



The Physical Layer

Chapter 2

- ▶ Theoretical Basis for Data Communications
- ▶ Guided Transmission Media
- ▶ Wireless Transmission
- ▶ Communication Satellites
- ▶ Digital Modulation and Multiplexing
- ▶ Public Switched Telephone Network
- ▶ Mobile Telephone System
- ▶ Cable Television

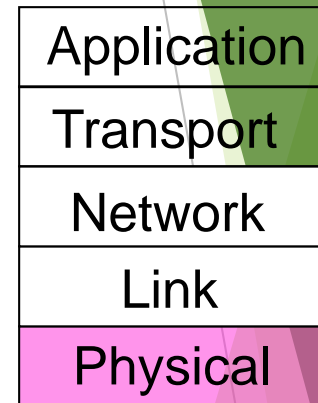
The Physical Layer

Foundation on which other layers build

- ▶ Properties of wires, fiber, wireless limit what the network can do

Key problem is to send (digital) bits using only (analog) signals

- ▶ This is called modulation



Theoretical Basis for Data Communication

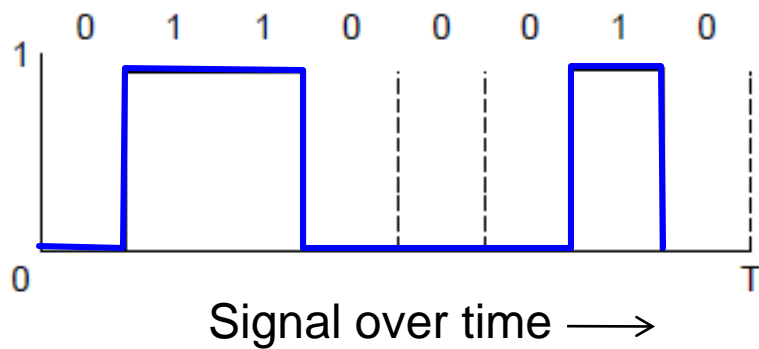
Communication rates have fundamental limits

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

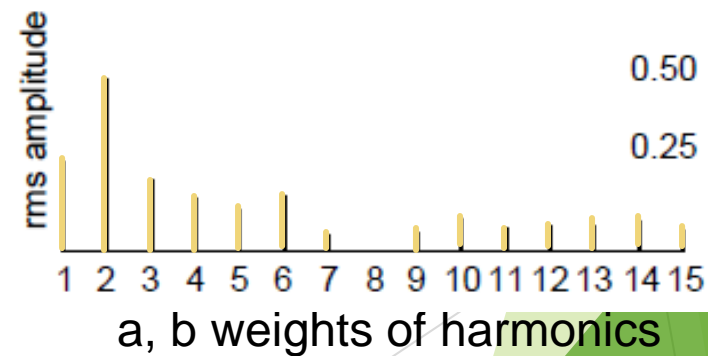
Fourier Analysis

- A time-varying signal can be equivalently represented as a series of frequency components (harmonics):

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

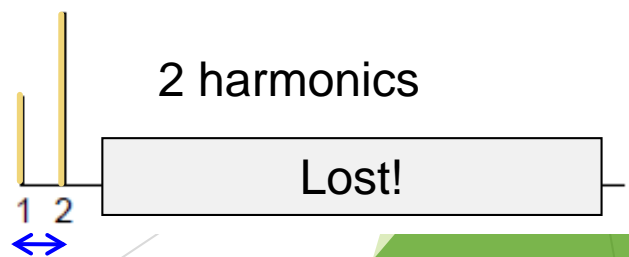
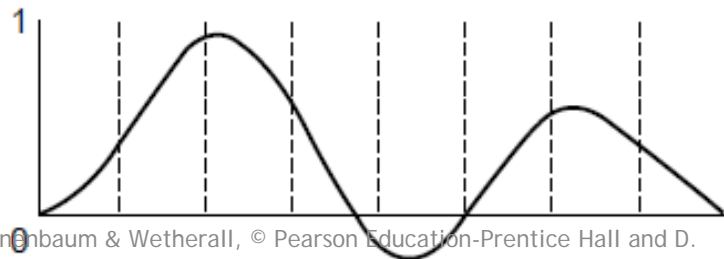
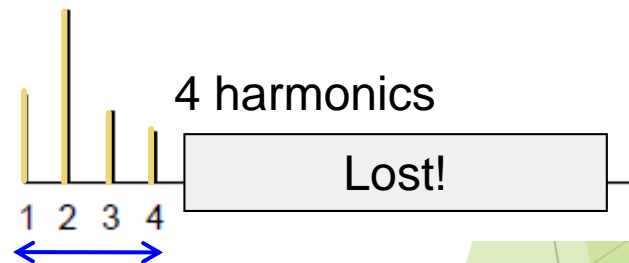
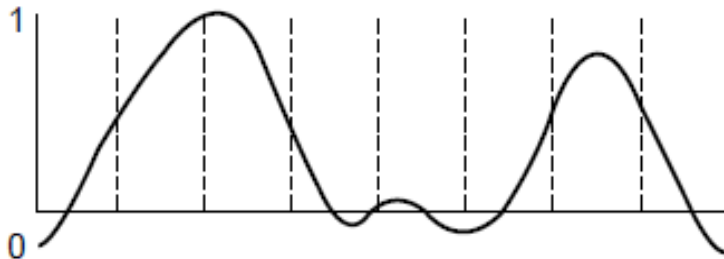
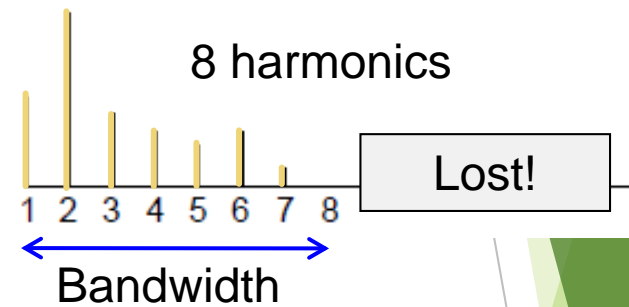
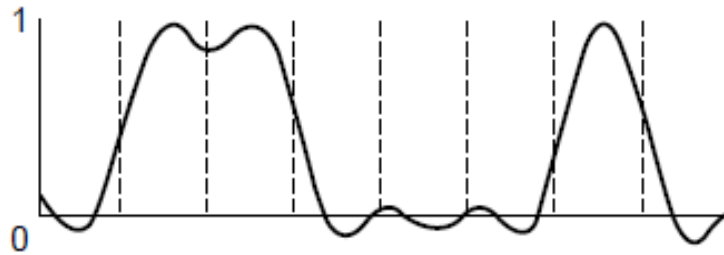


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Bandwidth-Limited Signals

- Having less bandwidth (harmonics) degrades the signal





Maximum Data Rate of a Channel

- ▶ Nyquist's theorem relates the data rate to the bandwidth (B) and number of signal levels (V):

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

- ▶ Shannon's theorem relates the data rate to the bandwidth (B) and signal strength (S) relative to the noise (N):

$$\text{Max. data rate} = B \log_2(1 + S/N) \text{ bits/sec}$$

↑
How fast signal
can change

↑
How many levels
can be seen

Guided Transmission (Wires & Fiber)

Media have different properties, hence performance

- ▶ Reality check
 - ▶ Storage media »
- ▶ Wires:
 - ▶ Twisted pairs »
 - ▶ Coaxial cable »
 - ▶ Power lines »
- ▶ Fiber cables »

Reality Check: Storage media

Send data on tape / disk / DVD for a high bandwidth link

- ▶ Mail one box with 1000 800GB tapes (6400 Tbit)
- ▶ Takes one day to send (86,400 secs)
- ▶ Data rate is 70 Gbps.

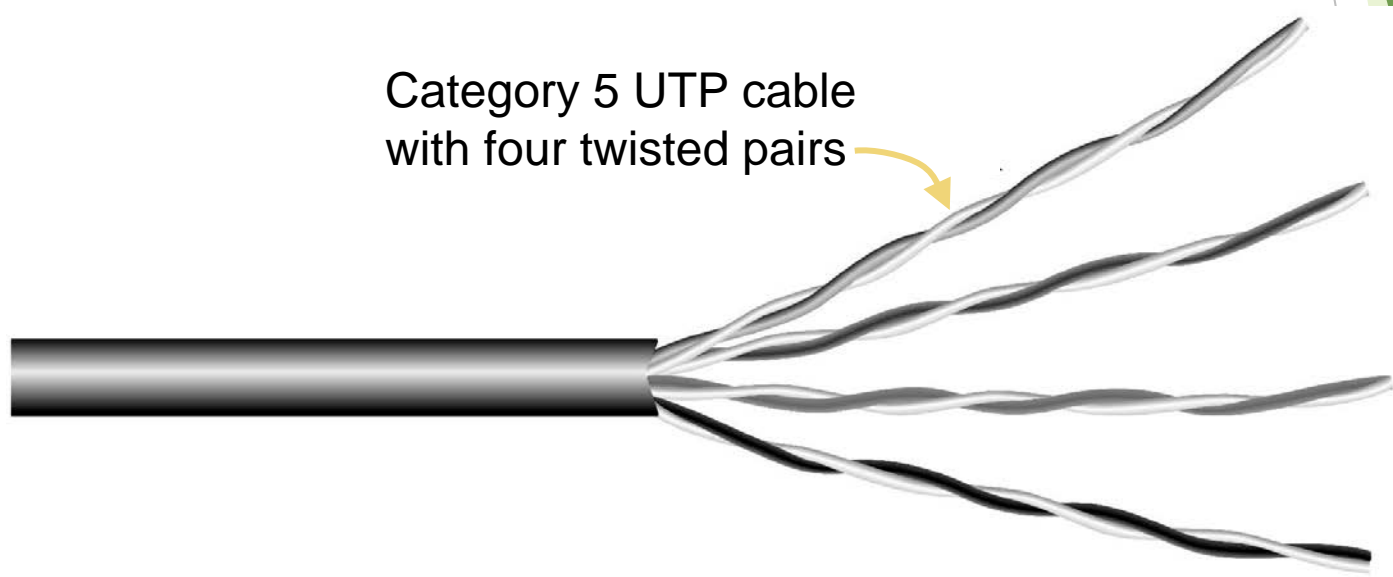
Data rate is faster than long-distance networks!

But, the message delay is very poor.

Wires – Twisted Pair

Very common; used in LANs, telephone lines

- ▶ Twists reduce radiated signal (interference)



Link Terminology

Full-duplex link

- ▶ Used for transmission in both directions at once
- ▶ e.g., use different twisted pairs for each direction

Half-duplex link

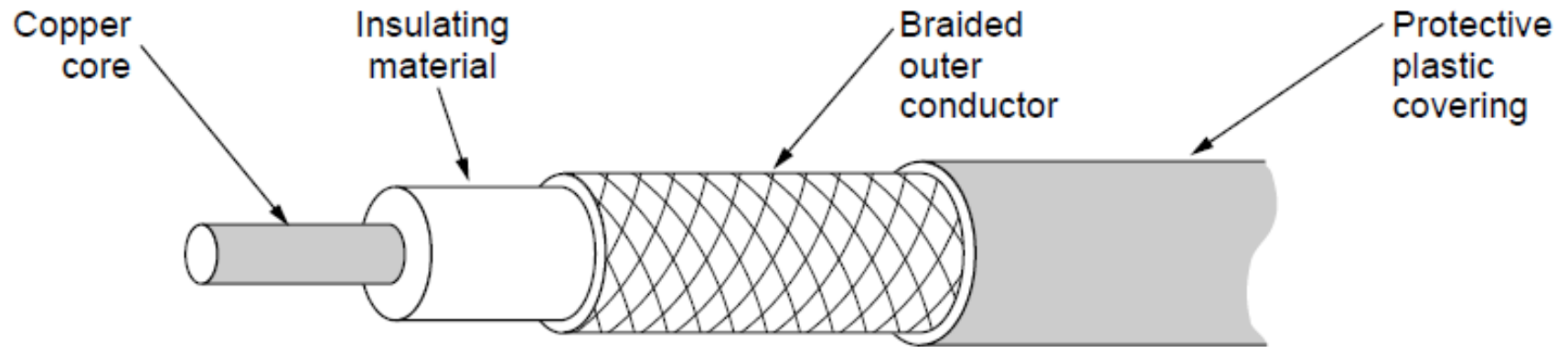
- ▶ Both directions, but not at the same time
- ▶ e.g., senders take turns on a wireless channel

Simplex link

- ▶ Only one fixed direction at all times; not common

Wires – Coaxial Cable (“Co-ax”)

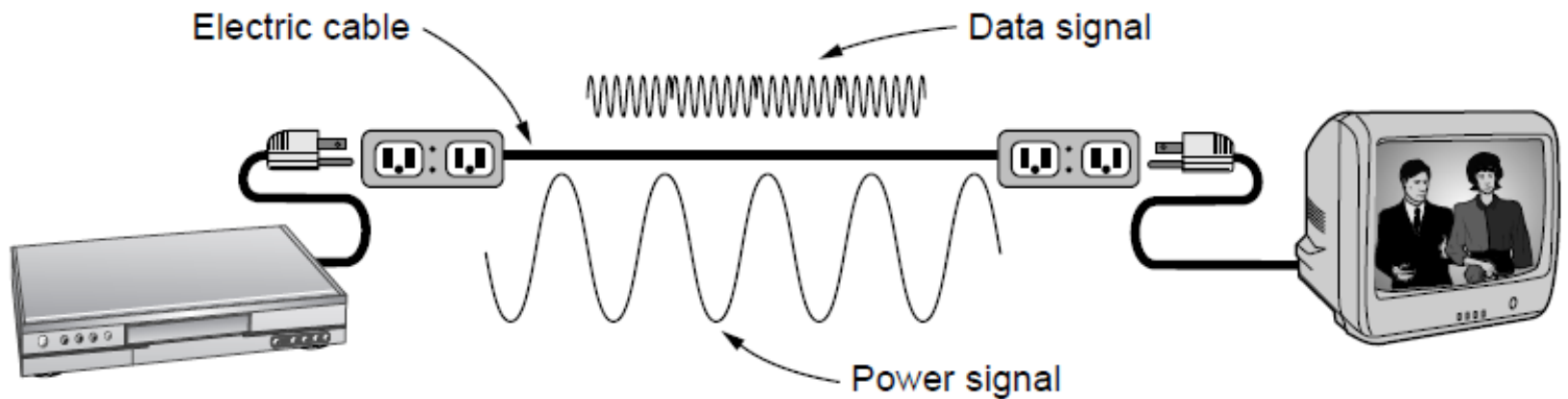
Also common. Better shielding and more bandwidth for longer distances and higher rates than twisted pair.



Wires – Power Lines

Household electrical wiring is another example of wires

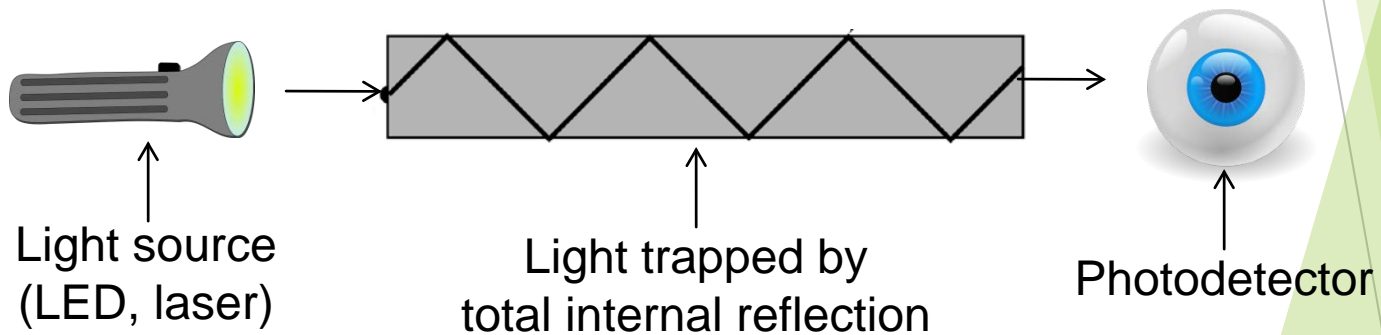
- ▶ Convenient to use, but horrible for sending data



Fiber Cables (1)

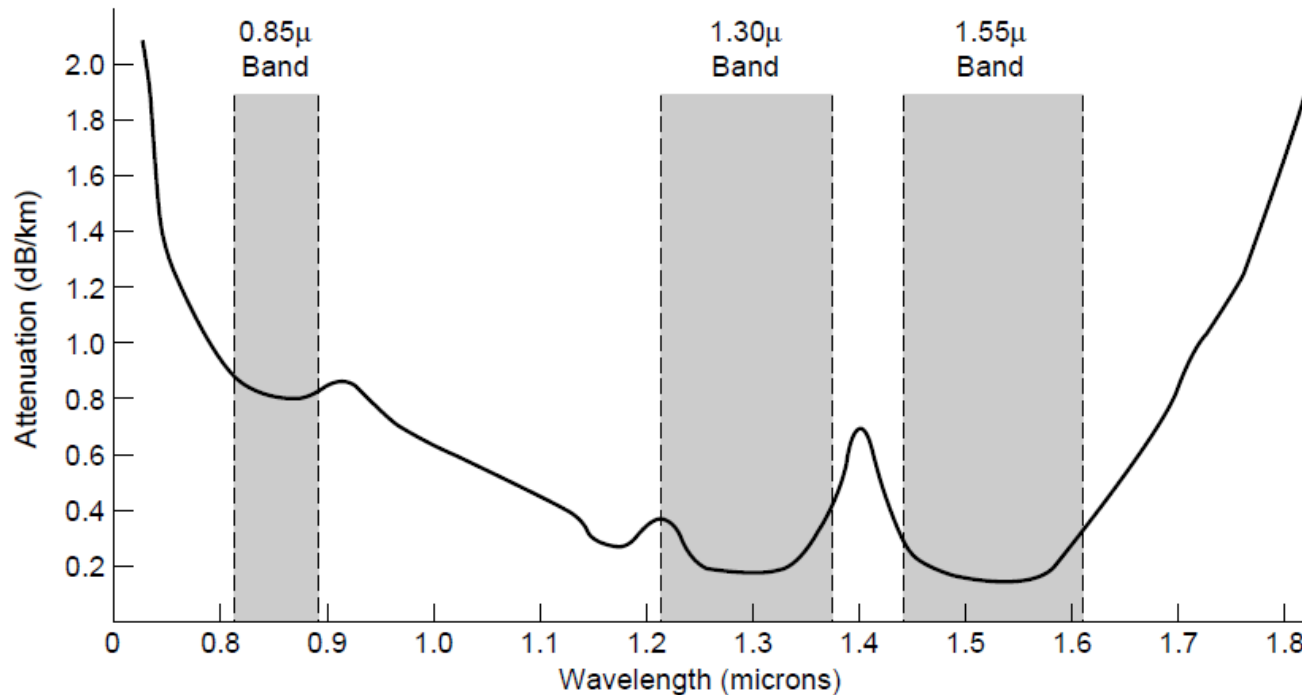
Common for high rates and long distances

- ▶ Long distance ISP links, Fiber-to-the-Home
- ▶ Light carried in very long, thin strand of glass



Fiber Cables (2)

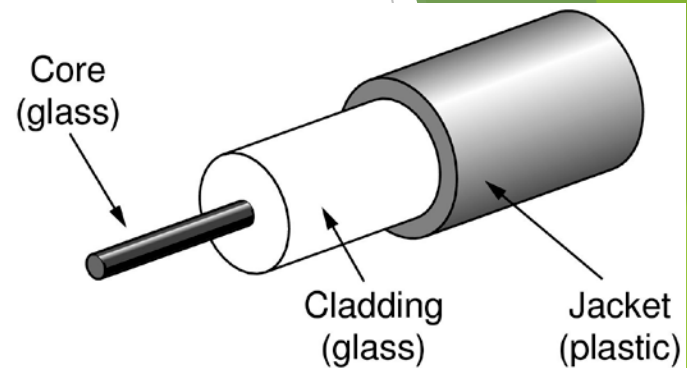
Fiber has enormous bandwidth (THz) and tiny signal loss – hence high rates over long distances



Fiber Cables (3)

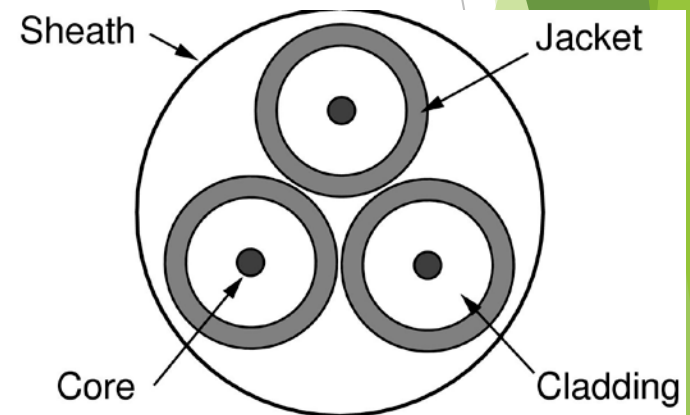
Single-mode

- ▶ Core so narrow (10um) light can't even bounce around
- ▶ Used with lasers for long distances, e.g., 100km



Multi-mode

- ▶ Other main type of fiber
- ▶ Light can bounce (50um core)
- ▶ Used with LEDs for cheaper, shorter distance links



Fibers in a cable



Fiber Cables (4)

Comparison of the properties of wires and fiber:

Property	Wires	Fiber
Distance	Short (100s of m)	Long (tens of km)
Bandwidth	Moderate	Very High
Cost	Inexpensive	Less cheap
Convenience	Easy to use	Less easy
Security	Easy to tap	Hard to tap

Wireless Transmission

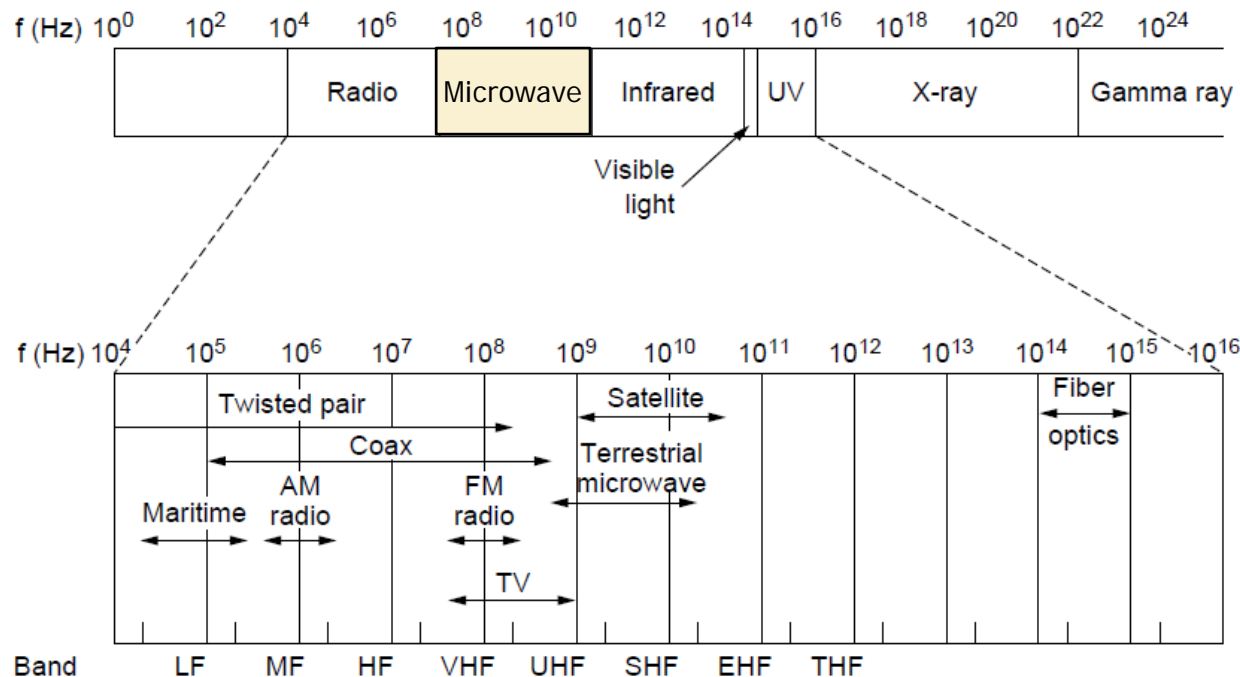
- ▶ Electromagnetic Spectrum »
- ▶ Radio Transmission »
- ▶ Microwave Transmission »
- ▶ Light Transmission »
- ▶ Wireless vs. Wires/Fiber »

Electromagnetic Spectrum (1)

Different bands have different uses:

- ▶ Radio: wide-area broadcast; Infrared/Light: line-of-sight
- ▶ Microwave: LANs and 3G/4G;

← Networking focus



To manage interference, spectrum is carefully divided, and its use regulated and licensed, e.g., sold at auction.

3 GHz
↓

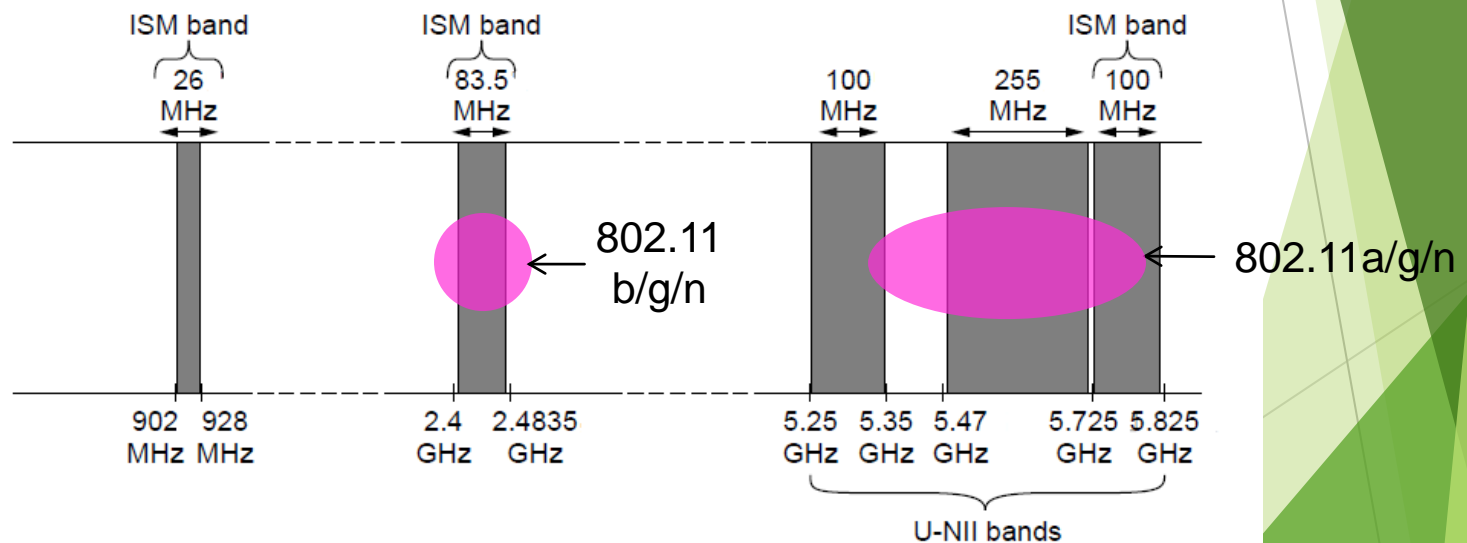


CN5E by Tanenbaum & Wetherall, © Pearson Education-Prentice Hall and D. Wetherall, 2011

Electromagnetic Spectrum (3)

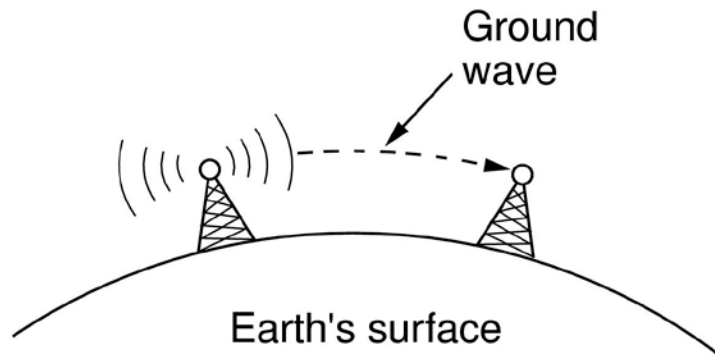
Fortunately, there are also unlicensed ("ISM") bands:

- ▶ Free for use at low power; devices manage interference
- ▶ Widely used for networking; WiFi, Bluetooth, Zigbee, etc.

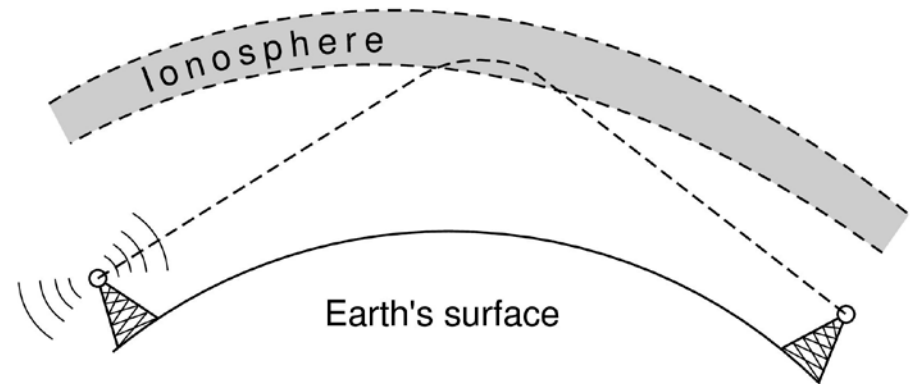


Radio Transmission

Radio signals penetrate buildings well and propagate for long distances
with path loss



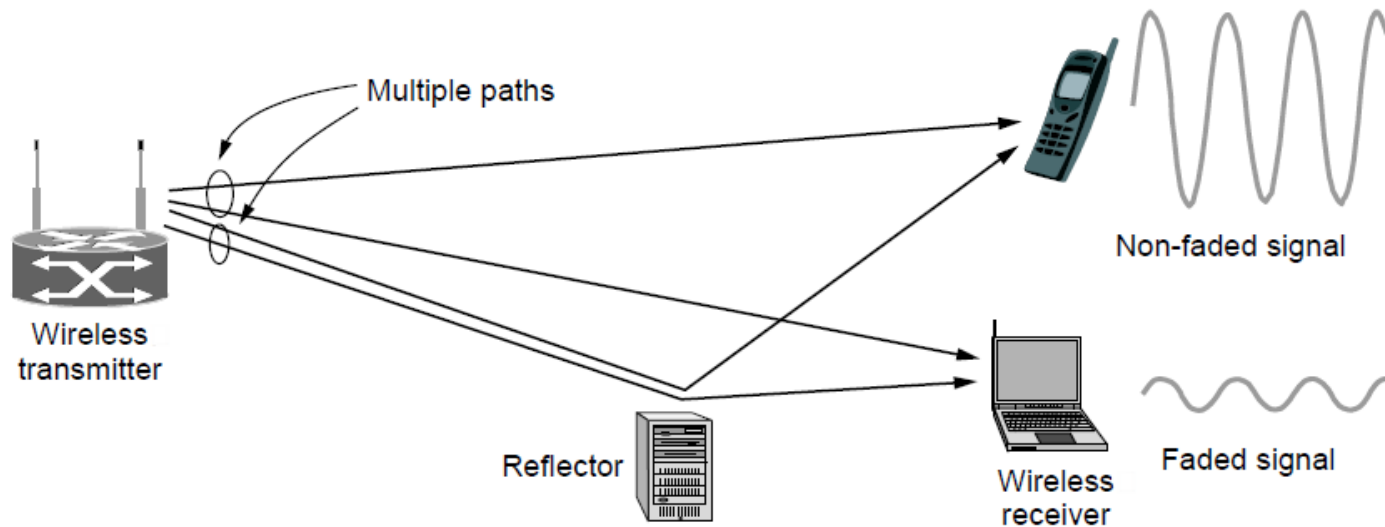
In the VLF, LF, and MF bands, radio waves follow the curvature of the earth



In the HF band, radio waves bounce off the ionosphere.

Microwave Transmission

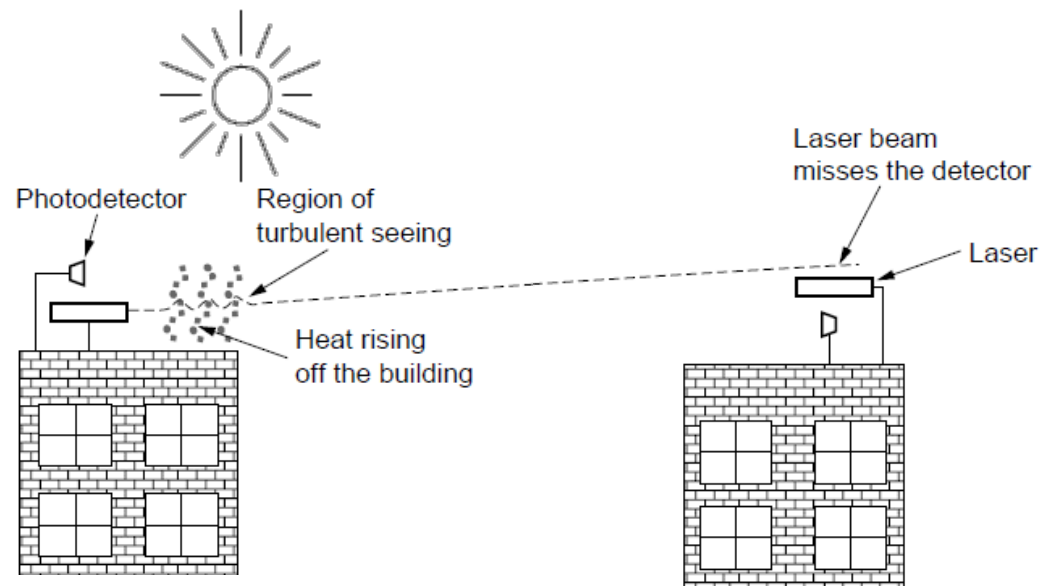
- ▶ Microwaves have much bandwidth and are widely used indoors (WiFi) and outdoors (3G, satellites)
 - ▶ Signal is attenuated/reflected by everyday objects
 - ▶ Strength varies with mobility due multipath fading, etc.



Light Transmission

Line-of-sight light (no fiber) can be used for links

- ▶ Light is highly directional, has much bandwidth
- ▶ Use of LEDs/cameras and lasers/photodetectors



Wireless vs. Wires/Fiber

Wireless:

- + Easy and inexpensive to deploy
- + Naturally supports mobility
- + Naturally supports broadcast
- ▶ Transmissions interfere and must be managed
- ▶ Signal strengths hence data rates vary greatly

Wires/Fiber:

- + Easy to engineer a fixed data rate over point-to-point links
- ▶ Can be expensive to deploy, esp. over distances
- ▶ Doesn't readily support mobility or broadcast

Communication Satellites

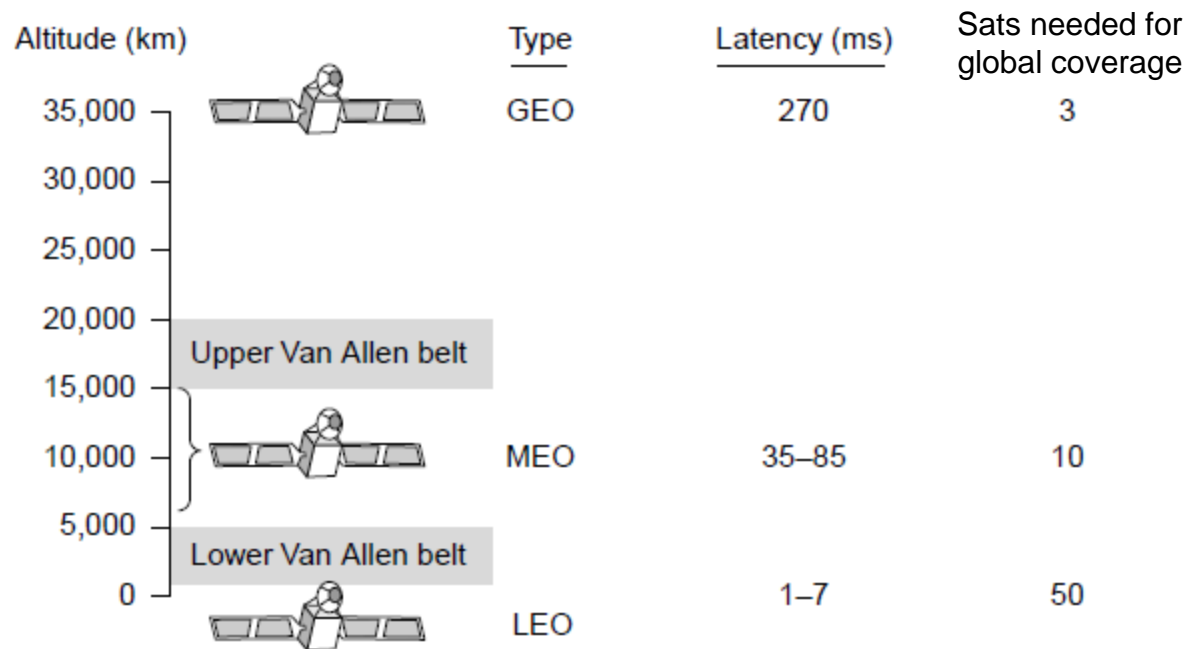
Satellites are effective for broadcast distribution and anywhere/anytime communications

- ▶ Kinds of Satellites »
- ▶ Geostationary (GEO) Satellites »
- ▶ Low-Earth Orbit (LEO) Satellites »
- ▶ Satellites vs. Fiber »

Kinds of Satellites

Satellites and their properties vary by altitude:

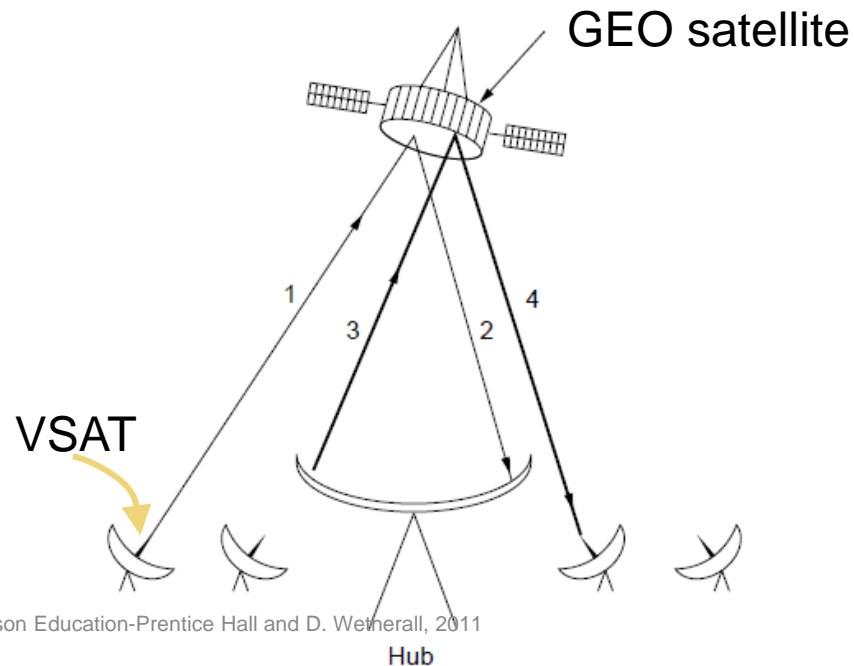
- ▶ Geostationary (GEO), Medium-Earth Orbit (MEO), and Low-Earth Orbit (LEO)



Geostationary Satellites

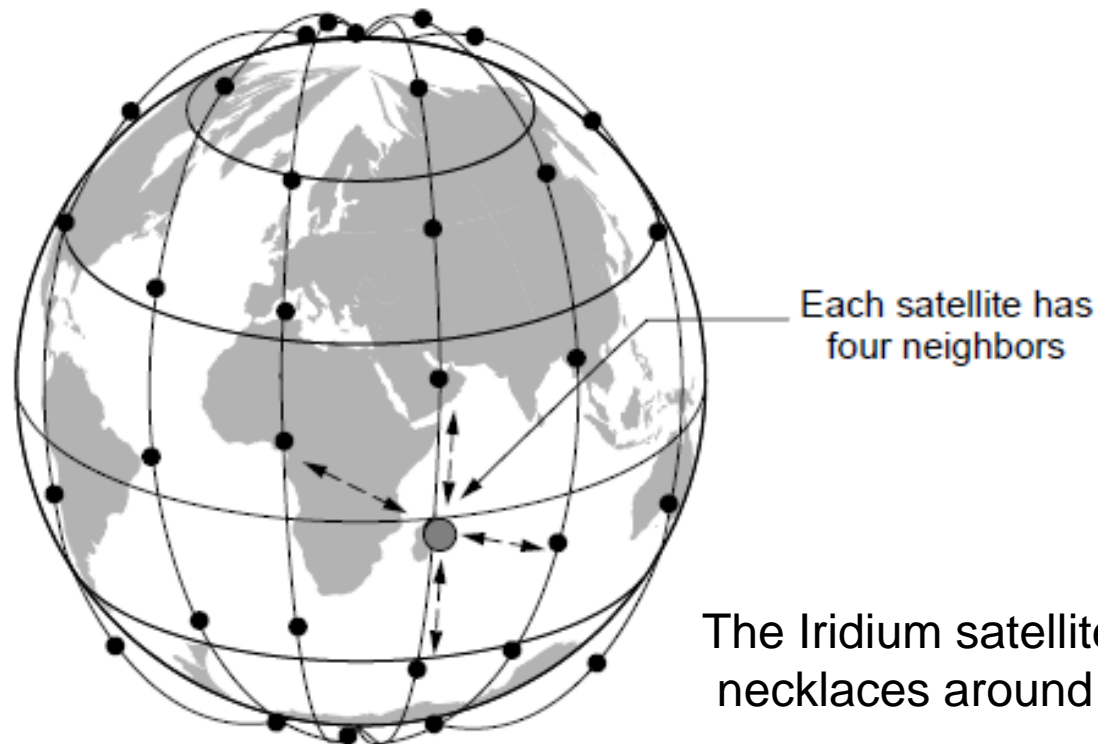
GEO satellites orbit 35,000 km above a fixed location

- ▶ VSAT (computers) can communicate with the help of a hub
- ▶ Different bands (L, S, C, Ku, Ka) in the GHz are in use but may be crowded or susceptible to rain.



Low-Earth Orbit Satellites

Systems such as Iridium use many low-latency satellites for coverage and route communications via them



Satellite vs. Fiber

Satellite:

- + Can rapidly set up anywhere/anytime communications (after satellites have been launched)
- + Can broadcast to large regions
- ▶ Limited bandwidth and interference to manage

Fiber:

- + Enormous bandwidth over long distances
- ▶ Installation can be more expensive/difficult

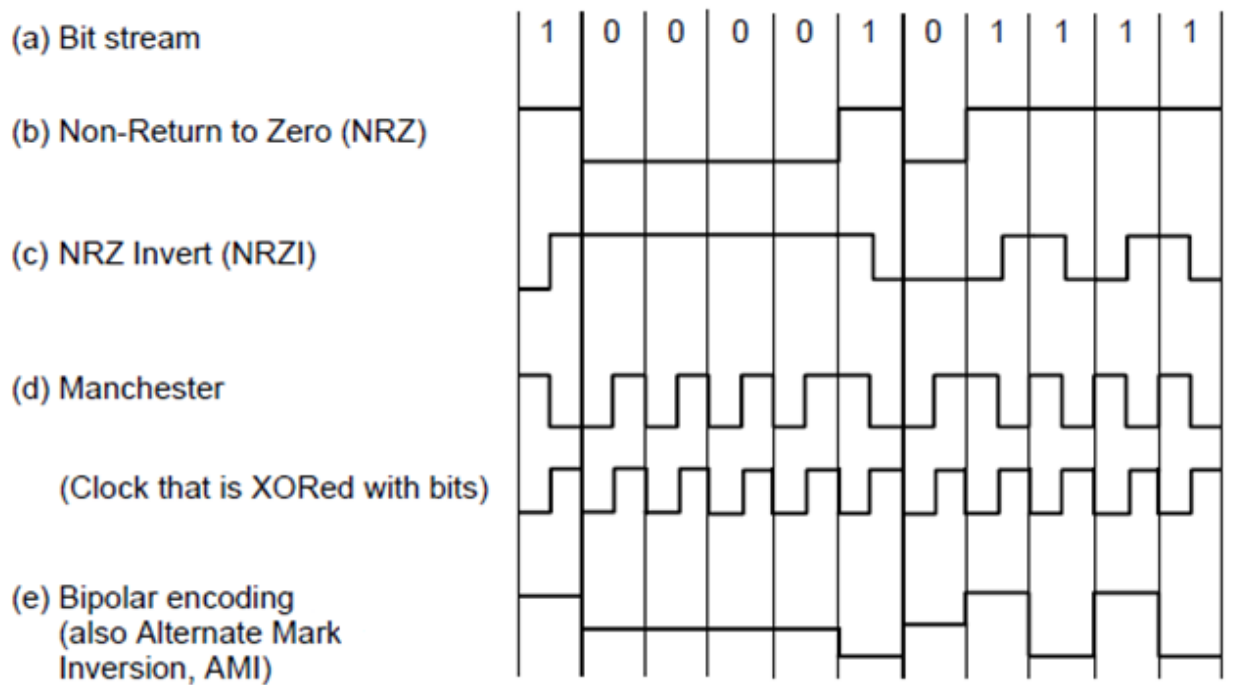
Digital Modulation and Multiplexing

Modulation schemes send bits as signals; multiplexing schemes share a channel among users.

- ▶ Baseband Transmission »
- ▶ Passband Transmission »
- ▶ Frequency Division Multiplexing »
- ▶ Time Division Multiplexing »
- ▶ Code Division Multiple Access »

Baseband Transmission

- ▶ Line codes send symbols that represent one or more bits
 - ▶ NRZ is the simplest, literal line code ($+1V = "1"$, $-1V = "0"$)
 - ▶ Other codes tradeoff bandwidth and signal transitions
- ▶





Clock Recovery

- ▶ To decode the symbols, signals need sufficient transitions

- ▶ Otherwise long runs of 0s (or 1s) are confusing, e.g.:

1 0 0 0 0 0 0 0 0 0 0 0 um, 0? er, 0?

- ▶ Strategies:

- ▶ Manchester coding, mixes clock signal in every symbol
 - ▶ 4B/5B maps 4 data bits to 5 coded bits with 1s and 0s:

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

- ▶ Scrambler XORs data with pseudorandom bits

Passband Transmission (1)

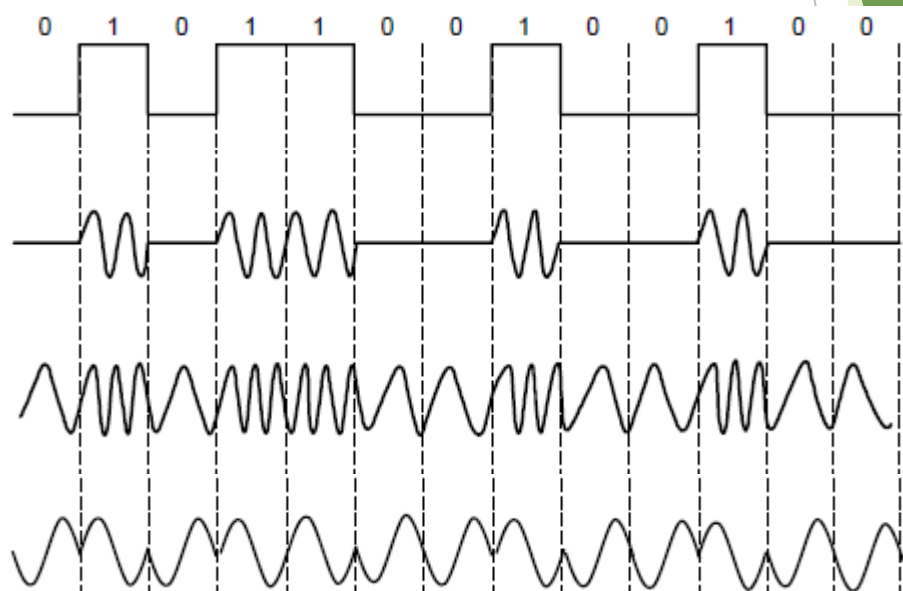
Modulating the amplitude, frequency/phase of a carrier signal sends bits in a (non-zero) frequency range

NRZ signal of bits

Amplitude shift keying

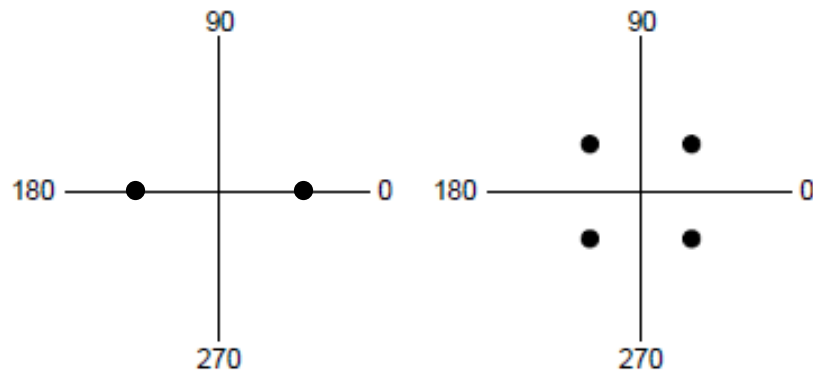
Frequency shift keying

Phase shift keying



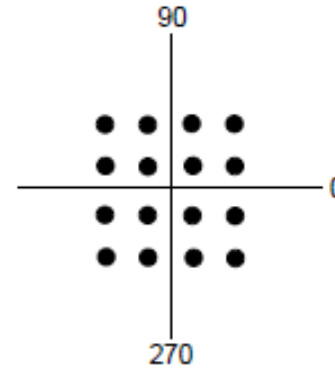
Passband Transmission (2)

Constellation diagrams are a shorthand to capture the amplitude and phase modulations of symbols:

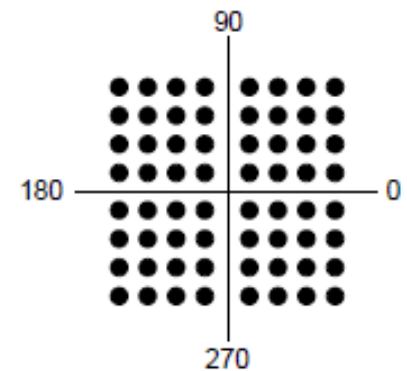


BPSK
2 symbols
1 bit/symbol

QPSK
4 symbols
2 bits/symbol



QAM-16
16 symbols
4 bits/symbol



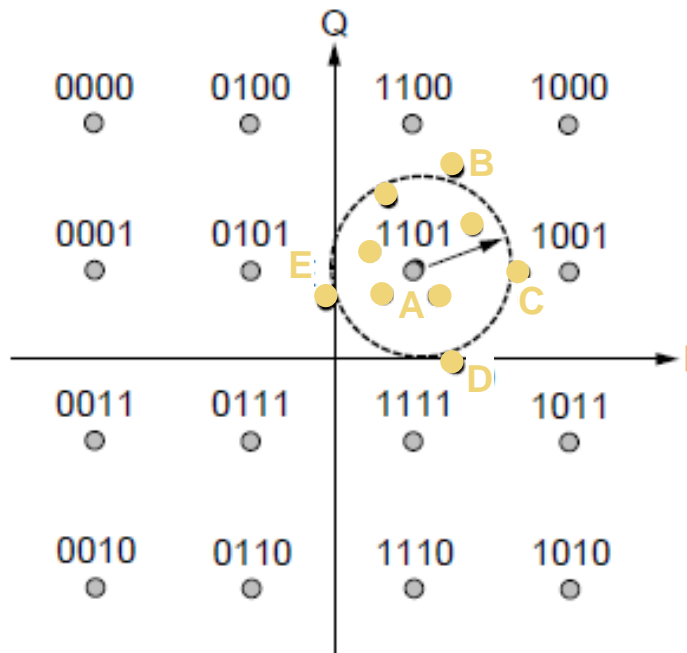
QAM-64
64 symbols
6 bits/symbol

BPSK/QPSK varies only phase

QAM varies amplitude and phase

Passband Transmission (3)

Gray-coding assigns bits to symbols so that small symbol errors cause few bit errors:



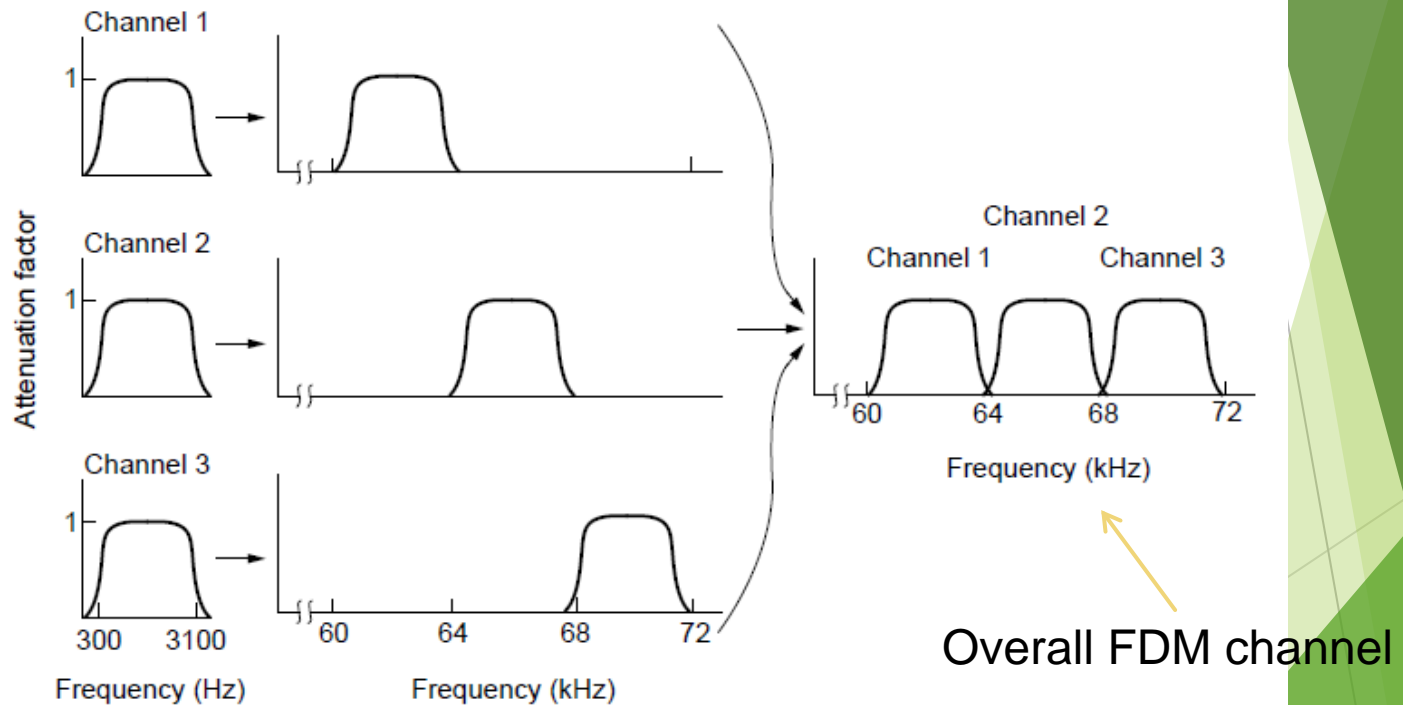
When 1101 is sent:

Point	Decodes as	Bit errors
A	1101	0
B	110 <u>0</u>	1
C	<u>1</u> 001	1
D	11 <u>1</u> 1	1
E	<u>0</u> 101	1

Frequency Division

Multiplexing (1)

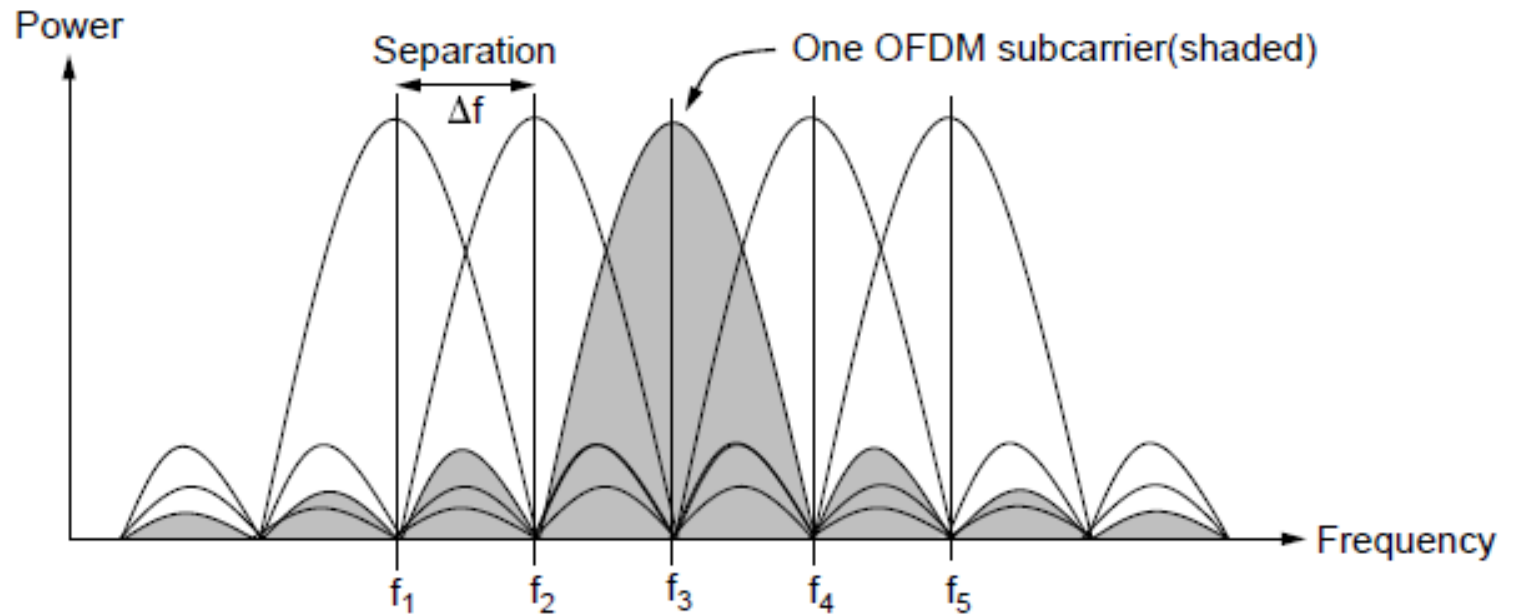
FDM (Frequency Division Multiplexing) shares the channel by placing users on different frequencies:



Frequency Division Multiplexing (2)

OFDM (Orthogonal FDM) is an efficient FDM technique used for 802.11, 4G cellular and other communications

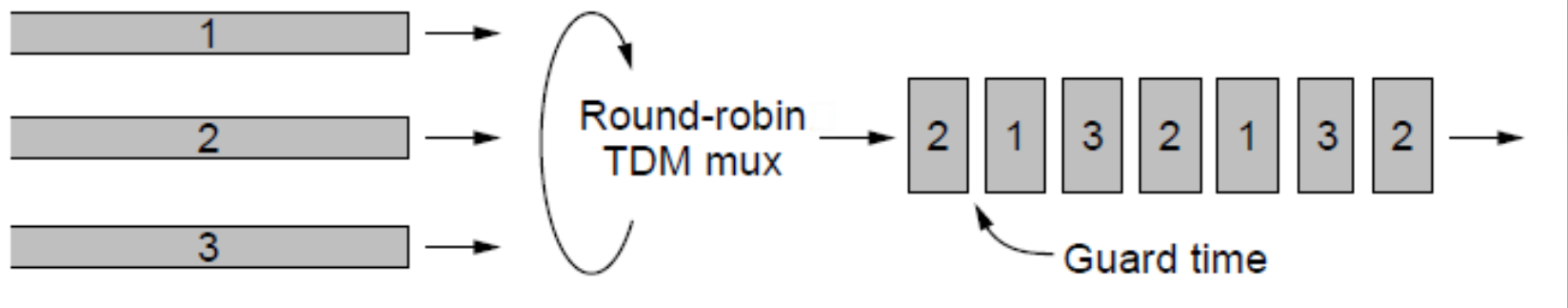
- ▶ Subcarriers are coordinated to be tightly packed



Time Division Multiplexing (TDM)

Time division multiplexing shares a channel over time:

- ▶ Users take turns on a fixed schedule; this is not packet switching or STDM (Statistical TDM)
- ▶ Widely used in telephone / cellular systems

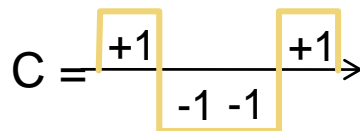
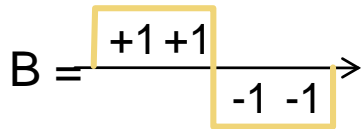
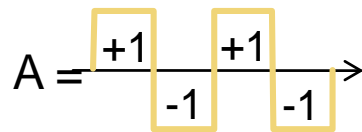


Code Division Multiple Access

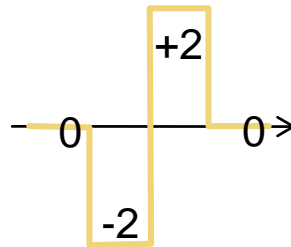
(CDMA) shares the channel by giving users a code

- ▶ Codes are orthogonal; can be sent at the same time
- ▶ Widely used as part of 3G networks

Sender Codes

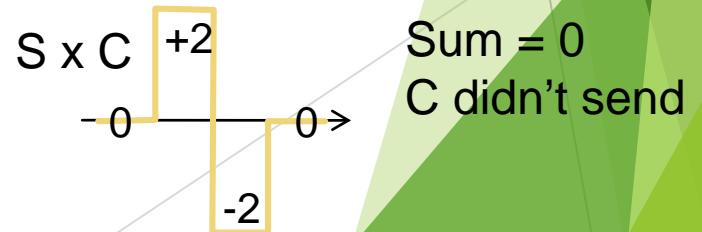
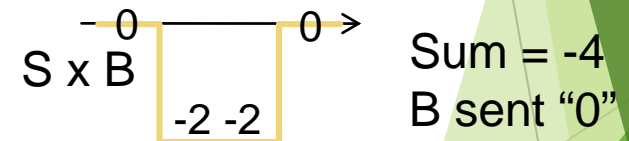
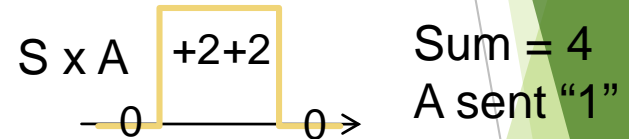


Transmitted Signal



$$S = +A - B$$

Receiver Decoding



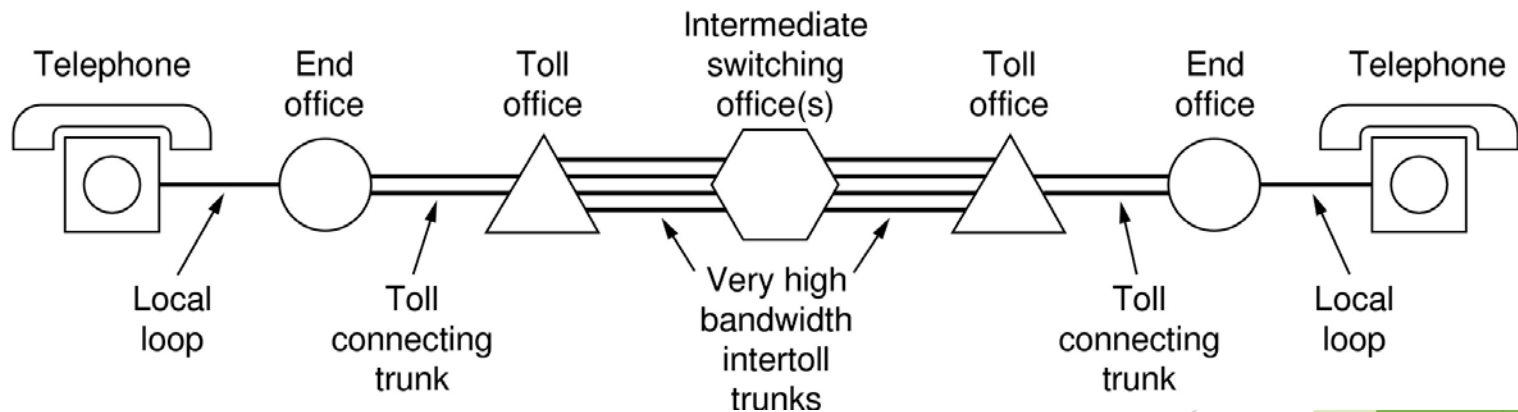
The Public Switched Telephone Network

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

Structure of the Telephone System

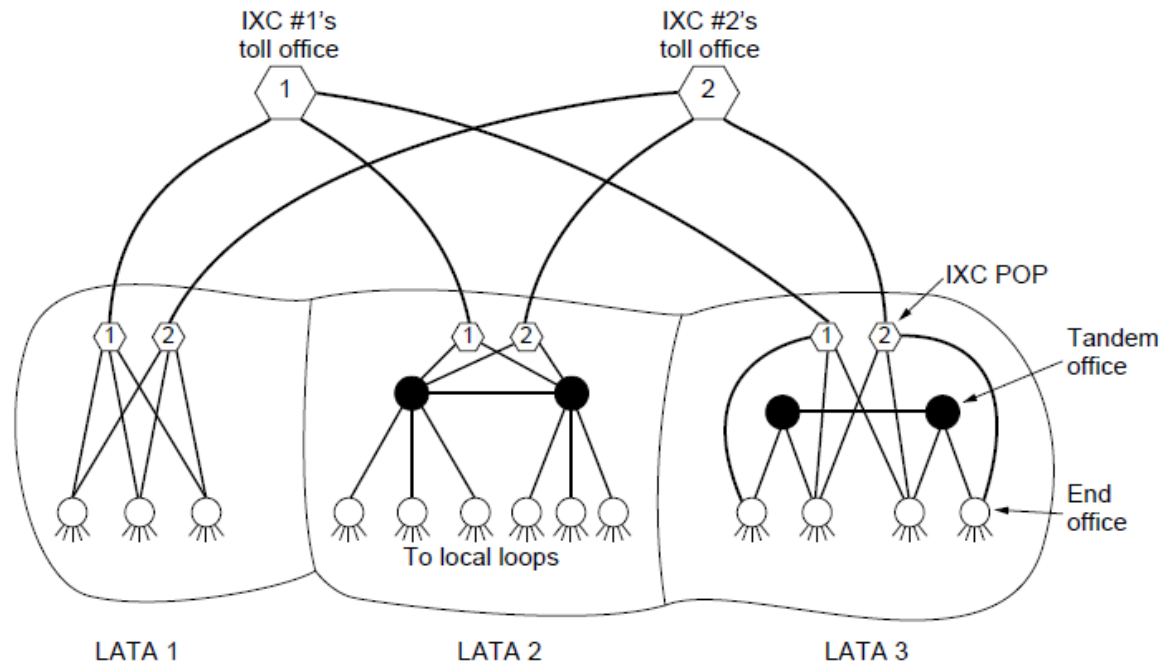
A hierarchical system for carrying voice calls made of:

- ▶ Local loops, mostly analog twisted pairs to houses
- ▶ Trunks, digital fiber optic links that carry calls
- ▶ Switching offices, that move calls among trunks



The Politics of Telephones

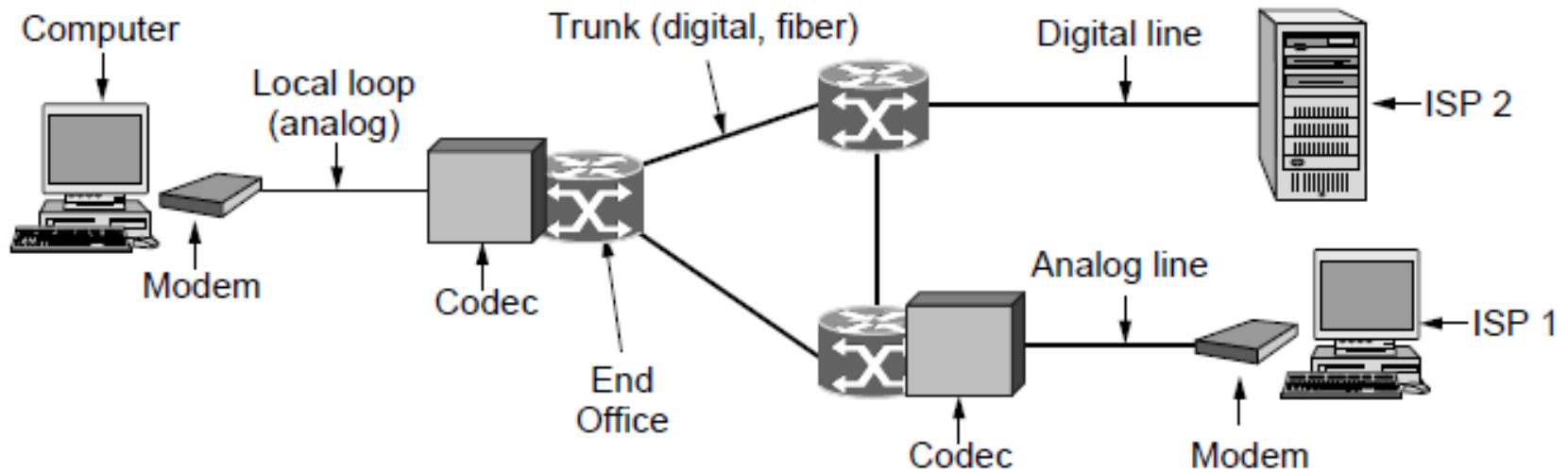
- ▶ In the U.S., there is a distinction for competition between serving a local area (LECs) and connecting to a local area (at a POP) to switch calls across areas (IXCs)
 - ▶ Customers of a LEC can dial via any IXC they choose



Local loop (1): modems

Telephone modems send digital data over an 3.3 KHz analog voice channel interface to the POTS

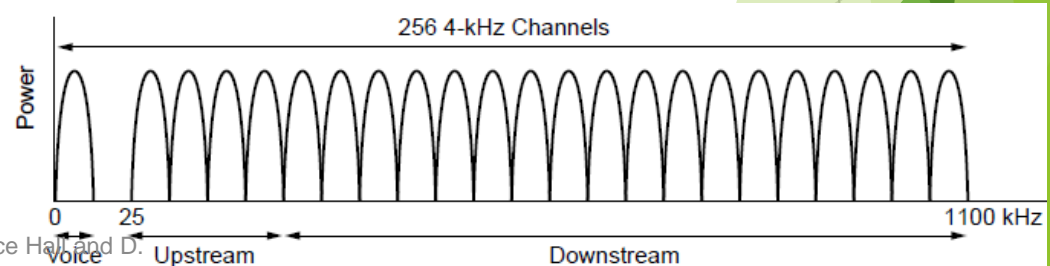
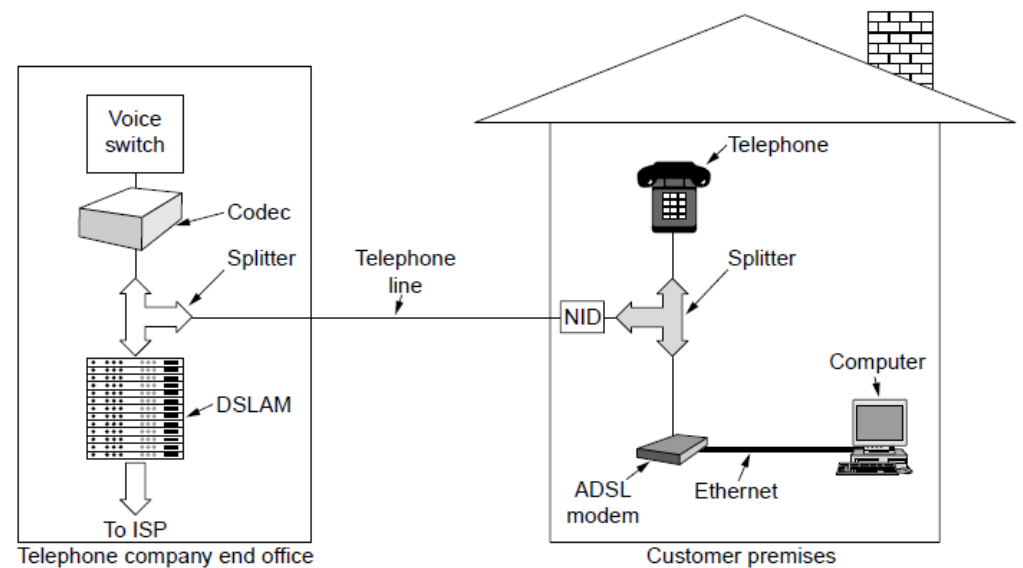
- ▶ Rates <56 kbps; early way to connect to the Internet



Local loop (2): Digital

DSL broadband sends data over the local loop to the local office using frequencies that are not used for POTS

- ▶ Telephone/computers attach to the same old phone line
- ▶ Rates vary with line
 - ▶ ADSL2 up to 12 Mbps
- ▶ OFDM is used up to 1.1 MHz for ADSL2
 - ▶ Most bandwidth down



Local loop (3): Fiber To The Home

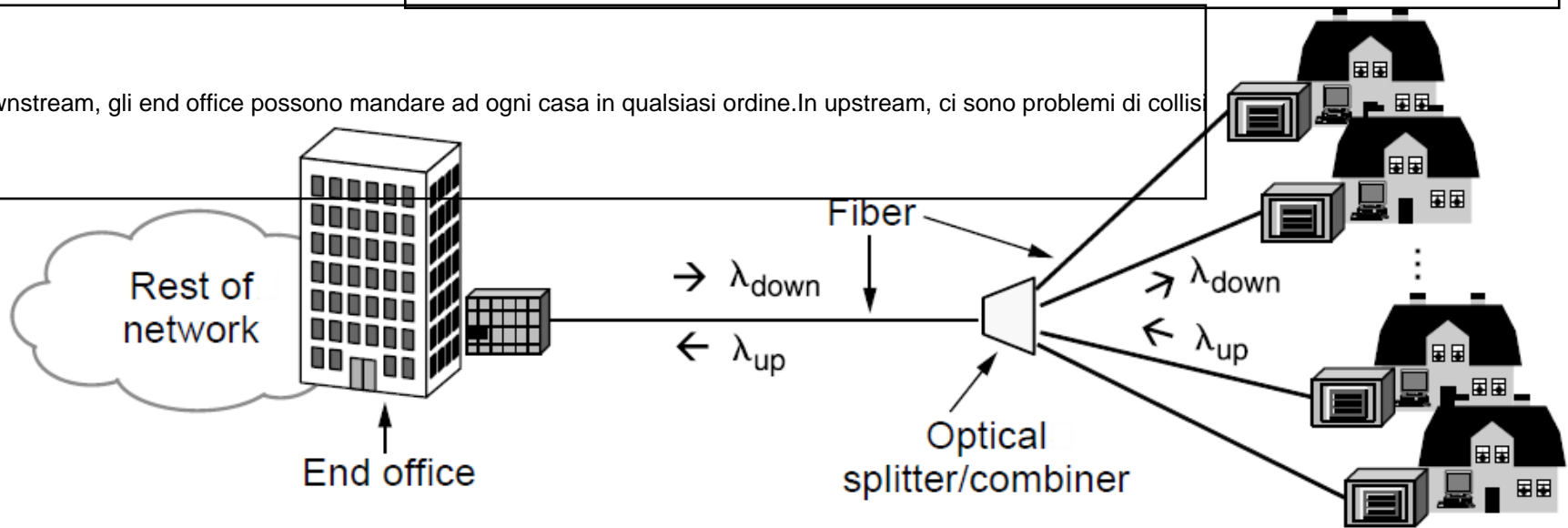
FTTH broadband relies on deployment of fiber optic cables to provide high data rates customers

- ▶ One wavelength can be shared among many houses

A livello del local loop. Fiber is passive (no amplifiers, etc.) Riduce i costi e la affidabilità (parti ridotte).

FTTx il local loop rimane sempre in rame poiché è sufficientemente veloce per le brevi distanze. Il problema

In downstream, gli end office possono mandare ad ogni casa in qualsiasi ordine. In upstream, ci sono problemi di collisione.

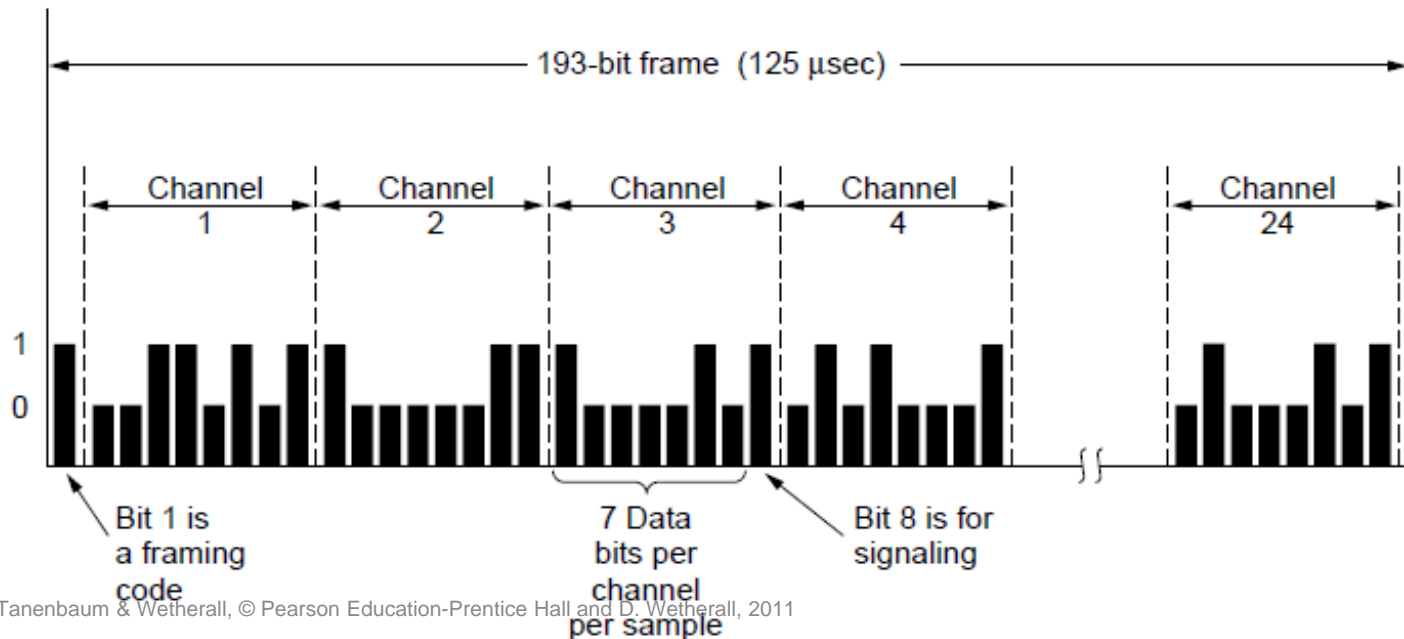


Trunks and Multiplexing (1)

pagg. 152-156.

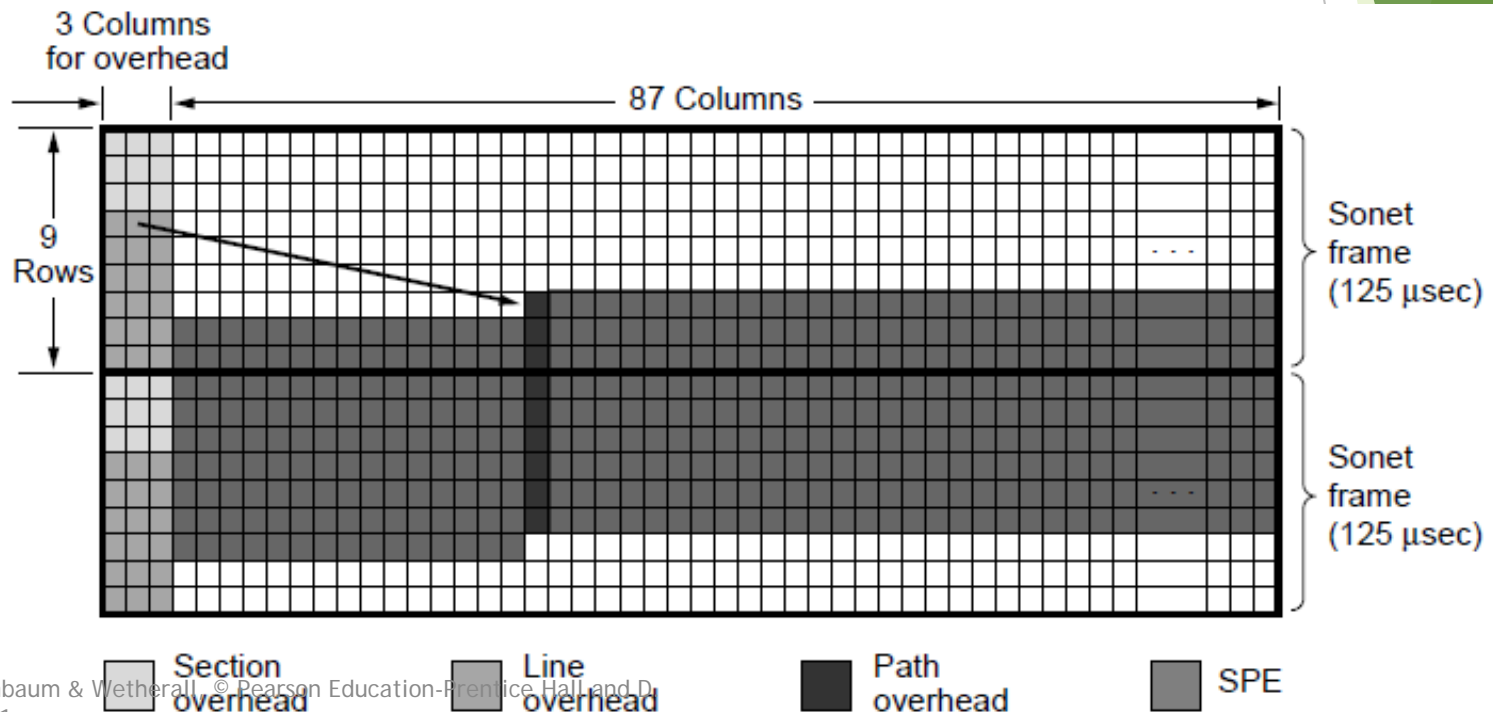
Calls are carried digitally on PSTN trunks using TDM

- ▶ A call is an 8-bit PCM sample each 125 μ s (64 kbps)
- ▶ Traditional T1 carrier has 24 call channels each 125 μ s (1.544 Mbps) with symbols based on AMI



Trunks and Multiplexing (2)

- ▶ SONET (Synchronous Optical NETWORK) is the worldwide standard for carrying digital signals on optical trunks
 - ▶ Keeps 125 μ s frame; base frame is 810 bytes (52Mbps)
 - ▶ Payload “floats” within framing for flexibility



Trunks and Multiplexing (3)

Hierarchy at 3:1 per level is used for higher rates

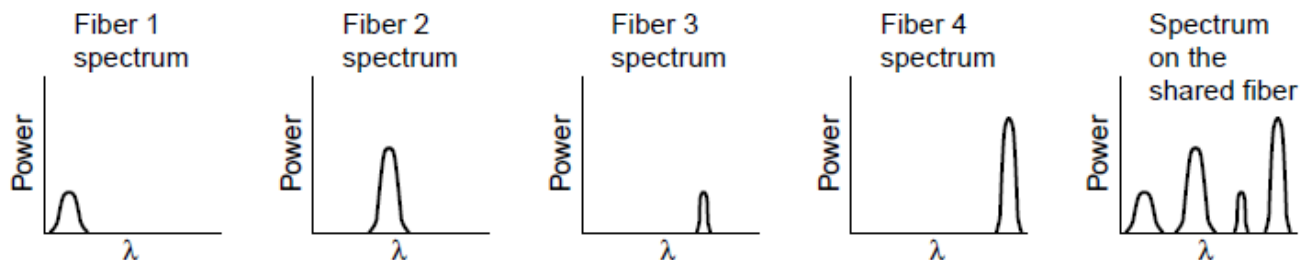
- ▶ Each level also adds a small amount of framing
- ▶ Rates from 50 Mbps (STS-1) to 40 Gbps (STS-768)

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

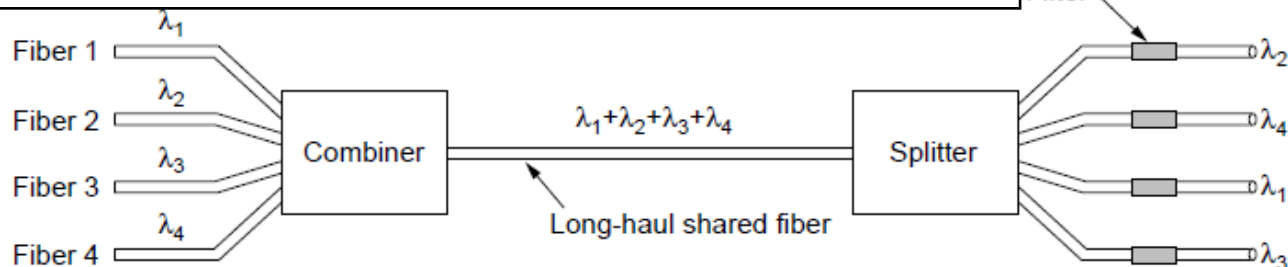
SONET/SDH rate hierarchy

Trunks and Multiplexing (4)

WDM (Wavelength Division Multiplexing), another name for FDM, is used to carry many signals on one fiber:



Più lunghezze d'onda sono combinate insieme e trasportate nella stessa fibra ottica. Dall

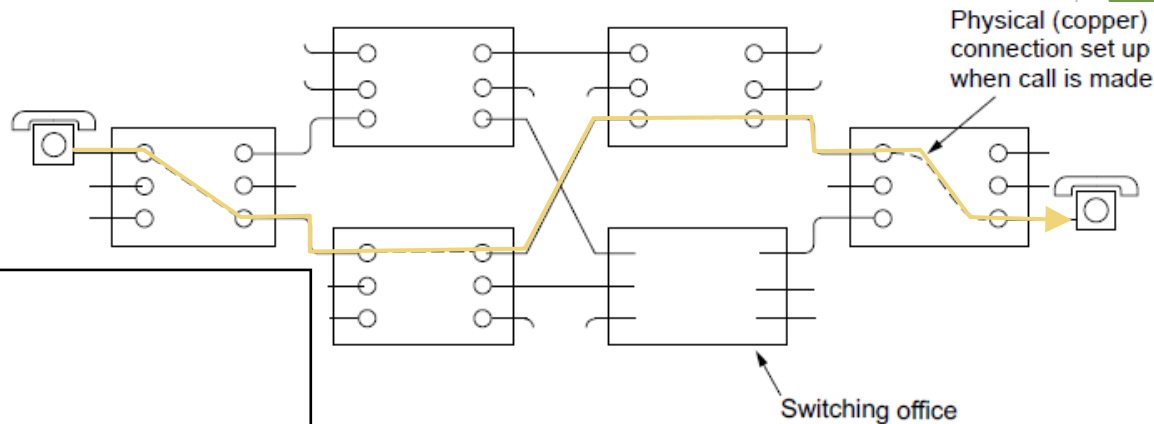


Switching (1)

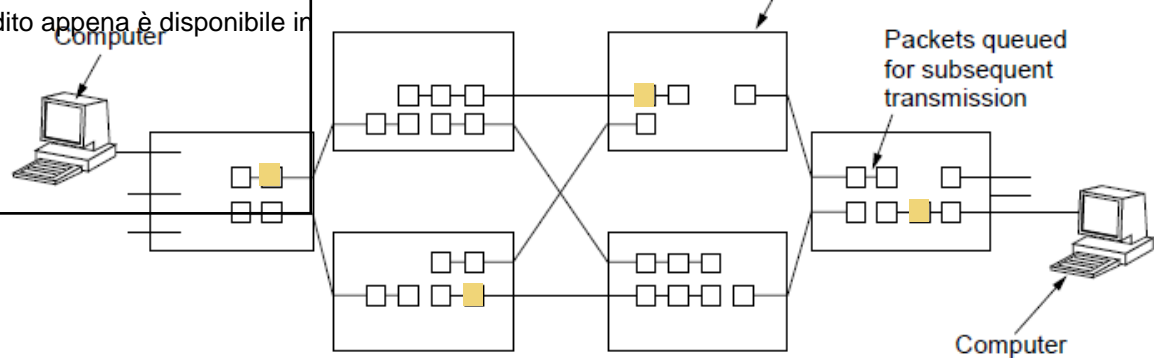
Circuit Switching: canale di comunicazione fisico. La path deve essere stabilita prima che possa avvenire

- PSTN uses circuit switching; Internet uses packet switching

PSTN:



Internet:



Switching (2)

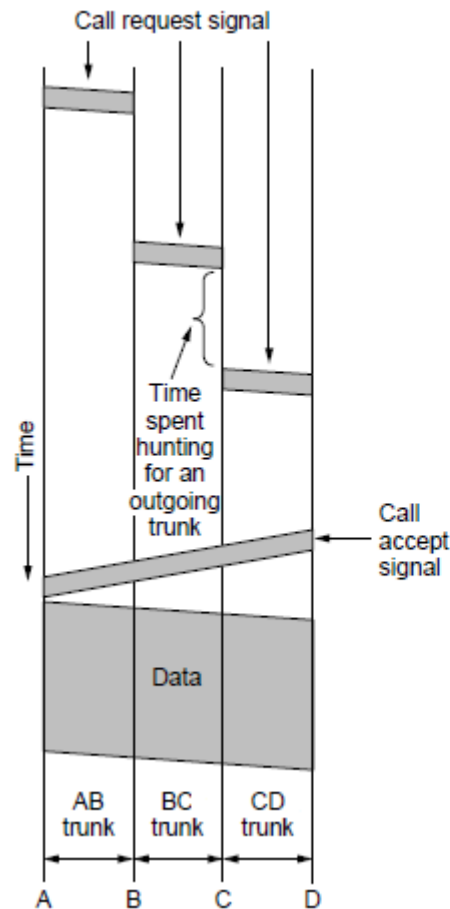
Le possibili path sono storate nel router che avrà il compito di aggiornare le strade percorribili. I pa

Circuit switching requires call setup (connection) before data flows smoothly

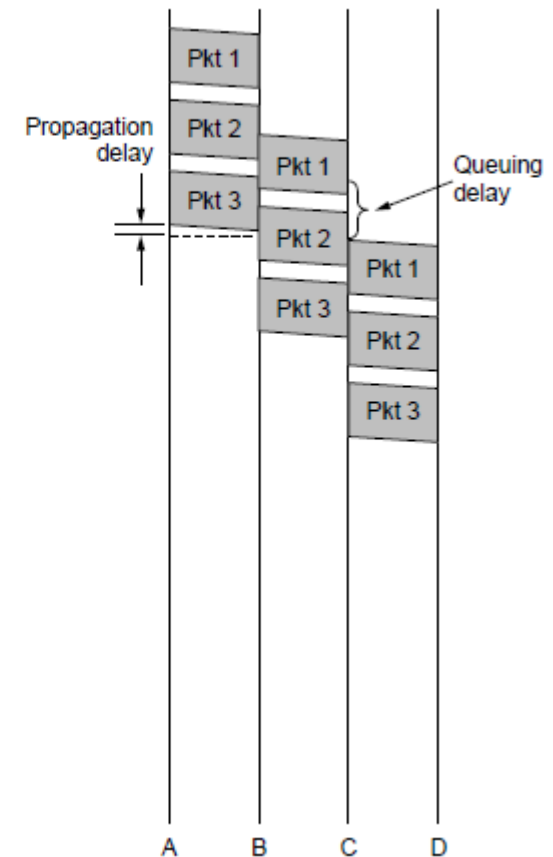
- ▶ Also teardown at end (not shown)

Packet switching treats messages independently

- ▶ No setup, but variable queuing delay at routers



Circuits



Packets

Switching (3)

Comparison of circuit- and packet-switched networks

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

Mobile Telephone System

- ▶ Generations of mobile telephone systems »
- ▶ Cellular mobile telephone systems »
- ▶ GSM, a 2G system »
- ▶ UMTS, a 3G system »

Generations of mobile telephone systems

1G, analog voice

- ▶ AMPS (Advanced Mobile Phone System) is example, deployed from 1980s. Modulation based on FM (as in radio).

2G, analog voice and digital data

- ▶ GSM (Global System for Mobile communications) is example, deployed from 1990s. Modulation based on QPSK.

3G, digital voice and data

- ▶ UMTS (Universal Mobile Telecommunications System) is example, deployed from 2000s. Modulation based on CDMA

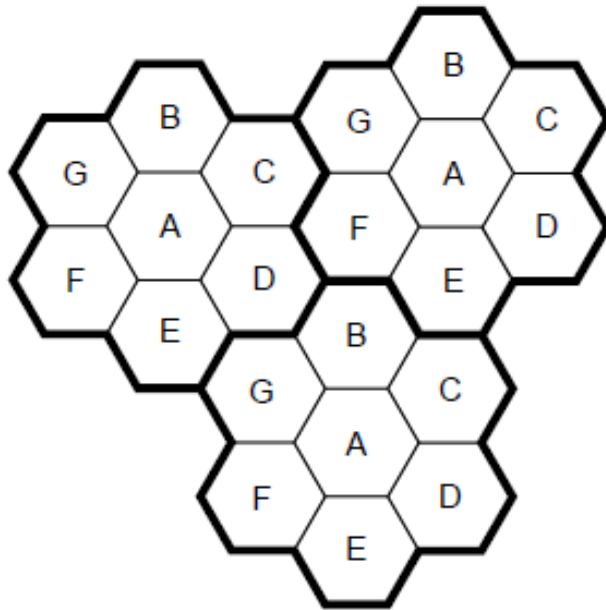
4G, digital data including voice

- ▶ LTE (Long Term Evolution) is example, deployed from 2010s. Modulation based on OFDM

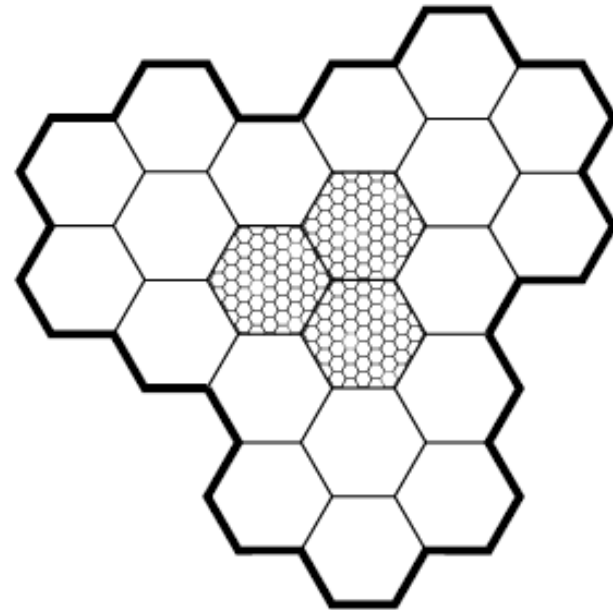
Cellular mobile phone systems

All based on notion of spatial regions called cells

- ▶ Each mobile uses a frequency in a cell; moves cause handoff
- ▶ Frequencies are reused across non-adjacent cells
- ▶ To support more mobiles, smaller cells can be used



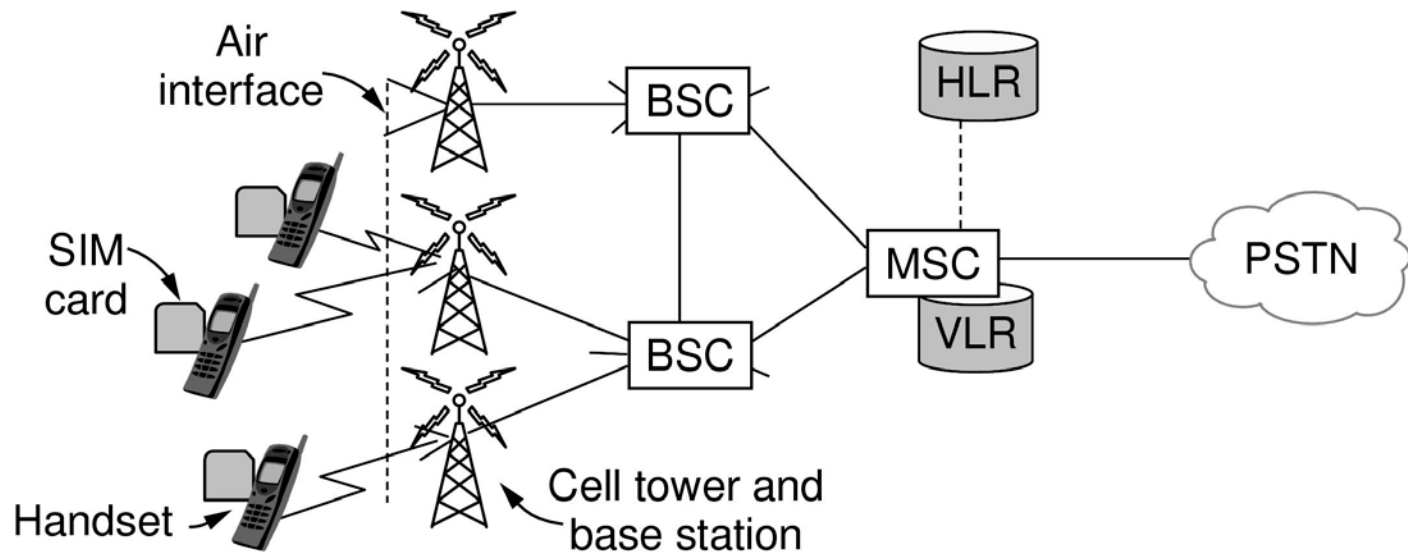
Cellular reuse pattern



Smaller cells for dense mobiles

GSM - Global System for Mobile Communications (1)

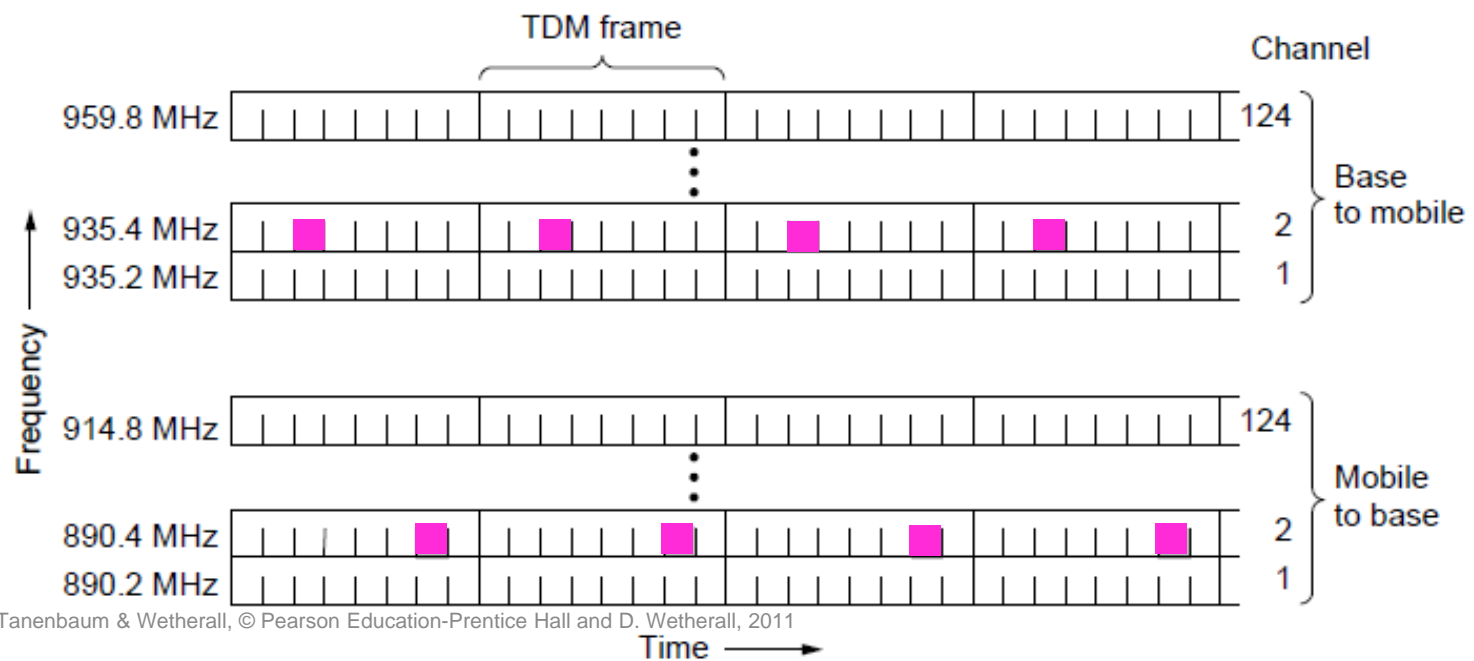
- ▶ Mobile is divided into handset and SIM card (Subscriber Identity Module) with credentials
- ▶ Mobiles tell their HLR (Home Location Register) their current whereabouts for incoming calls
- ▶ Cells keep track of visiting mobiles (in the Visitor LR)



GSM - Global System for Mobile Communications (2)

Air interface is based on FDM channels of 200 KHz divided in an eight-slot TDM frame every 4.615 ms

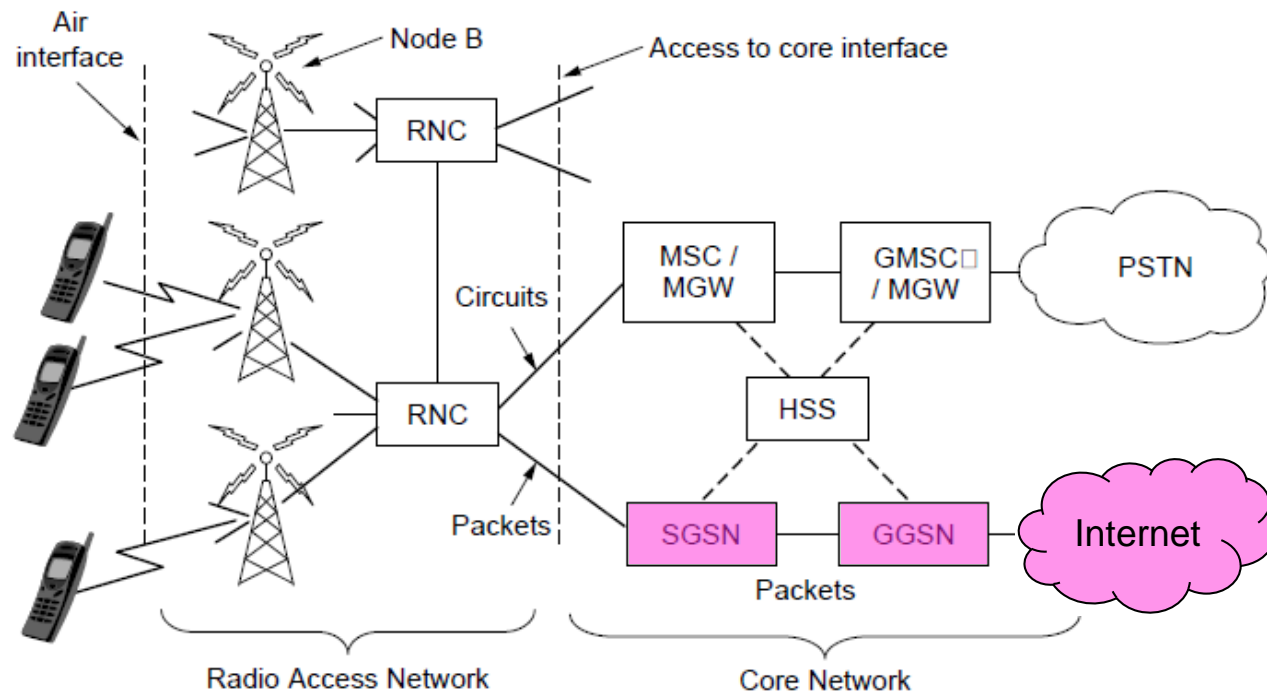
- ▶ Mobile is assigned up- and down-stream slots to use
- ▶ Each slot is 148 bits long, gives rate of 27.4 kbps



UMTS - Universal Mobile Telecommunications System (1)

Architecture is an evolution of GSM; terminology differs

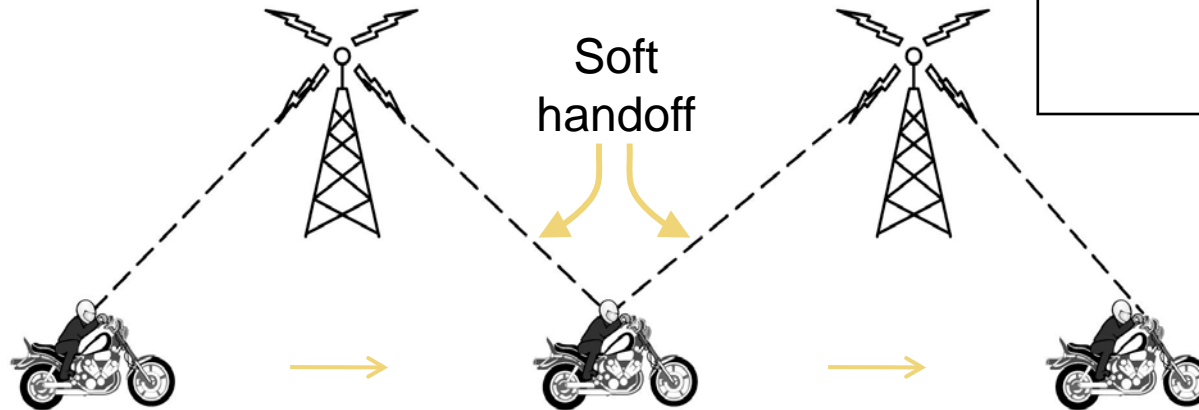
Packets go to/from the Internet via SGSN/GGSN



UMTS – Universal Mobile Telecommunications System (2)

Air interface based on CDMA over 5 MHz channels

- ▶ Rates over users <14.4 Mbps (HSPDA) per 5 MHz
- ▶ CDMA allows frequency reuse over all cells
- ▶ CDMA permits soft handoff (connected to both cells)



Soft Handoff: la connessione con un ripetitore

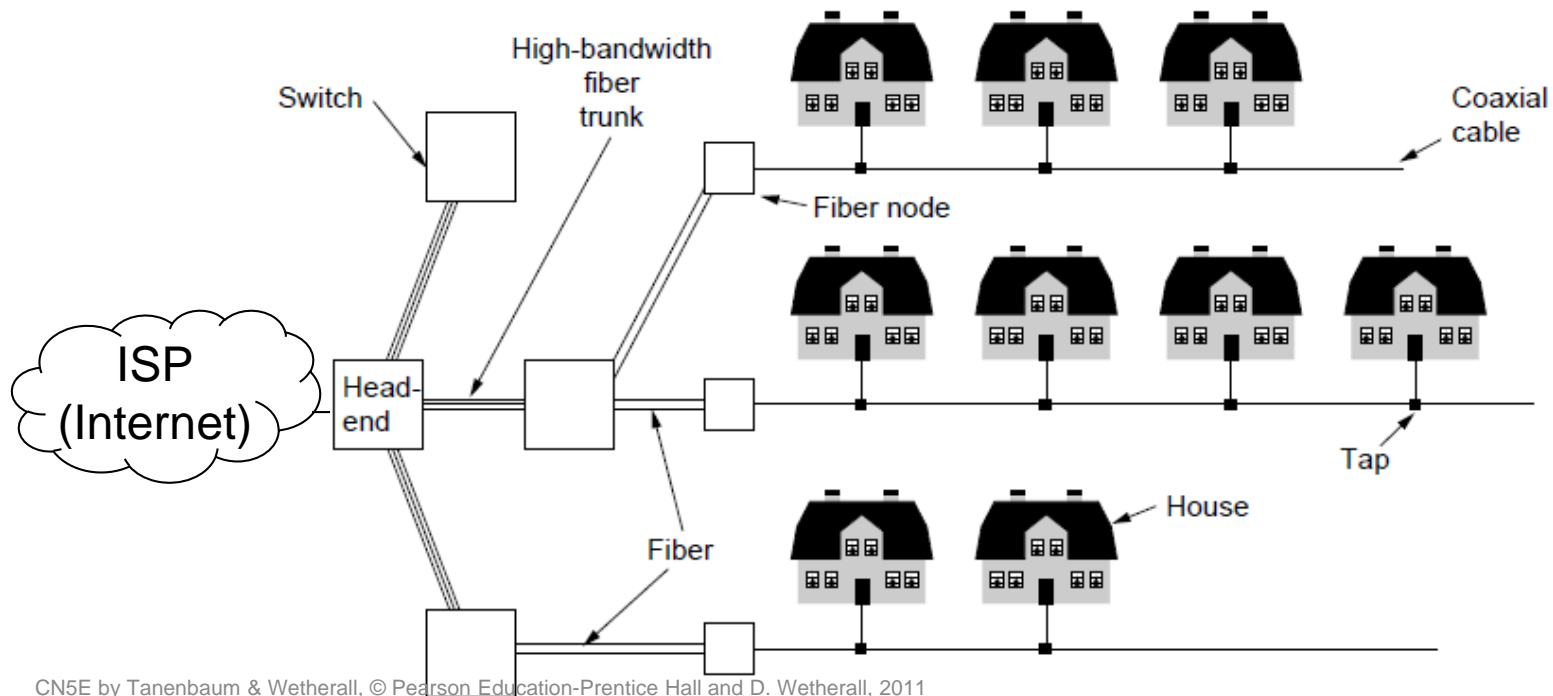
Cable Television

- ▶ Internet over cable »
- ▶ Spectrum allocation »
- ▶ Cable modems »
- ▶ ADSL vs. cable »

Internet over Cable

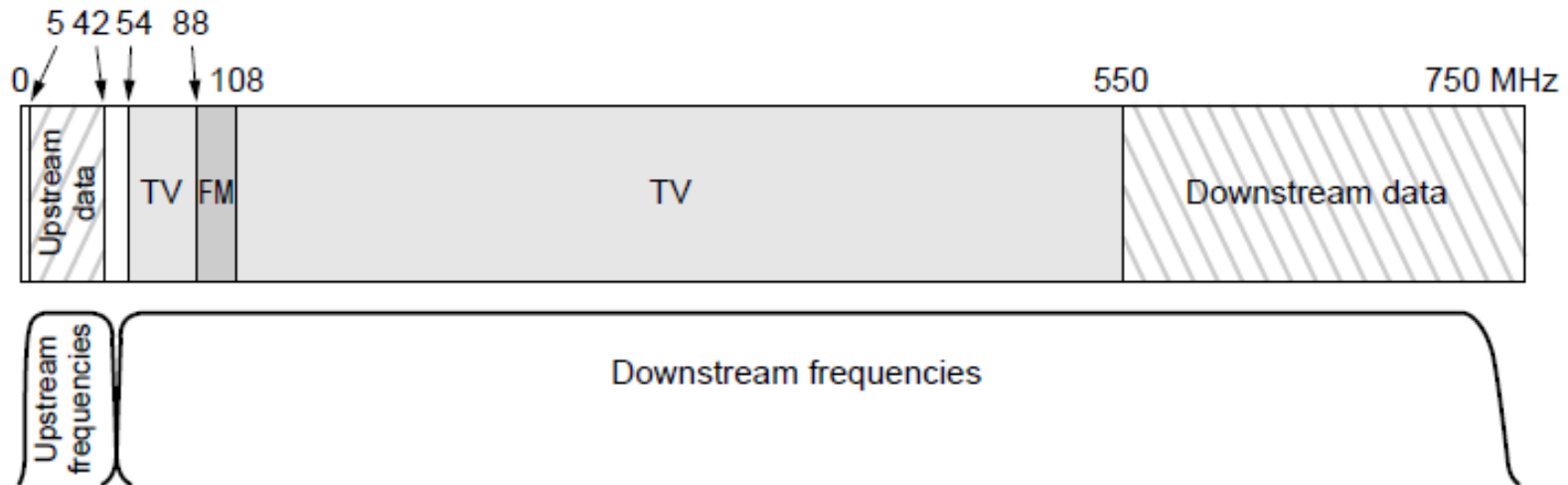
Internet over cable reuses the cable television plant

- ▶ Data is sent on the shared cable tree from the head-end, not on a dedicated line per subscriber (DSL)



Spectrum Allocation

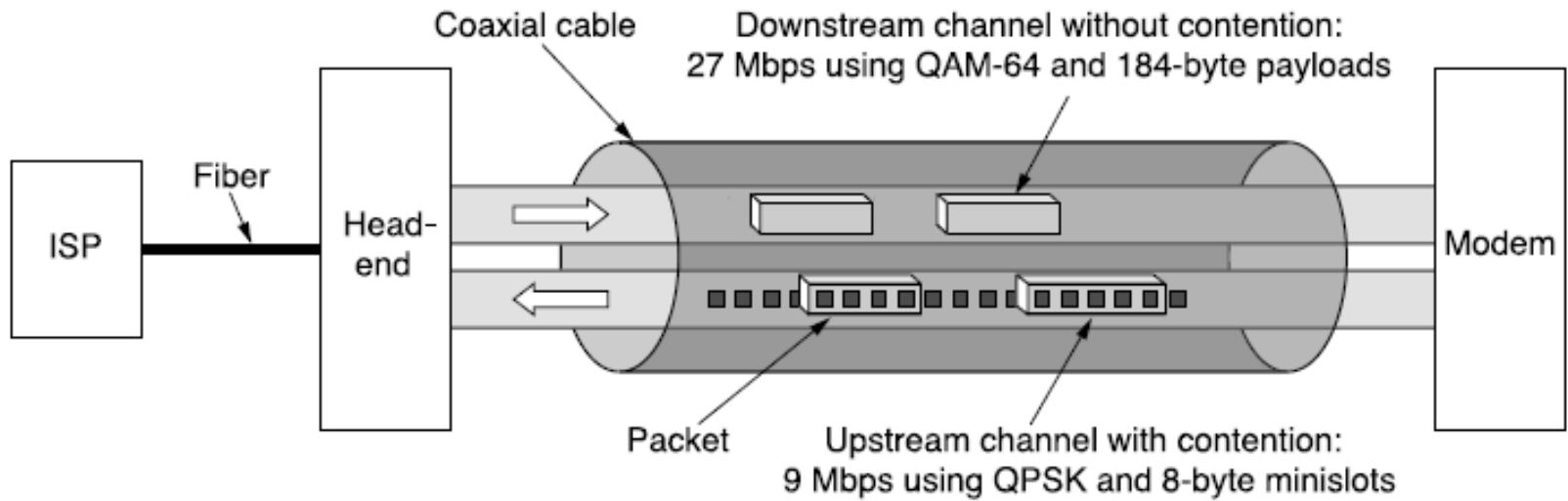
Upstream and downstream data are allocated to frequency channels not used for TV channels:



Cable Modems

Cable modems at customer premises implement the physical layer of the DOCSIS standard

- ▶ QPSK/QAM is used in timeslots on frequencies that are assigned for upstream/downstream data



Cable vs. ADSL

Cable:

- + Uses coaxial cable to customers (good bandwidth)
- ▶ Data is broadcast to all customers (less secure)
- ▶ Bandwidth is shared over customers so may vary

ADSL:

- + Bandwidth is dedicated for each customer
- + Point-to-point link does not broadcast data
- ▶ Uses twisted pair to customers (lower bandwidth)

End

Chapter 2