The Physical Layer: an overview
Chapter 2

Application
Transport
Network
Link
Physical

- Foundation on which other layers build
  - Properties of wires, fiber, wireless limit what the network can do
- We will cover theoretical basis of data transmission.
- Nature puts limits on the data sent over a channel.
- Properties of channels determine the performance
  - Throughput, latency, error rate
- We will cover three kinds of media
  - Guided (coper wire and fiber optics)
  - Wireless (terrestrial radio)
  - Satellite.
- Key problem is to send (digital) bits using only (analog) signals
  - This is called modulation
- We will cover communication system used by computer networks.

The Physical Layer

- 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

Theoretical Basis for Data Communication

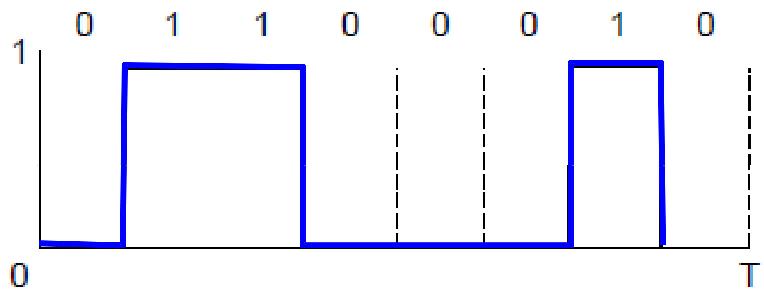
Communication rates have fundamental limits

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

Fourier Analysis

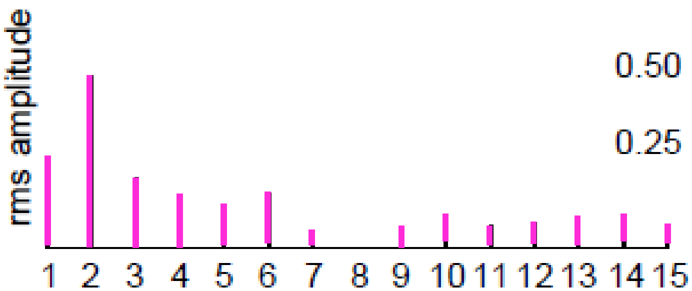
A time-varying signal can be equivalently represented as a series of frequency components (harmonics):

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



Signal over time ⟶

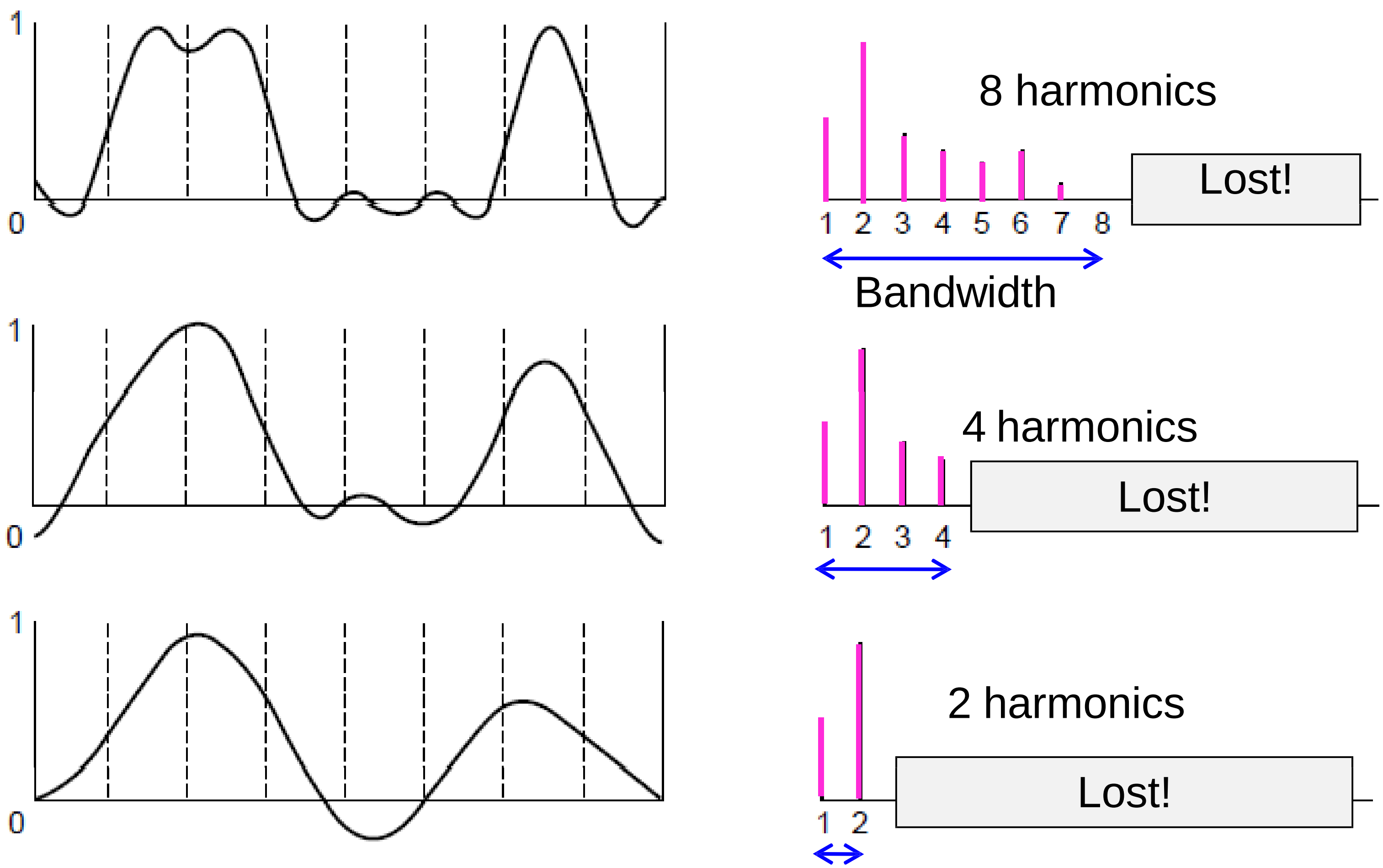
=



a, b weights of harmonics

Bandwidth-Limited Signals

Having less bandwidth (harmonics) degrades the signal



Maximum Data Rate of a Channel

- 1924, Henry Nyquist
  - Perfect channel has a finite transmission capacity
  - He derived an equation expressing the maximum data rate of the channel
  - Nyquist's theorem relates the data rate to the bandwidth (B) and number of signal levels (V)

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

- 1948, Shannon
  - Derived an equation expressing the maximum rate of the channel subject random noise.
  - Most important paper in information theory
- Shannon's theorem relates the data rate to the bandwidth (B) and signal strength (S) relative to the noise (N):

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

Guided Transmission (Wires & Fiber)

Media have different properties, hence performance

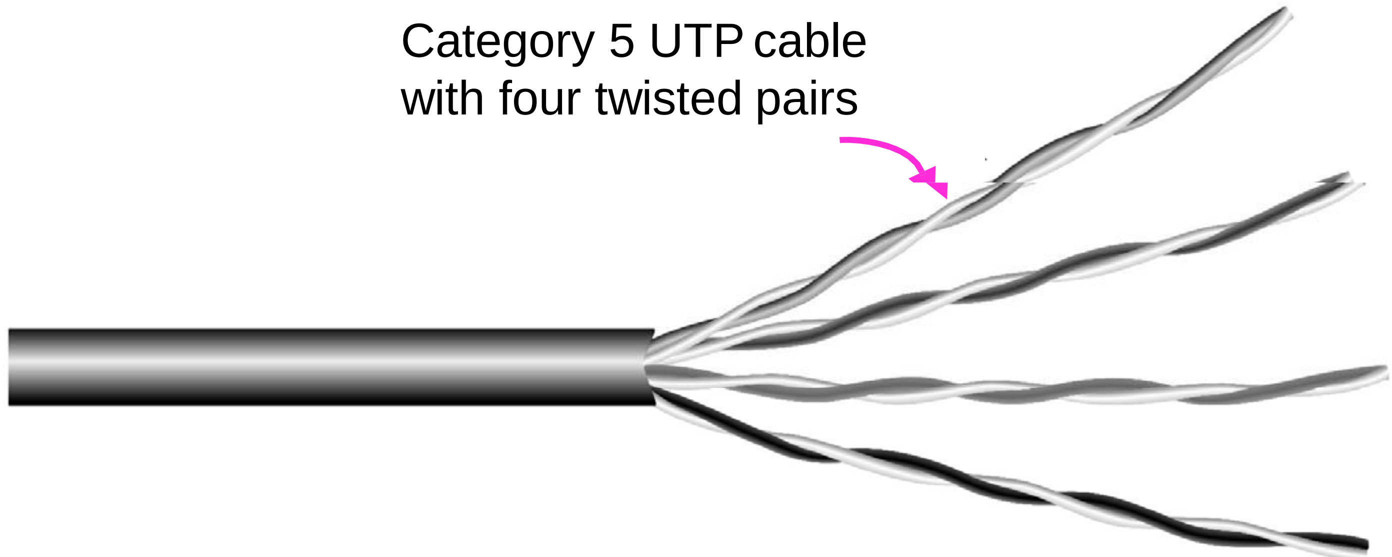
- Reality check
  - Storage media
- Wires:
  - Twisted pairs
  - Coaxial cable
  - Power lines
- Fiber cables

Reality Check: Storage media

- Send data on tape / disk / DVD for a high bandwidth link
  - Mail one box with 1000 800GB tapes (6400 Tera bits)
  - Takes one day to send (86,400 secs)
  - Data rate/bandwidth is 70 Gbps.
- Data rate is faster than long-distance networks! It is also cheap. But, the message delay is very poor.

Wires – Twisted Pair

- Very common; used in LANs, telephone lines
  - Twists reduce radiated signal (interference)
- Common application is telephone system and ADSL (Asymmetric Digital Subscriber Line)
- Can be used to transmit both analog and digital signals
- Bandwidth depends on the thickness of wire and distance travelled
- But, bandwidth of several megabits/sec can be achieved for few kilometers.
- Low cost and reasonable performance



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

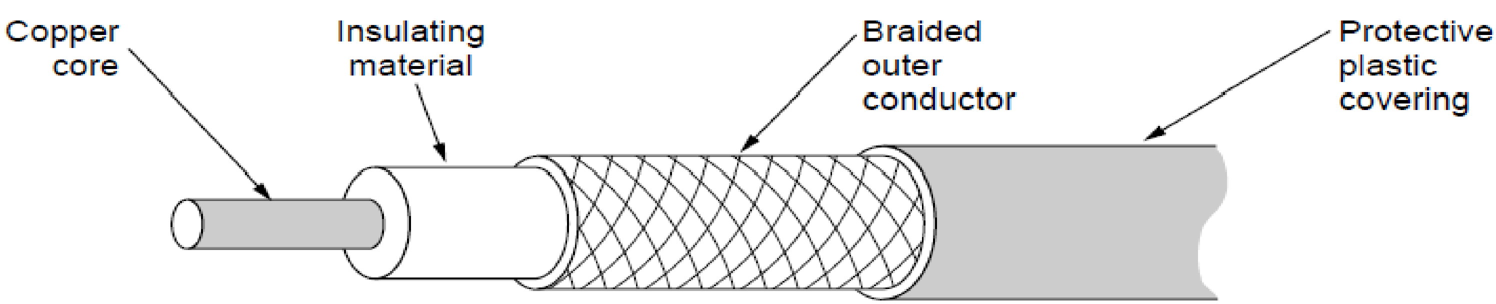
- Both directions, but not at the same time
- e.g., senders take turns on a wireless channel

Simplex link

- Only one fixed direction at all times; not common

Wires – Coaxial Cable (“Co-ax”)

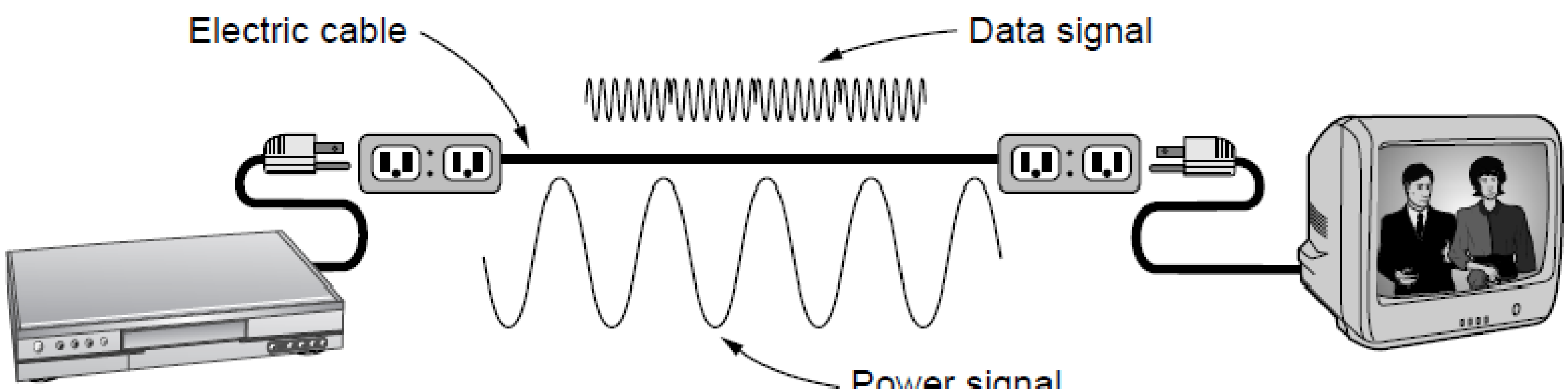
- A coaxial cable consists of still copper wire as a core, surrounded by an insulating material.
- Greater bandwidth than twisted pair
- Better shielding and more bandwidth for longer distances and higher rates than twisted pair.
- Bandwidth depends on cable quality and length
- Bandwidth is up to 1GHz
- Also common in long distance lines, cable lines, television networks.



Wires – Power Lines

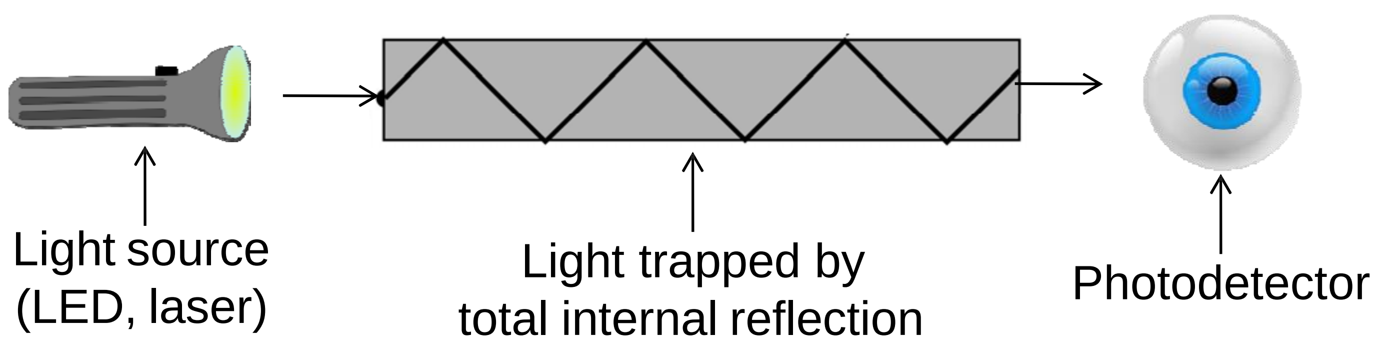
Household electrical wiring is another example of wires

- Convenient to use, but horrible for sending data
- 50-60 Hz
- Interference will be more, wires act like an antenna
- Efforts are going on



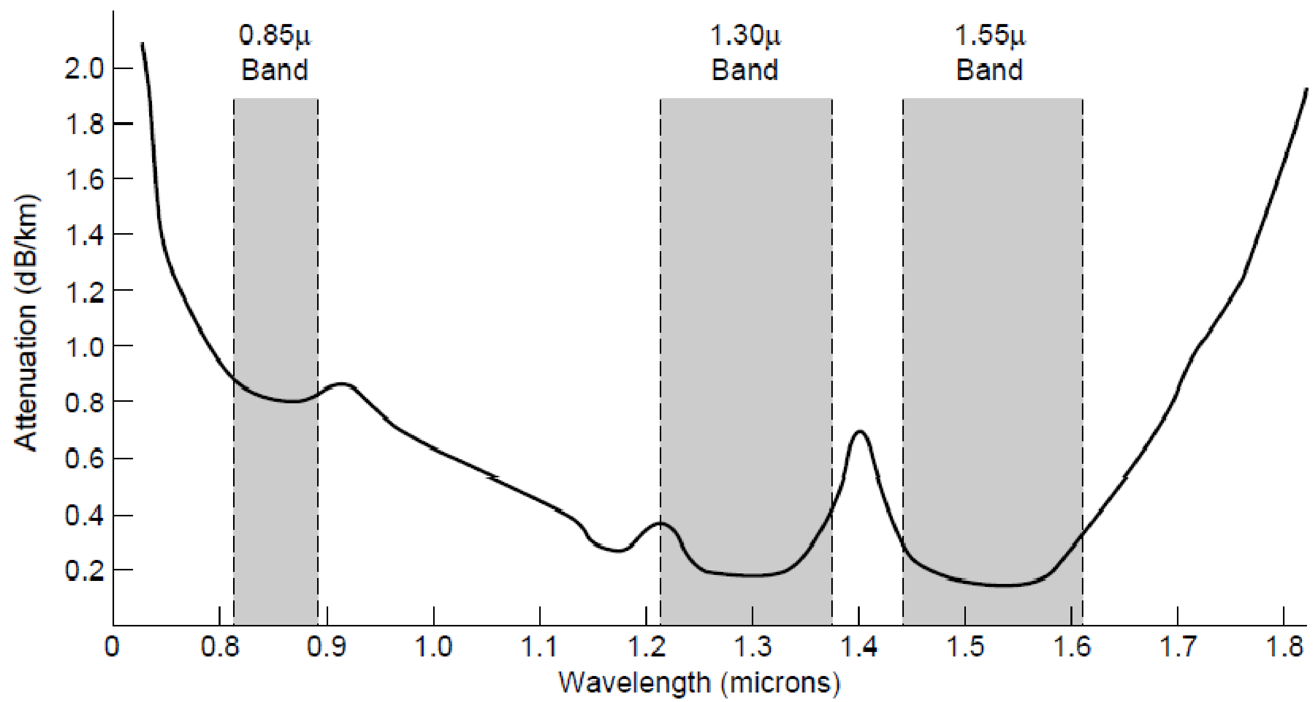
Fiber Cables (1)

- CPU speed has improved from 4.77 MHz (in the year 1981) to 3 GHz. Increased by a factor of 2500.
- Similarly, communication speed went from 45Mbps (telephone) to 100Gbps.Common for high rates and long distances and error rate went from 10^-5 to zero.
- Achievable bandwidth with fiber is 50,000 Gbps and difficult to reach. So, many channels are employed over a single fiber.
- Light source, transmission medium and detector
  - Light pulses are transmitted (presence=1 absence=0)
  - Transmission medium is unltra-thin fiber of glass.
- 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



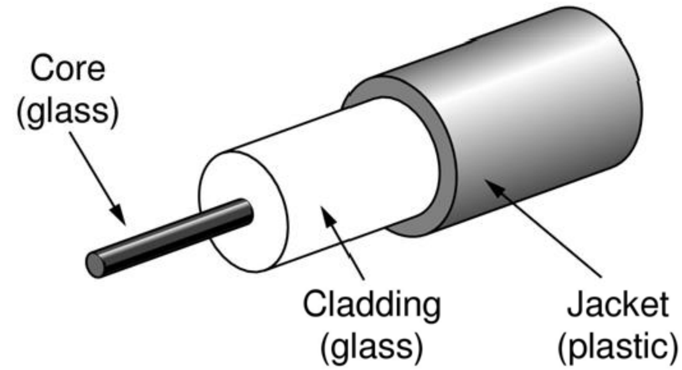
Fiber Cables (3)

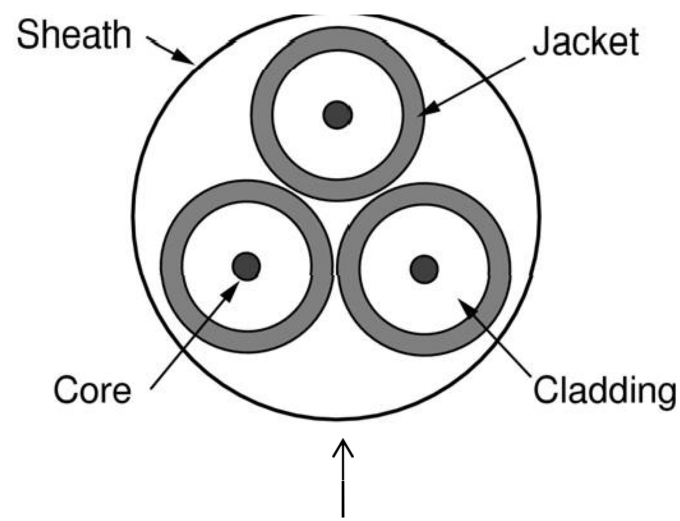
Single-mode

- 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

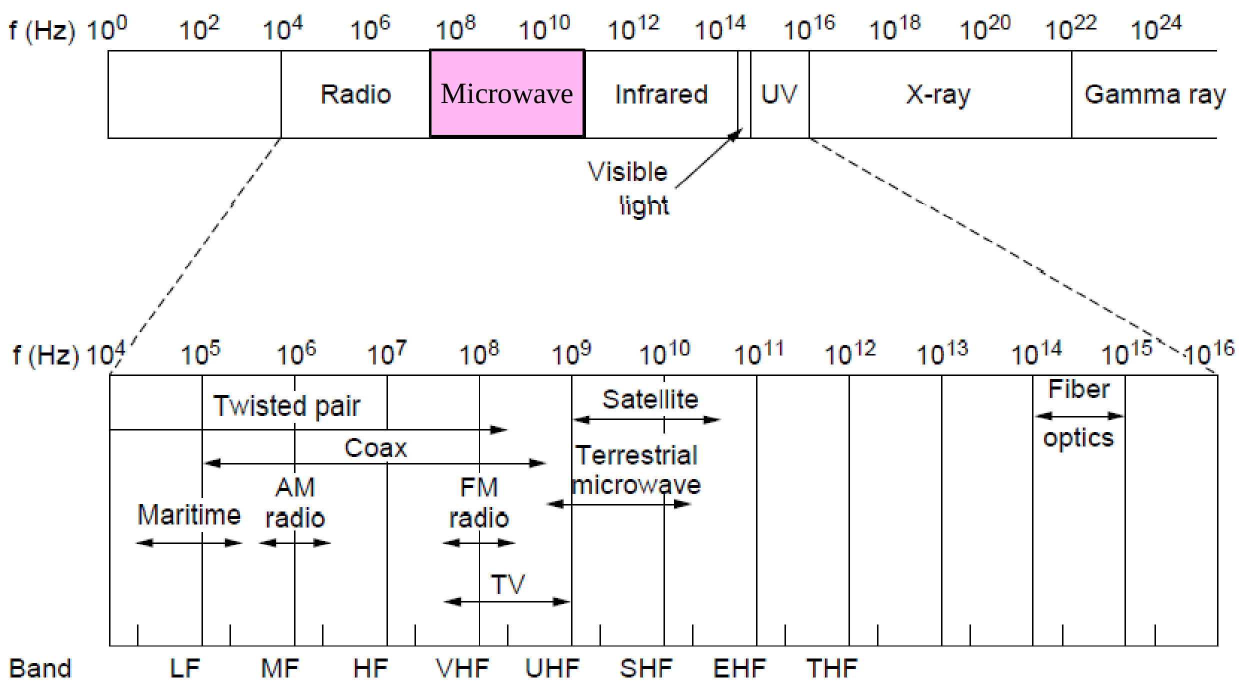
Wireless Transmission

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

Electromagnetic Spectrum (1)

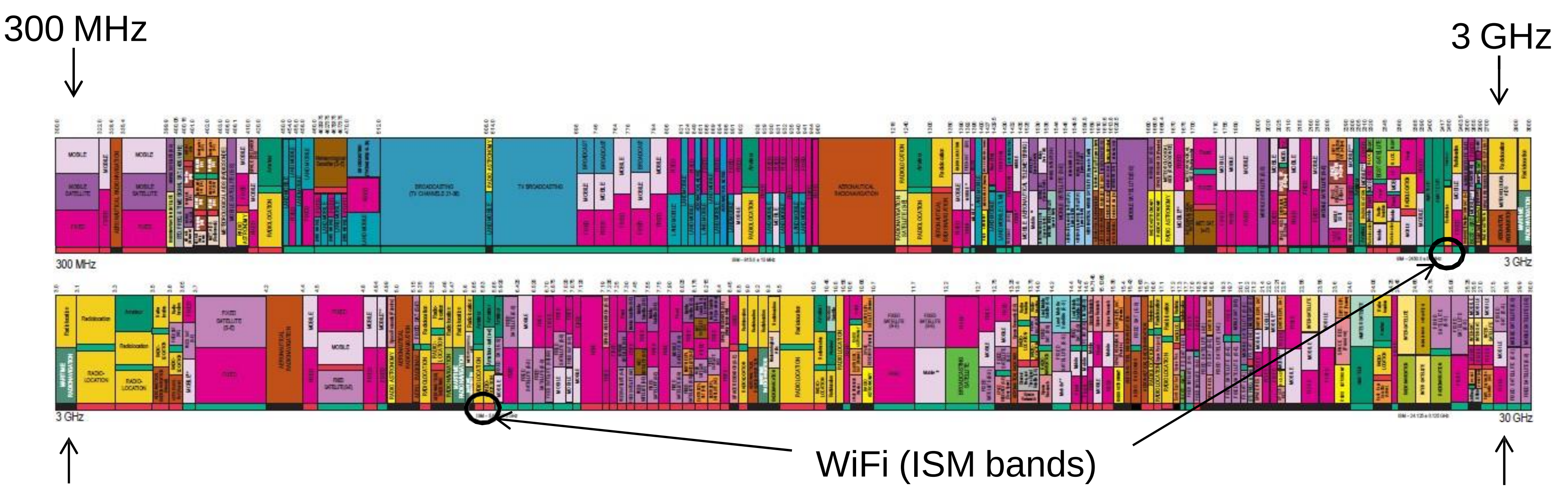
Different bands have different uses:

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



Electromagnetic Spectrum (2)

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



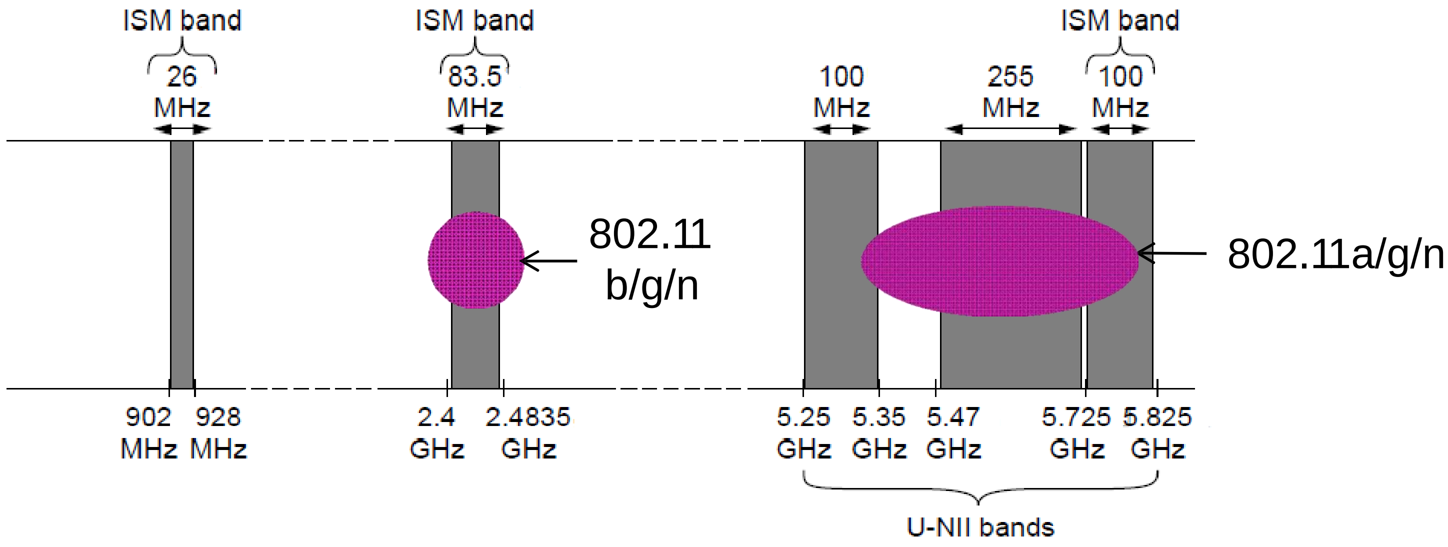
Source: NTIA Office of Spectrum Management, 2003

Part of the US frequency allocations

Electromagnetic Spectrum (3)

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

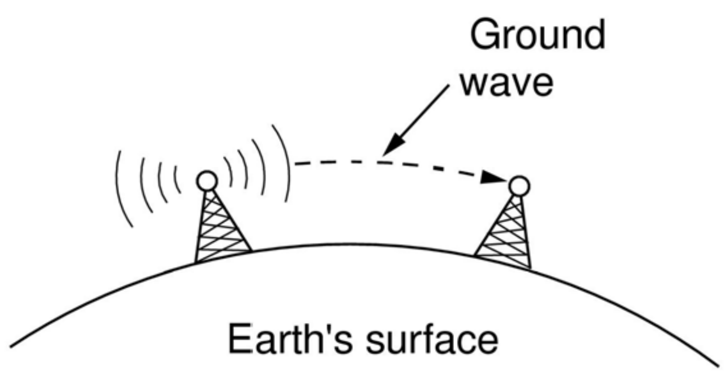
- Free for use at low power; devices manage interference
- Widely used for networking; WiFi, Bluetooth, Zigbee, etc.



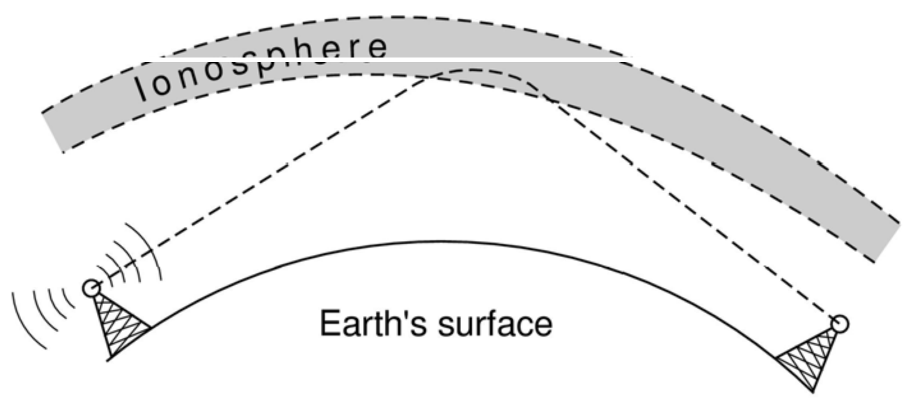
Industrial, scientific and medical networks (ISM networks)

Radio Transmission

- Radio signals penetrate buildings well and propagate for long distances with path loss (attenuation)
- At high frequencies, radio waves travel in a straight line.
- At all frequencies radio waves pass through obstacles, but power falls sharply



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

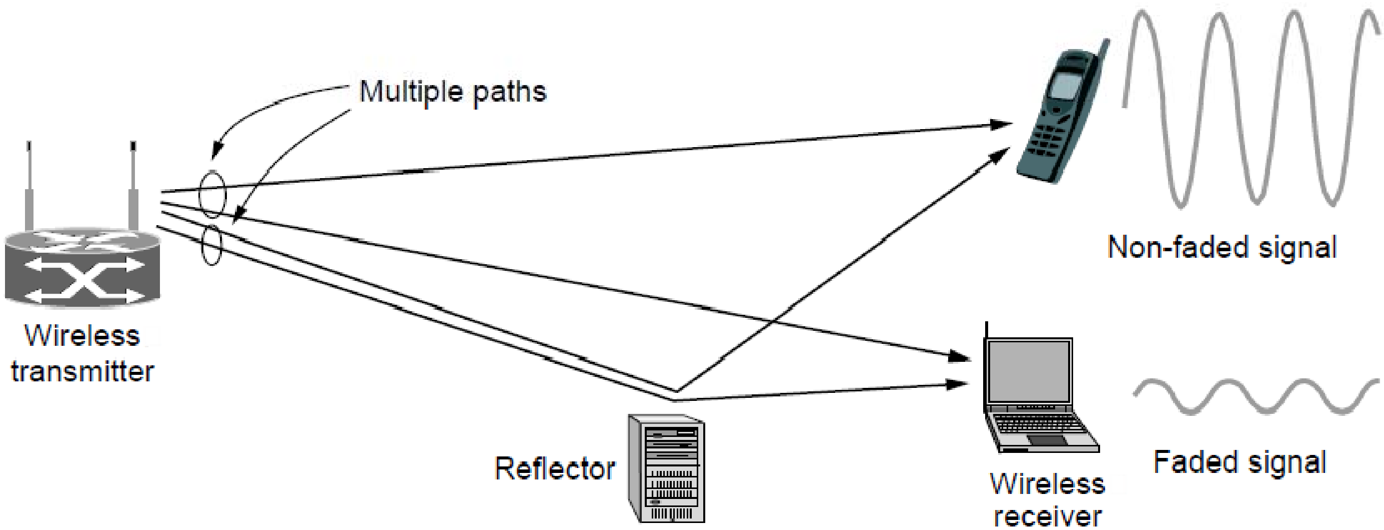


In the HF band, radio waves bounce off the ionosphere.

Microwave Transmission

Microwaves have much bandwidth and are widely used indoors (WiFi) and outdoors (3G, satellites)

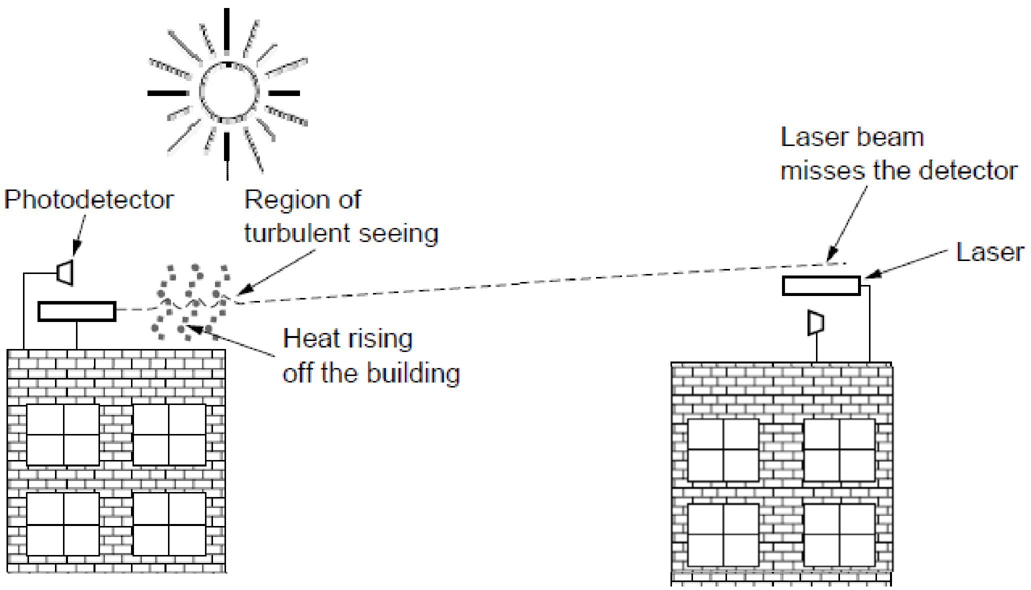
- Signal is attenuated/reflected by everyday objects
- Strength varies with mobility due multipath fading, etc.



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

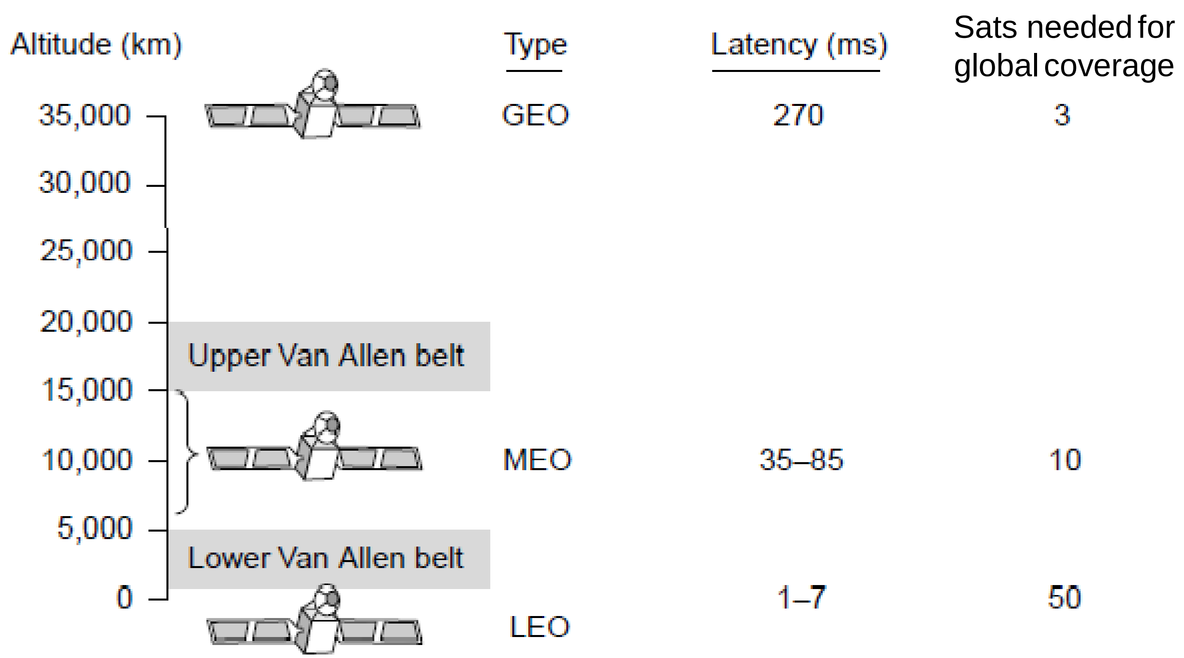
Satellites are effective for broadcast distribution and anywhere/anytime communications

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

Kinds of Satellites

Satellites and their properties vary by altitude:

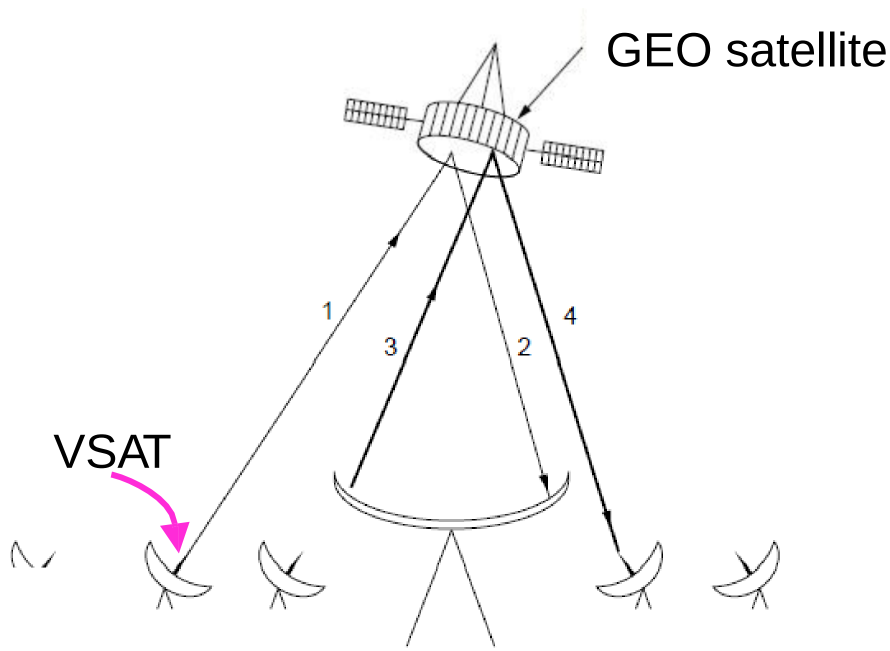
- Geostationary (GEO), Medium-Earth Orbit (MEO), and Low-Earth Orbit (LEO)



Geostationary Satellites

GEO satellites orbit 35,000 km above a fixed location

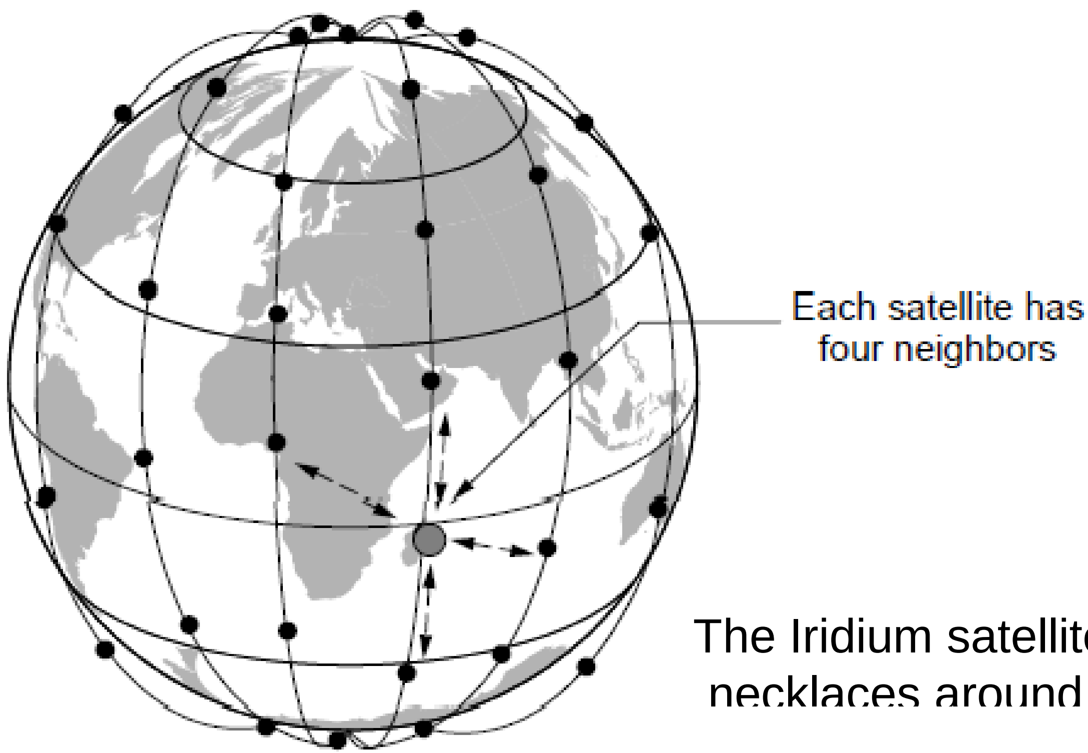
- VSAT (computers) can communicate with the help of a hub
- Different bands (L, S, C, Ku, Ka) in the GHz are in use but may be crowded or susceptible to rain.



A very small aperture terminal (VSAT) is a small-sized earth station used **in the transmit/receive of data, voice and video signals over a satellite communication network**, excluding broadcast television

Low-Earth Orbit Satellites

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



The Iridium satellites form six necklaces around the earth.

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

- Process of converting between bits and signals is called modulation.
- multiplexing schemes share a channel among users.

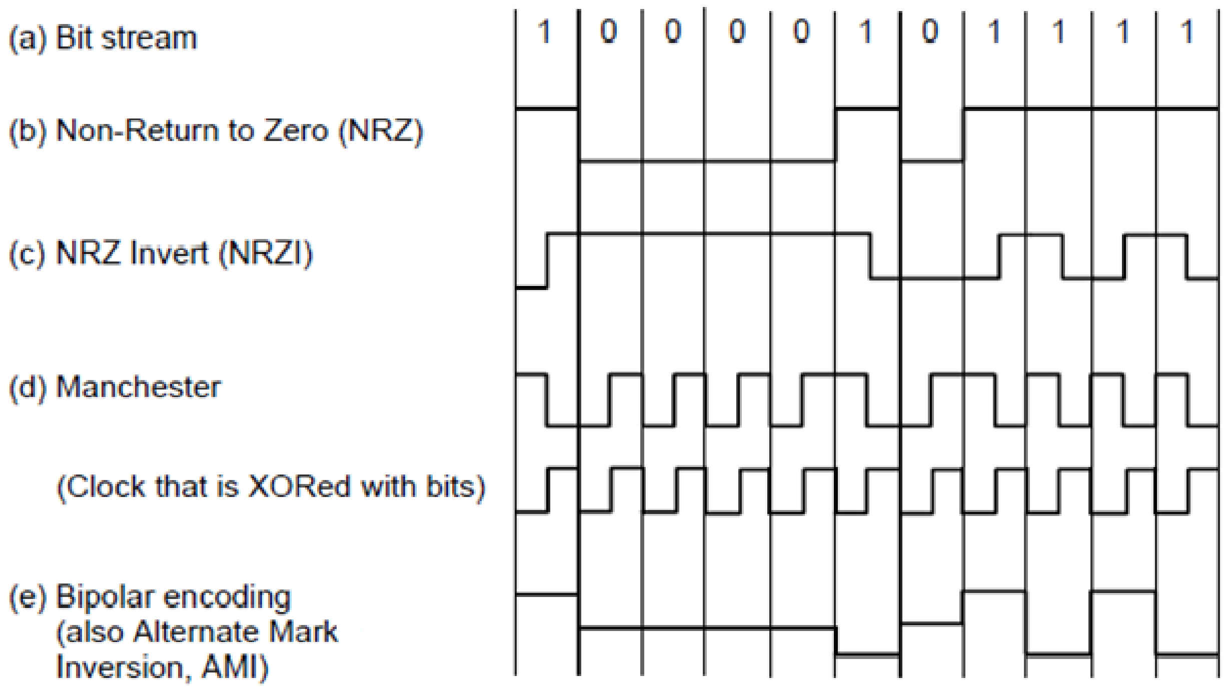
  - Baseband Transmission »
  - Passband Transmission »

  - Frequency Division Multiplexing »
  - Time Division Multiplexing »
  - Code Division Multiple Access »

Baseband Transmission

Line codes send symbols that represent one or more bits

- NRZ (**non-return-to-zero**) is the simplest, literal line code (+1V="1", -1V="0")
- Other codes tradeoff bandwidth and signal transitions

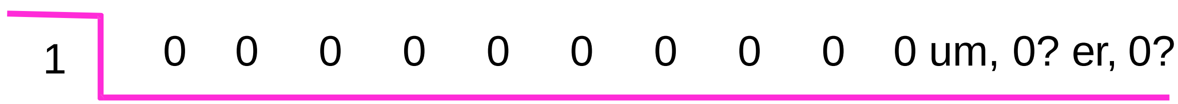


Four different line codes

Clock Recovery

To decode the symbols, signals need sufficient transitions

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



Strategies:

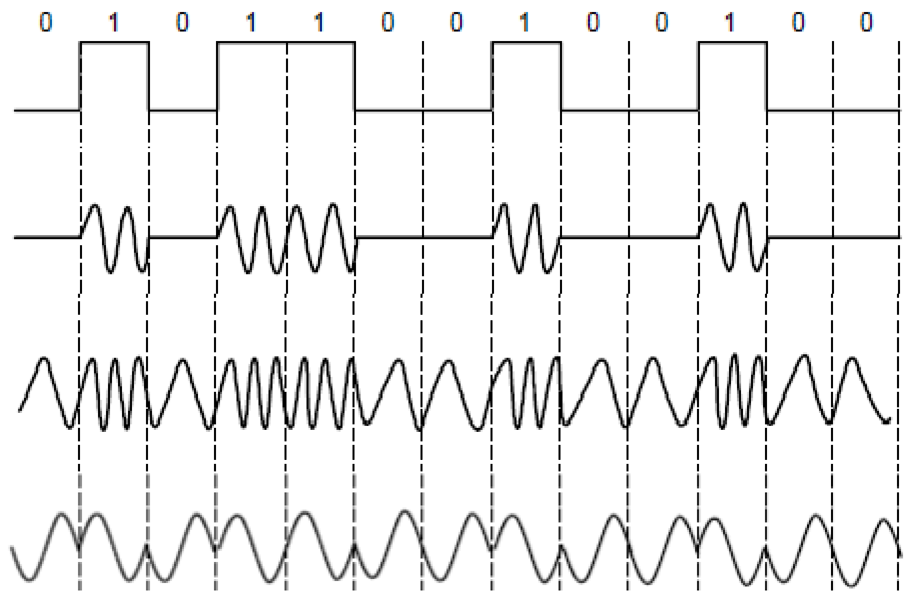
- Manchester coding, mixes clock signal in every symbol
- 4B/5B maps 4 data bits to 5 coded bits with 1s and 0s:

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 tx/rx 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

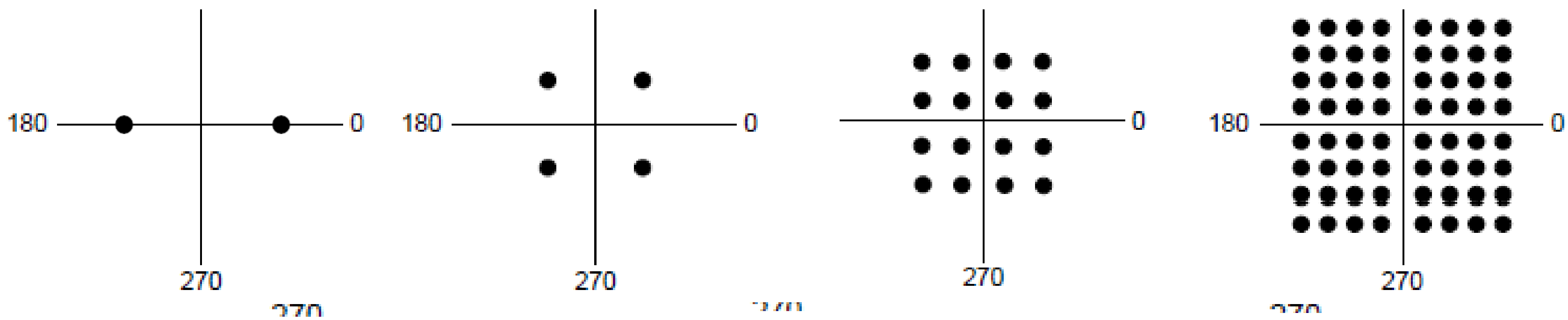
Amplitude shift keying

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

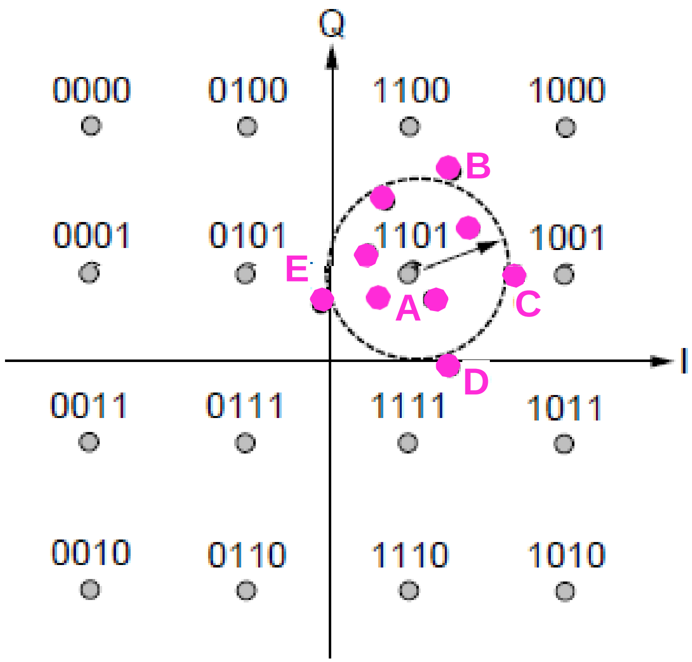
QAM-64
64 symbols
6 bits/symbol

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:

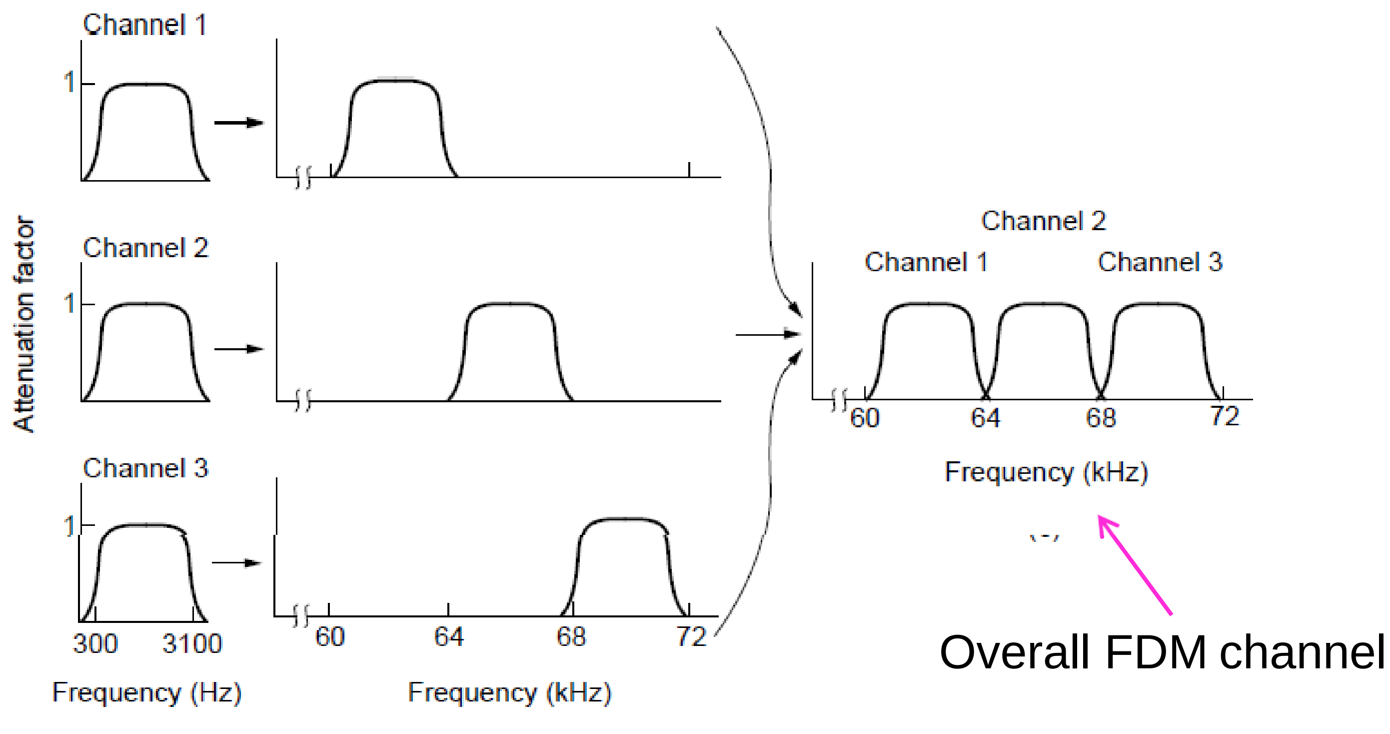


When 1101 is sent:

Point	Decodes as	Bit errors
A	1101	0
B	110<u>0</u>	1
C	1<u>0</u>01	1
D	11<u>1</u>1	1
E	<u>0</u>101	1

Frequency Division Multiplexing (1)

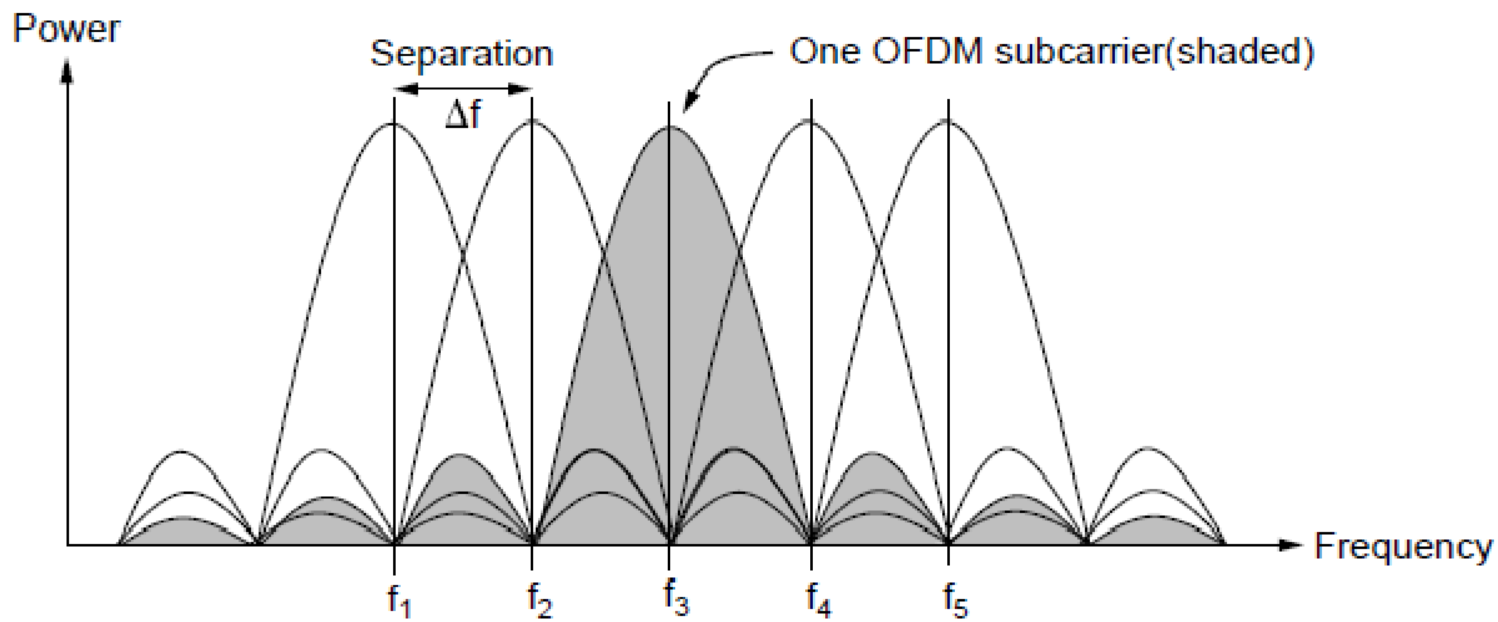
FDM (Frequency Division Multiplexing) shares the channel by placing users on different frequencies:



Frequency Division Multiplexing (2)

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

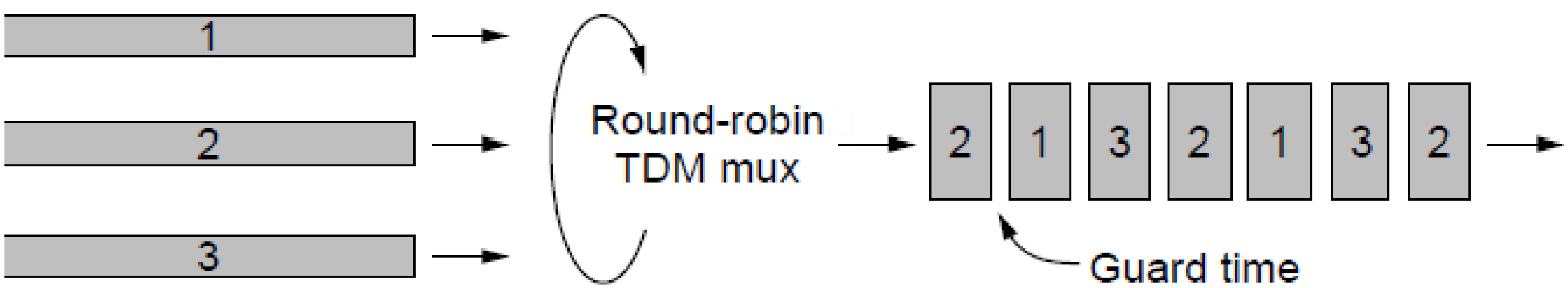
- Subcarriers are coordinated to be tightly packed



Time Division Multiplexing (TDM)

Time division multiplexing shares a channel over time:

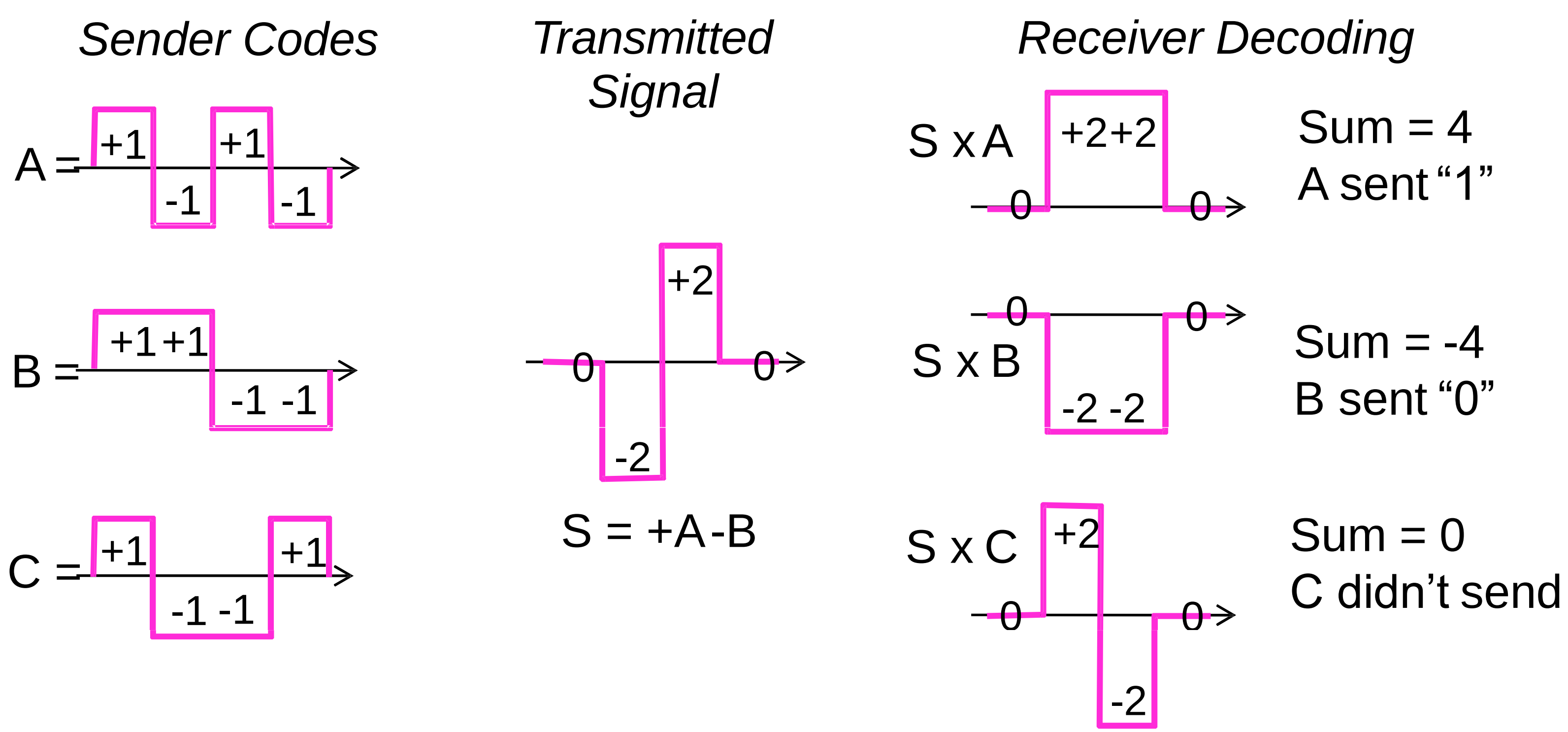
- Users take turns on a fixed schedule; this is not packet switching or STDM (Statistical TDM)
- Widely used in telephone / cellular systems



Code Division Multiple Access (CDMA)

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



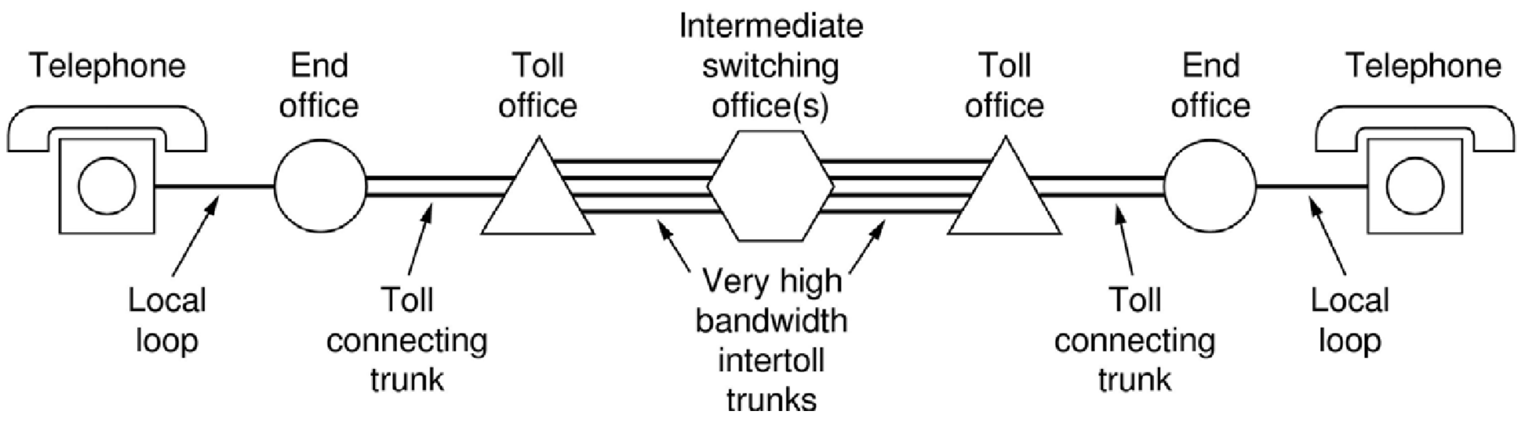
The Public Switched Telephone Network

- 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:

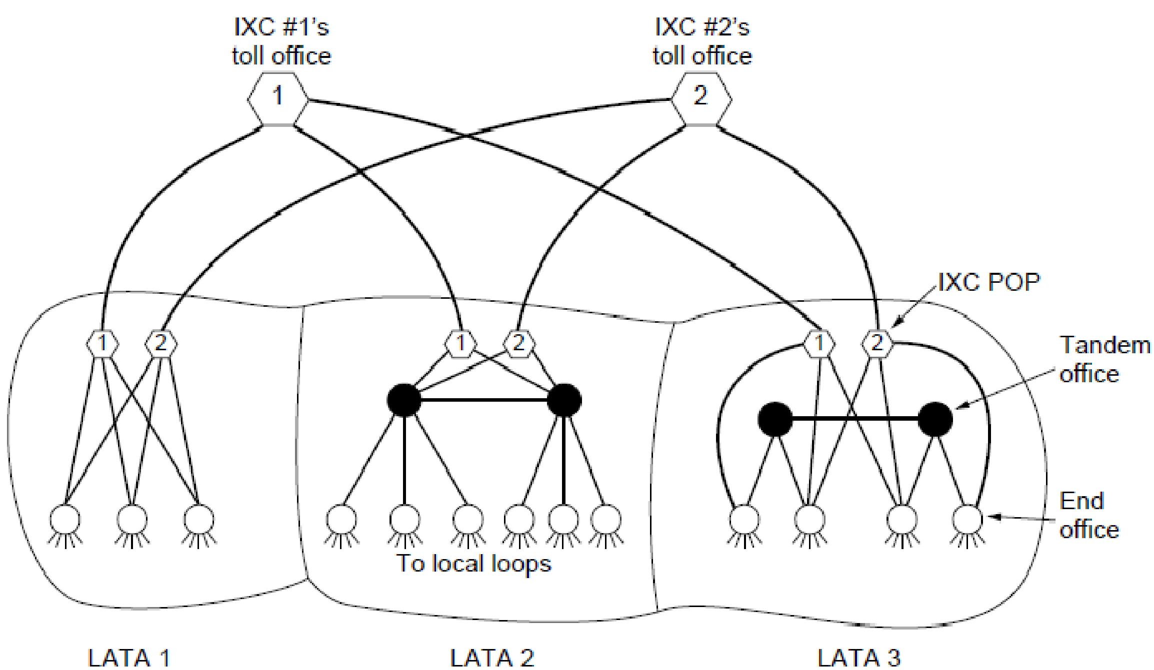
- Local loops, mostly analog twisted pairs to houses
- Trunks, digital fiber optic links that carry calls
- Switching offices, that move calls among trunks



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)

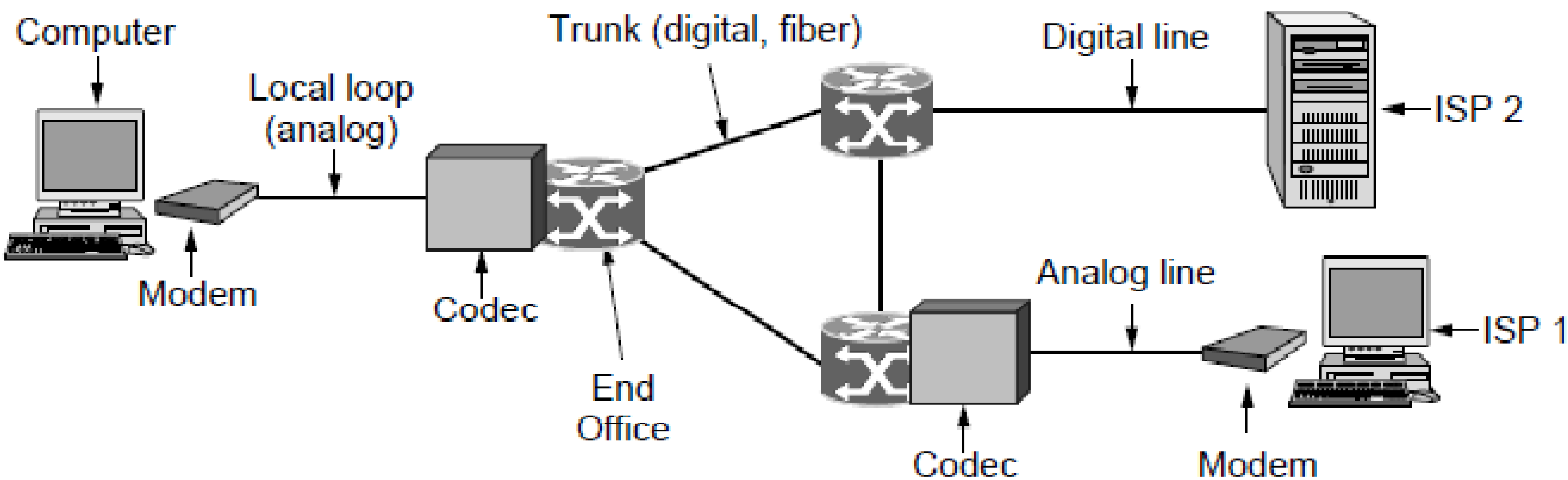
- Customers of a LEC can dial via any IXC they choose



Local loop (1): modems

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

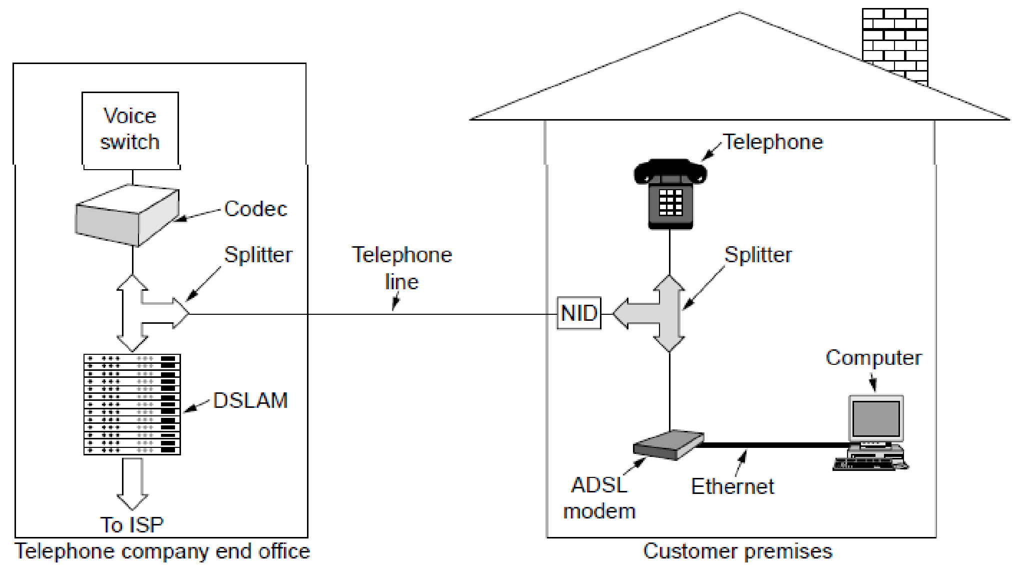
- Rates <56 kbps; early way to connect to the Internet

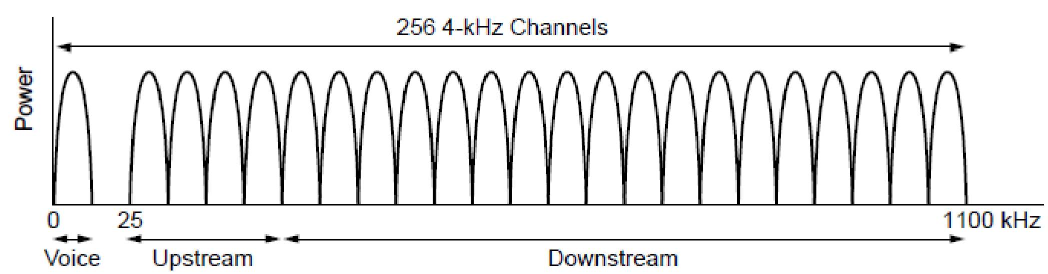


Local loop (2): Digital Subscriber Lines

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



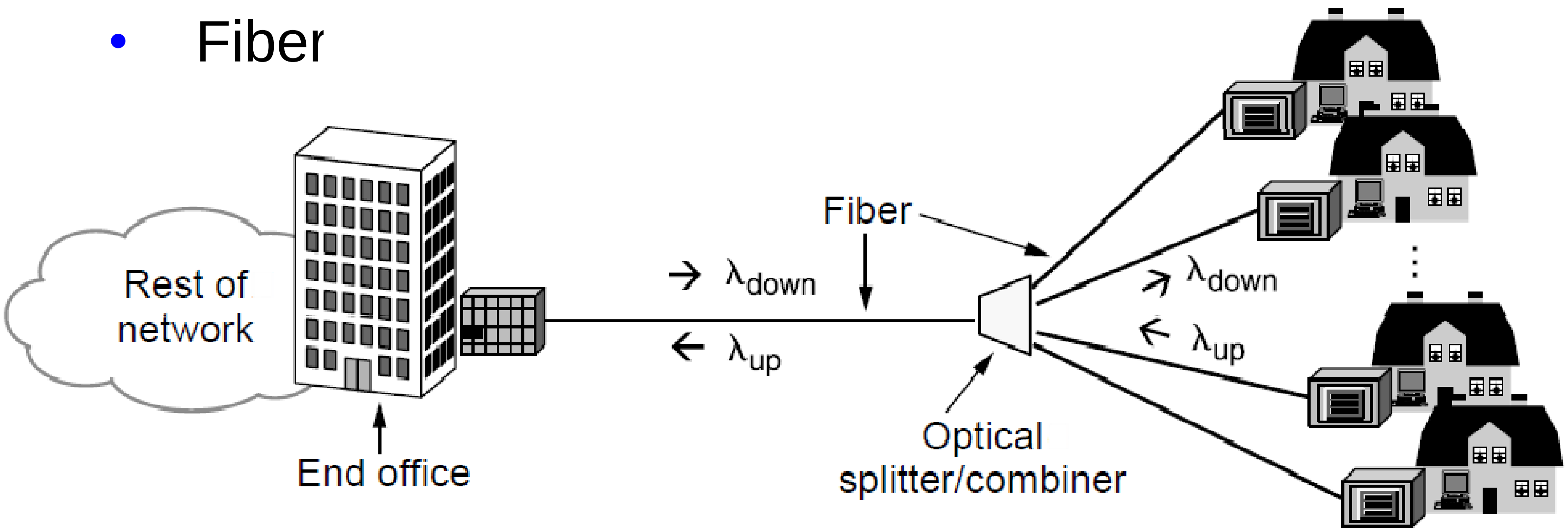


OFDM: Orthogonal Frequency Division Multiplexing
POTS: an analog voice transmission phone system implemented over copper twisted pair wires.

Local loop (3): Fiber To The Home

FTTH (Fiber To The Home) broadband relies on deployment of fiber optic cables to provide high data rates customers

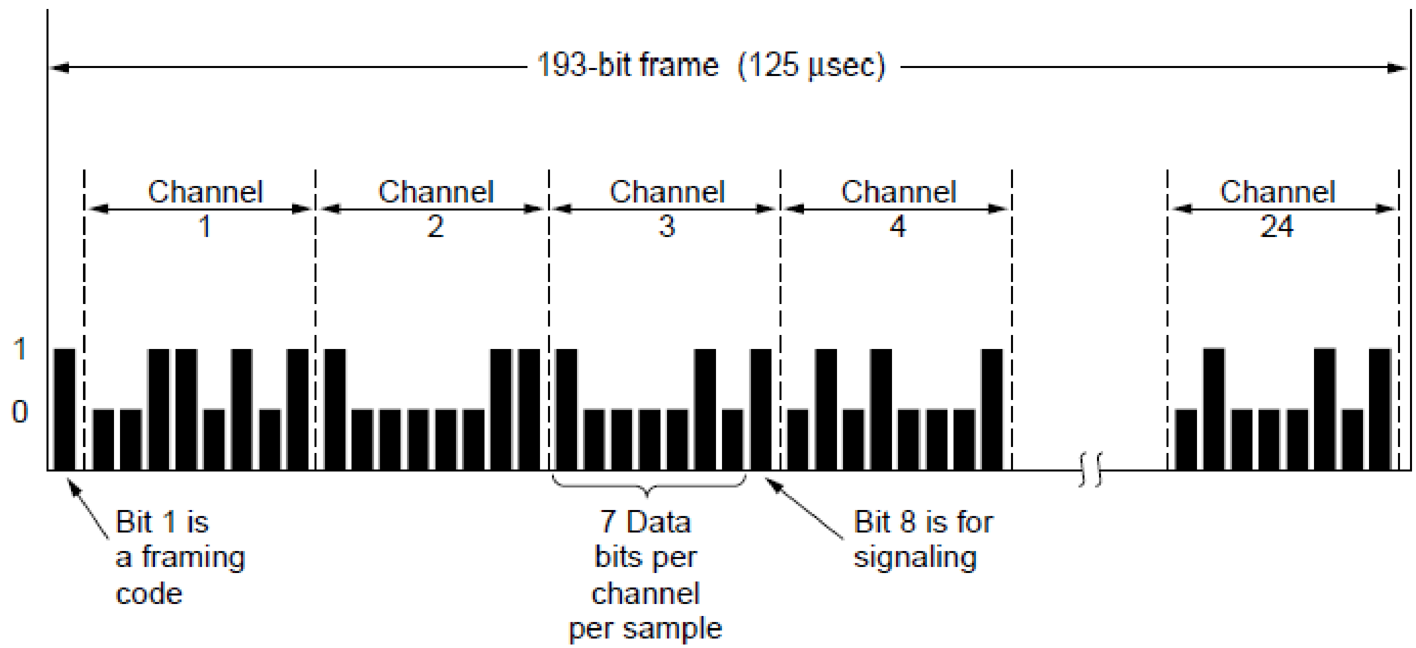
- One wavelength can be shared among many houses
- Fiber



Trunks and Multiplexing (1)

Calls are carried digitally on PSTN trunks using TDM

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

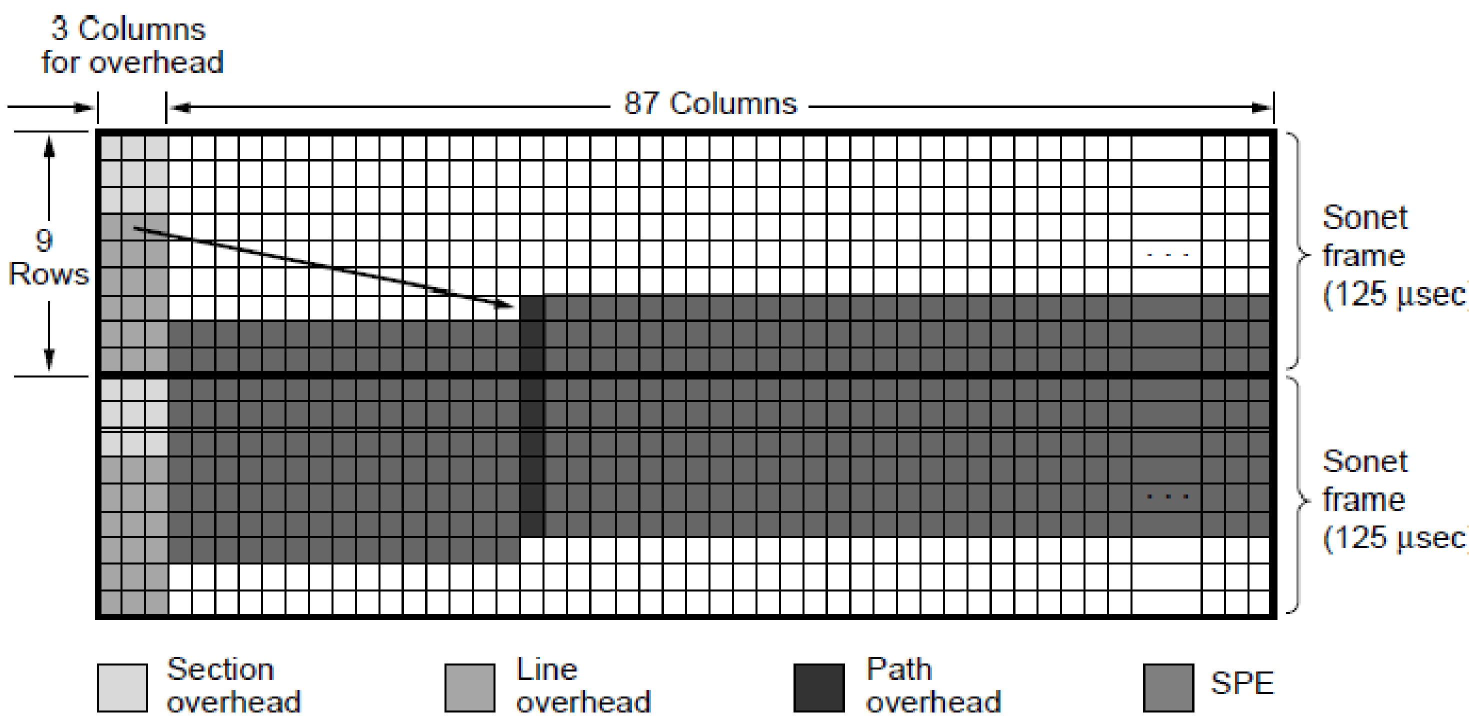


PSTN: Public Switched Telephone Network

Trunks and Multiplexing (2)

SONET (Synchronous Optical NETwork) is the worldwide standard for carrying digital signals on optical trunks

- Keeps 125 μs 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

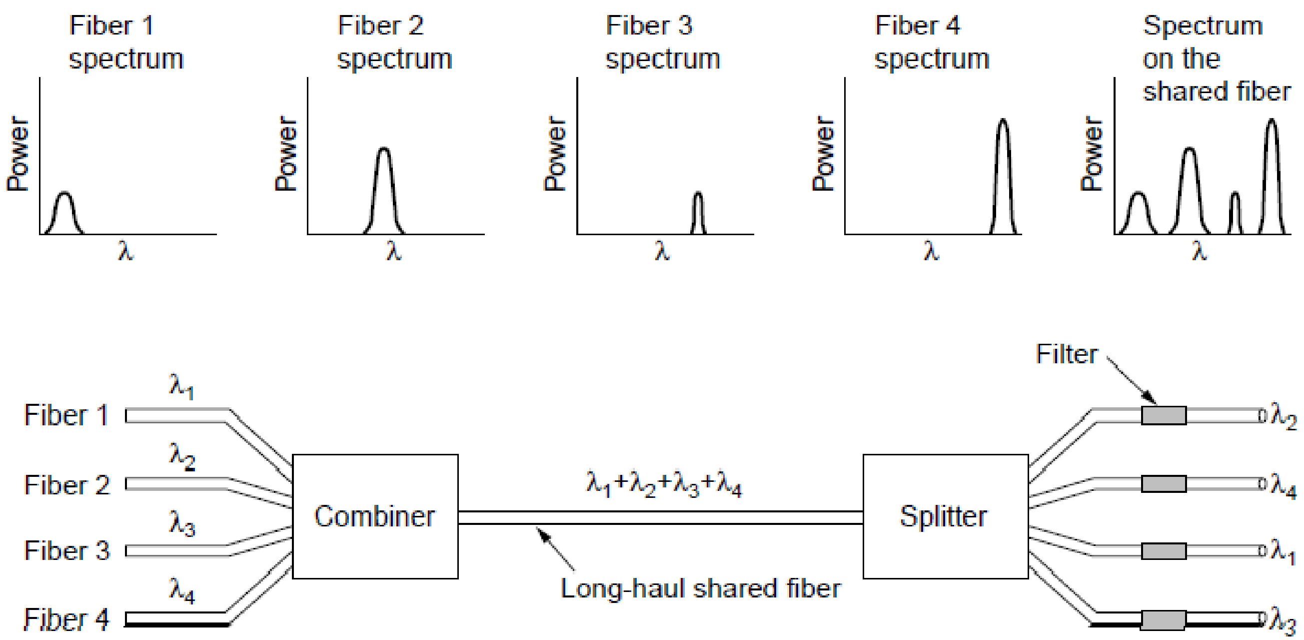
- Each level also adds a small amount of framing
- Rates from 50 Mbps (STS-1) to 40 Gbps (STS-768)

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:

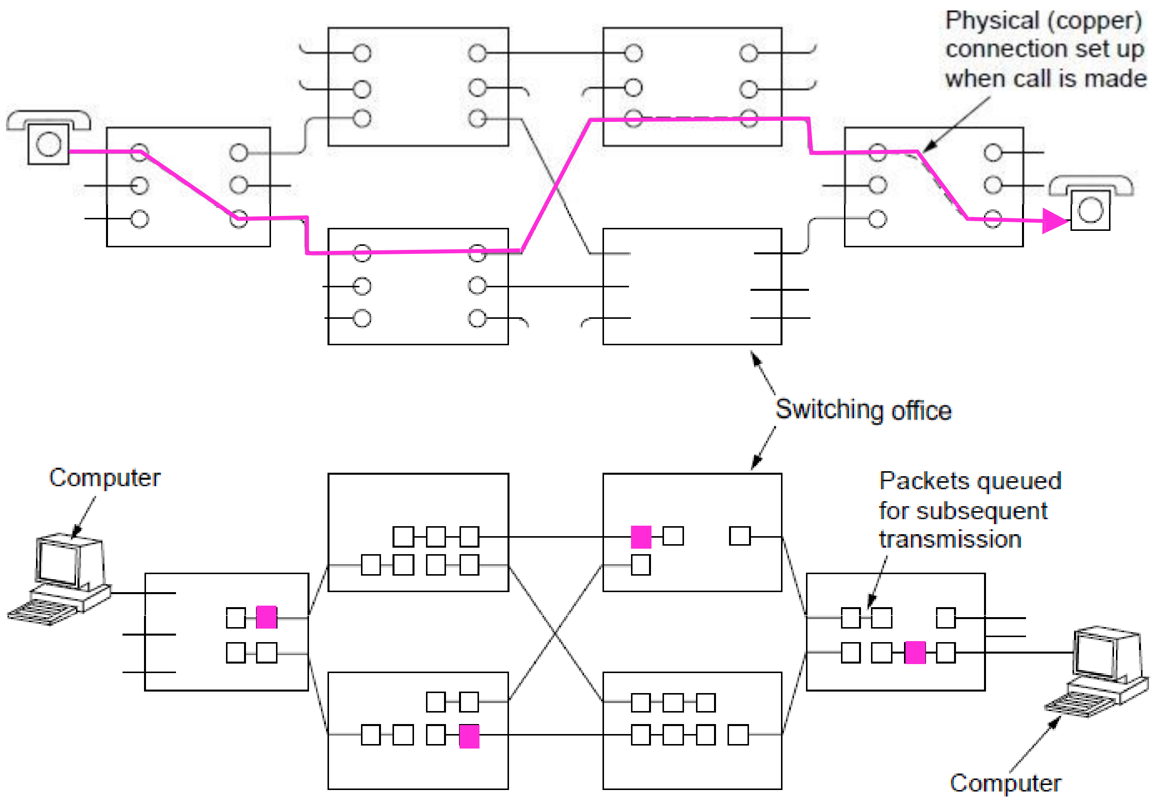


Switching (1)

PSTN uses circuit switching; Internet uses packet switching

PSTN:

Internet:



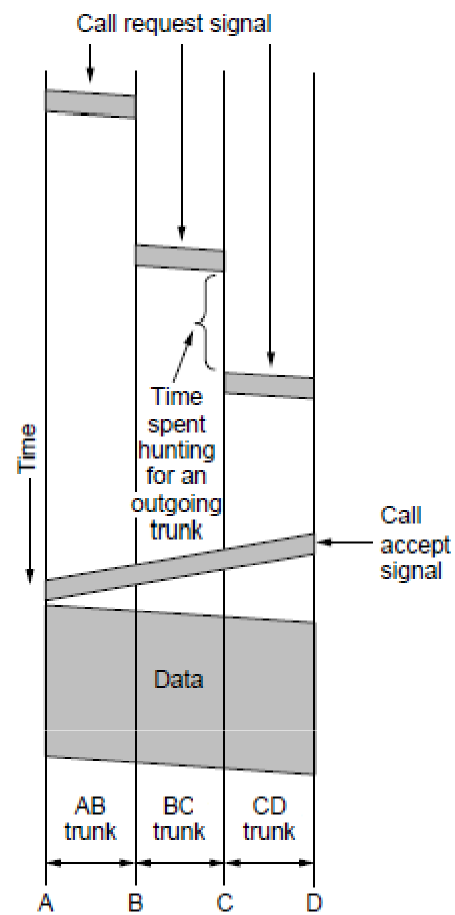
Switching (2)

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

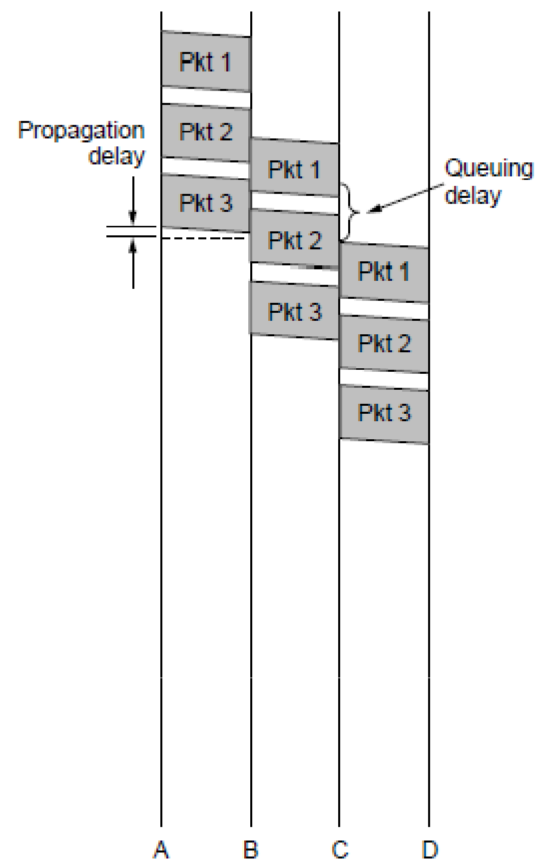
- Also teardown at end (not shown)

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

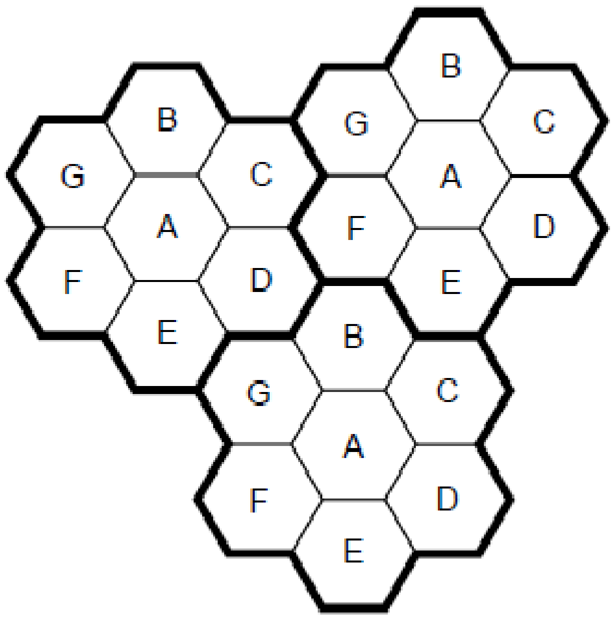
4G, digital data including voice

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

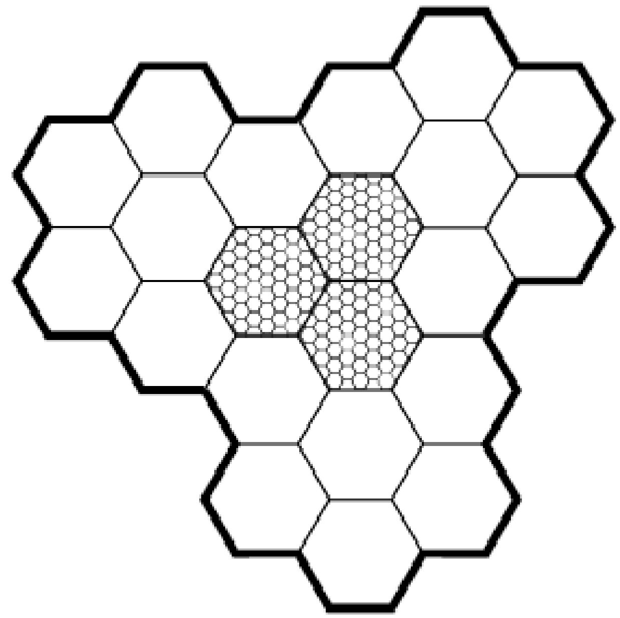
Cellular mobile phone systems

All based on notion of spatial regions called cells

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



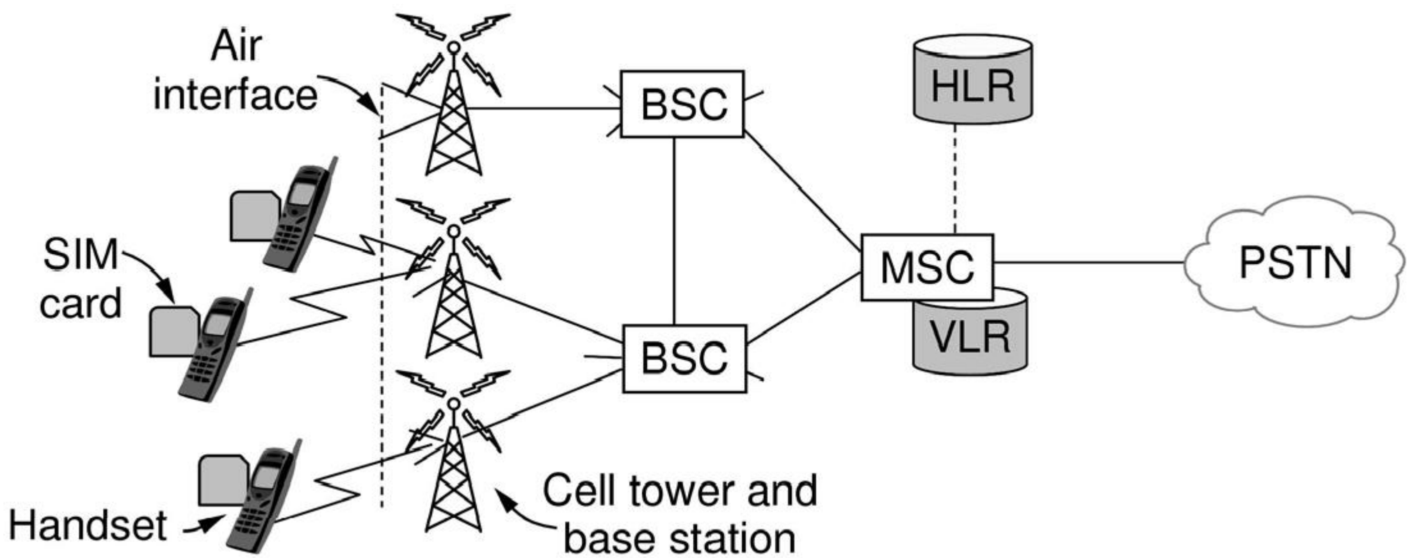
Cellular reuse pattern



Smaller cells for dense mobiles

GSM – Global System for Mobile Communications (1)

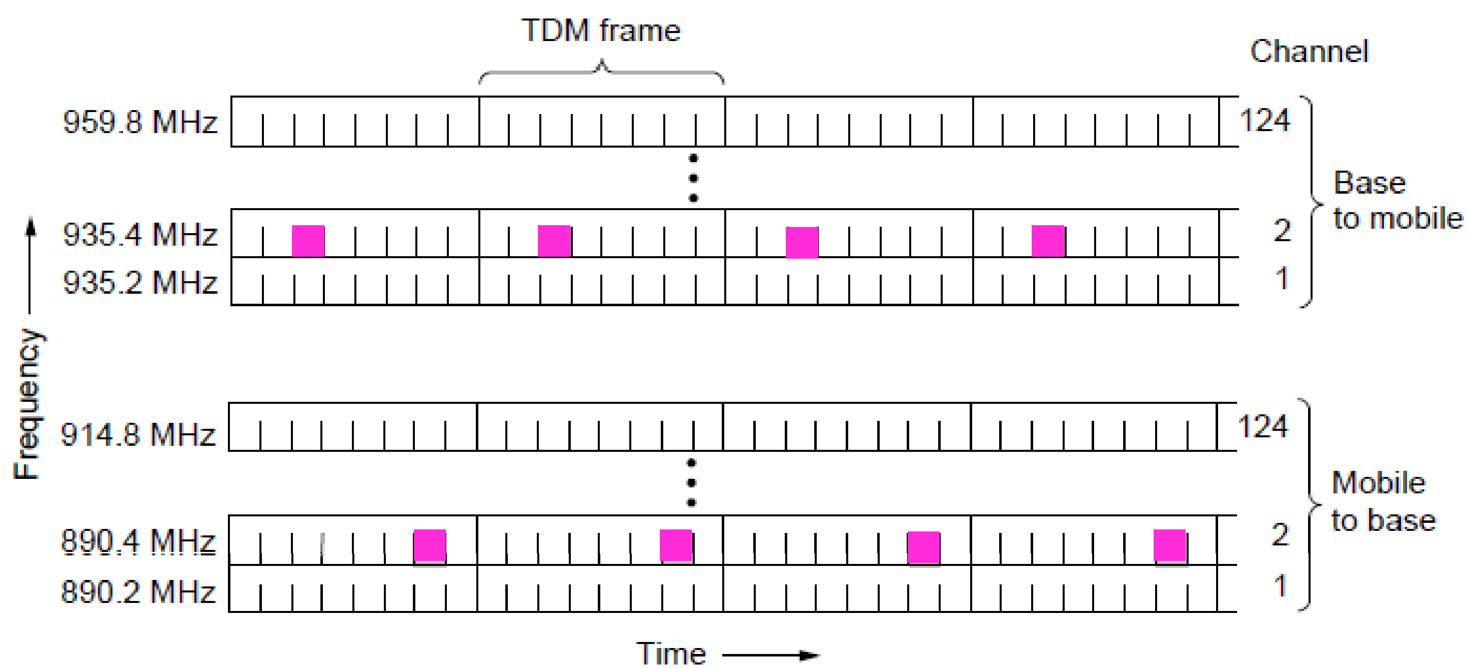
- Digital voice, Sophisticated technology
- Mobile is divided into handset and SIM card (Subscriber Identity Module) with credentials
- Mobiles tell their HLR (Home Location Register) their current whereabouts for incoming calls
- Cells keep track of visiting mobiles (in the Visitor LR)



GSM – Global System for Mobile Communications (2)

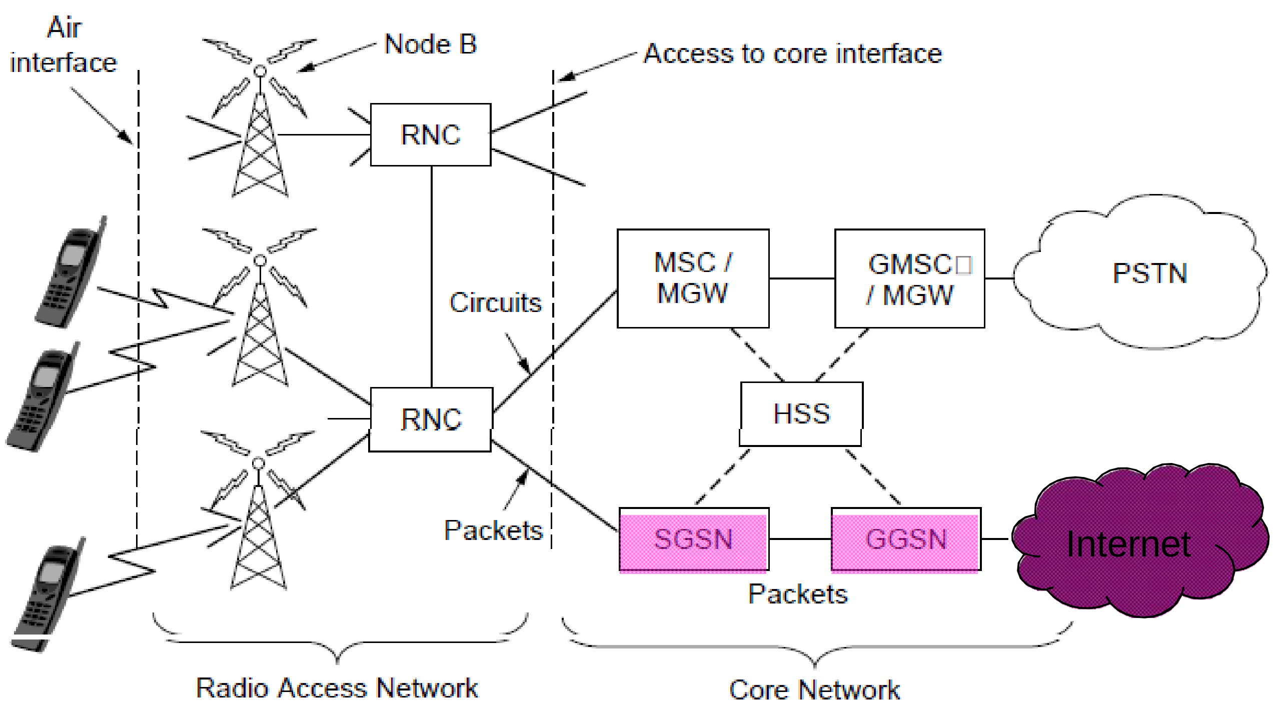
Air interface is based on FDM channels of 200 KHz divided in an eight-slot TDM frame every 4.615 ms

- 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)

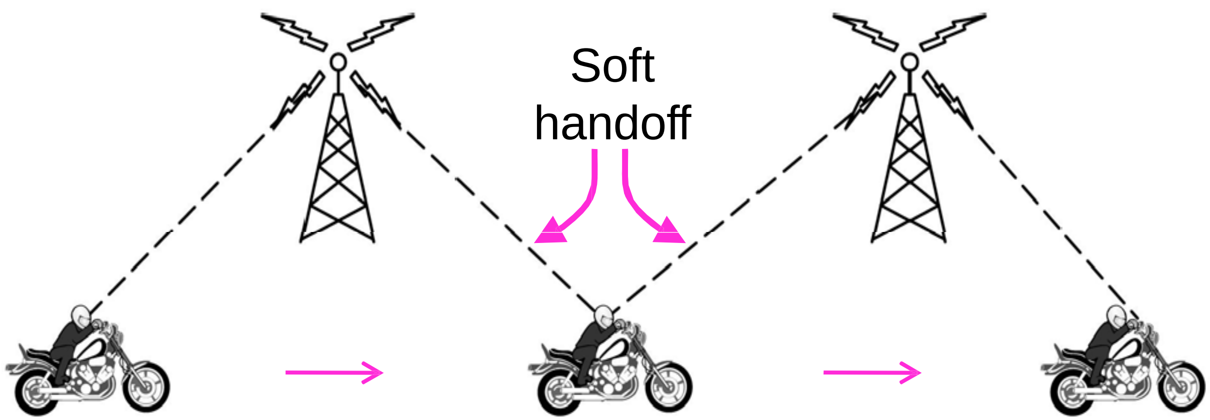
- Voice and data
- Architecture is an evolution of GSM; terminology differs Packets goes to/from the Internet via SGSN/GGSN



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)



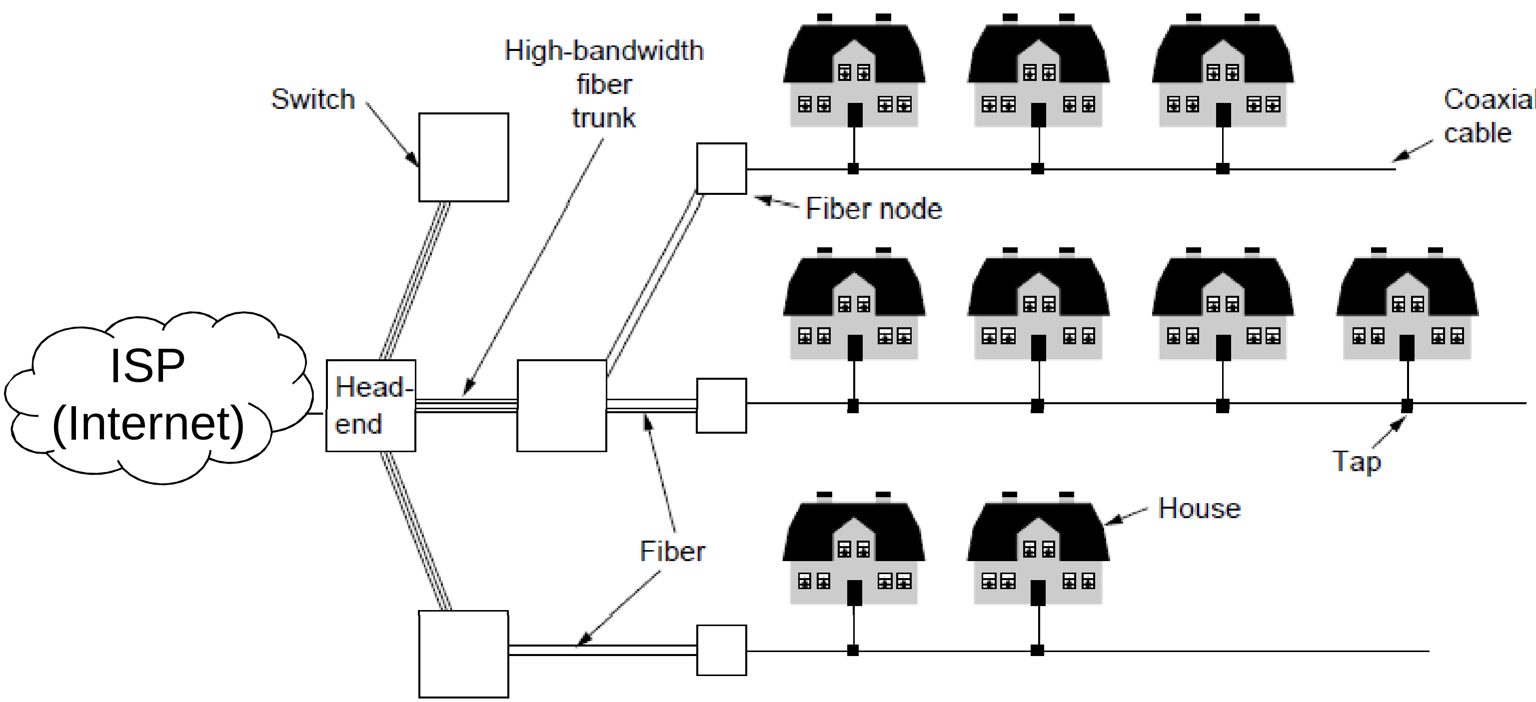
Cable Television

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

Internet over Cable

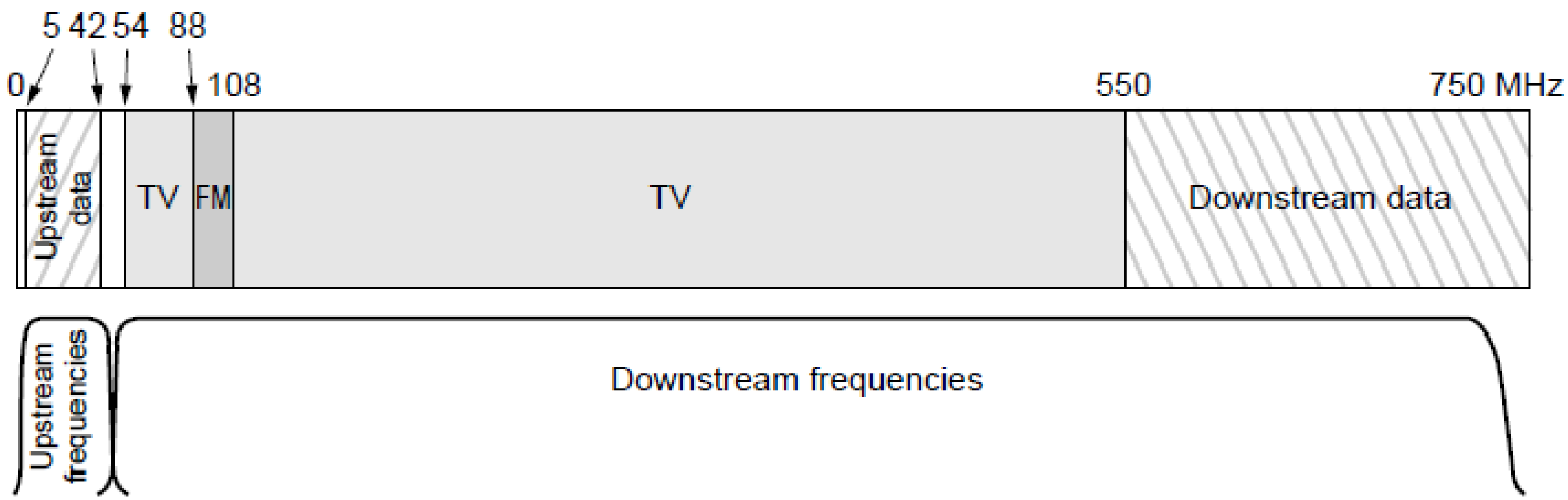
Internet over cable reuses the cable television plant

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



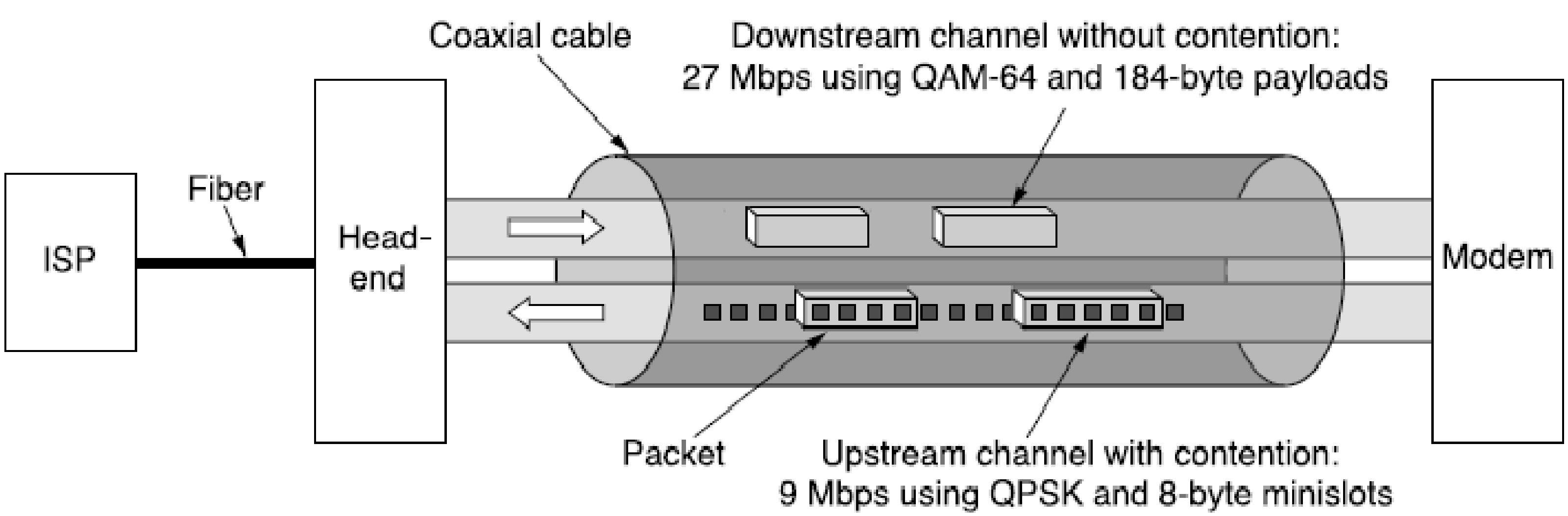
Spectrum Allocation

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



Cable Modems

- Internet access requires cable modem.
- Cable modems at customer premises implement the physical layer of the DOCSIS (data over cable service interface specification) standard
- Modem to computer is normally ethernet or USB. The other uses all of FDM,TDM and CDMA to share the bandwidth of the cable among the subscribers.



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)

Summary

- Physical layer is the basis of all networks
- Nature imposes two limits to determine bandwidth
  - Nyquist limit which deals with noiseless channels
  - Shannon limit which deals with noisy channels
- Transmission media can be guided or unguided
  - Guided: twisted pair, coaxial cable, and fiber optics
  - Unguided: radio, microwaves, infrared, laser through air and satellites.
- Digital modulation methods send bits over guided and unguided media
- Line codes operate at baseband, and signals can be placed in a passband by modulating the amplitude, frequency, and phase of the carreer.
- Telephone system is the basis for wide area networks
- Main components: local loops, trunks, and switches
  - ADSL offers speeds upto 40Mbps better than local loop
  - PONN brings fiber to home even greater access rates than ADSL
- Trunks carry digital information. They are multiplexed with WDM and provide many high capacity links over fibers as well as TDM to share each high data rate link between users.

Summary

- Both circuit switching and packet switching is important
- For mobile applications, the fixed telephone system is not suitable.
- Mobile phones have gone through three generations: 1G, 2G, 3G
- Cable television system is alternative system for network access. Bandwidth depends on other users as it is shared among the users.

End

Chapter 2