Computer Network

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The Physical Layer

Chapter 2

Outline of Physical Layer

-from end node, router, transmission, network perspectives

- It defines the electrical, timing and their interfaces by which bits are sent as signals over the channel.
- The lowest layer in the OSI protocol model, foundation on which the network is built
- The properties of different kinds of physical channel and transmission techniques will affect and determine the design and performance – throughput, latency, and error rate.
- In order for transmission over various channel, modulation is required. In order for efficient channel bandwidth usage, multiplexing is always employed.
- But channel bandwidth is always a precious resource and the overall data transmission rate is limited
- Three types of transmission media:
  - Guided (copper wire and fiber optics)
  - Wireless (terrestrial radio), and
  - Satellite

Outline of Physical Layer
-from end node, router, transmission, network perspectives

- Digital Modulation: How analog signals are converted into digital bits and back again.
- Multiplexing Schemes: Exploring how multiple conversations can be put on the same transmission medium at the same time without interfering with one another.
- The physical layer of end node, router, transmission, network take different functions and roles respectively
- Examples of communication systems used in practice for wide area computer networks:
  - The (fixed) telephone system
  - The mobile phone system, and
  - The cable television system.

Connecting Nodes and Links

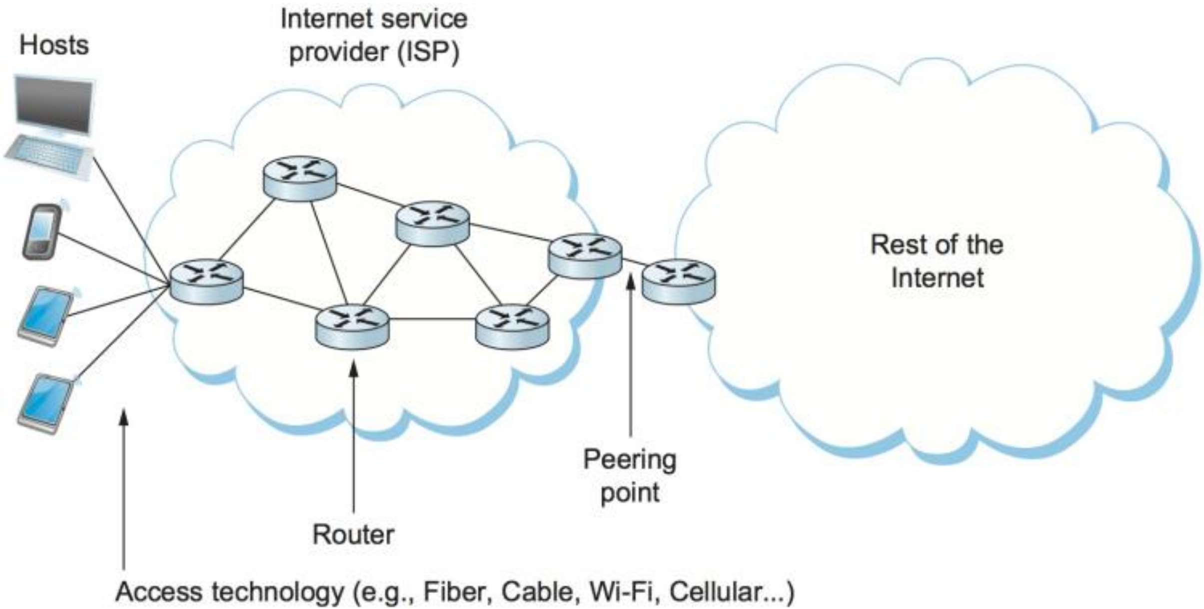


Figure 1. An end-user's view of the Internet.

Connecting Nodes and Links

two classes of hardware building blocks:

- nodes: convert message and information at app layer to packets and bits at lower layers
- links: various types of guided media or wireless, different transmission technologies, access network for last-mile links, long-distance high-speed links for trunk and backbone networks have different requirements, affected by economic and deployment issues

Design Issues

- Connectivity and reliability: modulation and encoding, framing, error detection, reliable delivery, and access mediation
- Network layer services
- Framing
- Error control
- Flow control

Theoretical Basis for Data Communication

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

Fourier Analysis

- We model the behavior of variation of voltage or current with mathematical functions
- **Fourier series** is used to expand any periodic function with period T

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

- ***f=1/T – fundamental frequency.***
- ***a_n, b_n – are the sine and cosine amplitudes of the n'th harmonic.***
- ***c – is a constant.***

Fourier Analysis

- Orthogonallity

$$\int_0^T \sin(2\pi k f t)\cos(2\pi n f t) = \begin{cases} 0 \; for \; k \neq n \\ \frac{T}{2} \; for \; k = n \end{cases}$$

- Func

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

Bandwidth-Limited Signals

- The reason why we break down the signal into the potentially infinite sum of pure periodical signal with the frequency ***ω=2πnf*** is because each frequency component is affected differently by the channel.
- Example:
  - ASCII **b** character encoded in 8-bits 01100010.
  - Fourier analysis of this signal yields the coefficients:

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

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

Bandwidth-Limited Signals

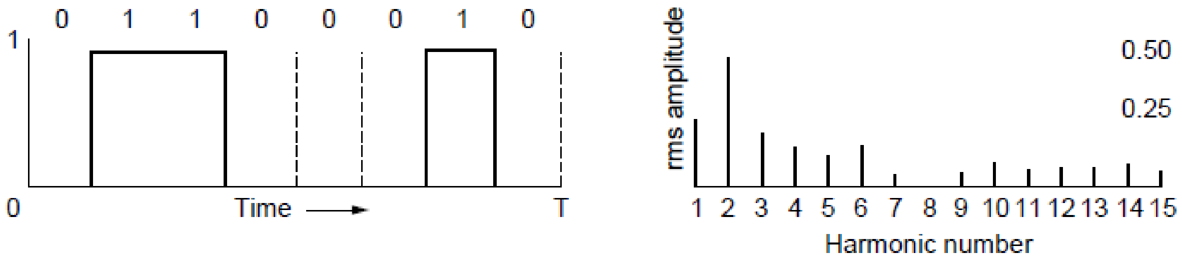
- $\sqrt{{a_n}^2 + {b_n}^2}$ - amplitudes of the terms
- Amplitude squares are proportional to the energy of the corresponding signal that is being transmitted.
- No transmission occurs without some loss of power.
- If all the Fourier components were equally diminished the resulting signal would be reduced in amplitude but not distorted.
- This is not the case.
  - For a wire the amplitudes are transmitted mostly undiminished up to some frequency $\boldsymbol{f_c}$.
  - **Bandwidth** is the range of frequencies without being attenuated.
  - In practice the quoted bandwidth is from 0 to the frequency at which the received power has fallen by half.

Bandwidth-Limited Signals

- Example:
  - Filters are commonly used to limit the bandwidth of a signal.
  - 802.11 wireless channels are allowed signals up to (roughly) 20 MHz
  - Analog TV channels occupy 6 MHz each.

- **Baseband** – signal that run from 0 to a maximum frequency allowed.
- **Passband** – signal that are shifted in frequency to occupy the higher range but of equal bandwidth as a baseband.

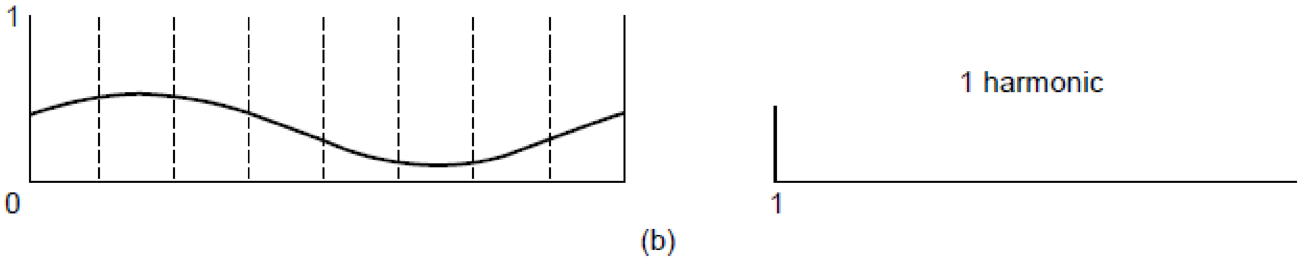
Bandwidth-Limited Signals (1)



(a)

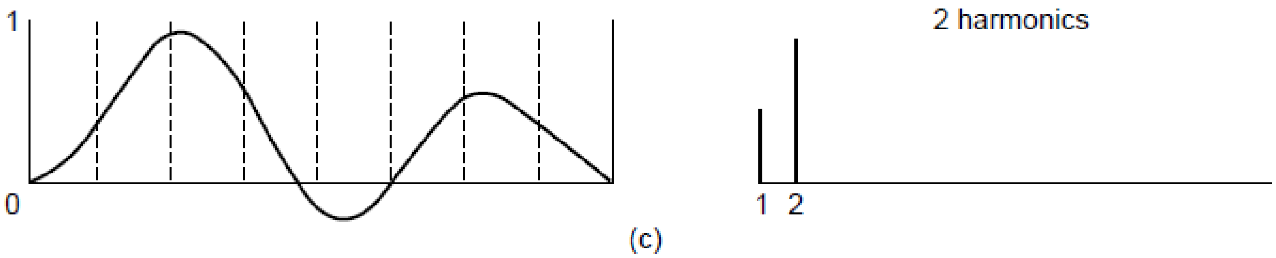
A binary signal and its root-mean-square Fourier amplitudes.

Bandwidth-Limited Signals (2)



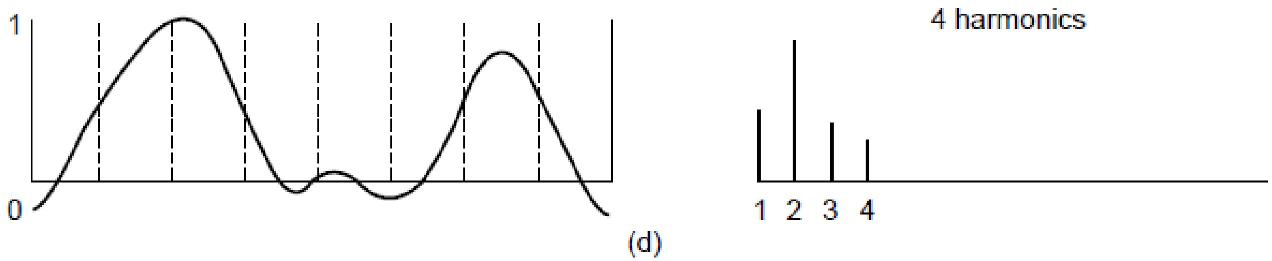
(b)-(e) Successive approximations to the original signal.

Bandwidth-Limited Signals (3)



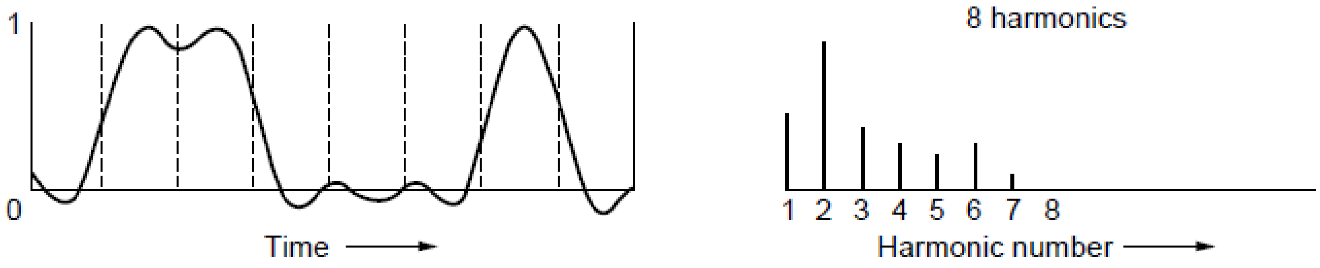
(b)-(e) Successive approximations to the original signal.

Bandwidth-Limited Signals (4)



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

Bandwidth-Limited Signals (5)



(e)

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

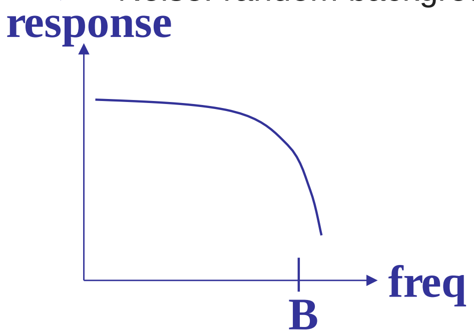
Bandwidth-Limited Signals (6)

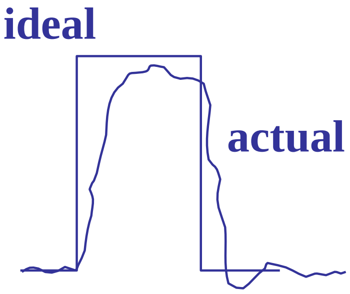
Bps	T (msec)	First harmonic (Hz)	# Harmonics sent
300	26.67	37.5	80
600	13.33	75	40
1200	6.67	150	20
2400	3.33	300	10
4800	1.67	600	5
9600	0.83	1200	2
19200	0.42	2400	1
38400	0.21	4800	0

Relation between data rate and harmonics for our example.

No Infinite Channel Bandwidth
No Ideal Signal

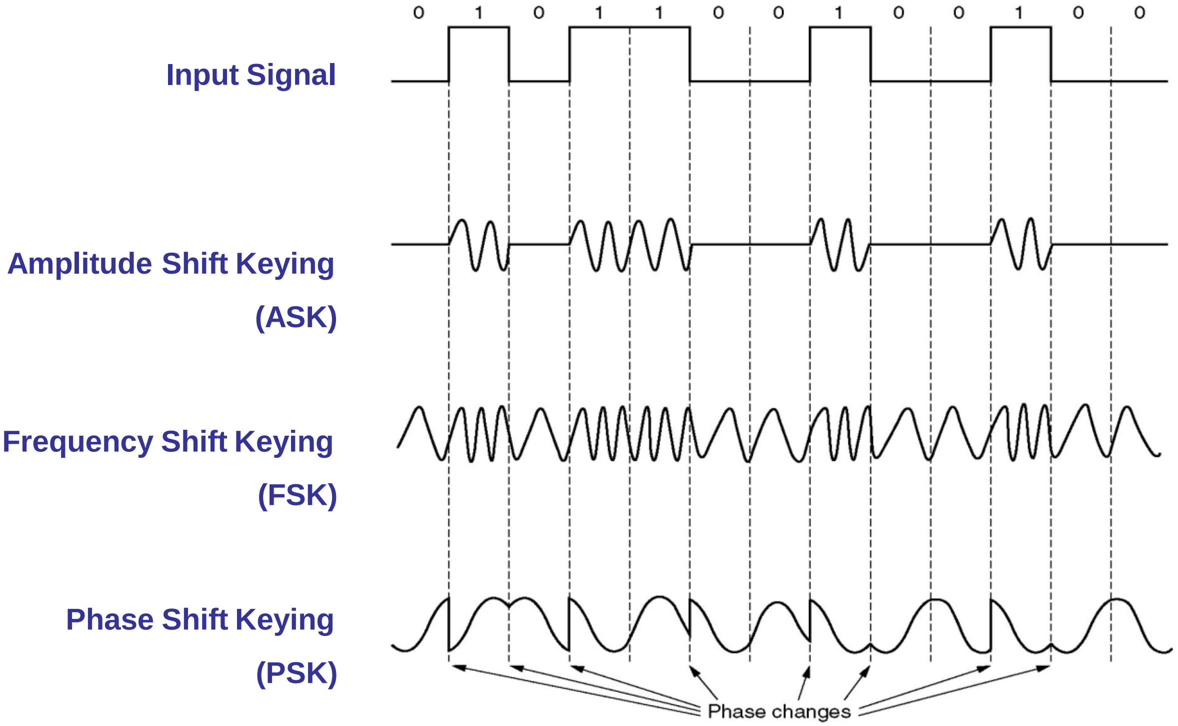
- No channel is perfect and the original signal gets modified along the way
  - Attenuation: signal power absorbed by medium
  - Distortion: frequency, phase changes
  - Noise: random background “signals”





- Different mediums distort different signals differently
- Note: that here “bandwidth” means frequency over which signals cannot pass through channel

Forms of Digital Modulation

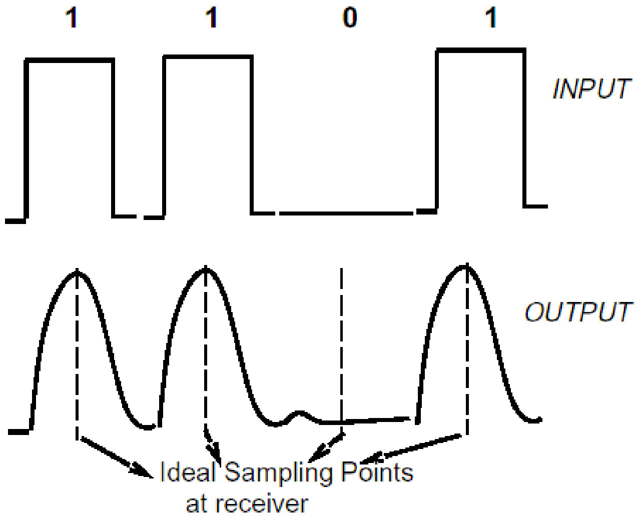


Why Different Modulation Schemes?

- Properties of channel and desired application
  - AM vs FM for analog radio
- Efficiency
  - Some modulations can encode many bits for each symbol (subject to Shannon limit – more on this next class)
- Aiding with error detection
  - Dependency between symbols… can tell if a symbol wasn't decoded correctly
- Transmitter/receiver Complexity

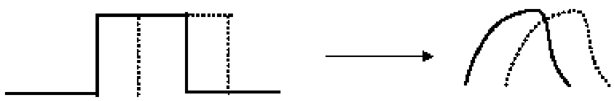
Sampling

- To reconstruct signal we need to sample it



Intersymbol Interference

- Bandlimited channels cannot respond faster than some maximum frequency *f*
  - Channel takes some time to settle
- Attempting to signal too fast will mix symbols
  - Previous symbol still “settling in”
  - Mix (add/subtract) adjacent symbols
  - Leads to intersymbol interference (ISI)



- OK, so just how fast can we send symbols?

Bit Rate

- Bit Rate: ***b*** bits/sec
- Time required to send 8 bits one bit at a time is 8/***b*** sec
- First harmonic of this signal is ***b*/8 Hz**

- **Example: Telephone line**
  - **Bandwidth ~3000 Hz**
  - **Number of highest harmonic is ~3000/(*b*/8) = 24,000/b**

The Maximum Data Rate of a Channel

- Nyquist's theorem

$$\text{maximum data rate} = 2B \log_2 (V \; bits/sec)$$

- Noisy Channel
  - SNR – Signal-to-Noise Ratio: (S/N)
  - 10log10(S/N) dB

$$\text{maximum number of bits / sec} = B \log_2 (1 + S/N)$$

- Shannon's formula for capacity of a noisy channel

The Maximum Data Rate of a Channel

- ADSL (Asymmetric Digital Subscriber Line), Internet Access over normal telephone lines, uses 1 MHz bandwidth.
- The SNR depends strongly on the distance of the home from the telephone exchange – SNR of ~40 dB for a short line of 1-2 km is consider very good quality.
- Maximum Data Rate is ~13Mbps.
  - B = 1 MHz
  - 10log10(S/N) = 40 dB => S/N=10,000
  - Blog2(1+S/N) = 1 MHz*log2(10,001) ≈13 MHz.

How many kinds of Networks?

- **Classification of networks from different perspectives**
  - **Transmission media: Wired (UTP, coaxial cables, fiber-optic cables) and Wireless including radio, microwave, millimeter wave, laser, infrared, sound, ...**
  - **Network size: PAN, LAN and WAN (and MAN)**
  - **Management method: Peer-to-peer and Client/Server, distributed, decentralized**
  - **Topology (connectivity): Bus, Star, Ring, Tree, Cellular...**

Transmission Media

- **Two main categories:**
  - **Guided — wires, cables**
  - **Unguided — wireless transmission, e.g. radio, microwave, millimeter wave, laser, infrared, sound, sonar etc**
- **Guided media:**
  - **Twisted-Pair cables:**
    - ➢ **Unshielded Twisted-Pair (UTP) cables**
    - ➢ **Shielded Twisted-Pair (STP) cables**
  - **Coaxial cables**
  - **Power lines**
  - **Fiber-optic cables**

Twisted Pairs

- Telephony Lines (ADSL) – Twisted pair of wires.
- Category 5
  - 100 Mbps Ethernet uses two pairs; one pair for each direction.
  - 1 Gbps Ethernet uses all four pairs in both directions simultaneously.
- Defintions:
  - Full-duplex link
  - Half-duplex link
  - Simplex link
- Category 6 and 7 soon will be needed to carry rates of 10 Gbps and higher.

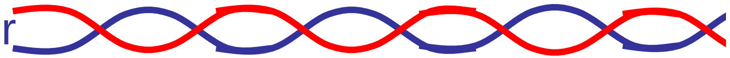
Coaxial Cable

- It has better shielding and greater bandwidth than unshielded twisted pairs.
  - 50 ohm is used for digital transmission
  - 75 ohm is used for analog transmission and cable television as well as data communication.
- Its construction provides high bandwidth and excellent noise immunity.
- Bandwidth – few GHz
- Widely used for cable televisions and metropolitan area networks.

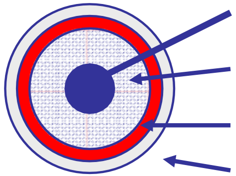
Copper

- Typical examples
  - Category 5/6 Twisted Pair 10M-10Gbps 50-100m
  - Coaxial Cable 10-100Mbps

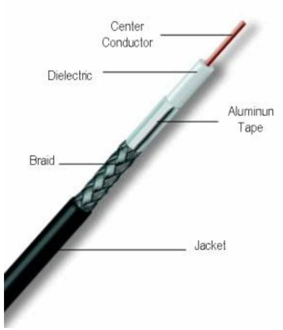
twisted pair



coaxial cable (coax)



copper core
insulation
braided outer conductor
outer insulation

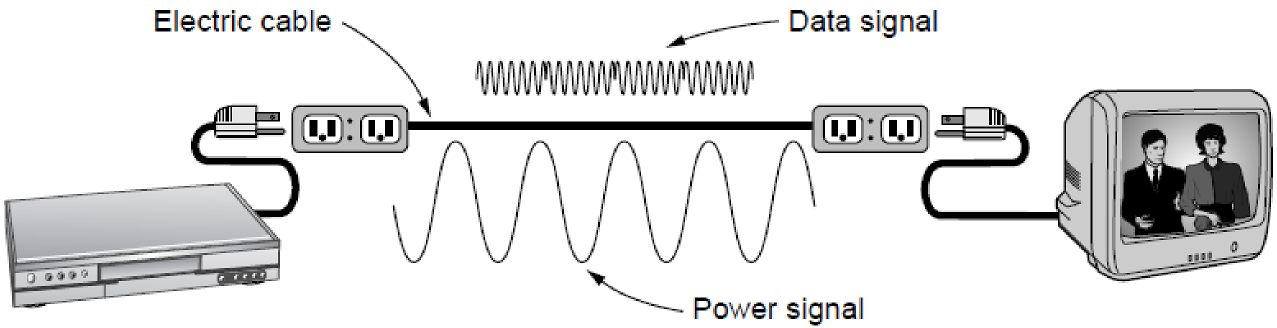


Power Lines

- High-rate communication of interest recently.
  - Inside home as a LAN
  - Outside home for broadband Internet access.
- Convenient way to perform networking
- Problem with wiring since they do attenuate significantly for higher frequencies.

- International standards are under development.

Power Lines



A network that uses household electrical wiring.

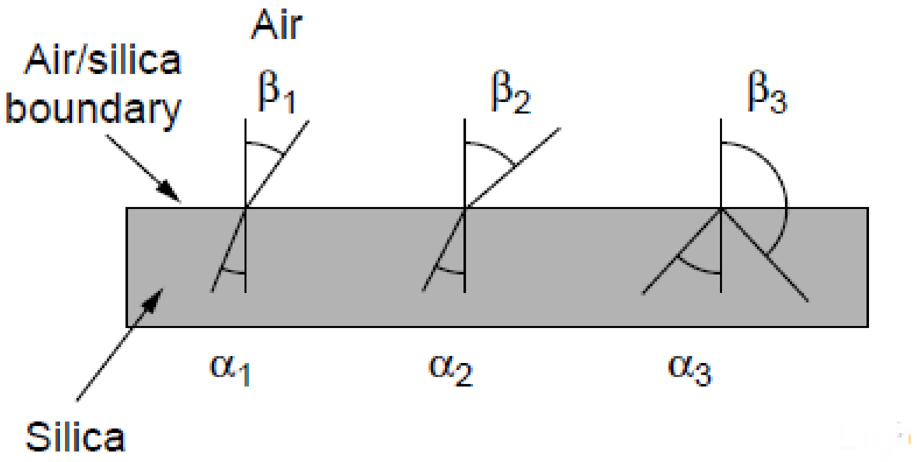
Fiber Optics

- Moore's Law – doubling of the number of transistors per chip roughly every 2 years:
  - Original IBM PC clock speed 4.77 MHz
  - 28 years latter PC's run four-core CPU's at 3 GHz.
  - Increase of a factor of around 2500, 16 per decade.
- Wide area communication links went
  - From 45 Mbps (T3 line in telephone system),
  - To 100 Gbps. This is hard threshold is due to our inability to convert between electrical and optical signals any faster.
- Race between computing power and communication.
- An optical transmission system has 3 key componenets:
  - The light source
  - The transmission medium, and
  - The detector.

Fiber Optics

- By convention:
  - A pulse of light indicates a 1 bit, and
  - the absence of light indicates a 0 bit
- Attaching light source to one end of an optical fiber, and
- Detector to the other end, we have:
  - A unidirectional data transmission system
  - Accepts an electrical signal,
  - Converts and transmits it by light pulses, and
  - Reconverts back the output to an electrical signal at the receiving end.
- The transmission system would leak light and be useless in practice if it were not for an interesting principle of physics:

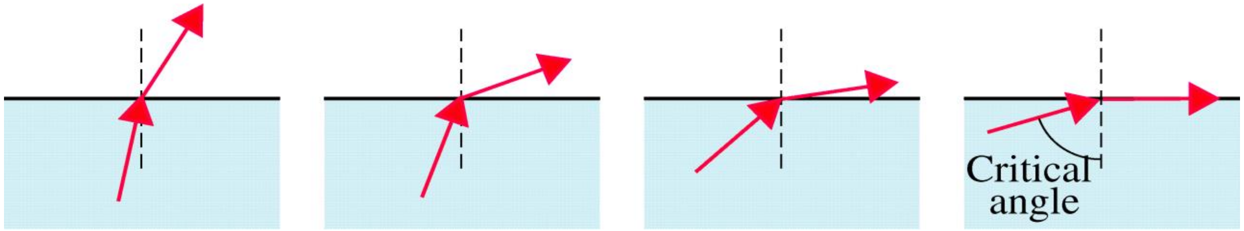
Fiber Optics (1)



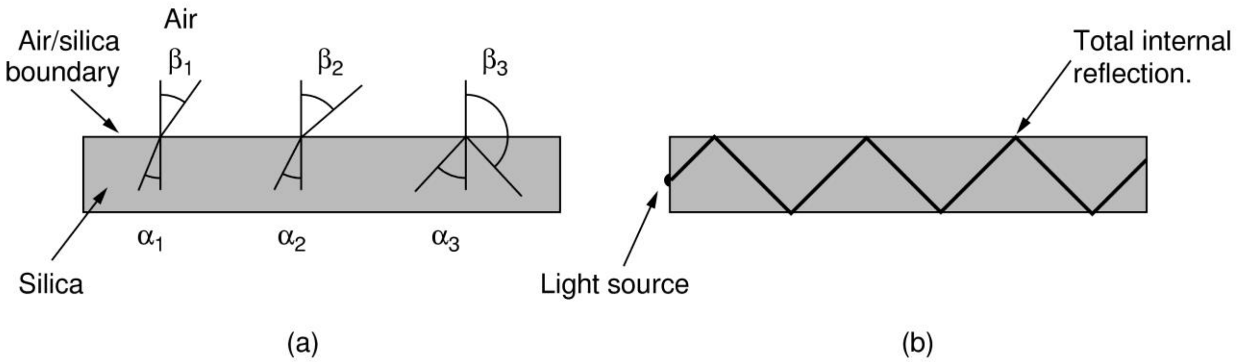
Three examples of a light ray from inside a silica fiber impinging on the air/silica boundary at different angles.

Fiber-Optic Cables

- **Light travels at 3×10^{8} ms^{-1} in free space and is the fastest possible speed in the Universe**
- **Light slows down in denser media, e.g. glass**
- **Refraction occurs at interface, with light bending away from the normal when it enters a less dense medium**
- **Beyond the *critical angle* $\Rightarrow$ total internal reflection**



Fiber Optics (2)



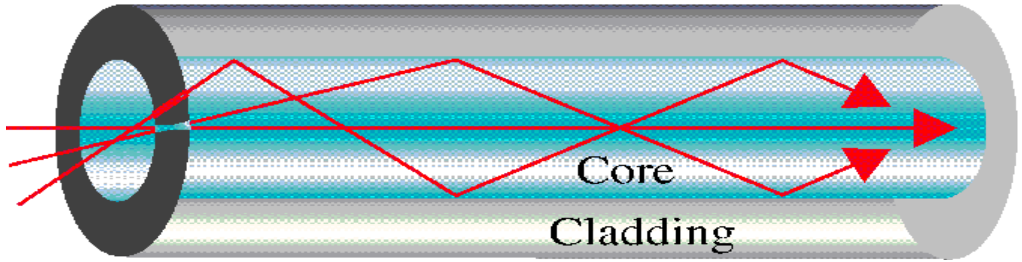
Light trapped by total internal reflection.

Fiber Optics

- Every light ray that has incidence angle greater then critical angel will be refracted internally: **multimode fiber**
- If fiber’s diameter is reduced to a few wavelength's of light it acts like a wave guide and the light can propagate only in a straight line without bouncing: **single-mode fiber**.

- Transmit data rate of 100 Gbps for 100 km without amplification.

- **An optical fiber consists of a core (denser material) and a cladding (less dense material)**
- **Simplest one is a multimode step-index optical fiber**
- **Multimode = multiple paths, whereas step-index = refractive index follows a step-function profile (i.e. an abrupt change of refractive index between the core and the cladding)**
- **Light bounces back and forth along the core**
- **Common light sources: LEDs and lasers**

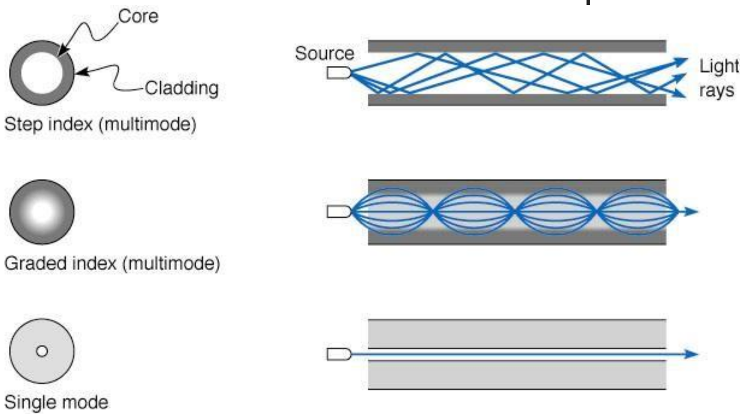


Fiber Optics

- Typical examples
  - Multimode Fiber

100Mbps-10Gb 1-100Gbps

500-2000m 100m-40km



Cheaper to drive (LED vs laser) & terminate

Longer distance (low attenuation)
Higher data rates (low dispersion)

Transmission of Light Through Fiber

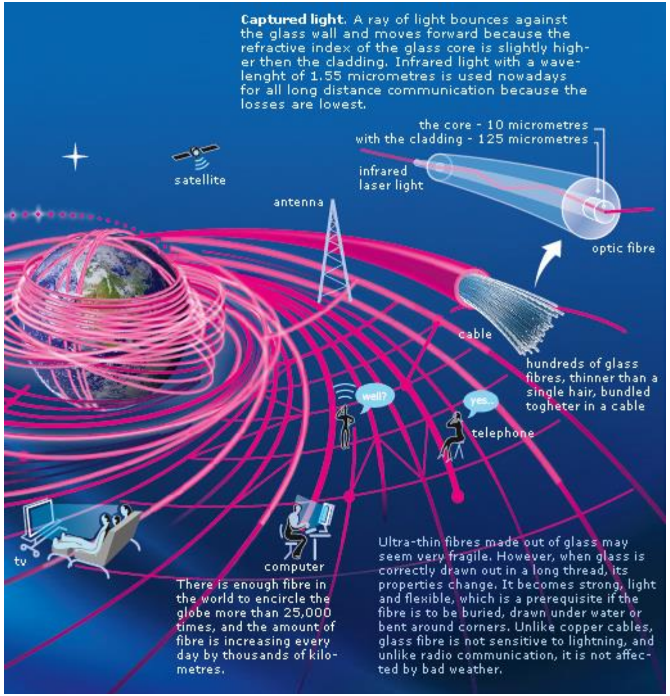
- Attenuation of light through glass depends on the wavelength of the light (as well as on some physical properties of the glass).
- It is defined as the ratio of input to output signal power.
  - Figure on the next slide shows the attenuation in units of decibels per linear kilometer of fiber.

Fiber Optics

- 1.3 micron band
- Bandwidth of 0.17 microns
  - λ_1 = 1.25 microns => $f_1 = 3x10^8/1.25x10^{-6}$
  - λ_2 = 1.35 microns => $f_2 = 3x10^8/1.35x10^{-6}$
  - Bandwidth: $f_2 - f_1$= 30,000 x 10^9 = 30,000 GHz
  - Signal-to-noise Ratio 10 dB

  => 300 Tbps.

Charles K. Kao — Father of Fiber Optics
Nobel Laureate 2009, Former CUHK President

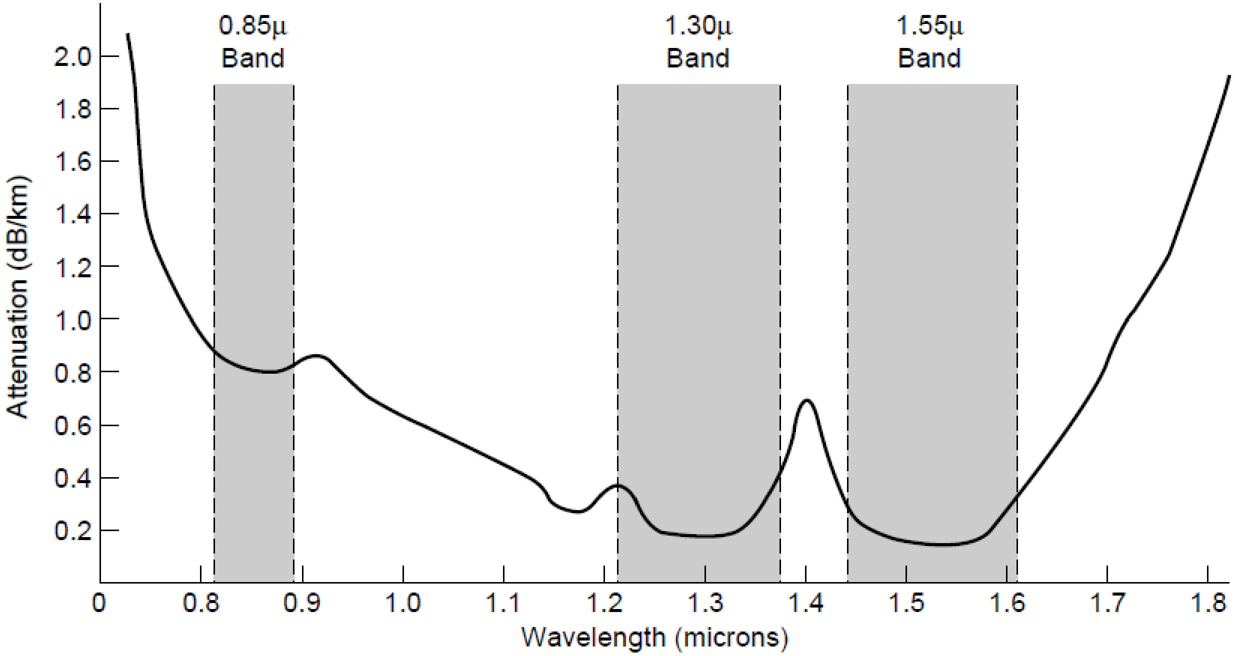


Advantages and Disadvantages

- Noise resistance — external light is blocked by outer jacket
- Less signal attenuation — a signal can run for miles without regeneration (currently, the lowest measured loss is about ~4% or 0.16dB per km)
- Higher bandwidth — currently, limits on data rates come from the signal generation/reception technology, not the fiber itself

- Cost — Optical fibers are expensive
- Installation/maintenance — any crack in the core will degrade the signal, and all connections must be perfectly aligned

Transmission of Light Through Fiber



Attenuation of light through fiber
in the infrared region

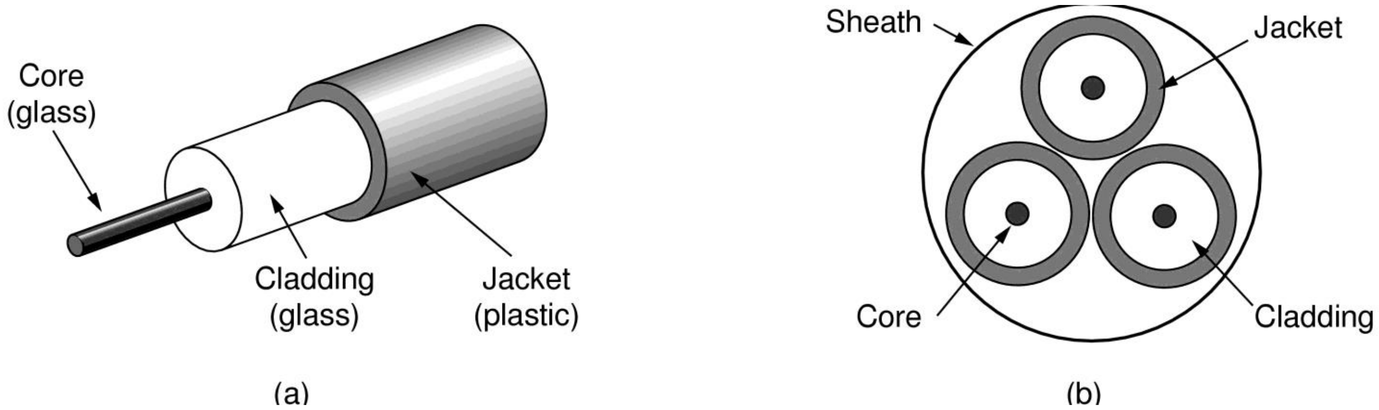
Transmission of Light Through Fiber

- Three wavelengths bands are most commonly used at present for optical communication:
  - 0.85μ
  - 1.30μ and
  - 1.55μ
  - They have bands ranging from 25,000 to 30,000 GHz wide.
- **Chromatic dispersion** – the spreading of wave as it propagates down on a fiber.
- **Solitons** – making the pulses in a special shape related to the reciprocal of the hyperbolic cosine causes nearly all the dispersion effects to cancel out. This was achieved in Lab env.

Fiber Cables

- Similar to Coaxial except they are without the braid. (See figure in the next slide).
- In Multimode fibers, core is typically 50 microns (~ thickness of human hair).
- In Single-mode fibers the core is 8-10 microns.

Fiber Cables (1)



Views of a fiber cable

Fiber Cables

- Core is enclosed in by glass cladding with a lower index of refraction than the core to keep all the light in the core.
- Thin plastic jacked to protect the cladding.
- Fibers are typically grouped in bundles protected by an outer sheath.
- Fiber Cables are:
  - Laid on the ground within a meter of the surface,
  - Transoceanic fiber cables are buried in trenches as the are laid on the see floor.
- Fibers are connected in three different ways:
  1. They can terminated in connectors and be plugged into fiber sockets; connectors lose about 10%-20% of the light but they make it easy to reconfigure systems
  2. Spliced mechanically obtained by carefully cutting ends next to each other and placed within a special sleeve and clamp them in place. Alignment can be improved by passing light through the junction and then making adjustments as necessary.
  3. Two pieces of fiber can be fused (melted) together to form a solid connection. Fused cable can be almost as good as a single drawn fiber. But even here there some amount of loss.

Fiber Cables

- Two types of technologies are used to drive the signals:
  - LED (Light Emitting Diodes), and
  - Semiconductor Lasers.
- They can be tuned in wavelengths by inserting:
  - Febry-Perot interferometers, or
  - Mach-Zehnder interferometers
- Febry-Perot interferometers are simple resonant cavities consisting of two parallel mirrors. The length of the cavity selects out those wavelengths that fit inside an integral number of times.
- Mach-Zehnder interferometers separate the light into two beams. The beams travel slightly different distances. Then they are recombined at the end and are in phase for only certain wavelengths.

Fiber Cables (2)

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

A comparison of semiconductor diodes
and LEDs as light sources

Fiber Cables

- Receiving end of an optical fiber consists of a photodiode, which gives off an electrical pulse when struck by light.
- The response time of photodiodes that convert the signal from the optical to the electrical domain limits data rates to about 100 Gbps.
- Terminal noise is also an issue hence the light should be injected with sufficient energy in order to be detected.
- By making the pulses powerful enough the error rate can be made arbitrarily small.

Fiber Optics vs. Copper Wire

- Fiber has numerous advantages:
  - Higher bandwidths,
  - Low attenuation (50 km vs. 5 km repeaters)
  - Not affected by power surges, electromagnetic interference, or power failures.
  - Not affected by corrosive chemicals in the air.
  - It is thin and lightweight.
  - Cable ducts are full – hence removing copper wires and replacing them with Fiber is good alternative.

Fiber Optics vs. Copper Wire

- Disadvantages of Fiber Optics:
  - Requires highly skilled workers,
  - They can be damaged easily,
  - Two way transmission requires either two different fibers or two different bands of the same fiber.

- Future of all fixed data communication over more than short distances is clearly with fiber.

Wireless Transmission

- The Electromagnetic Spectrum
- Radio Transmission
- Microwave Transmission
- Infrared Transmission
- Light Transmission

Attenuation and loss over air channels, refraction and multipath fading, interferences cross channels or nearby, air interfaces and protocols, antenna design and optimization, power management and optimization

Electromagnetic Spectrum

- Electromagnetic waves were predicted by James Clerk Maxwell in 1865.
- Those waves were observed by Heinrich Hertz in 1887.

- Number of oscillations per second are called **frequency** and a measured by **Hz**.
- The distance between two consecutive maxima (or minima) is called a **wavelength**.

Physics of Electromagnetic Wave

- A *wave* is the propagation of a vibration through the medium.
- Alternating ***compression*** and ***rarefaction*** phases create a ***traveling wave***.

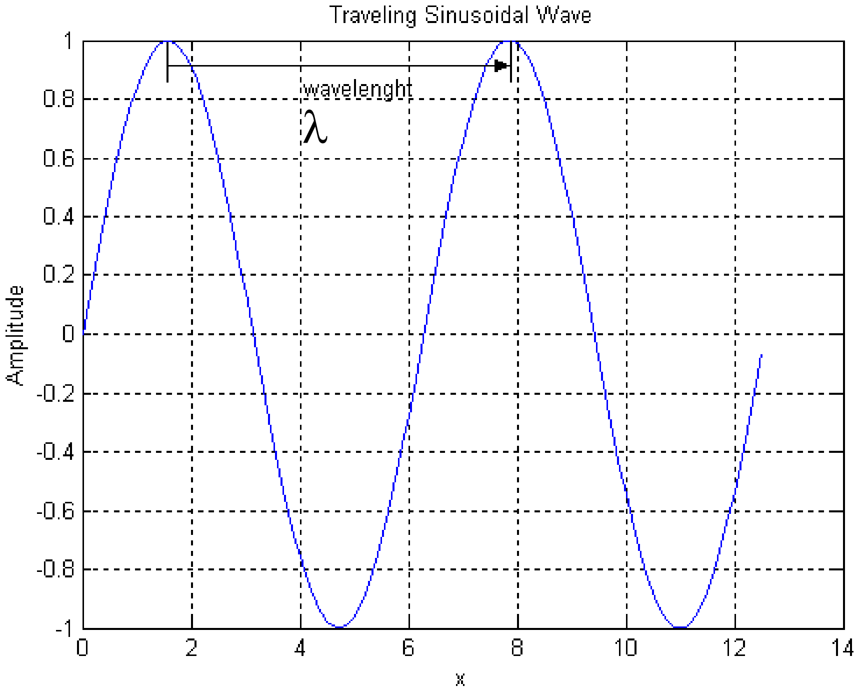
Electromagnetic Wave

- ***Wavelength***,
  - λ: distance between two consecutive peak compressions (or rarefactions) in space (not in time).
  - Wavelength, λ,is also the distance the wave travels in one cycle of the vibration of air particles.
- ***Frequency***,
  - f: is the number of cycles of compression (or rarefaction) of air particle vibration per second.
  - Wave travels a distance of f wavelengths in one second.

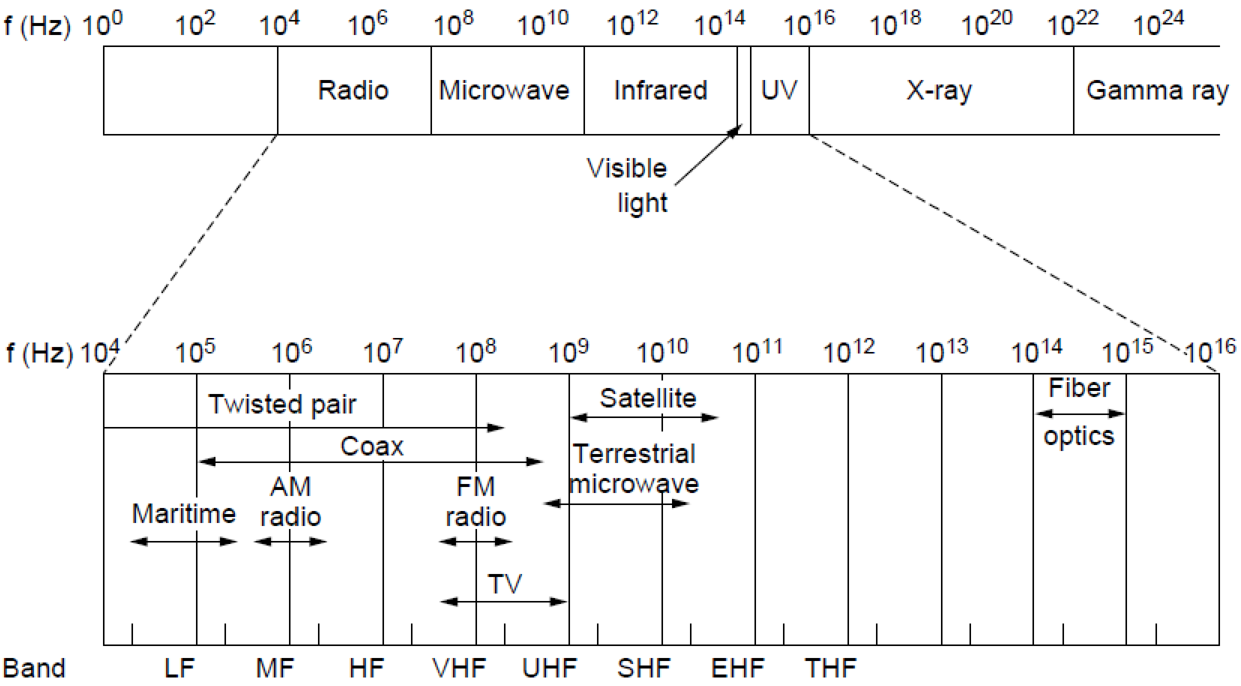
Electromagnetic Wave

- Velocity of the wave in vacuum is constant and is about equal to **speed of light**, c, independent of the wavelength:
  - $c = 3x10^8$ m/sec
  - $c = f\lambda$.
- In other mediums (e.g., air) the speed of wave is about 2/3 of the total speed of light and slightly frequency dependent.

Traveling Wave



The Electromagnetic Spectrum (1)



The electromagnetic spectrum and its uses for communication

Wireless Transmission

- Attenuation and loss over air channels
- refraction and multipath fading
- interferences cross channels or nearby
- air interfaces and protocols
- antenna design and optimization
- power management and optimization

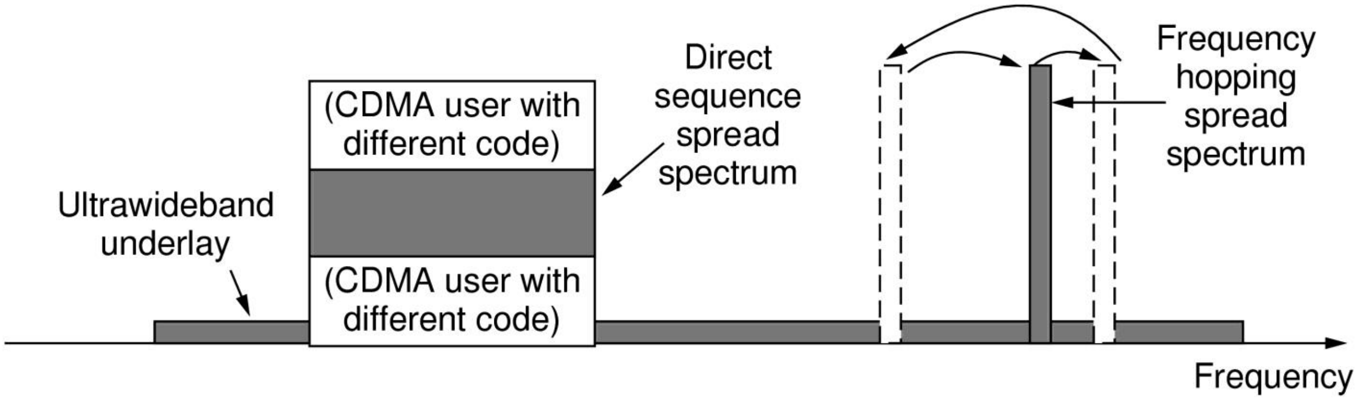
Wireless Transmission

- Most transmission use relatively narrow frequency band ($\Delta f/f_c << 1$):
  - High transmission power
  - Low power consumption
  - Low signal attenuation and distortion, jitter or chromatic dispersion called in optical fiber
  - Reasonable data rates
  - Suitable for dense multiplexing of channels
  - Subject to multipath fading
- Three variations of spread spectrum communication that uses much higher bandwidth:

Wireless Transmission

1. **Frequency hopping spread spectrum**
   - 100’s frequency hop's per second
     - Popular military communications
     - Makes transmissions hard to detect
     - Next to Impossible to jam
     - Offers good resistance to multipath fading
     - High resistance to narrowband fading
   - Used commercially: Bluetooth

The Electromagnetic Spectrum (2)



Spread spectrum and ultra-wideband (UWB) communication

Wireless Transmission

2. **Direct sequence spread spectrum**
   - Uses a code sequence to spread the data signal over a wider frequency band.
     - CDMA (Code Division Multiple Access)
     - High resistance to narrowband fading

Wireless Transmission

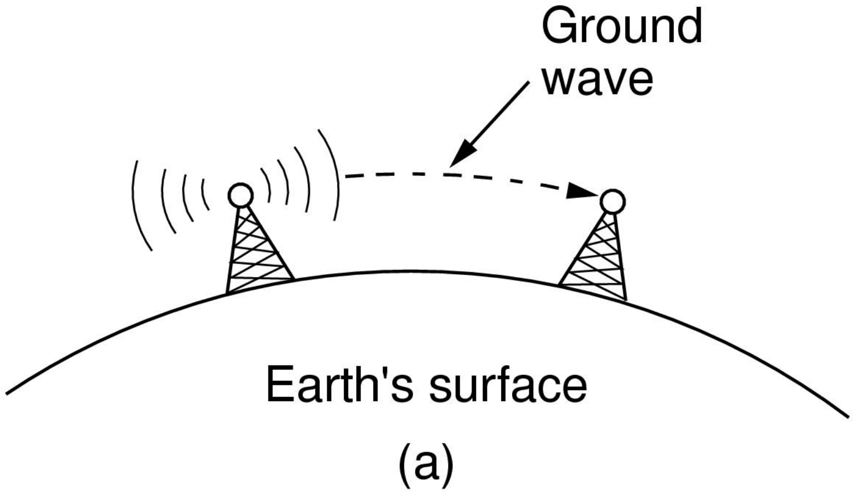
3. Ultra-WideBand (UWB)

- Sends a series of rapid pulses, varying their positions to communicate information.
- The rapid transitions lead to a signal that is spread thinly over a vary wide frequency band.
- Bandwidth of the signal of UWB is at least 500MHz or at least 20% of the center frequency band.
- It is transmitted at a low-power but with very high bandwidth.
- The other high-energy low bandwidth signals do not interfere with it.

Radio Transmission

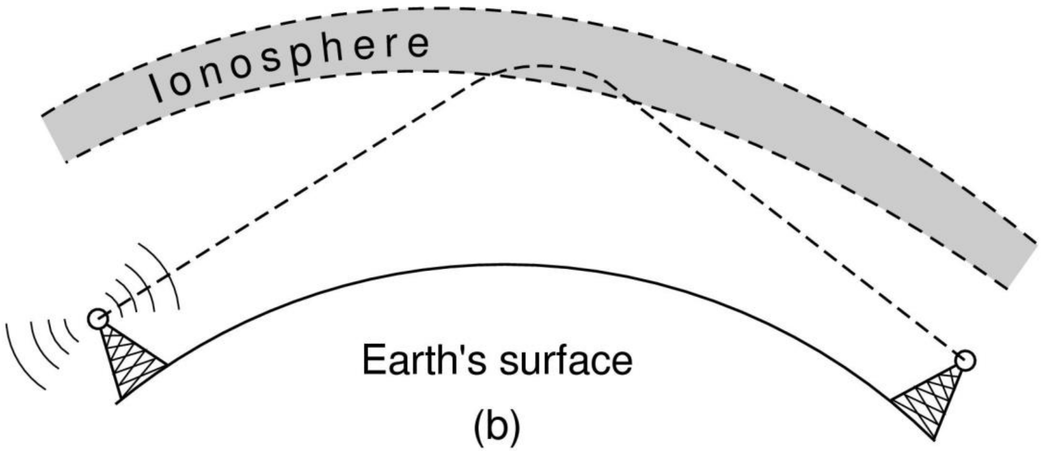
- RF waves are:
  - Easy to generate
  - Can travel a long distance,
  - Penetrate buildings easily,
  - Hence they are used for communication.

Radio Transmission (1)



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

Radio Transmission (2)



In the HF and VHF band, they bounce off the ionosphere.

Microwave Transmission

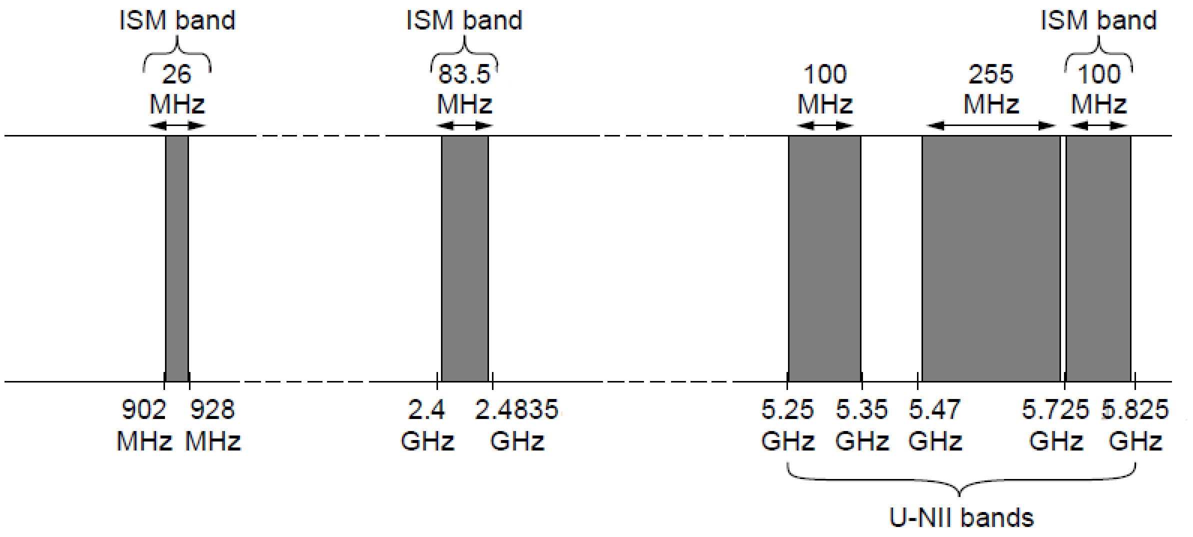
- Above 100 MHz the waves travel in nearly straight line and hence they can be narrowly focused.
- Higher S/N ratio is obtained by parabolic antenna.
- Transmission and Reception antennas must be carefully aligned.
  – Multiple transmissions possible without interference.
- MCI and AT&T built its entire system with microwave communications passing between towers tens of kilometers apart.

Microwave Transmission

- **Multipath fading** is often a serious problem for Microwaves.
- **Multipath fading** – delayed waves may arrive out of phase with the direct wave and can cause cancelation.

- It is a widely used technology.
  - Cost very little to set up a communication channels.
  - It is relatively inexpensive putting up towers (50 km apart) relative to putting a 50 km fiber-optic wire.

Electromagnetic Spectrum

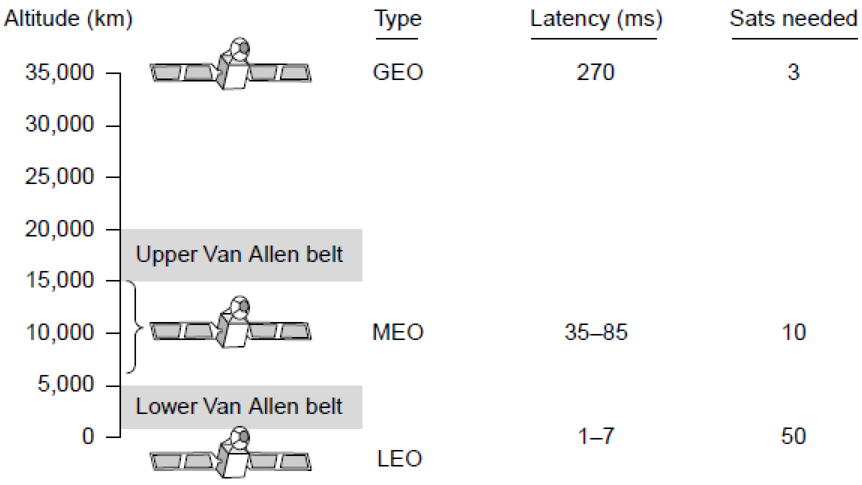


ISM and U-NII bands used in the United States by wireless devices

Communication Satellites

- Geostationary Satellites
- Medium-Earth Orbit Satellites
- Low-Earth Orbit Satellites
- Satellites Versus Fiber

Communication Satellites



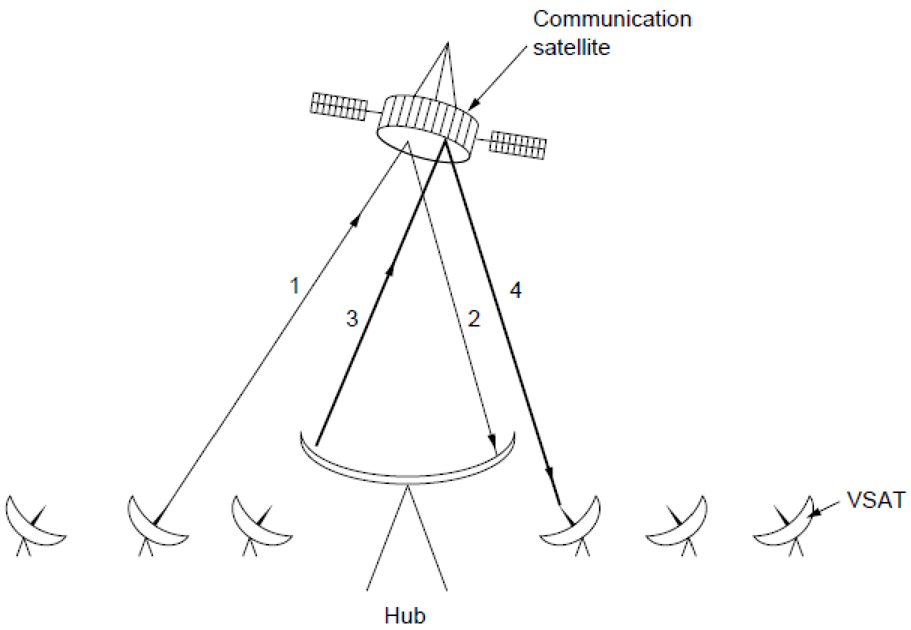
Communication satellites, some properties, including: altitude above earth, round-trip delay time, number of satellites for global coverage.

Geostationary Satellites (1)

Band	Downlink	Uplink	Bandwidth	Problems
L	1.5 GHz	1.6 GHz	15 MHz	Low bandwidth; crowded
S	1.9 GHz	2.2 GHz	70 MHz	Low bandwidth; crowded
C	4.0 GHz	6.0 GHz	500 MHz	Terrestrial interference
Ku	11 GHz	14 GHz	500 MHz	Rain
Ka	20 GHz	30 GHz	3500 MHz	Rain, equipment cost

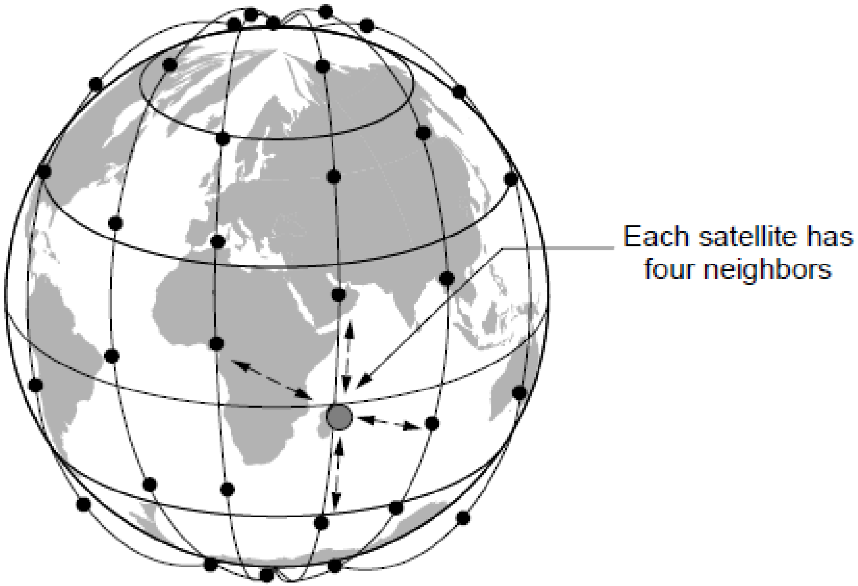
The principal satellite bands

Geostationary Satellites (2)



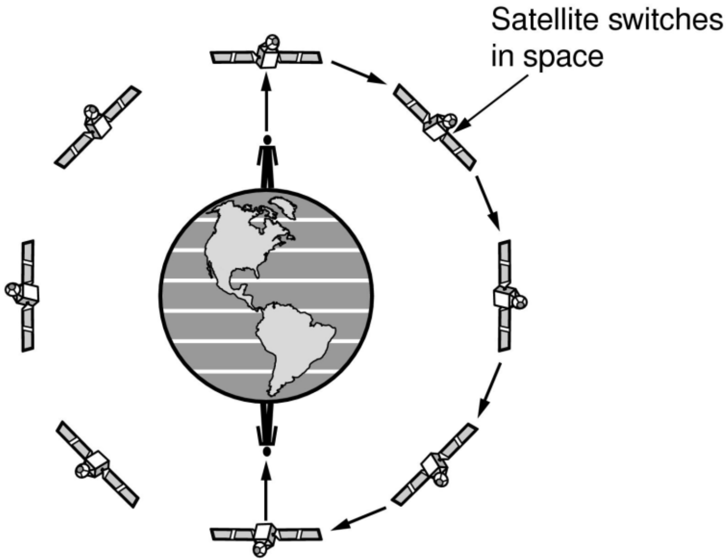
VSATs using a hub.

Low-Earth Orbit Satellites (1)



The Iridium satellites form six necklaces around the earth.

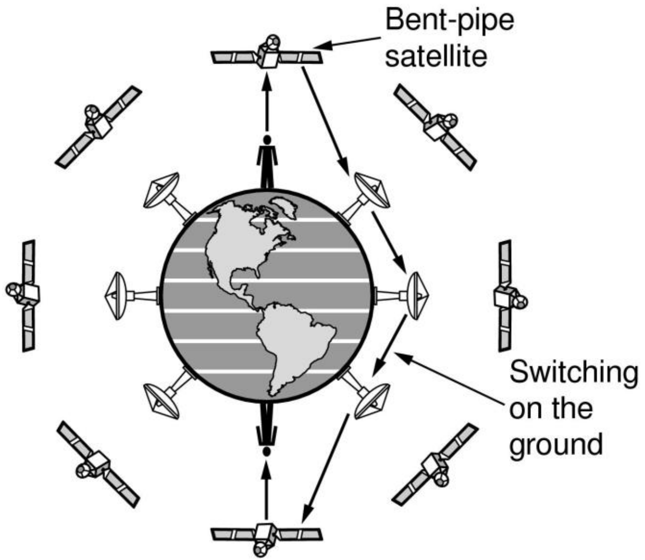
Low-Earth Orbit Satellites (2)



(a)

Relaying in space.

Low-Earth Orbit Satellites (3)



(b)

Relaying on the ground

Network Topology

- Classification of network topology by topology structure has important influence on the design and implementation, function, management, reliability and cost of the whole network.
- What kind of network topology should be selected depends on factors including actual needs, technologies, costs, management and maintanenence.
- The topological structure of computer network system mainly includes bus, star, ring, tree and grid.

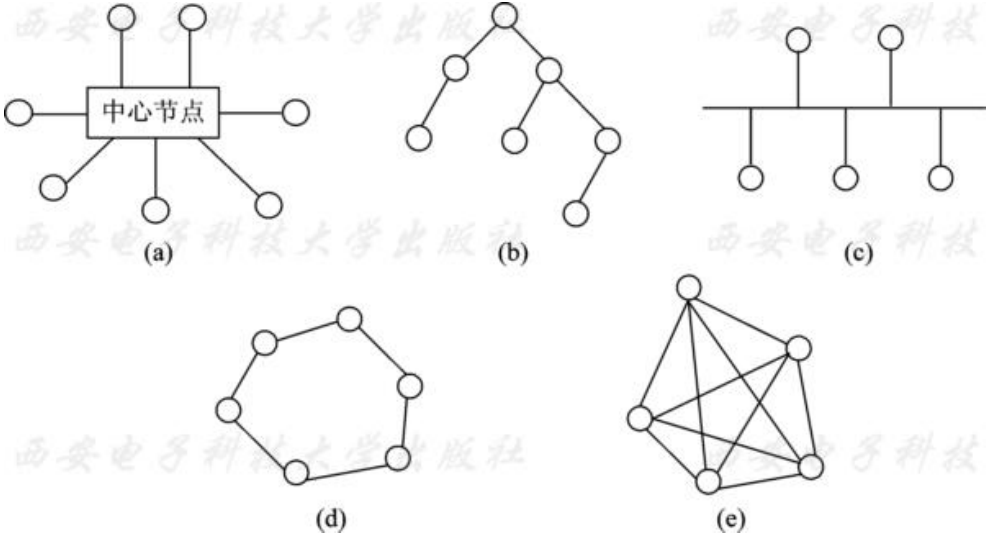


Figure. Schematic diagram of network topology

(a) star structure; (b) tree structure; (c) bus structure; (d) ring structure; (e) network structure

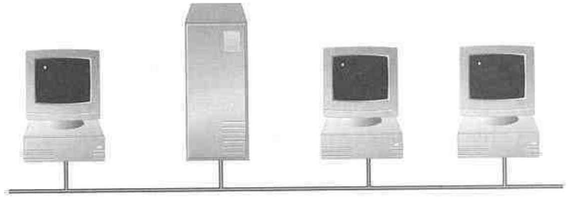
Network Topology

- LANs and small area networks have simple structures, interconnecting and wide area networks are complex.
- Different topologies and structures impact traffic distribution, routing and networking protocols.
- Provide redundancy, multipath routing and fault tolerant capabilities.
- Represented and modeled by graph with nodes and vertex, links and edges, directed or not-directed, weighted or not-weighted.

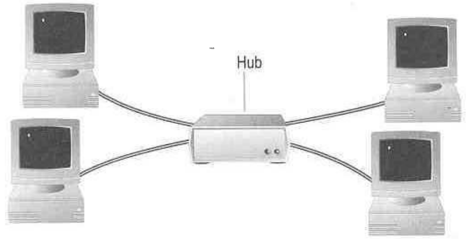
Topology — 3 basic types

- How so many computers are connected together?

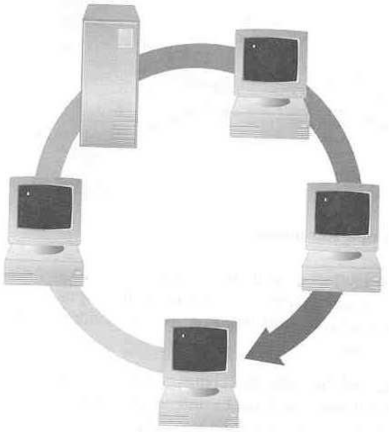
Bus Topology



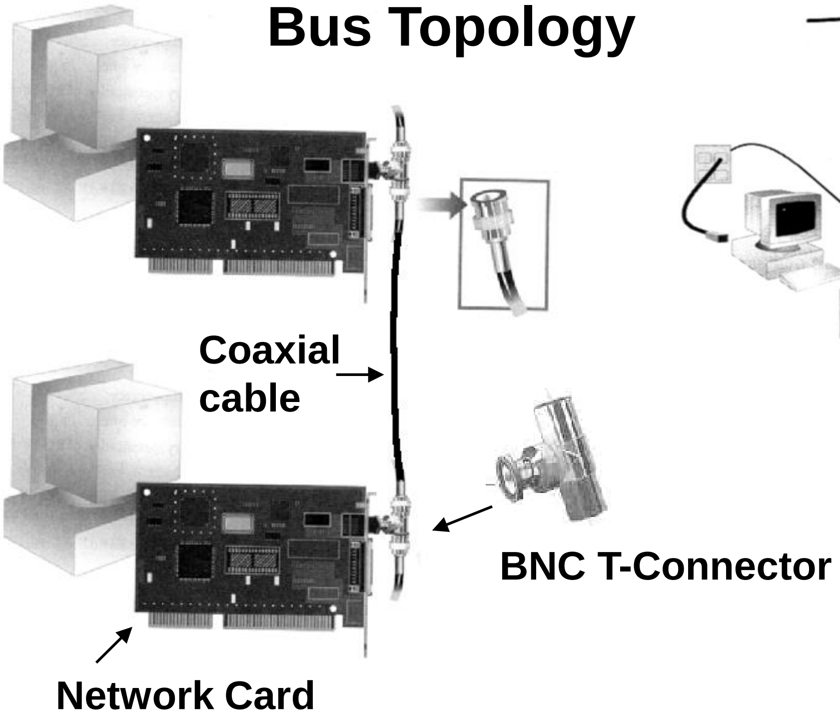
Star Topology

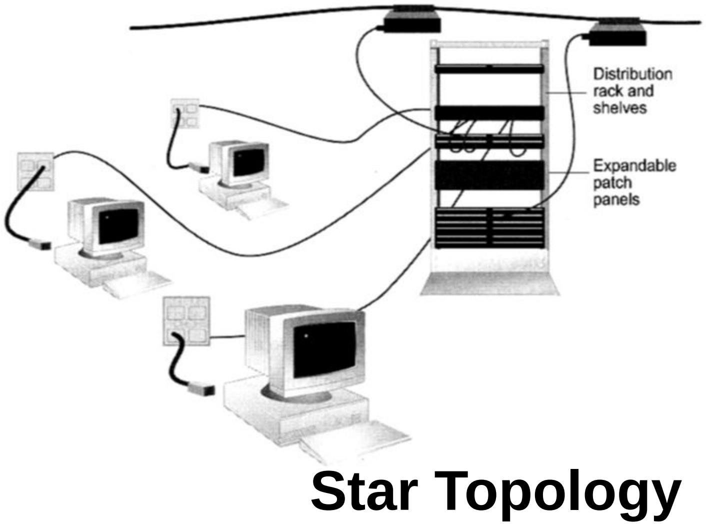


Ring

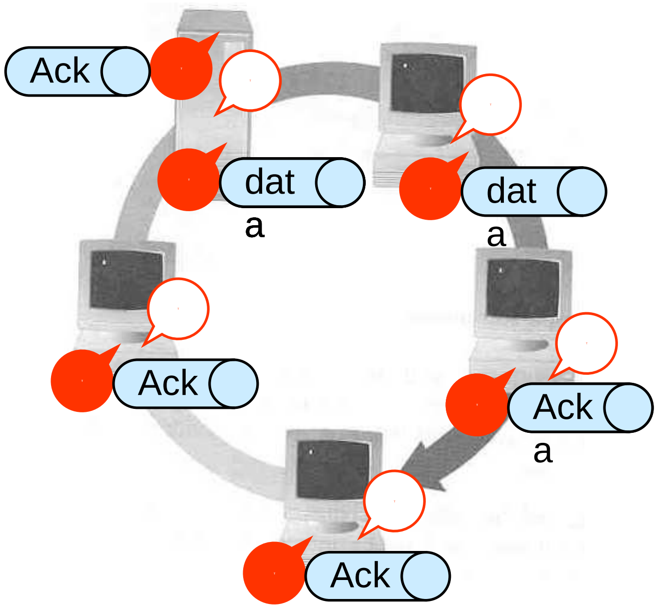


How to construct a network with Bus / Star Topology?





- **Ring Topology**
  - Every computer serves as a repeater to boost signals
  - Typical way to send data:
    - Token passing
      - only the computer who gets the token can send data
  - Disadvantages
    - Difficult to add computers
    - More expensive
    - If one computer fails, whole network fails



Digital Modulation and Multiplexing

- Baseband Transmission
- Passband Transmission
- Frequency Division Multiplexing
- Time Division Multiplexing
- Code Division Multiplexing

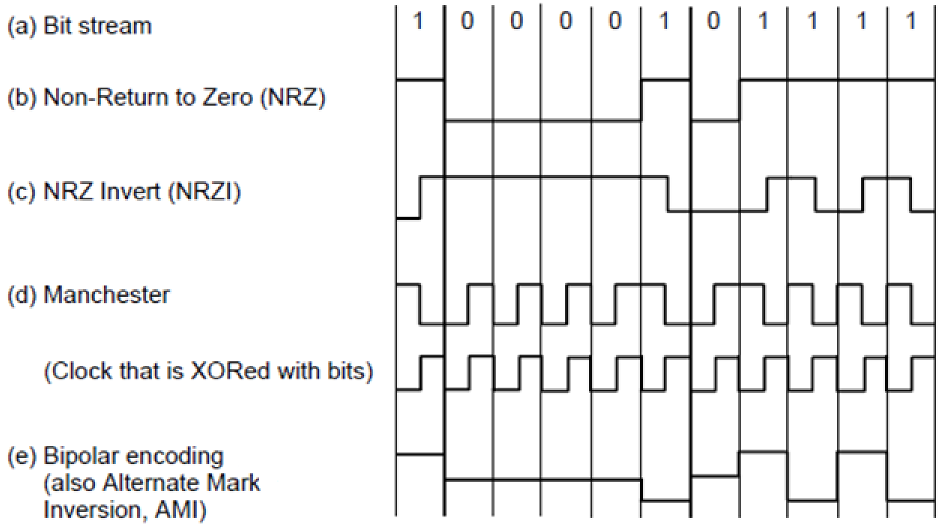
Transmission Encoding

- Encoding is for expediating the channel transmission effectiveness and efficiency
- Variant channel encoding formats employed and adopted, such as NRZ, NRZI, Manchester, and 4B/5B etc.
- The purpose is to assist recovering clock signals from the bit streams and synchronization between the sender and receiver

Transmission Encoding

- The purpose is to assist recovering clock signals from the bit streams and synchronization between the sender and receiver
- Secondly, narrow and limit signal bandwidths for transmission, this helps signal recovery at the receiver side and helps channel multiplexing and transmission line usage efficiency.

Baseband Transmission



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

Bandwidth Efficiency

- Bandwidth is often a limited resource.
  - Higher-frequency signals are increasingly attenuated
  - Higher-frequency signals require faster electronics.
- Using limited bandwidth more efficiently:
  - Using more than 2 signal levels.
  - With four (4) signal levels we could transmit 2 bits with a single **symbol**.
    - Symbol rate vs. Bit rate.

Clock Recovery

- Solving the problem of large number of repeated bits (e.g., 15 zeros) requires accurate clocking with is expensive solution for commodity equipment.
- Strategies:
  - Sending separate clock signal to the receiver.
    - Good solution for a computer buses or short cables in which there several parallel lines.
    - Wasteful solution for most networks links.

Clock Recovery

- Incorporating clock into the signal itself:
  - Manchester encoding is used in classic Ethernet.
  - XOR-ing the clock signal with zero it low to high transition (just like the clock).
  - XOR-ing with 1 it makes it is inverted and makes a high-to-low transition.
  - Downside – 2 times the bandwidth of the original signal.

Clock Recovery

- A different strategy is based on the idea that we should code the data to ensure that there are enough transitions in the signal.
  - NRZ coding will have problems only for long runs of 0’s and 1’s (not for short ones).
  - First step would be to code a 1 as a transition and 0 as a no transition (NRZI – Non-Return-to-Zero Inverted)
  - USB (Universal Serial Bus) standard uses NRZI.
  - Long run of zeros have the same problem as the original.

Clock Recovery

- 4B/5B – every 4 bits is mapped into a 5-bit pattern with a fixed translation table.
  - This table is crafted with no more than three consecutive 0s.
  - Adds 25% overhead (better than 100% as in Manchester Encoding).

Clock Recovery

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

4B/5B mapping.

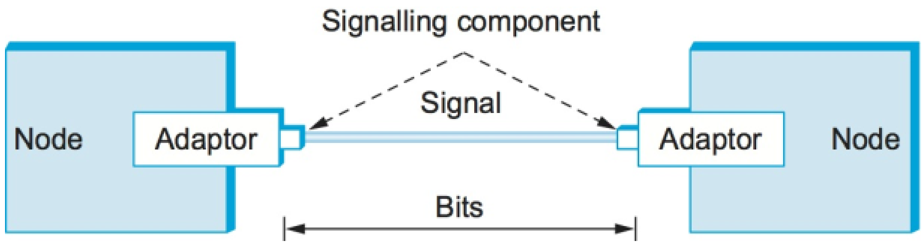


Figure 1. Signals travel between signalling components; bits flow between adaptors.

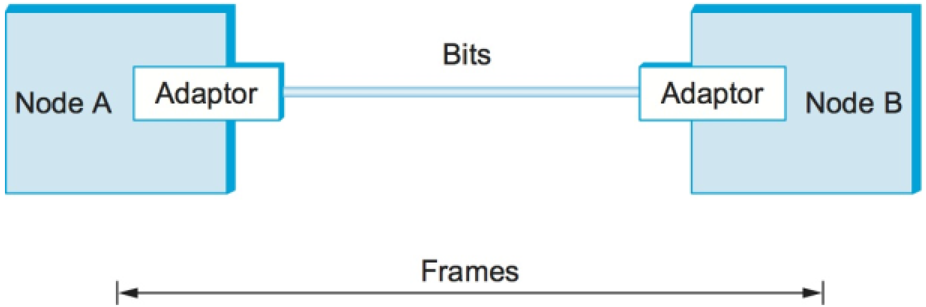


Figure 1. Bits flow between adaptors, frames between hosts.

Clock Recovery

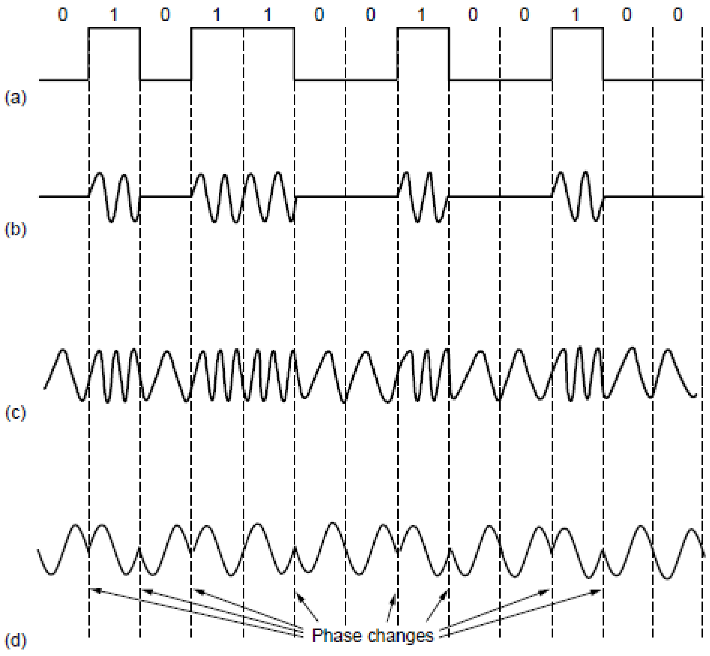
- There are plenty of free combinations in 4B/5B mapping to use it for control signals:
  - 1111 – represents an idle line
  - 1100 – represents start of the frame.
- "Random" Data:
  - Scrambling of the data. need descrambling at the receiving side
  - XOR data with a pseudo random sequence.
  - Additional advantages:
    - No extra bandwidth is need.
    - It is better than original signal (white noise spectrum of random process)
    - Energy is equally spread across all bandwidth uniformly.

Baseband to Passband Signals

1. Shift the Baseband to Passband without using extra energy of the signal.
2. Transmit the Passband signal.
3. In receiver translate back to original Baseband.

- Shifting of a Baseband to a Passband requires modulation.
- Digital modulation can be done on:
  - Amplitude
  - Frequency, or
  - Phase

Passband Transmission (1)

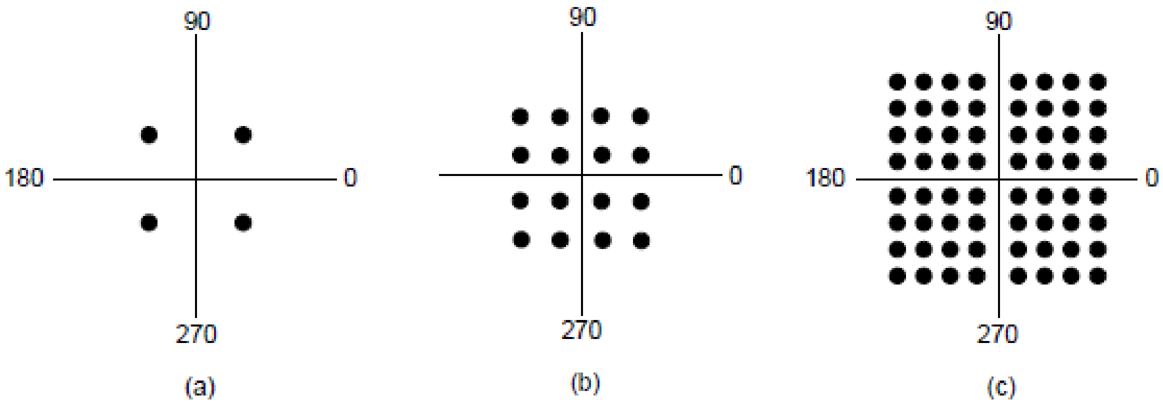


(a) A binary signal. (b) Amplitude shift keying.
(c) Frequency shift keying. (d) Phase shift keying.

Passband Transmission

- Binary Phase Shift Keying (BPSK) –
  - Binary refers to two symbols (0 and 180^o) not that the symbols represent 2 bits.
- Quadrature Phase Shift Keying (QPSK) is the better solution:
  - Using 45^o, 135^o, 225^o, and 315^o to transmit 2 bits of information per symbol.

Passband Transmission (2)

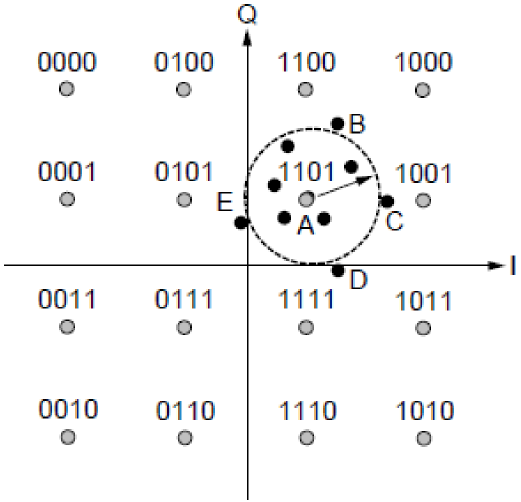


Constellation Diagram
(a) QPSK. (b) QAM-16. (c) QAM-64.

Code Assignment

- It is important to note that the Constellation graphs of the previous slide does not tell how to assign the codes to each combination.
- Example:
  - With QAM-16 if one symbol stood for 0111 and the neighboring symbol stood for 1000 – if the receiver mistakenly picks the adjacent symbol it will cause all of the bits to be wrong.
  - A better coding scheme will allow adjacent symbols to have only one bit difference (Gray Code)

Passband Transmission



When 1101 is sent:

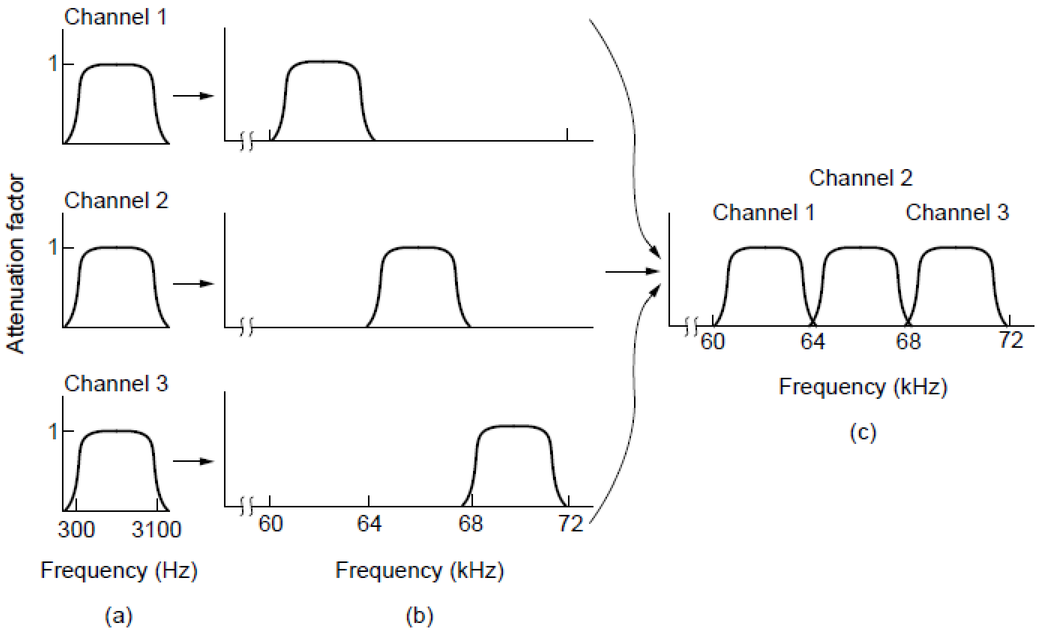
Point	Decodes as	Bit errors
A	1101	0
B	110<u>0</u>	1
C	1<u>0</u>01	1
D	11<u>1</u>1	1
E	<u>0</u>101	1

Gray-coded QAM-16.

Frequency Division Multiplexing

- The modulation schemes allow us to send one signal to convey bits with wired or wireless communication channels.
- It cost the same amount of money to install and maintain a high-bandwidth transmission line as a low-bandwidth between two different offices (e.g., cost is incurred in digging up a trench).
- Multiplexing schemes have been developed to share lines among many signals:
  - Frequency Division Multiplexing (FDM).
  - Telephone networks use guard bands to perform FDM (3100 Hz bandwidth uses 4000 Hz channel).

Frequency Division Multiplexing (1)

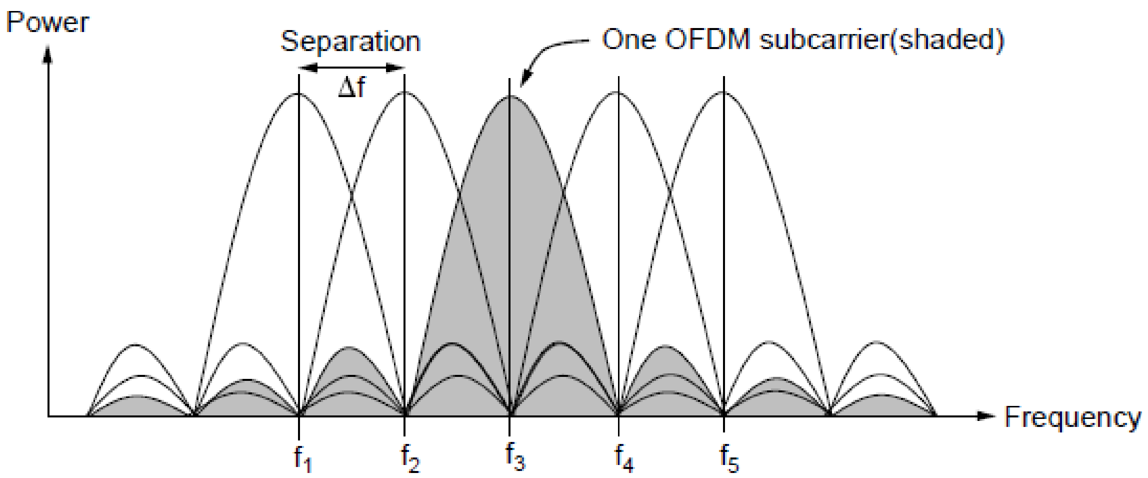


Frequency division multiplexing. (a) The original bandwidths.
(b) The bandwidths raised in frequency.
(c) The multiplexed channel.

Frequency Division Multiplexing

- When sending digital data it is possible to divide spectrum efficiently without using guard bits.
- Orthogonal Frequency Division Multiplexing (OFDM) – the channel bandwidth is divided into many subcarriers that independently send data.
  - Subcarriers are packed tightly together in the frequency domain.
  - Signals from each subcarrier extend into adjacent ones.
  - Frequency response of each subcarrier is designed so that it is zero at the center of the adjacent subcarriers.
  - Sampling is done without interference from their neighbors.

Frequency Division Multiplexing (3)

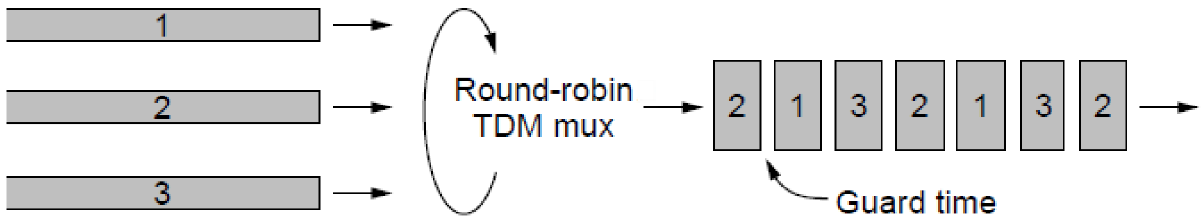


Orthogonal frequency division multiplexing (OFDM).

Time Division Multiplexing

- Time Division Multiplexing (TDM).
  - Round robbing of each user that uses a complete bandwidth to transmit data during the time that was allocated.
- Used in telephone and cellular networks

Time Division Multiplexing



Time Division Multiplexing (TDM).

Code Division Multiplexing

- Code Division Multiplexing (CDM) – works in completely different way from FDM or TDM.
  - Form of a spread spectrum communication approach.
  - This CDM is better know as **CDMA** (**Code Division Multiple Access**).
- TDM – Group of people communicate verbally but at different times.
- FDM – Group of people communicate a different pitches at the same time.
- CDMA – Group of people communicate at the same time but using different languages. Goal is to be able to filter out the langue of choice and consider everything else as noise.

Code Division Multiplexing

- Simplified CDMA:
  - Each bit time is subdivided into short intervals called **chips**.
  - There are typically 64-128 chips per bit.
  - Each station is assigned a unique **m**-bit code called a **chip sequence**.
  - Chip sequence will be represented in parenthesis.
  - We will be using +1 and -1 to represent bits.
  - To transmit
    - 1 bit, a station sends its chip sequence.
    - 0 bit, a station sends inverted chip sequence.
    - No other patterns are permitted.
  - Example m = 8 bits.
    - Station A chip sequence = (-1 -1 -1 +1 +1 -1 +1 +1)
    - `1 – (-1 -1 -1 +1 +1 -1 +1 +1)`
    - `0 – (+1 +1 +1 -1 -1 +1 -1 -1)`

Code Division Multiplexing

- Increasing the amount of information to be send from ***b*** bits/sec to ***mb*** bits/sec means that the bandwidth needed for CDMA is greater by a factor of m than the bandwidth needed for station using FDM.
  - If we have a 1 MHz band available for 100 stations, with FDM each one would have 10 kHz and could send at 10 kbps (assuming 1 bit per Hz).
  - With CDMA, each station uses the full 1 MHz so the chip rate is 100 chips per bit spread the station’s bit rate of 10 kbps across the channel.

Code Division Multiplexing (1)

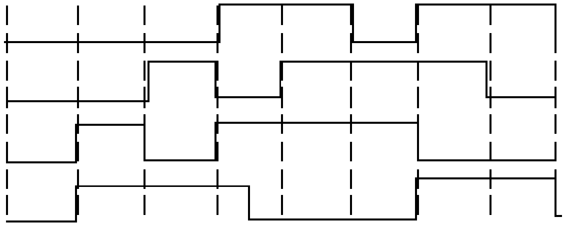
A = (–1 –1 –1 +1 +1 –1 +1 +1)

B = (–1 –1 +1 –1 +1 +1 +1 –1)

C = (–1 +1 –1 +1 +1 +1 –1 –1)

D = (–1 +1 –1 –1 –1 –1 +1 –1)

(a)



(b)

(a) Chip sequences for four stations.

(b) Signals the sequences represent

CDMA

- **S** - indicates the m-chip vector for station S.
- $\bar{\mathbf{S}}$ - indicates the negated signal.
- All paired chip sequences are **orthogonal**, meaning that:
  - **S•T = 0 => Walsh Code** to produce the sequences.

$$\mathbf{S \bullet T} \equiv \frac{1}{m}\sum_{i=1}^{m} S_i T_i = 0$$

– Note that if **S•T** = 0 then so is $\mathbf{S \bullet \bar{T}}$ = 0. Also

$$\mathbf{S \bullet S} \equiv \frac{1}{m}\sum_{i=1}^{m} S_i S_i = \frac{1}{m}\sum_{i=1}^{m} {S_i}^2 = \frac{1}{m}\sum_{i=1}^{m} (\mp 1)^2 = 1, \text{ and}$$

$$\mathbf{S \bullet S} \equiv +1$$

Code Division Multiplexing (2)

$$
\begin{aligned}
S_1 &= C &&= (-1\ +1\ -1\ +1\ +1\ +1\ -1\ -1)\\
S_2 &= B+C &&= (-2\ \ 0\ \ 0\ \ 0\ +2\ +2\ \ 0\ -2)\\
S_3 &= A+\overline{B} &&= (\ \ 0\ \ 0\ -2\ +2\ \ 0\ -2\ \ 0\ +2)\\
S_4 &= A+\overline{B}+C &&= (-1\ +1\ -3\ +3\ +1\ -1\ -1\ +1)\\
S_5 &= A+B+C+D &&= (-4\ \ 0\ -2\ \ 0\ +2\ \ 0\ +2\ -2)\\
S_6 &= A+B+\overline{C}+D &&= (-2\ -2\ \ 0\ -2\ \ 0\ -2\ +4\ \ 0)
\end{aligned}
$$

(c)

$$
\begin{aligned}
S_1 \bullet C &= [1+1-1+1+1+1-1-1]/8 = 1\\
S_2 \bullet C &= [2+0+0+0+2+2+0+2]/8 = 1\\
S_3 \bullet C &= [0+0+2+2+0-2+0-2]/8 = 0\\
S_4 \bullet C &= [1+1+3+3+1-1+1-1]/8 = 1\\
S_5 \bullet C &= [4+0+2+0+2+0-2+2]/8 = 1\\
S_6 \bullet C &= [2-2+0-2+0-2-4+0]/8 = -1
\end{aligned}
$$

(d)

(a) Six examples of transmissions.

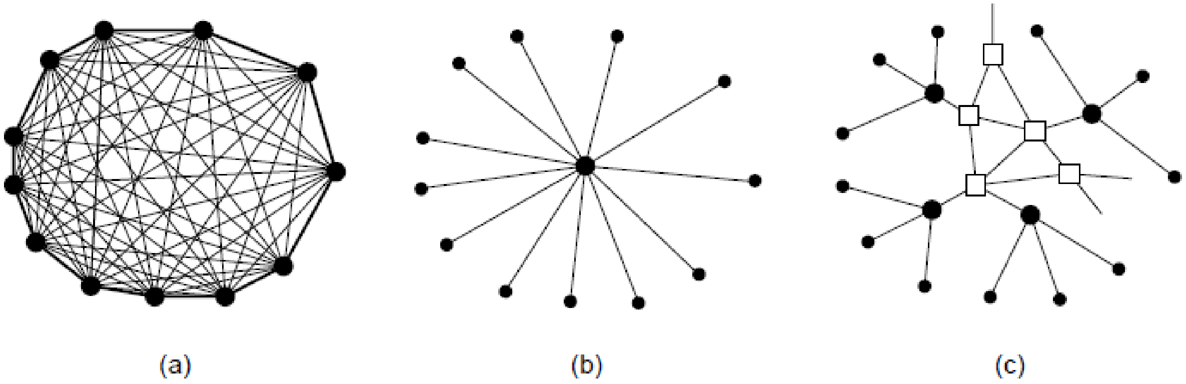
(b) Recovery of station C's

PUBLIC SWITCHED TELEPHONE SYSTEM

The Public Switched Telephone Network

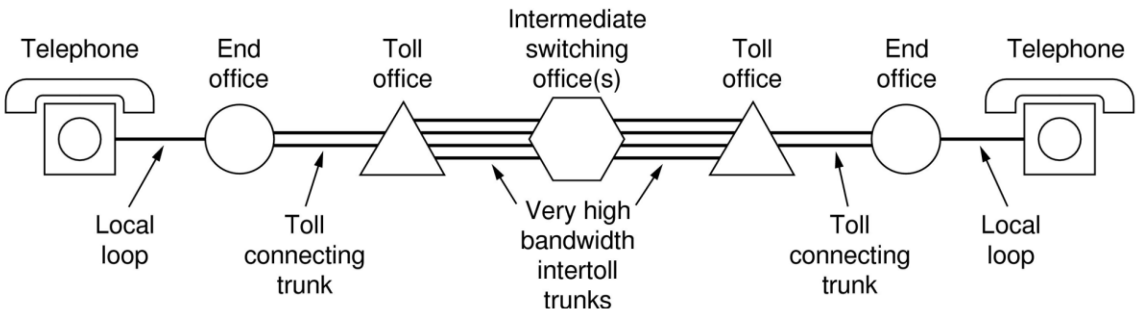
- Structure of the telephone system
- Local loop: modems, ADSL, and fiber
- Trunks and multiplexing
- Switching

Structure of the Telephone System (1)



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

Structure of the Telephone System (2)



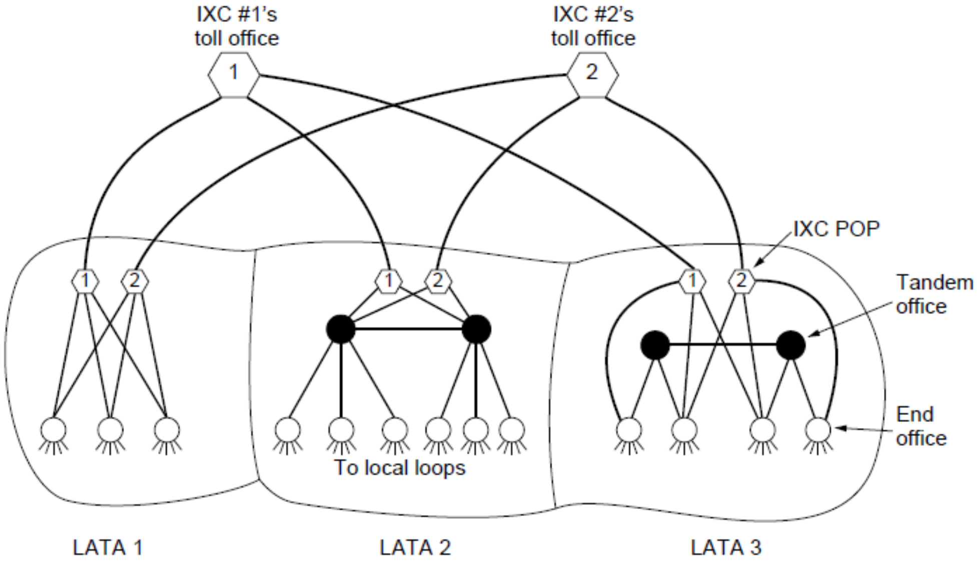
A typical circuit route for a long-distance call.

Structure of the Telephone System (3)

Major Components

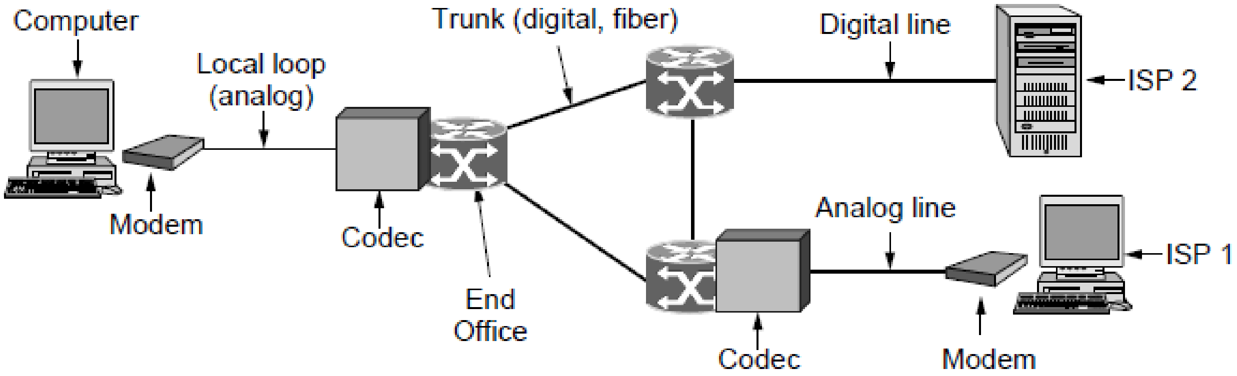
1. Local loops analog twisted pairs to houses, businesses).
2. Trunks (digital fiber optic links between switching offices).
3. Switching offices (calls are moved from one trunk to another).

The Hierarchy of Telephone System



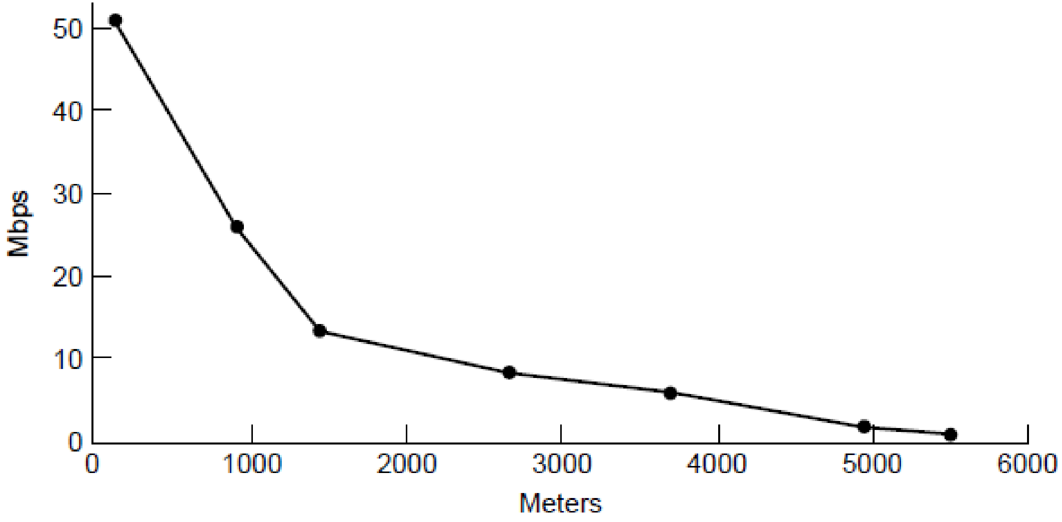
The relationship of LATAs, LECs, and IXCs. Circles are LEC switching offices. Hexagons belong to IXC whose number is in it.

Telephone Modems



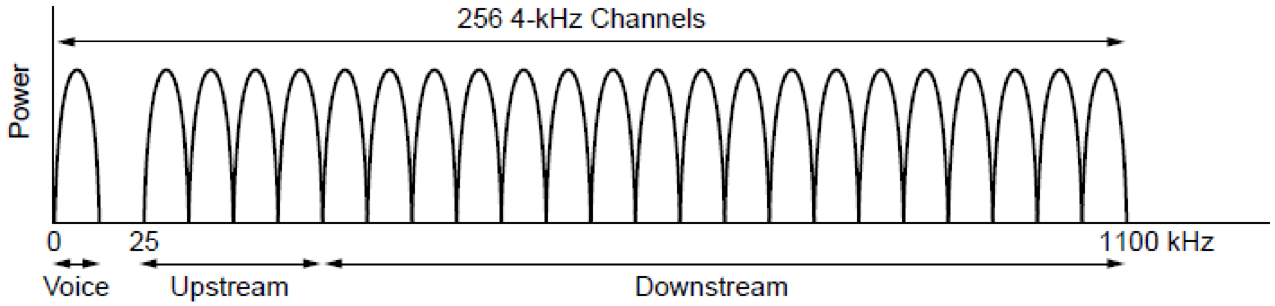
Use of both analog and digital transmission for computer-to-computer call. Conversion done by modems and codecs.

Digital Subscriber Lines (1)



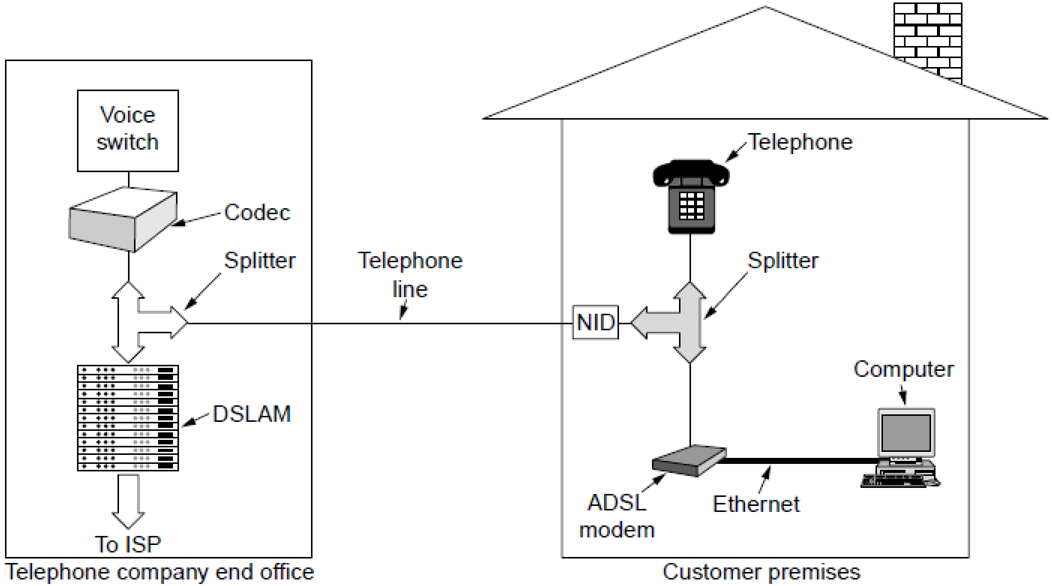
Bandwidth versus distance over Category 3 UTP for DSL.

Digital Subscriber Lines (2)



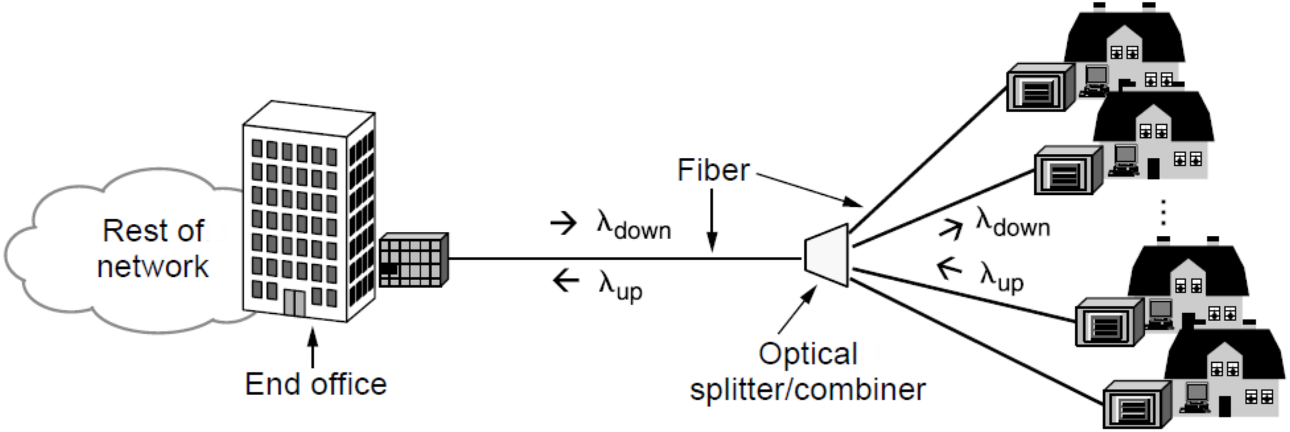
Operation of ADSL using discrete multitone modulation.

Digital Subscriber Lines (3)



A typical ADSL equipment configuration.

Fiber To The Home



Passive optical network for Fiber To The Home.

Digitizing Voice Signals

- Frequency Division Multiplexing (FDM) was used for many years to multiplex 4k Hz voice channels.
  - 12 calls (60 kHz – 108 kHz) make a **group**
  - 5 groups (60 calls) make a **supergroup**
  - **FDM requires analog circuitry.**
- Time Division Multiplexing (TDM)
  - Can be handled entirely by digital electronics.
  - Conversion is needed from analog to digital in the end office.
  - Digitalization is carried out at the end office by the **codec sampling 8000 samples per second (125 μsec/sample).**
  - **PCM (Pulse Code Modulation) - Data rate of uncompressed voice-grade telephone call is 8 bits every 125 μsec or 64 kbps**

Digital Telephone Communication System

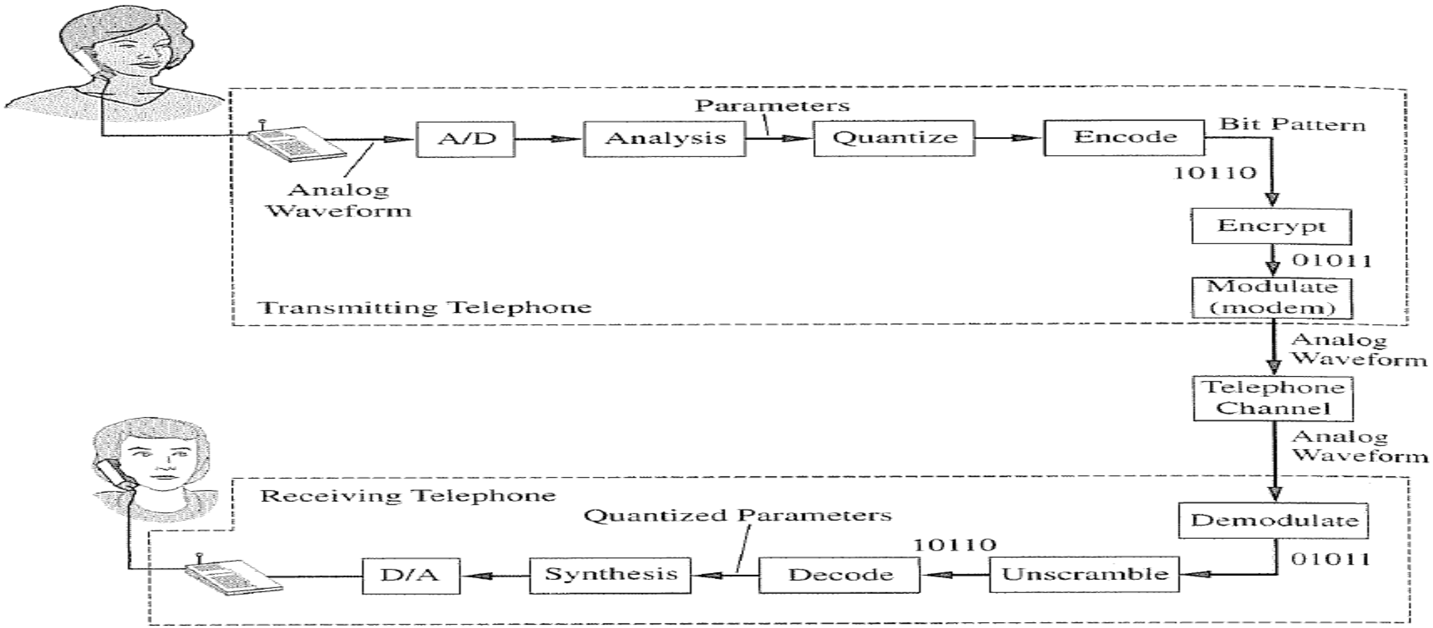


Figure 12.1 An example digital telephone communication system.

Uniform Quantization

Fundamentals

- Scalar Quantization Example:
  - Assume there M=4 reconstruction levels.
  - Amplitude of the input signal x[n] falls in the range of [0,1]
  - Decision levels and Reconstruction levels are equally spaced:
    - Decision levels are [0,1/4,1/2,3/4,1]
    - Reconstruction levels assumed to be [0,1/8,3/8,5/8,7/8]
  - Figure 12.4 in the next slide.

Example of Uniform 2-bit Quantizer

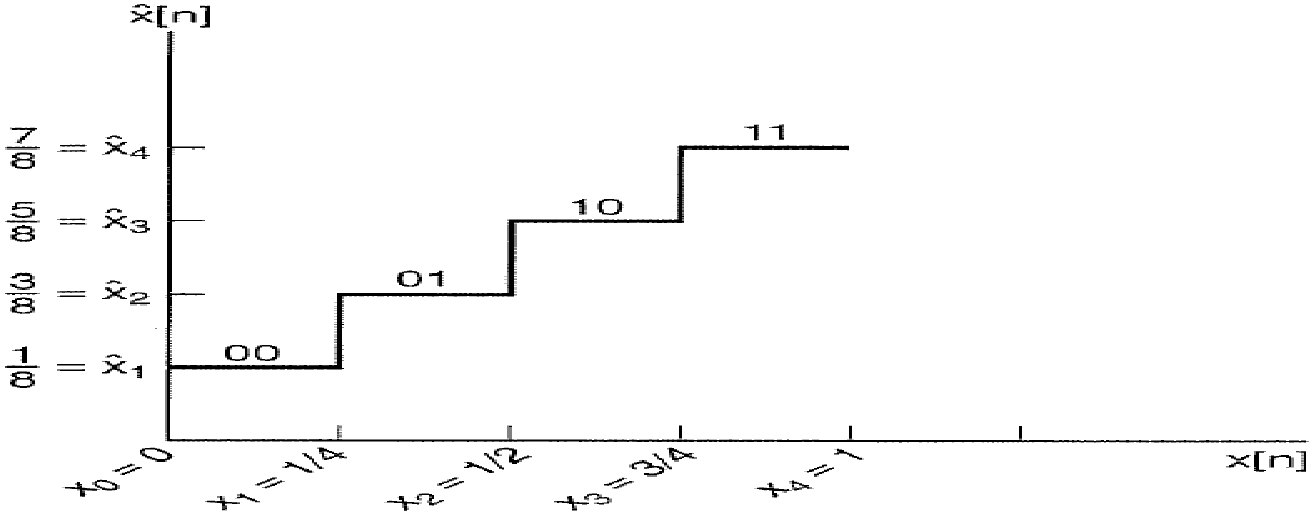
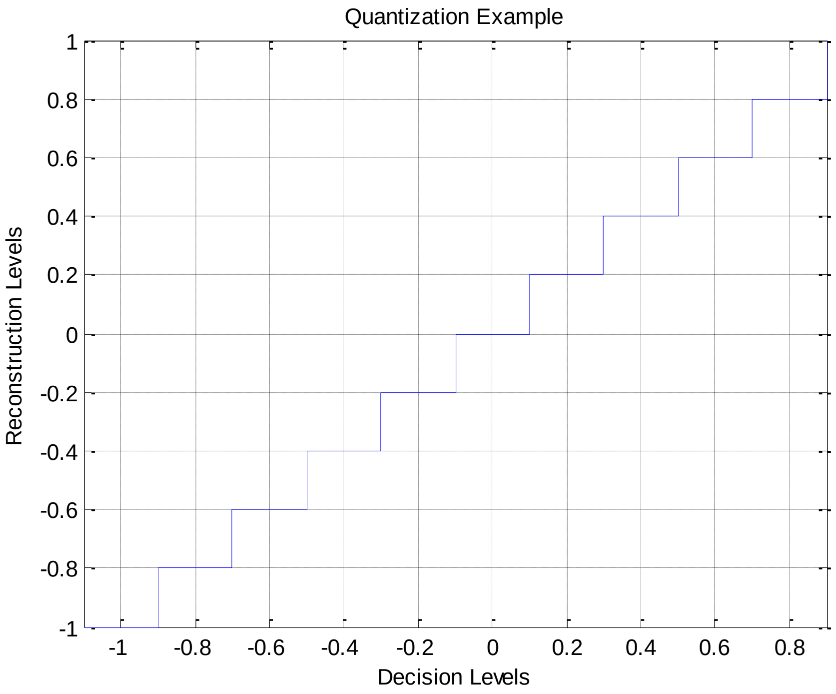
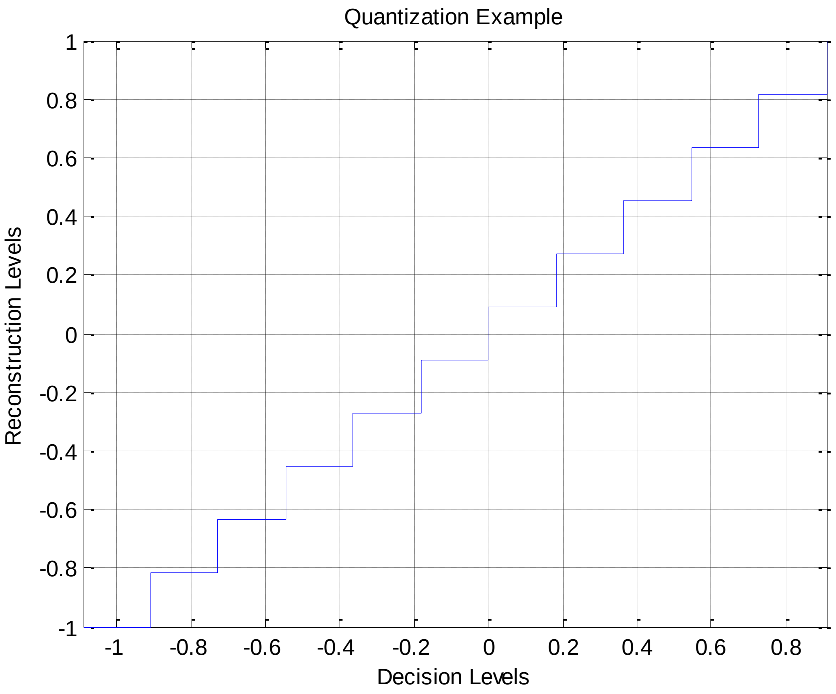


Figure 12.4 An example of uniform 2-bit quantization where the reconstruction and decision levels are uniformly spaced. The number of reconstruction levels $M = 4$ and the input falls in the range [0, 1].

Uniform Quantization



Uniform Quantization



Uniform Quantizer

- A uniform quantizer is one whose decision and reconstruction levels are uniformly spaced. Specifically:

$$x_i - x_{i-1} = \Delta, \qquad 1 \le i \le M$$

$$\hat{x}_i = \frac{x_i + x_{i-1}}{2}, \qquad 1 \le i \le M$$

- Δ is the step size equal to the spacing between two consecutive decision levels which is the same spacing between two consecutive reconstruction levels (Exercise 12.1).
- Each reconstruction level is attached a ***symbol*** – the ***codeword***. Binary numbers typically used to represent the quantized samples (Figure 12.4).

Uniform Quantizer

- ***Codebook***: Collection of codewords.
- In general with B-bit binary codebook there are 2^B different quantization (or reconstruction) levels.
- ***Bit rate*** is defined as the number of bits B per sample multiplied by sample rate f_s:

$$I = Bf_s$$

- Decoder inverts the coder operation taking the codeword back to a quantized amplitude value (e.g., 01 → $\hat{x}_2$).
- Often the goal of speech coding/decoding is to maintain the bit rate as low as possible while maintaining a required level of quality.
- Because sampling rate is fixed for most applications this goal implies that the bit rate be reduced by decreasing the number of bits per sample

Uniform Quantizer

- Designing a uniform scalar quantizer requires knowledge of the maximum value of the sequence.
- Typically the range of the speech signal is expressed in terms of the standard deviation of the signal.
  - Specifically, it is often assumed that: $-4\sigma_x \le x[n] \le 4\sigma_x$ where σ_x is signal's standard deviation.
  - Under the assumption that speech samples obey Laplacian pdf there are approximately 0.35% of speech samples fall outside of the range: $-4\sigma_x \le x[n] \le 4\sigma_x$.
  - Assume B-bit binary codebook $\Rightarrow 2^B$.
  - Maximum signal value $x_{max} = 4\sigma_x$.

Uniform Quantizer

- For the uniform quantization step size Δ we get:

$$\frac{2x_{\max}}{\Delta} = 2^B \;\Rightarrow\; 2x_{\max} = \Delta 2^B \;\Rightarrow\; \Delta = \frac{2x_{\max}}{2^B}$$

- Quantization step size Δ relates directly to the notion of ***quantization noise***.

Quantization Noise

- Two classes of quantization noise:
  - ***Granular Distortion***
  - ***Overload Distortion***

Granular Distortion

$$\hat{x}[n] = x[n] + e[n]$$

- x[n] unquantized signal and e[n] is the quantization noise.
- For given step size Δ the magnitude of the quantization noise e[n] can be no greater than $\Delta/2$, that is:

$$-\frac{\Delta}{2} \leq e[n] \leq \frac{\Delta}{2}$$

- Figure 12.5 depicts this property were:

$$e[n] = \hat{x}[n] - x[n]$$

Quantization Noise

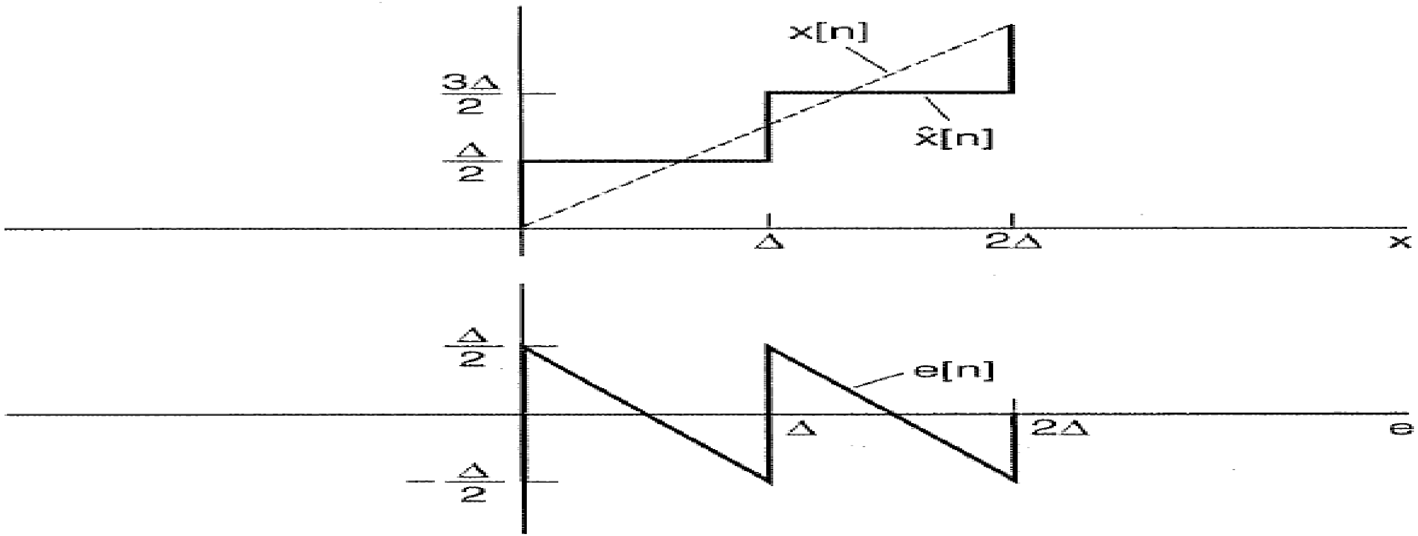
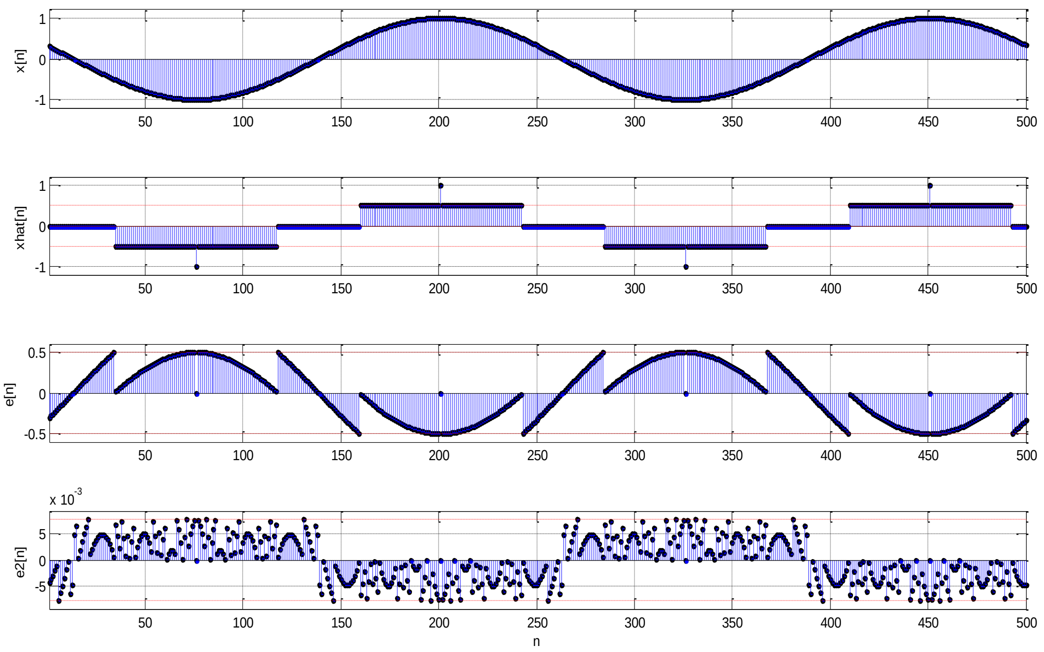


Figure 12.5 Quantization noise for a linearly changing input $x[n] = n$. The quantization noise is given by $e[n] = x[n] - \hat{x}[n]$, where $\hat{x}[n] = Q(x[n])$, with Q the quantization operator. For this case of a linearly-changing input, the quantization noise is seen to be signal-dependent.

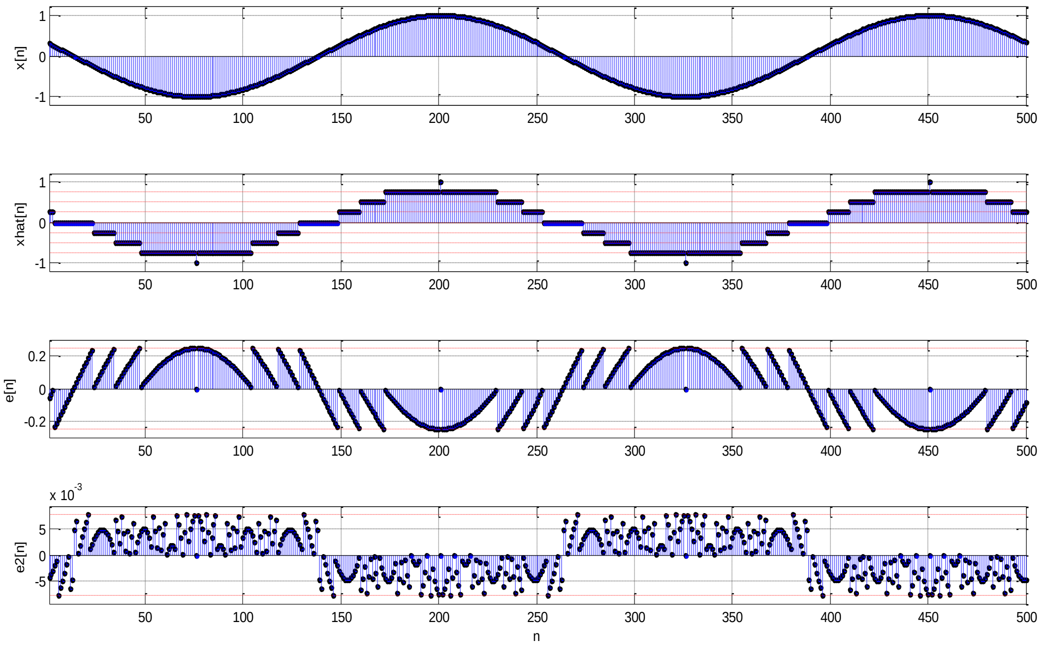
Overload Distortion

- Maximum-value constant:
  - $x_{max} = 4\sigma_x$ $(4\sigma_x \leq x[n] \leq 4\sigma_x)$
  - For Laplacian pdf, 0.35% of the speech samples fall outside the range of the quantizer.
  - ***Clipped*** samples incur a quantization error in excess of $\pm\Delta/2$.
  - Due to the small number of clipped samples it is common to neglect the infrequent large errors in theoretical calculations.

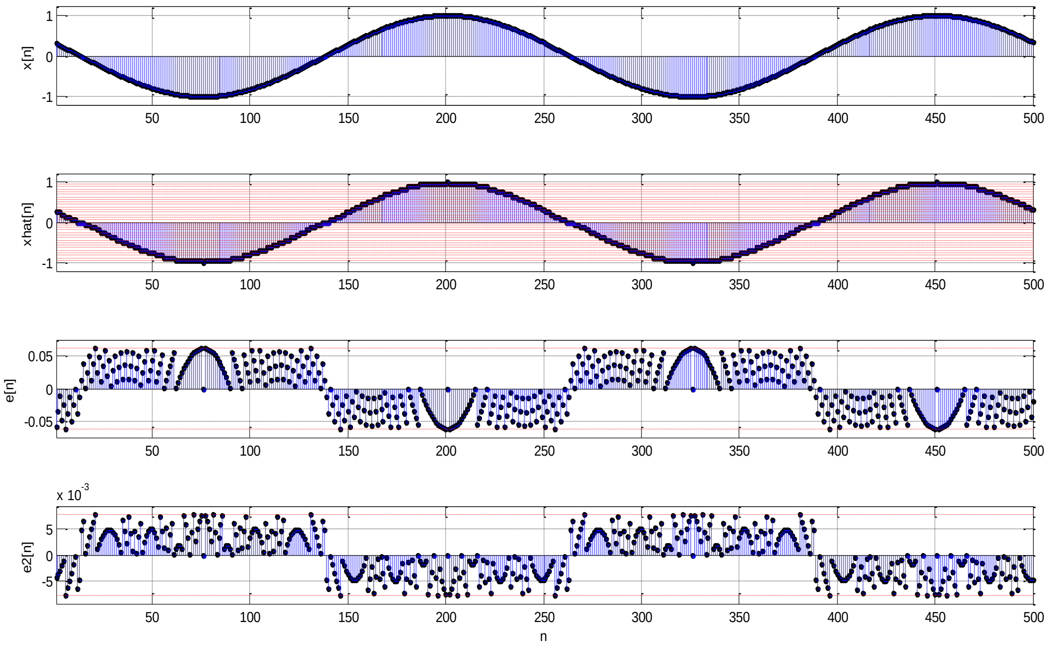
Quantization2(10, 500, 2);



Quantization2(10, 500, 3);



Quantization2(10, 500, 5);



Quantization Noise

- ***Statistical Model of Quantization Noise***
  - Desired approach in analyzing the quantization error in numerous applications.
  - Quantization error is considered an ergodic white-noise random process.
  - The autocorrelation function of such a process is expressed as:

$$r_e[m] = E(e[n]e[n+m])$$

$$r_e[m] = \begin{cases} \sigma_e^2 & , m = 0 \\ 0 & , m \neq 0 \end{cases}$$

Quantization Error

- Previous expression states that the process is uncorrelated.
- Furthermore, it is also assumed that the quantization noise and the input signal are uncorrelated, i.e.,
  - $E(x[n]e[n+m])=0, \ \forall m$.
- Final assumption is that the pdf of the quantization noise is uniform over the quantization interval:

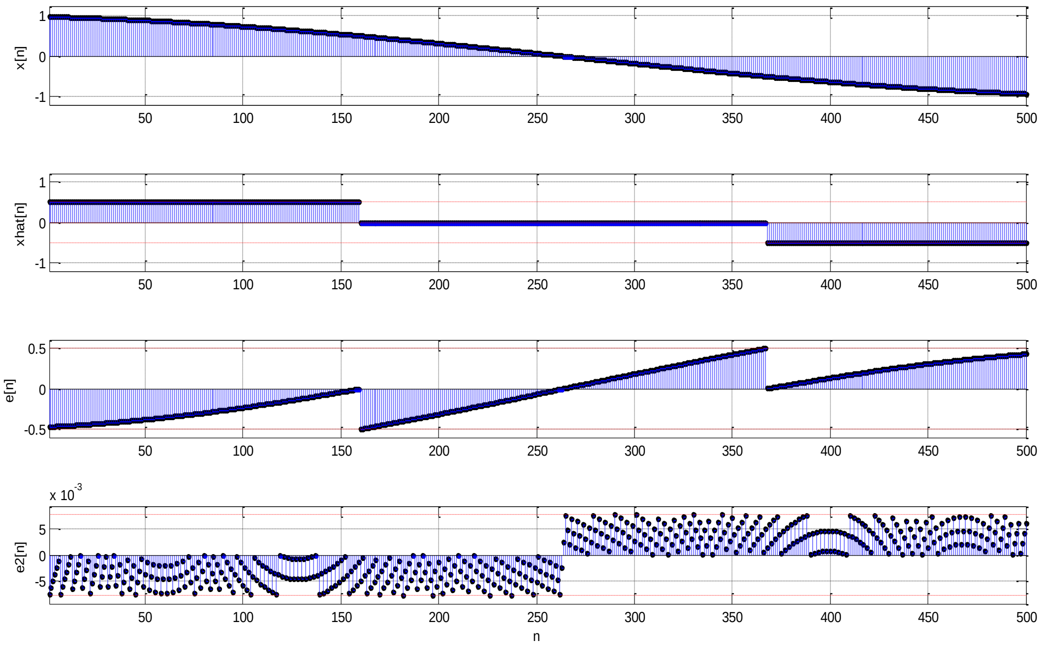
$$p_e(e) = \begin{cases} \dfrac{1}{\Delta} & , -\dfrac{\Delta}{2} \le e \le \dfrac{\Delta}{2} \\ 0 & , otherwise \end{cases}$$

Quantization Error

- Stated assumptions are not always valid.
  - Consider a slowly varying – linearly varying signal ⇒ then e[n] is also changing linearly and is signal dependent (see Figure 12.5 in the previous slide).
  - Correlated quantization noise can be annoying.
  - When quantization step Δ is small then assumptions for the noise being uncorrelated with itself and the signal are roughly valid when the signal fluctuates rapidly among all quantization levels.
  - Quantization error approaches a white-noise process with an impulsive autocorrelation and flat spectrum.

- One can force e[n] to be white-noise and uncorrelated with x[n] by adding white-noise to x[n] prior to quantization.

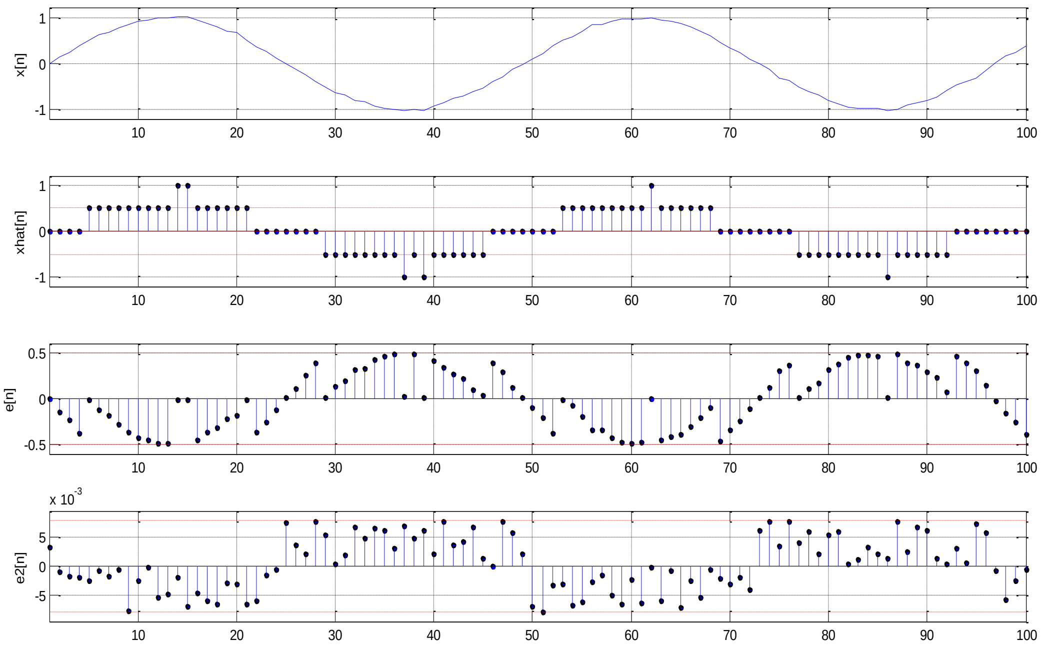
Quantization Error



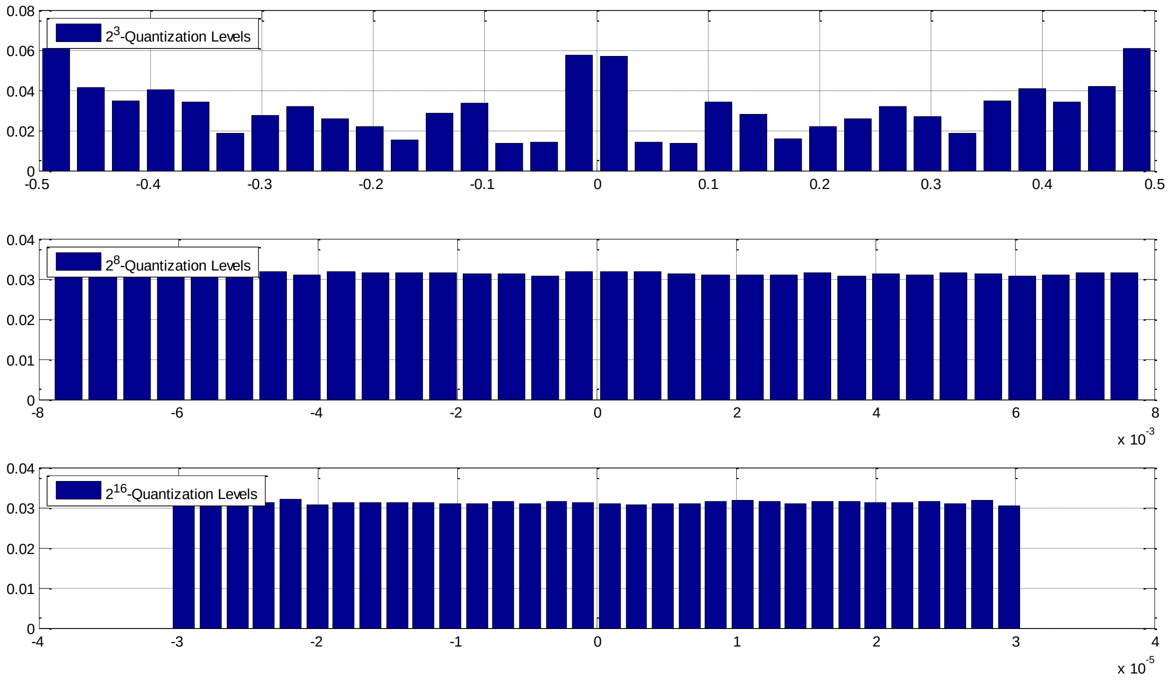
Quantization Error

- Process of adding white noise is known as ***Dithering***.
- This decorrelation technique was shown to be useful not only in improving the perceptual quality of the quantization noise but also with image signals.
- ***Signal-to-Noise Ratio***
  - A measure to quantify severity of the quantization noise.
  - Relates the strength of the signal to the strength of the quantization noise.

Quantization3(sig, 48000, 100, 2, 32);



Quantization3(sig, 48000, 100, 2, 32);



Quantization Error

- SNR is defined as:

$$SNR = \frac{\sigma_x^2}{\sigma_e^2} = \frac{E\left(x^2[n]\right)}{E\left(e^2[n]\right)} \approx \frac{\frac{1}{N}\sum_{n=0}^{N-1} x^2[n]}{\frac{1}{N}\sum_{n=0}^{N-1} e^2[n]}$$

- Given assumptions for
  - Quantizer range: $2x_{max}$, and
  - Quantization interval: $\Delta = 2x_{max}/2^B$, for a B-bit quantizer
  - Uniform pdf, it can be shown that (see Exercise 12.2):

$$\sigma_e^2 = \frac{\Delta^2}{12} = \frac{\left(2x_{\max}/2^B\right)^2}{12} = \frac{x_{\max}^2}{(3)2^{2B}}$$

Quantization Error

- Thus SNR can be expressed as:

$$SNR = \frac{\sigma_x^2}{\sigma_e^2} = \sigma_x^2 \left(\frac{(3)2^{2B}}{x_{\max}^2} \right) = \frac{(3)2^{2B}}{\left(x_{\max} / \sigma_x \right)^2}$$

- Or in decibels (dB) as:

$$SNR(dB) = 10 \log_{10} \left(\frac{\sigma_x^2}{\sigma_e^2} \right) = 10 \left(\log_{10} 3 + 2B \log_{10} 2 \right) - 20 \log_{10} \frac{x_{\max}}{\sigma_x}$$

$$\approx 6B + 4.77 - 20 \log_{10} \frac{x_{\max}}{\sigma_x}$$

- Because $x_{max} = 4\sigma_x$, then

$$\boxed{SNR(dB) \approx 6B - 7.2}$$

Quantization Error

- Presented quantization scheme is called ***pulse code modulation*** (PCM).
- B-bits per sample are transmitted as a codeword.
- Advantages of this scheme:
  - It is ***instantaneous*** (no coding delay)
  - Independent of the signal content (voice, music, etc.)
- Disadvantages:
  - It requires minimum of 11 bits per sample to achieve “toll quality” (equivalent to a typical telephone quality)
  - For 10000 Hz sampling rate, the required bit rate is: B=(11 bits/sample)x(10000 samples/sec)=110,000 bps=110 kbps
  - For CD quality signal with sample rate of 20000 Hz and 16-bits/sample, SNR(dB) =96-7.2=88.8 dB and bit rate of 320 kbps.

Non-uniform Quantization

Nonuniform Quantization

- Uniform quantization may not be optimal (SNR can not be as small as possible for certain number of decision and reconstruction levels)
- Consider for example speech signal for which x[n] is much more likely to be in one particular region than in other (low values occurring much more often than the high values).
- This implies that decision and reconstruction levels are not being utilized effectively with uniform intervals over $\pm x_{max}$.
- A Nonuniform quantization that is optimal (in a least-squared error sense) for a particular pdf is referred to as the ***Max quantizer***.
- Example of a nonuniform quantizer is given in the figure in the next slide.

Nonuniform Quantization

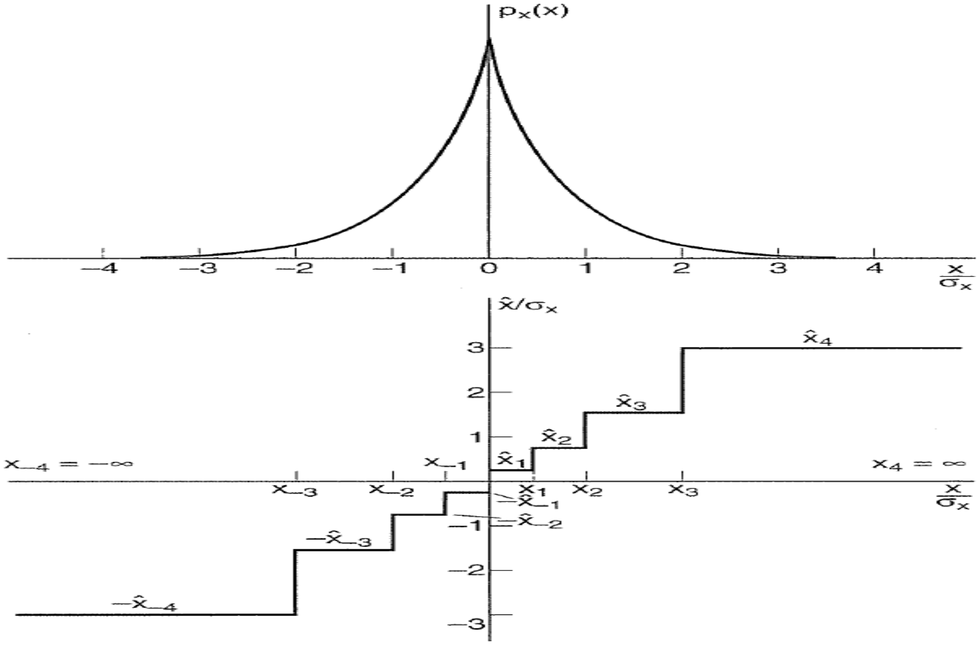


Figure 12.6 3-bit nonuniform quantizer: (a) Laplacian pdf; (b) decision and reconstruction levels.

SOURCE: L.R. Rabiner and R.W. Schafer, *Digital Processing of Speech Signals* [71]. ©1978, Pearson Education, Inc. Used by permission.

Nonuniform Quantization

- Max Quantizer
  - Problem Definition: For a random variable x with a known pdf, find the set of M quantizer levels that minimizes the quantization error.
  - Therefore, finding the decision and boundary levels x_i and $\hat{x}_i$, respectively, that minimizes the mean-squared error (MSE) distortion measure:

$$D=E[(x-\hat{x})^2]$$

  - E-denotes expected value and $\hat{x}$ is the quantized version of x.
  - It turns out that optimal decision level x_k is given by:

$$x_k = \frac{\hat{x}_{k+1} + \hat{x}_k}{2}, \qquad 1 \le k \le M\text{-}1$$

Nonuniform Quantization

- Max Quantizer (cont.)
  - The optimal reconstruction level x_k is the centroid of $p_x(x)$ over the interval $x_{k-1} \leq x \leq x_k$:

$$\hat{x}_k = \int_{x_{k-1}}^{x_k} \left[\frac{p_x(x)}{\int_{x_{k-1}}^{x_k} p_x(x')dx'} \right] x dx = \int_{x_{k-1}}^{x_k} \tilde{p}_x(x) dx$$

  - It is interpreted as the mean value of x over interval $x_{k-1} \leq x \leq x_k$ for the normalized pdf p(x).
  - Solving last two equations for x_k and x_k is a nonlinear problem in these two variables.
    - Iterative solution which requires obtaining pdf (can be difficult).

Nonuniform Quantization

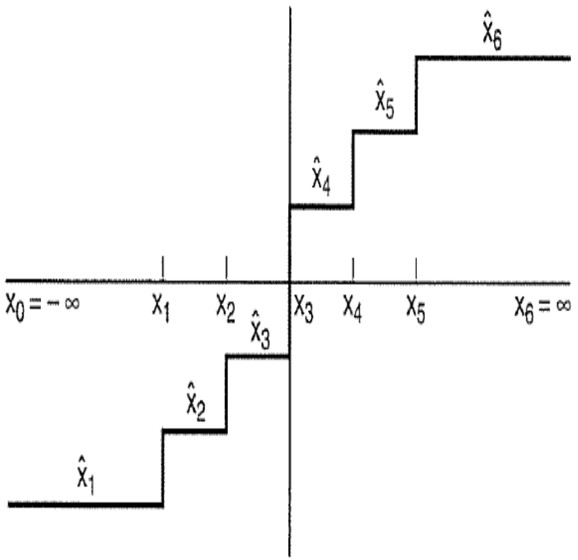


Figure 12.8 Nonuniform quantization example with number of reconstruction levels $M = 6$.

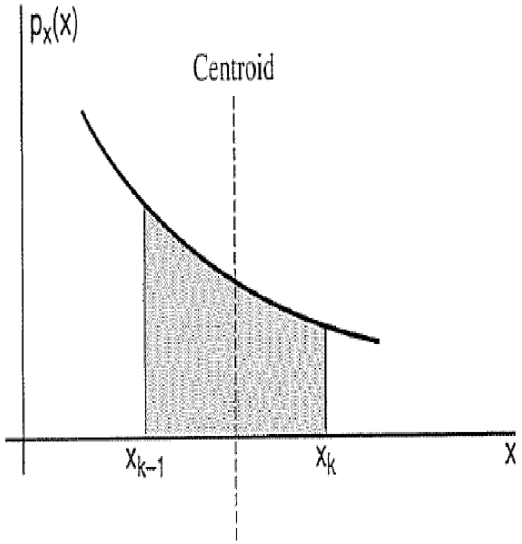


Figure 12.9 Centroid calculation in determining the optimal MSE reconstruction level.

Companding

- Alternative to the nonuniform quantizer is ***companding***.
- It is based on the fact that uniform quantizer is optimal for a uniform pdf.
  - Thus if a nonlinearity is applied to the waveform x[n] to form a new sequence g[n] whose pdf is uniform then
  - Uniform quantizer can be applied to g[n] to obtain g[n], as depicted in the Figure 12.10 in the next slide.

^

Companding

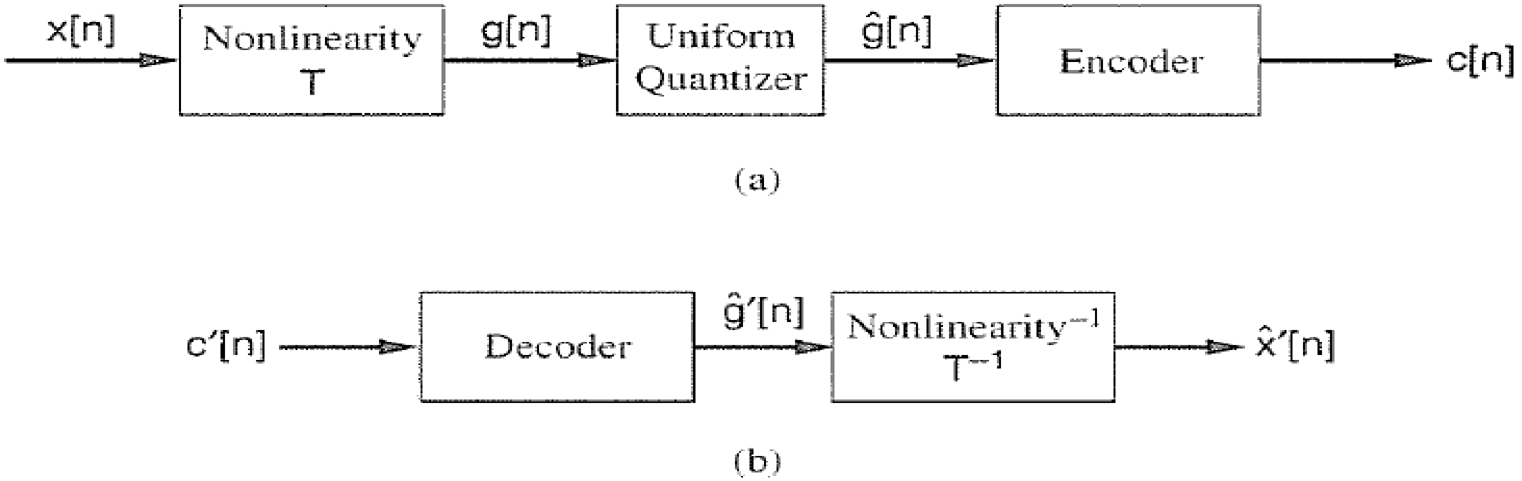


Figure 12.10 The method of companding in coding and decoding: (a) coding stage consisting of a nonlinearity followed by uniform quantization and encoding; (b) an inverse nonlinearity occurring after decoding.

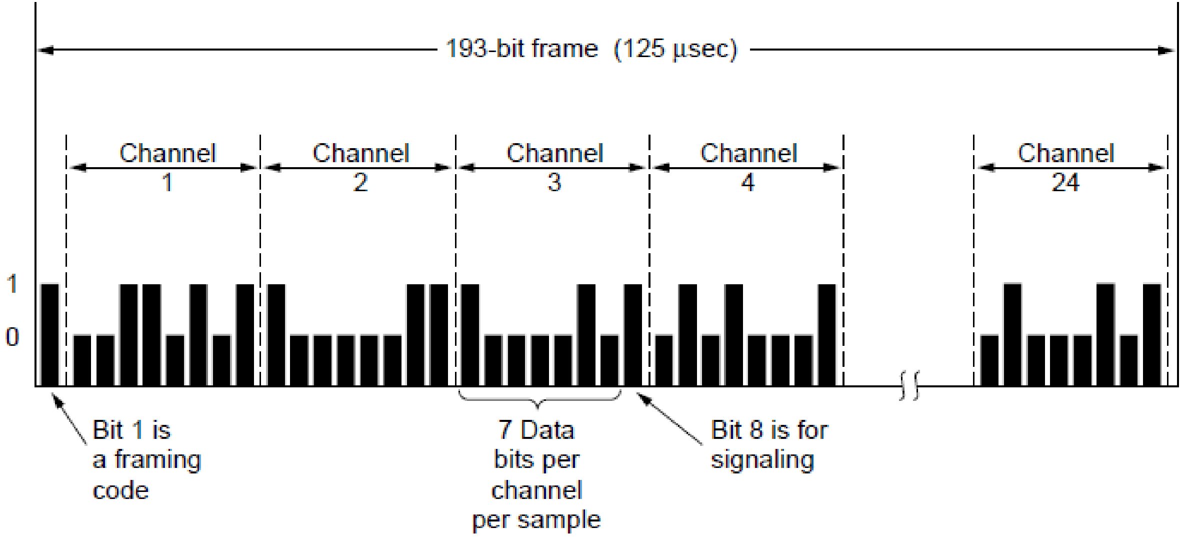
Companding

- A number of other nonlinear approximations to nonlinear transformation that achieves uniform density are used in practice which do not require pdf measurement.
- Specifically: A-law and μ–law companding (ITU G.711).
- μ-law coding is give by:

$$T(x[n]) = x_{\max} \frac{\log\left(1+\mu \frac{|x[n]|}{x_{\max}}\right)}{\log(1+\mu)} sign(x[n])$$

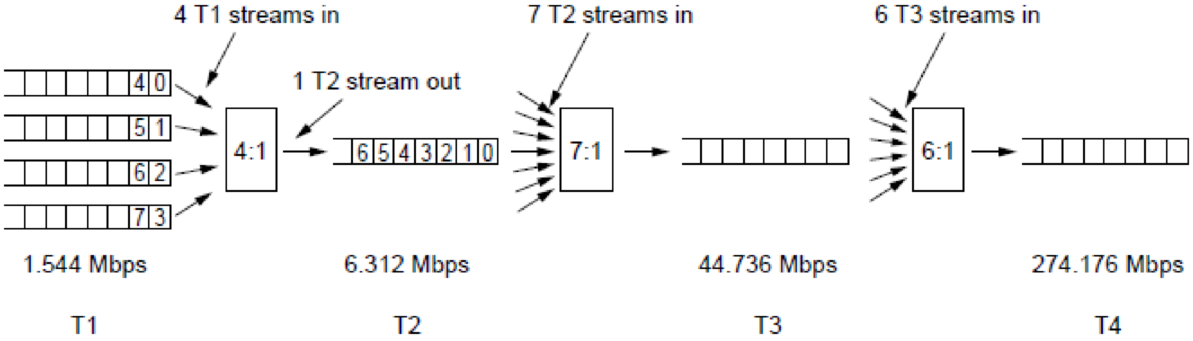
- ITU (then CCITT) international standard coder at 64 kbps is an example application of μ-law coding.
  - μ-law transformation followed by 7-bit uniform quantization giving toll quality speech.
  - Equivalent quality of straight uniform quantization achieved by 11 bits.

Time Division Multiplexing (1)



The T1 carrier (1.544 Mbps). USA and Japan

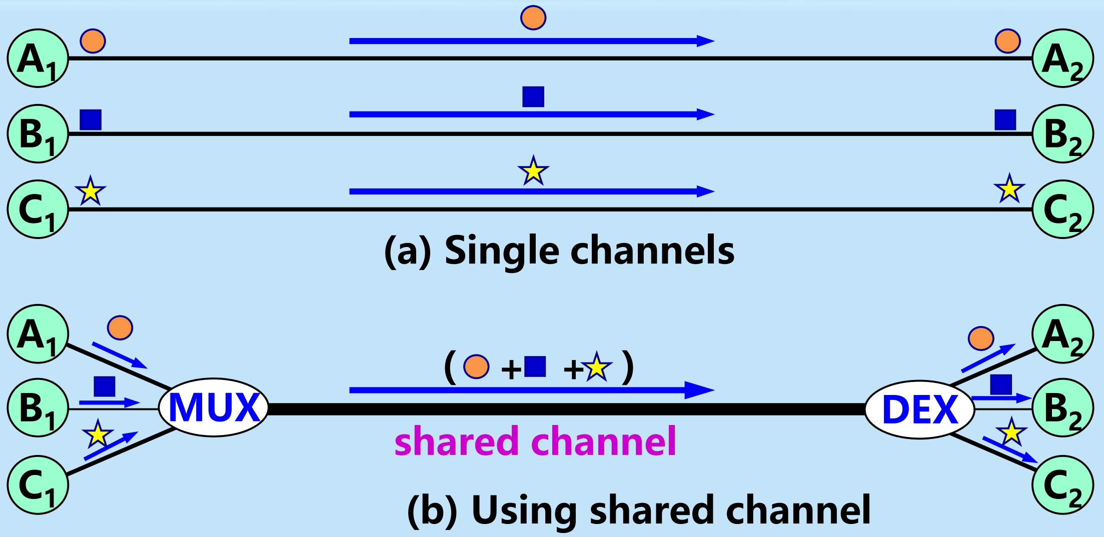
Time Division Multiplexing (2)



Multiplexing T1 streams into higher carriers

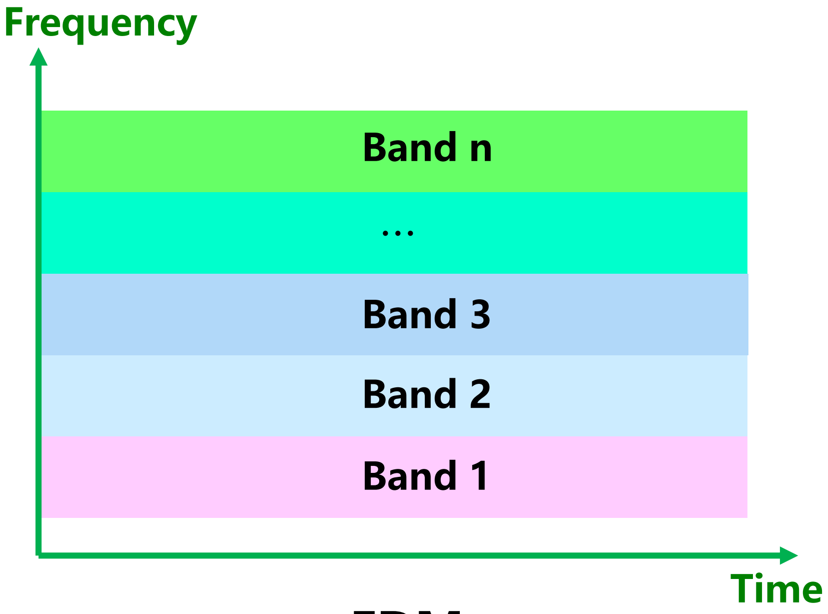
TDM、FDM and STDM

Multiplexing is a fundamental concept in communications technology. It allows users to communicate using a Shared channel, reducing costs and increasing utilization.



FDM (Frequency Division Multiplexing)

- The whole bandwidth is divided into several parts. After the user is allocated a certain frequency band, he/she occupies the band throughout the communication process.
- All users of frequency division multiplexing use different bandwidth resources at the same time

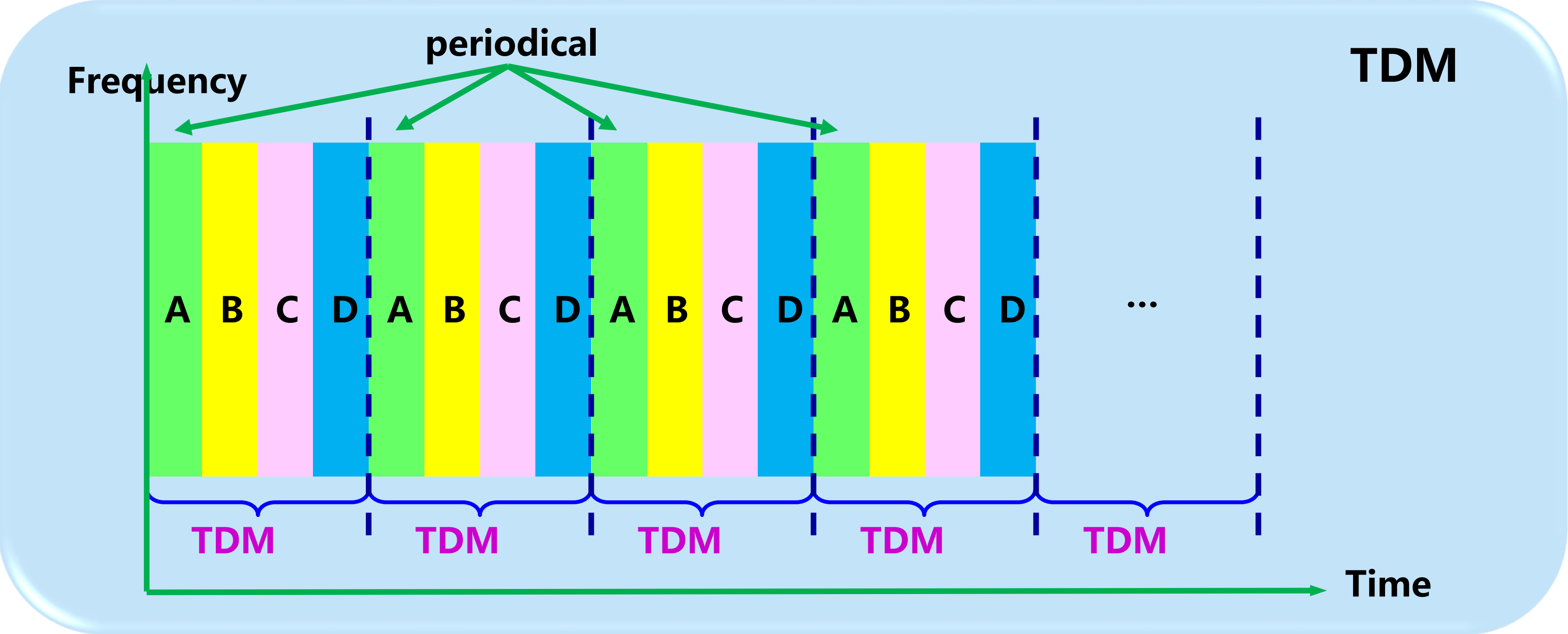


FDM

TDM (Time Division Multiplexing)

- Time division multiplexing is the division of time into equal length TDM frames. Each time division multiplexed user occupies a fixed number of slots in each TDM frame.
- The time slots occupied by each user occur periodically (the period is the length of the TDM frame).
- TDM signals are also known as isochronous signals.
- All users of TDM occupy the same bandwidth at different times.

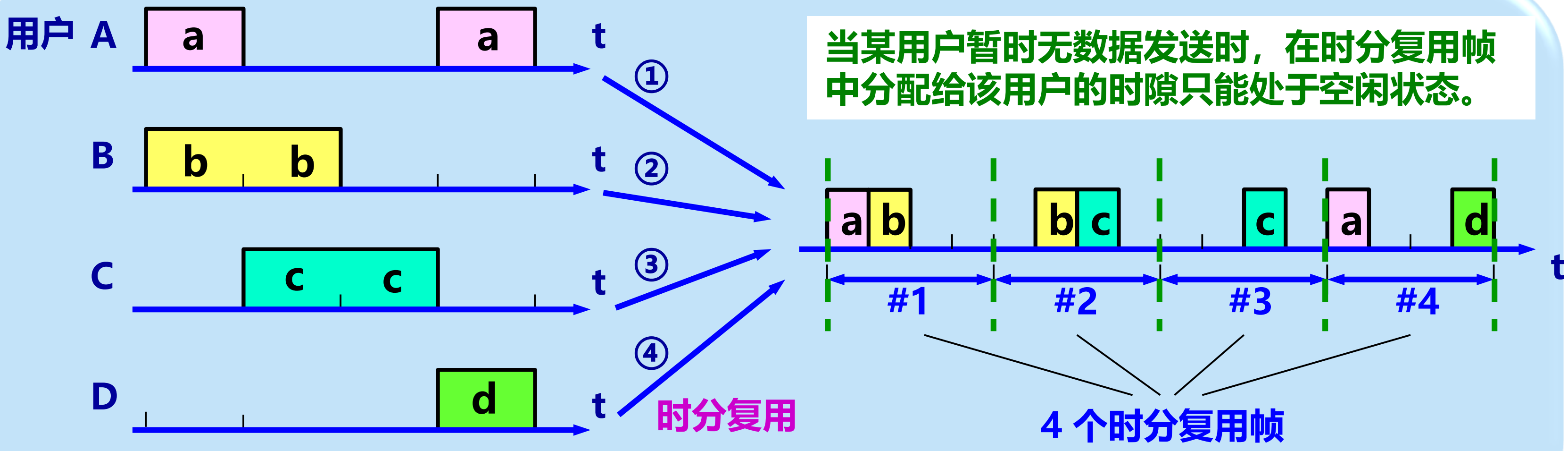
TDM



periodical
Frequency
TDM
A B C D A B C D A B C D A B C D
...
TDM TDM TDM TDM TDM
Time

时分复用可能会造成线路资源的浪费

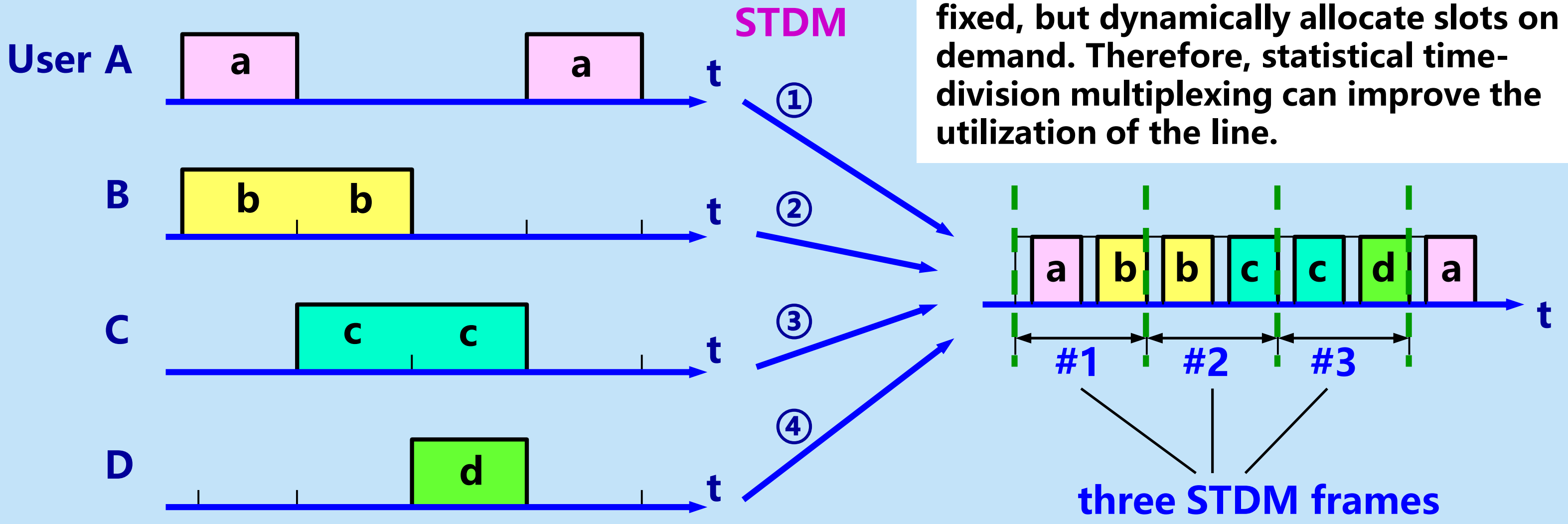
使用时分复用系统传送计算机数据时，由于计算机数据的突发性质，用户对分配到的子信道的利用率一般是不高的。



时分复用可能会造成线路资源的浪费

STDM (Statistic TDM)

STDM frames do not allocate slots fixed, but dynamically allocate slots on demand. Therefore, statistical time-division multiplexing can improve the utilization of the line.



Working Principles of STDM

Wavelength Division Multiplexing

- A form of FDM as well as TDM is used to take advantage of the tremendous bandwidth of optic channels – Wavelength Division Multiplexing (WDM).
- The principle of WDM is depicted in the figure in the next slides.

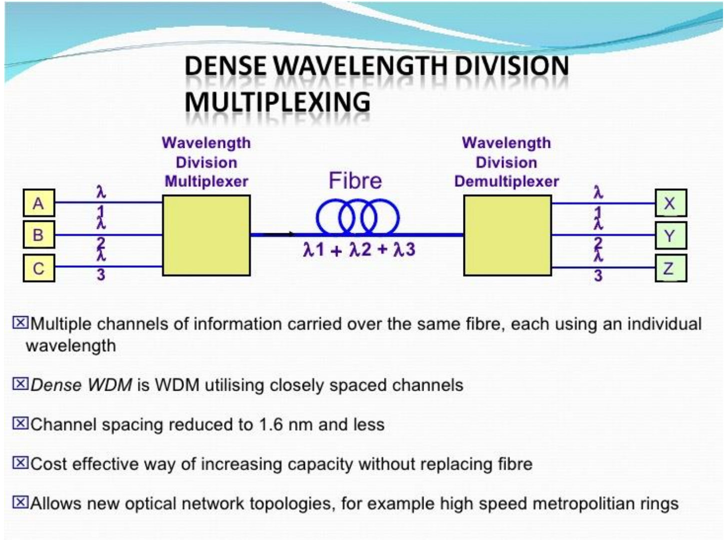
Wavelength Division Multiplexing

- Bandwidth of a single channel is about 25,000 GHz
- In theory there is room for 2500 10 Gbps (even at 1 bit per Hz).

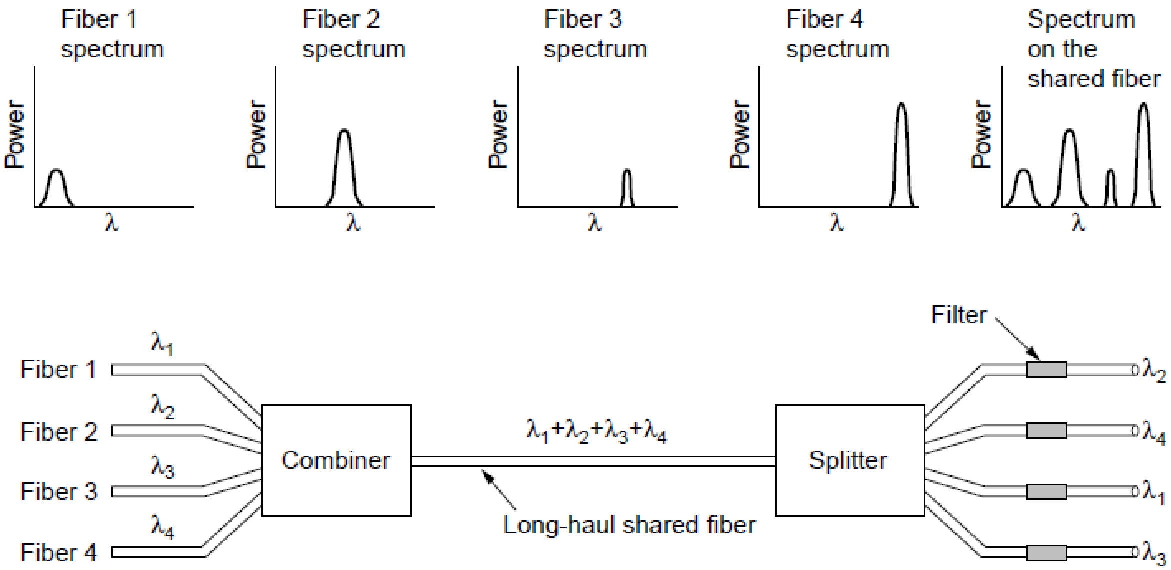
- WDM was invented in 1990
  - 1990: First commercial system had 8 channel running 2.5 Gbps (per channel)
  - 1998: 40 channels running 2.5 Gbps
  - 2006: 192 channels with 10 Gbps or 64 channels with 40 Gbps => 2.56 Tbps. Sufficient bandwidth to transmit 80 full-length DVD movies per second.

Optical fiber WDM， Greatly Improved Channel Bandwidths

- **Dr. Tingye Li, Optical fiber WDM Poineer, OSA USA**
- **Two short stories, Tingye Li， AT&T and Bell Labs**



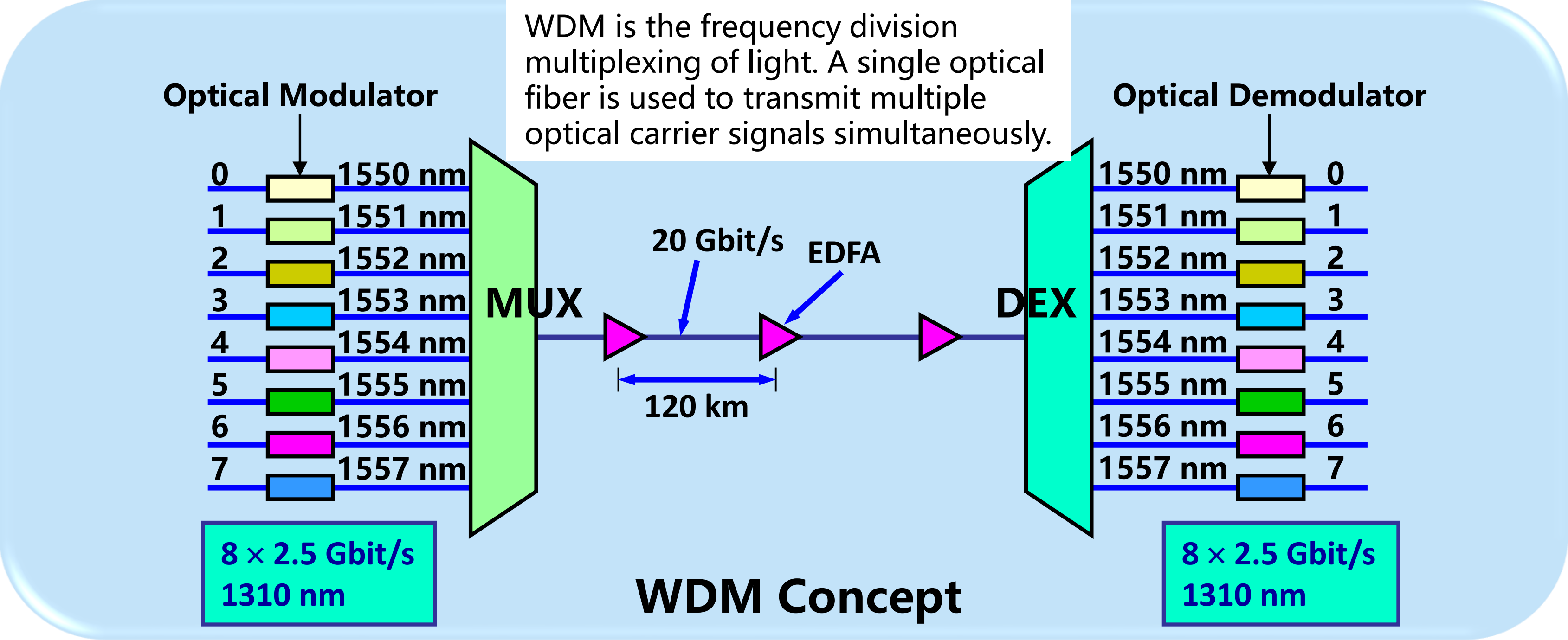
Wavelength Division Multiplexing



Wavelength division multiplexing

WDM(Wavelength Division Multiplexing)

WDM is the frequency division multiplexing of light. A single optical fiber is used to transmit multiple optical carrier signals simultaneously.



SONET/SDH

- After breakup of AT&T in 1986 multiple long-distance carriers were connected with all different optical TDM systems.
- Standard was needed (Bellcore 1985)
  - SONET (Synchronous Optical NETwork), telecommunications industry’s standard for very-high-speed TDM over optical fiber
  - ITU provided its recommendations (G.707, G.708 and G.709) in 1989 – called SDH (Synchronous Digital Hierarchy).

SONET/SDH

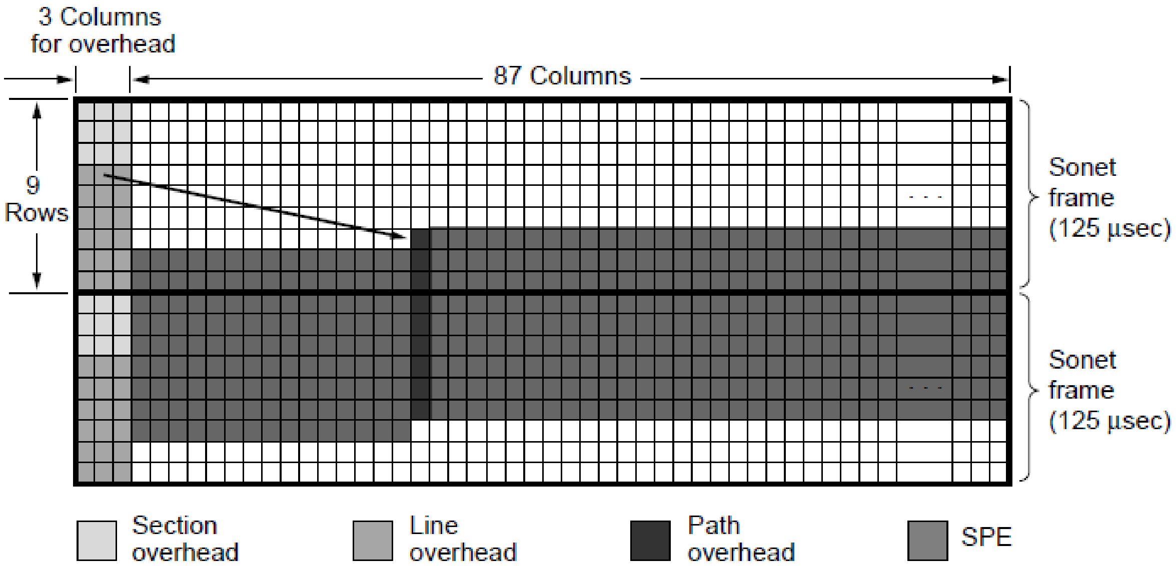
- SONET Design Goals:
  1. Make it possible for different carriers to interwork - Common signaling standard with respect to wavelength, timing framing structure, and other issues.
  2. Unifying US, European and Japanese digital systems (all were based on 64 kbps PCM channels but combined them in different (and incompatible) ways.
  3. Provide the way to multiplex multiple digital channels.
     - At that time T3 with the rate of 44.737 Mbps was the highest in use.
     - T4 was mentioned and anything behind that was not even defined.
     - SONET extended this into hierarchy to gigabits/sec and beyond range.

SONET/SDH

4. Providing support for operations, administration, and maintenance (OAM) – needed to manage the network.

- SONET is a synchronous system that requires each sender to be tied to a common clock.
- Synchronization is done with precision of 1 part to 10^9.
- Frame is comprised of 810 bytes:
  - 90 columns x 9 rows
  - 8x810 = 6480 bits transmitted at 8000 times per second.
  - 51.84 Mbps.
  - STS-1 (Synchronous Transport Signal – 1).

SONET/SDH (1)



Two back-to-back SONET frames.

SONET/SDH

- Data rates and multiplexing hierarchy is presented in the next slide figure.

SONET/SDH (2)

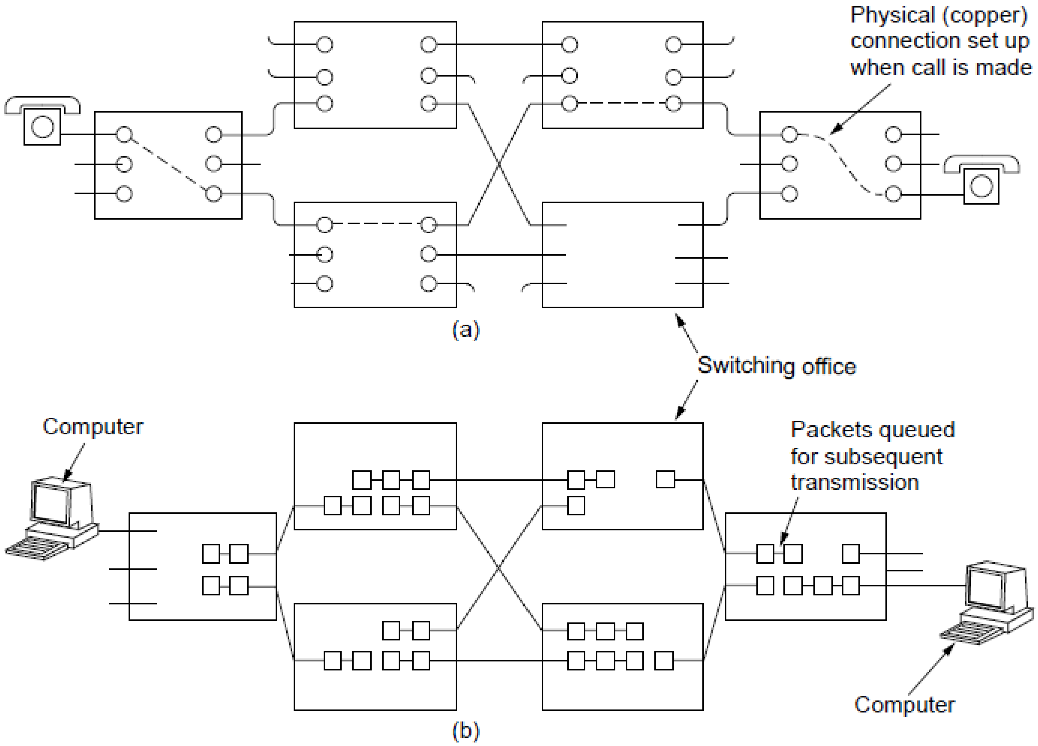
SONET		SDH	Data rate (Mbps)		
Electrical	Optical	Optical	Gross	SPE	User
STS-1	OC-1		51.84	50.112	49.536
STS-3	OC-3	STM-1	155.52	150.336	148.608
STS-12	OC-12	STM-4	622.08	601.344	594.432
STS-48	OC-48	STM-16	2488.32	2405.376	2377.728
STS-192	OC-192	STM-64	9953.28	9621.504	9510.912
STS-768	OC-768	STM-256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

SONET and SDH multiplex rates.

Circuit Switching/Packet Switching

- The phone system can be divided into two principal parts:
  - Outside the plant (local lops and trunks).
  - Inside the plant (switching offices).
- Two switching technologies used:
  - Circuit switching, and
  - Packet switching.

Circuit Switching/Packet Switching (1)

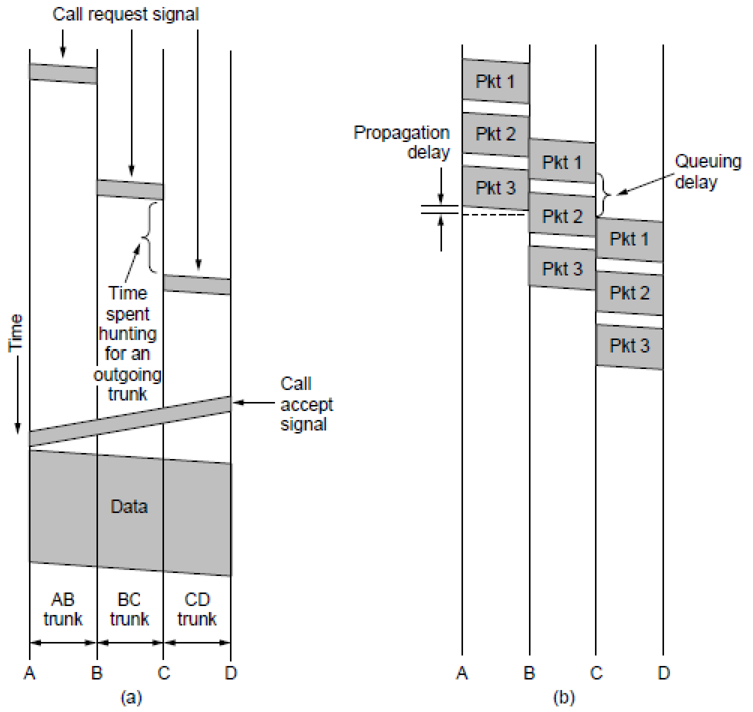


(a) Circuit switching. (b) Packet switching.

Circuit Switching

- Before a call can be made a connection must be established in its entirety.
- During the establishment of the direct path from two end users the system will hunt to find it.
- It may take up to 10 sec.
- However, once the path is set-up
  - The only delay for data is the propagation time for the signal to travel to the destination: 5 msec per 1000 km.
  - There is no danger of congestion.

Circuit Switching/Packet Switching (2)



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

Computer Networks, Fifth Edition by Andrew Tanenbaum and David Wetherall, © Pearson Education-Prentice Hall, 2011

Packet Switching

- Provides alternate way of performing switching.
- Store-and-forward method applied by routers make it possible for the packets to be send immediately.
  - No a priory path is being established
  - No guarantees that the packed will arrive in order
  - Packets are limited in size
  - Delay is generally shorter than in circuit switching

Circuit Switching/Packet Switching

- Different delays compared to circuit switching
  - Queuing delay in the router can be caused by congestions during traffic time, vs.
  - Set-up time can cause significant delay.
- Circuit vs. Packet Switching
  - Guaranteed services and wasting resources vs. Not guaranteeing the service and not wasting resources.
  - Packet Switching is more fault tolerant.
  - Charging is different: Time vs. Volume

Circuit Switching/Packet Switching (3)

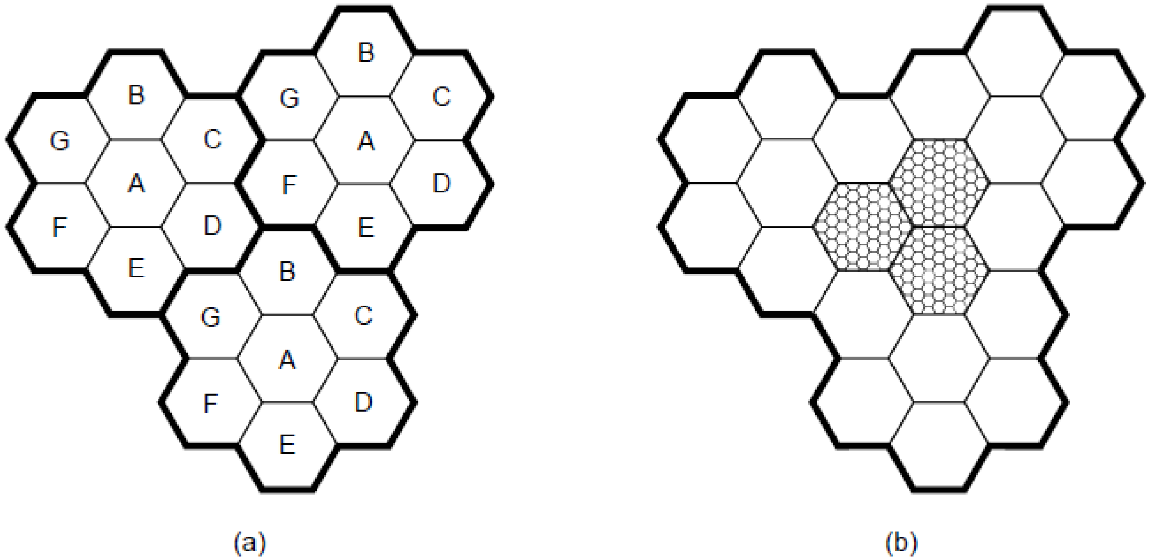
Item	Circuit switched	Packet switched
Call setup	Required	Not needed
Dedicated physical path	Yes	No
Each packet follows the same route	Yes	No
Packets arrive in order	Yes	No
Is a switch crash fatal	Yes	No
Bandwidth available	Fixed	Dynamic
Time of possible congestion	At setup time	On every packet
Potentially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

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

Mobile Telephone System

- First-Generation (1G) Mobile Phones Analog Voice
- Second-Generation (2G) Mobile Phones Digital Voice
- Third-Generation (3G) Mobile Phones Digital Voice + Data
- Fourth-Generation (4G) Faster Rates for Data. LTE long-term evolution means through many years, cannot happen quickly: MIMO+OFDMA
- 5G: much higher speeds and broad bandwidths

Advanced Mobile Phone System



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

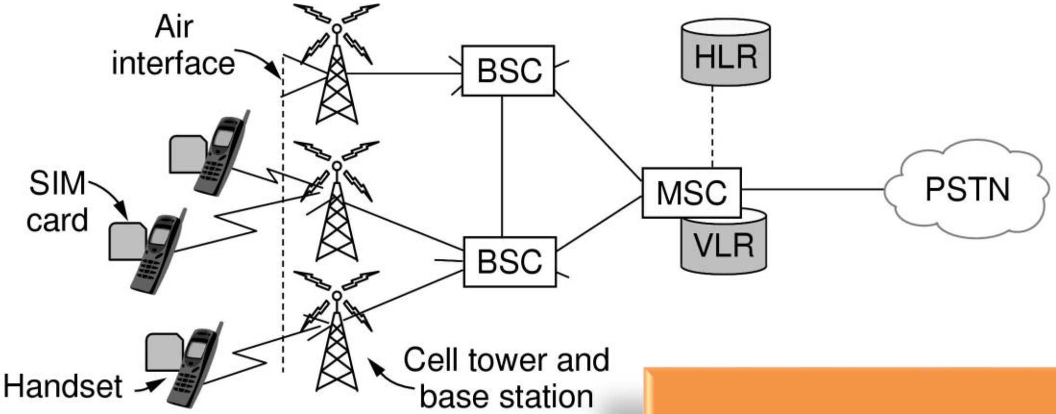
Advanced Mobile Phone System

- Uses FDM to separate the channels.
  - 832 full duplex channels organized in pair of simplex channels.
  - FDD (Frequency Division Duplex) arrangement.
- The 832 simplex channels from 824-849 MHz are used for mobile to base station transmission,
- The 832 simplex channels from 869-894 MHz are used for base station to mobile transmission.

Advanced Mobile Phone System

- 4 categories of 832 channels:
  - Control Channels (base to mobile) are used to manage the system
  - Page Channels (base to mobile) alert mobile users to calls for them
  - Access Channels (bidirectional) are used for call setup and channel assignment.
  - Data Channels (bidirectional) carry voice, fax, or data.

GSM—The Global System for Mobile Communications (1)



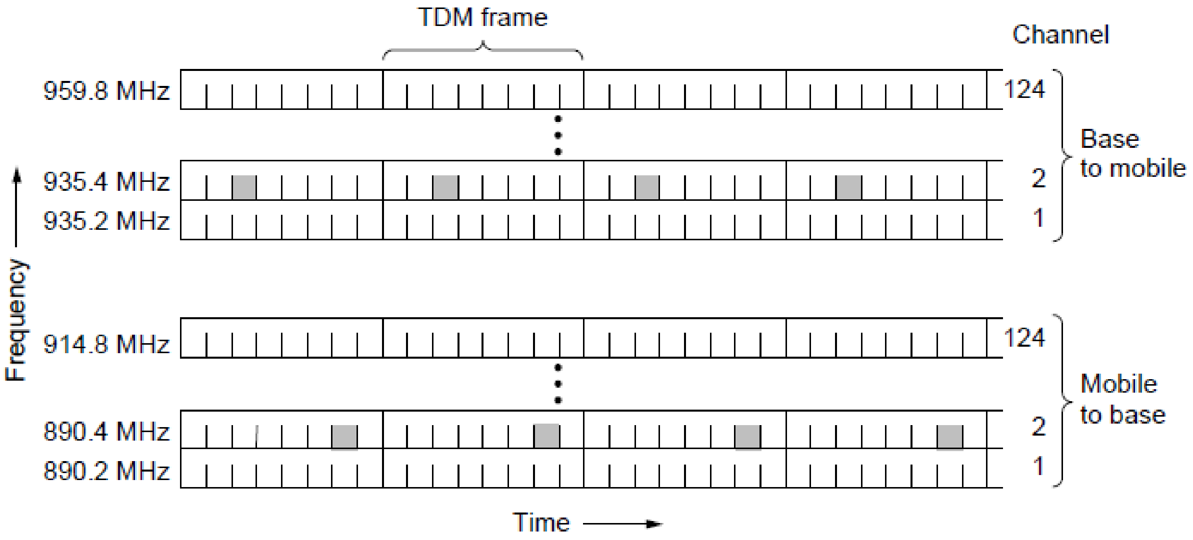
SIM – Subscriber Identity Module
BSC – Base Station Controller
VLR – Visitor Location Register
HLR – Home location Register

GSM mobile network architecture.

GSM

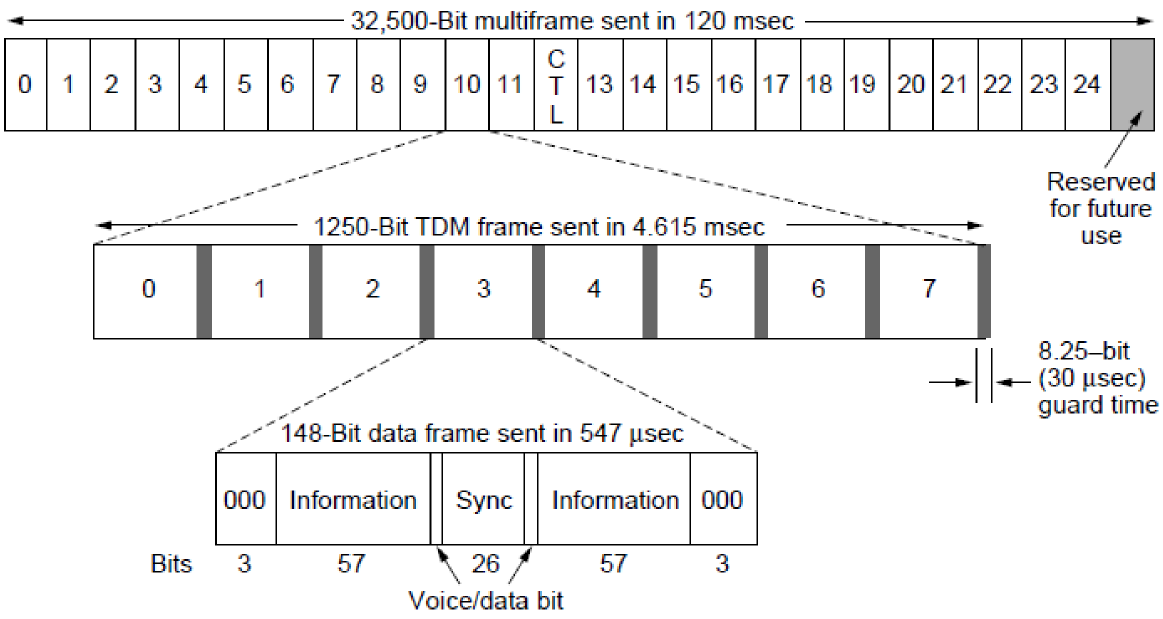
- Runs on a range of frequencies:
  - 900 MHz
  - 1800 MHz
  - 1900 MHz
- Each is mobile phone transmits in one frequency and it receives at the other higher frequency – 55 MHz.
- Each frequency pair (receive and transmit) is split by time-division multiplexing.
- Wireless GSM channel is 200 kHz as shown in the next slide:

GSM—The Global System for Mobile Communications (2)



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

GSM—The Global System for Mobile Communications (3)



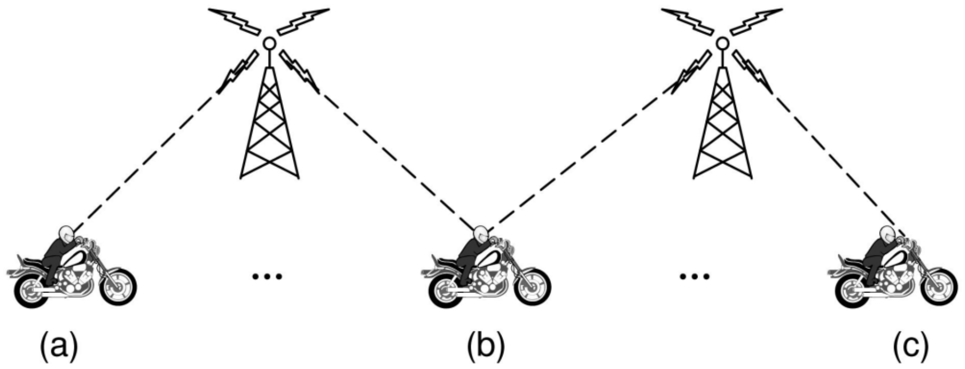
A portion of the GSM framing structure.

Digital Voice and Data (1)

Basic services intend by IMT-2000 network

- High-quality voice transmission.
- Messaging (replacing email, fax, SMS, chat).
- Multimedia (music, videos, films, television).
- Internet access (Web surfing, incl. audio, video).

Digital Voice and Data (2)

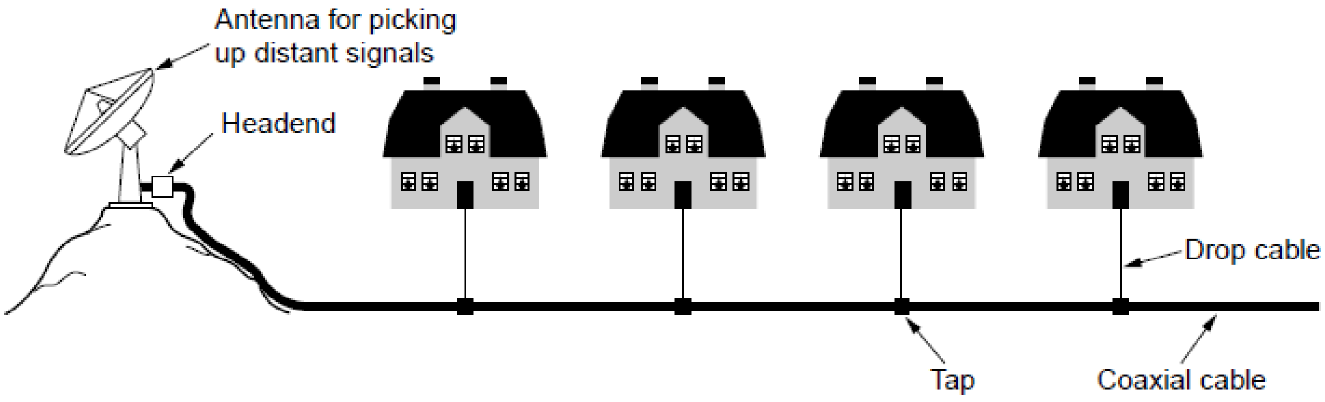


Soft handoff (a) before, (b) during, and (c) after.

Cable Television

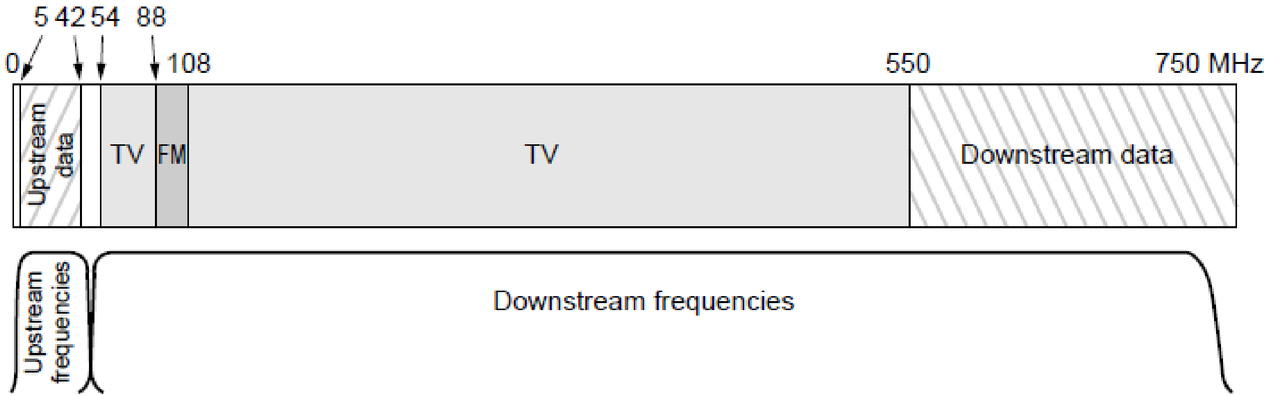
- Community antenna television
- Internet over cable
- Spectrum allocation
- Cable modems
- ADSL versus cable

Community Antenna Television



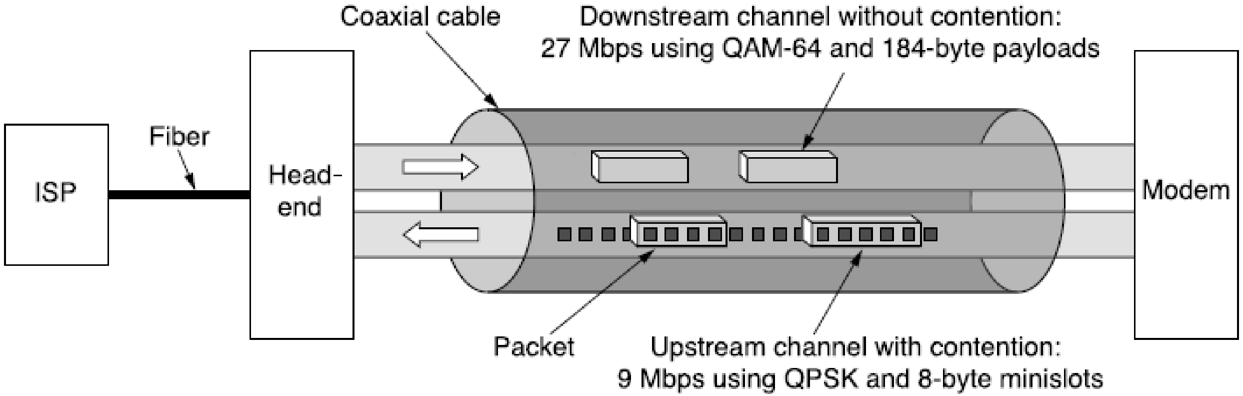
An early cable television system

Spectrum Allocation



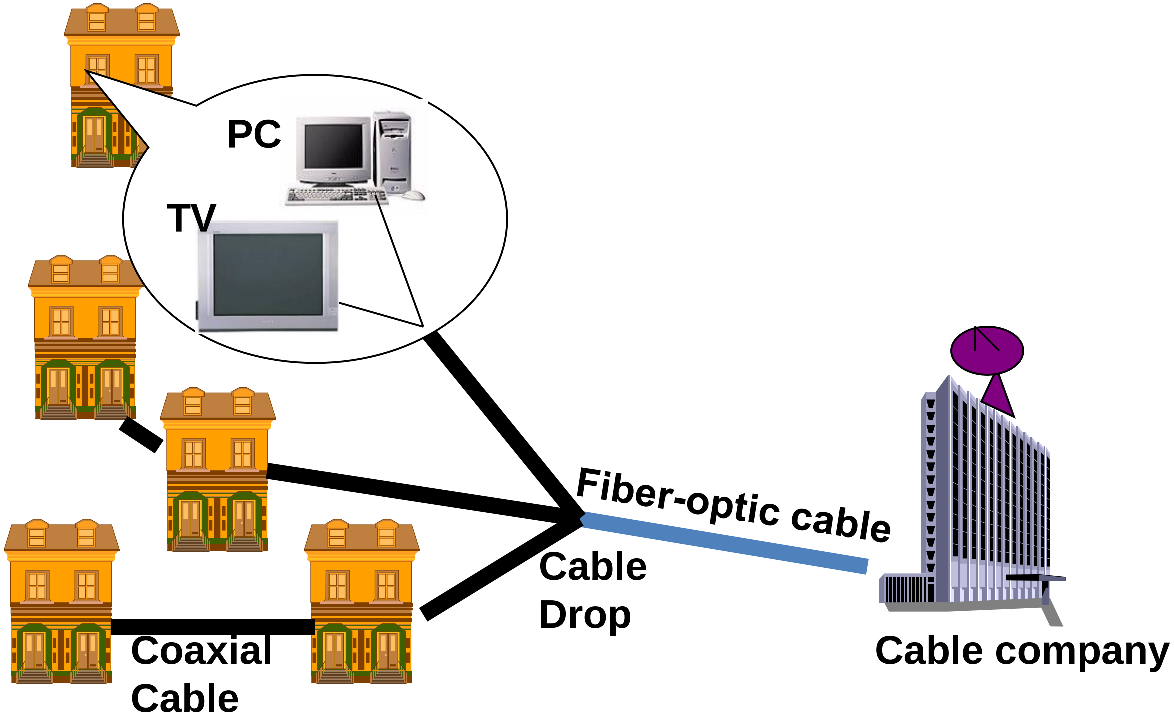
Frequency allocation in a typical cable TV system used for Internet access.

Cable Modems



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

The connection is shared by a number of subscribers, hence may raise performance and security problems



Teryon Cable Modem

Ethernet
link to PC

Coaxial link
from cable TV
socket

End

Chapter 2