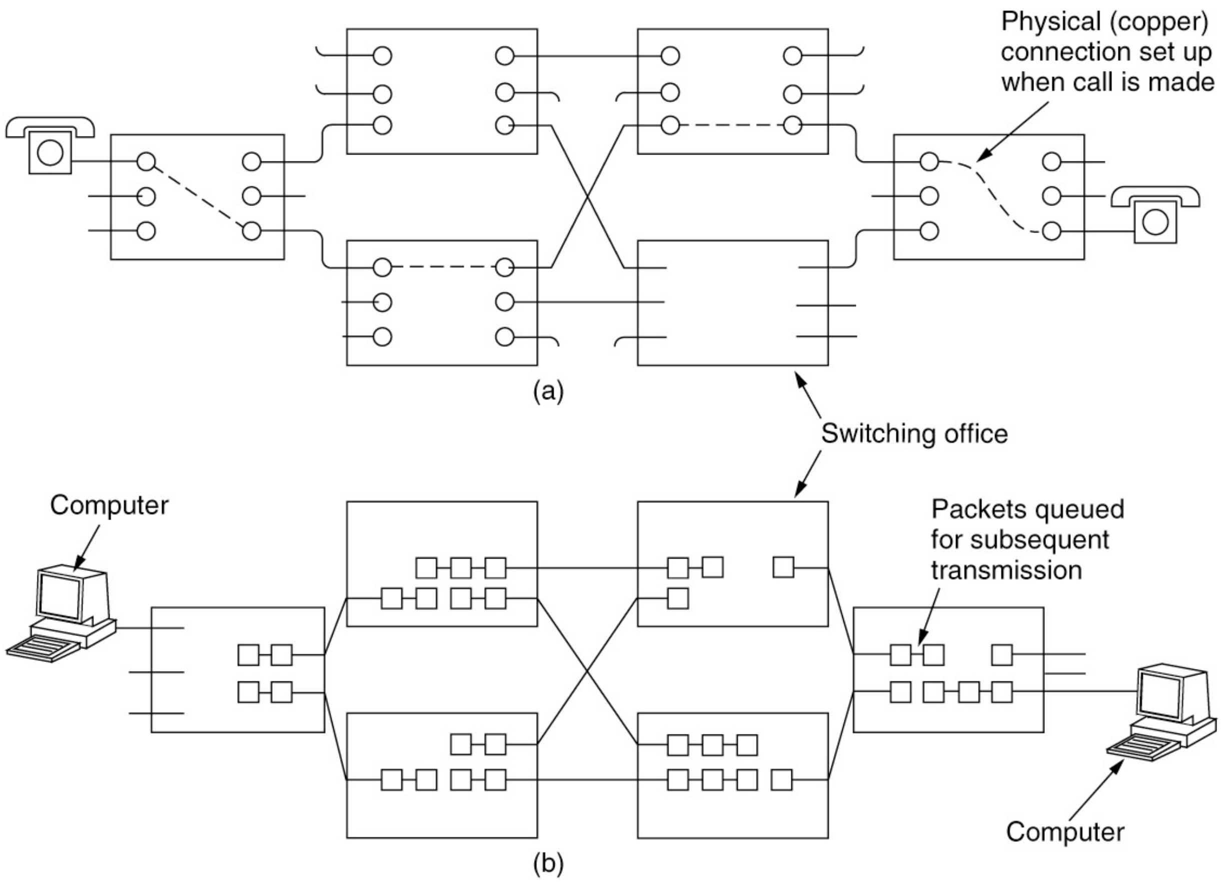
SONET		SDH	Data rate (Mbps)		
Electrical	Optical	Optical	Gross	SPE	User
STS-1	OC-1		51.84	50.112	49.536
STS-3	OC-3	STM-1	155.52	150.336	148.608
STS-12	OC-12	STM-4	622.08	601.344	594.432
STS-48	OC-48	STM-16	2488.32	2405.376	2377.728
STS-192	OC-192	STM-64	9953.28	9621.504	9510.912
STS-768	OC-768	STM-256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

SONET and SDH multiplex rates.

Switching

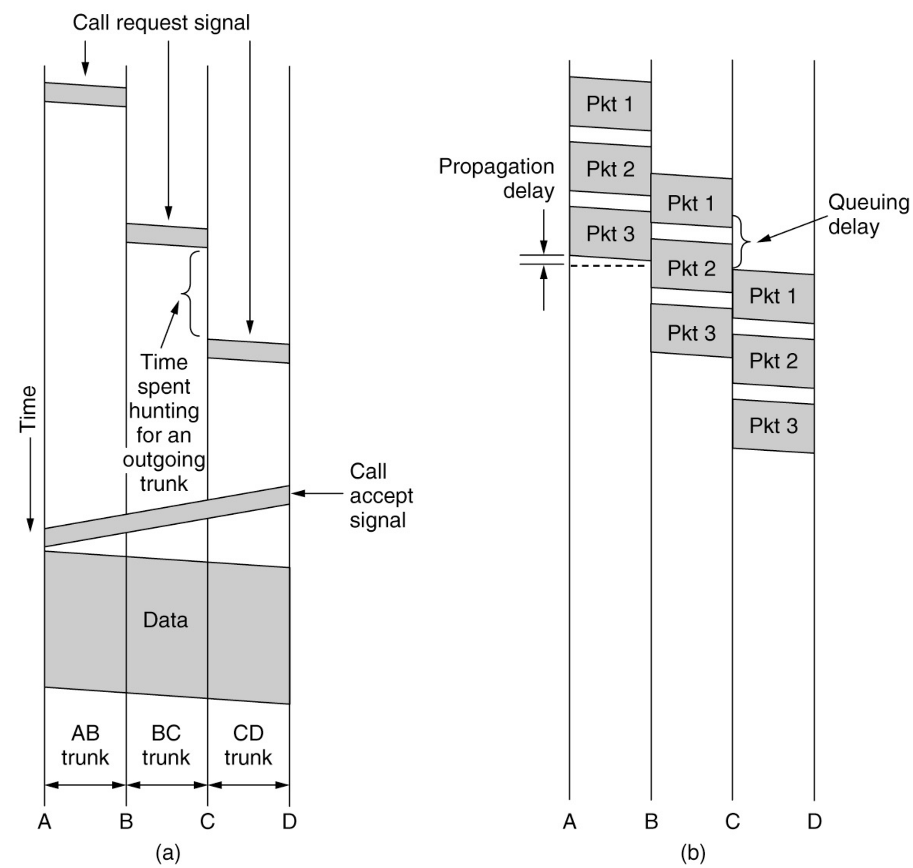
- Phone system principal parts
  - Outside plant (outside switching offices)
  - Inside plant (inside switching offices)
- Two different switching techniques
  - Circuit switching: traditional telephone system
  - Packet switching: voice over IP technology

Circuit Switching (1 of 2)



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

Circuit Switching (2 of 2)



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

Packet Switching

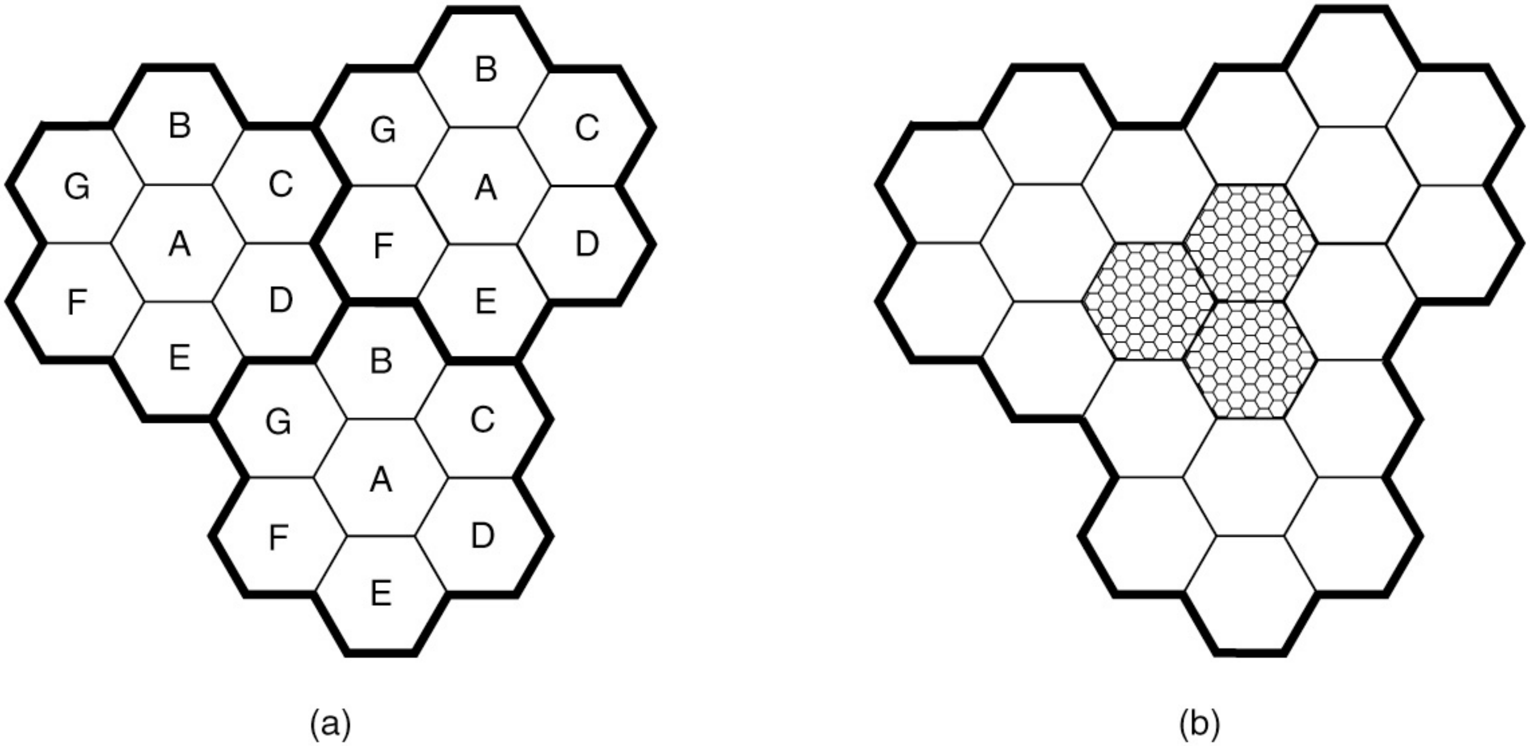
Item	Circuit switched	Packet switched
Call setup	Required	Not needed
Dedicated physical path	Yes	No
Each packet follows the same route	Yes	No
Packets arrive in order	Yes	No
Is a switch crash fatal	Yes	No
Bandwidth available	Fixed	Dynamic
Time of possible congestion	At setup time	On every packet
Potentially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

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

Cellular Networks

- Mobile phone distinct generations
- The initial three generations: 1G, 2G, 3G
  - Provided analog voice, digital voice, and both digital voice and data (Internet, email, etc.) respectively
- 4G technology adds capabilities
  - Physical layer transmission techniques and IP-based femtocells
  - 4G is based on packet switching only (no circuit switching)
- 5G being rolled out now
  - Supports up to 20 Gbps transmissions and denser deployments
  - Focus on reducing network latency

Common Concepts: Cells, Handoff, Paging



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

First-Generation (1G) Technology: Analog Voice

- 1946 push to talk systems
- 1960 IMTS (Improved Mobile Telephone System)
  - Two frequencies: one for sending, one for receiving
- 1983 AMPS (Advanced Mobile Phone System)
  - Analog mobile phone system
  - Cells are typically 10 to 20 km across
  - Used FDM to separate channels
  - 832 full-duplex channels that consist of a pair of simplex channels used (Frequency Division Duplex)
  - Each simplex channel is 30 kHz wide
  - 832 channels in AMPS are divided into four categories

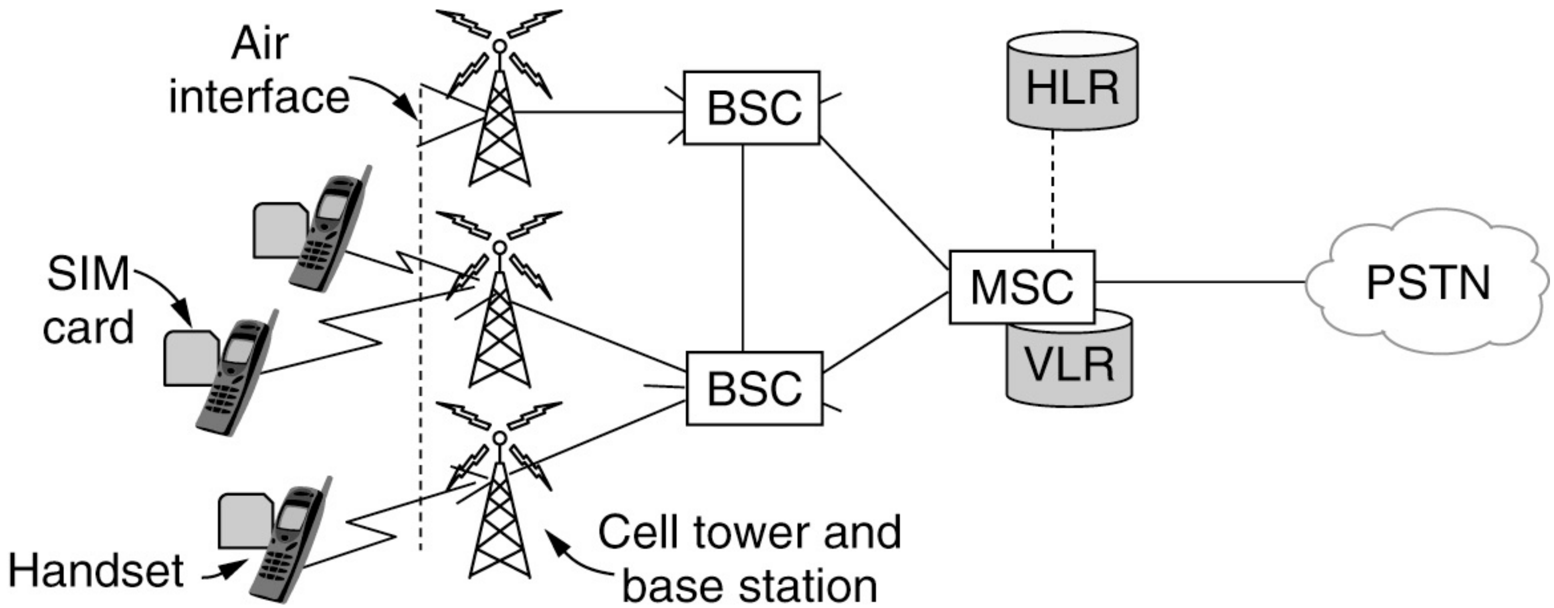
Call Management

- Outgoing calls
  - Phone switched on, number entered, CALL button hit
  - Phone transmits called number and its own identity on the access channel
  - Base informs the MSC and MSC looks for a channel for the call
- Incoming calls
  - Idle phones continuously listen to the paging channel to detect messages directed at them
  - Packet sent to base station in the current cell as a broadcast on the paging channel
  - The called phone responds on the access channel
  - Called phone switches to channel and starts ringing sound

Second-Generation (2G) Technology: Digital Voice

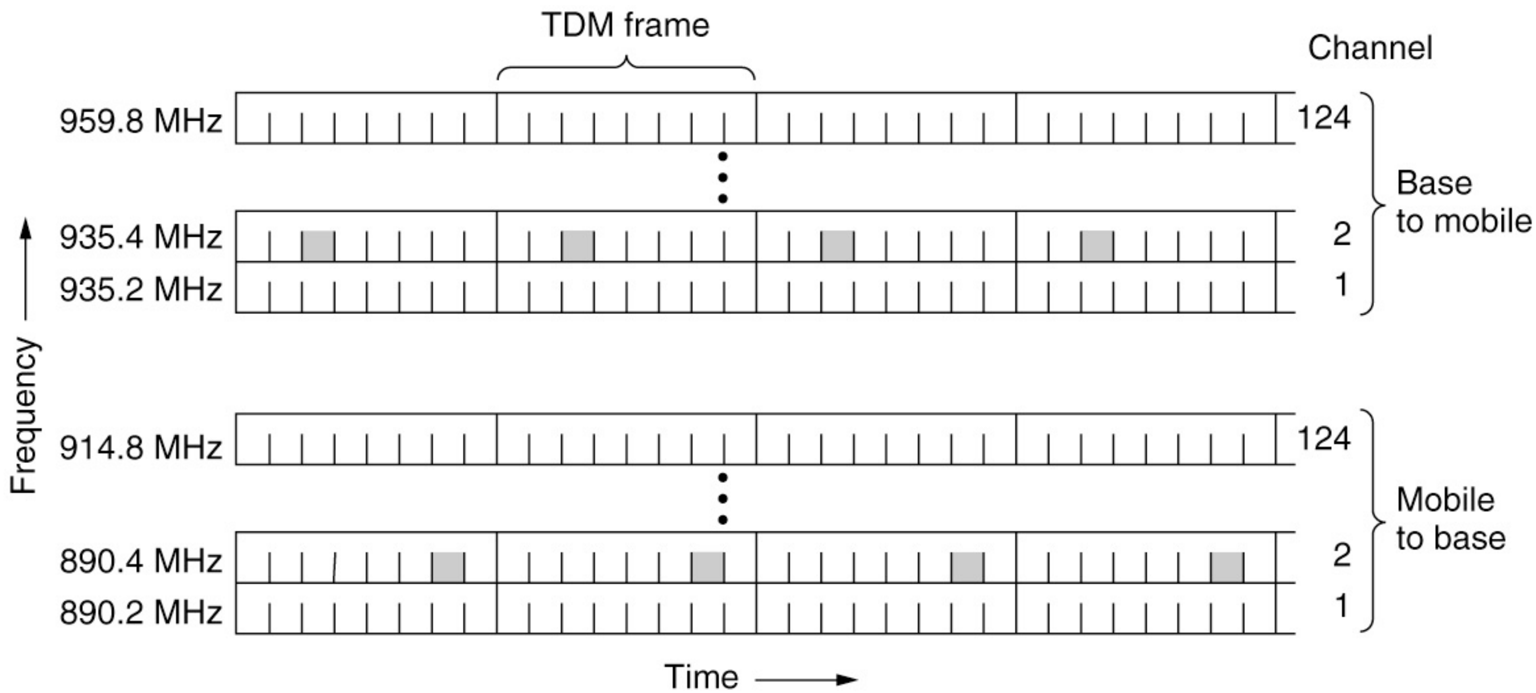
- Digital advantages
  - Provides capacity gains by allowing voice signals to be digitized and compressed
  - Improves security by allowing voice and control signals to be encrypted
  - Deters fraud and eavesdropping, whether from intentional scanning or echoes of other calls due to RF propagation
  - Enables new services such as text messaging
- Three systems developed
  - D-AMPS (Digital Advanced Mobile Phone System)
  - GSM (Global System for Mobile communications)
  - CDMA (Code Division Multiple Access)

GSM: The Global System for Mobile Communications (1 of 3)



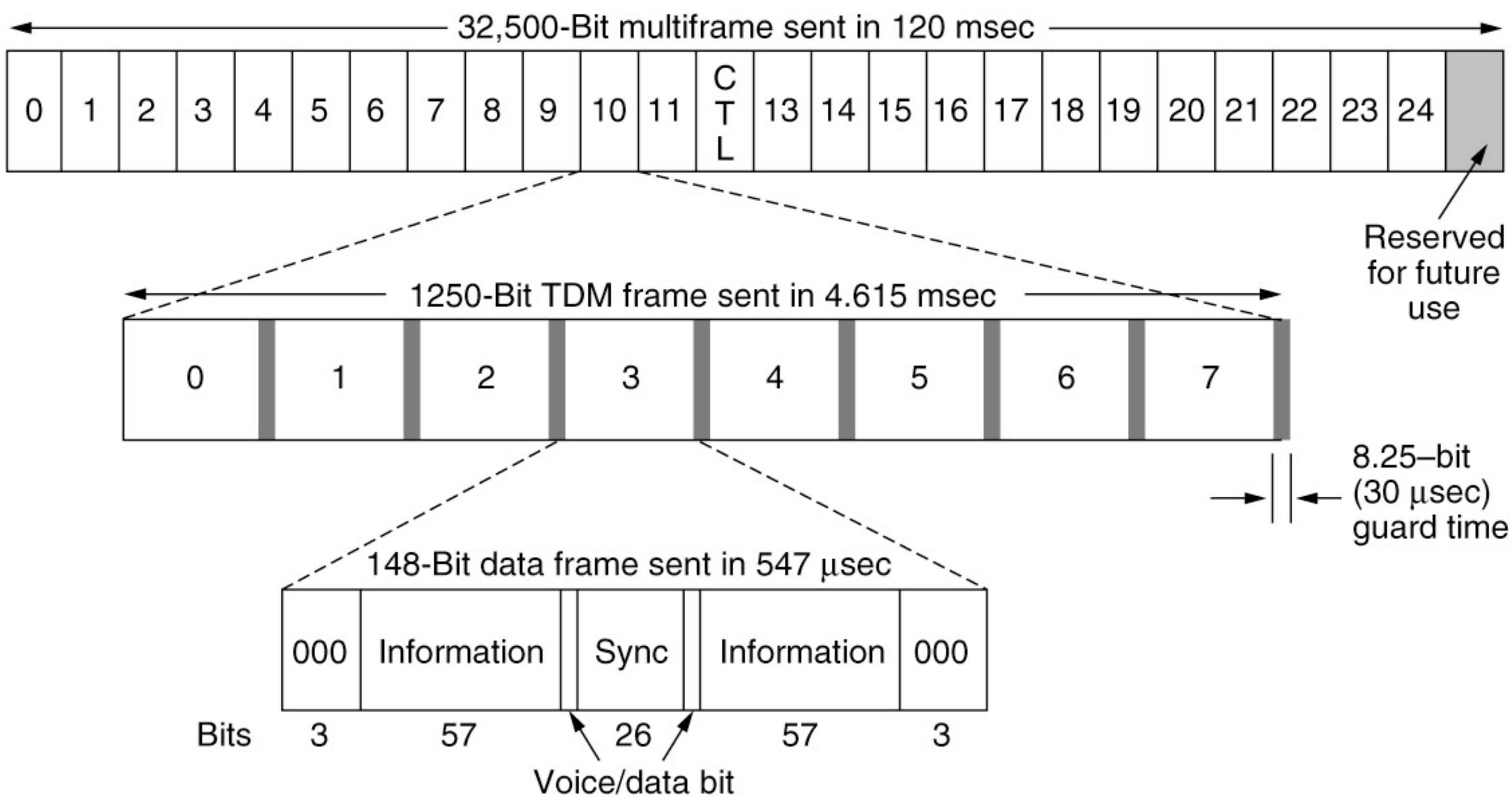
GSM mobile network architecture.

GSM: The Global System for Mobile Communications (2 of 3)



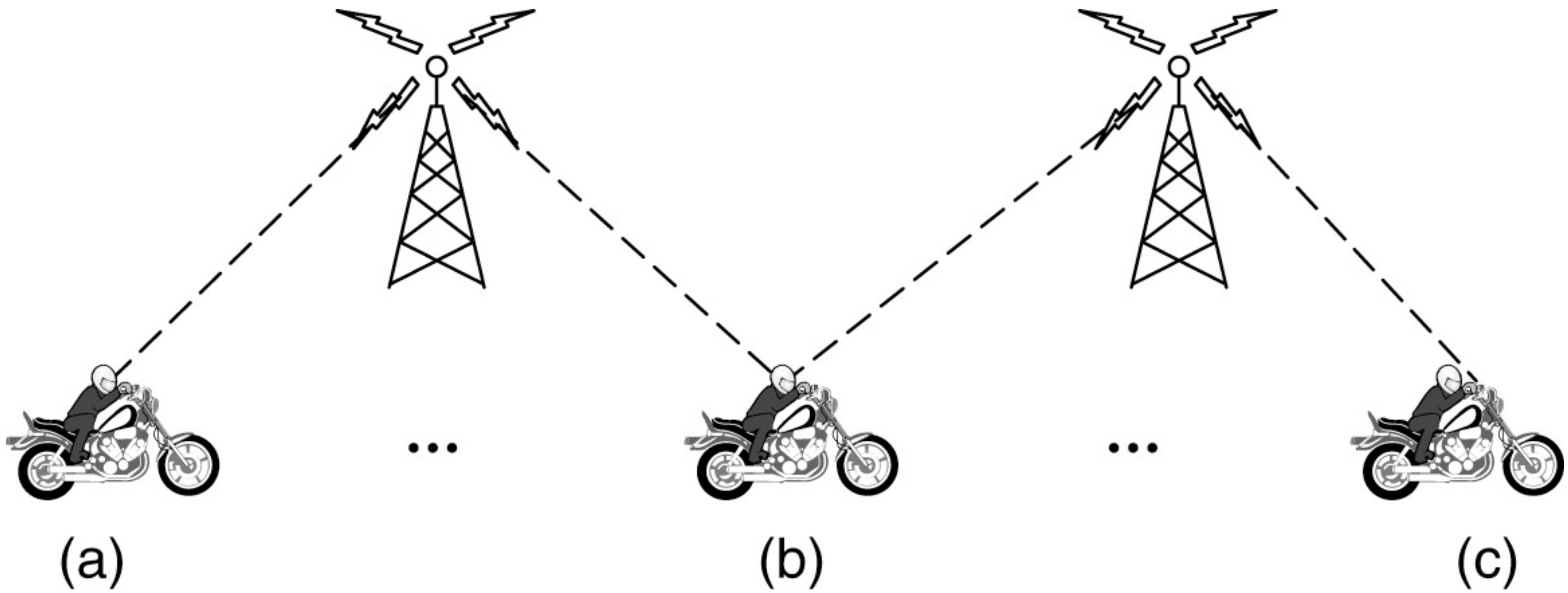
GSM uses 124 frequency channels, each of which uses an eight-slot TDM system.

GSM: The Global System for Mobile Communications (3 of 3)



A portion of the GSM framing structure.

Third-Generation (3G) Technology: Digital Voice and Data



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

Fourth-Generation (4G) Technology: Packet Switching

- Also called IMT Advanced
- Based completely on packet-switched technology
- EPC (Evolved Packet Core) allows packet switching
  - Simplified IP network separating voice traffic from the data network
  - Carries both voice and data in IP packets
  - Voice over IP (VoIP) network with resources allocated using the statistical multiplexing approaches
  - The EPC must manage resources in such a way that voice quality remains high in the face of network resources that are shared among many users
    - If you read this section, it just keeps getting more complex.

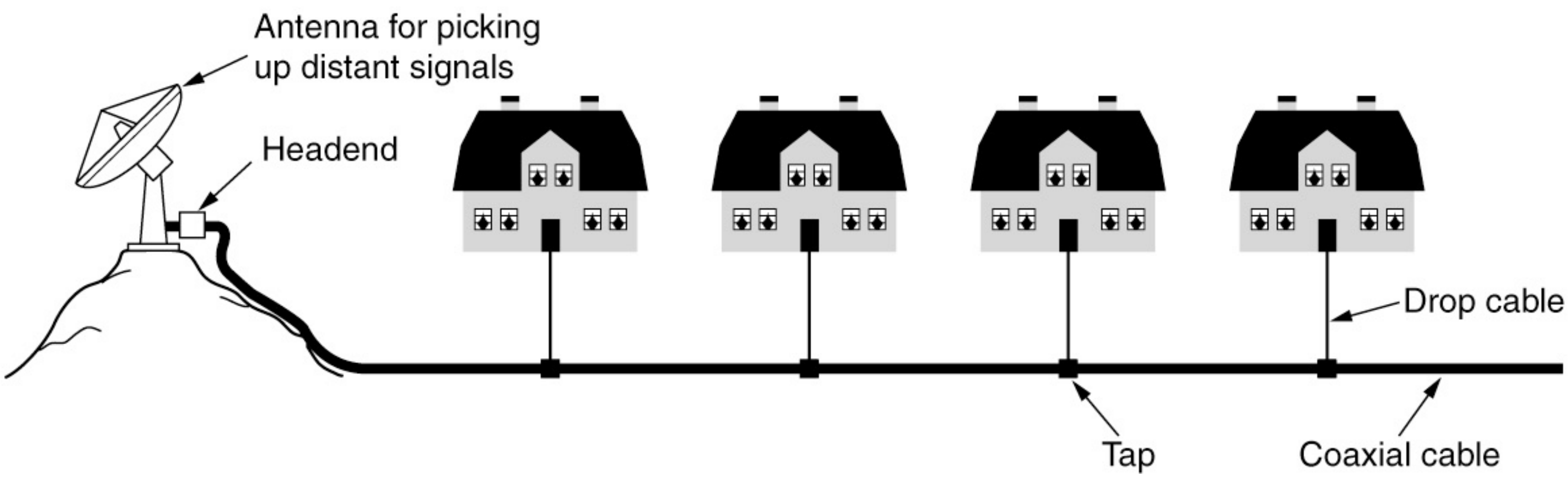
Fifth-Generation (5G) Technology

- Two main factors
  - Higher data rates and ‘lower latency’ than 4G technologies
    - What technology lowers latency?
- Technology used to increase network capacity
  - Ultra-densification and offloading
  - Increased bandwidth with millimeter waves
  - Increased spectral efficiency through advances in massive MIMO (Multiple-Input Multiple-Output) technology
- Network slicing “feature”
  - Lets cellular carriers create multiple virtual networks on top of the same shared physical infrastructure
  - Can devote network portions to specific customer use cases
    - What do we know about static allocation of resources?

Cable Networks

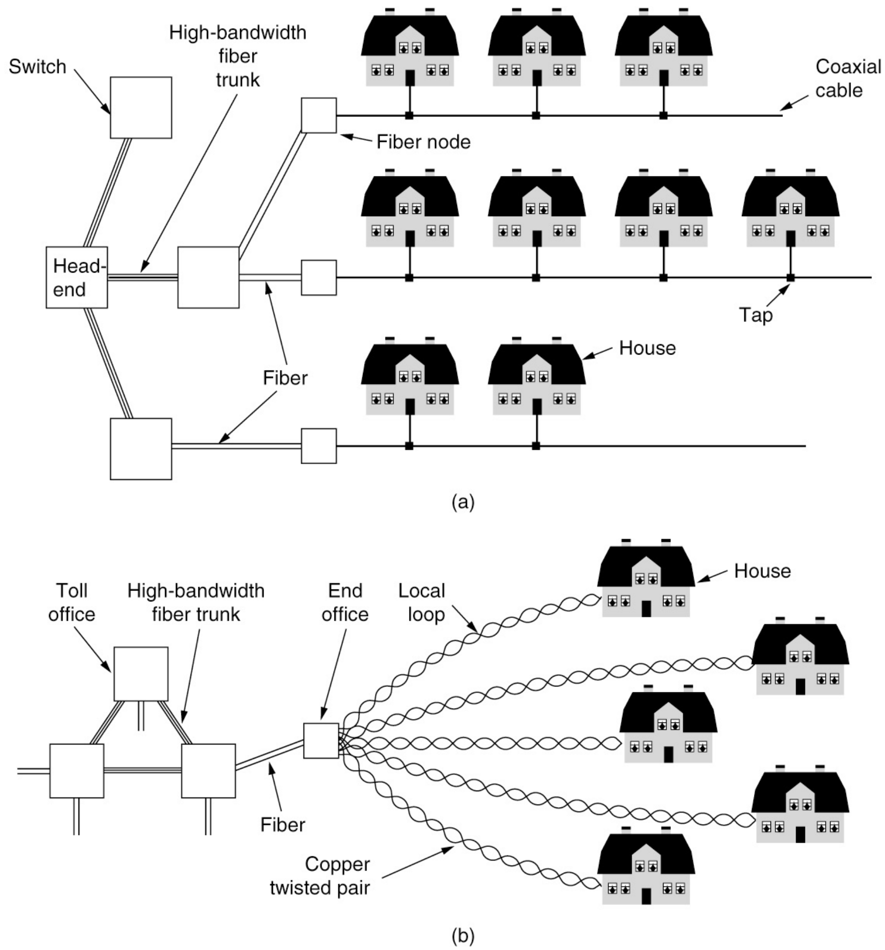
- Cable networks
  - Will factor heavily into future broadband access networks
- Many people nowadays get their television, telephone, and Internet service over cable
- 2018 DOCSIS standard
  - Provides information related to modern cable network architectures

A History of Cable Networks: Community Antenna Television



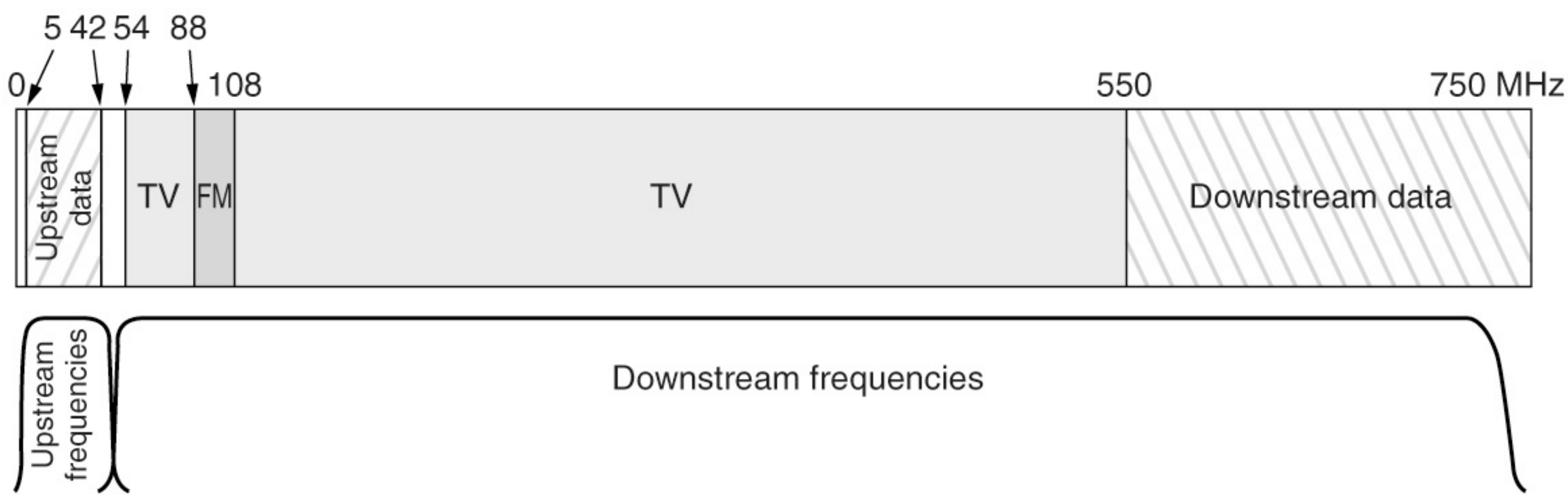
An early cable television system.

Broadband Internet Access Over Cable: HFC Networks (1 of 2)



(a) Hybrid Fiber-Coax cable network. (b) The fixed phone system.

Broadband Internet Access Over Cable: HFC Networks (2 of 2)

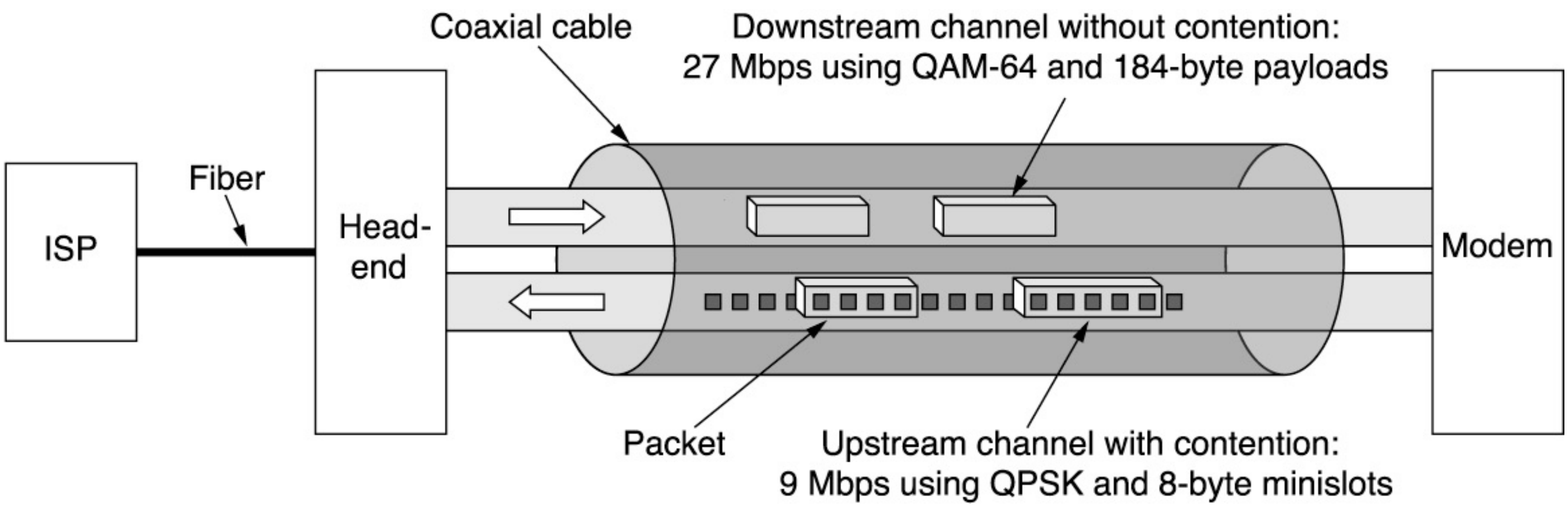


Frequency allocation in a typical cable TV system used for Internet access.

DOCSIS

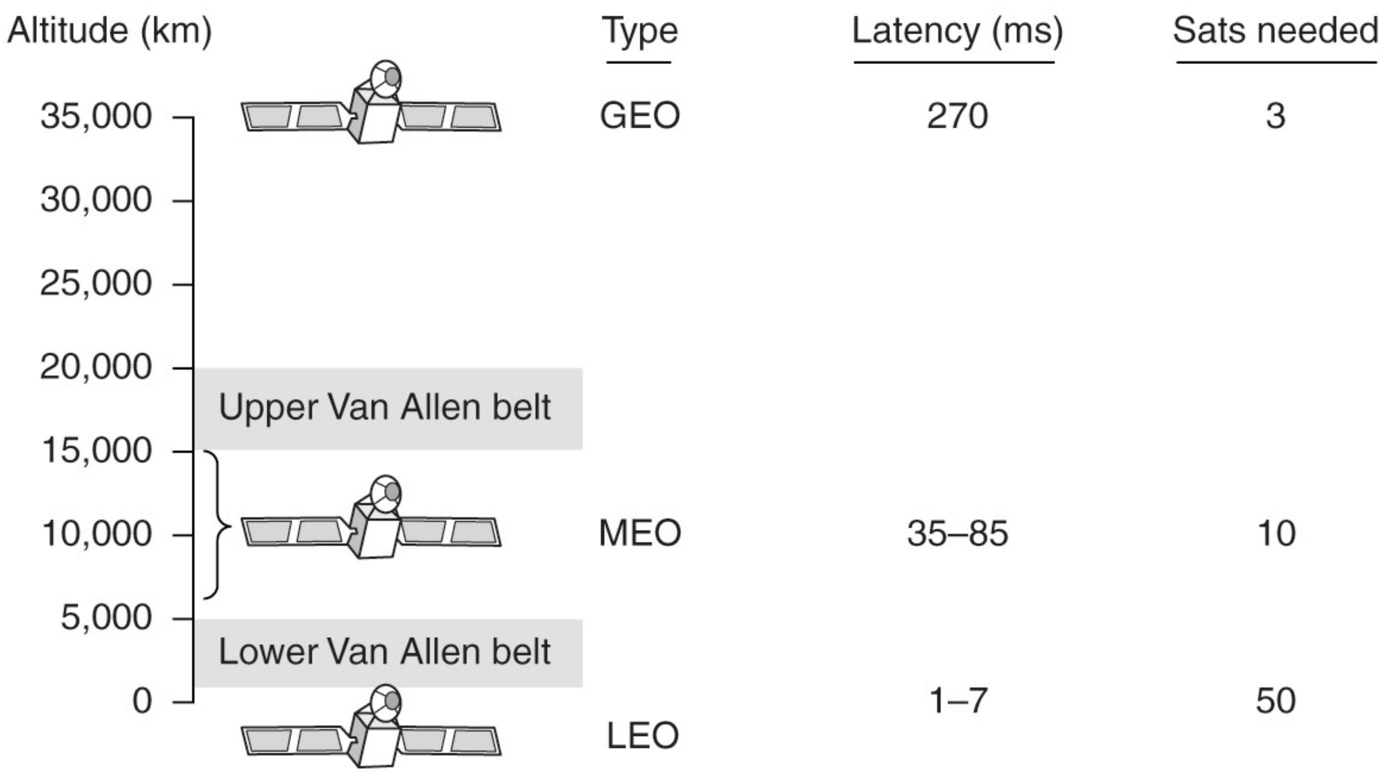
- DOCSIS (Data Over Cable Service Interface Specification) 3.1 latest version
  - Introduced Orthogonal Frequency Division Multiplexing (OFDM)
  - Introduced wider channel bandwidth and higher efficiency
  - Enabled over 1 Gbps of downstream capacity per home
- Extensions to DOCSIS 3.1
  - Full Duplex operation (2017) and DOCSIS Low Latency (2018)
- Cable Internet subscribers require a DOCSIS cable modem
- Modem-to-home network interface: Ethernet connection

Resource Sharing in DOCSIS Networks: Nodes and Minislots



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

Communication Satellites



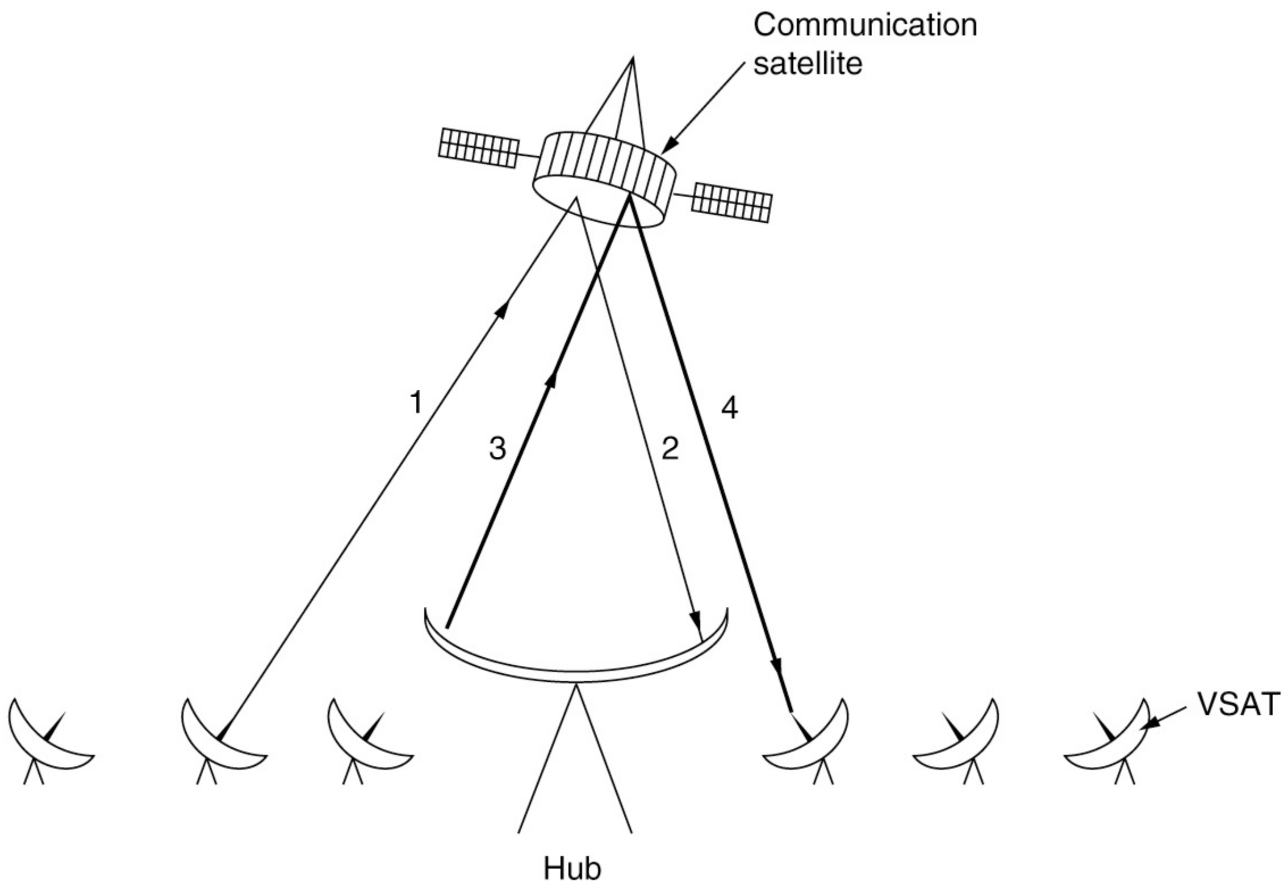
Communication satellites and some of their properties, including altitude above the earth, round-trip delay time, and number of satellites needed for global coverage.

Geostationary Satellites (1 of 2)

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 of 2)

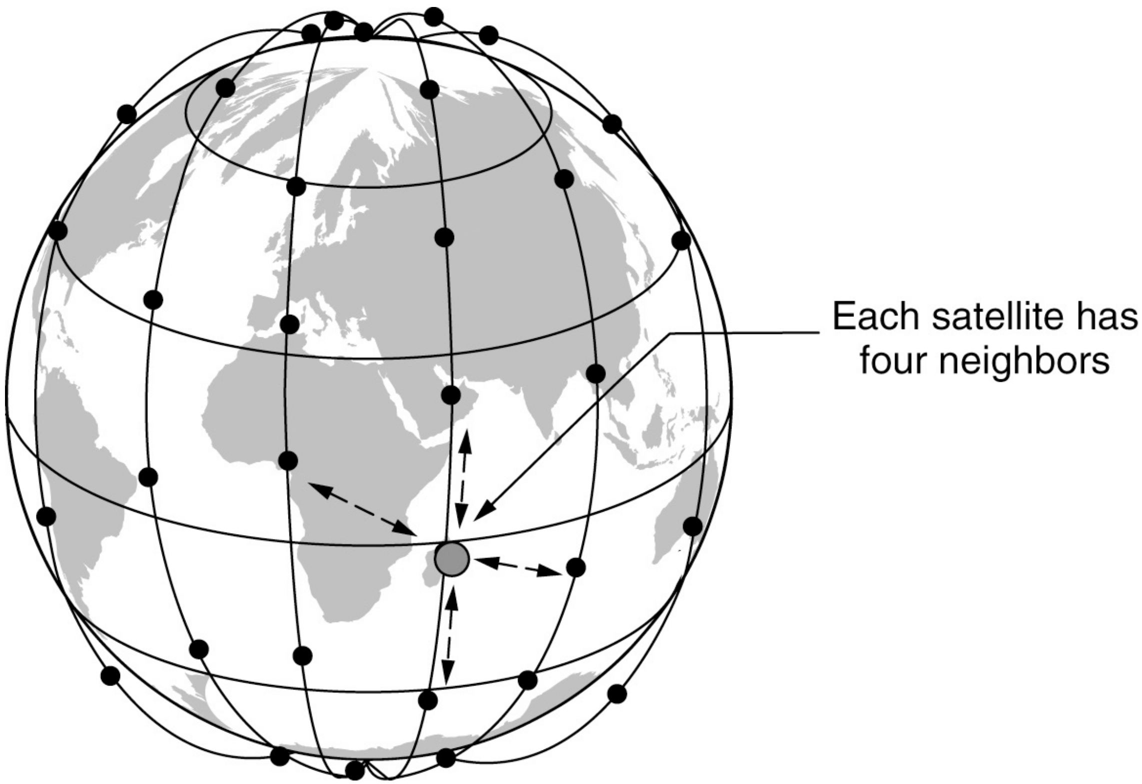


VSATs using a hub.

Medium-Earth Orbit Satellites

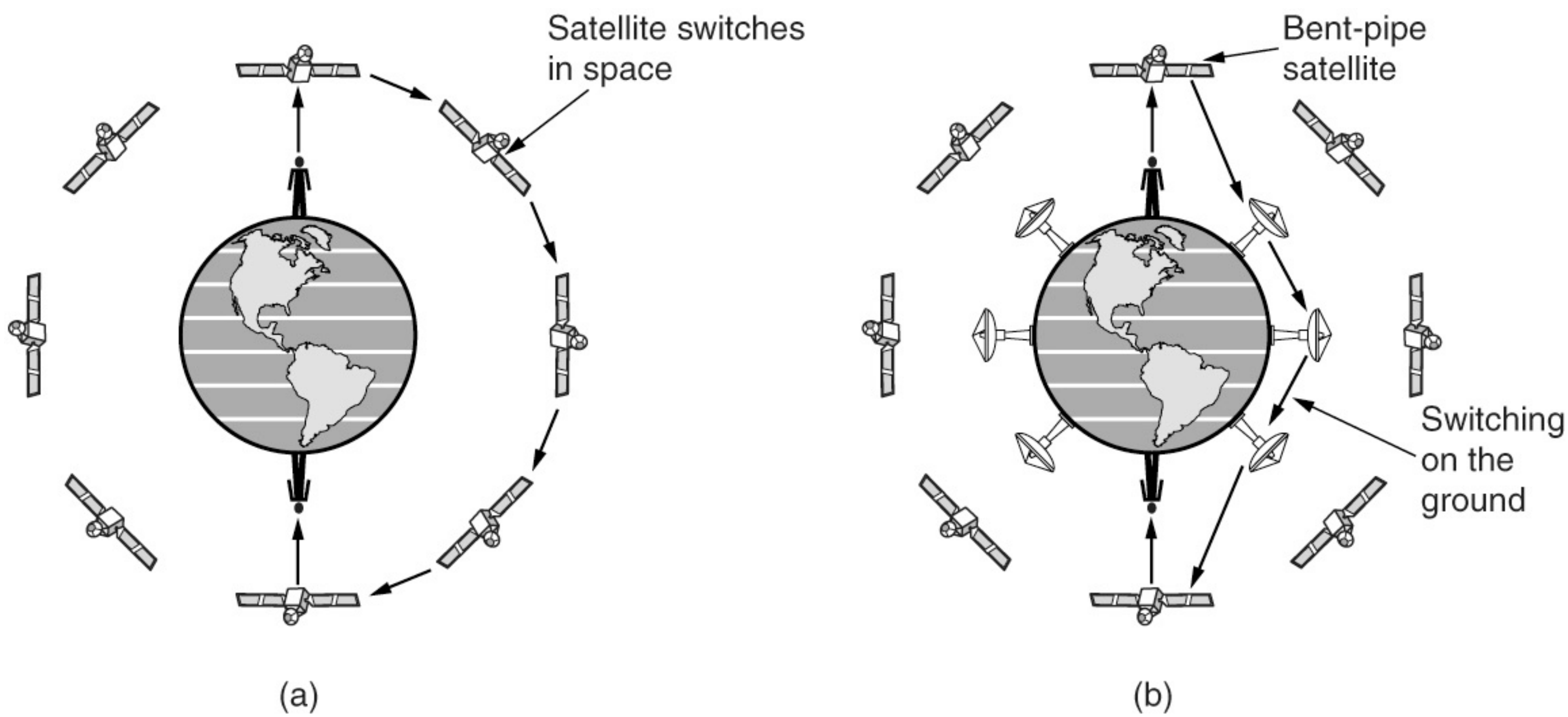
- MEO (Medium-Earth Orbit) satellites
  - Found at lower altitudes - between the two Van Allen belts
  - Drift slowly in longitude (6 hours to circle the earth)
  - Must be tracked as they move through the sky
  - Have a smaller footprint on the ground
  - Require less powerful transmitters to reach them
- Used for navigation systems
- Example:
  - Constellation of roughly 30 GPS (Global Positioning System) satellites orbiting at about 20,200 km

Low-Earth Orbit Satellites (1 of 2)



The Iridium satellites form six necklaces around the earth.

Low-Earth Orbit Satellites (2 of 2)



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

Terrestrial Access Networks: Cable, Fiber, and ADSL

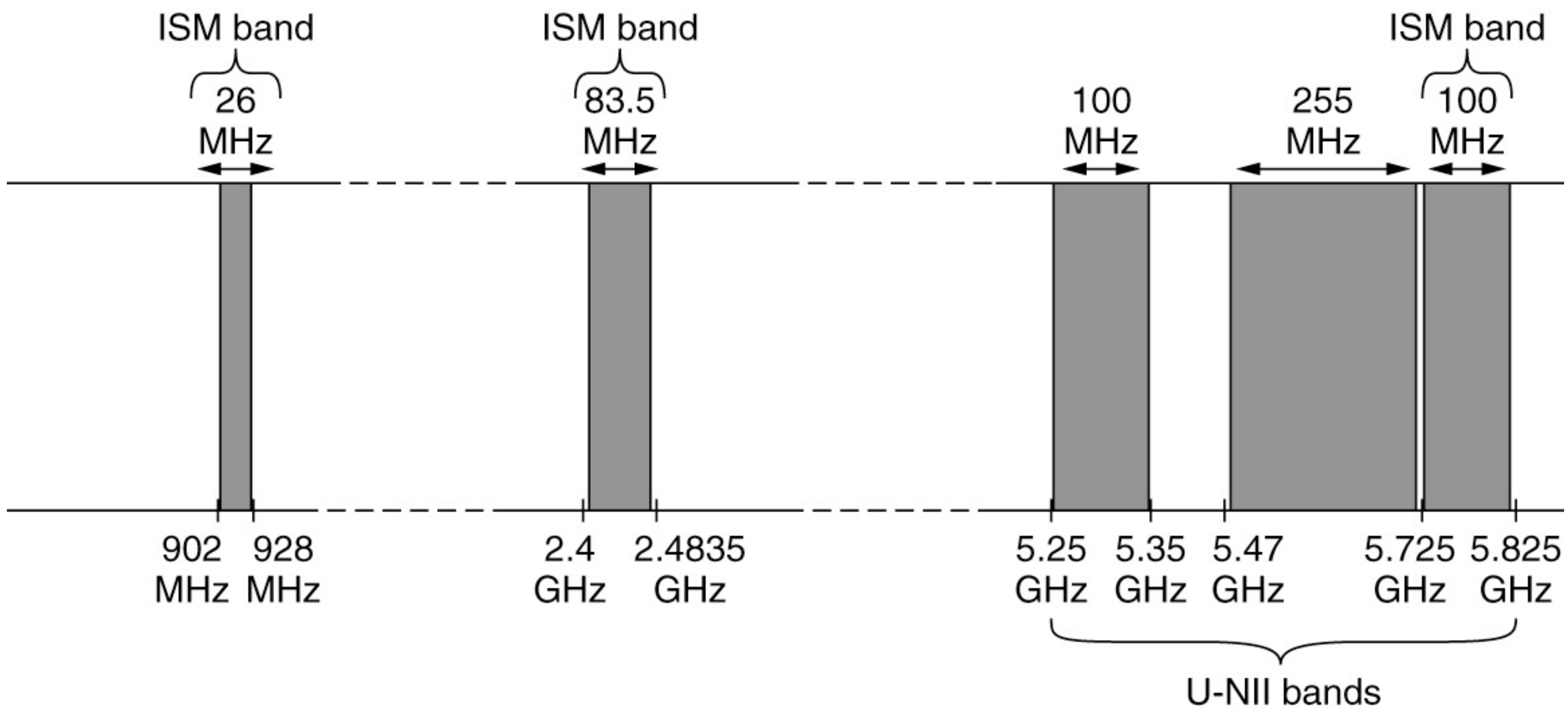
- Similarities
  - Comparable service and comparable prices
  - Use fiber in the backbone
- Differences
  - Last-mile access technology at the physical and link layers
  - Bandwidth consistency
  - Cable subscribers share the capacity of a single node
  - Maximum speeds
  - Availability
  - Security

Satellites Versus Terrestrial Networks

- Communication satellites niche markets
  - Rapid deployments
  - Places where the terrestrial infrastructure is poorly developed
  - When broadcasting is essential
- United States has some competing satellite-based Internet providers
- Satellite Internet access seeing a growing interest
  - In-flight Internet access

Policy (Politics) at the Physical Layer

Spectrum Allocation



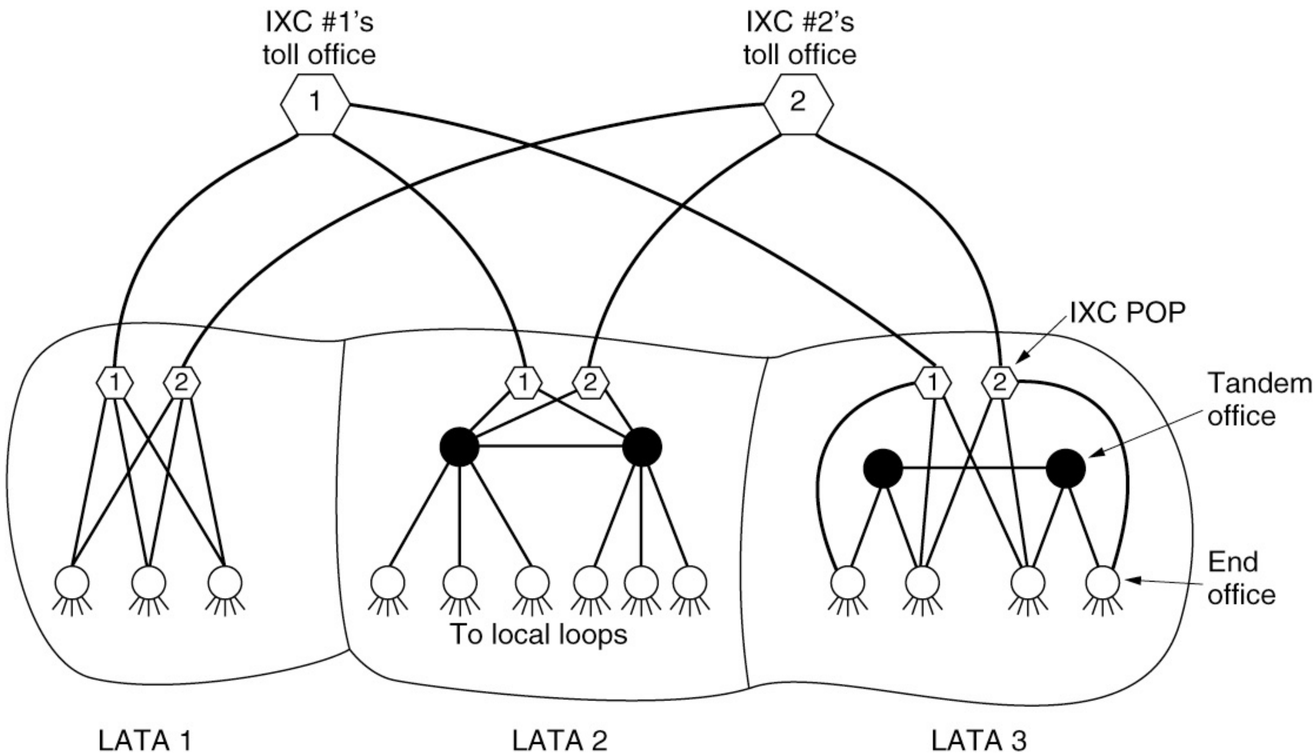
ISM and U-NII bands used in the United States by wireless devices.

The Cellular Network

- Political and tiny marketing decisions can have a huge impact on the deployment of cellular networks
- Areas where U.S. and Europe differ
  - Digital mobile phone systems
  - Phone numbers
  - Widespread use of prepaid mobile phones in Europe
- Future areas of concern
  - Auctioning of coveted spectrum bands for 5G
  - Rise of MVNOs (Mobile Virtual Network Operators)

Policy (Politics) at the Physical Layer

The Telephone Network



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

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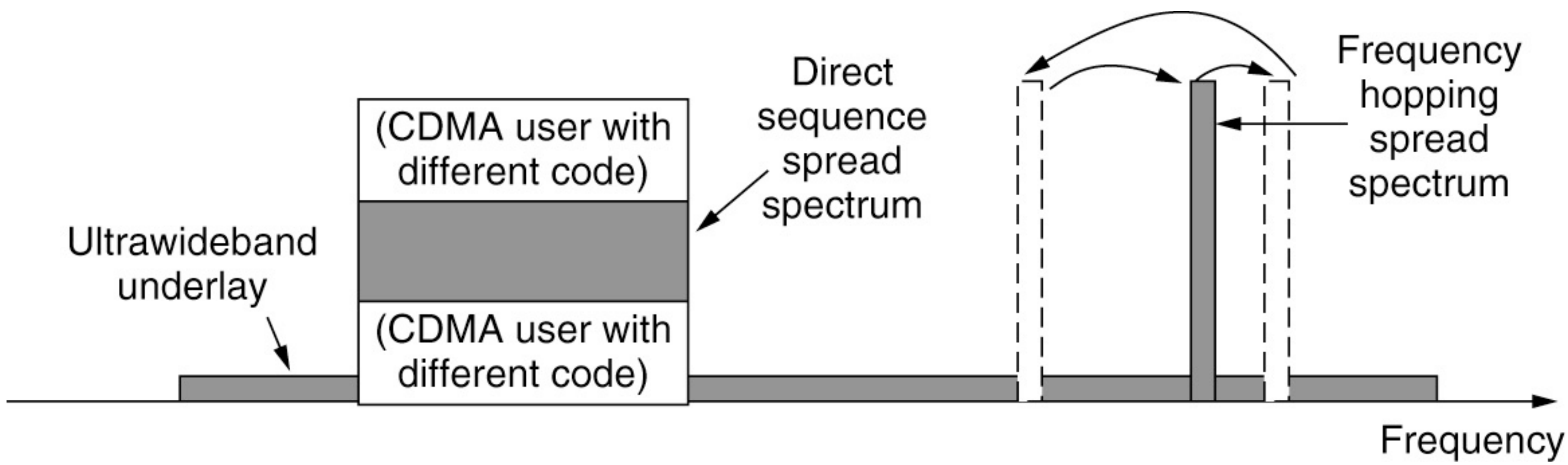
Direct Sequence Spread Spectrum



Direct sequence spread spectrum uses a code sequence to spread the data signal over a wider frequency band.