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

Revised: August 2011

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

| Application |
| Transport |
| Network |
| Link |
| Physical |

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):

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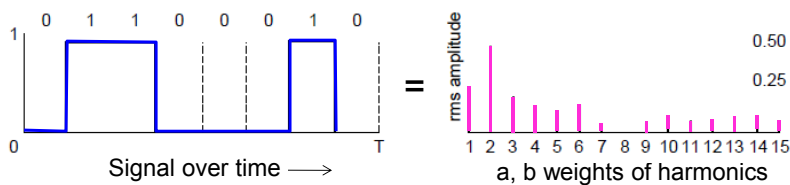
Fourier Analysis - 2

The a_n amplitudes can be computed for any given $g(t)$ by multiplying both sides of Eq. (2-1) by $\sin(2\pi kft)$ and then integrating from 0 to T. Since

$$\int_0^T \sin(2\pi kft) \sin(2\pi nft) \, dt = \begin{cases} 0 \text{ for } k \neq n \\ T/2 \text{ for } k = n \end{cases}$$

only one term of the summation survives: a_n. The b_n summation vanishes completely. Similarly, by multiplying Eq. (2-1) by $\cos(2\pi kft)$ and integrating between 0 and T, we can derive b_n. By just integrating both sides of the equation as it stands, we can find c. The results of performing these operations are as follows:

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

Fourier Analysis - 3

voltage output by the transmitting computer. The Fourier analysis of this signal yields the coefficients:

$$a_n = \frac{1}{\pi n}[\cos(\pi n/4) - \cos(3\pi n/4) + \cos(6\pi n/4) - \cos(7\pi n/4)]$$

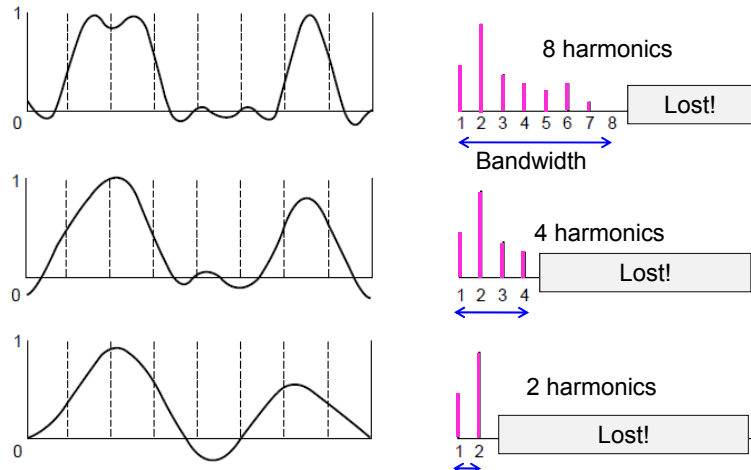$$b_n = \frac{1}{\pi n}[\sin(3\pi n/4) - \sin(\pi n/4) + \sin(7\pi n/4) - \sin(6\pi n/4)]$$

$$c = 3/4$$

The root-mean-square amplitudes, $\sqrt{a_n^2 + b_n^2}$, for the first few terms are shown on the right-hand side of Fig. 2-1(a). These values are of interest because their squares are proportional to the energy transmitted at the corresponding frequency.

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Bandwidth-Limited Signals

Having less bandwidth (harmonics) degrades the signal

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Energy and Power

- Energy for any signal is defined as:

$$E_s = \int \left| g(t) \right|^2 dt$$

- Then Energy for g(t) is infinite!

- Power for any signal is defined as:

$$P_s = \frac{1}{T} \int_0^T \left| g(t) \right|^2 dt$$

- What is the power for signal g(t)?

- What is the power for signal g(t) when only 4 harmonics are included?

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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.
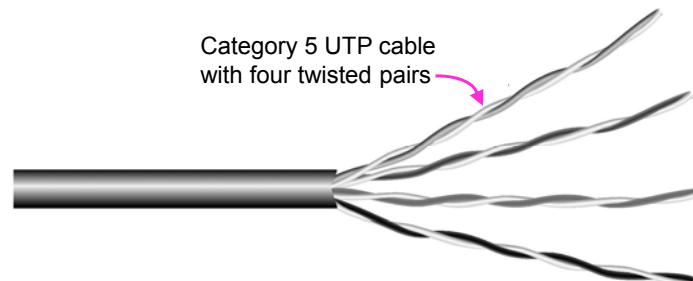
Data rate is faster than long-distance networks!

But, the message delay is very poor.

Wires – Twisted Pair

Very common; used in LANs, telephone lines
- Twists reduce radiated signal (interference)

Category 5 UTP cable
with four twisted pairs

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
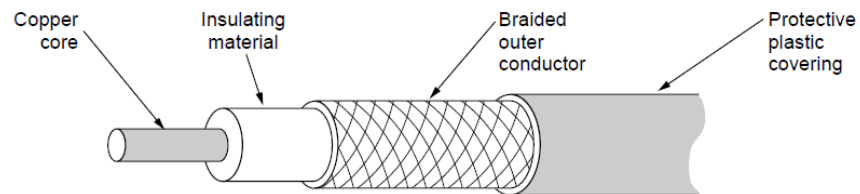- e.g., senders take turns on a wireless channel

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.

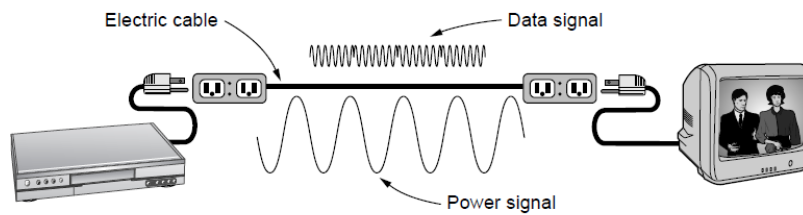Copper core — Insulating material — Braided outer conductor — Protective plastic covering

Wires – Power Lines

Household electrical wiring is another example of wires
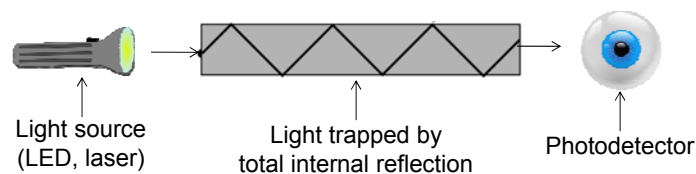- Convenient to use, but horrible for sending data

Fiber Cables (1)

Common for high rates and long distances
- Long distance ISP links, Fiber-to-the-Home
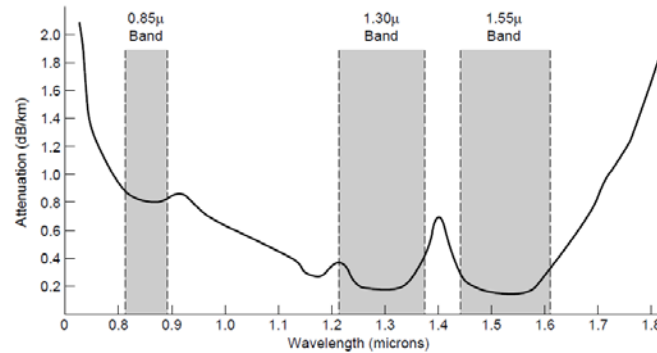- Light carried in very long, thin strand of glass

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Fiber Cables (2)

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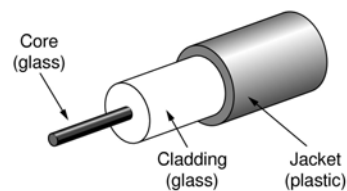loss – hence high rates over long distances

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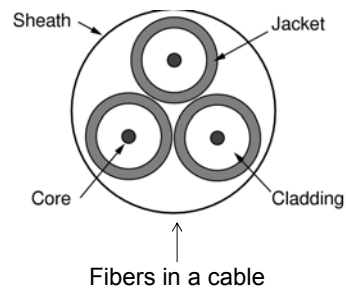
Fiber Cables (3)

<u>Single-mode</u>

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

<u>Multi-mode</u>

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

Fibers in a cable

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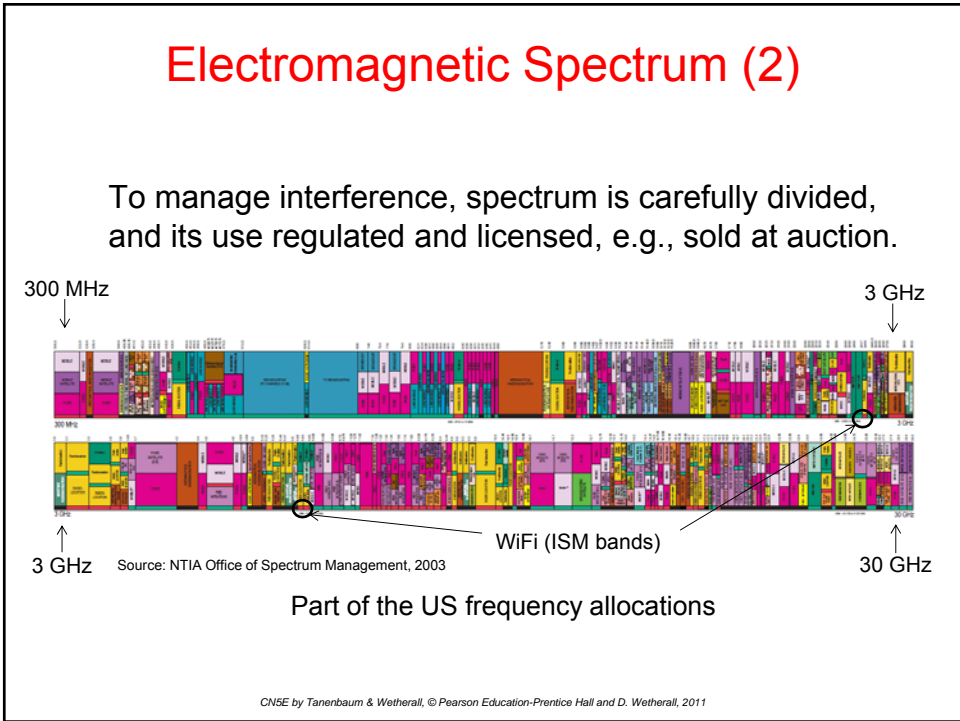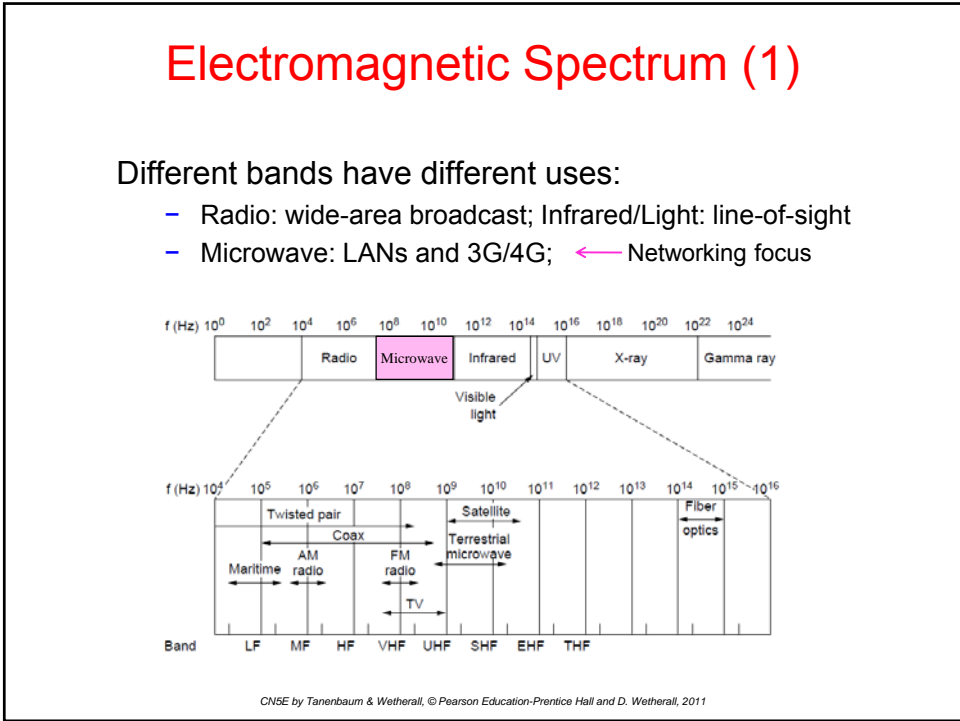# Fiber Cables (4)

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

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Electromagnetic Spectrum (2)

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

300 MHz

3 GHz

WiFi (ISM bands)

3 GHz   Source: NTIA Office of Spectrum Management, 2003   30 GHz

Part of the US frequency allocations

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Electromagnetic Spectrum (3)
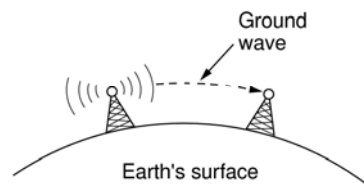
Fortunately, there are also unlicensed ("ISM") bands:
- Free for use at low power; devices manage interference
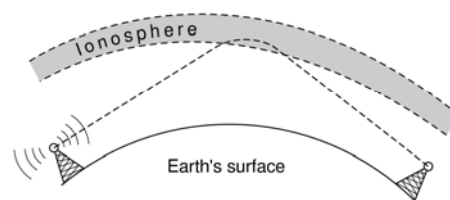- Widely used for networking; WiFi, Bluetooth, Zigbee, etc.
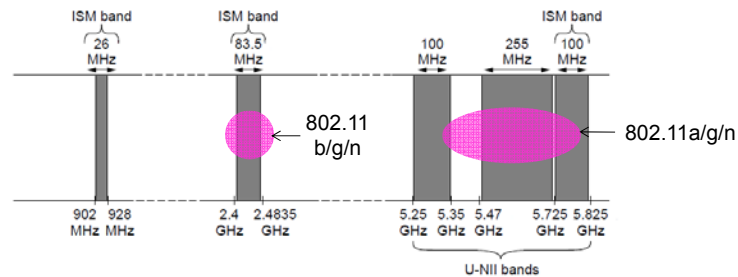
Radio Transmission

Radio signals penetrate buildings well and propagate for long distances with <u>path loss</u>

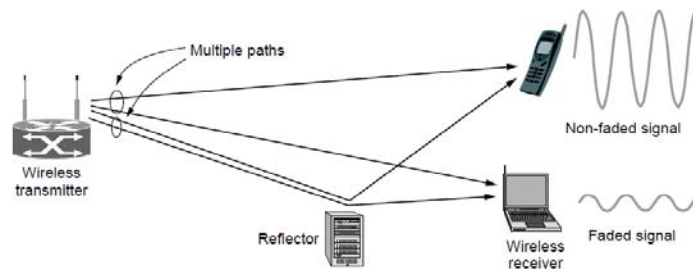In the VLF, LF, and MF bands, radio waves follow the curvature of the earth

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
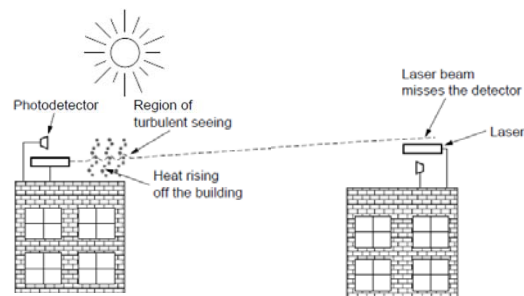- Strength varies with mobility due multipath fading, etc.

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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

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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

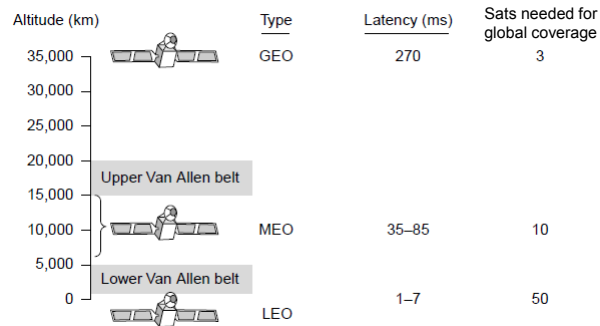Satellites are effective for broadcast distribution and anywhere/anytime communications

- • 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)

Altitude (km)	Type	Latency (ms)	Sats needed for global coverage
35,000	GEO	270	3
10,000	MEO	35–85	10
0	LEO	1–7	50

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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.
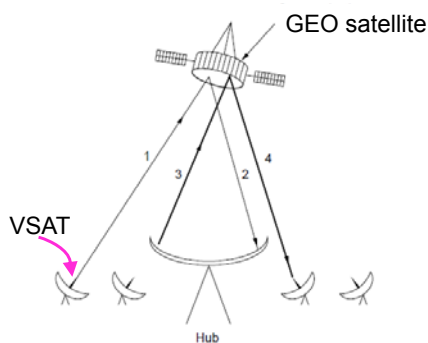
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Low-Earth Orbit Satellites

Systems such as Iridium use many low-latency satellites for coverage and route communications via them
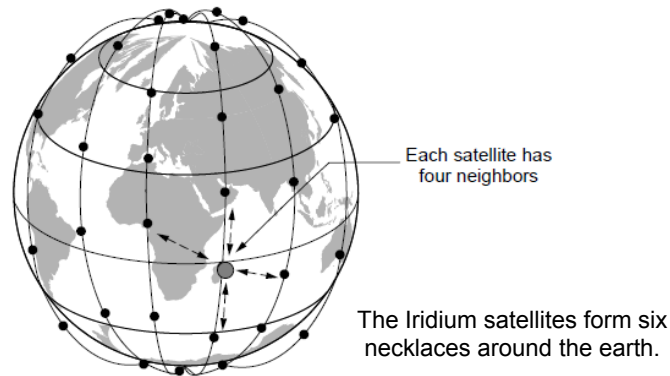
Each satellite has four neighbors

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

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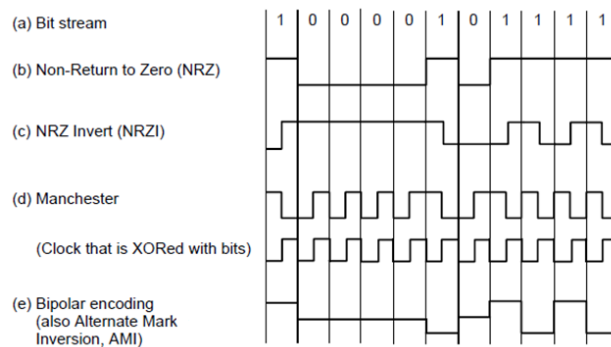multiplexing schemes share a channel among users.

- 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

	Bit stream: 1 0 0 0 0 1 0 1 1 1 1
(a) Bit stream	
(b) Non-Return to Zero (NRZ)	
(c) NRZ Invert (NRZI)	
(d) Manchester	
(Clock that is XORed with bits)	
(e) Bipolar encoding (also Alternate Mark Inversion, AMI)	

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.:

1 | 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 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
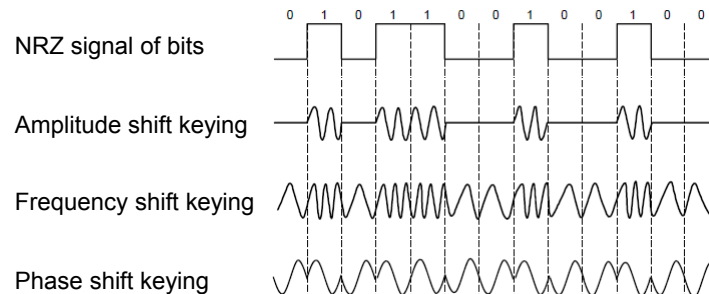
NRZ signal of bits

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:
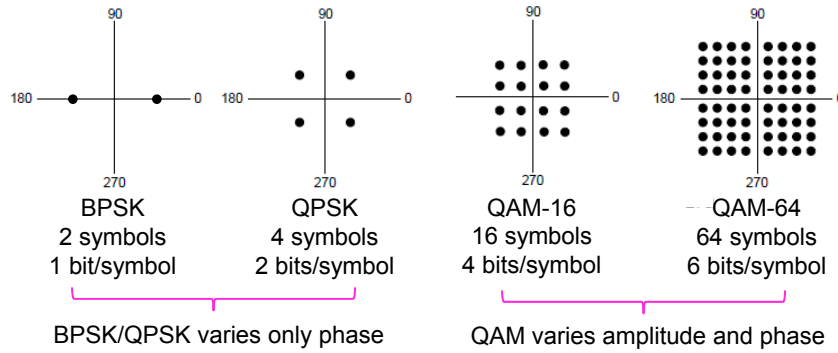
BPSK	QPSK	QAM-16	QAM-64
2 symbols	4 symbols	16 symbols	64 symbols
1 bit/symbol	2 bits/symbol	4 bits/symbol	6 bits/symbol

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:
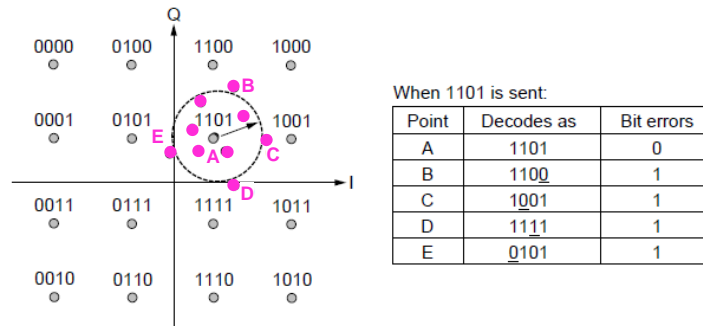
When 1101 is sent:

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:
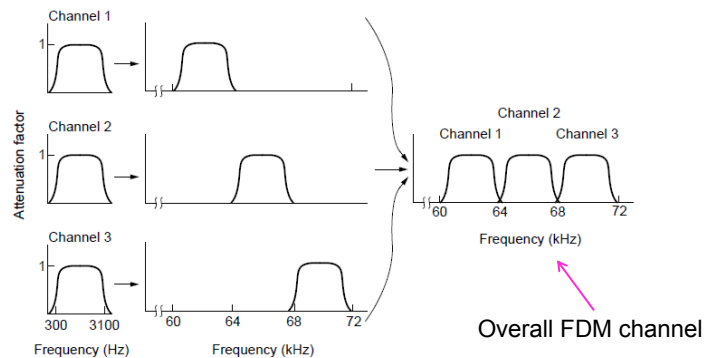
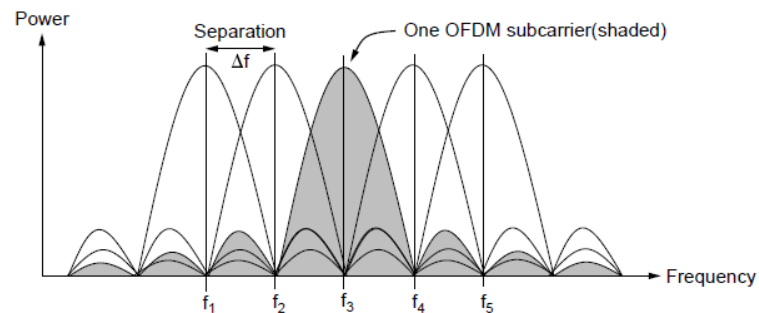Overall FDM channel

Frequency Division Multiplexing (2)

OFDM (Orthogonal FDM) is an efficient FDM technique used for 802.11, 4G cellular and other communications
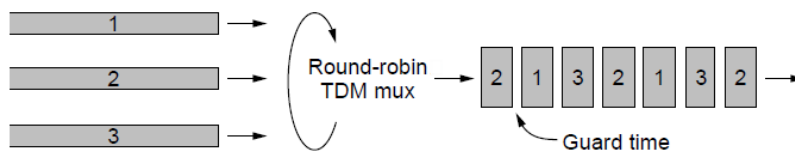• Subcarriers are coordinated to be tightly packed

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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)
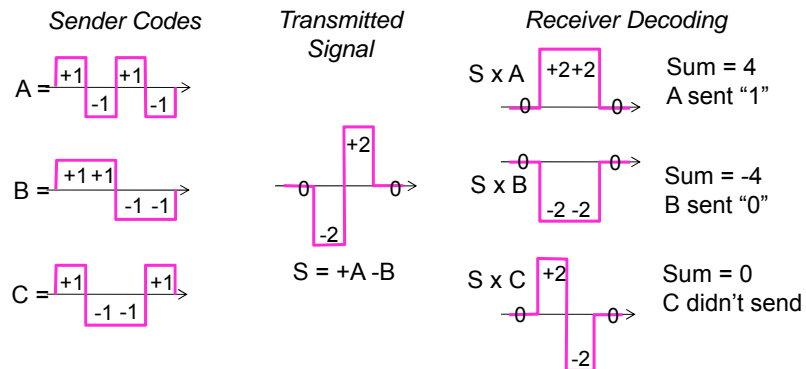- Widely used in telephone / cellular systems

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

21

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
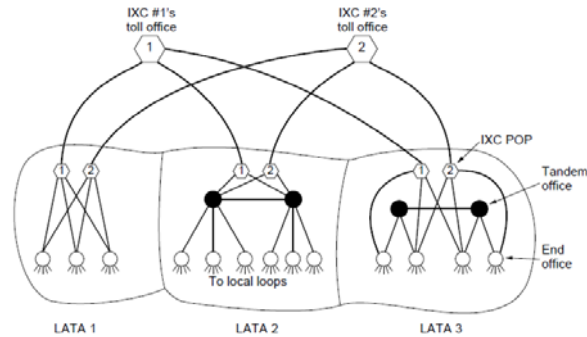- Switching offices, that move calls among trunks
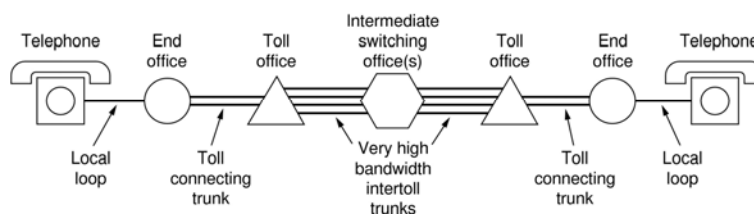
The Politics of Telephones

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)

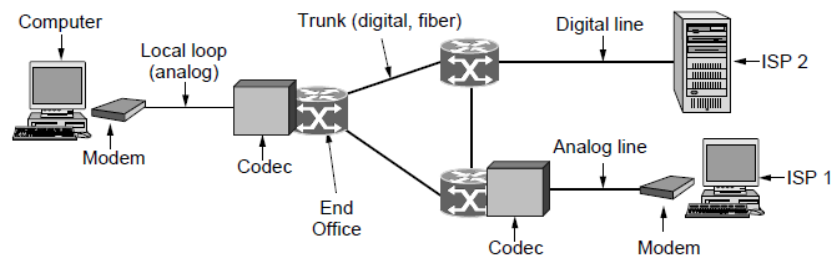- Customers of a LEC can dial via any IXC they choose

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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

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Local loop (2): Digital Subscriber Lines

DSL <u>broadband</u> 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
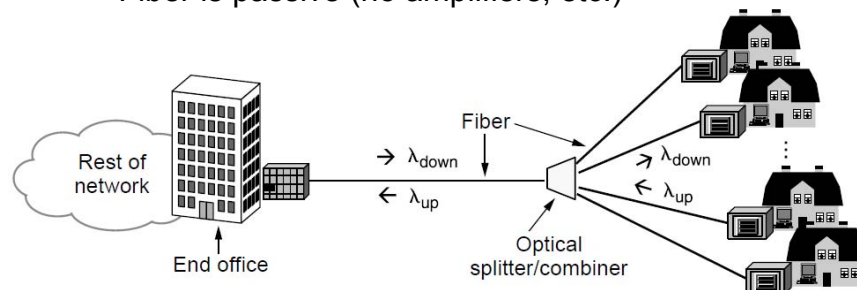 - Most bandwidth down
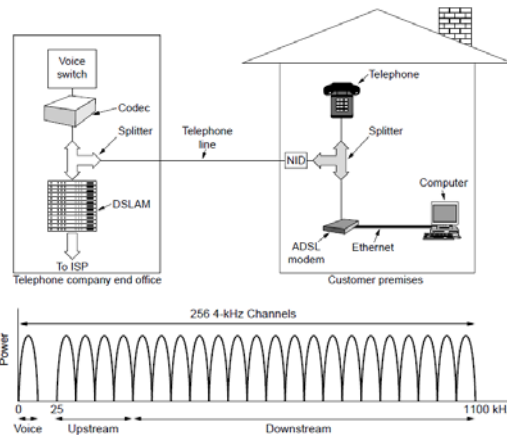
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Local loop (3): Fiber To The Home

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

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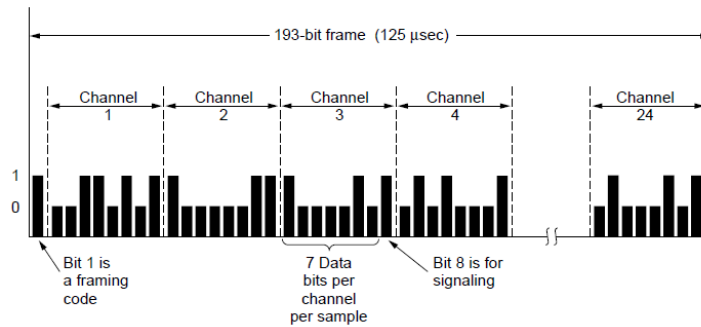- Fiber is passive (no amplifiers, etc.)

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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

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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
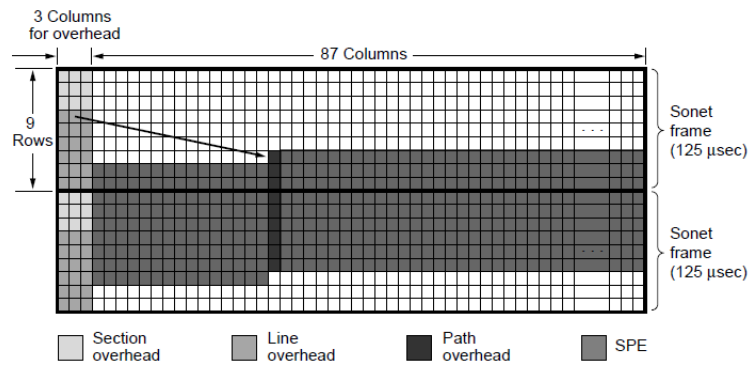
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Trunks and Multiplexing (3)

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:
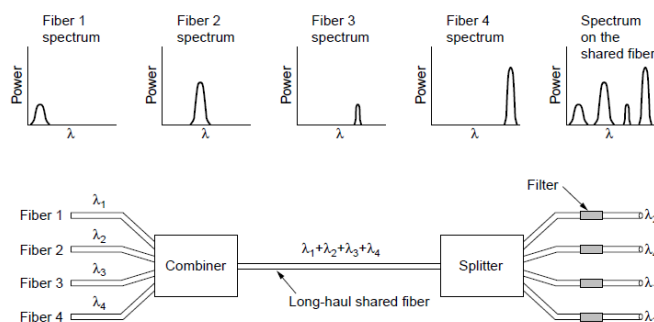
Switching (1)

PSTN uses circuit switching; Internet uses packet switching
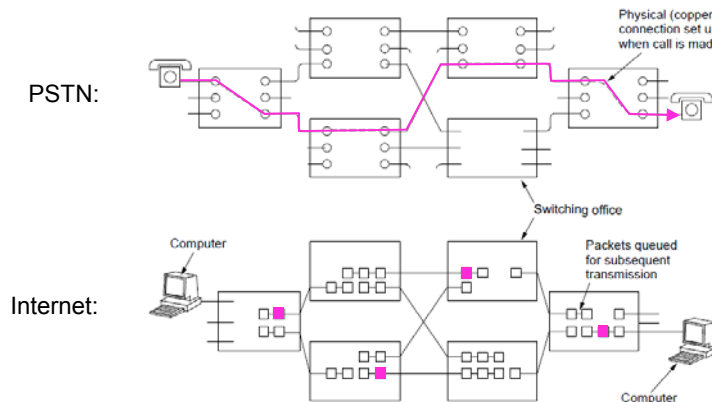
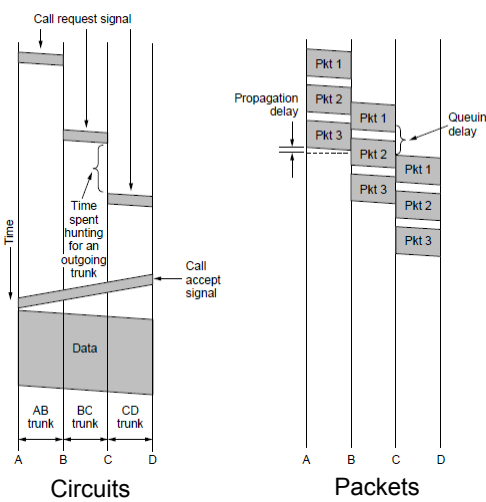*CN5E by Tanenbaum & Wetherall, © Pearson Education-Prentice Hall and D. Wetherall, 2011*

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

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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

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Mobile Telephone System

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

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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
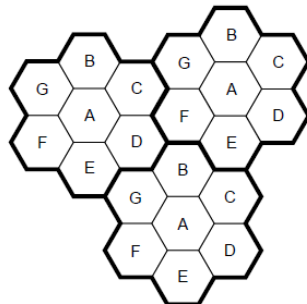
4G, digital data including voice
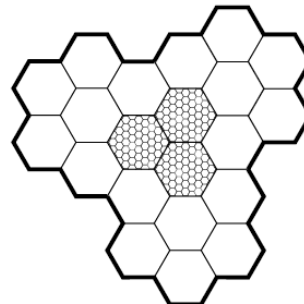- LTE (Long Term Evolution) is example, deployed from 2010s. Modulation based on OFDM

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
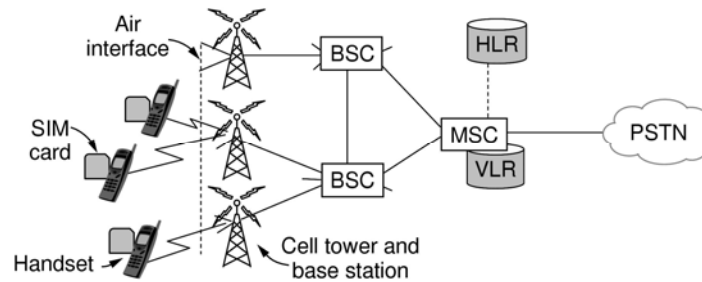

Cellular reuse pattern   Smaller cells for dense mobiles

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)

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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
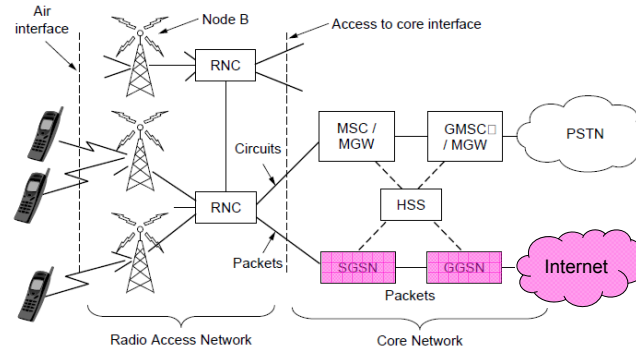
- Mobile is assigned up- and down-stream slots to use
- Each slot is 148 bits long, gives rate of 27.4 kbps
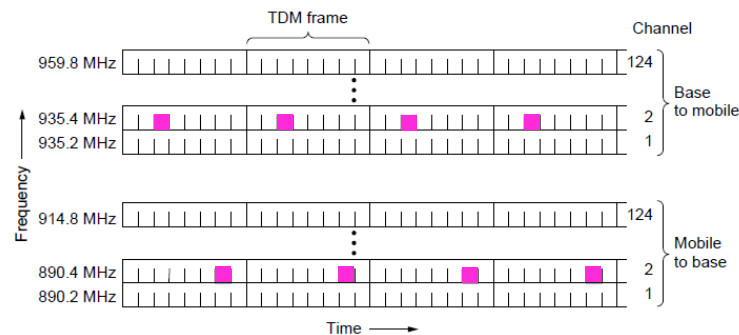
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UMTS – Universal Mobile Telecommunications System (1)

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

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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)
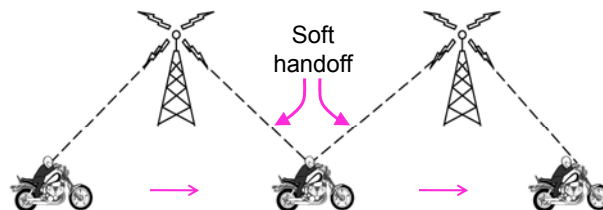
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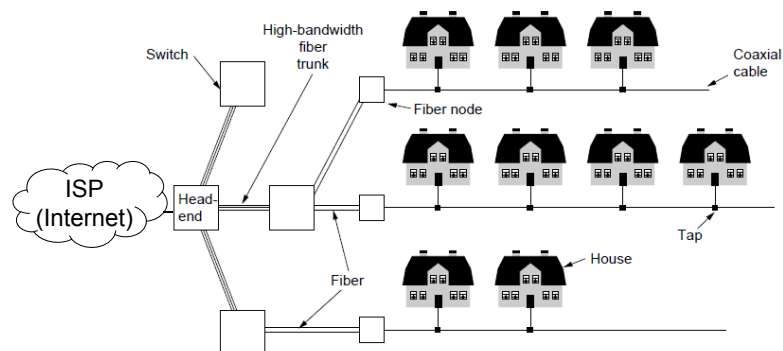
Cable Television

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

Internet over Cable

Internet over cable reuses the cable television plant

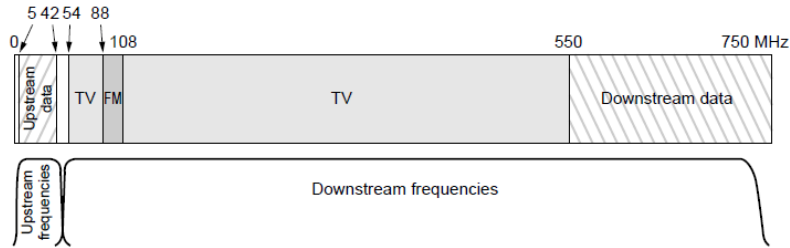- Data is sent on the shared cable tree from the head-end, not on a dedicated line per subscriber (DSL)

Spectrum Allocation

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

Cable Modems

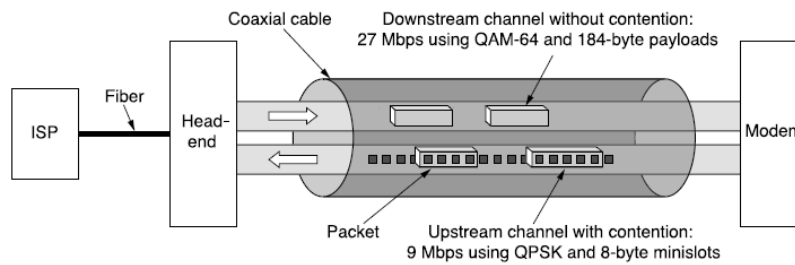Cable modems at customer premises implement the physical layer of the DOCSIS standard

- 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