Computer Network
(CSE 3034)

Text book: Computer Networks by Andrew S. Tanenbaum

Introduction to the course

Syllabus :

- Introduction(Chapter 1)
- **The Physical Layer(Chapter 2)**
- The Data Link Layer(Chapter 3)
- The Medium Access Control Sublayer(Chapter 4)
- The Network Layer(Chapter 5)
- The Transport layer(Chapter 6)
- The Application layer(Chapter 7)
- Network security(Chapter 8)

The Physical Layer

The Physical Layer

- Theoretical analysis of data transmission
- Transmission media.
    - Guided (copper wire and fiber optics)
    - wireless (terrestrial radio)
    - Satellite
- Examples of communication systems used in practice for wide area computer networks

Theoretical Basis for Data Communication

Pre -requisite

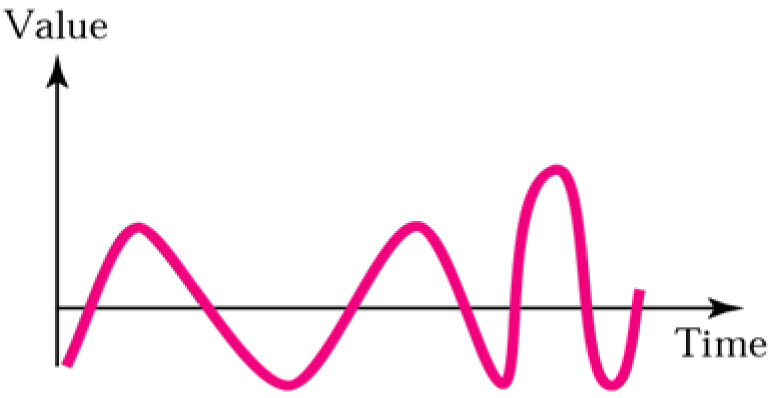
➢ Involvement of two signals : Digital and Analog

Analog signal

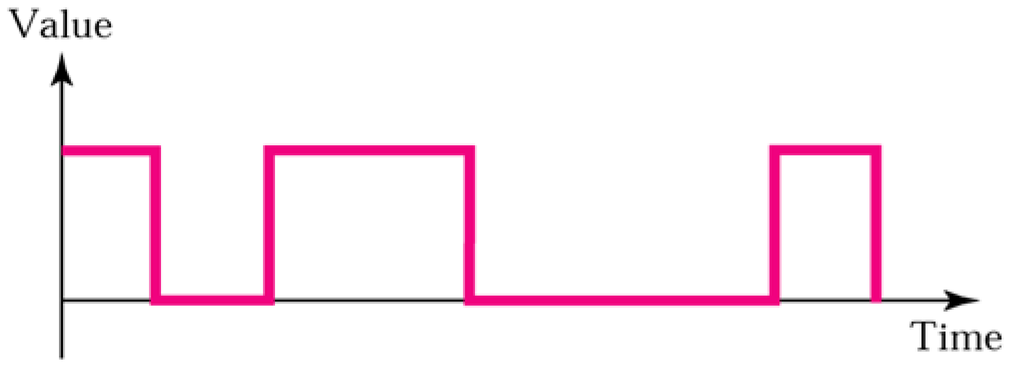
- Continuous waveform
- Can have a infinite number of values in a range
- Ex : Human voice

Digital signal

- Discrete
- Can have only a limited number of values
  E.g., 0 and 1, i.e., two levels, for binary signal
- Ex : Computer data



a. Analog signal



b. Digital signal

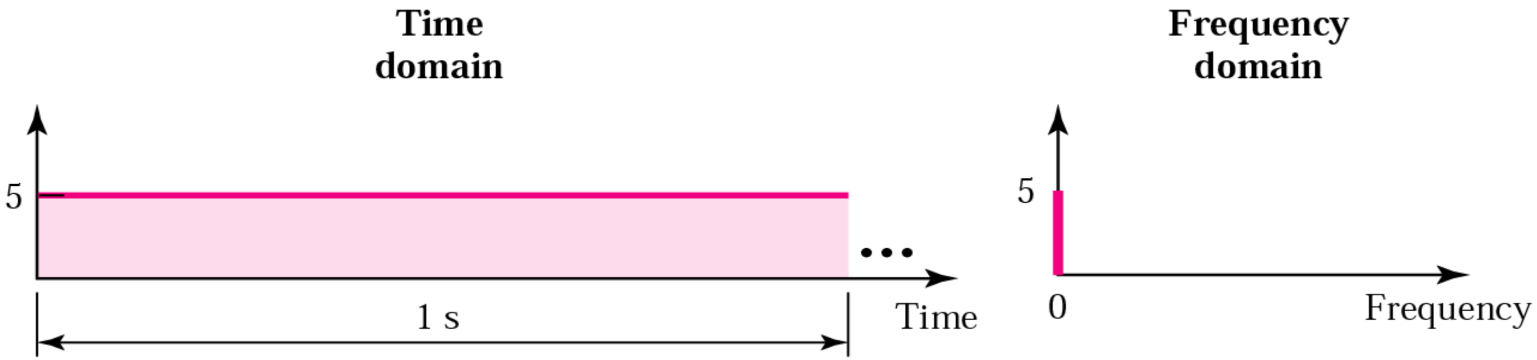
- Computer to modem : Digital
- Modem to modem : Analog

Theoretical Basis for Data Communication(cont.)

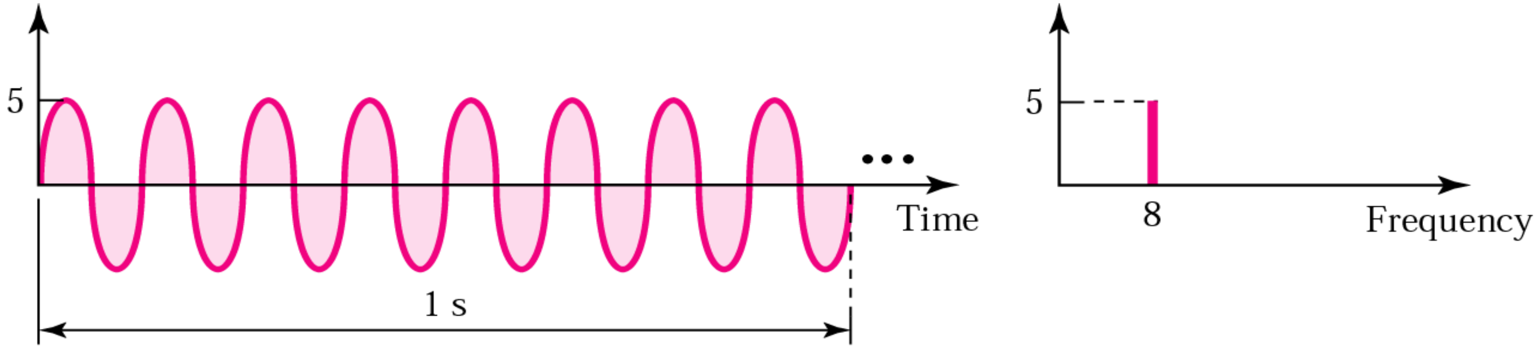
Pre -requisite

Time Vs. Frequency Domain:

- A signal can be represented in either the ***time*** domain or the ***frequency*** domain.
- An analog signal is best analyzed in the ***frequency*** domain.



a. A signal with frequency 0



b. A signal with frequency 8

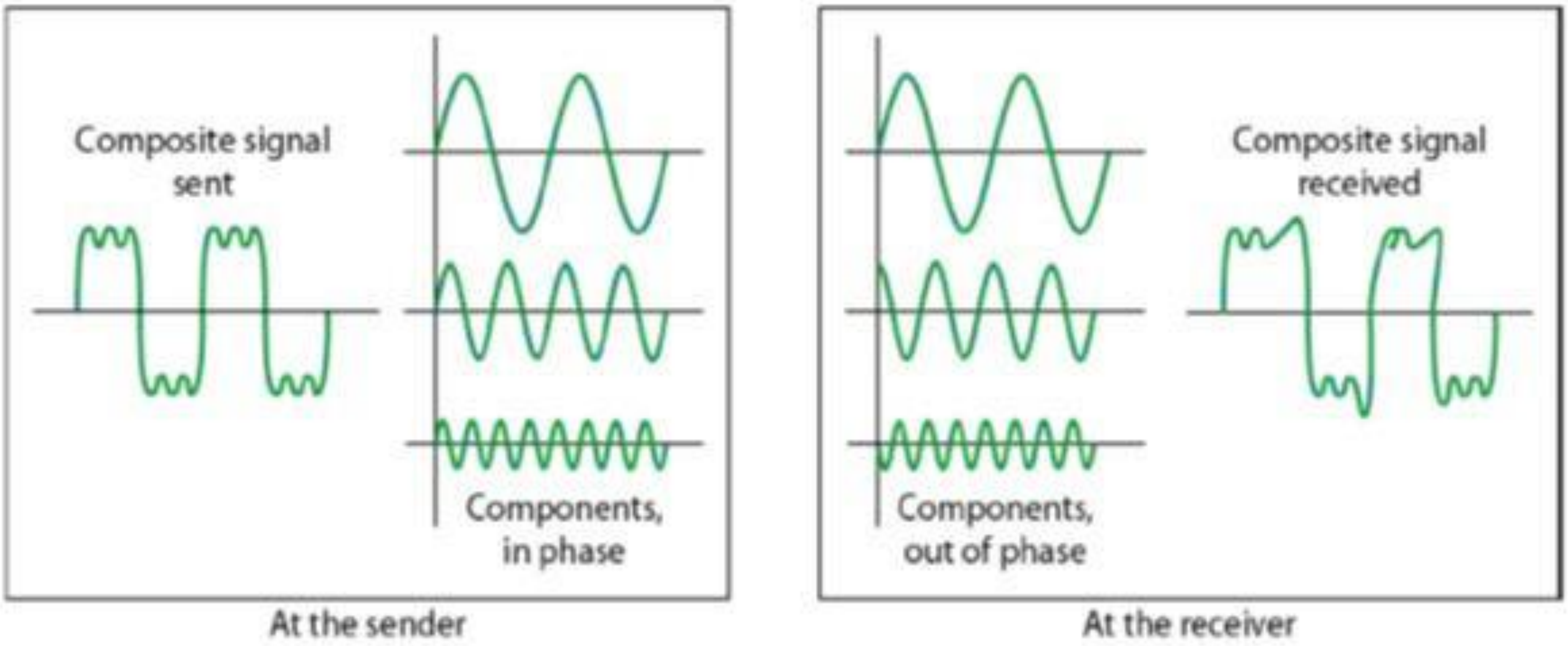
Theoretical Basis for Data Communication(cont.)

Pre -requisite

Composite signal:

- Single-frequency sine wave is not useful for data communication.
  - If a single sine wave was used to convey conversation over the phone, we would always hear just a buzz.
  - If we sent one sine wave to transfer data, we would always be sending alternating 0's and 1's, which does not have any communication value.
- If we want to use sine wave for communication, we need to change one or more of its characteristics. For e.g., to send 1 bit, we send a maximum amplitude, and to send 0, the minimum amplitude.
- When we change one or more characteristics of a single-frequency signal, it becomes a **composite signal** made up of many frequencies (**or harmonics**).
- A composite signal is well analyzed in frequency domain.

Composite signal:



Theoretical Basis for Data Communication(cont.)

Pre -requisite

Frequency spectrum:

- The description of a signal using the frequency domain and containing all its components is called the frequency spectrum of the signal.

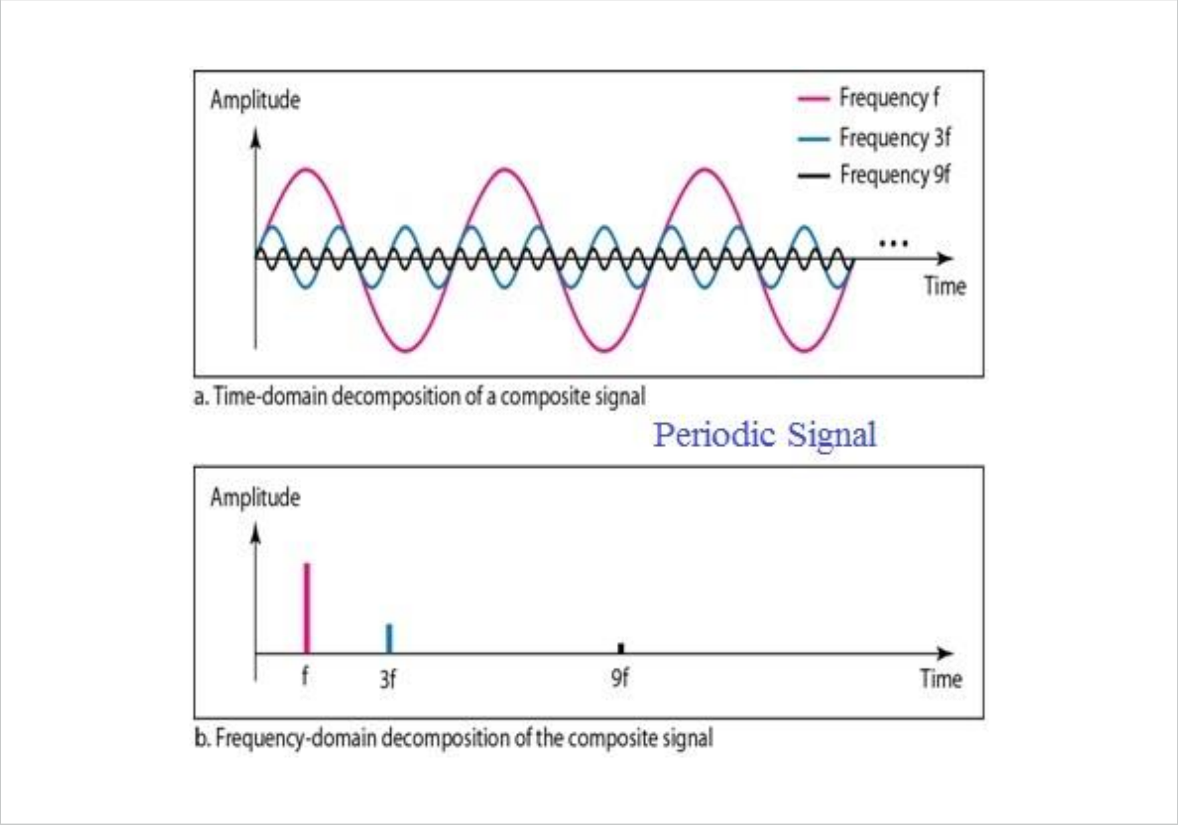
Frequency spectrum of an approximation with only three harmonics

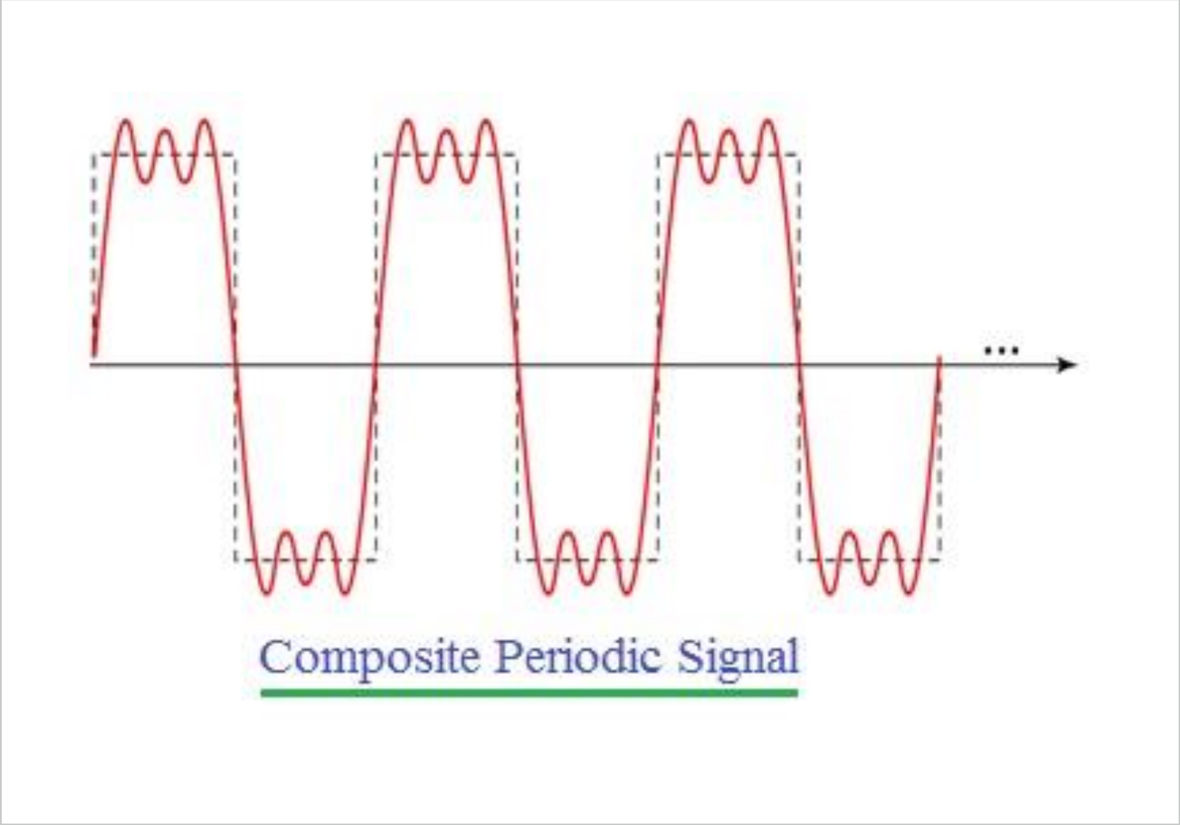
- **Fourier analysis :** Used to analyze the composite signal in frequency domain.
  - Fourier series : For periodic signal
  - Fourier transform : For aperiodic signal

Periodic Signal

- Definition: A signal is periodic signal when it is repeated over cycle of time or regular interval of time. This means periodic signal repeats its pattern over a period. The function f(x) can be periodic if it satisfies following equation.

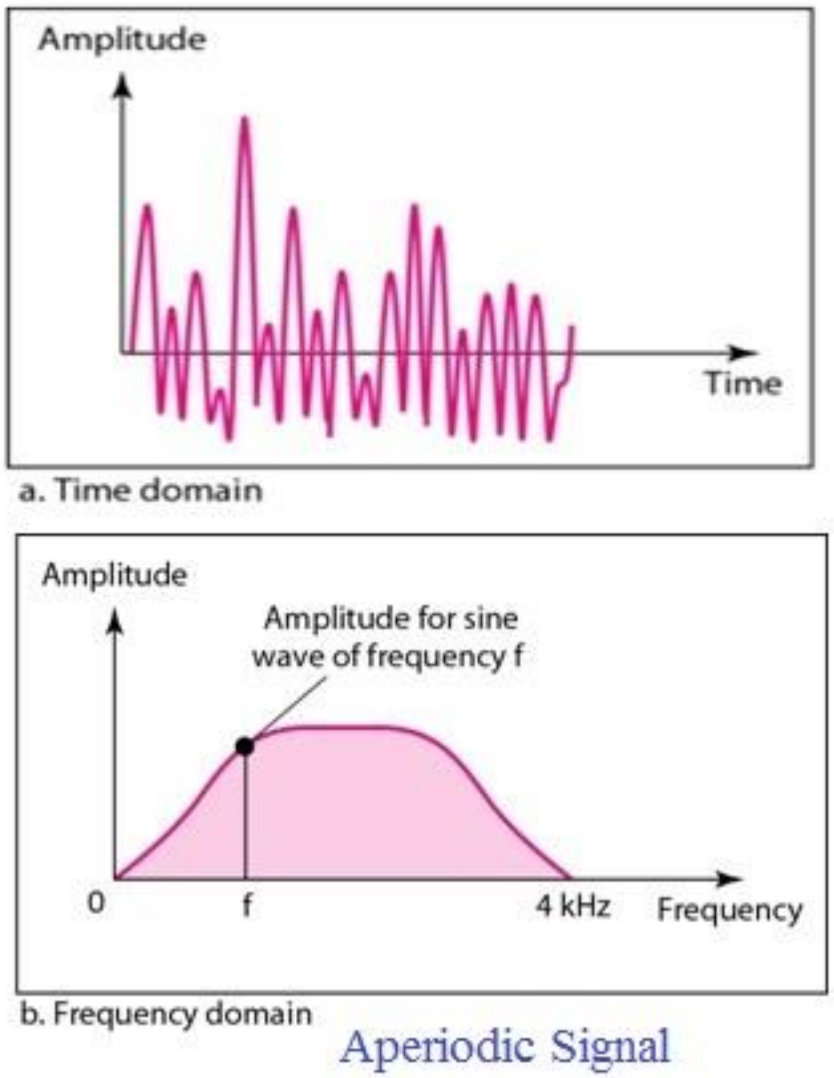
$$f(x + p) = f(x)$$





Aperiodic Signal or Non-periodic Signal

- Definition: A signal is non-periodic or aperiodic signal when it does not repeat its pattern over a period (i.e., interval of time).



Theoretical Basis for Data Communication(cont.)

- Information can be transmitted on wires in the form of variation in voltage or current with time (say *f(t)*).
- Signal behaviour can be modelled and analysed mathematically.

Fourier Analysis:

- A time-varying periodic signal can be represented as a series of frequency components (harmonics): Normally termed as Fourier series

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

***f* = *1/T* – fundamental frequency.**

***a_n* , *b_n* –** are the sine and cosine amplitudes of the ***n*'th harmonic.**

***c* –** is a constant.

Theoretical Basis for Data Communication (cont.)

The function can be reconstructed; that is, if the period, T, is known and the amplitudes are given.

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

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

$$c = \frac{2}{T}\int_0^T g(t)\,dt$$

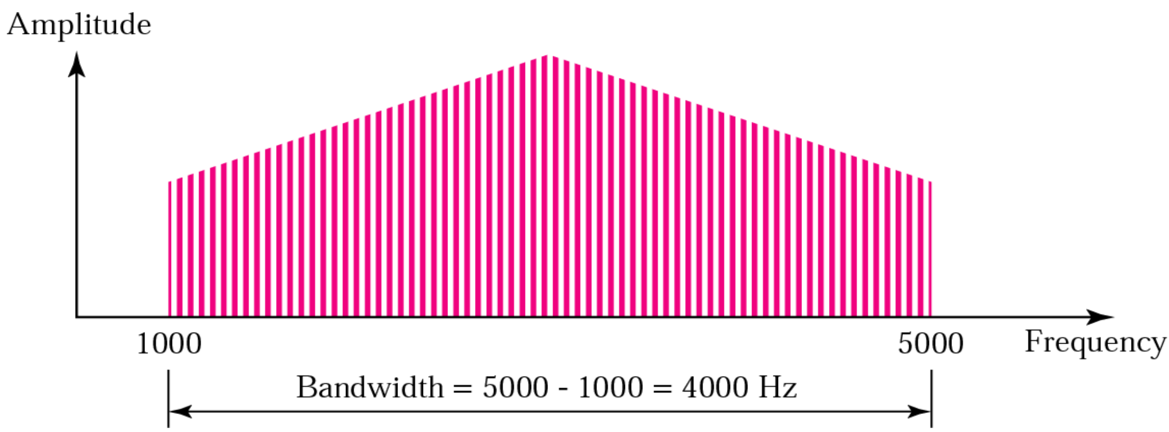
Note :

A data signal that has a finite duration thus can be handled by just imagining that it repeats the entire pattern over and over forever (i.e., the interval from T to 2T is the same as from 0 to T, etc.).

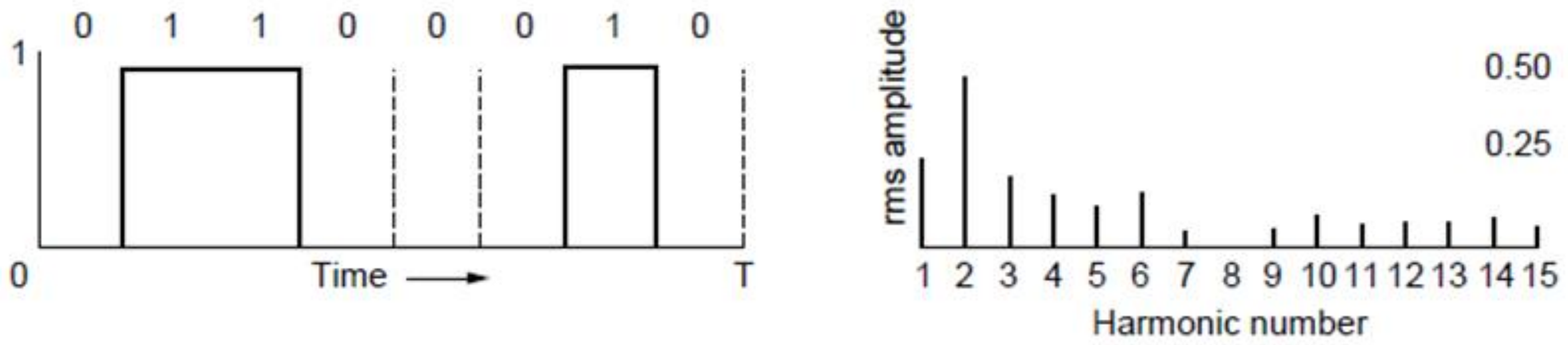
Theoretical Basis for Data Communication (cont.)

Bandwidth limited signal

- The range of frequencies that a medium can **pass** without loosing one-half of the power contained in that signal is called its **bandwidth**.
- At the signal level, bandwidth is also considered as cut-off frequency (HZ).
- For data transmission it is bits/sec.



Ex: 8-bit (01100010) data transmission

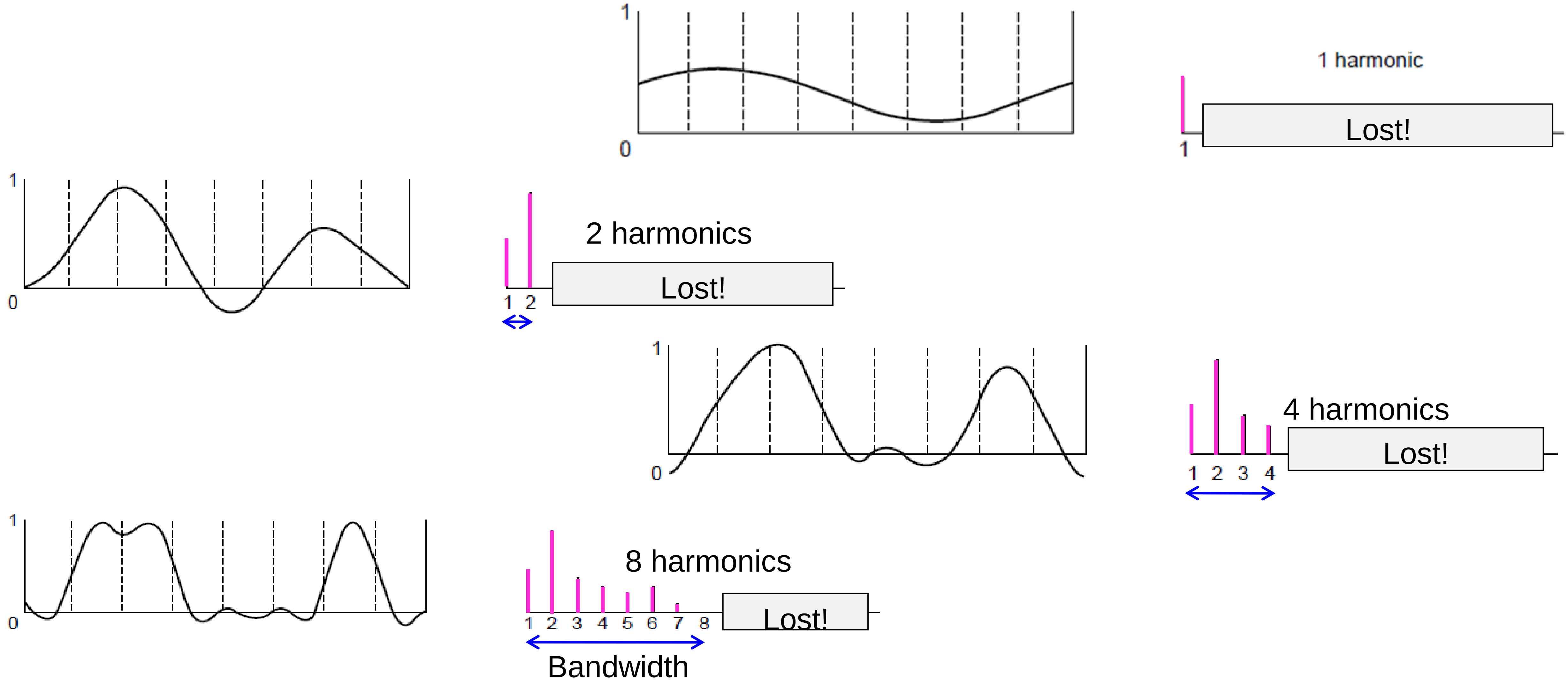


A binary signal and its root-mean-square Fourier amplitudes.

Theoretical Basis for Data Communication (cont.)

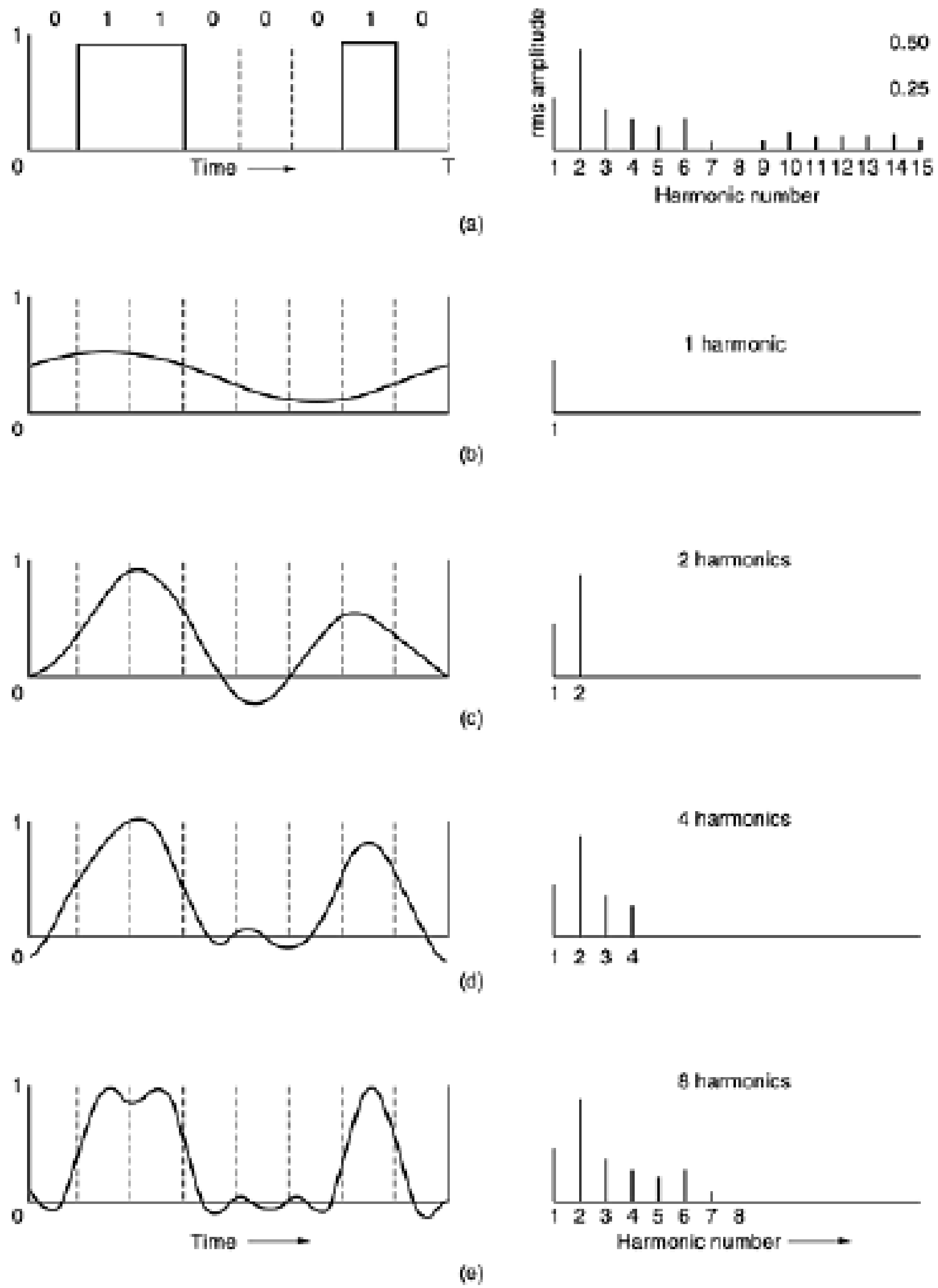
Bandwidth limited signal

- Having less bandwidth (harmonics) degrades the signal.



Having less bandwidth (harmonics) degrades the signal

Figure 2-1. (a) A binary signal and its root-mean-square Fourier amplitudes. (b)-(e) Successive approximations to the original signal.



Theoretical Basis for Data Communication (cont.)
Bandwidth limited signal

Let a bit rate is b bits/sec.

Time to send 8 bits is $8/b$ sec.

The frequency of the first harmonics is $b/8$ Hz.

The voice-grade line, has cut off frequency just above 3000 Hz. This restriction means that the number of the highest harmonic passed through is roughly $3000/(b/8)$ or $24000/b$, (the cut-off is not sharp).

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

Theoretical Basis for Data Communication (cont.)

Maximum Data Rate of a Channel

- Two theorems.
  - Nyquist
  - Shannon
- Nyquist theorem : For noiseless channel
- Shannon's theorem : For noisy channel

Theoretical Basis for Data Communication (cont.)

Maximum Data Rate of a Channel

Nyquist theorem

- If an arbitrary signal passes through a low-pass filter of bandwidth H, the filtered signal can be completely reconstructed by making only 2H (exact) samples per second.
- Relates the data rate to the bandwidth (H) and number of signal levels (V) on a noiseless channel.

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

- Ex : A noiseless 3-kHz channel cannot transmit binary (i.e., two-level) signals at a rate exceeding 6000 bps.

$$Max\ data\ rate = 2 \times 3000 \times log_2 2 = 6000 \times 1 = 6000\text{bps}$$

Theoretical Basis for Data Communication (cont.)

Maximum Data Rate of a Channel

Shannon's theorem

- Assumes the presence of thermal noise in the channel due to movement of molecules always.
- The strength of the signal is expressed in the form of 10 log10 (signal power/noise power)(i.e. in dB)
- Relates the data rate to the bandwidth (H) and signal strength (S) relative to the noise (N).

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

- A channel of 3000-Hz bandwidth with a signal to thermal noise ratio (S/N) of 30 dB can never transmit much more than 30,000 bps.

$$10\log_{10}(S/N) = 30 \rightarrow \log_{10}(S/N) = 3 \rightarrow (S/N) = 10^3 \rightarrow 1000$$

$$Max\ data\ rate$$
$$= 3000 \times \log_2(1 + 1000) = 3000 \times \log_2 1001 = 3000 \times 9.967 < 30000$$

Example

We have a channel with a 1 MHz bandwidth. The SNR for this channel is 63; what is the appropriate bit rate and signal level?

Solution

First, we use the Shannon formula to find our upper limit. $\boxed{\text{Max. data rate} = H \log_2(1 + S/N) \text{ bits/sec}}$

$$C = H \log_2 (1 + S/N) = 10^6 \log_2 (1 + 63) = 10^6 \log_2 (64) = 6 \text{ Mbps}$$

Then we use the Nyquist formula to find the number of signal levels. $\boxed{\text{Max. data rate} = 2H \log_2 V \text{ bits/sec}}$

$$6 \text{ Mbps} = 2 \times 1 \text{ MHz} \times \log_2 V \rightarrow L = 8$$

Theoretical Basis for Data Communication (cont.)

Maximum Data Rate of a Channel

Q1. A noiseless 8-kHz channel is sampled every 1 sec. What is the maximum data rate if the 2 level digital signal are used?

Answer :

Number of samples/sec = 2 X 8KHz = 16,000 samples/sec

Assuming each sample is represented by 2 bits, the data rate = 16,000 X 2 = 32 Kbps

Q2. Television channels are 6 MHz wide. How many bits/sec can be sent if four-level digital signals are used? Assume a noiseless channel.

Answer :

Max. data rate = $2H \log_2 V$ bits/sec

Given H = 6 MHz, V = 4

Data rate = $2 \times 6 \times 10^6 \times (\log_2 4)$ = 24 Mbps

Theoretical Basis for Data Communication (cont.)

Maximum Data Rate of a Channel

Q3. If a binary signal is sent over a 3-kHz channel whose signal-to-noise ratio is 20 dB, what is the maximum achievable data rate?

Answer :

Max. data rate = H $\log_2(1 + S/N)$ bits/sec

Given S/N = 20 dB = 100, H = 3 KHz

Data rate = $3 \times 10^3 \times (\log_2 101)$ = 19.975 Kbps

However according to Nyquist theorem with this data rate the signal can't be reconstructed at the receiving end.

So, the maximum data rate = 2 X 3 KHz = 6 Kbps (assuming 1 bit/sample)

Guided transmission media

- Magnetic media
- Twisted pairs
- Coaxial cable
- Fiber optics

Guided transmission media (cont.)

Magnetic media

- Exactly not satisfying the criteria of a computer network.
- Can be used when the transmission rate is slow and a higher amount of data is to be transferred in a stipulated time.
- Uses magnetic tape or removable media.
- Physically transported to the destination machine.

Example :

For a bank with many gigabytes of data to be backed up daily on a second machine (so the bank can continue to function even in the face of a major flood or earthquake), it is likely that no other transmission technology can even begin to approach magnetic tape for performance.

Guided transmission media (cont.)

Twisted Pair

- One of the oldest and still most common transmission media.
- Consists of two insulated copper wires(typically about 1 mm thick) twisted together in a helical form, just like a DNA molecule.
- Effectively less radiation from each wire.

  (Two wires in parallel can act as antenna, when twisted waves from different twists cancel out)
- Low cost.
- Adequate performance.
- Most common application of the twisted pair is the telephone system.
- Can run several kilometres without amplification, but for longer distances, repeaters are needed.
- More than one twisted pairs can run in parallel for a substantial distance being bundled together and encased in a protective sheath.
- Can be used for transmitting either analog or digital signals.
- Bandwidth depends on the thickness of the wire and the distance travelled.

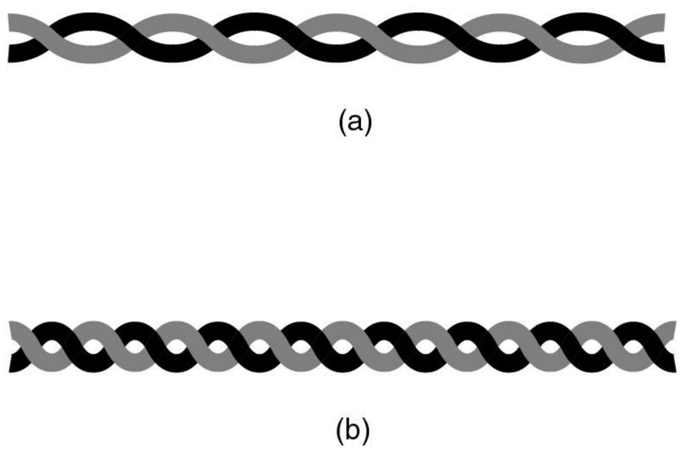
  (several megabits/sec can be achieved for a few kilometres)

Guided transmission media (cont.)

Twisted Pair

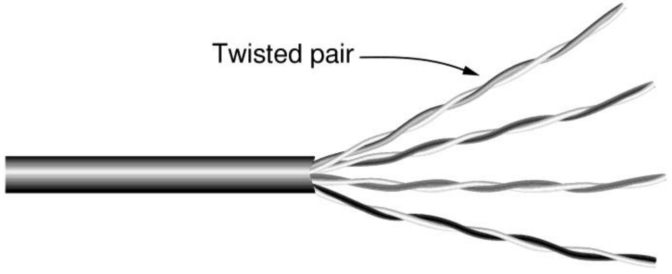
Types :

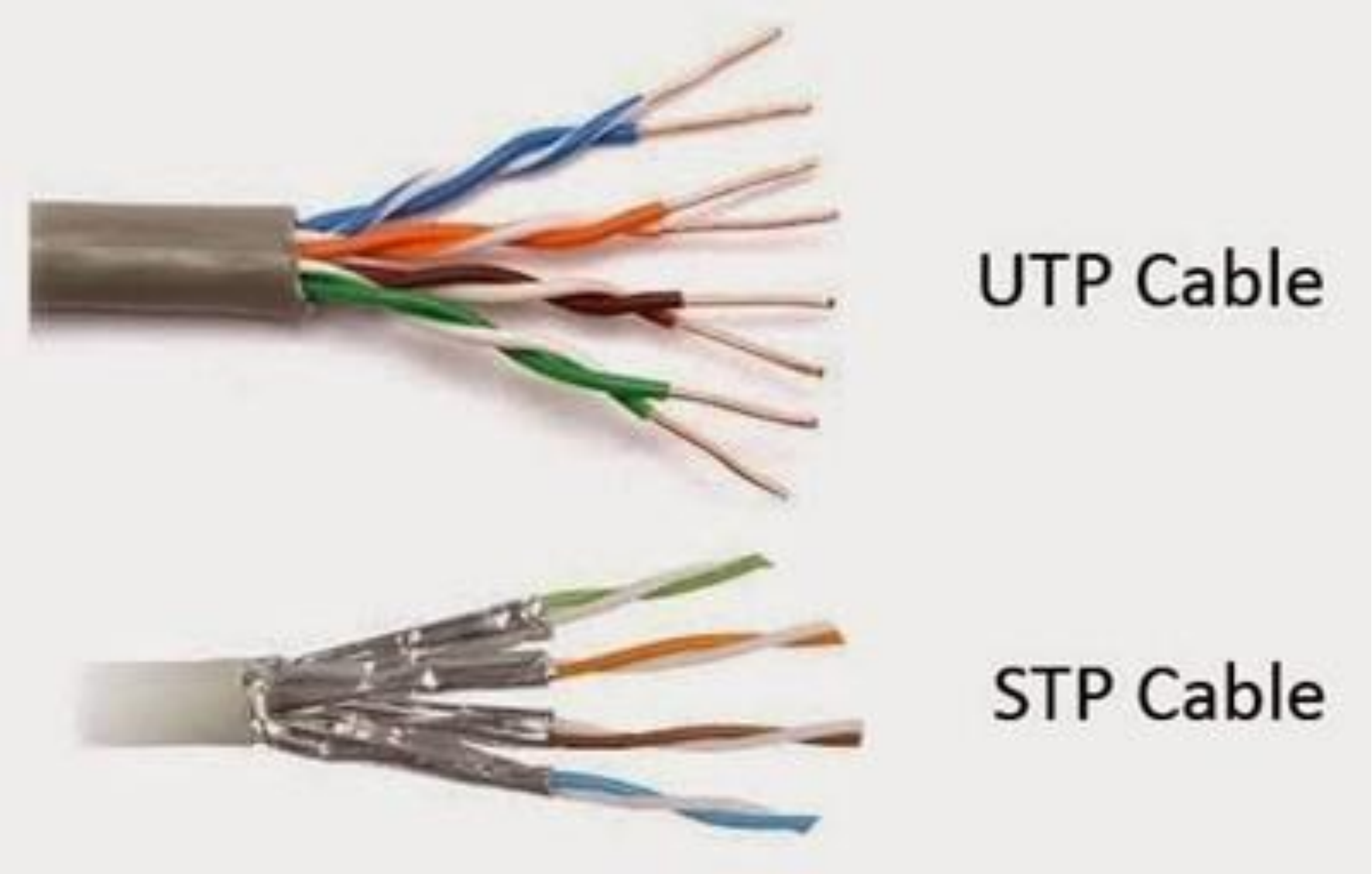
- UTP (unshielded twisted pair)
  - Category 3 :
    - Two insulated wires gently twisted together and four such pairs grouped in a plastic sheath
    - 16 MHz
  - Category 5 :
    - Similar to category 3, but more twists per centimeter.
    - Less crosstalk.
    - Better-quality signal over longer distances
    - More suitable for high-speed computer communication.
    - 100 MHz.
- STP (shielded twisted pair) : Not popularly used, bulky than UTP



(a) Category 3 UTP. (b) Category 5 UTP.

Category 5 UTP cable with four twisted pairs




UTP Cable
STP Cable

Guided transmission media (cont.)

Co-axial Cable

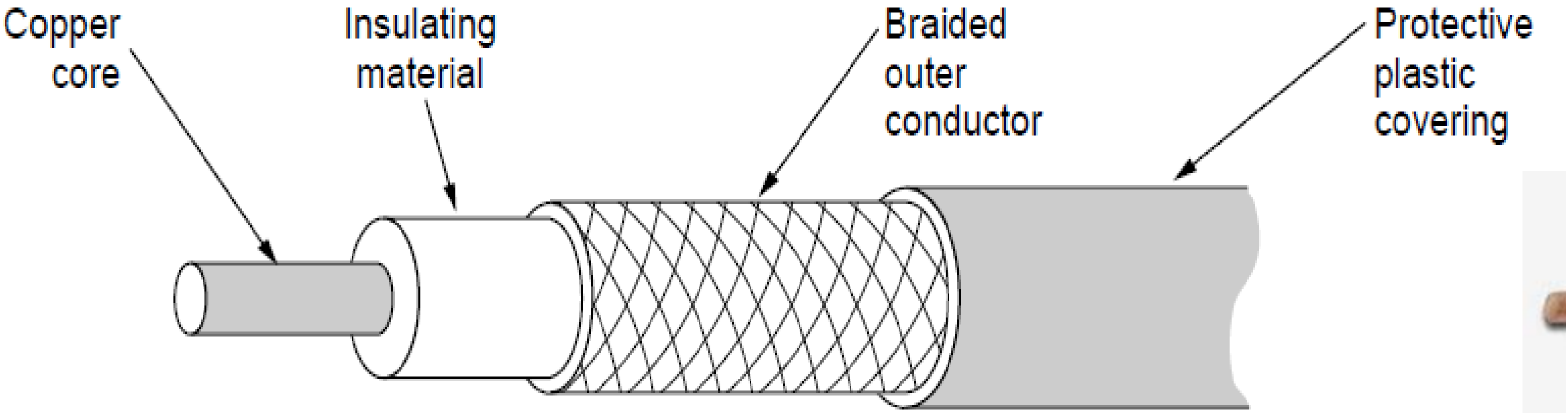
- Better shielding than twisted pairs.
- Span longer distances at higher speeds.
- Two kinds :
  - 50 ohm : Intended for digital transmission.
  - 75 ohm : Mostly analog (Initially for cable TV and now also for internet).
- High bandwidth (close to 1 GHz).
- Excellent noise immunity.

Guided transmission media (cont.)

Coaxial Cable

Construction :

- Two conductors : Inner and outer
- Inner conductor : Consists of a stiff copper wire as the core, surrounded by an insulating material.
- The insulator is encased by a cylindrical conductor (outer conductor), often as a closely-woven braided mesh.
- The outer conductor is covered in a protective plastic sheath.



Cutaway view of a coaxial cable

Guided transmission media (cont.)

Fiber Optics

- Widely accepted high speed data communication technology.
- Most common is 1Gbps (but also possible up to 10 Gbps).
- Common for high rates and long distances.
- Popular in the term FTTH (fiber to the home) for internet access.

<u>Optical transmission system:</u>

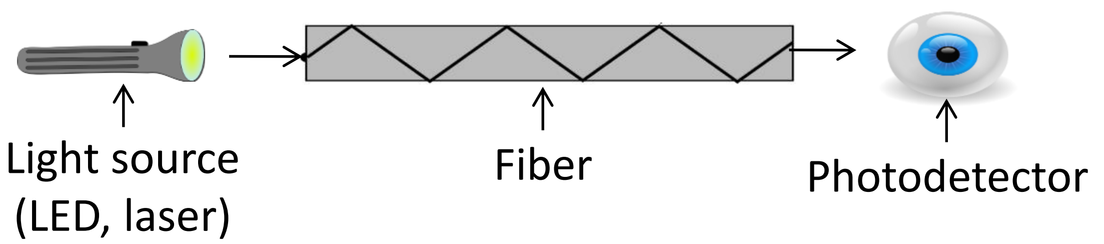
Three key components :

(1) Light source : Generates a pulse of light (bit ‘1’) and absence of light (bit ‘0’).

(2) Transmission medium : Ultra-thin fiber of glass.

(3) Photo detector : Generates an electrical pulse when light falls on it.

By attaching a light source to one end of an optical fiber and a detector to the other, we have a unidirectional data transmission system that accepts an electrical signal, converts and transmits it by light pulses, and then reconverts the output to an electrical signal at the receiving end.

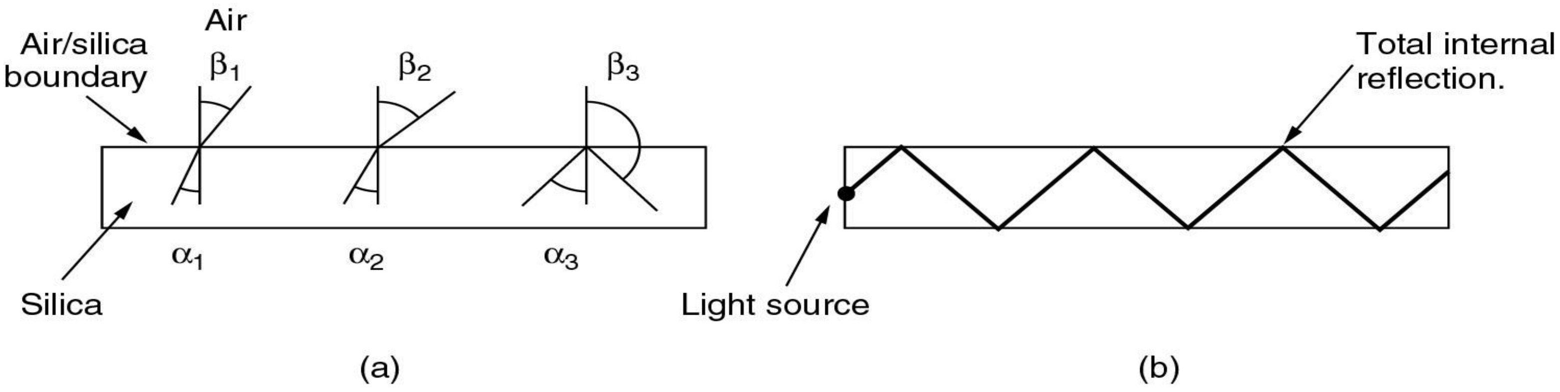


Guided transmission media (cont.)

Fiber Optics

Physics behind transmission of light :

- Aim : To avoid loss of light in transmission medium.
- When a light ray passes from one medium to another (e.g. fused silica to air), the ray is refracted (bent) at the silica/air boundary.
- For angles of incidence above a certain critical value, the light is reflected back into the silica; none of it escapes into the air.
- Thus, a light ray incident at or above the critical angle is trapped inside the fiber, and can propagate for many kilometers with virtually no loss.



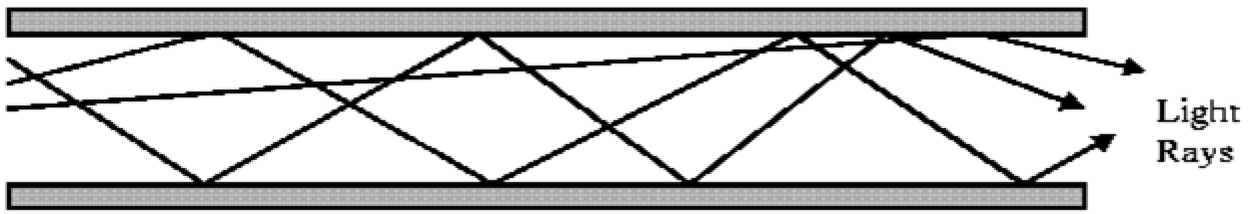
(a) Three examples of a light ray from inside a silica fiber impinging on the air/silica boundary at different angles.
(b) Light trapped by total internal reflection.

Guided transmission media (cont.)

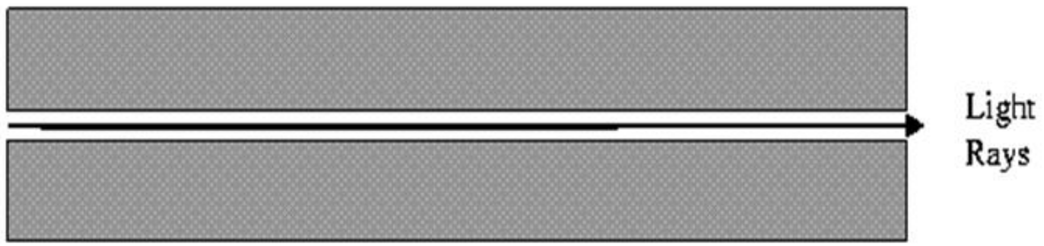
Fiber Optics

Multi mode Vs Single mode:

- Multiple light ray can incident at different angles (but above critical angle), to transmit from one end of the transmission medium to other through reflection.
- Fiber used with this property is called a **multimode** fiber.



- If the fiber's diameter is reduced to a few wavelengths of light, the light can propagate only in a straight line, without bouncing.
- Fiber used with this property is called a **singlemode** fiber.
- Single-mode fibers are more expensive but are widely used for longer distances.



Guided transmission media (cont.)

Fiber Optics

<u>Fiber Cables:</u>

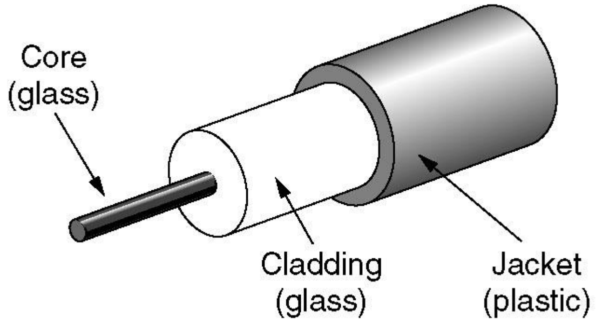
Core : Thin glass fiber at the center through which the light propagates that carries the information.

- 50 microns in diameter for multimode.
- 8 to 10 microns in diameter for singlemode.

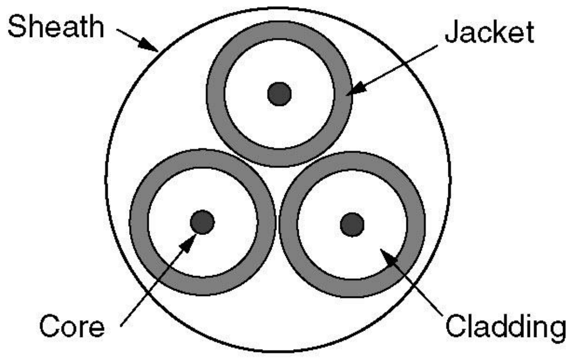
Cladding : The core is surrounded by a glass cladding with a lower index of refraction than the core, to keep all the light in the core.

Jacket : Thin plastic jacket to protect the cladding.

Sheath : Fibers are typically grouped in bundles, protected by an outer sheath.

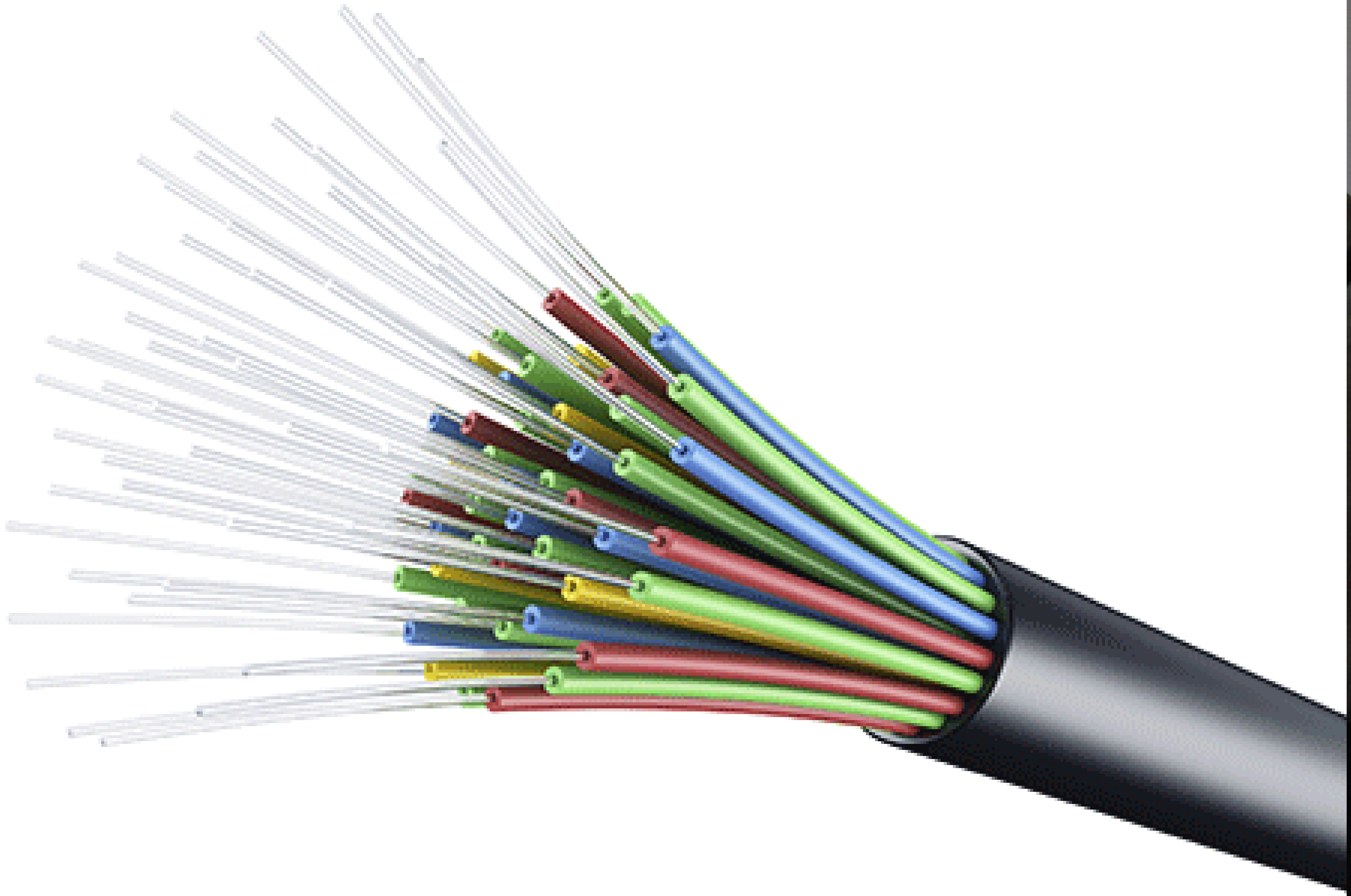


(a)



(b)

(a) Side view of a single fiber. (b) End view of a sheath with three fibers.



Optical fiber

Guided transmission media (cont.)

Fiber Optics

Connection between fibers:

Three different ways.

- They can terminate in connectors and be plugged into fiber sockets.
- Mechanical splices just lay the two carefully-cut ends next to each other in a special sleeve and clamp them in place.
- Two pieces of fiber can be fused (melted) to form a solid connection.

For all three kinds of splices, reflections can occur at the point of the splice (i.e. attenuation/loss).

Guided transmission media (cont.)

Fiber Optics

Light source and comparison:

1. Light emitting diode (LED).
2. Semiconductor LASER.

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

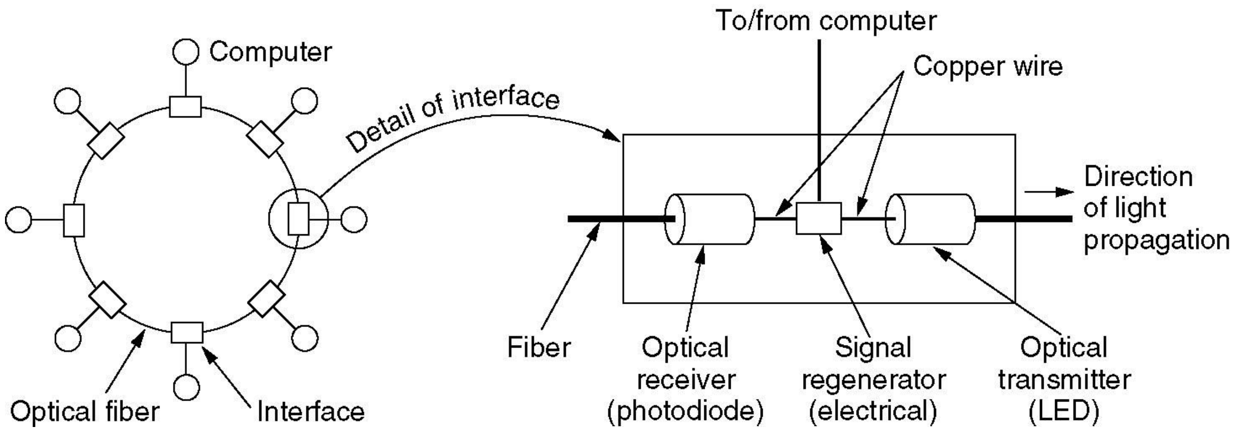
A comparison of semiconductor laser and LEDs as light sources

Guided transmission media (cont.)

Fiber Optics

Fiber Optic Networks:

- Used for LANs as well as for long-haul transmission, although tapping into it is more complex than connecting to an Ethernet.
- Two types of interface :
  - Passive : At the transmitting and receiving end.
  - Active : In between two fiber cable for increasing the strength of the signal (if falls down)



A fiber optic ring with active repeaters

Guided transmission media (cont.)

Fiber Optics Vs Copper Wire: A comparison

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

- Fulfils the need of mobile users to get connected with network for accessing data in their laptops, notebooks etc.
- Use radio waves or infrared light to transmit data.
  - The Electromagnetic Spectrum
  - Radio Transmission
  - Microwave Transmission
  - Infrared and Millimeter Waves
  - Light wave Transmission

Wireless Transmission(cont.)

The Electromagnetic Spectrum

- When electrons move, they create electromagnetic waves that can propagate through space (even in a vacuum).
- Electromagnetic waves are characterized with two variables:
  1. Frequency (f)
  2. Wavelength (λ)
- In vacuum, all electromagnetic waves travel at the same speed (speed of light (c), no matter what their frequency.
- The fundamental relation between f, λ, and c (in vacuum) is

$$c = f\lambda$$

- When an antenna of the appropriate size is attached to an electrical circuit, the electromagnetic waves can be broadcast efficiently and received by a receiver some distance away.(Basic principle behind wireless communication)

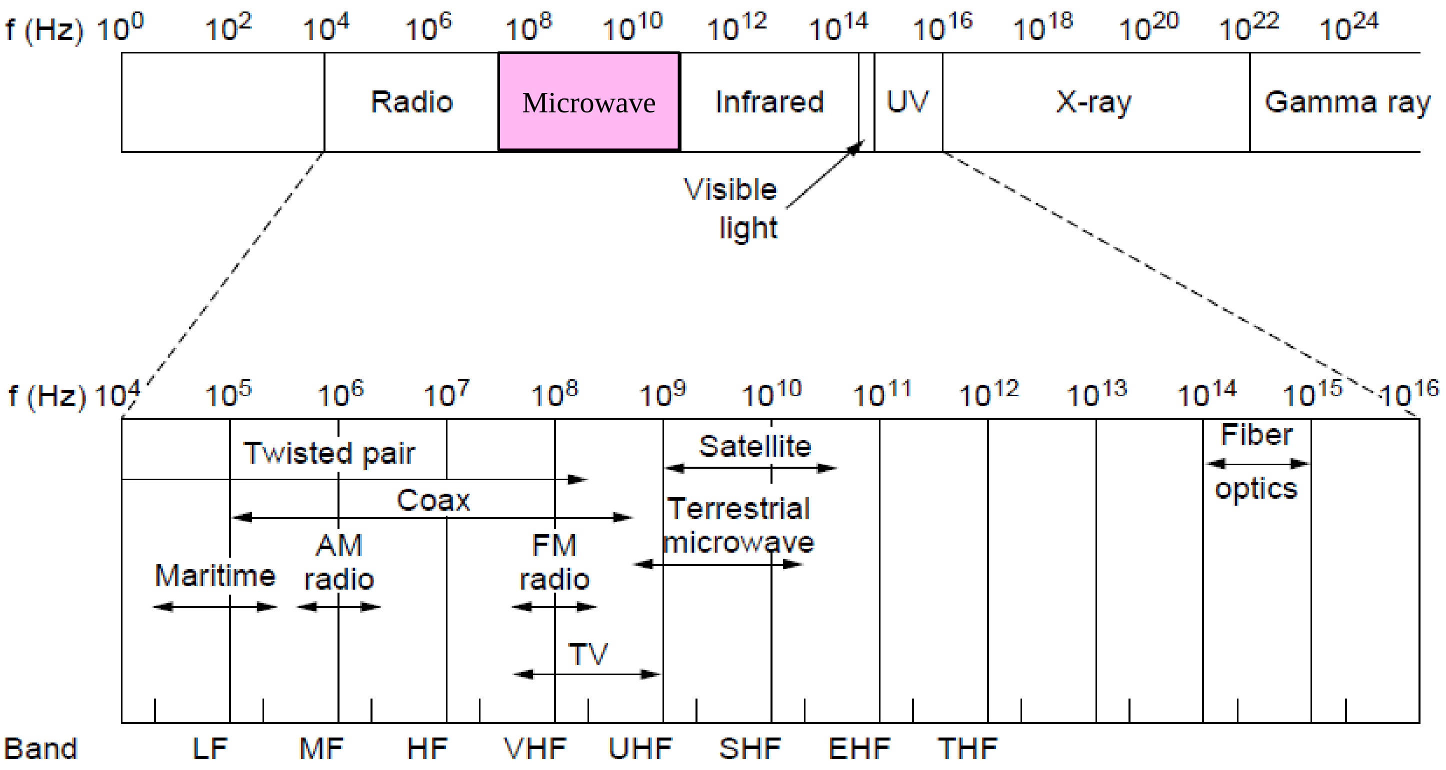
Wireless Transmission(cont.)

The Electromagnetic Spectrum

- Different bands have different uses:
  - Radio: wide-area broadcast; Infrared/Light: line-of-sight
  - Microwave: LANs and 3G/4G; ⟵ Networking focus

- The radio, microwave, infrared, and visible light portions of the spectrum can be used for transmitting information through modulation.

- UV light, X-rays, and gamma rays would be even better, due to their higher frequencies.
- They are hard to produce and modulate, do not propagate well through buildings, and are dangerous to living things.



Wireless Transmission(cont.)

The Electromagnetic Spectrum

- The amount of information that an electromagnetic wave can carry is related to its bandwidth.
- At low frequencies it is possible to encode a few bits per Hertz.
- At high frequencies it is possible to encode as many as 8 bits per Hertz.

  (e.g. a coaxial cable with a 750 MHz bandwidth can carry several gigabits/sec.)
- Bandwidth depends on width of the wavelength of the EM wave.

$$\Delta f = \frac{c\,\Delta\lambda}{\lambda^2}$$

- wider the band, the higher the data rate.

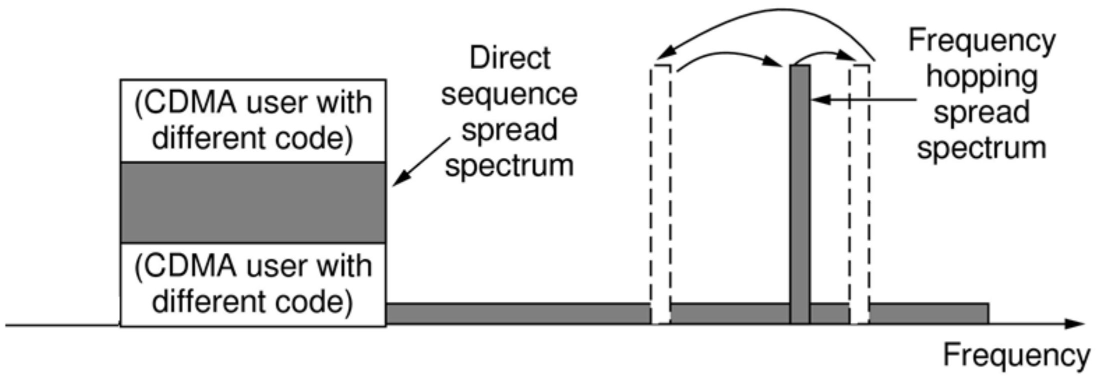
(e.g. a 1.3 micron band with $\Delta\lambda = 0.17 \times 10^{-6}$ supports 30 THz bandwidth or data rate of 240 Tbps)

Wireless Transmission(cont.)

The Electromagnetic Spectrum

Types of transmissions with respect to bandwidth :

- Narrowband transmission
  - Efficient use of spectrum
  - Good quality transmission
- Wideband transmission
  - FHSS (Frequency hopping spread spectrum)
    - The transmitter hops from frequency to frequency hundreds of times per second.
    - Popular in military communications.
    - Makes transmissions hard to detect.
    - Impossible to jam.
    - Offers good resistance to multipath fading (avoids interference)
  - DSSS (Direct sequence spread spectrum)
    - Uses a code sequence to spread the signal over a wide frequency band (e.g. CDMA).
    - Spectrally efficient for multiple signal transmission sharing same channel.



Wireless Transmission(cont.)

Radio Transmission

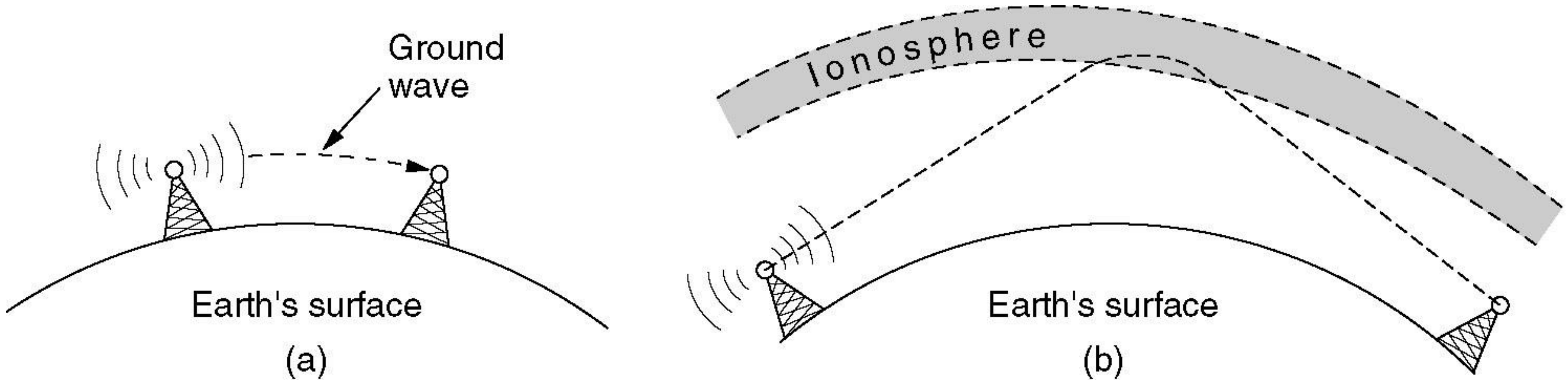
- Data transmits in the form of radio signals(or waves).
- Air/free space - medium of transmission
- RF waves are:
  - Easy to generate
  - Can travel a long distance
  - Penetrate buildings easily
  - Mostly omnidirectional (so, transmitter and receiver do not have to be carefully aligned physically)

Wireless Transmission(cont.)

Radio Transmission

Transmission property is frequency dependent.

- At low frequencies, radio waves pass through obstacles well, but the power falls off sharply with distance from the source, roughly as $1/r^2$ in air.
- At high frequencies, radio waves tend to travel in straight lines and bounce off obstacles.



(a) In the VLF, LF, and MF bands, radio waves follow the curvature of the earth.

(b) In the HF band, they bounce off the ionosphere.

Wireless Transmission(cont.)

Microwave Transmission

- The signals (or waves)above 100 MHz that travels in nearly straight line.
- Mostly uses parabolic antenna to achieve higher S/N ratio.
- Requires carefully alignment between transmission and Reception antennas.
- Before fiber optics, for decades these microwaves formed the heart of the long-distance telephone transmission system.
- Since the microwaves travel in a straight line, if the towers are too far apart, the earth will get in the way and thus requires repeater in between.
- Suffers from low penetration capability through buildings.
- Possibility of multipath fading due to reflected wave(delayed version of transmitted wave).

Wireless Transmission(cont.)

Infrared and Millimetre Waves

- Widely used for short-range communication(e.g. The remote controls used on televisions, VCRs, and stereos all use infrared communication.)
- Relatively directional, cheap and easy to build.
- Major drawback: they do not pass through solid objects, but can be treated as advantage (e.g. infrared transmission in one room never interferes to infrared transmission in other room.)
- No government license is needed to operate an infrared system.
- Mostly for indoor use.

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

Public Switched Telephone Network (PSTN)

When the distances between computers are large or there are many computers to communicate with each other, the cables may have to pass through a public road or other public right of way.

Issues :

- Costs of running private cables are usually prohibitive.
- Stringing private transmission lines across (or underneath) public property is also illegal.

Solution to the issues :

- Rely on the existing telecommunication facilities (i.e. **PSTN**).

PSTN :

- Initially designed to provide voice communication service.
- Acceptable for data communication with lower magnitude of performance.

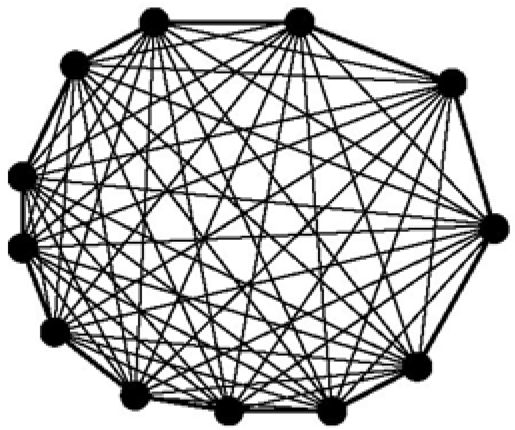
  (e.g. A cable running between two computers can transfer data at 10^9 bps, In contrast, a dial-up line has a maximum data rate of 56 kbps)
- Trade off between speed and data communication services.

Note : In the due course of time with the use of advanced technology the performance w.r.t data communication through dial up service has also been enhanced.

Public Switched Telephone Network (cont.)

Structure of the Telephone System

- Soon after the commercialization of telephone instrument (in 1876), there was a high demand of interconnection between a pair of telephones in different houses in cities.
- Within a year, the cities were covered with wires (for making connections between a pair of phones) passing over houses and trees in a wild jumble.



Fully-interconnected network.

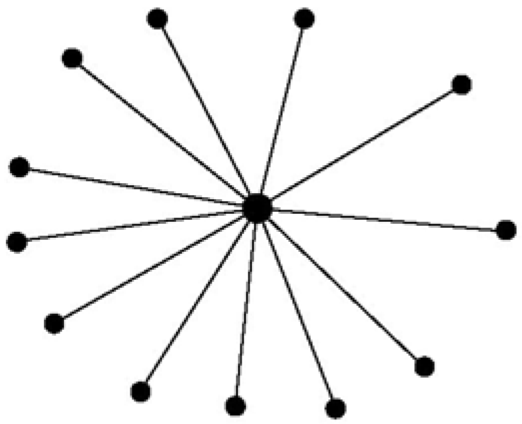
- It became immediately obvious that the model of connecting every telephone to every other telephone, as shown in above figure, was not going to work.

Public Switched Telephone Network (cont.)

Structure of the Telephone System

- Formation of Bell Telephone Company, which opened its first switching office in 1878.
- The company ran a wire to each customer's house or office.
- Establishment of call between two customers takes place through the switching office.

  (i.e. an operator makes the connection between caller and callee manually using a jumper wire.)



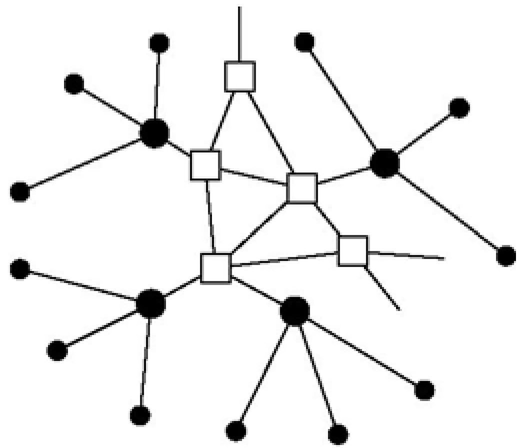
Centralized switch.

- A requirement of switching office in every city.

Public Switched Telephone Network (cont.)

Structure of the Telephone System

- People wanted to make long distance calls between cities, so the Bell system began to connect the switching offices.
- To connect every switching office to every other switching office by means of a wire between them quickly became unmanageable as happened in the beginning for connecting two telephones.
- Second-level switching offices were installed, and grew in number to fulfil the need.
- The system takes a look of hierarchical structure of offices.



Two-level hierarchy.

Public Switched Telephone Network (cont.)

Structure of the Telephone System

Three major parts of the telephone system to provide connection between two customers.

- The switching offices.
- The wires between the customers and the switching offices.
- The long-distance connections between the switching offices.

This basic Bell System model has remained essentially intact for over 100 years.

Concept of Local loop :

- Each telephone has two copper wires coming out of it that go directly to the telephone company's nearest end office situated at a distance between 1 to 10 km.
- The two-wire connections between each subscriber's telephone and the end office are known in the trade as the **local loop**.

Public Switched Telephone Network (cont.)

Structure of the Telephone System

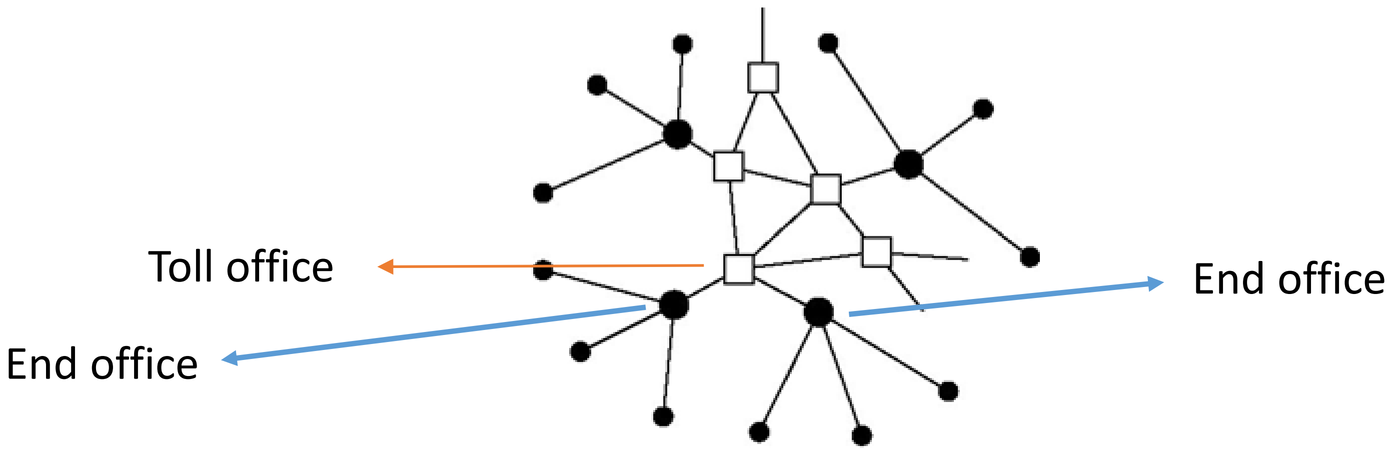
Communication process through telephone system:

Case 1 : Both subscribers attached to same end office.

- The switching mechanism within the office sets up a direct electrical connection between the two local loops.

Case 2 : Both subscribers attached to two different end office.

- Each end office has a number of outgoing lines(known as trunks) to one or more nearby switching centers, called toll offices.
- If both end offices are connected to same toll office, connection is limited within same toll office.

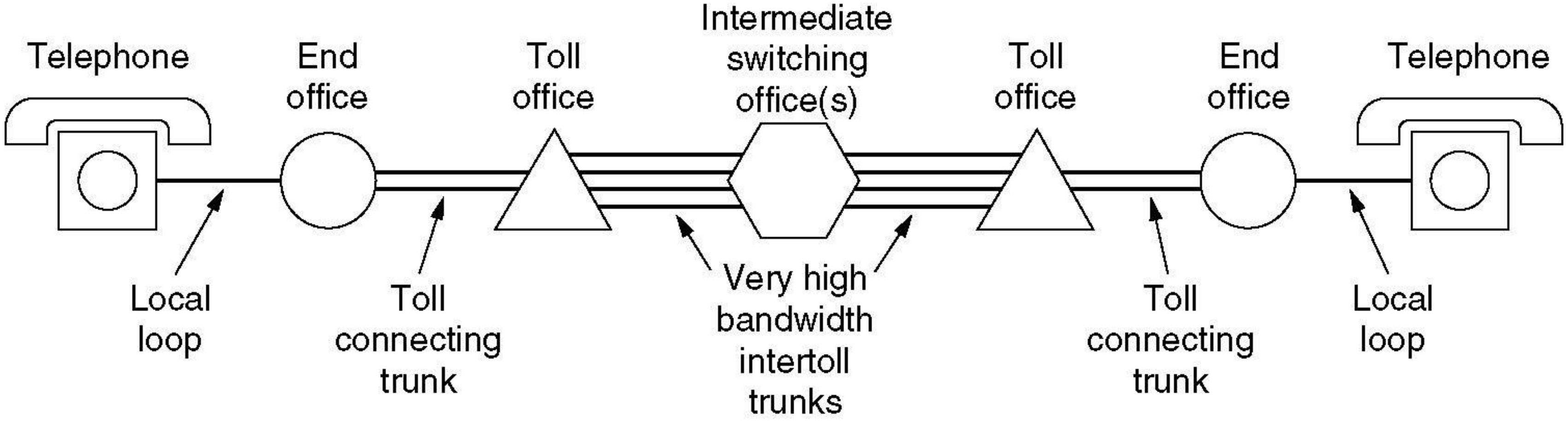


Public Switched Telephone Network (cont.)

Structure of the Telephone System

Case 3 : The caller and callee do not have a toll office in common.

➢ Communication established with the help of higher level in hierarchy (i.e. high bandwidth Inter toll trunks)



A typical circuit route for a medium-distance call.

Transmission media :

- ➢ Local loops consist of category 3 twisted pairs nowadays (early days, uninsulated wires spaced 25 cm apart on telephone poles).
- ➢ Between switching offices, coaxial cables, microwaves, and especially fiber optics are widely used.

Public Switched Telephone Network (cont.)

Structure of the Telephone System

Components in technical term in telephone system and their importance:

Three major components.

1. Local loops (analog twisted pairs going into houses and businesses).
    - Gives access to everyone into the whole system, so important.
2. Trunks (digital fiber optics connecting the switching offices).
    - For long haul trunks transmission of multiple calls together through single fiber(i.e. multiplexing) is an important issue.
3. Switching offices (where calls are moved from one trunk to another).
    - Switching can be done in different ways, so important.

The Local Loop: Modems, ADSL and Wireless

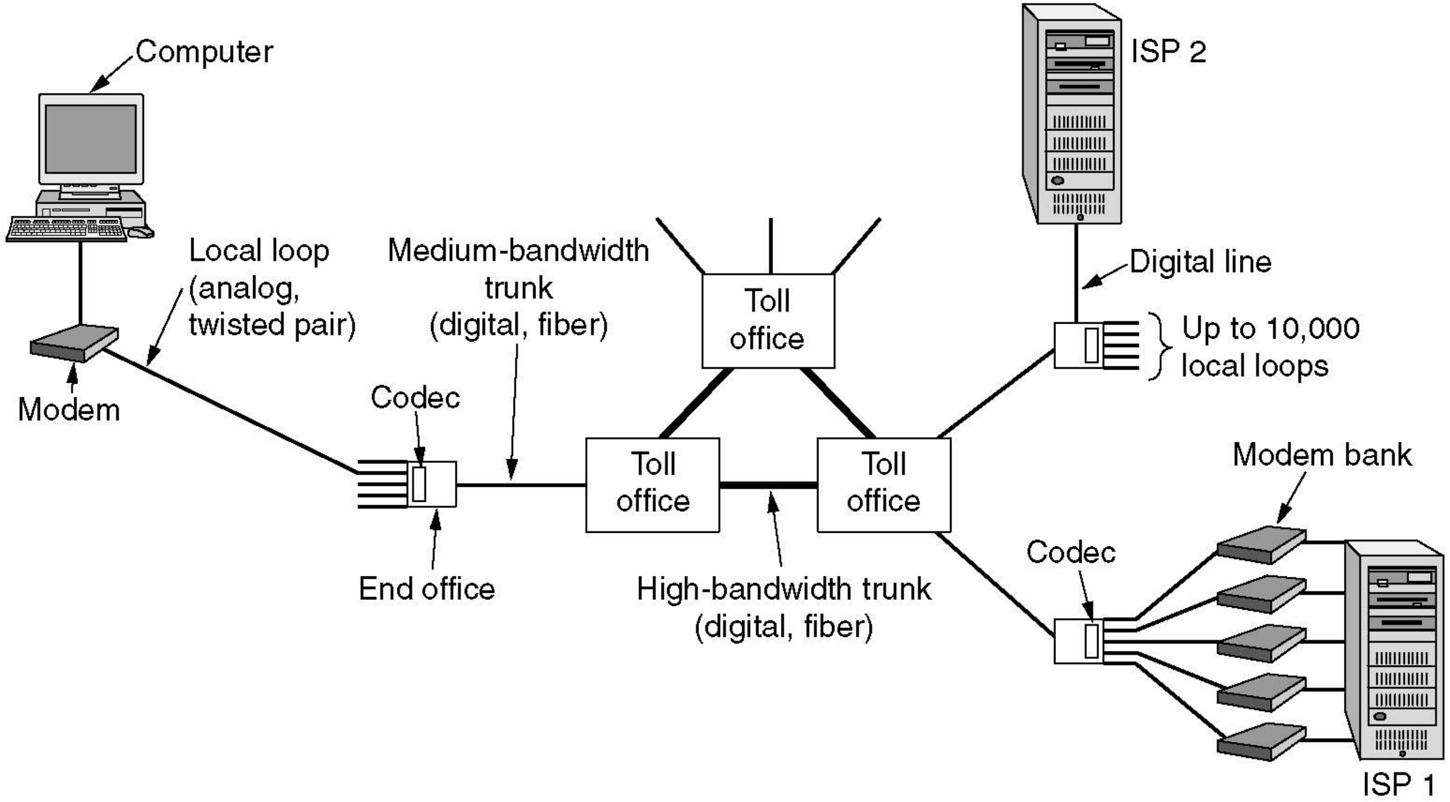
The computer to computer communication through telephone system involves both analog and digital transmission.

Local loop : Analog

End office – Toll office : Digital

Toll office – Toll office : Digital

Conversion between analog and digital done by modems and codecs.



The use of both analog and digital transmission for a computer to computer call.

The Local Loop: Modems, ADSL and Wireless(cont.)

- Though the computer works with digital data comprising of less error, due to the imperfectness of transmission line the received signal in a telephone system may not be equal to the transmitted signal.
- Transmission lines suffer from three major problems: attenuation, delay distortion, and noise.

Attenuation:

- Loss of energy due to transmission over a distance (i.e. distance dependent).
- Loss of energy due to transmission of multiple frequency component in a signal (i.e. frequency dependent).
- Usually recovered by the use of amplifiers and equalizers.

Delay distortion:

- Caused due to transmission of multiple frequency component at different speeds.

Noise:

- Unwanted energy from sources other than transmitter (e.g. thermal noise, cross talk and impulse noise).
- Thermal noise : Caused by the random motion of the electrons in a wire and is unavoidable.
- Crosstalk : Caused by inductive coupling between two wires that are closed to each other.
- Impulse noise : Caused by spikes in the power line.

The Local Loop: Modems, ADSL and Wireless(cont.)

Modems

- Short form for Modulator-Demodulator.
- Modulation in transmitting end and demodulation in receiving end.

Why modulation ?

- Square waves used in digital signals have a wide frequency spectrum and thus are subject to strong attenuation and delay distortion.
- Baseband (DC) signalling found unsuitable except at slow speeds and over short distances.
- Solution : AC signalling (e.g. use of sine wave of 1-2 KHz to carry digital signal).
- Carrier signal changes its characteristics (i.e. amplitude, frequency or phase) according to baseband signal – Modulation.

The Local Loop: Modems, ADSL and Wireless(cont.)

Modems

Amplitude Modulation : ASK (Amplitude Shift Keying)

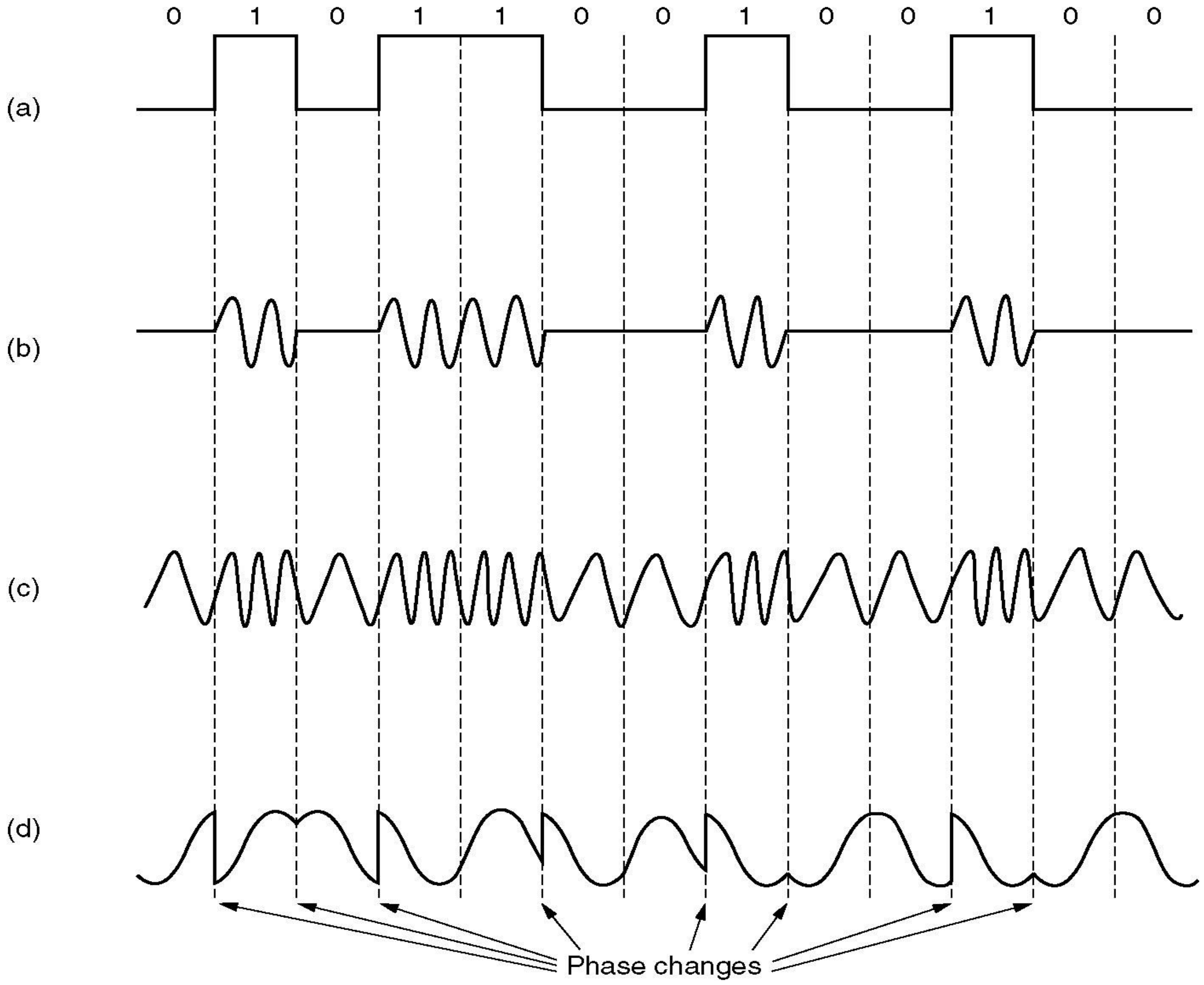
- Change in amplitude of carrier based on amplitude of baseband.
- For Binary signal two different amplitudes are used.

Frequency Modulation : FSK (Frequency Shift keying)

- Change in frequency of the carrier based on amplitude of baseband.
- For binary signal two different frequencies are used.

Phase Modulation : PSK (Phase shift Keying)

- Phase of the carrier changes based on amplitude of baseband signal.
- For binary signal two (0^0 and 180^0)/four phase angles (45^0, 135^0, 225^0, or 315^0) are used depending on no. of bits transmitted per time interval.
- Ex : BPSK, QPSK



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

The Local Loop: Modems, ADSL and Wireless(cont.)

Modems

Concept of Bandwidth, Baud rate, Symbol rate, bit rate :

The data transmission rate in the channel can be associated with various terminologies such as bandwidth, baud rate, symbol rate and bit rate.

Bandwidth : Property of transmission medium which represents the range of frequencies that pass through it with minimum attenuation (measured in Hz).

Baud rate : The number of samples/sec made to be transmitted.

Symbol rate : The amount of information sample(i.e. symbol) transmitted per second.

(If each sample denotes one piece of information is a symbol, then baud rate is same as symbol rate)

Bit rate : Amount of information sent over the channel and is equal to the number of symbols/sec times the number of bits/symbol.

(Note : The modulation technique decides the no. of bits to be used to represent a symbol(e.g. in QPSK each symbol is represented by 2 bits))

Example :
If the baud rate is 2400 and each symbol is represented by 1 bit (‘0’ or ‘1’), then bit rate is 2400 bps.
If the baud rate is 2400 and each symbol is represented by 2 bits, then bit rate is 4800 bps.

The Local Loop: Modems, ADSL and Wireless(cont.)

Modems

- All advanced modems use a combination of modulation techniques to transmit multiple bits per baud.
- Often multiple amplitudes and multiple phase shifts are combined to transmit several bits/symbol.

QPSK **(Quadrature PSK)**:

4 combinations, 2 bits/symbol.

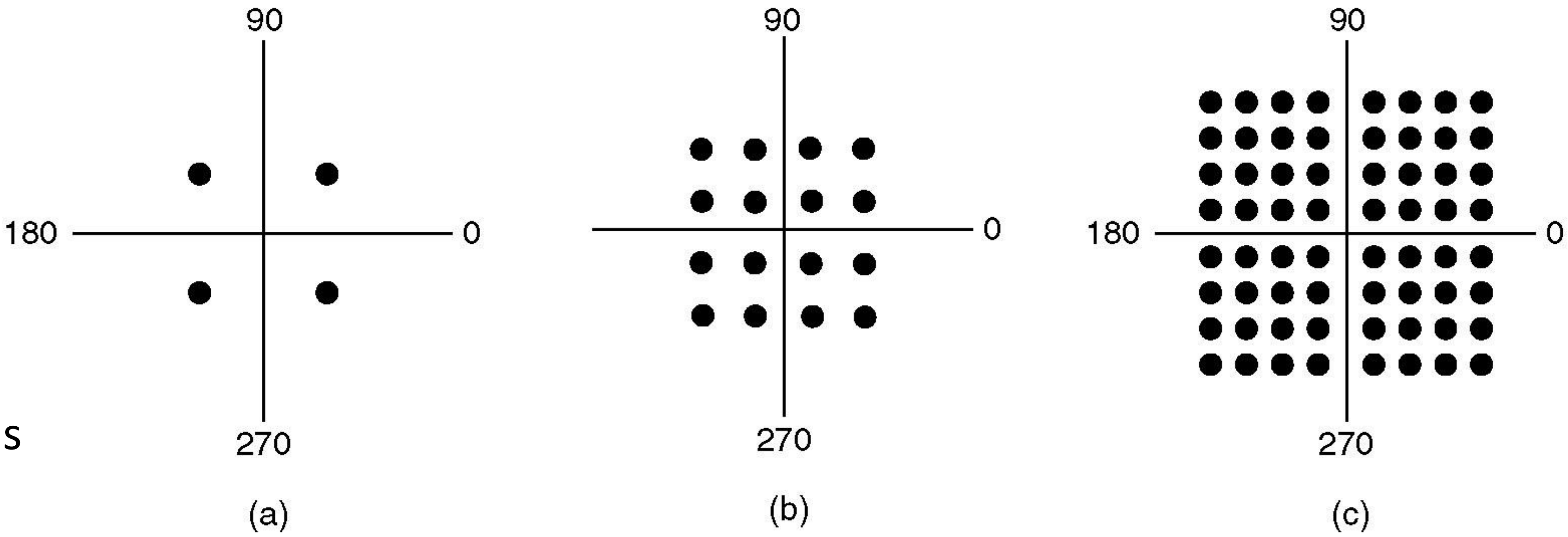
QAM 16 :

16 combinations, 4 bits/symbol.

QAM 64 :

64 combinations, 6 bits/symbol.

- This kind of representation is known as Constellation diagram.
- Modems used at both ends must support same constellation pattern.



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

The Local Loop: Modems, ADSL and Wireless(cont.)

Modems

Questions on data rate and modulation:

Question.

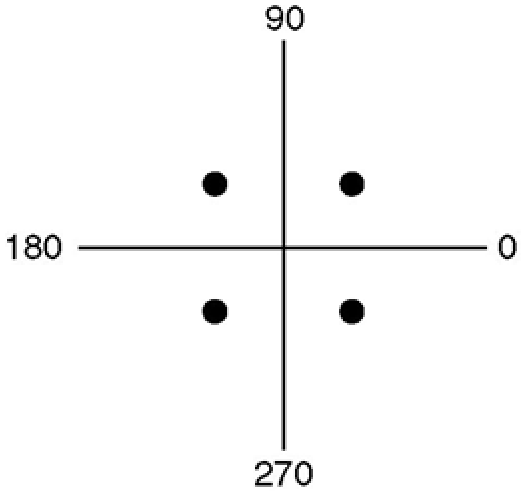
A modem constellation diagram has data points at the following coordinates: (1, 1), (1, -1), (-1, 1), and (-1, -1). How many bps can a modem with these parameters achieve at 1200 baud?

Answer :

4 combinations – 2 bits/symbol

Baud rate = Symbol rate = 1200

Bit rate = 1200 X 2 = 2400 bps



The Local Loop: Modems, ADSL and Wireless(cont.)

Modems

Questions on data rate and modulation:

Question 1.

A modem constellation diagram has data points at the following coordinates: (0, 1) and (0, 2). Does the modem use phase modulation or amplitude modulation?

Solution :

The two points indicates a phase shift of 0^0 with two different amplitudes. So the modulation used is only amplitude modulation.

Question 2.

In a constellation diagram, all the points lie on a circle cantered on the origin. What kind of modulation is being used?

Solution :

All the points lie on the circle, which means all points are at equal distant from origin. However, the angle of each point with respect to +ve X axis drawn from origin are different, that means the points differs in phase. Since frequency modulation is not used in constellation diagram, the kind of modulation specified here is phase modulation.

The Local Loop: Modems, ADSL and Wireless(cont.)

Modems

Modulation supporting to error correction :

- Even a small amount of noise in the detected amplitude or phase can result in an error.
- Higher speeds modems do error correction by adding extra bits to each sample.
- Modulation process allows the data bits along with correction (say parity)bits : Ex- Trellis Coded Modulation

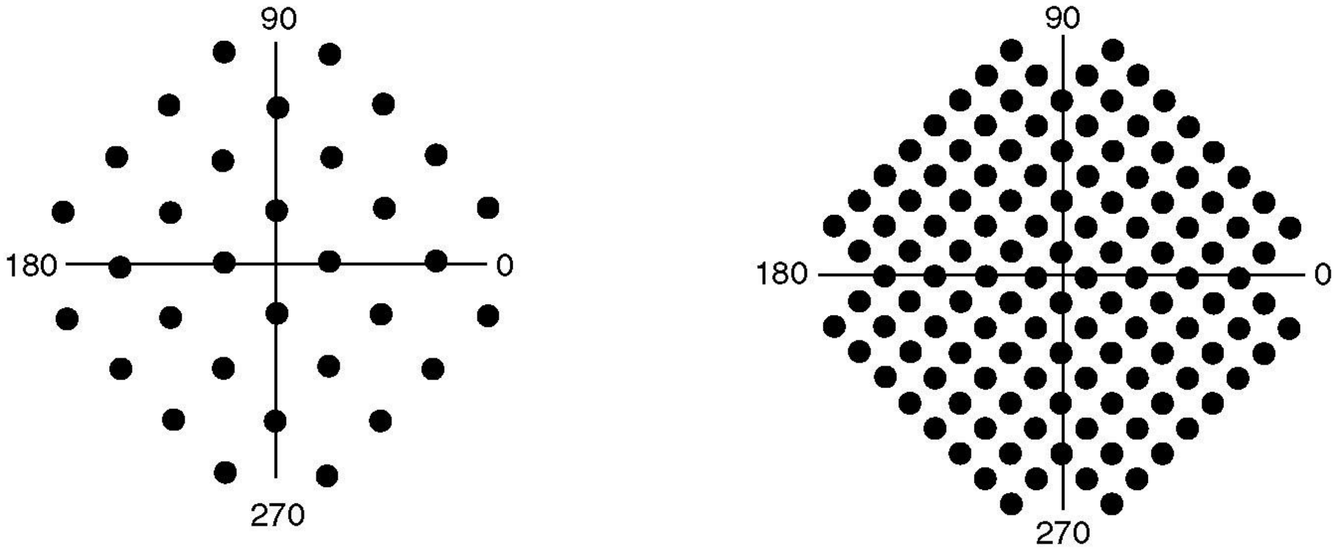
Modems using this type modulation :

V.32

- 32 constellation points
- 4 data bits and 1 parity bit per symbol

V.32 bis

- 128 constellation points
- 6 data bits and 1 parity bit per symbol



(a) (b)

(a) V.32 for 9600 bps.

(b) V.32 bis for 14,400 bps.

The Local Loop: Modems, ADSL and Wireless(cont.)

Modems

Some faster modems :

- V.90 offers 56kbps download and 33.6 kbps upload speeds.
- In uploading, the analog signal must be sampled at the switching stations which means the data rate for uploading is limited to 33.6 as earlier. But, there is no sampling in the downloading, hence no noise , hence no Shannon's limit (theoretically at least).
- Beyond V.90 is V.92 in which the upload speed can be at 48kbps.

The Local Loop: Modems, ADSL and Wireless(cont.)

Modems

All modern modems allow traffic in both directions at the same time (by using different frequencies for different directions).

Full duplex : A connection that allows traffic in both directions simultaneously.

Ex : A two lane road

Half duplex : A connection that allows traffic either way, but only one way at a time.

Ex : A single railroad

Simplex : A connection that allows traffic only one way.

Ex : (1) A one-way street

(2) An optical fiber with a laser on one end and a light detector on the other end

The Local Loop: Modems, ADSL and Wireless(cont.)

Modems

Questions :

Q1. Is an oil pipeline a simplex system, a half-duplex system, a full-duplex system, or none of these?

Ans : Oil can flow in either direction, but not both ways at once. So, half-duplex.

Q2. How many frequencies does a full-duplex QAM-64 modem use?

Ans : Two, one for upstream and one for downstream.

The Local Loop: Modems, ADSL and Wireless(cont.)

Digital Subscriber Lines (DSL)

- Demand for increased internet access speed among users.
- Cable TV industry supports a speed up to 10 Mbps.
- To compete with telephone industries offered digital services over local loop (i.e. **DSL)**.
- Supports more bandwidth than standard telephone services (i.e. **broadband**)
- Most popular is **ADSL (Asymmetric DSL).**

Technical justification of having more bandwidth :

Telephone systems used for voice

- The point where each local loop terminates in the end office, signal passes through a filter that attenuates all frequencies below 300 Hz and above 3400 Hz (i.e. bandwidth of 3100 Hz).

Telephone systems using DSL

- The incoming line coming through DSL is connected to a different switch, where the above said filter is absent, thus making the entire capacity of the local loop available.

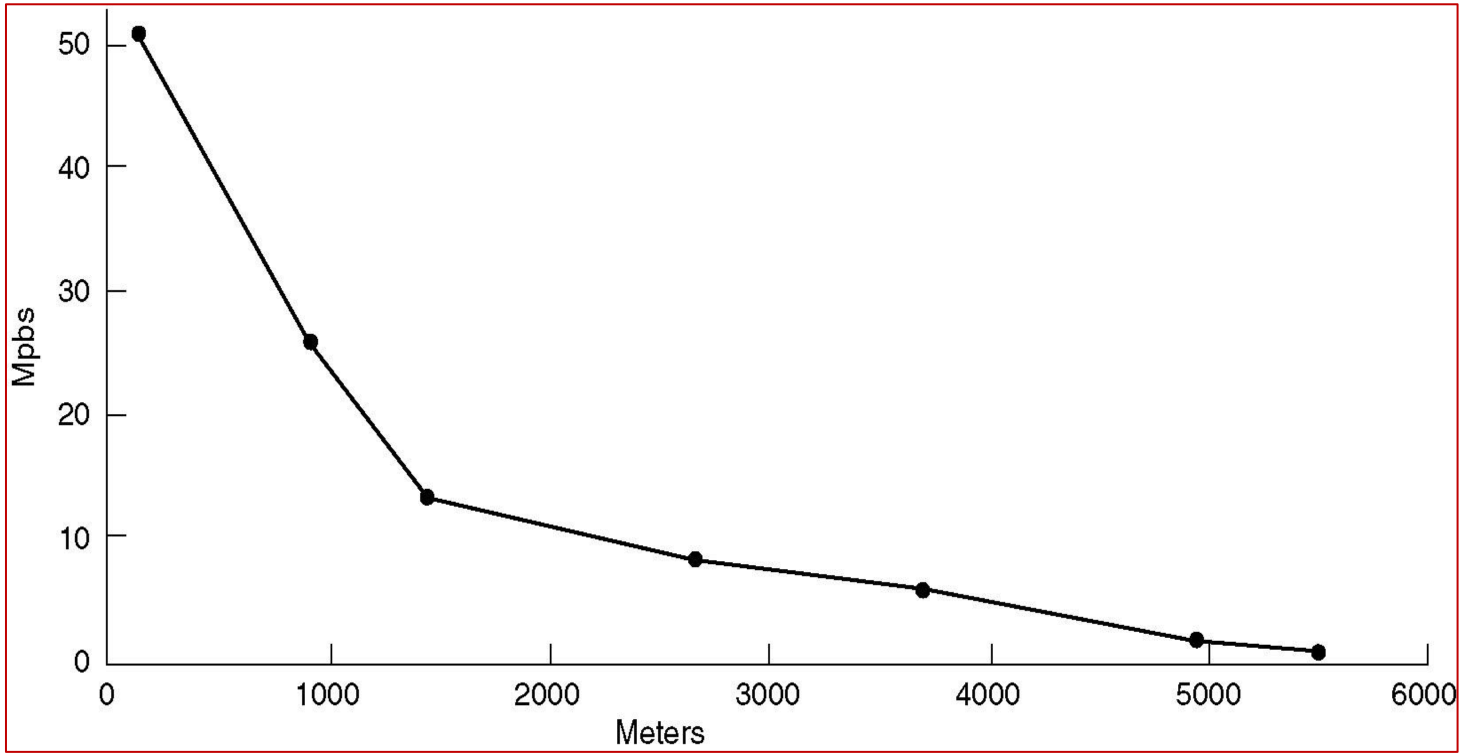
The Local Loop: Modems, ADSL and Wireless(cont.)

Digital Subscriber Lines (DSL)

The capacity of the local loop depends on several factors, including its length, thickness, and general quality.

DSL service is designed keeping 4 goals in mind.

- Services must work over the existing category 3 twisted pair local loops.
- They must not affect customers' existing telephones and fax machines.
- They must be much faster than 56 kbps.
- They should be always on, with just a monthly charge but no per-minute charge.



Bandwidth versus distance over category 3 UTP for DSL

The Local Loop: Modems, ADSL and Wireless(cont.)

Digital Subscriber Lines (DSL)

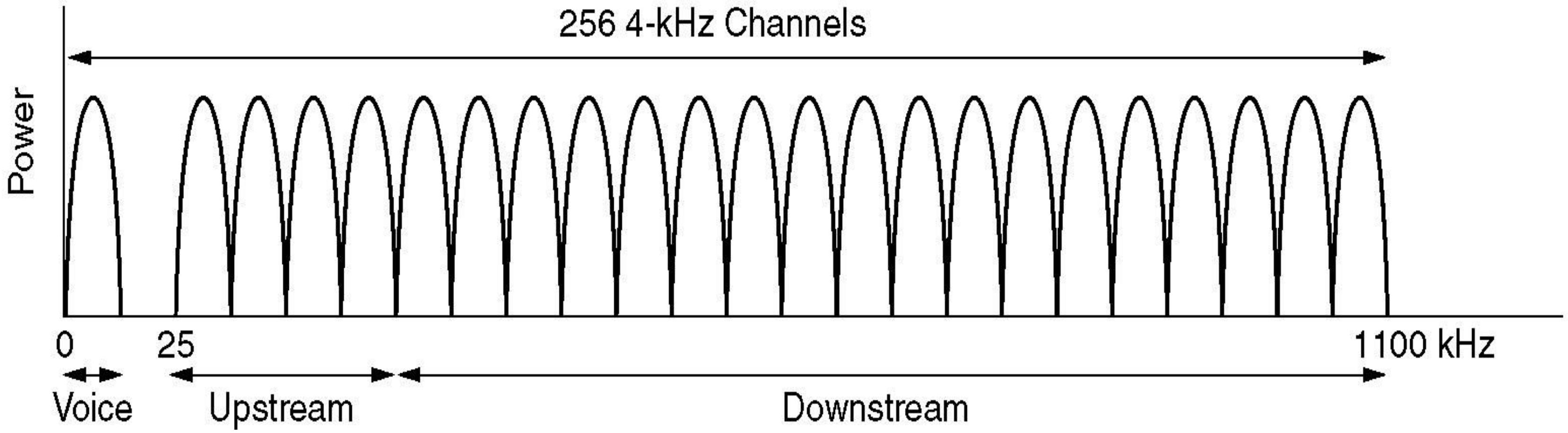
Working of ADSL:

- Uses a spectrum of 1.1 MHz.
- Works through division of the allocated spectrum either of two ways.

1. Divides the spectrum into three bands :
   - (i) POTS (Plain Old Telephone Service)
   - (ii) upstream (user to end office)
   - (iii) downstream (end office to user)
2. Divides the spectrum into 256 channels each of size roughly 4312.5 Hz (Discrete Multi Tone).
   - Channel 0 : POTS
   - Channels 1-5 ; guard band between voice and data
   - Two for control channels, one for downstream and one for upstream
   - Remaining are partitioned between upstream and downstream for data : depends on the service provider; usually it is asymmetric giving 80-90% for download and remaining for upstream – hence the word Asymmetric

The Local Loop: Modems, ADSL and Wireless(cont.)

Digital Subscriber Lines (DSL)



Operation of ADSL using discrete multi tone modulation.

The Local Loop: Modems, ADSL and Wireless(cont.)

Digital Subscriber Lines (DSL)

- Within each channel, modulation scheme similar to V.34 is used
- QAM with 15 bits per baud
- 4000 baud instead of 2400
- Depending on need and line quality the data rate is different for different channel.
- With 224 downstream channels, download speed 13.44 Mbps is theoretically possible
- In practice, S/N ratio is never good enough to achieve this rate, but 8 Mbps is possible on short runs over high quality local loops

The Local Loop: Modems, ADSL and Wireless(cont.)

Digital Subscriber Lines (DSL)

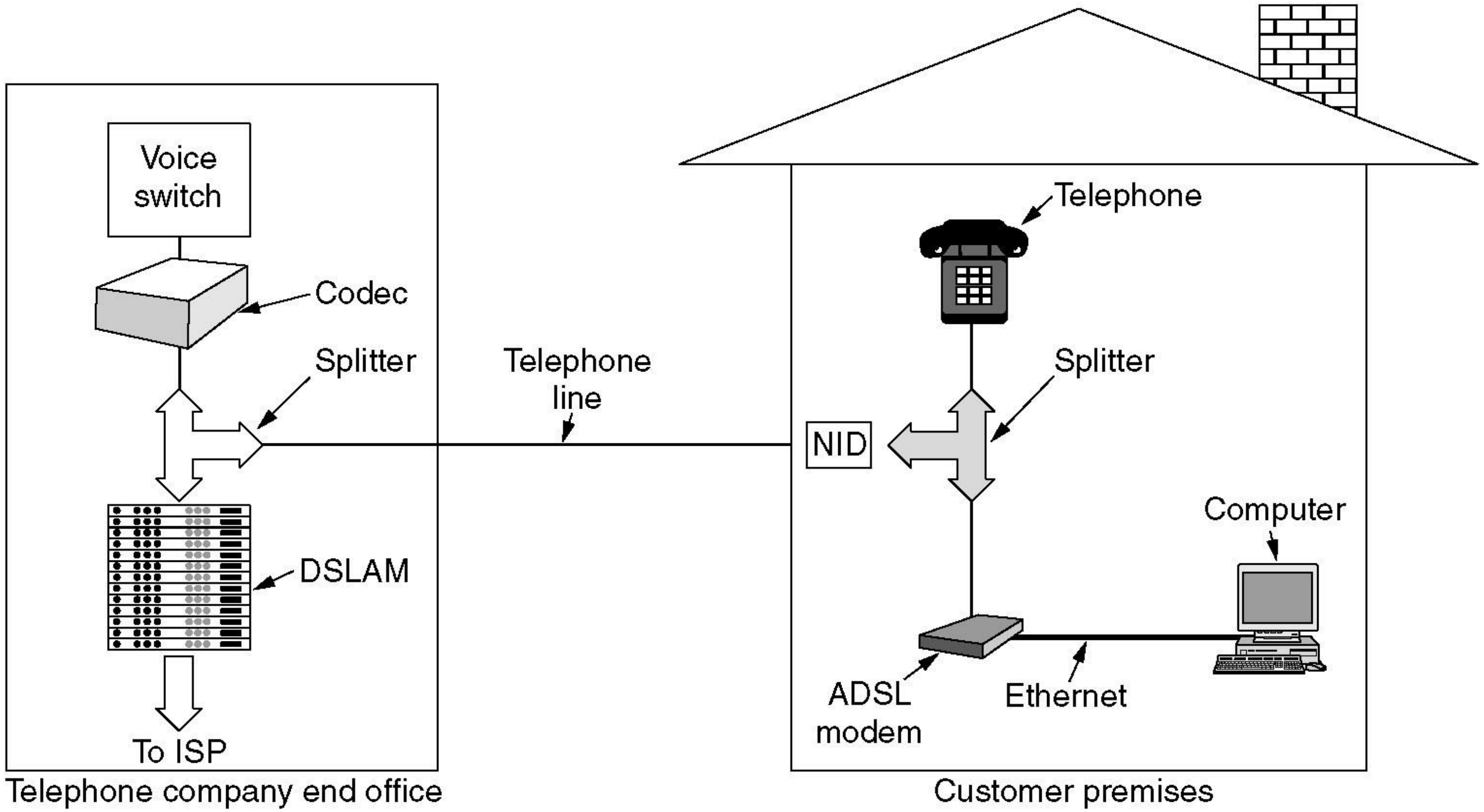
Installation requirement of ADSL

Customer premises :

- NID (Network Interface Device)
- Splitter
- ADSL modem

End office :

- Splitter
- DSLAM
  (Digital Subscriber Line Access Multiplexer)



A typical ADSL equipment configuration

The Local Loop: Modems, ADSL and Wireless(cont.)

Digital Subscriber Lines (DSL)

Question :

An ADSL system using DMT allocates 3/4 of the available data channels to the downstream link. It uses QAM-64 modulation on each channel. What is the capacity of the downstream link?

Answer :

There are 256 channels in all, minus 6 for POTS and 2 for control, leaving 248 for data.

3/4 of 248 = 186 channels for downstream.

ADSL modulation uses 4000 baud rate.

With QAM-64 (i.e. 6 bits/baud) modulation the bit rate is 24,000 bps in each of the 186 channels. The capacity of downstream is

24,000 X 186 = 4.464 Mbps

The Local Loop: Modems, ADSL and Wireless(cont.)

Wireless Local Loop

- Started with an interest from private local companies to compete with existing monopolist telephone company.
- Objective : to provide better service at low price than existing monopolist telephone company.
- Uses a cheaper alternative to the traditional twisted pair local loop : **WLL (Wireless Local Loop)**
- A fixed telephone using a wireless local loop is a bit like a mobile phone, but there are three crucial technical differences.
  - High-speed Internet connectivity
  - Installation of a large directional antenna on customer roof pointed at the Company's end office
  - The user does not move, eliminating all the problems with mobility and cell handoff
- Popular in the term **fixed wireless**
- Used in two types of services
  - MMDS (Multichannel Multipoint Distribution Service)
  - LMDS (Local Multipoint Distribution Service)

The Local Loop: Modems, ADSL and Wireless(cont.)

Wireless Local Loop

MMDS(Multichannel Multipoint Distribution Service)

- Uses microwaves in 198 MHz band at 2.1 GHz frequency range
- Range of about 50km
- Advantage : Technology is well established and equipment readily available
- Disadvantage : Bandwidth available is not much and must be shared by several users

LMDS(Local Multipoint Distribution Service)

- Uses millimeter waves as an alternative to low bandwidth of MMDS (Operative after arrival of gallium arsenide ICs because silicon ICs were difficult to operate)
- Range of frequencies : 28-31 GHz in U.S & 40 GHz in Europe
- Covers 2-5 km range (Thus requires many towers to cover a city)
- Uses multiple directional antennas to cover different sectors in geographical area
- Uses asymmetric bandwidth like ADSL(say 36 Gbps for downstream and 1 Mbps for upstream)

The Local Loop: Modems, ADSL and Wireless(cont.)

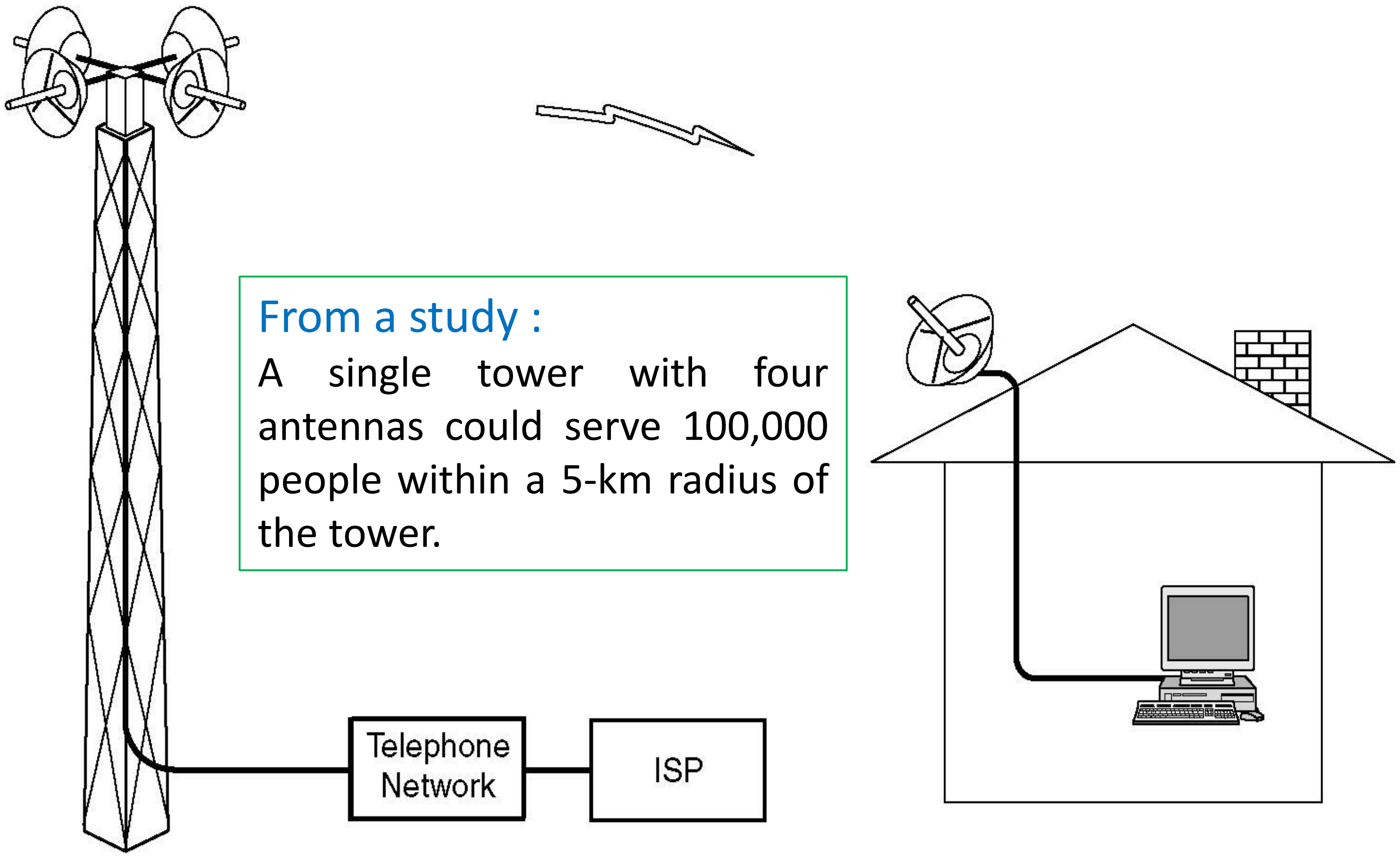
Wireless Local Loop

Problems with MM waves in LMDS:

- Highly directional : hence there must be a clear line of sight between the roof top antennas and the tower.
- Leaves absorb these waves well, so the tower must be high enough to avoid having trees in the line of sight.
- A clear line of sight in December may not be clear in July when the trees are full of leaves.
- Rain also absorbs these waves.

LMDS works with IEEE 802.16 standard.

From a study :
A single tower with four antennas could serve 100,000 people within a 5-km radius of the tower.



Architecture of an LMDS system

Trunks and Multiplexing

- Keeping in view of economy, telephone companies have developed elaborate schemes for multiplexing many conversations over a single physical trunk.
- Two basic categories :
  - FDM (Frequency Division Multiplexing) :The frequency spectrum is divided into frequency bands, with each user having exclusive possession of some band.

    (In fiber optics in the form of WDM (Wavelength Division Multiplexing)
  - TDM (Time Division Multiplexing) : The users take turns (in a round-robin fashion), each one periodically getting the entire bandwidth for a little burst of time.

Example :

- AM radio broadcasting : Allocated spectrum is about 1MHz, roughly 500 to 1500 kHz.
- Different frequencies are allocated to different broadcasting stations.

  (i.e. FDM)
- Individual stations can have music and advertising transmission alternate in time on the same frequency.

  (i.e. TDM)

Trunks and Multiplexing (cont.)

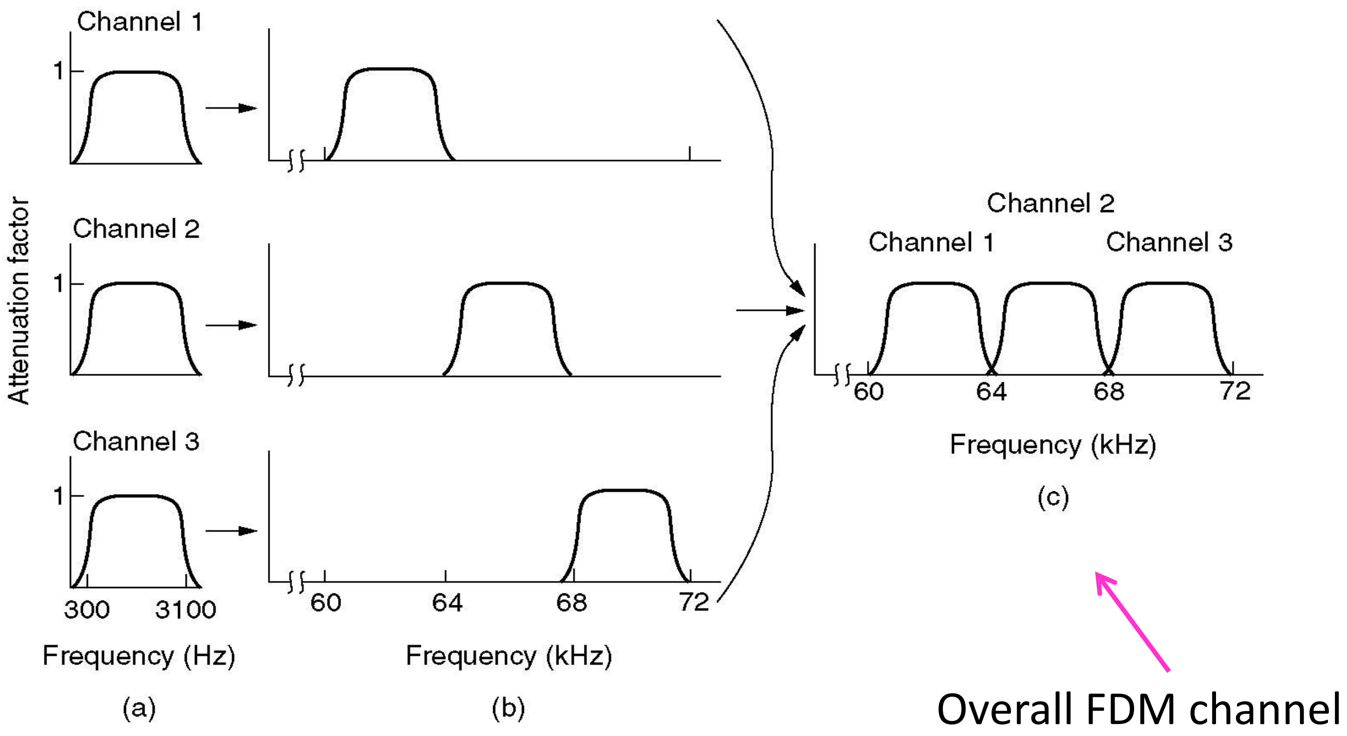
Frequency Division Multiplexing

Steps in FDM :

- First, the voice channels are raised in frequency, each by a different amount in the allocated spectrum.
- Second, they can be combined because no two channels now occupy the same portion of the spectrum.

Standard form of FDM :

- Group : Twelve 4000Hz voice channels multiplexed into a 48 KHz band (e.g. 12 – 60 KHz band & 60 – 108 KHz band).
- Supergroup : Combination of 5 groups.
- Mastergroup : Combination of 5/10 supergroups.



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

Trunks and Multiplexing (cont.)

Frequency Division Multiplexing

Question :

Ten signals, each requiring 4000 Hz, are multiplexed on to a single channel using FDM. How much minimum bandwidth is required for the multiplexed channel? Assume that the guard bands are 400 Hz wide.

Answer :

There are ten 4000 Hz signals to multiplexed.

Spectrum width = 10 X 4000 = 40,000 Hz

Each guard band = 400 Hz

No. of guard bands required to avoid interference in between 10 signals = 9

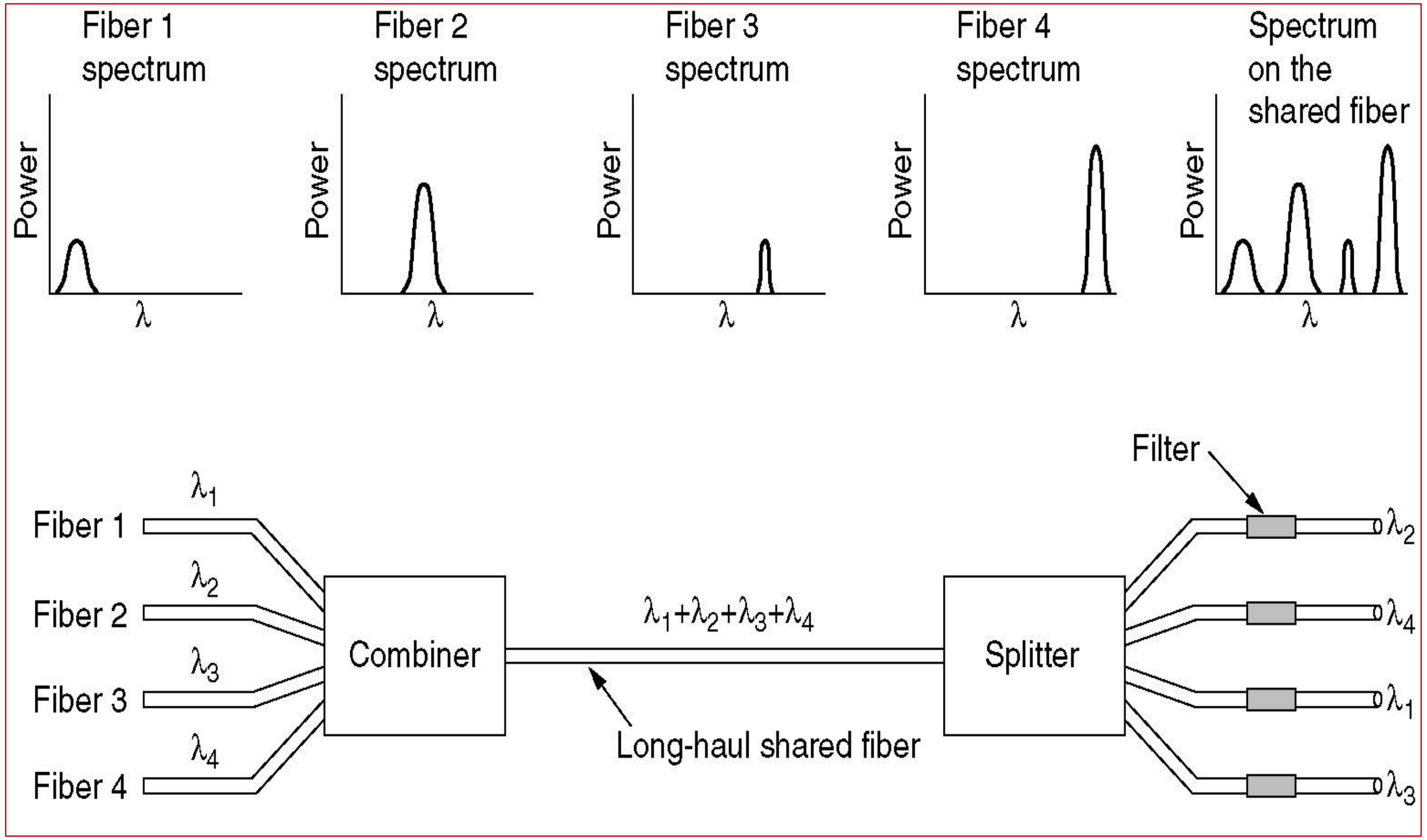
Spectrum used for guard band = 9 X 400 = 3600 Hz

Minimum bandwidth required for the multiplexed channel = 40,000 + 3,600 = 43,600 Hz

Trunks and Multiplexing (cont.)

Wavelength Division Multiplexing

- Used in fiber optic channel.
- Signals with different wavelength coming through different fibers combined through optical combiner (here 4).
- Transmitted through a shared fiber over long distance.
- At the far end, the beam is split up over as many fibers as there were on the input side using specially-constructed core that filters out all but one wavelength.
- Just like FDM at high frequencies.
- Requires diffraction grating.



Wavelength division multiplexing

Trunks and Multiplexing (cont.)

Wavelength Division Multiplexing

Growth of WDM :

- 1990: 8 wavelengths X 2.5 Gbps → 20Gbps
- 1998: 40 X 2.5 Gbps → 100Gbps
- 2001: 96 X 10 Gbps → 960Gbps : enough to transmit 30 full-length movies per second.
- As more and more wavelengths are being discovered in a single fiber, WDM is getting denser and now the name DWDM (dense WDM) is being used.

Trunks and Multiplexing (cont.)

Time Division Multiplexing

- WDM : applicable only on optical fiber and not on copper, but a lot of copper is there and also analog.
- FDM : used on copper and microwave but requires analog circuitry and may not be suitable for computer.
- Solution : TDM : unfortunately, can be used only for digital data.
  - ❖ Requires A/D conversion at the end office (since local loops uses analog signaling) before being multiplexed and transmitted in the trunk.
  - ❖ Uses **Codecs**

Trunks and Multiplexing (cont.)

Time Division Multiplexing

CODEC : PCM (Pulse Code Modulation) :

- Uses 8000 samples/sec or one sample/125 µsec.

  (Satisfies Nyquist criteria as telephone channel bandwidth is 4000 Hz)
- All the time intervals (a pulse) within the telephone system are multiples of 125 µsec.
- Technique is known as PCM.
- Each sample is represented in the form of a 8-bit number.

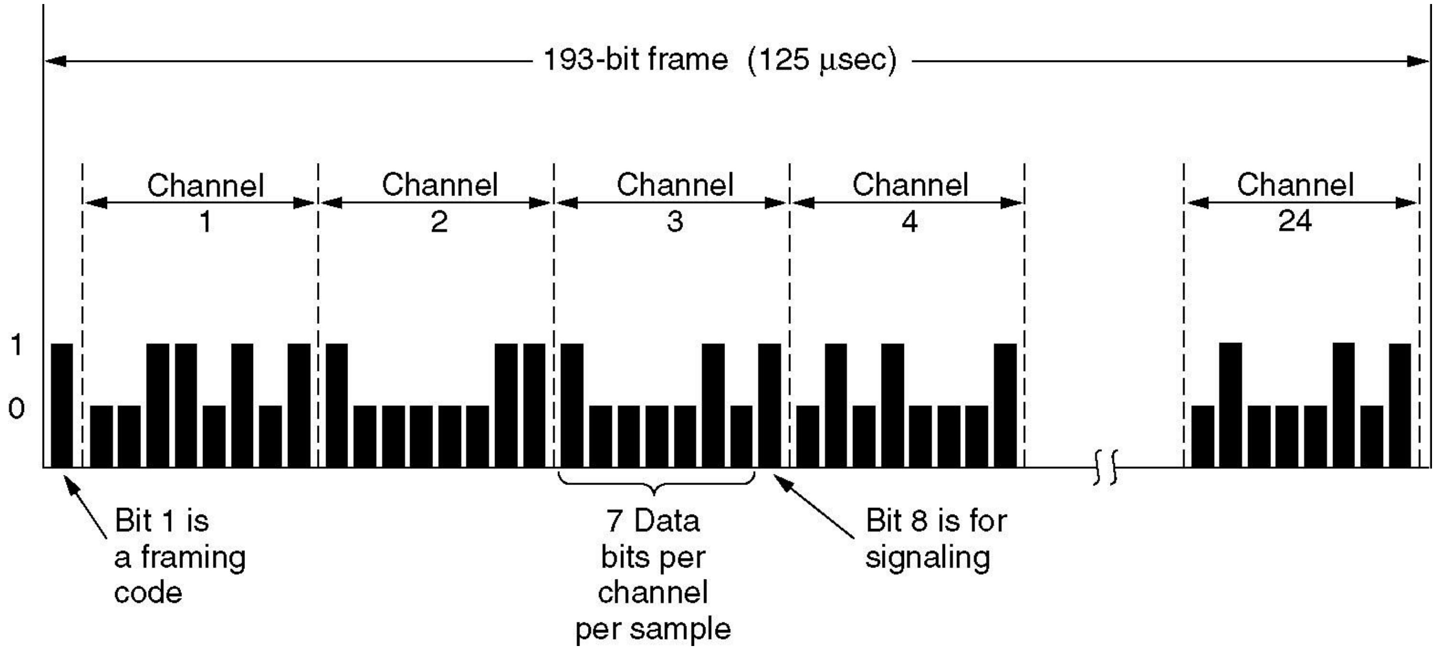
Different schemes incorporating PCM were used for implementing TDM.
Example : **T1** carrier

Trunks and Multiplexing (cont.)

Time Division Multiplexing

T1 Carrier :

- Used for multiplexing 24 voice channels from local loops.
- Analog signals from these 24 channels are sampled on a round-robin basis with the resulting analog stream being fed to the codec rather than having 24 separate codecs.
- Each of these 24 channel insert 8 bits (7 data + 1 control) for each sample.
- Bits for each channel is (7 X 8000) = 56,000 bps of data and (1 X 8000) = 8000 bps of signaling information.
- Bits at codec w.r.t each sample from 24 channels is 24 X 8 = 192 bits along with one extra bit for synchronization (i.e. 193 bits).
- Data rate/sec is 1.544 Mbps



The T1 carrier (1.544 Mbps).

Trunks and Multiplexing (cont.)

Time Division Multiplexing

- The TDM using the PCM technique has been standardized with 1.544 Mbps with some variations in T1.
  - 8000 bps of signalling information is too much so no. of bits used to represent a data is 8 bit (instead of 7 bit).
  - Implemented with two possible approaches.
    1. Common channel signalling :

       The extra bit (which is attached onto the rear rather than the front of the 193-bit frame) takes on the data values in the odd frames and contains signaling information for all the channels in the even frames.
    2. Channel-associated signaling :
       - Each channel has its own private signaling subchannel
       - Subchannel allocation : one of the eight user bits in every sixth frame is used for signaling (i.e. five out of six samples are 8 bits wide, and the other one is only 7 bits wide)

Trunks and Multiplexing (cont.)

Time Division Multiplexing

E1 Carrier :

- Another standard carrier besides T1 carrier used in TDM with PCM technique.
- 8000 samples/sec
- Accepts 32 channels with 8-bit data samples:
  - 30 channels for data + 2 channels for signaling
- Each group of four frames provides 64 bits of signaling :
  - Half for channel associated signaling + half for frame sync
- Capacity : 32 X 8 X 8000 = 2.04 Mbps

Trunks and Multiplexing (cont.)

Time Division Multiplexing

Differential Pulse Code Modulation and Delta Modulation :

- Objective : Reduction in no. of bits needed per channel without loosing information.
- Principle: Signal changes relatively slowly compared to the sampling frequency, so that much of the information in the 7- or 8-bit digital level is redundant.
- Appropriate for both speech encoding and digitization of analog signal.

In Differential Pulse Code Modulation :

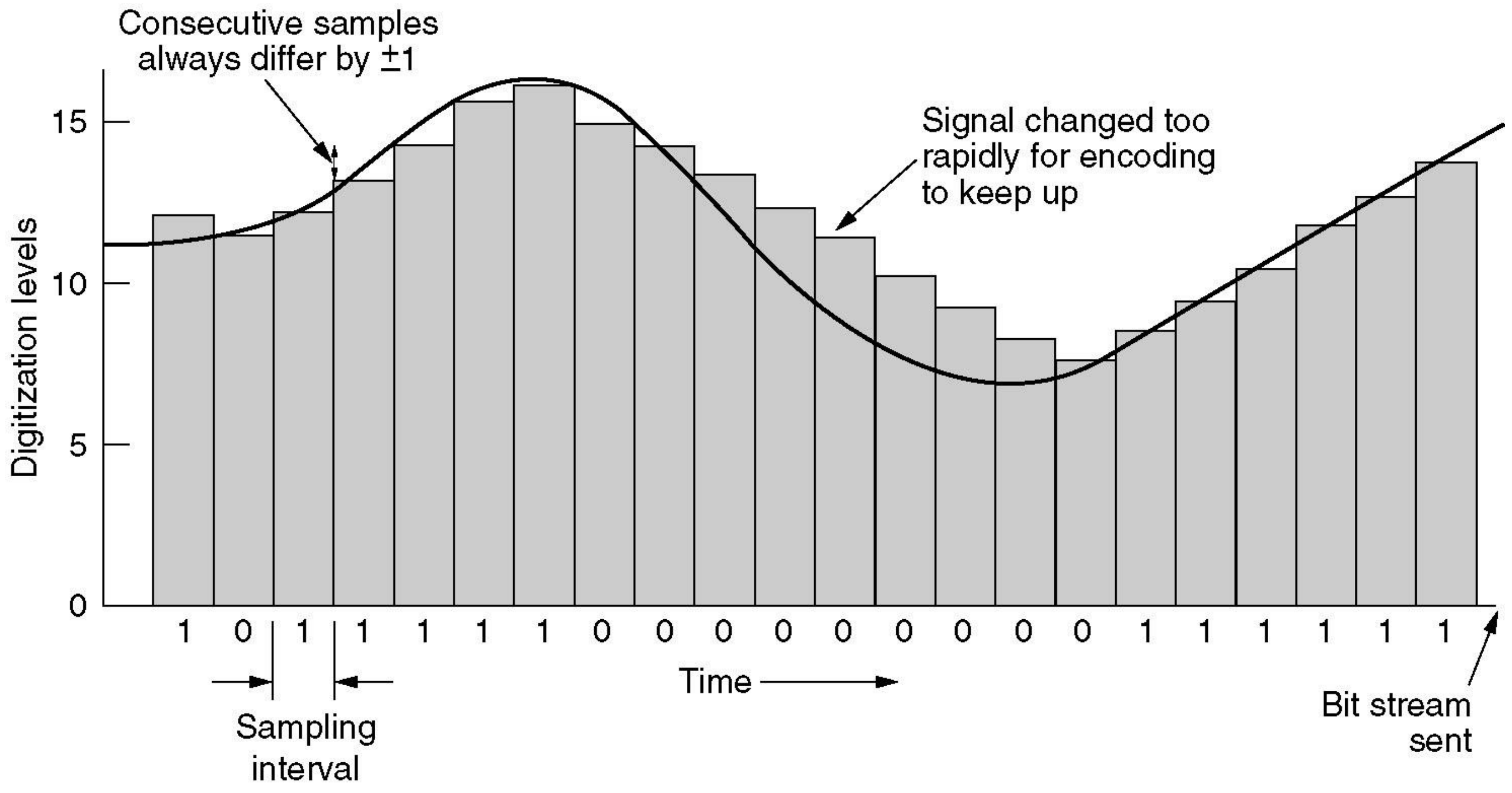
- Instead of digitized amplitude, difference between current value and previous one is digitized
- Jumps of magnitude ± 16 and more are rare in 128 levels. So 5 instead of 7 bits are sufficient.
- If the signal jumps occasionally widely, the information is lost

In Delta Modulation :

- Compare the current sample and previous one with a difference in ± 1.
- For difference of +1, transmits 1 & for difference of -1 transmits 0.
- If signal changes too fast then information is lost.

Trunks and Multiplexing (cont.)

Time Division Multiplexing



Delta modulation

Trunks and Multiplexing (cont.)

Time Division Multiplexing

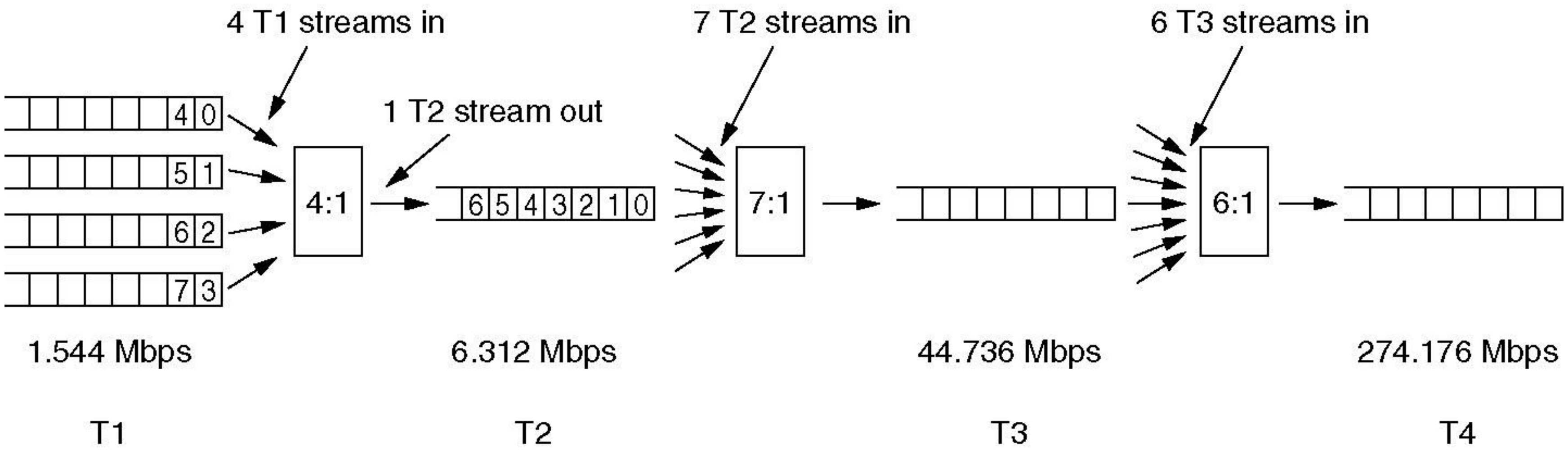
Predictive Encoding :

- Extrapolate the previous few values to predict the next value.
- Encode the difference between actual and the predicted signal
- Transmitter and receiver must have to use same prediction algorithm

Trunks and Multiplexing (cont.)

Time Division Multiplexing

- TDM allows carrier hierarchy.
  - Level 1 : Four T1 channels being multiplexed onto one T2 channel.
  - Level 2 : Seven T2 streams are combined bitwise to form a T3 stream.
  - Level 3 : Six T3 streams are joined to form a T4 stream.
- At each step a small amount of overhead is added for framing and recovery in case the synchronization between sender and receiver is lost.



Multiplexing T1 streams onto higher carriers

Trunks and Multiplexing (cont.)

Time Division Multiplexing

Q. What signal-to-noise ratio is needed to put a T1 carrier on a 50-kHz line?

Answer :

To send a T1 signal we need $H \log_2(1 + S/N) = 1.544 \times 10^6$ with $H = 50{,}000$.

This yields $S/N = 2^{30} - 1$, which is about 93 dB.

Switching

From PSTN working point of view the structure can be seen as combination of two parts.

- Outside the plant (local loops and trunks).
- **Inside the plant (switching offices).**

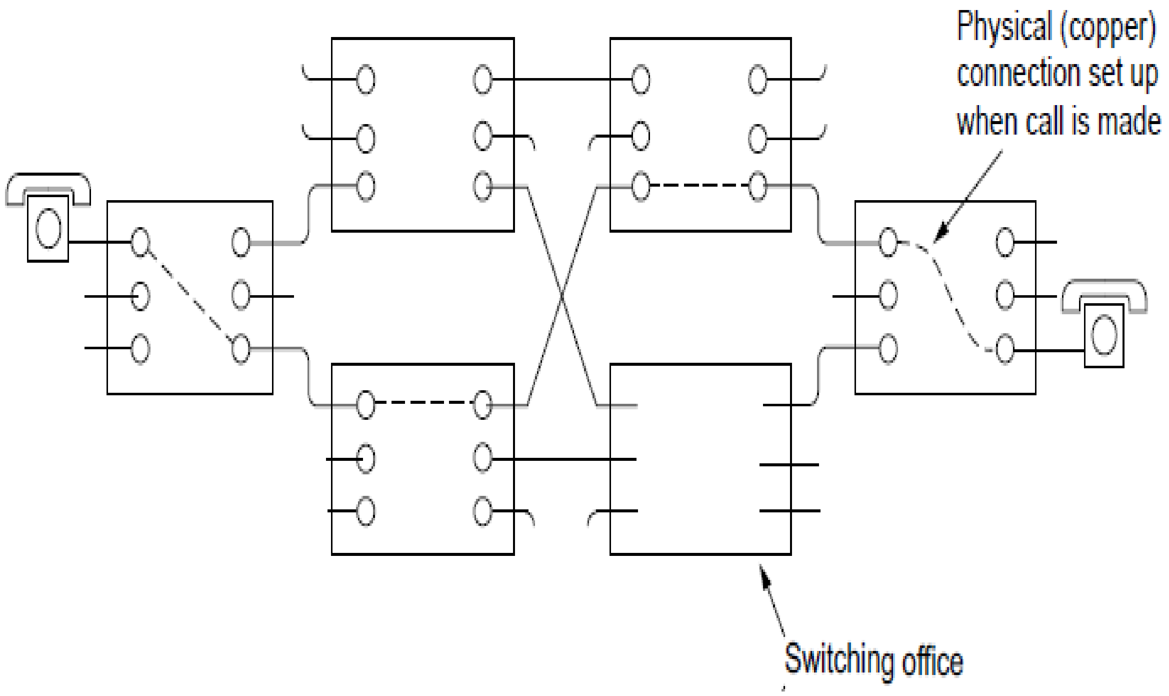
Two switching technologies used:

- Circuit switching
- Message switching (mostly obsolete now)
- Packet switching

Switching (cont.)

Circuit Switching

- When a telephone call is placed, the switching equipment within the telephone system seeks out a physical path all the way from transmitter’s telephone to the receiver's telephone.
- The end office and toll office (here the six rectangles) in the physical path are called as switching offices.
- Each office has more than one (here three) incoming lines and more than one (here three) outgoing lines.
- When a call passes through a switching office, a physical connection is established between the line on which the call came in and one of the output lines, as shown by the dotted lines.
- In the early days of the telephone, the connection was made by the operator plugging a jumper cable into the input and output sockets.
- once a call has been set up, a dedicated path between both ends exists and will continue to exist until the call is finished.



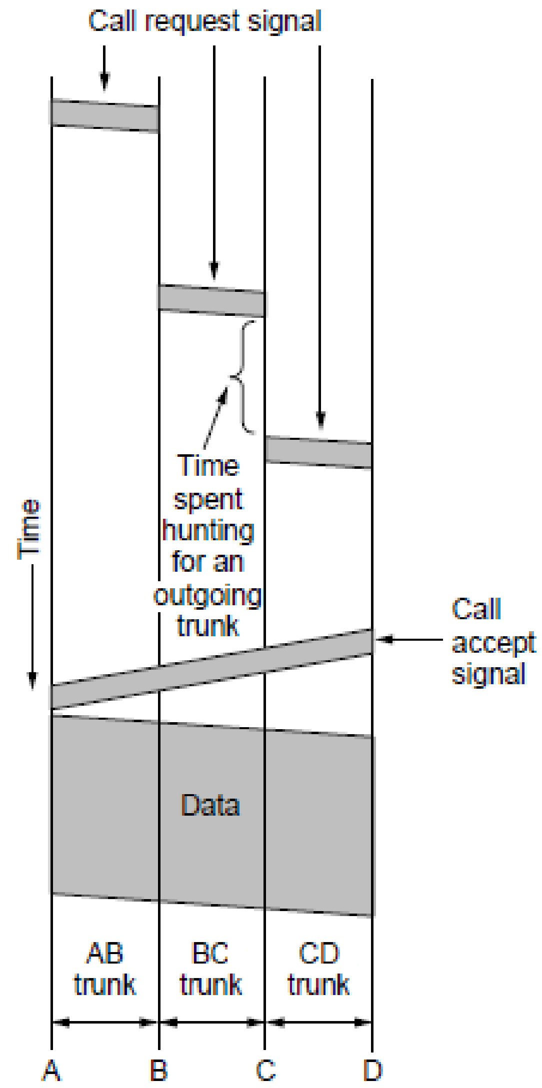
Circuit switching.

Switching (cont.)

Circuit Switching

Process of call progress in circuit switching :

- Set up an end-to-end path before any data can be sent (i.e. dialing at transmitting end and ringing at receiving end).
- The elapsed time between the end of dialing and the start of ringing can easily be 10 sec, more on long-distance or international calls.
- During the establishment of the direct path from two end users the system will hunt to find it.
- 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 (i.e. once the call has been put through, you never get busy signals).
  - The busy signal might be heard before the connection has been established due to lack of switching or trunk capacity.



Timing of events in circuit switching

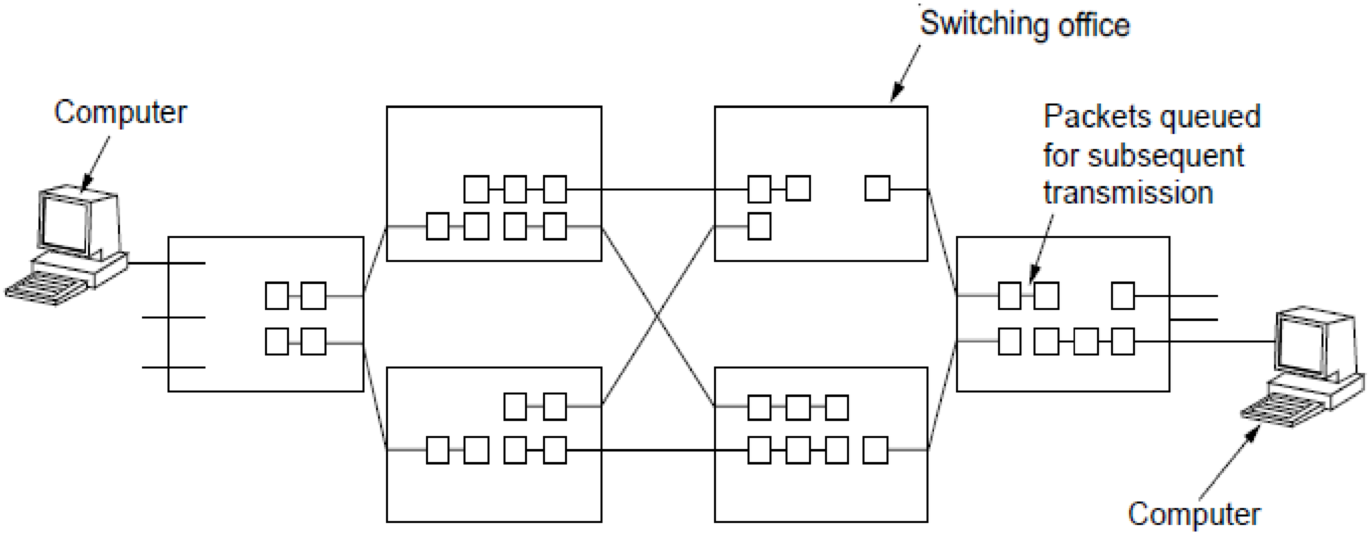
Switching (cont.)

Packet Switching

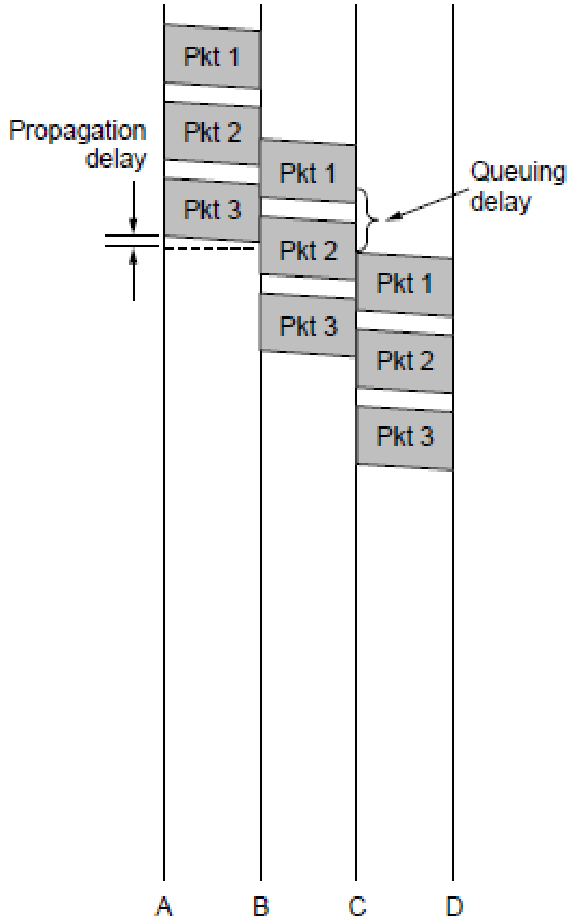
- Alternative to circuit switching.
- Individual packets are sent as need be, with no dedicated path being set up in advance.
- It is up to each packet to find its way to the destination on its own.
- Uses store and forward concept at the routers(i.e. at switching offices).
- Limitation in no. of packets through inclusion of fixed size buffer at the routers (i.e. no user can block a transmission line for longer time).
- In case of multi packet message, a packet is forwarded only if has been arrived as entirety before the arrival of second packet (arrival of packets may not be in order).
- Reduced delay and improved throughput in compare to message switching.

Switching (cont.)

Packet Switching



Packet switching



Timing of events in packet switching

Switching (cont.)

Circuit Vs. Packet Switching

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