The Physical Layer

Chapter 2

A. Guided Transmission Media
   1. Twisted Pair cable
   2. Optics cable
B. Wireless Transmission
C. Reading
   1. Communication Satellites
   2. Digital Modulation and Multiplexing
   3. Public Switched Telephone Network
   4. Mobile Telephone System
   5. Cable Television

Revised and modified by Thaodtp: January 2024

Performance

Two fundamental metrics for measuring network performance

- Bandwidth
- Delay

Bandwidth

In computer networks, Bandwidth → Channel Capacity

- # of bits that *can* be transmitted through the system over a period of time

Throughput

- The measured performance of a system
- No. of bits *actually* transmitted per second

Bandwidth

Dial up

- Bandwidth = 56 Kbps

ADSL

- Bandwidth = 2 Mbps and 512 Kbps

Ethernet

- 10 M, 100M, 1G

Wi-Fi

- 11 Mbps, 54Mbps (802.11b/g), 300Mbps(802.11n Wi-Fi 4)
- 1730Mbps (802.11ac Wi-Fi 5), ~10Gbps (802.11ax Wi-Fi 6)

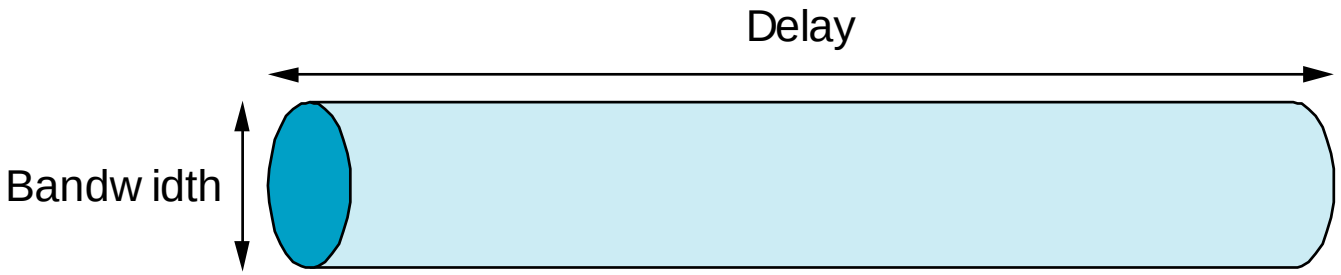
Optical Fiber

- 2.5 G, 10G, 50 G

Bandwidth x Delay

Considering the network as a pipe:

delay x bandwidth = capacity



The pipe should be ideally always full

- How many bits the sender must transmit before the 1st bit arrives at the receiver?

Bandwidth vs Delay

Telephone

- Low bandwidth
- Short delay

Email

- High bandwidth
- Long delay

What is the bandwidth of my lecture?

My speaking speed is 100 wpm

The average length of words is 4.5 letters

Each letter is 8 bits

1 minute my presentation can deliver 3600 bits

The bandwidth = 60 bps

Magnetic Media

Write the data onto magnetic media, such as DVDs

Physically transport the tape to the destination machine

Read them back again

Magnetic Media

An Ultrium tape can hold 200 Gb

A box 60x60x60 can hold about 1000 of these tapes, equivalent to 200 terabytes, or 1600 terabits

It takes 24 hours to deliver the box

Bandwidth = 1600 terabits / 86400 s = 19 Gbps

The cost = 4000 USD / box + 1000 USD shipping = 5000 USD / 200 Tb

3 cents / 1 Gigabytes

Lesson from magnetic media

Download film or buy DVD ?

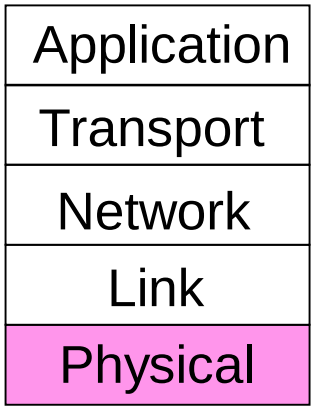
The Physical Layer

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



A. Guided Transmission (Wires & Fiber)

Media have different properties, hence performance

- Wires:
  - Twisted pairs »
  - Coaxial cable »
  - Power lines »
- Fiber cables »

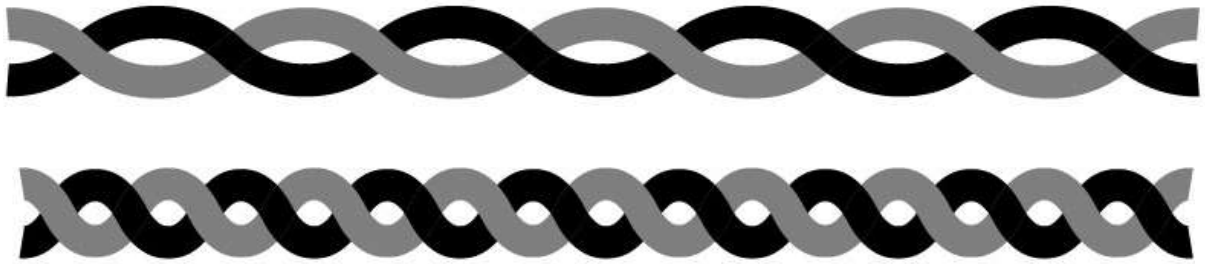
Cable Type	*Bandwidth*
Twisted Pair	0 - 100 MHz
Coaxial Cable	0 - 600 MHz
Optical Fiber	0 - 1 GHz

1. TWISTED PAIR (UTP/STP)

Simply two wires twisted together - the twisting cuts down on electrical interference

Heavily used in the phone system

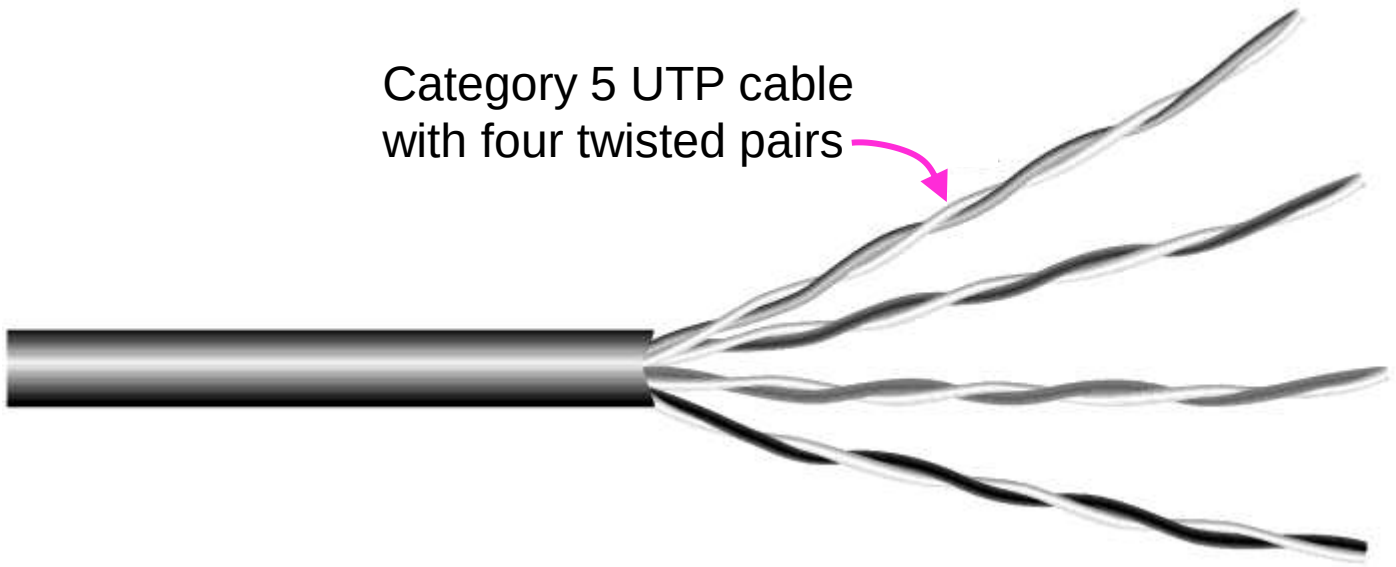
Category 3 and 5 - with 5 having more twists and better insulation



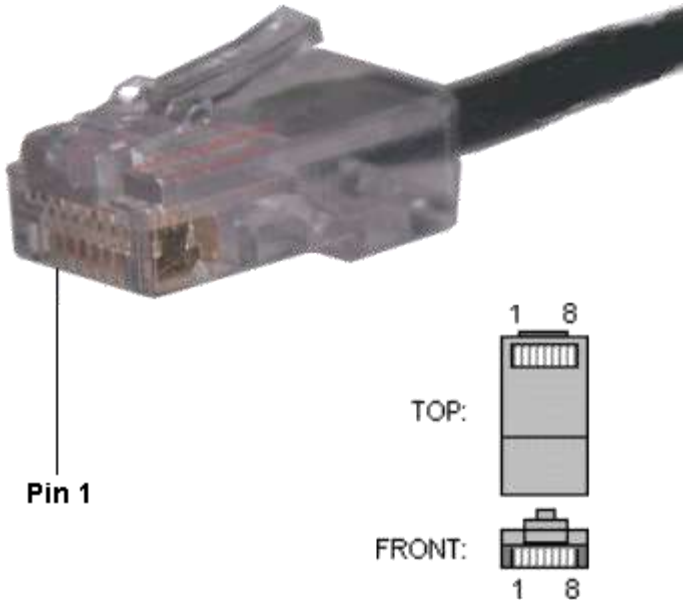
Wires – Twisted Pair

Very common; used in LANs, telephone lines

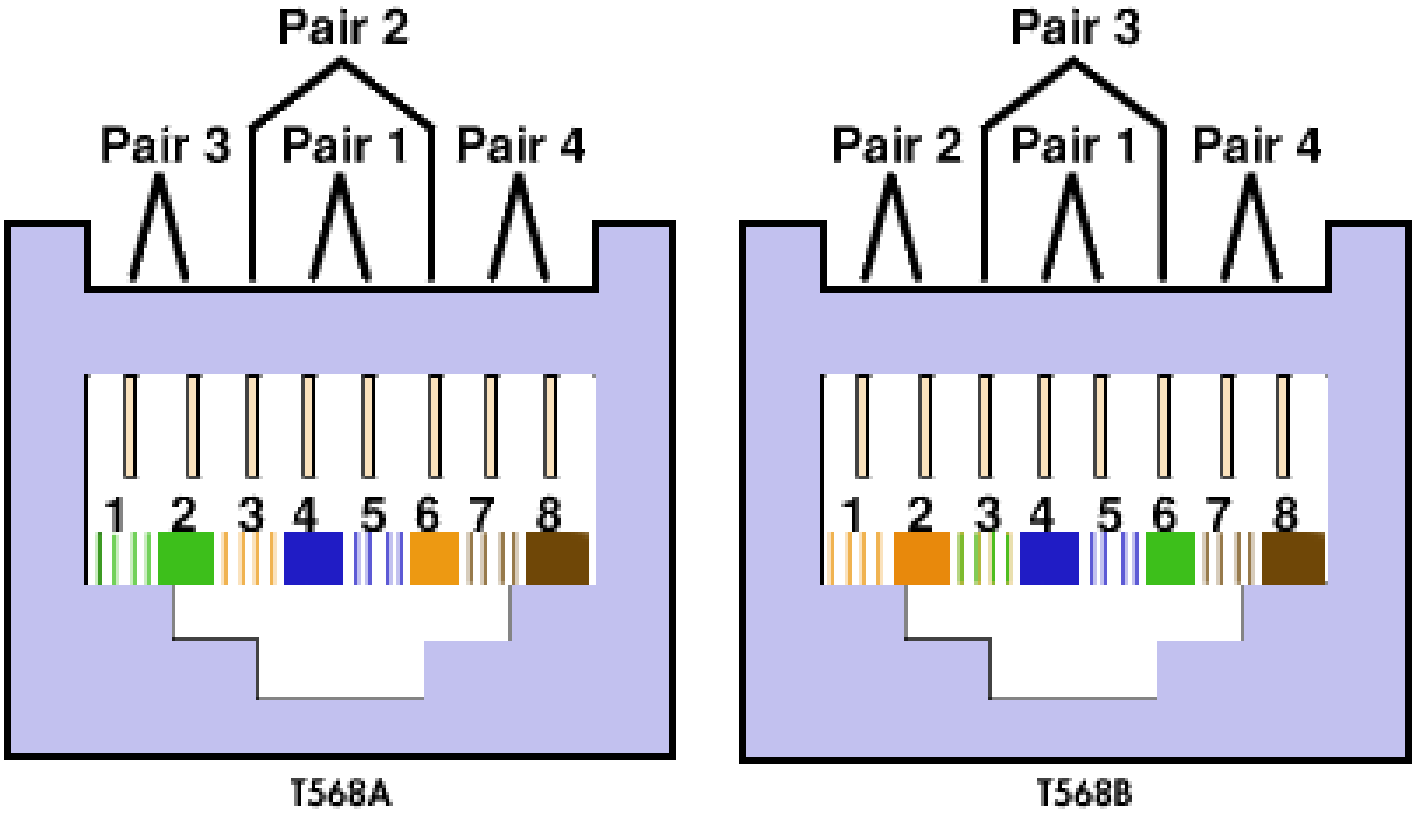
- Twists reduce radiated signal (interference)



RJ-45 connector

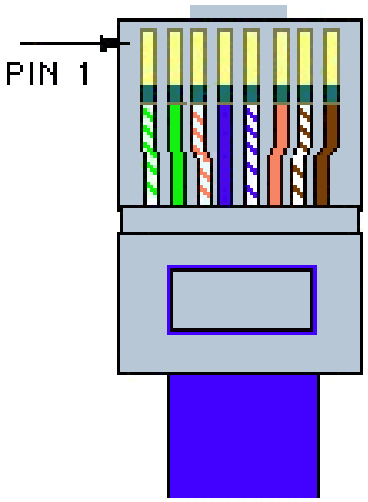


Pin #	Ethernet 10BASE-T 100BASE-TX	EIA/TIA 568A	EIA/TIA 568B or AT&T 258A
1	Transmit +	White with green strip	White with orange stripe
2	Transmit -	Green with white stripe or solid green	Orange with white stripe or solid orange
3	Receive +	White with orange stripe	White with green stripe
4	N/A	Blue with white stripe or solid blue	Blue with white stripe or solid blue
5	N/A	White with blue stripe	White with blue stripe
6	Receive -	Orange with white stripe or solid orange	Green with white stripe or solid
7	N/A	White with brown strip or solid brown	White with brown strip or solid brown
8	N/A	Brown with white stripe or solid brown.	Brown with white stripe or solid brown.

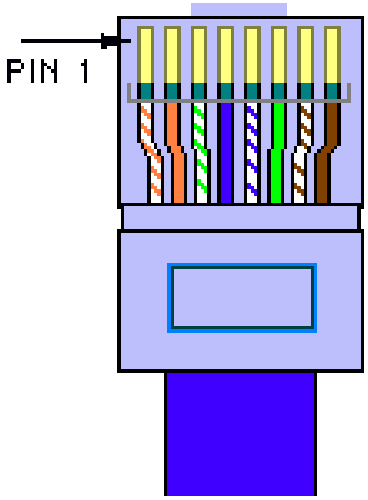

Pair 2
Pair 3
Pair 1
Pair 4
1 2 3 4 5 6 7 8
T568A
Pair 3
Pair 2
Pair 1
Pair 4
1 2 3 4 5 6 7 8
T568B

Crossover Cable

RJ-45 PIN	RJ-45 PIN
1 Rx+	3 Tx+
2 Rc-	6 Tx-
3 Tx+	1 Rc+
6 Tx-	2 Rc-



568A Male



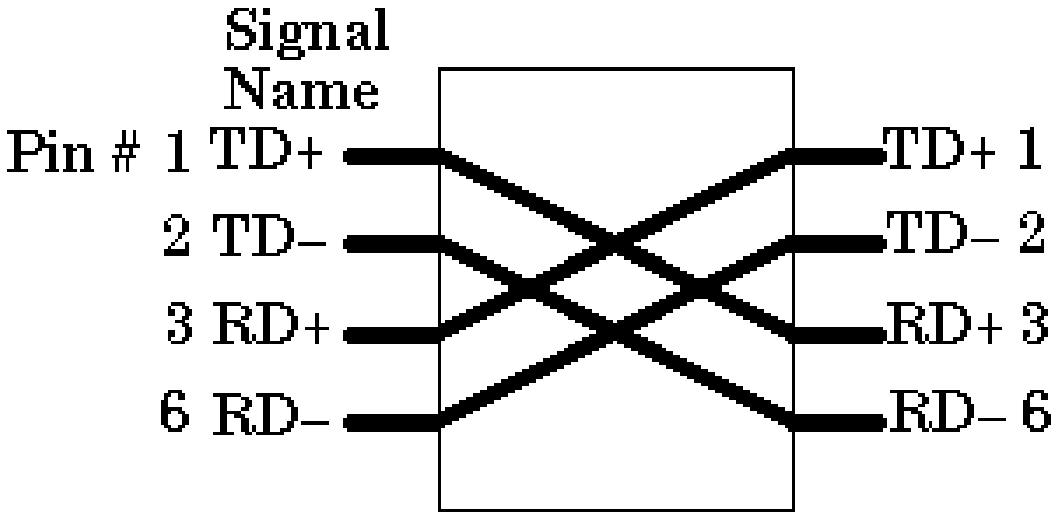
568B Male

Straight Through Cable

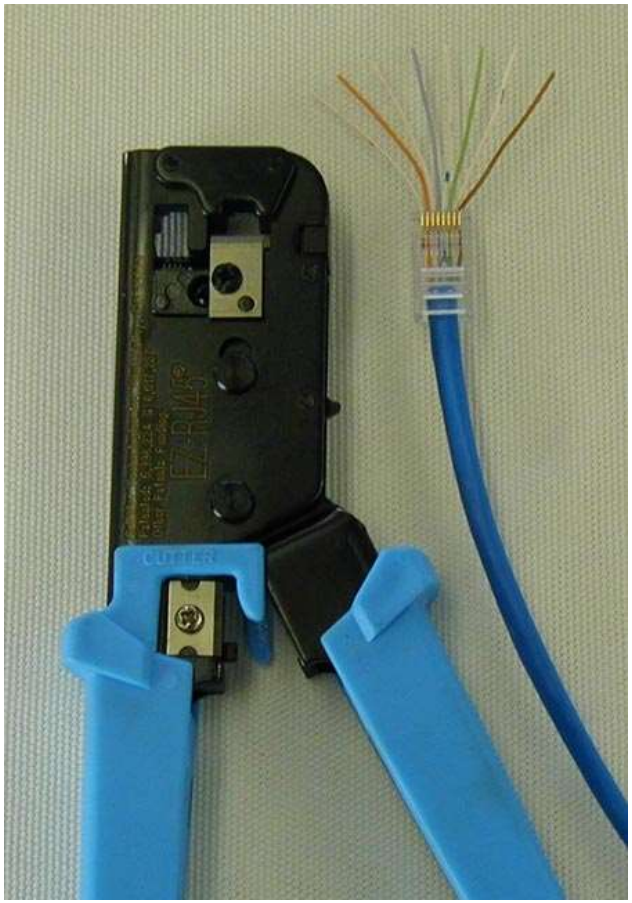
1 Tx+	1 Rc+
2 Tx-	2 Rc-
3 Rc+	3 Tx+
6 Rc-	6 Tx-

Crossover cable

When connecting two twisted-pair:



Cable crimper and tester



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

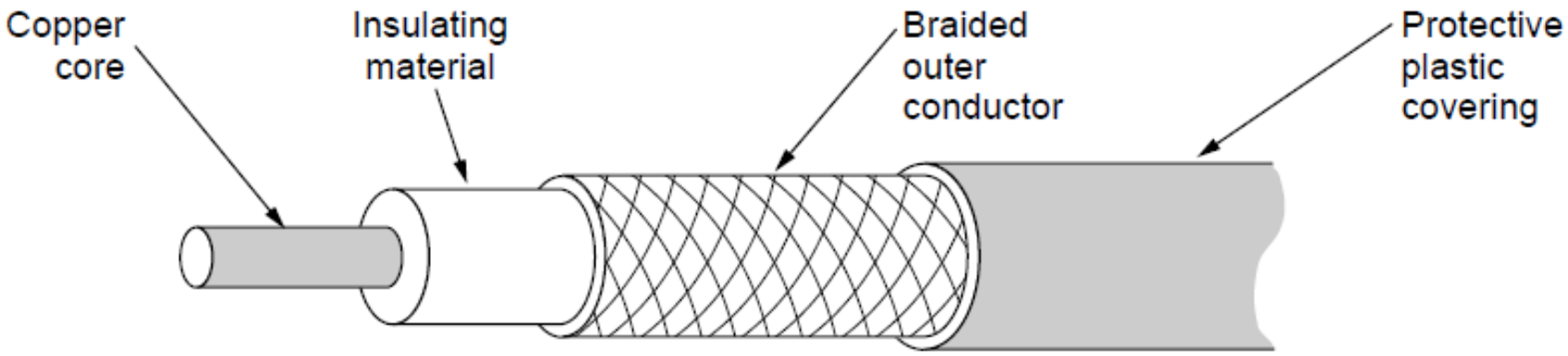
- Both directions, but not at the same time
- e.g., senders take turns on a wireless channel

Simplex link

- Only one fixed direction at all times; not common

Wires – Coaxial Cable ("Co-ax")

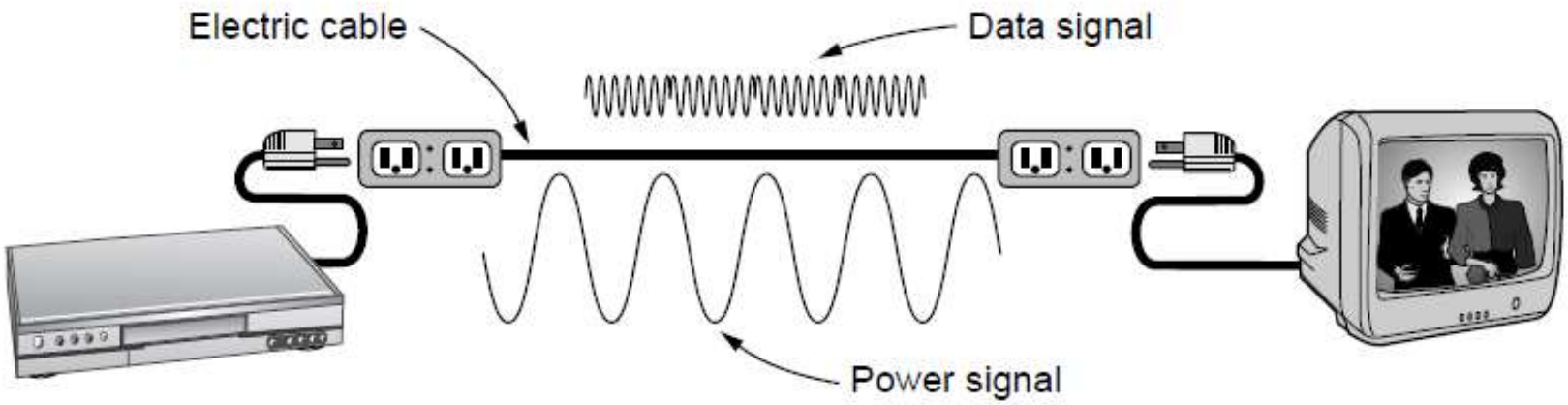
Also common. Better shielding and more bandwidth for longer distances and higher rates than twisted pair.



Wires – Power Lines

Household electrical wiring is another example of wires

- Convenient to use, but horrible for sending data



2. Fiber Optics

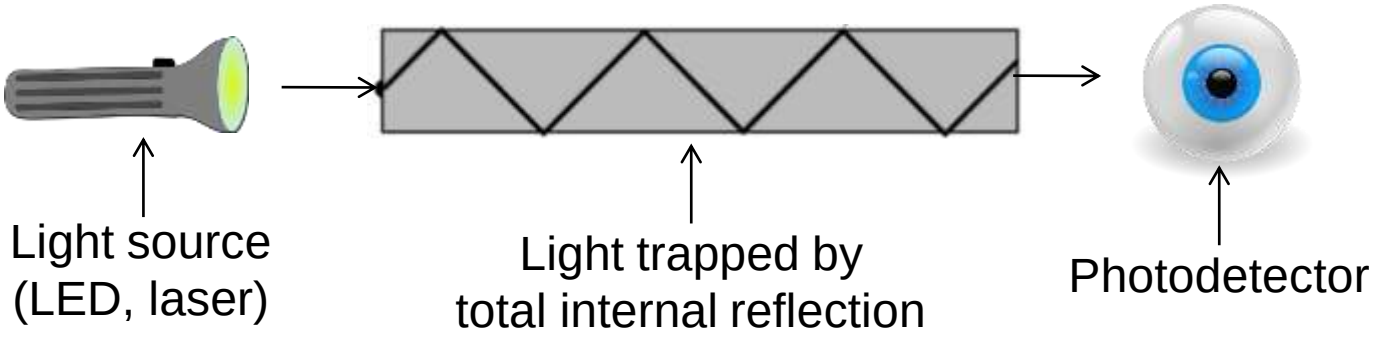
Three key components

- The light source
- The transmission medium
- The detector

Fiber Cables

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 Optics

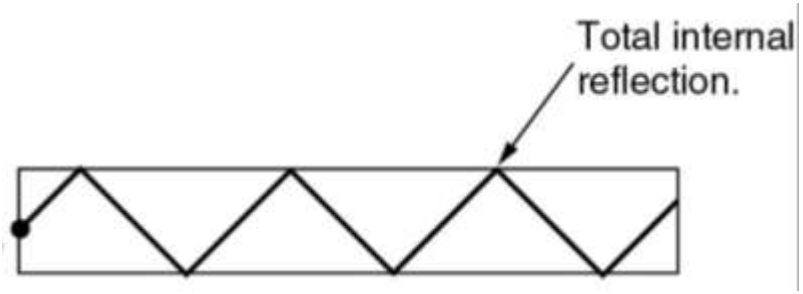
Light source comparison

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

Fiber Optics

Achievable bandwidth in excess of 50 Tbps

- Current signaling limit of 10 Gbps



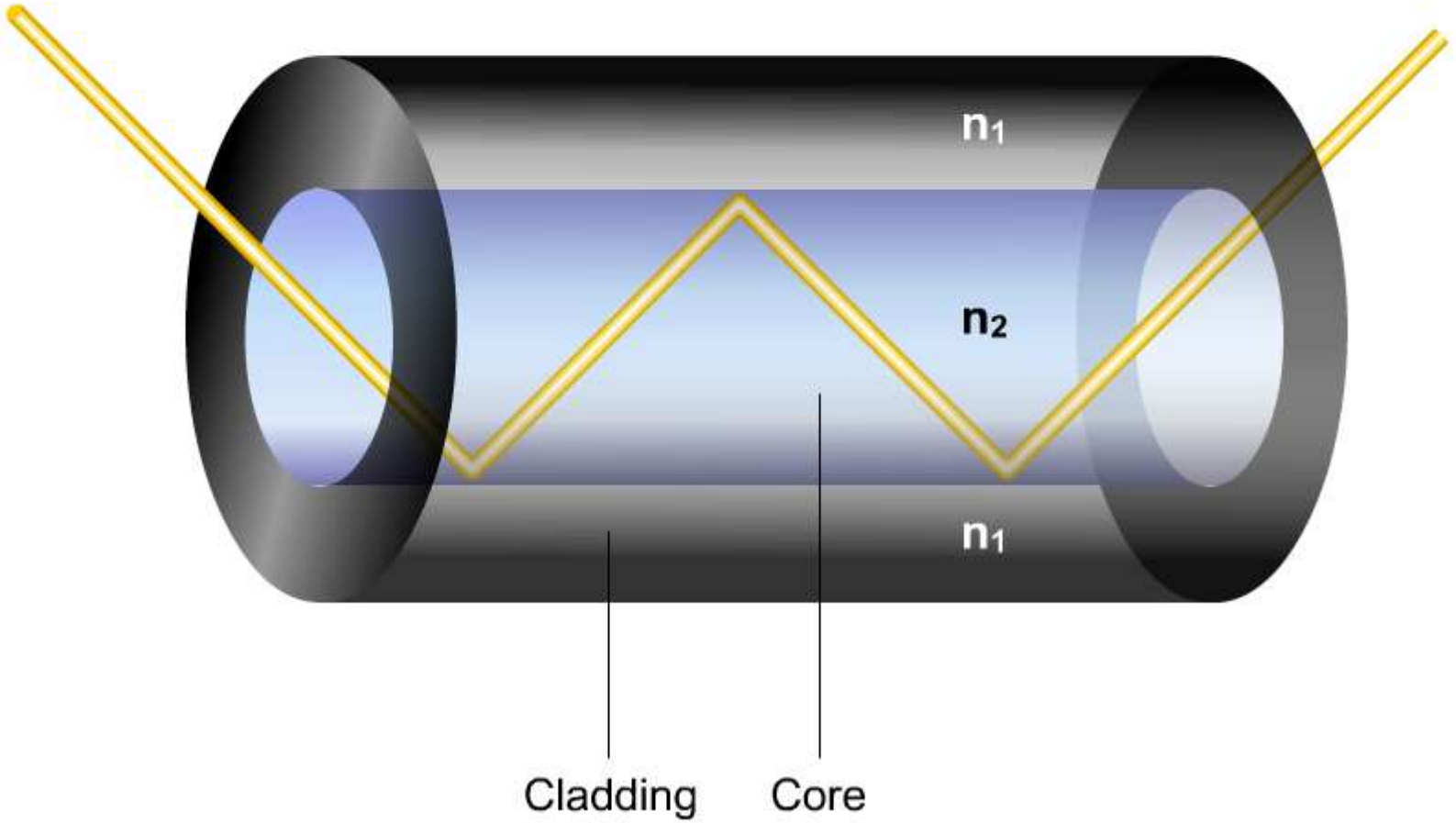
Multimode Fiber

Single-mode Fiber

Total Internal Reflection

FIGURES

1
2
3
4



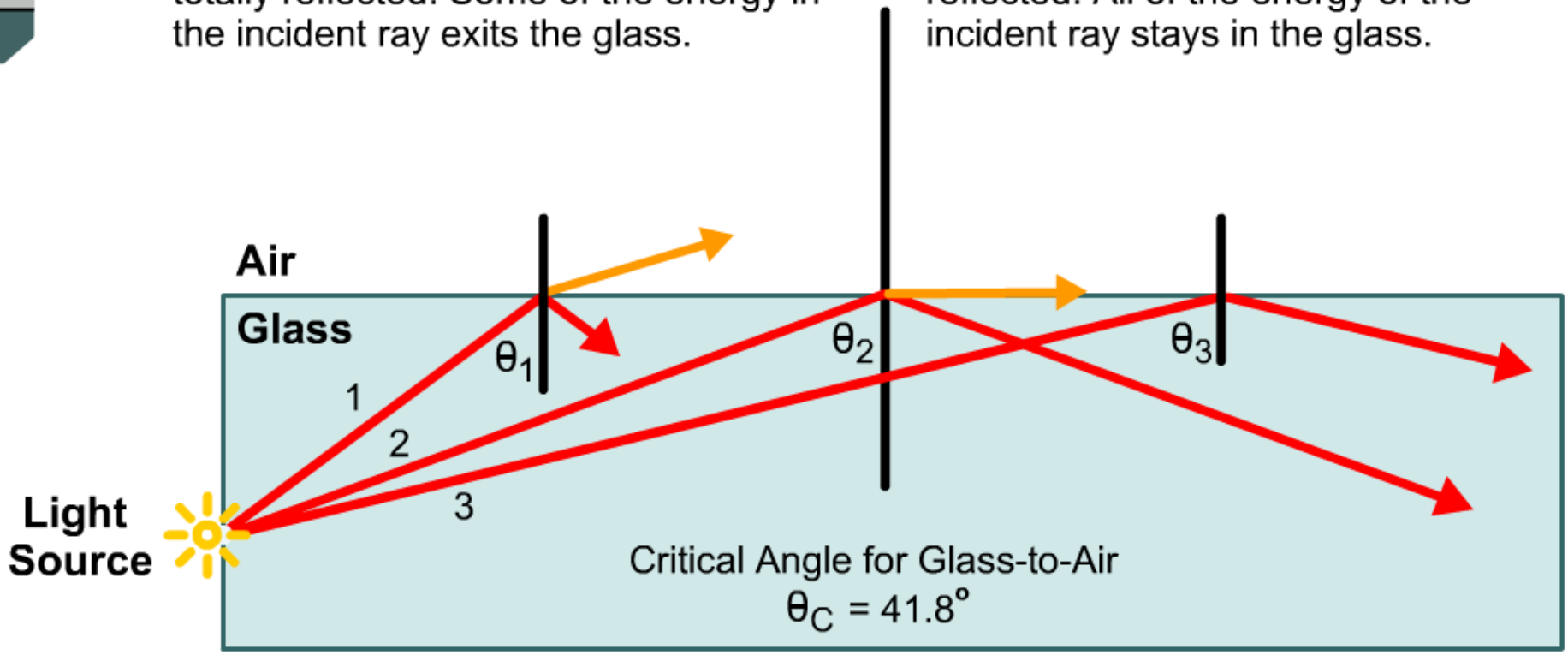
Total Internal Reflection

FIGURES

1
2
3
4

Light incident at any angle smaller than or equal to the critical angle is not totally reflected. Some of the energy in the incident ray exits the glass.

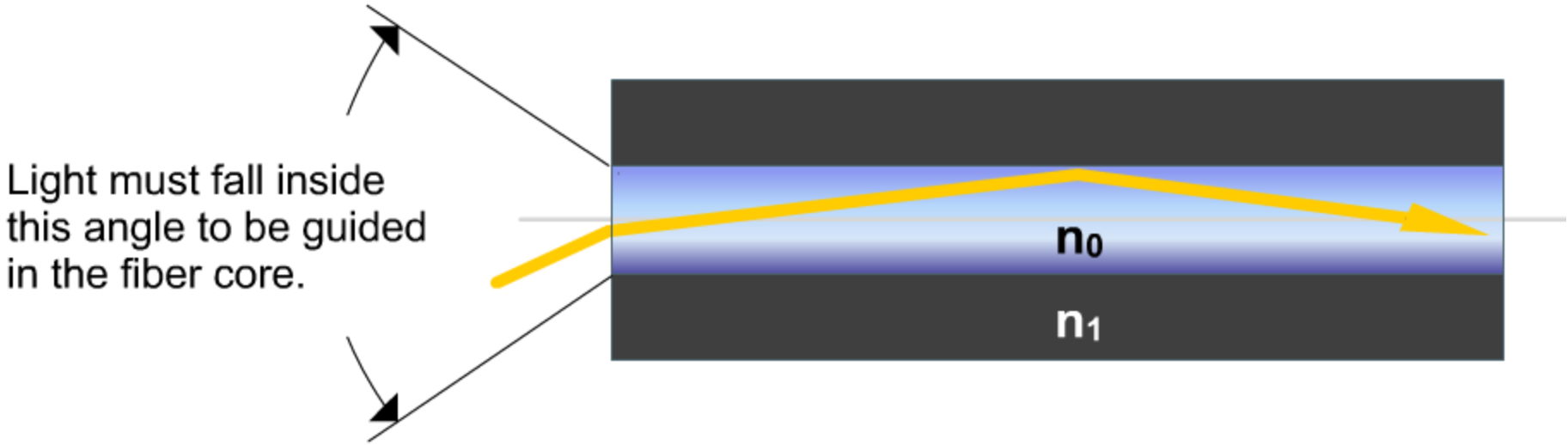
Light incident at any angle greater than the critical angle is totally reflected. All of the energy of the incident ray stays in the glass.



Ray 1: $\theta_1 < \theta_C$, so ray reflects and refracts

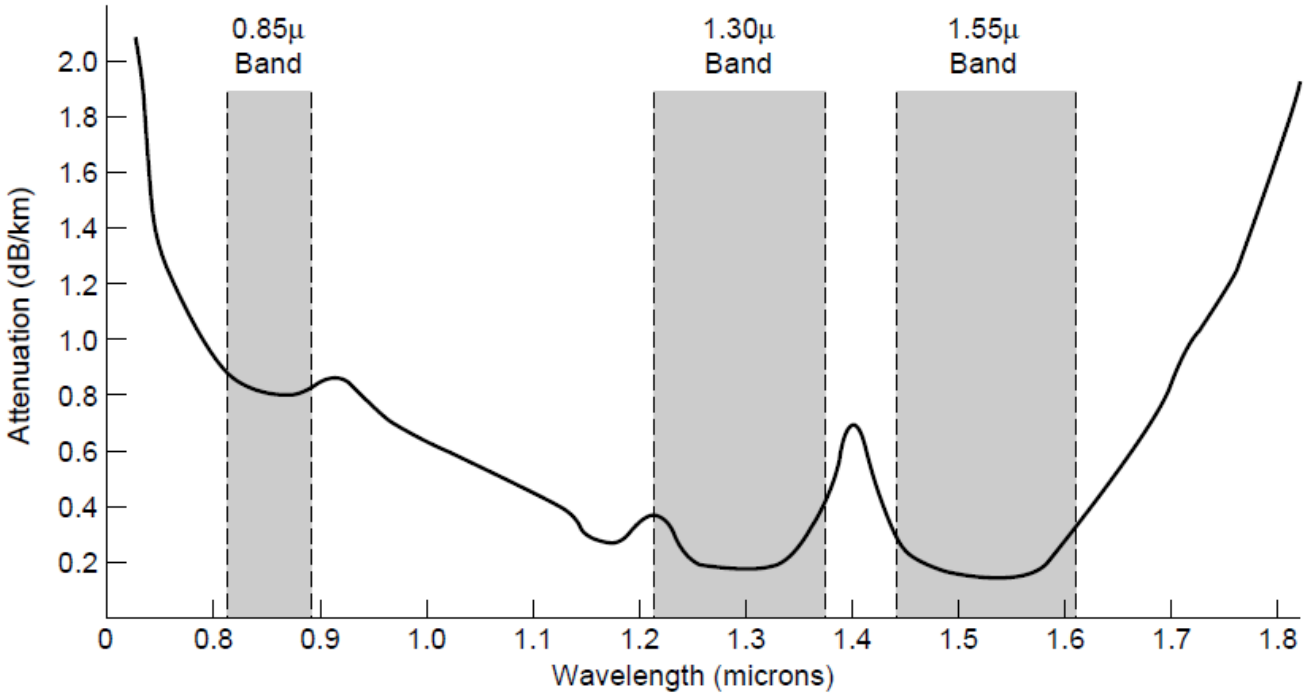
Ray 2: $\theta_2 = \theta_C$, so ray reflects and refracts

Ray 3: $\theta_3 > \theta_C$, so ray is totally internally reflected


Light must fall inside
this angle to be guided
in the fiber core.
n_0
n_1

Fiber Cables

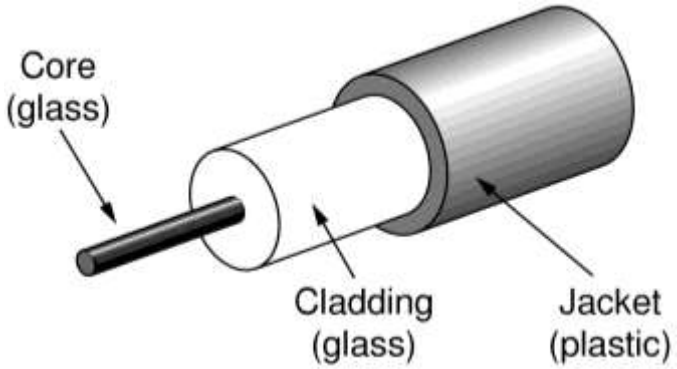
Fiber has enormous bandwidth (THz) and tiny signal loss – hence high rates over long distances



Fiber Cables

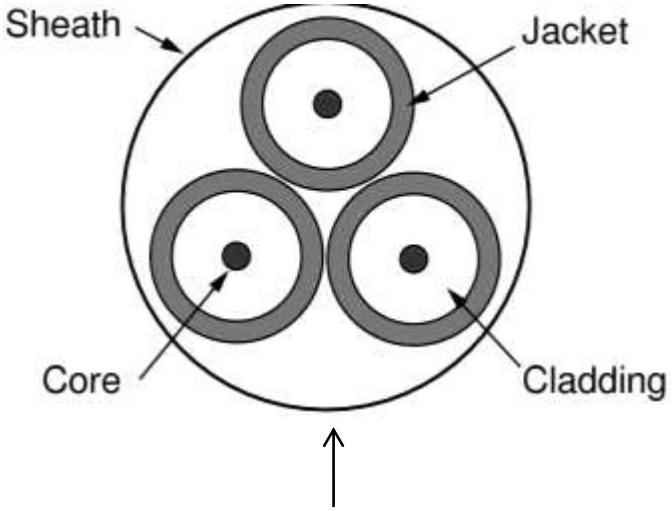
Single-mode

- 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



Transmission Media

Comparison of Fiber Optics and Copper Wire

	Fiber	**Copper**
Bandwidth	Higher	Lower
Distance between repeaters	50 Km	5 Km
Interference	Low	High
Physical	Thinner/Lighter	
Security	More	Less
Learning Curve	Complex	Easier
Physical Damage	More	Less
Flow	Uni-directional	Bi-directional
Cost	Expensive	Cheap

Converter

Typical Application Using TC1000 RS-232 Asynchronous Fiber Optic Modems

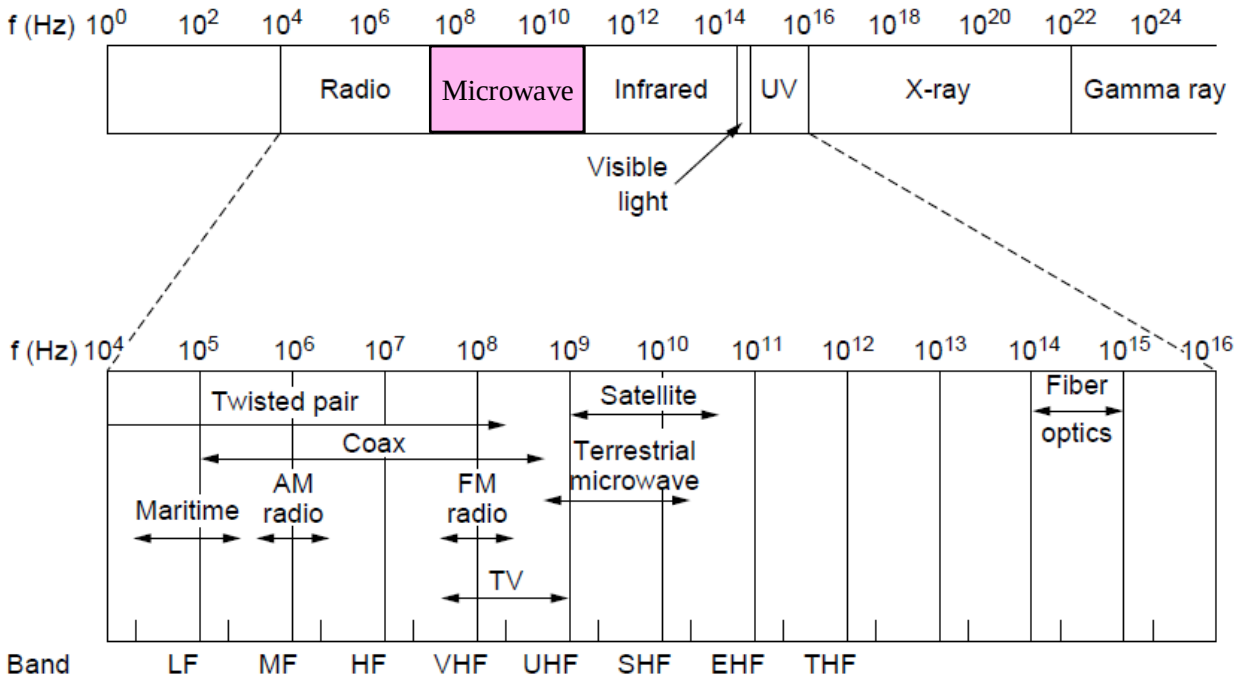
B. Wireless Transmission

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

Electromagnetic Spectrum (1)

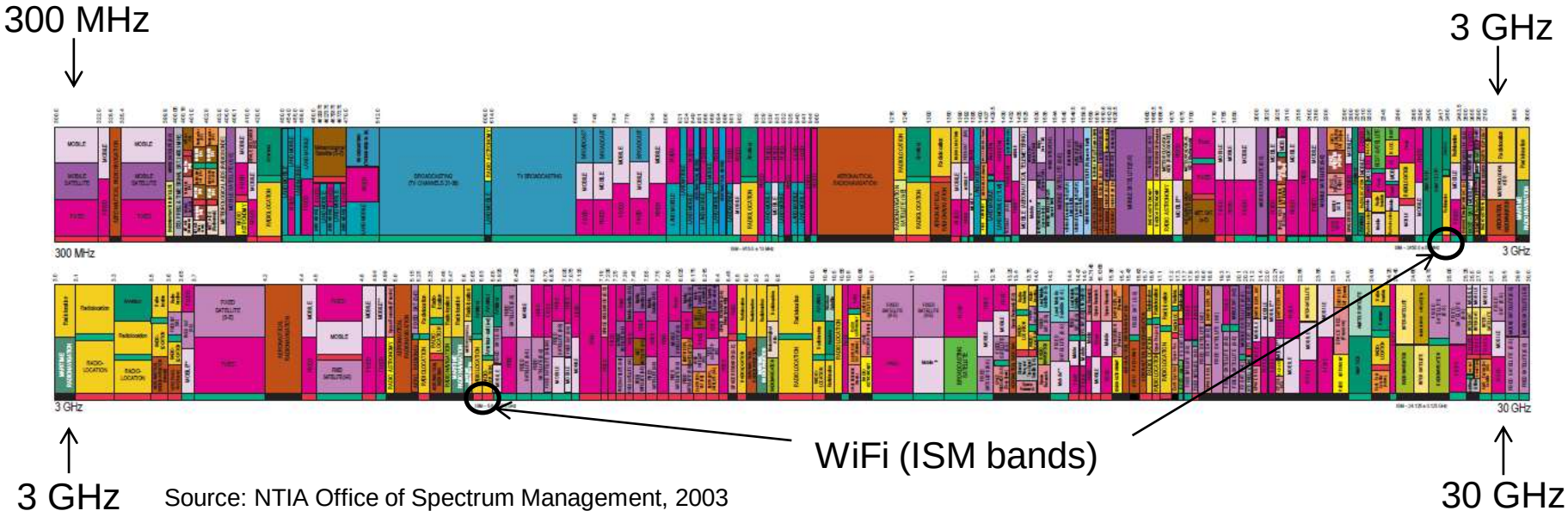
Different bands have different uses:

- 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.



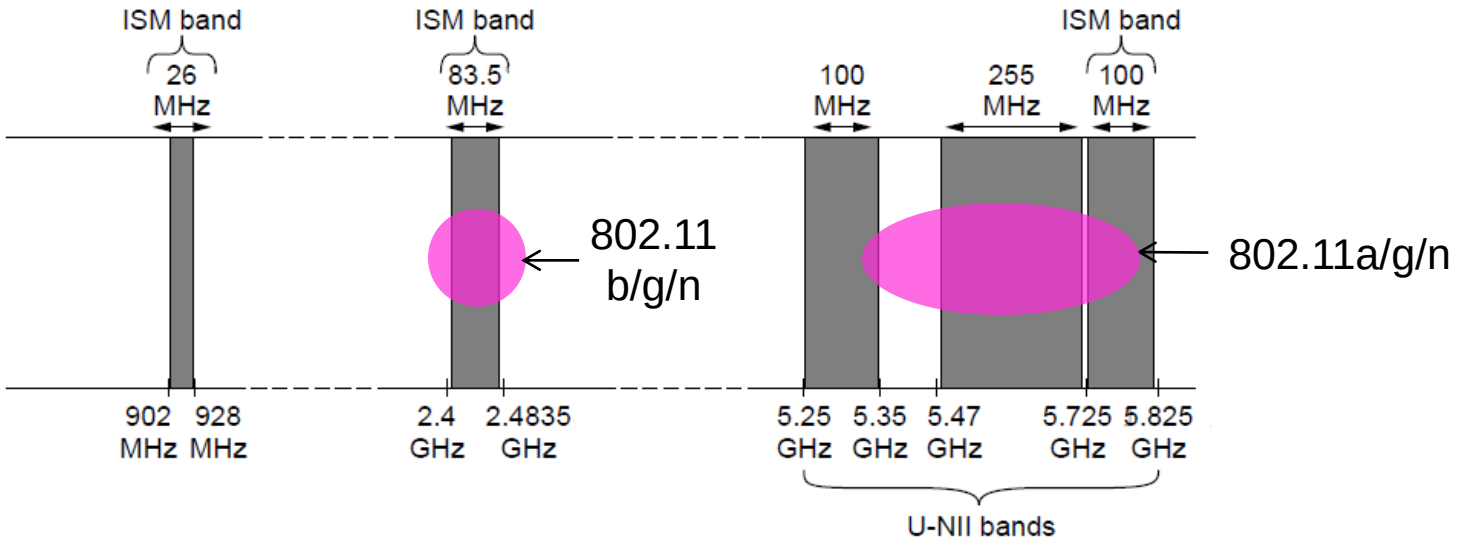
Source: NTIA Office of Spectrum Management, 2003

Part of the US frequency allocations

Electromagnetic Spectrum (3)

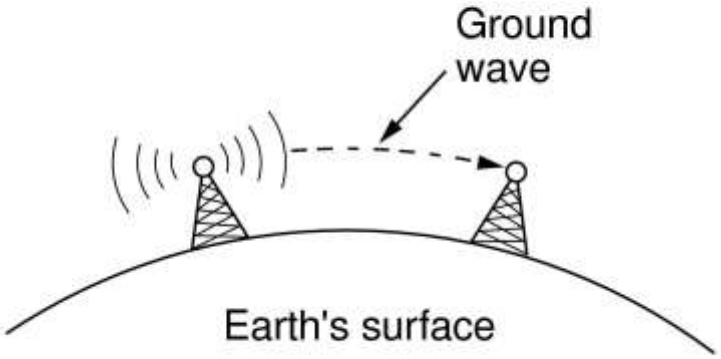
Fortunately, there are also unlicensed ("ISM") bands:

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

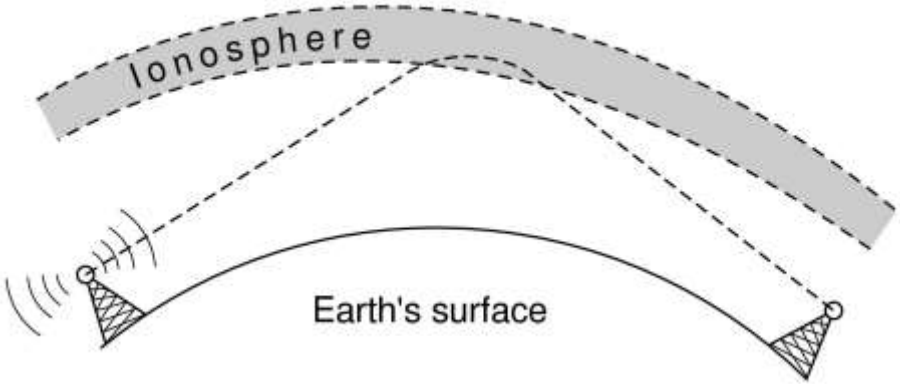


Radio Transmission

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

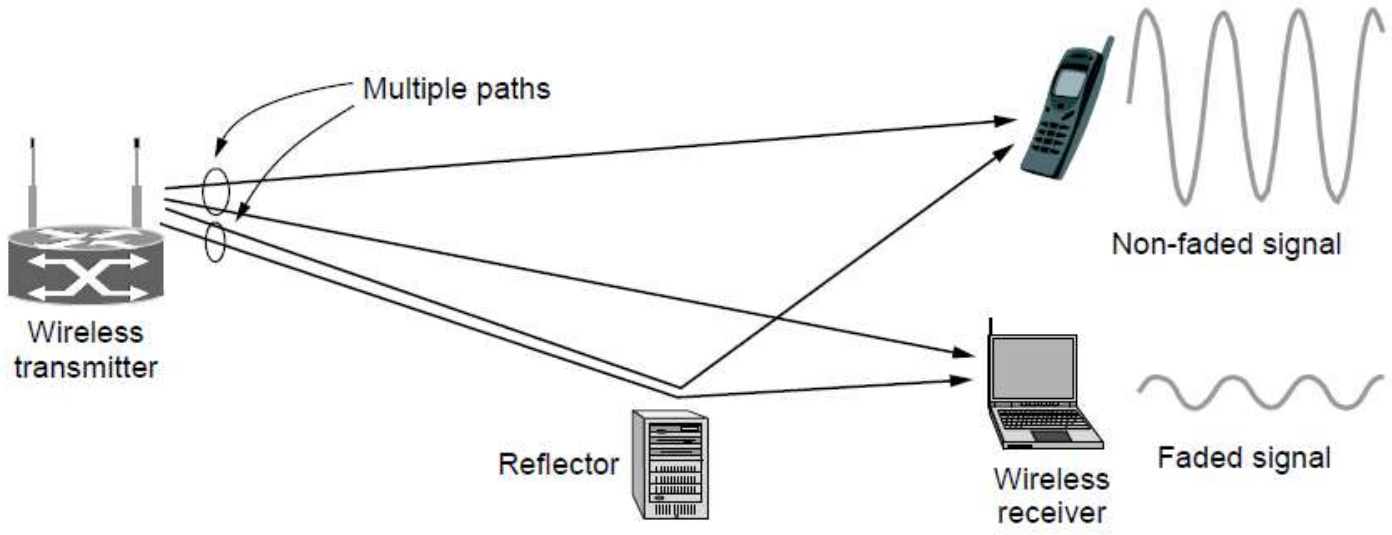


In the HF band, radio waves bounce off the ionosphere.

Microwave Transmission

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

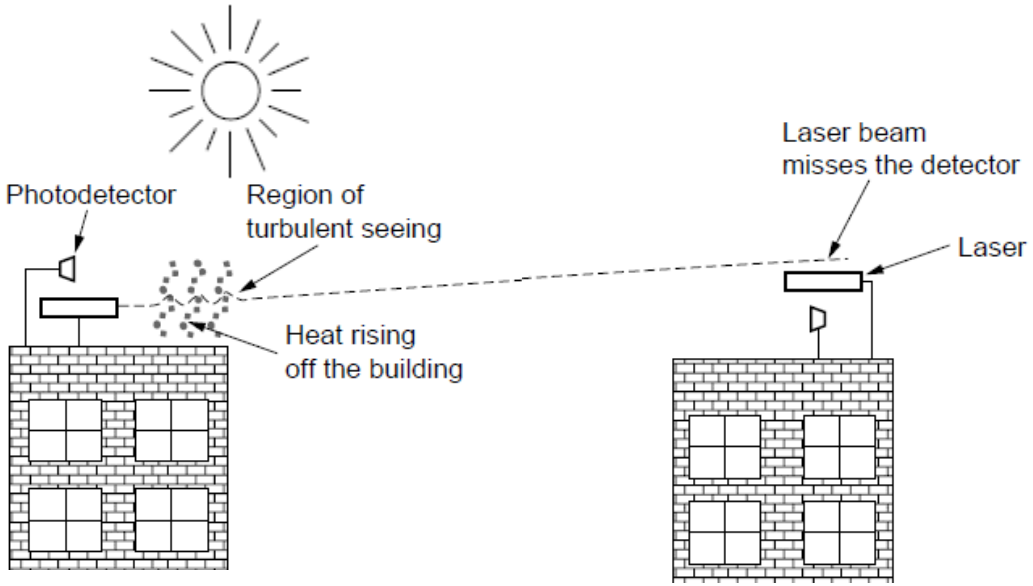
- Signal is attenuated/reflected by everyday objects
- Strength varies with mobility due multipath fading, etc.



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

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Revised and modified by Thaodtp: January 2024

1. Communication Satellites

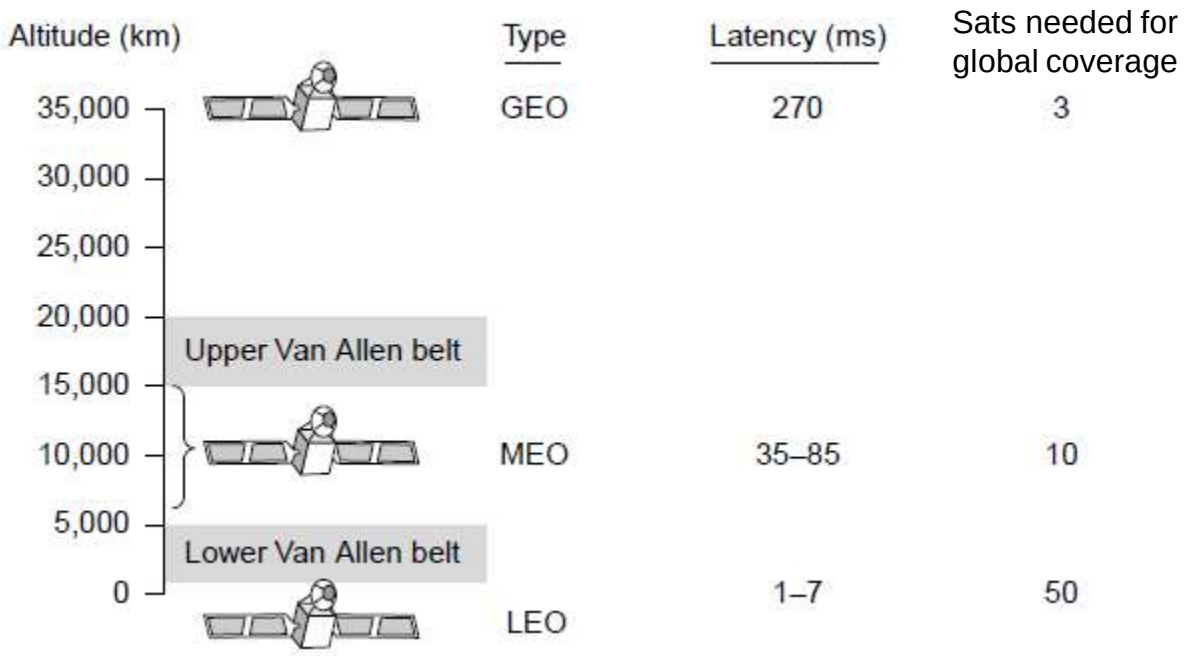
Satellites are effective for broadcast distribution and anywhere/anytime communications

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

Kinds of Satellites

Satellites and their properties vary by altitude:

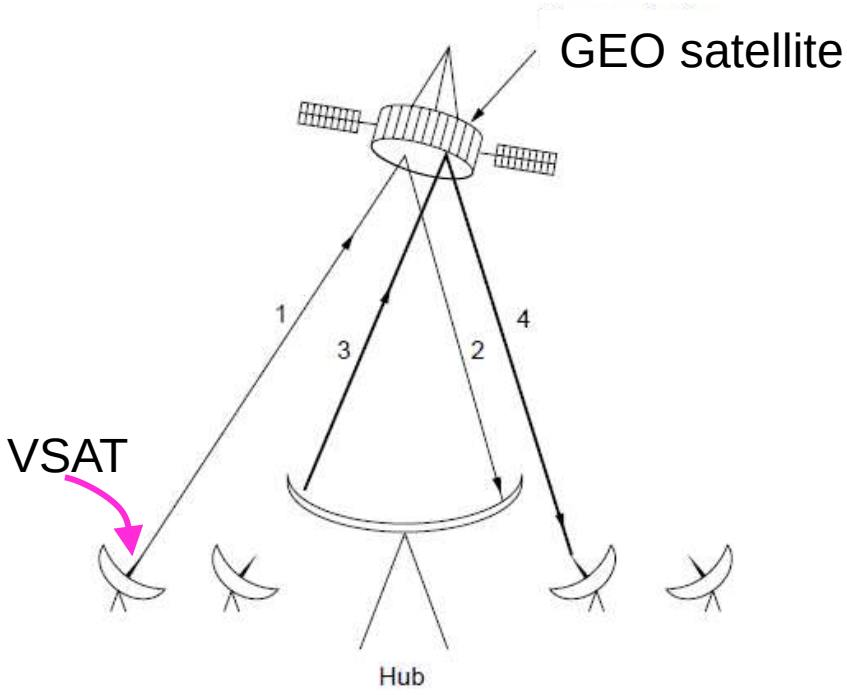
- Geostationary (GEO), Medium-Earth Orbit (MEO), and Low-Earth Orbit (LEO)



Geostationary Satellites

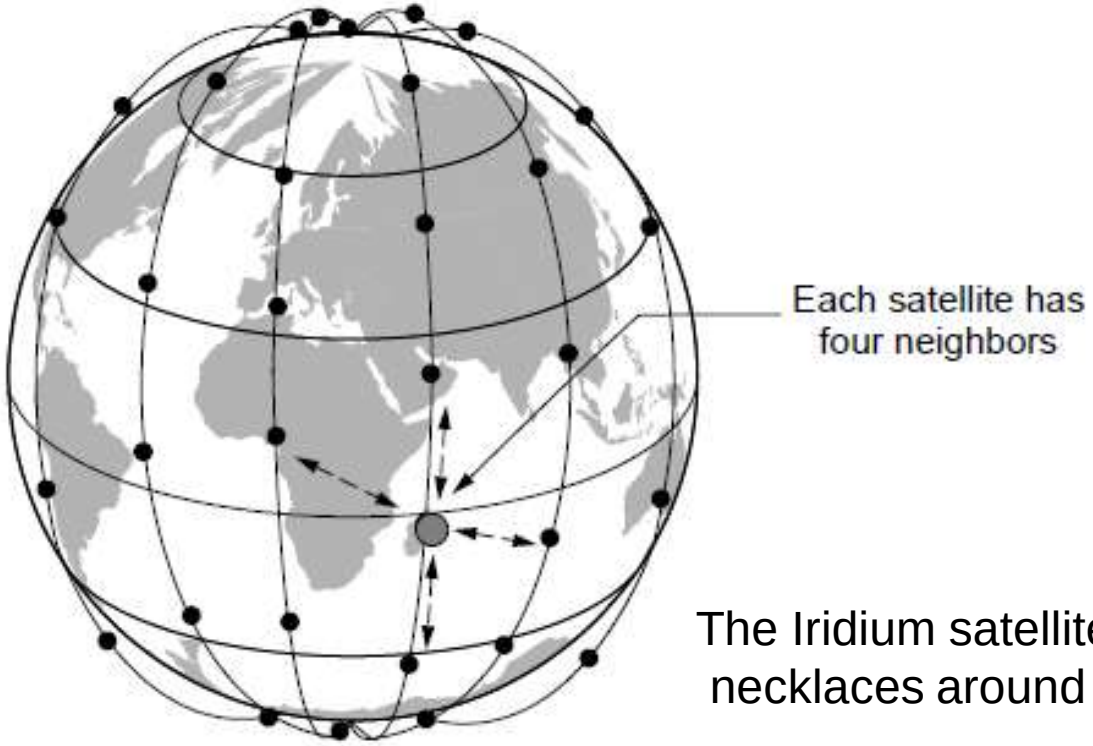
GEO satellites orbit 35,000 km above a fixed location

- 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



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

2. Digital Modulation and Multiplexing

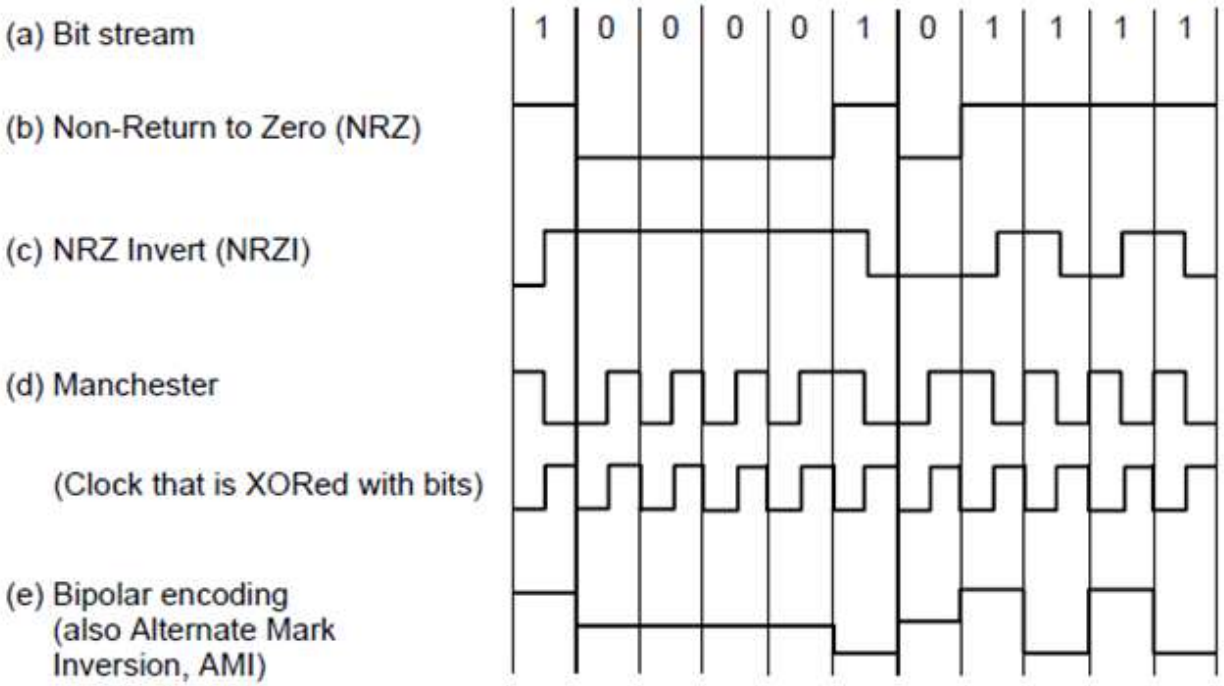
Modulation schemes send bits as signals;
multiplexing schemes share a channel among users.

- 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



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:

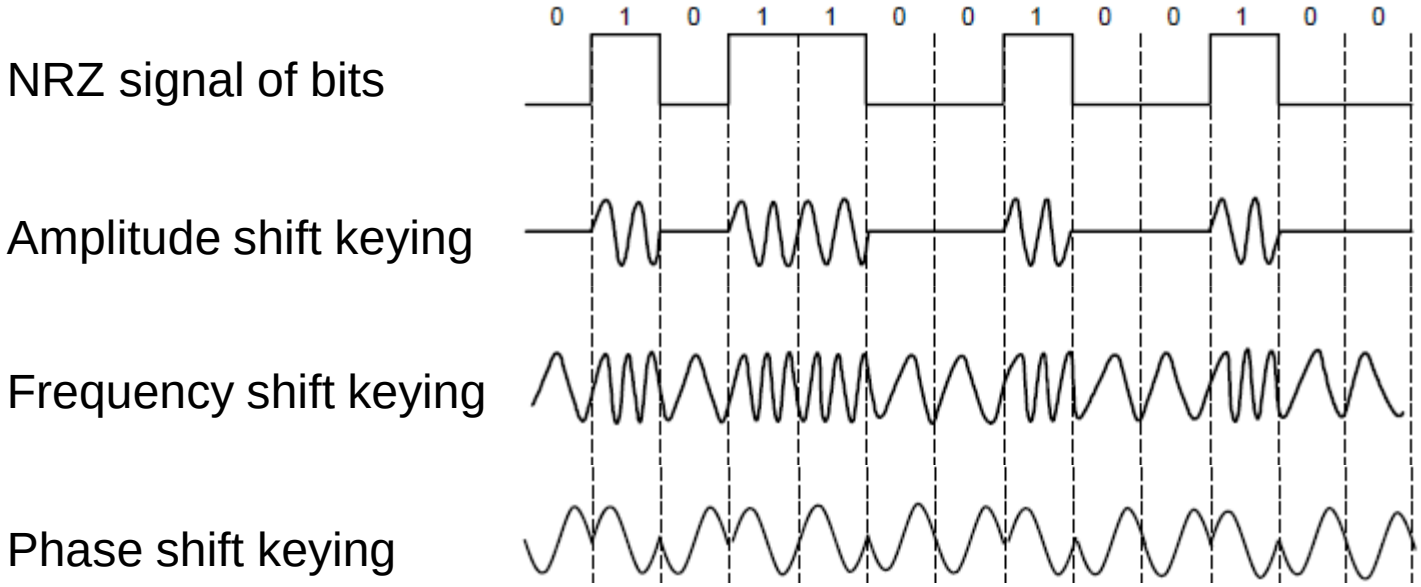
- Manchester coding, mixes clock signal in every symbol
- 4B/5B maps 4 data bits to 5 coded bits with 1s and 0s:

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

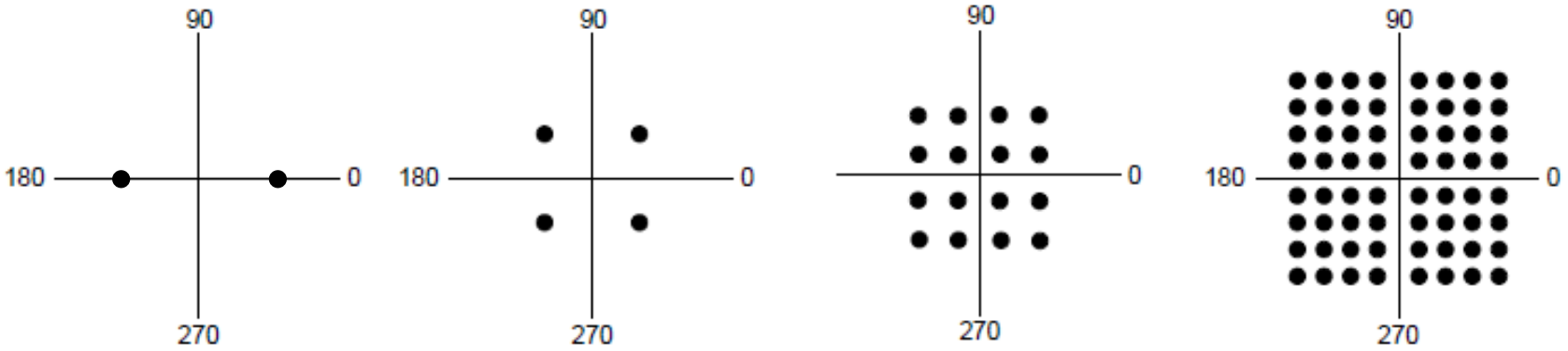
Passband Transmission (1)

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



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

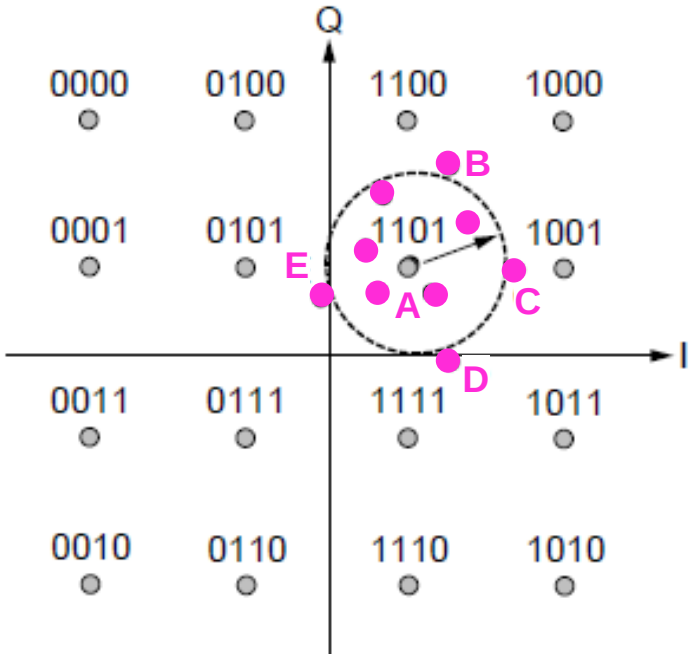
QAM-64
64 symbols
6 bits/symbol

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:

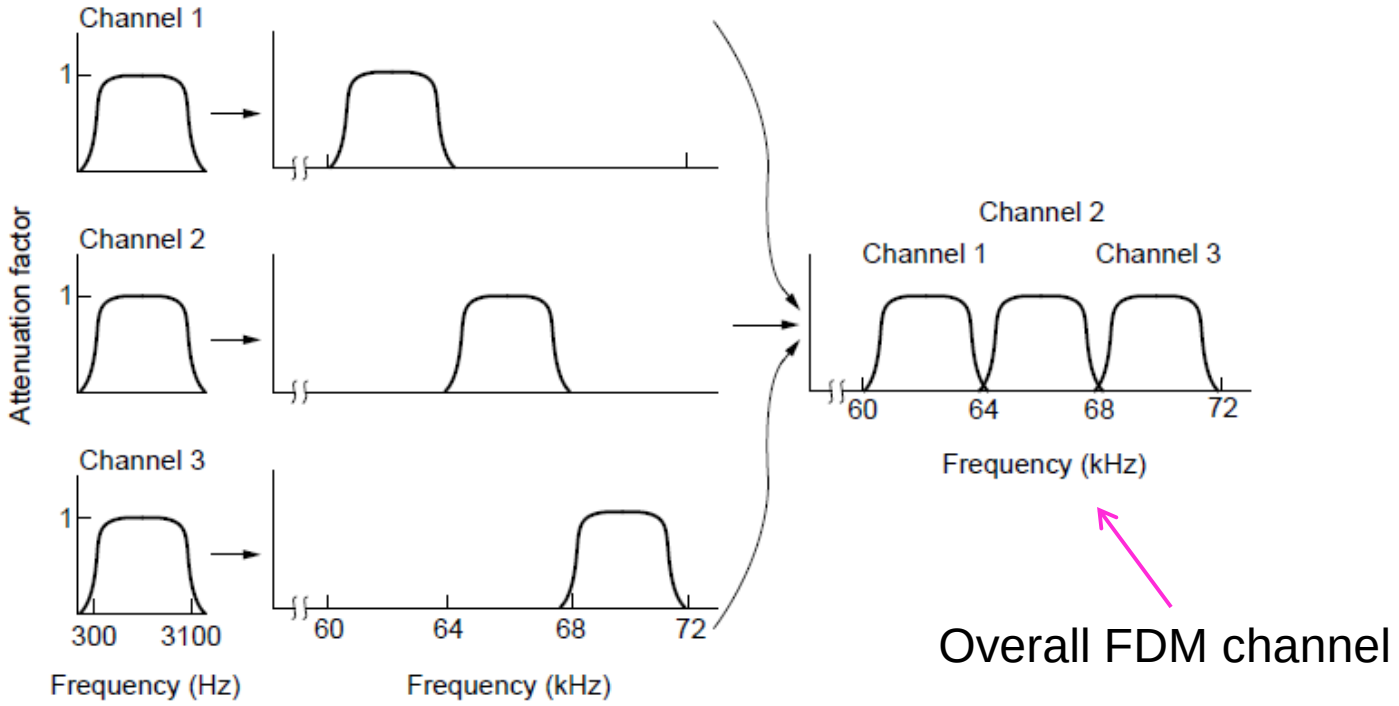


When 1101 is sent:

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

Frequency Division Multiplexing (1)

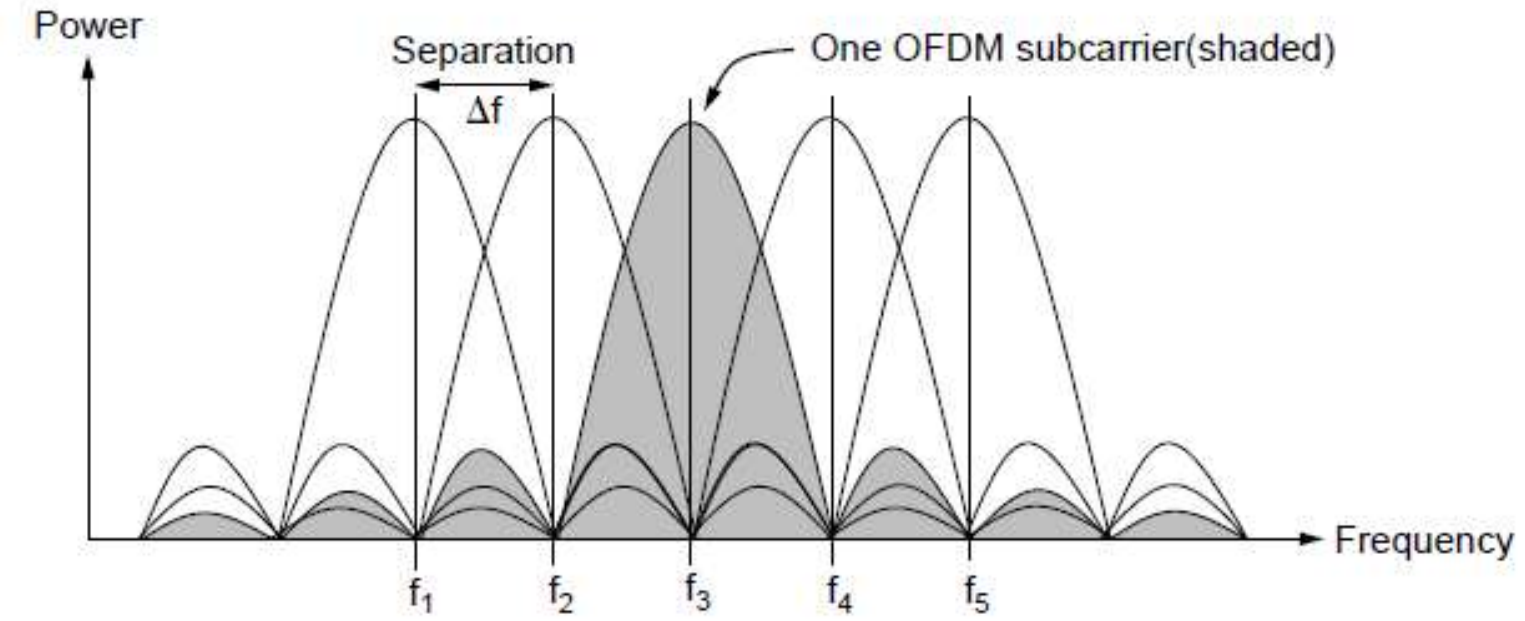
FDM (Frequency Division Multiplexing) shares the channel by placing users on different frequencies:



Frequency Division Multiplexing (2)

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

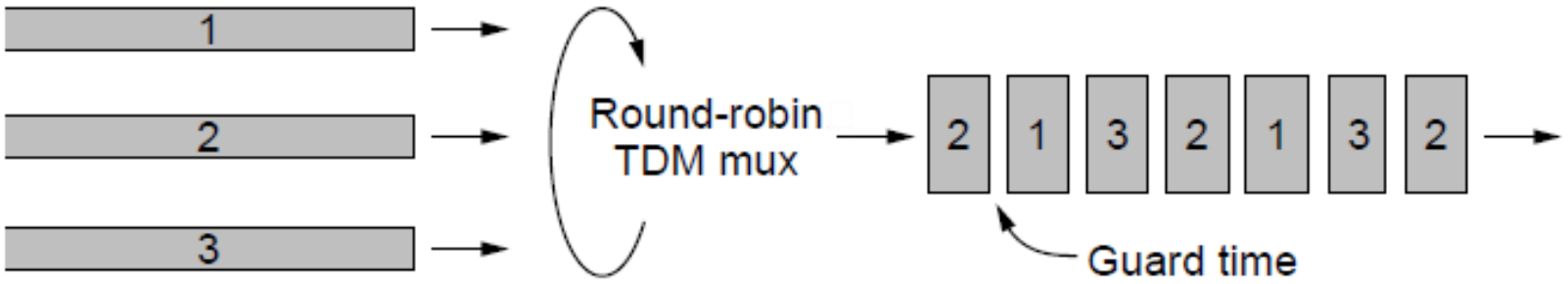
- Subcarriers are coordinated to be tightly packed



Time Division Multiplexing (TDM)

Time division multiplexing shares a channel over time:

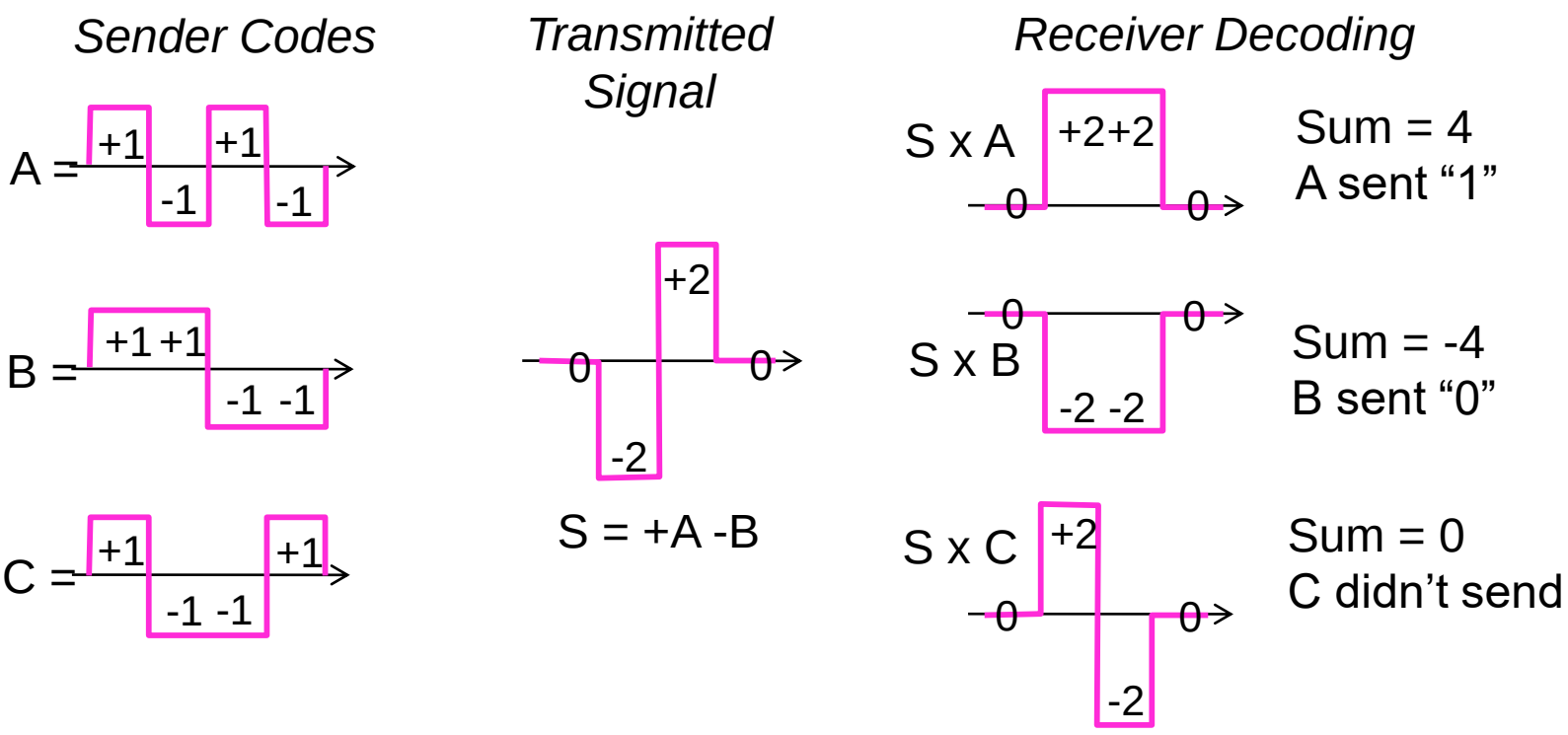
- Users take turns on a fixed schedule; this is not packet switching or STDM (Statistical TDM)
- Widely used in telephone / cellular systems



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



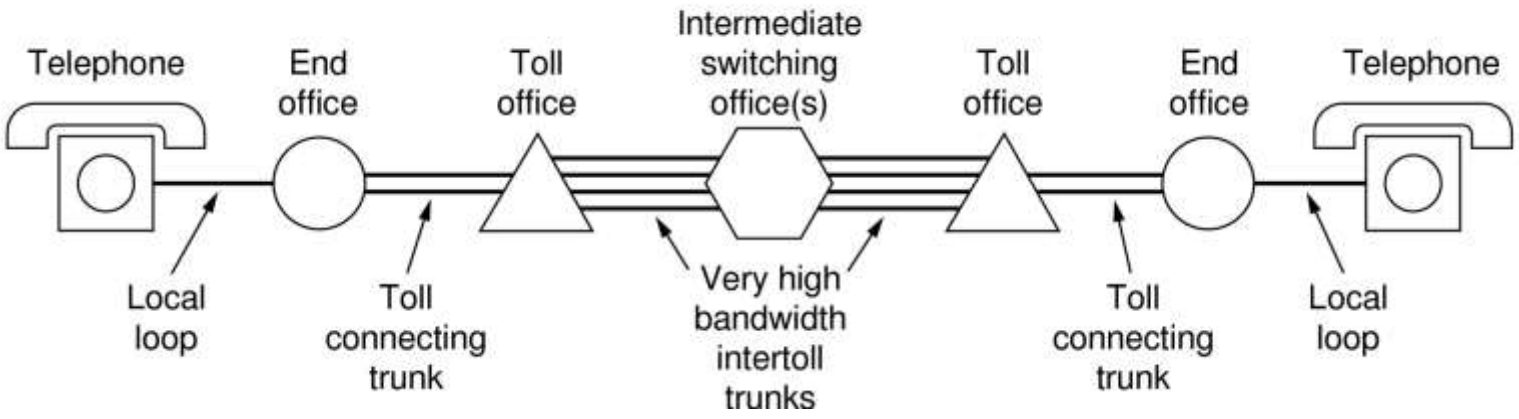
3. The Public Switched Telephone Network

- 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:

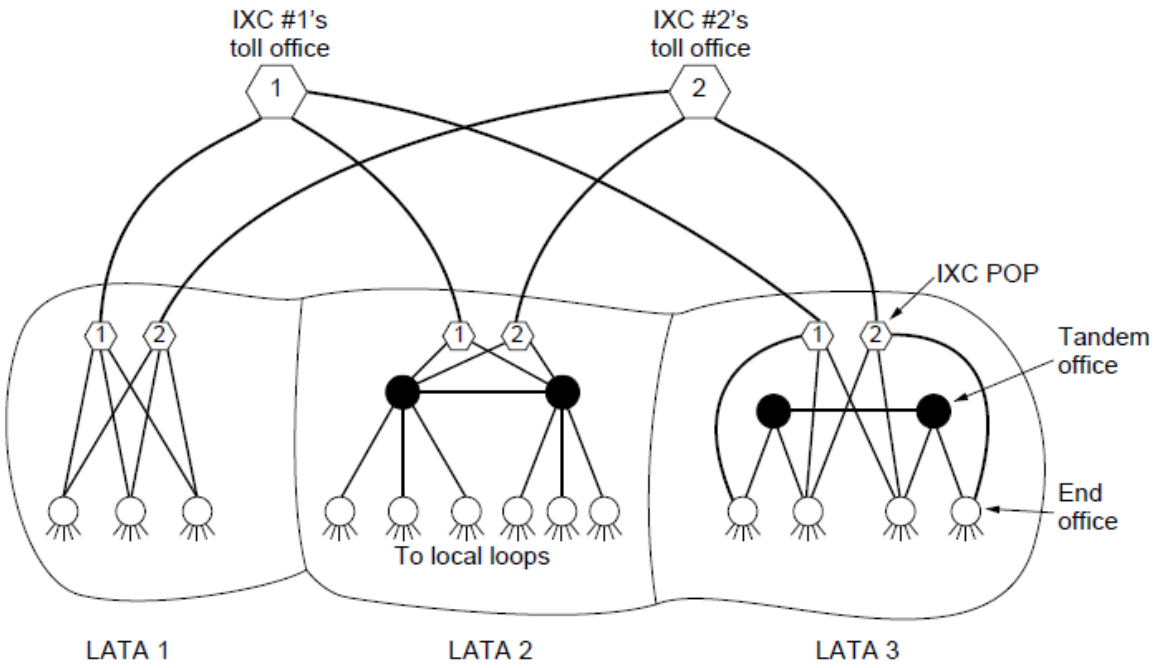
- Local loops, mostly analog twisted pairs to houses
- Trunks, digital fiber optic links that carry calls
- Switching offices, that move calls among trunks



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)

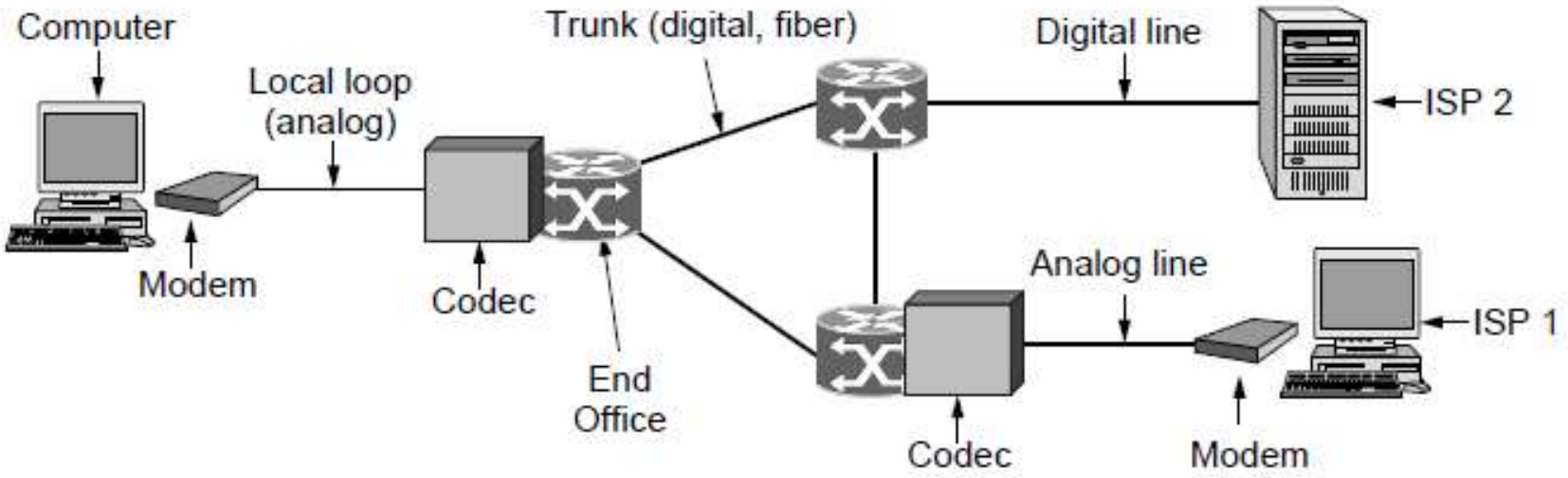
- Customers of a LEC can dial via any IXC they choose



Local loop (1): modems

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

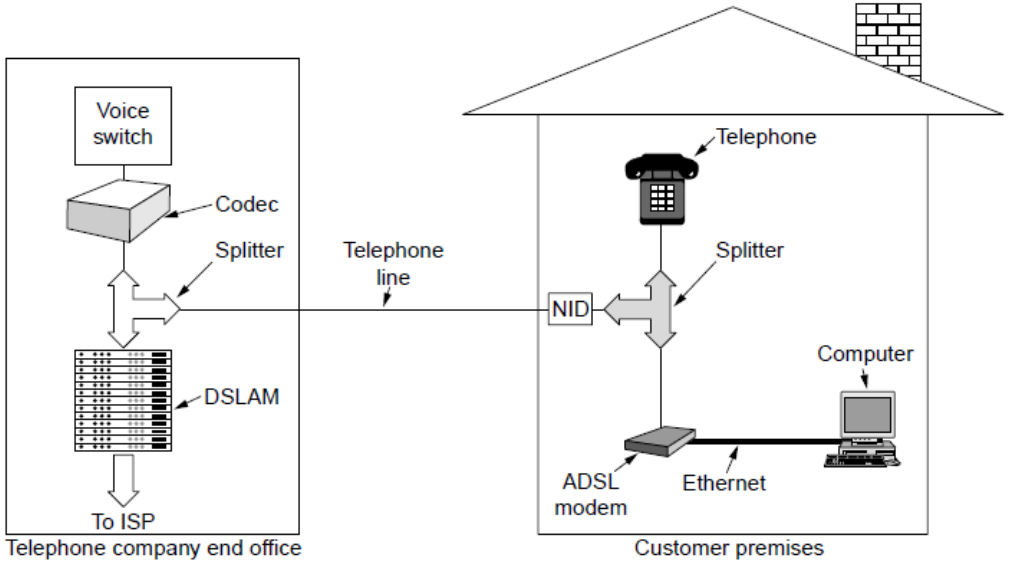
- Rates <56 kbps; early way to connect to the Internet

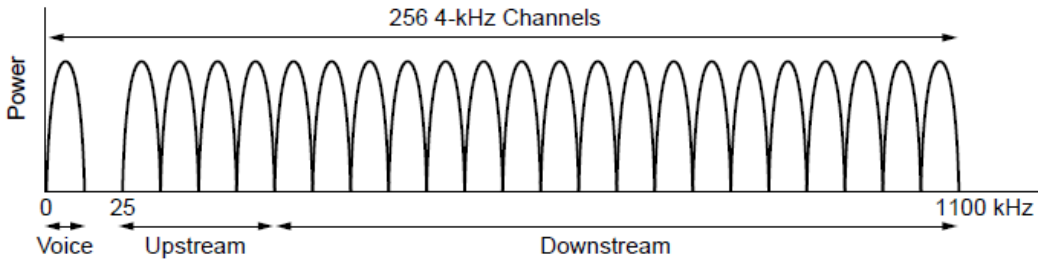


Local loop (2): Digital Subscriber Lines

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

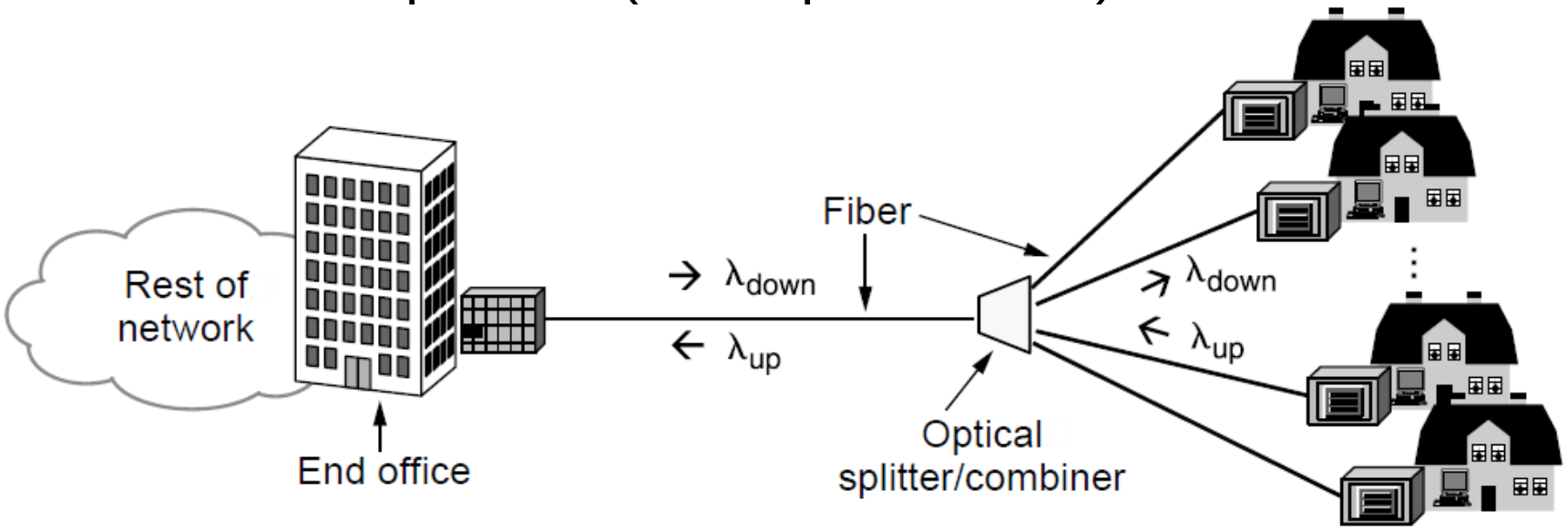




Local loop (3): Fiber To The Home

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

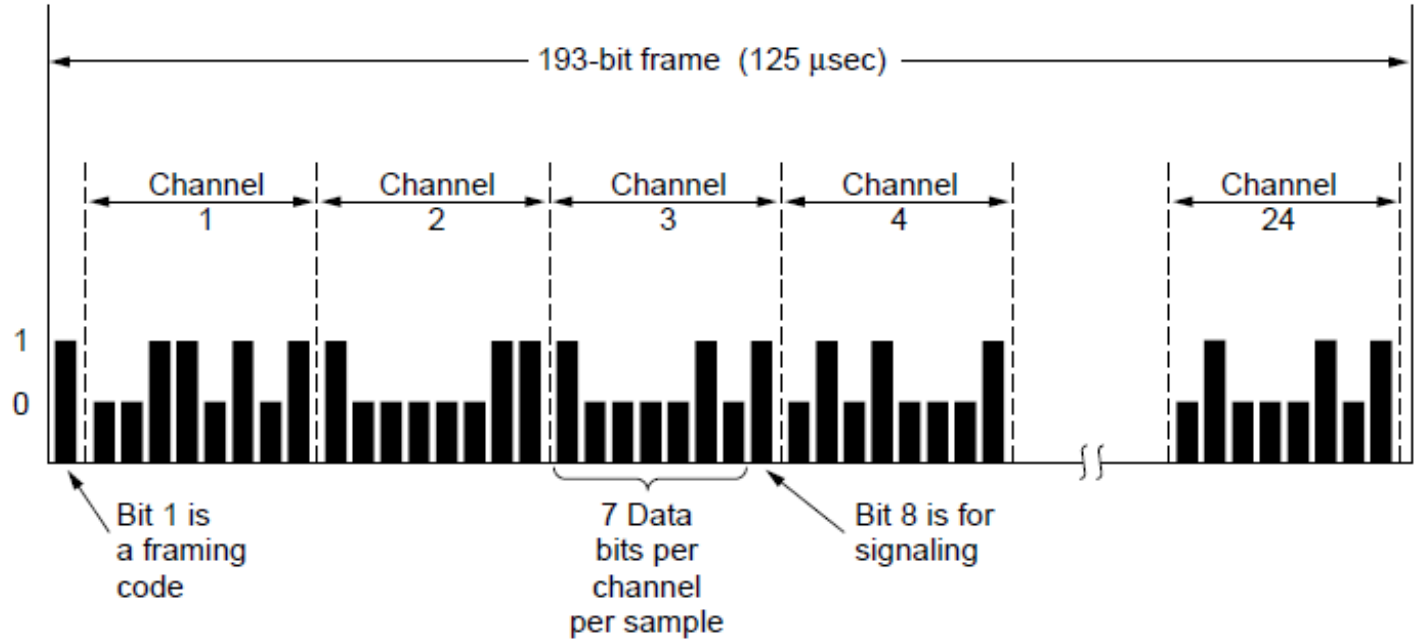
- One wavelength can be shared among many houses
- Fiber is passive (no amplifiers, etc.)



Trunks and Multiplexing (1)

Calls are carried digitally on PSTN trunks using TDM

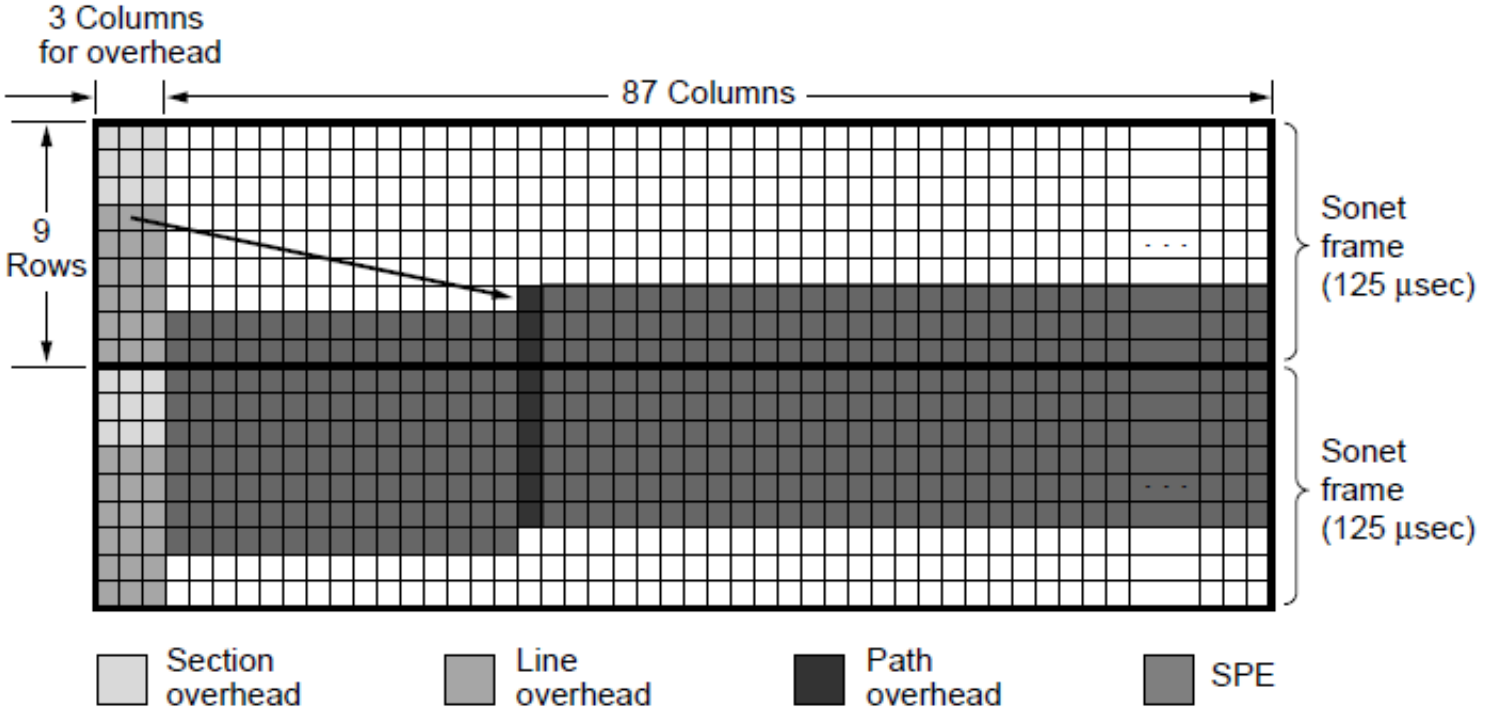
- A call is an 8-bit PCM sample each 125 μs (64 kbps)
- Traditional T1 carrier has 24 call channels each 125 μs (1.544 Mbps) with symbols based on AMI



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

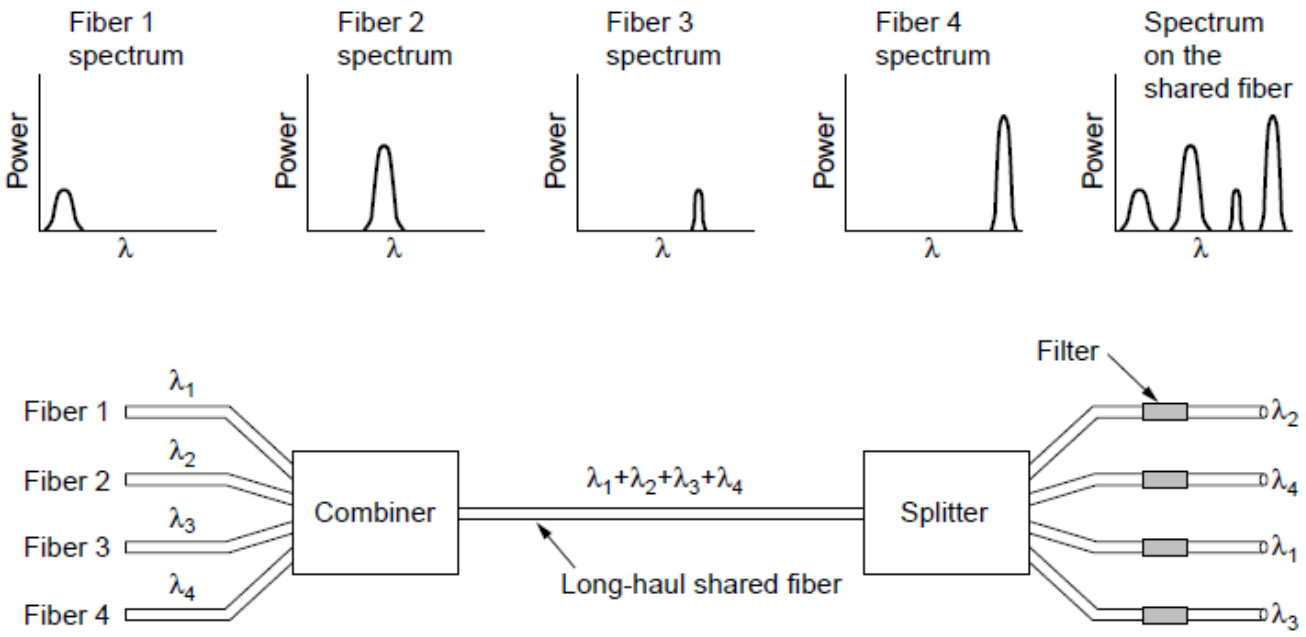
- Each level also adds a small amount of framing
- Rates from 50 Mbps (STS-1) to 40 Gbps (STS-768)

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:

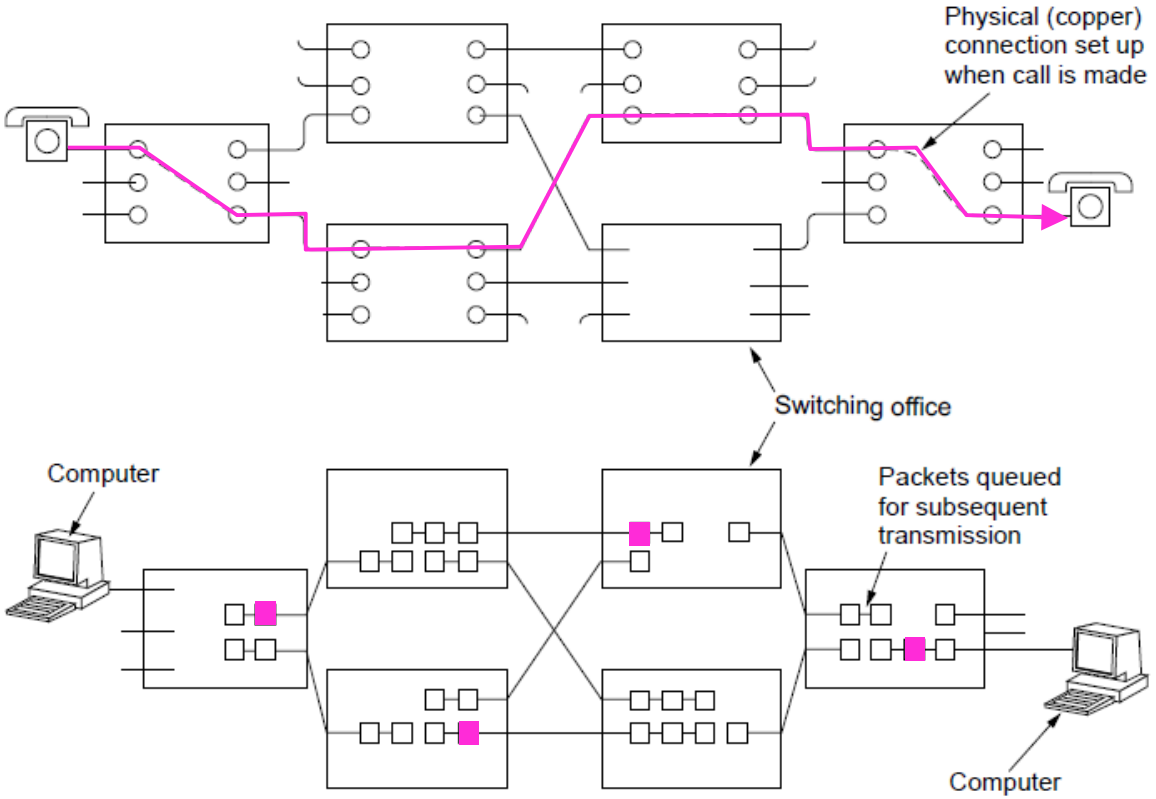


Switching (1)

PSTN uses circuit switching; Internet uses packet switching

PSTN:

Internet:



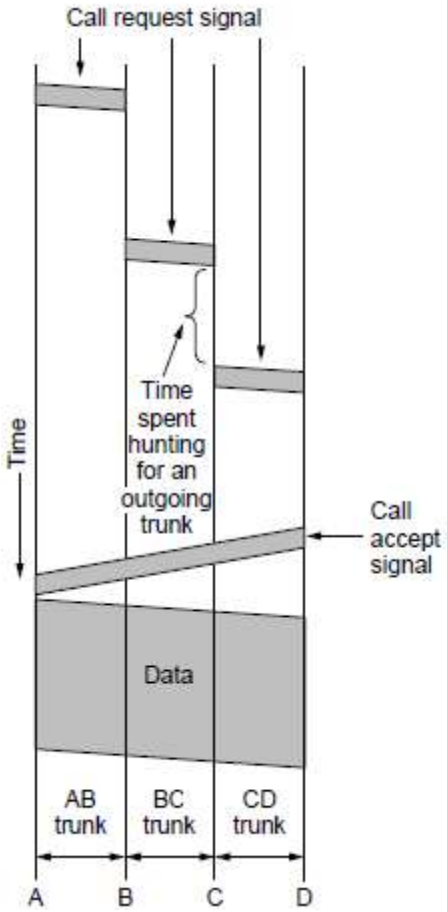
Switching (2)

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

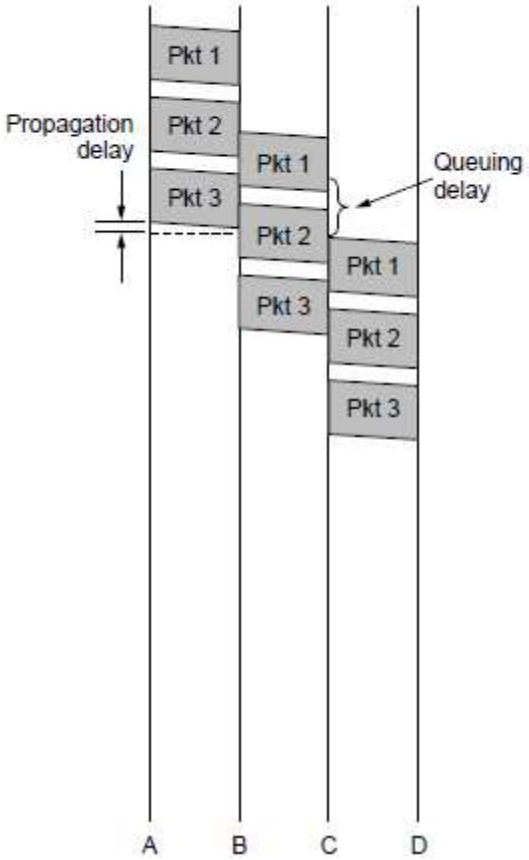
- Also teardown at end (not shown)

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

4. 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

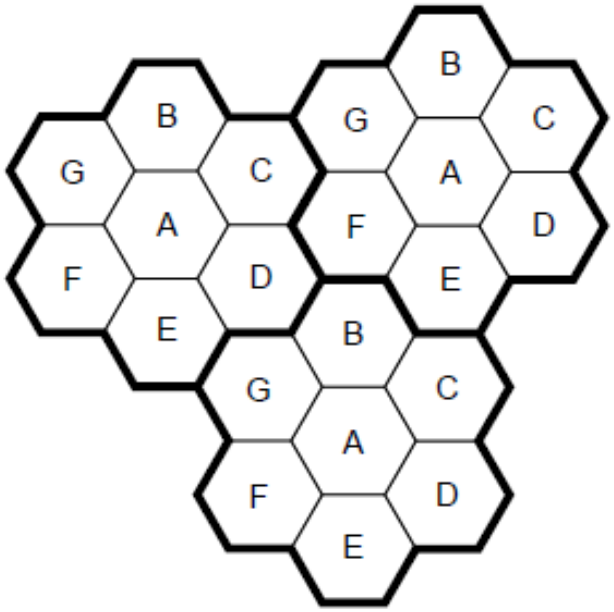
4G, digital data including voice

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

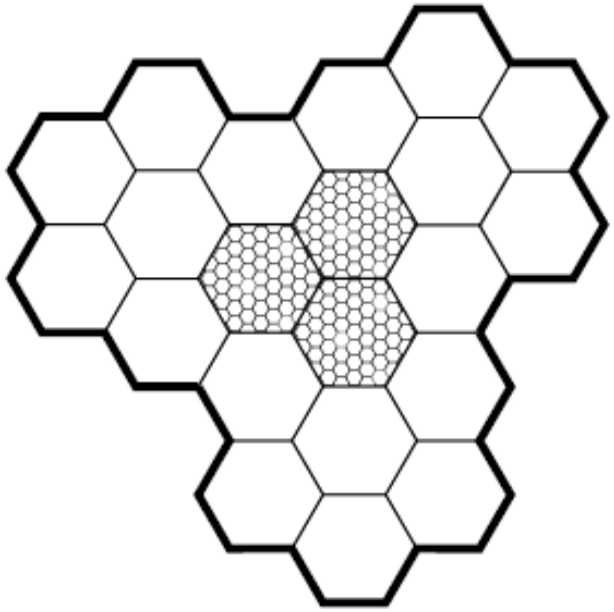
Cellular mobile phone systems

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



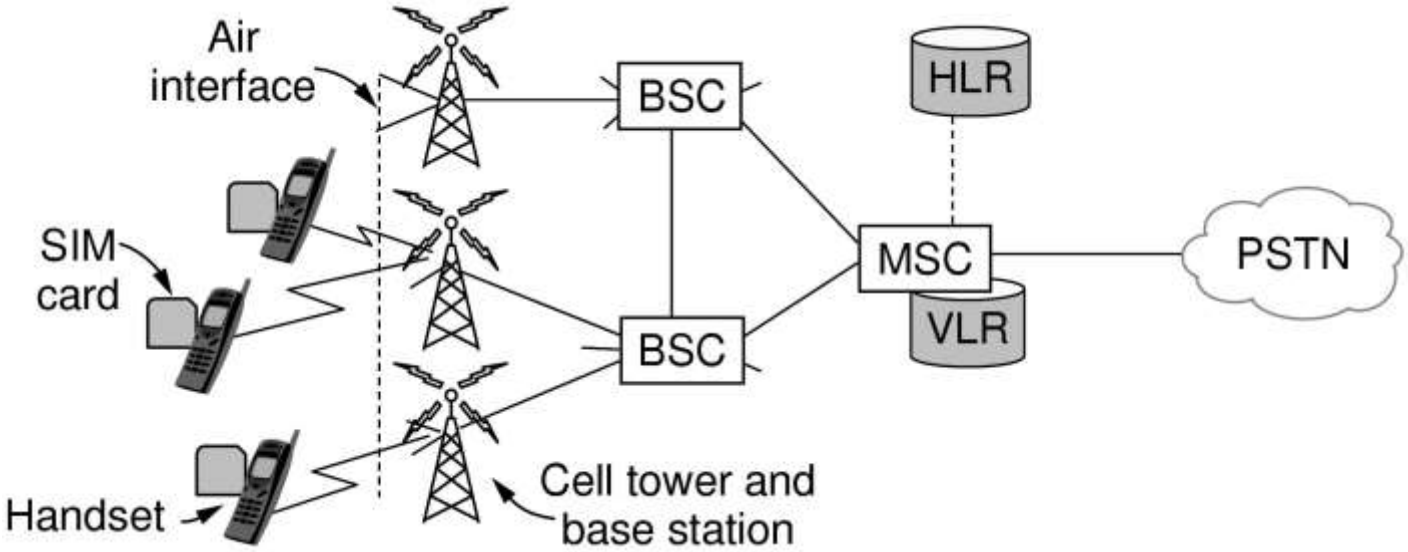
Cellular reuse pattern



Smaller cells for dense mobiles

GSM – Global System for Mobile Communications (1)

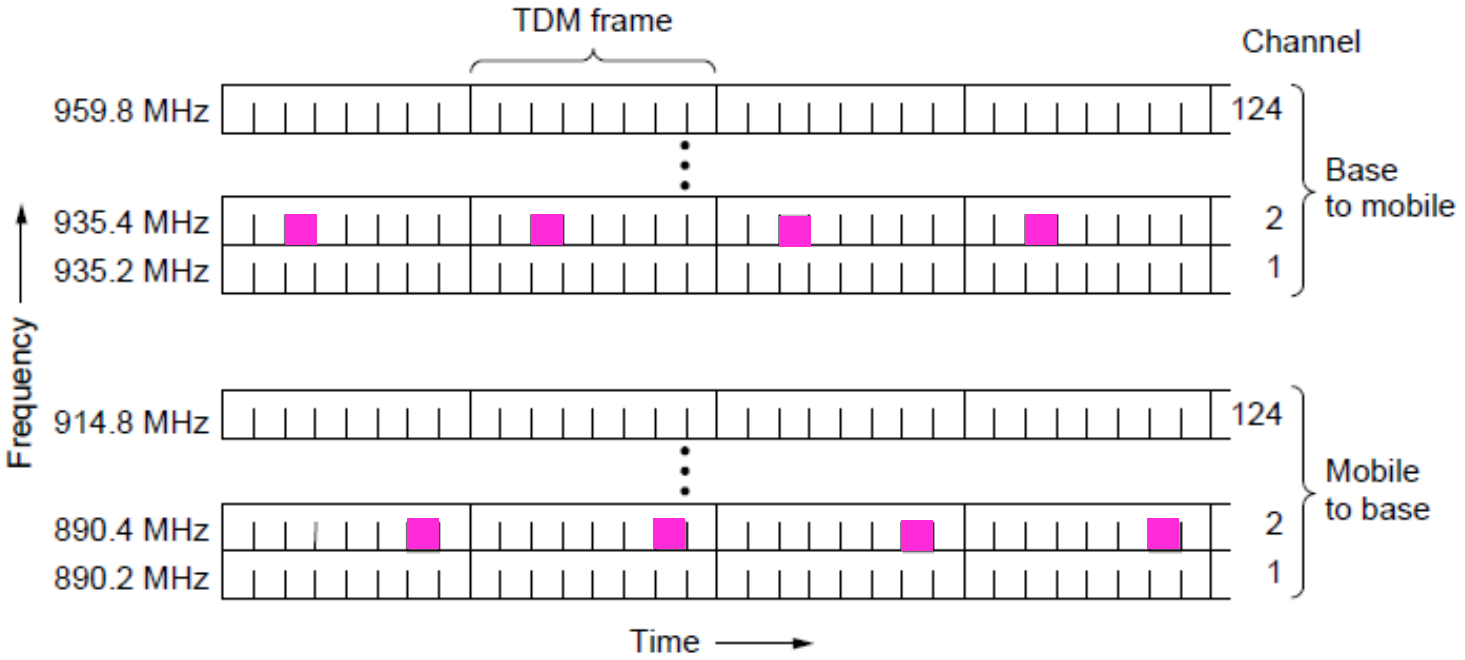
- Mobile is divided into handset and SIM card (Subscriber Identity Module) with credentials
- Mobiles tell their HLR (Home Location Register) their current whereabouts for incoming calls
- Cells keep track of visiting mobiles (in the Visitor LR)



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

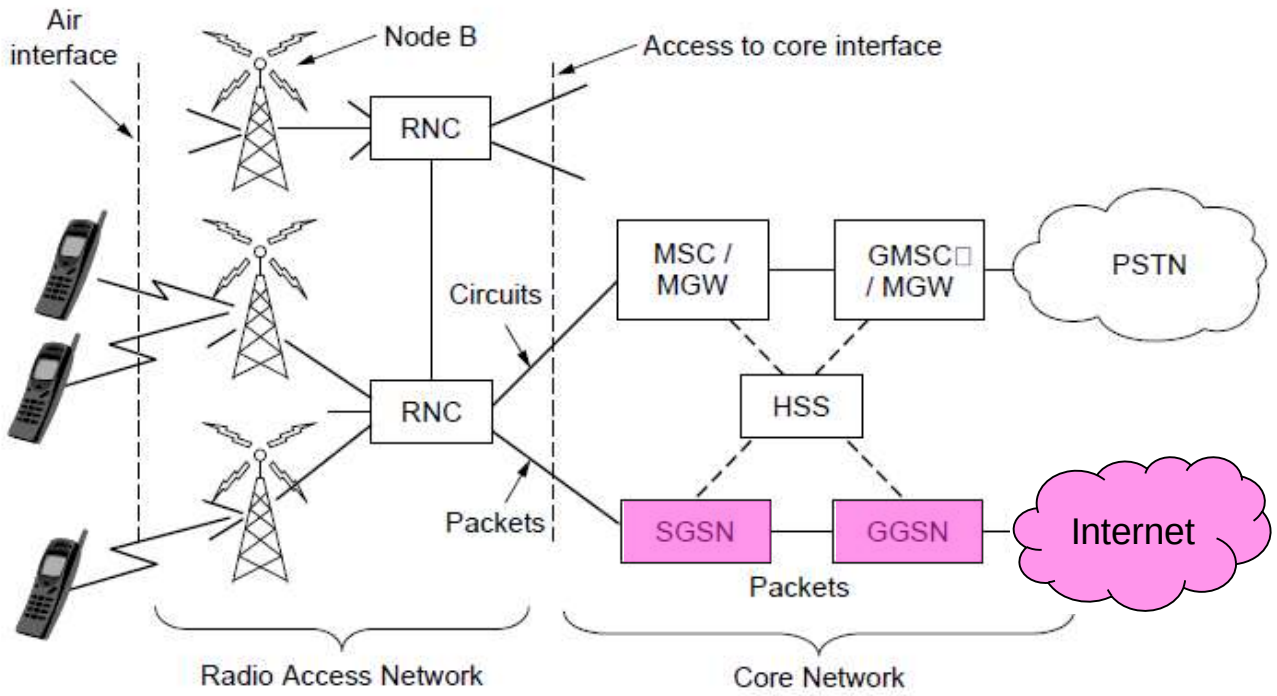
- Mobile is assigned up- and down-stream slots to use
- Each slot is 148 bits long, gives rate of 27.4 kbps



UMTS – Universal Mobile Telecommunications System (1)

Architecture is an evolution of GSM; terminology differs

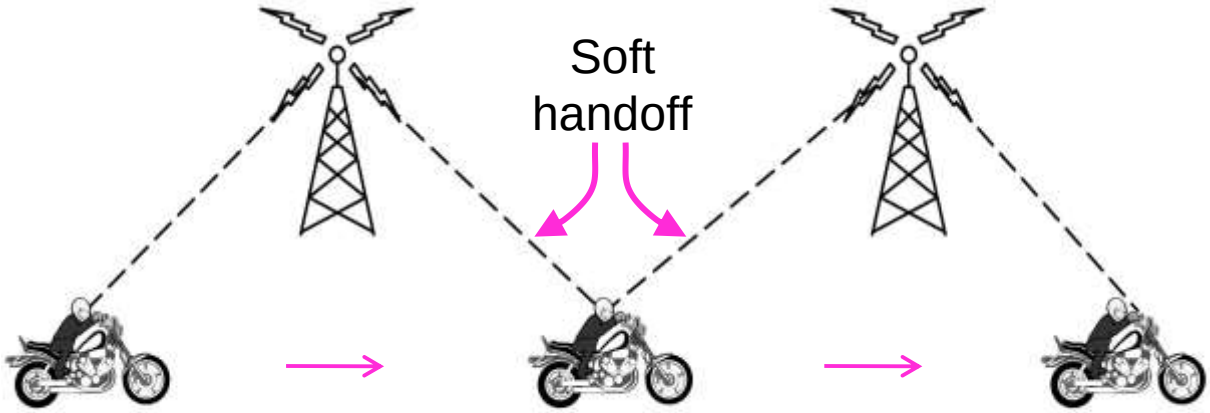
Packets goes to/from the Internet via SGSN/GGSN



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)



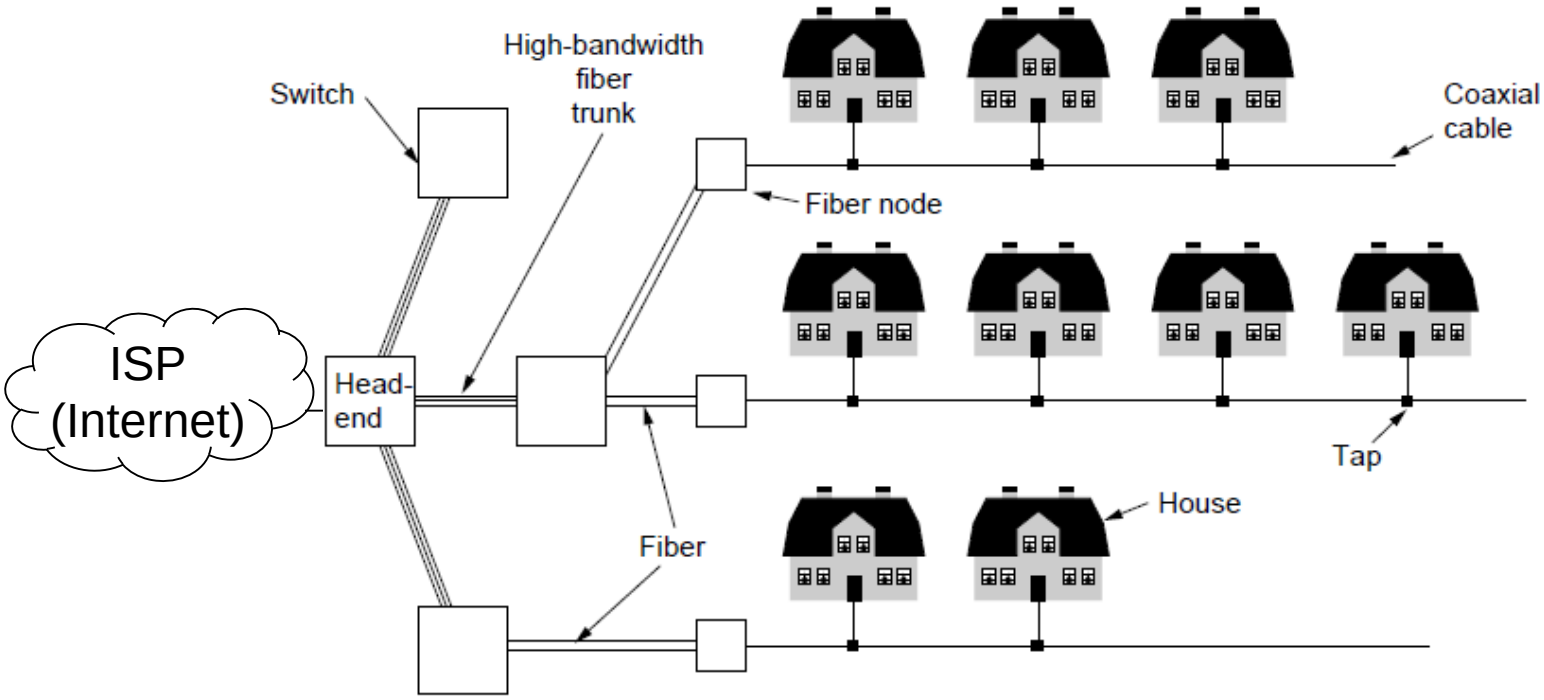
5. Cable Television

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

Internet over Cable

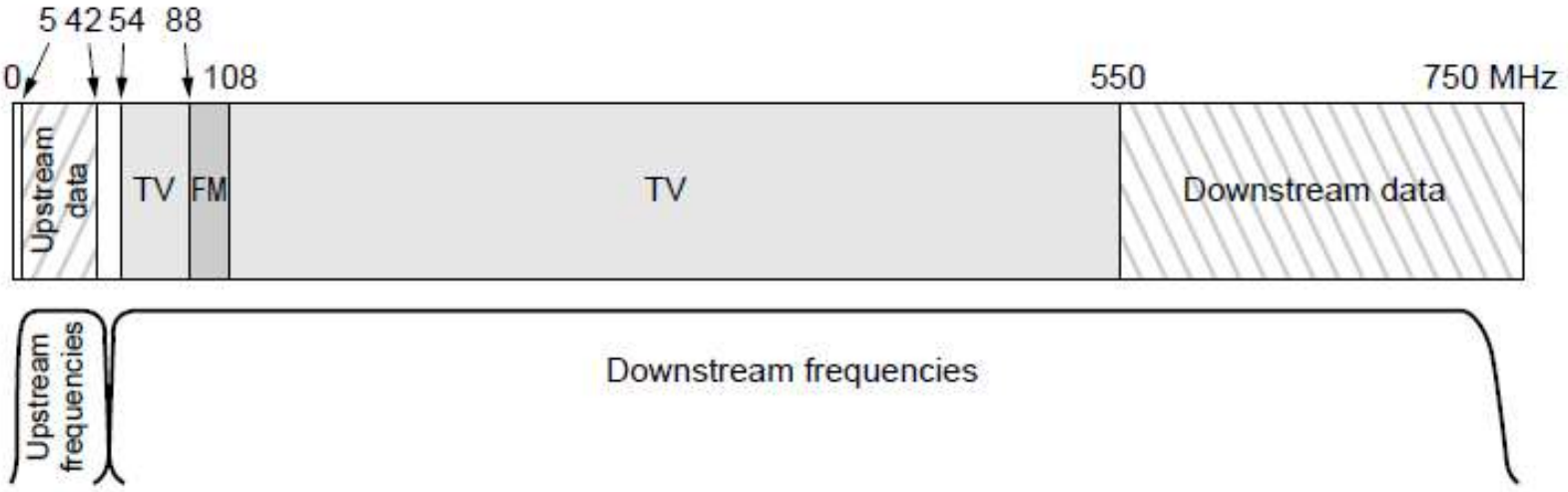
Internet over cable reuses the cable television plant

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



Spectrum Allocation

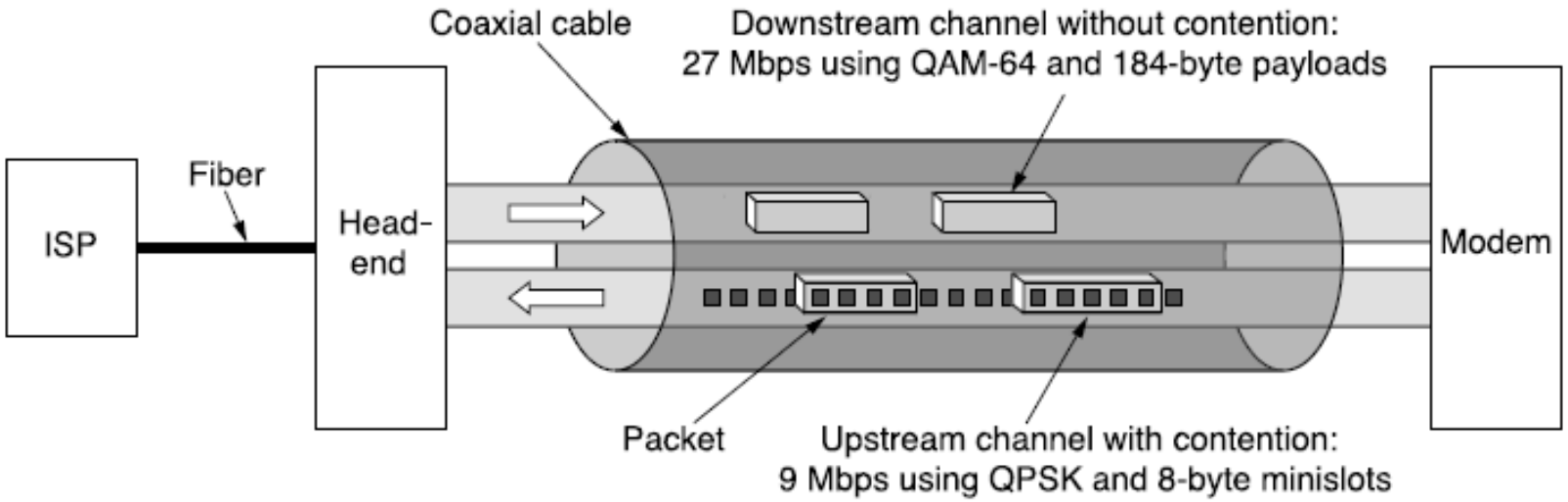
Upstream and downstream data are allocated to frequency channels not used for TV channels:



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