Computer Network and Distributed Systems

Physical Layer

PART 2

Electromagnetic Wave

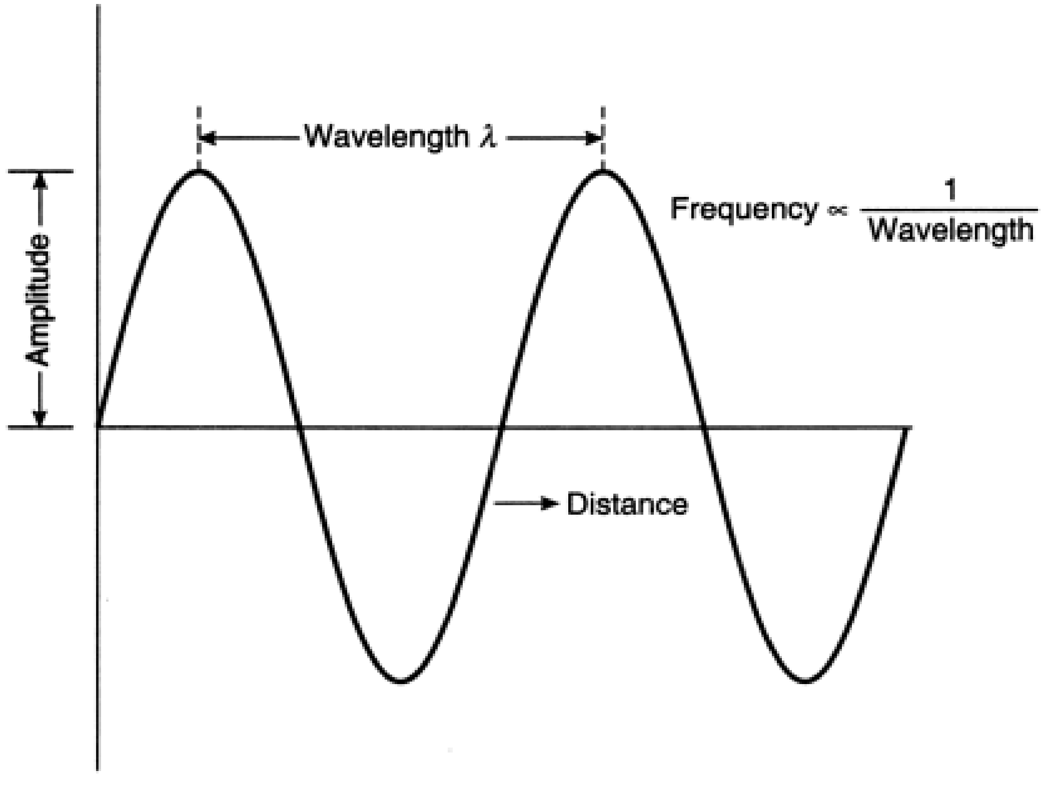
- A wave of energy propagated in an electromagnetic field

- All energy in the universe travels in waves and those waves radiate outwards from a source

- Just as waves ripple outwards from a stone tossed in a pond

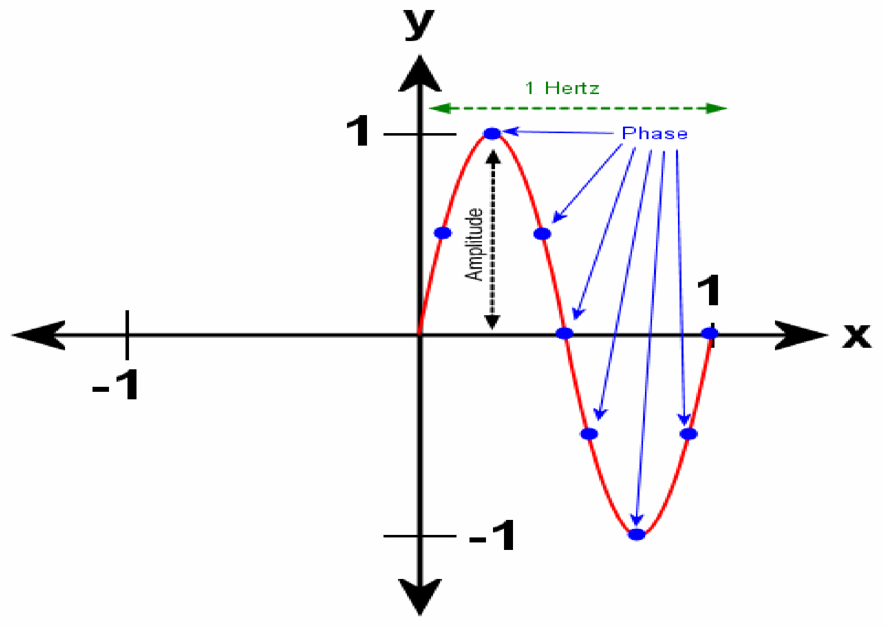
Electromagnetic Wave Contd...

A typical Electromagnetic Wave (time domain representation)



Electromagnetic Wave Contd...

- All radiation(electromagnetic energy) is said to have :
  - Wavelength : Measured in distance (meters)
  - Frequency : Measured in time (cycles per second)
  - Amplitude : Measured in power (electron volts)
  - Phase (what value the wave has at any single instant in time)



Electromagnetic Wave Contd...

An electromagnetic wave has a frequency and a wavelength associated with it and travels at the speed of light (in vacuum), or **c**.

The relationship among these wave characteristics can be described by

$vW = f\lambda$

- where **vW** is the propagation speed of the wave (here **$vW = c$**)
- **f** is the frequency
- **λ** is the wavelength

So that for all electromagnetic waves **$c = f\lambda$**

Hence **$f = c/\lambda$** or **$f \propto 1/\lambda$** → High frequency electromagnetic wave has lower wavelength

Data and Signal

- Data: entities that convey meaning
  - Can be analog (audio, video) or digital (text, numbers)
  - We consider only digital data i.e. the entities consist of sequence of 0’s and 1’s

- Signal: Electric / electromagnetic representations of data
  - Can be analog or digital
  - Different signals can be used to represent same data

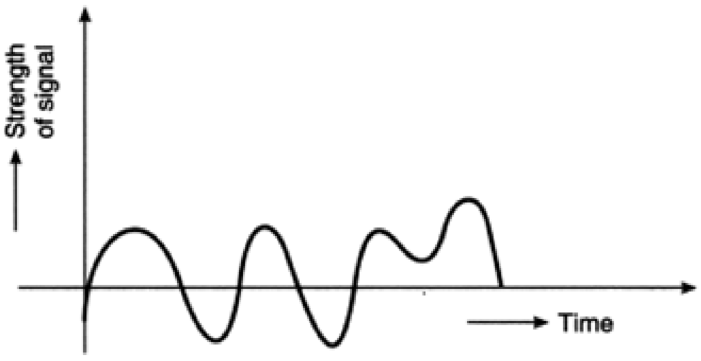
- Encoding: representing data with signals

- Transmission: communication of data by propagation and processing of signals

Analog Signal

An Analog signal is one in which the signal intensity varies in a smooth fashion (continuous) over time

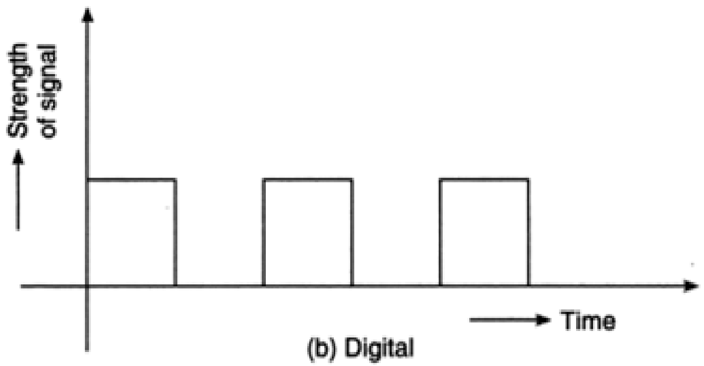
- Could be simple or composite signal
- A single-frequency sine wave is not useful in data communications, composite signals used



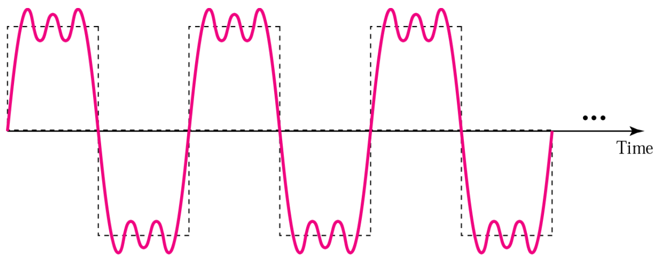
(a) Analog

Digital Signal

A Digital Signal is one in which the signal intensity maintains a constant level (discrete) for some period of time and then changes another constant level



- Usually non-periodic
- Bit rate: number of bits sent in 1 second (bps)
- Digital signal is a composite analog signal, having bandwidth ∞ (infinity)



Simple Signal

A Simple signal is the signal having exactly one frequency component – qualified by its frequency of oscillation

- So a simple signal is the same as any electromagnetic wave
- A single-frequency sine wave is not useful in data communications, composite signals used

Time domain representation

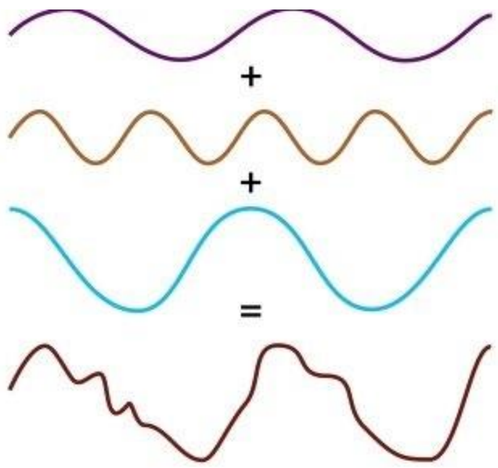
***Note** : The Carrier Signal used for modulation belongs to this category*

Composite or Complex Signal

Time domain representation

A Complex signal is having multiple frequency components and represented by the sum of weighted frequency components

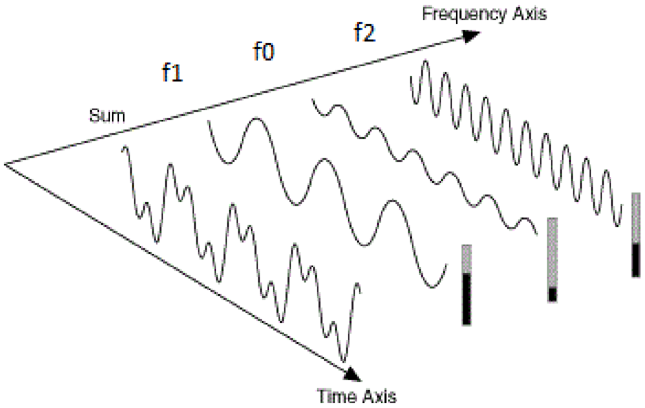
Fourier analysis: any composite signal is a combination of simple sine waves with different frequencies, amplitudes, phases

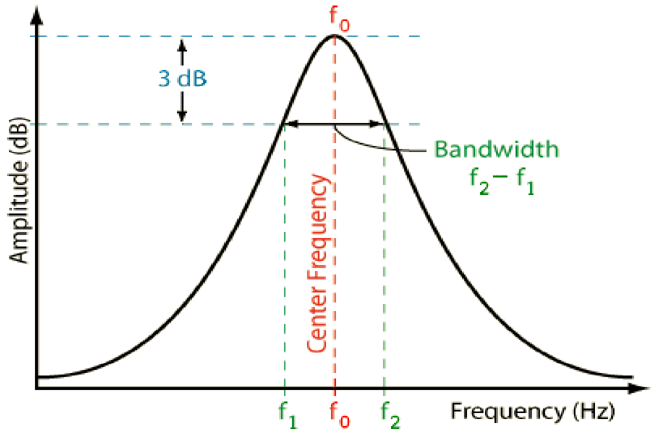


***Note** : The Audio, Video Signals are belongs to complex signal*

Bandwidth of a Signal

- Bandwidth can be imagined as a frequency width, sort of the fatness of the signal
- To convey information, an information signal needs to contain many different frequencies and it is this span of their frequency content that is called its bandwidth.
- The human voice, for example, spans in frequency from 30 Hz to 10 Khz.
- The more information in a signal, the larger the bandwidth of the information signal
- Bandwidth of the RHS signal is (f2-f1)





Relationship between data-rate & bandwidth

- Any transmission medium can accommodate only a limited band of frequencies
  - This limits the data rate that can be carried

- The greater the bandwidth of a medium, the higher is the data rate that can be transmitted, also more expensive the medium

- A given bandwidth can support various data rates, depending on the requirements of the receiver

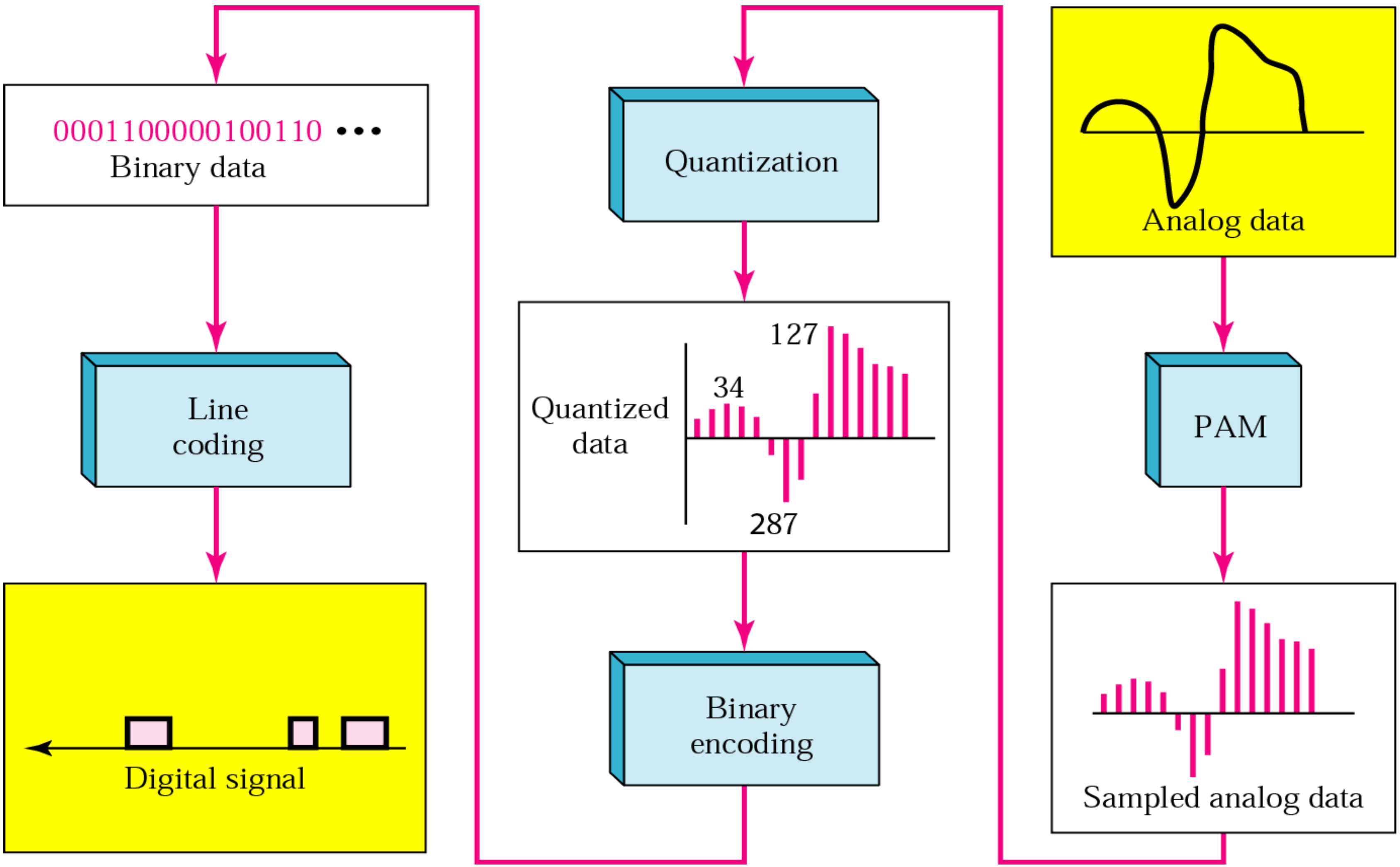
Analog data, digital signal

- Digitization
  - Conversion of analog data into digital signal
  - Digital signal can then be transmitted using NRZ-L or some other code
  - Sampling rate required?
  - Quantization: approximate the sampled (analog) value to a digital level

- Methods
  - Pulse Mode Modulation (PCM)
  - Delta modulation: non-linear encoding
    - Quantization levels not evenly spaced

Encoding analog data to digital signal

For your study



Analog Transmission

- Analog signal transmitted without regard to content
- May be analog data (e.g. voice) or digital data (e.g. binary data passed through a modem)
- Attenuated over distance
- Use (cascaded) amplifiers to boost signal
- Also amplifies noise

Digital Transmission

- Concerned with content
- Can be transmitted only a limited distance before integrity endangered by noise, attenuation
- Repeaters used
  - Repeater receives signal, recovers the bit pattern
  - Retransmits a new signal
- Digital transmission becoming more and more popular

Transmission Impairments

- Signal received may differ from signal transmitted

- Effect on analog signal
  - degradation of signal quality

- Effect on digital signal
  - bit errors may get introduced

- Caused by
  - *Attenuation and attenuation distortion*
  - *Delay distortion*
  - *Noise*

Modulation

Modulation is the process of conveying an information / message signal (for example a digital bit stream or an analog audio signal) inside another signal (called Carrier signal) that can be physically transmitted over medium (wired or wireless)

Carrier Signal

- The purpose of the carrier is usually –
  - Either to transmit the information through space as an electromagnetic wave (as in radio communication)
  - Or to allow several carriers at different frequencies to share a common physical transmission medium

- Carrier signal is very high frequency, as high frequency wave propagation is more suitable for long-distance.

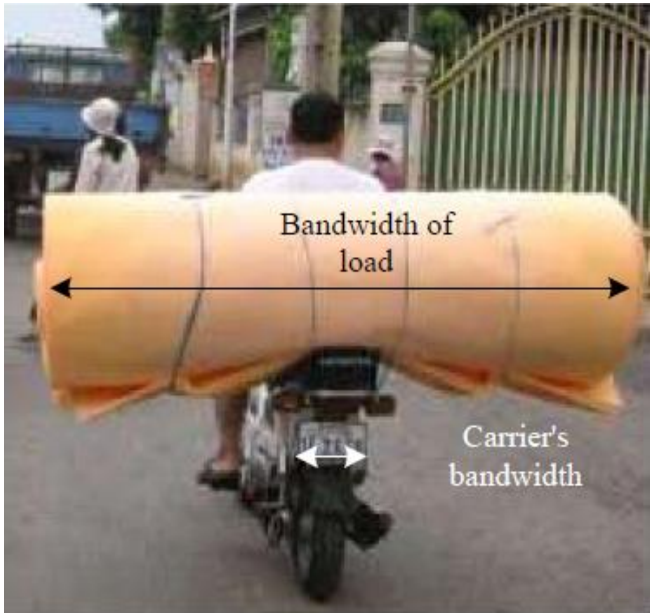
- The bandwidth of a carrier signal is zero. That is because a carrier is composed of a single frequency

- Carrier frequency places the information signal into a suitable position in the electromagnetic spectrum.

Bandwidth and Carrier Signal Analogy

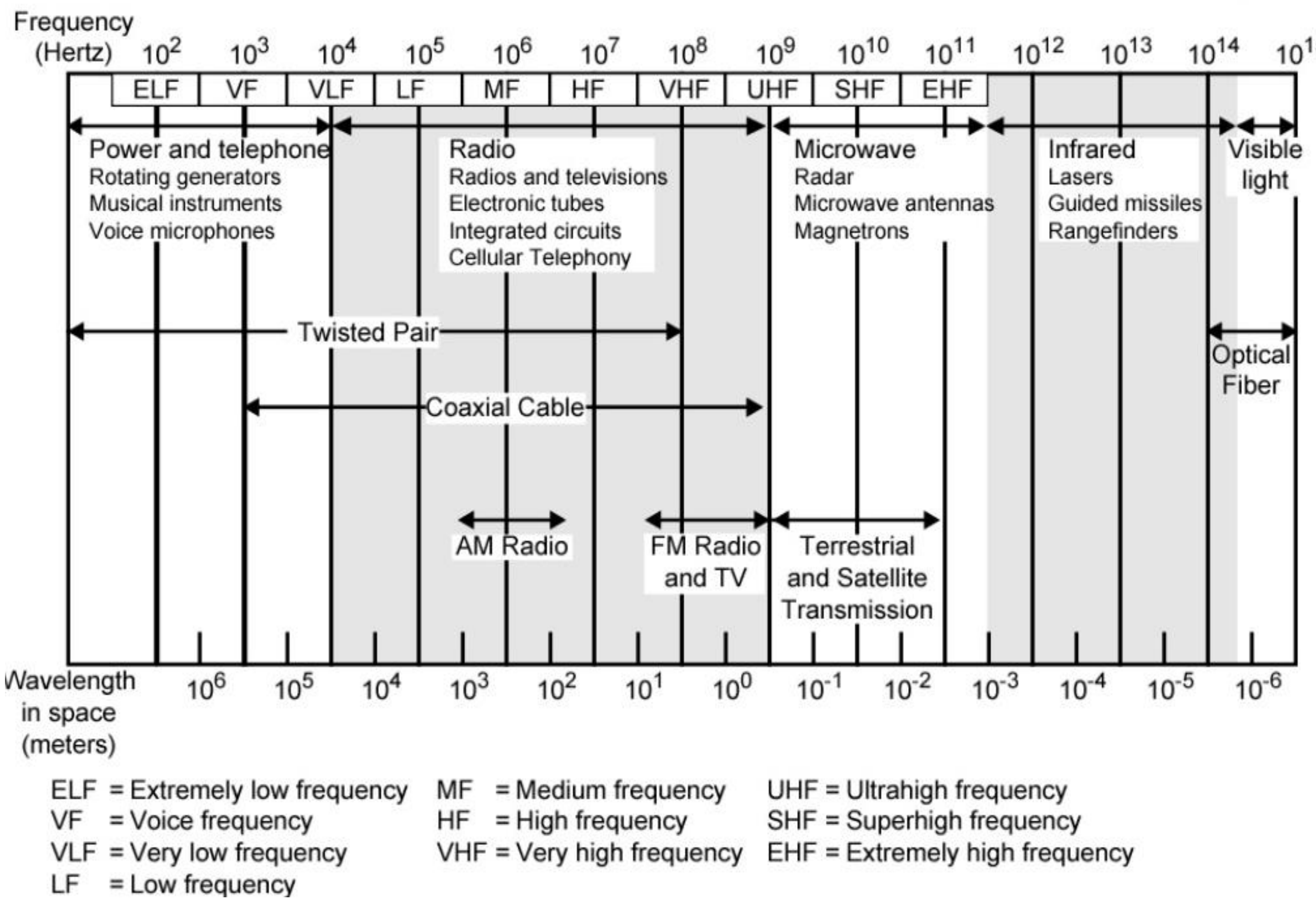
The modulated signal takes on the bandwidth of the information signal it is carrying like this person on the motorcycle.

He is the modulated signal and his bandwidth just went from near zero, without the load, to the size of the mattress which is his "information" signal.



Band or Spectrum

The electromagnetic spectrum is the range of all possible frequencies of electromagnetic radiation

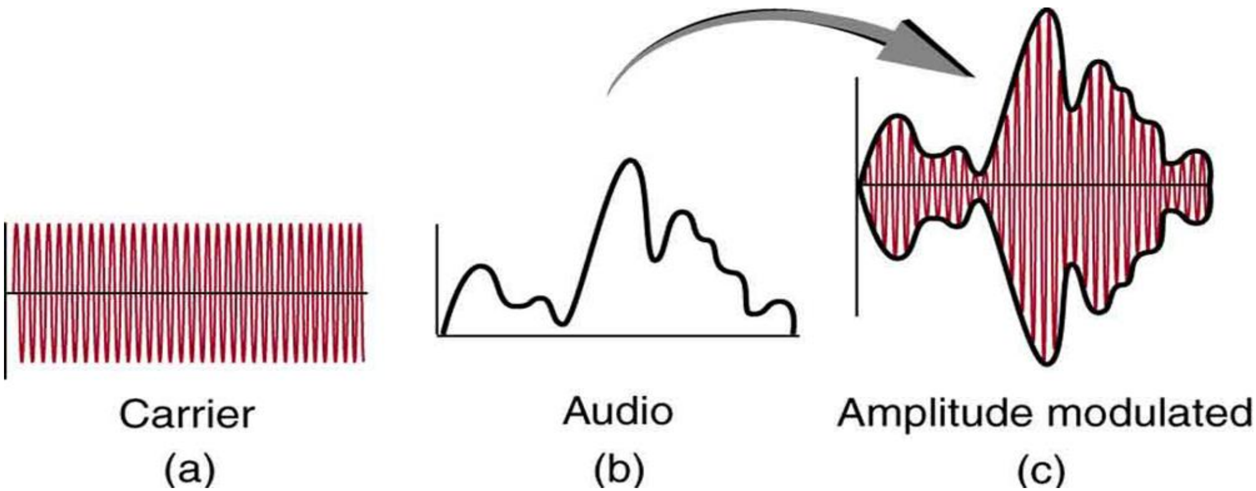


Analog Modulation

Analog modulation : Amplitude Modulation (AM)

AM works by varying the strength (amplitude) of the carrier signal in proportion to the waveform being sent.

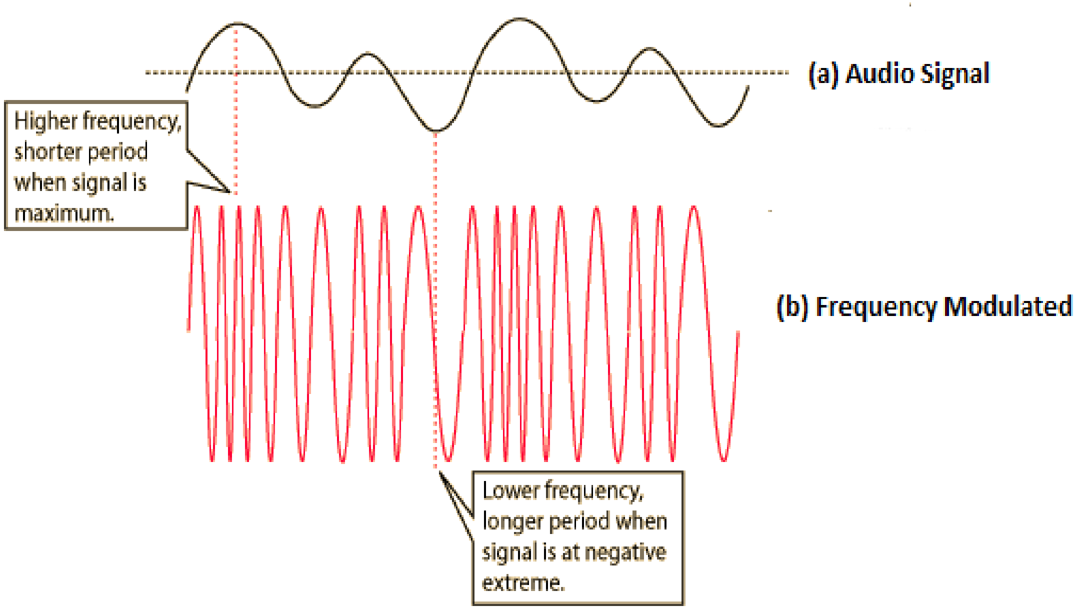
Note : Frequency and Phase of the carrier signal remains constant



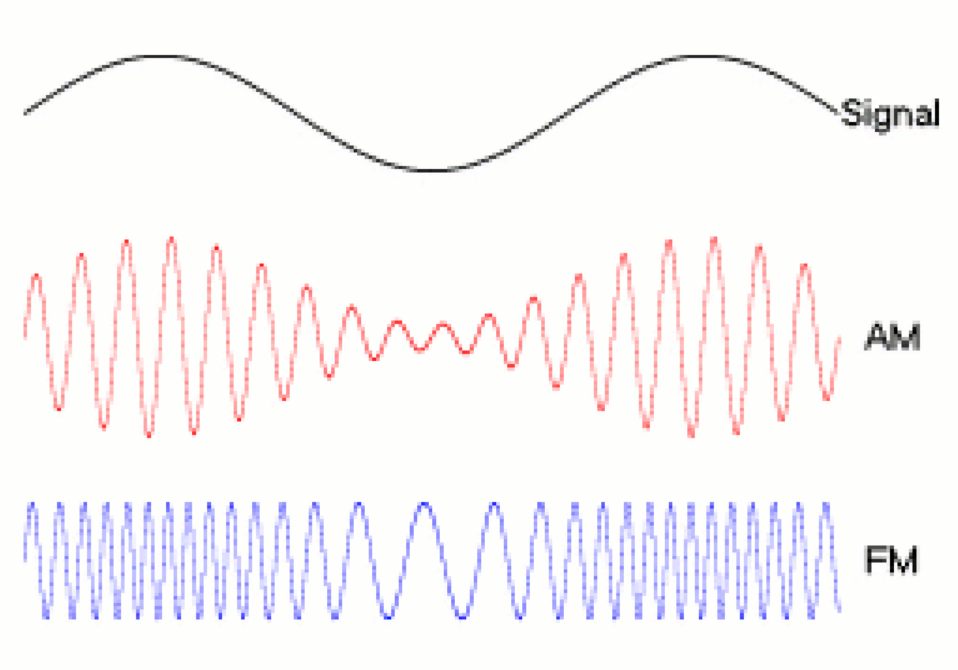
Analog modulation : Frequency Modulation (FM)

FM works by varying the frequency of the carrier signal in proportion to strength (amplitude) the waveform being sent.

Note : Amplitude and Phase of the carrier signal remains constant



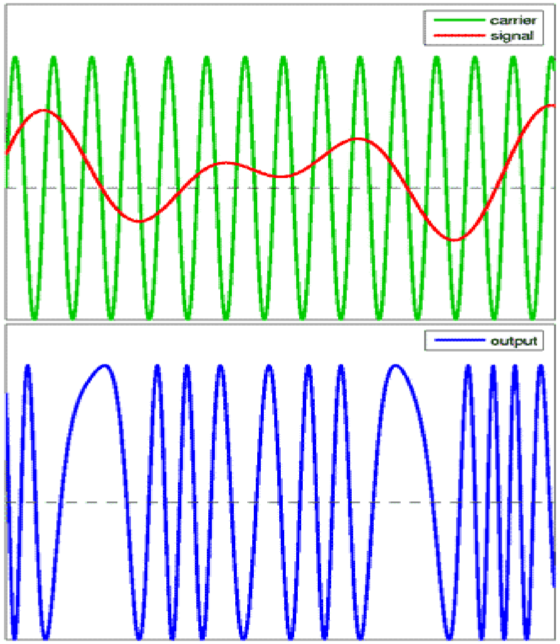
AM and FM demonstration



Analog modulation : Phase Modulation (PM)

PM works by varying the phase of the carrier signal (advancing or retarding) in proportion to strength (amplitude) the waveform being sent.

Note : Amplitude and Frequency of the carrier signal remains constant



Digital Modulation (Data Encoding)

Digital Modulation / Data Encoding

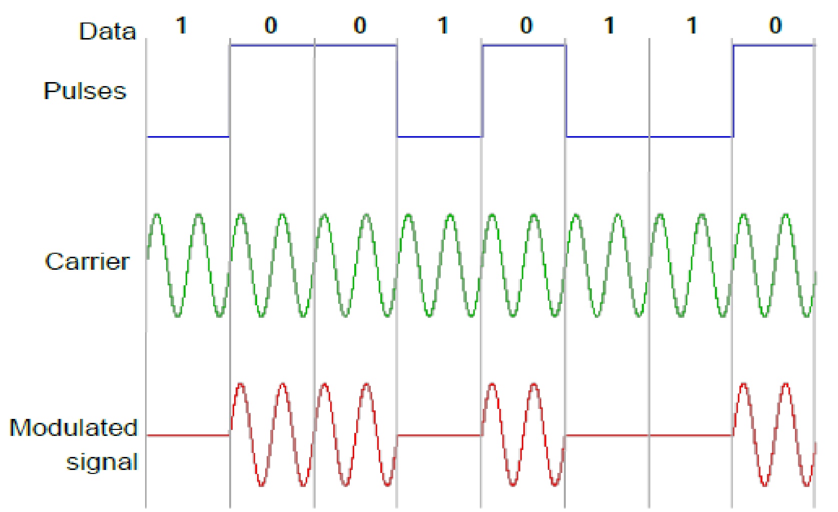
- Digital modulation is a process when an analog carrier signal is modulated by a digital bit stream.

- Digital modulation method can be considered as digital-to-analog conversion and the corresponding demodulation or detection as analog-to-digital conversion.

- A modem (modulator-demodulator) converts digital data to analog signal.
  - There are 3 ways to modulate a digital signal on an analog carrier signal.

Amplitude Shift Keying (ASK)

Two binary values are represented by two different amplitude of the carrier frequencies



<u>Advantage :</u>

✓Simple and Requires low bandwidth

<u>Disadvantage :</u>

✓Very susceptible to noise interference – noise usually (only) affects the amplitude. That causes rapid fluctuations the signal's amplitude

<u>Application :</u>

✓Not used for wireless radio transmissions (apart from infrared systems), but favored for optical transmissions in wired networks

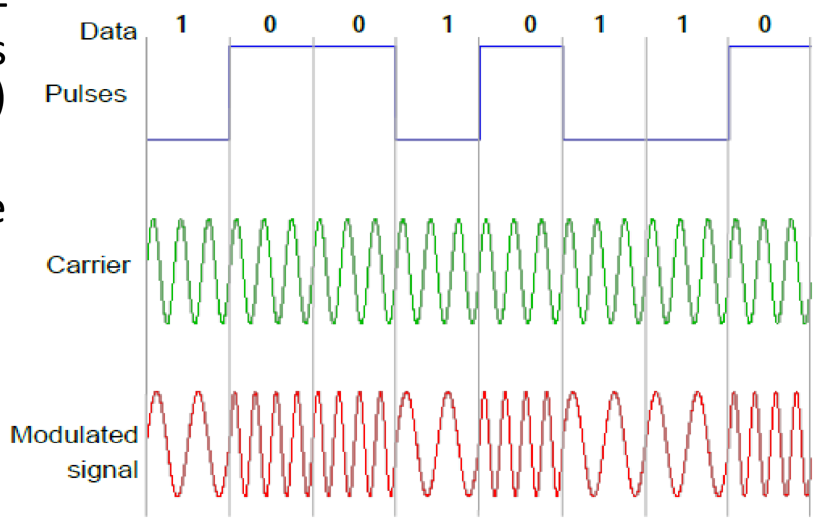
Frequency Shift Keying (FSK)

Two binary values are represented by two different frequencies

Advantage :

✓FSK is less susceptible to errors than ASK – receiver looks for specific frequency changes over a number of intervals, so voltage (noise) spikes can be ignored.

✓Easy to decode and suitable for long distance communication



Disadvantage :

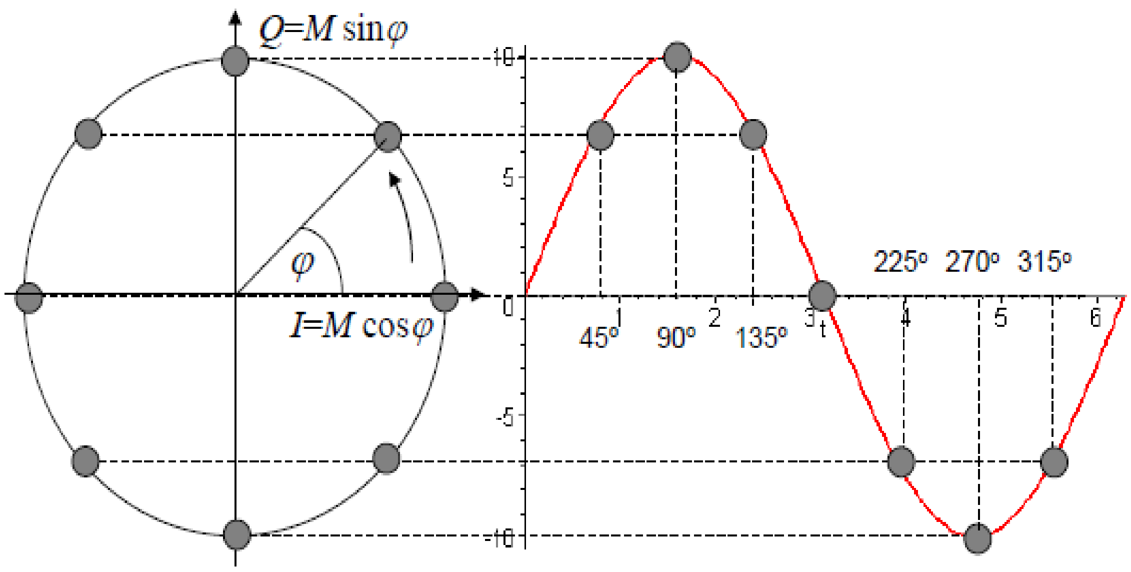
✓FSK requires higher bandwidth than ASK

Application :

✓Used over voice lines (telephone lines) as well radio transmission, etc.

Phase Domain

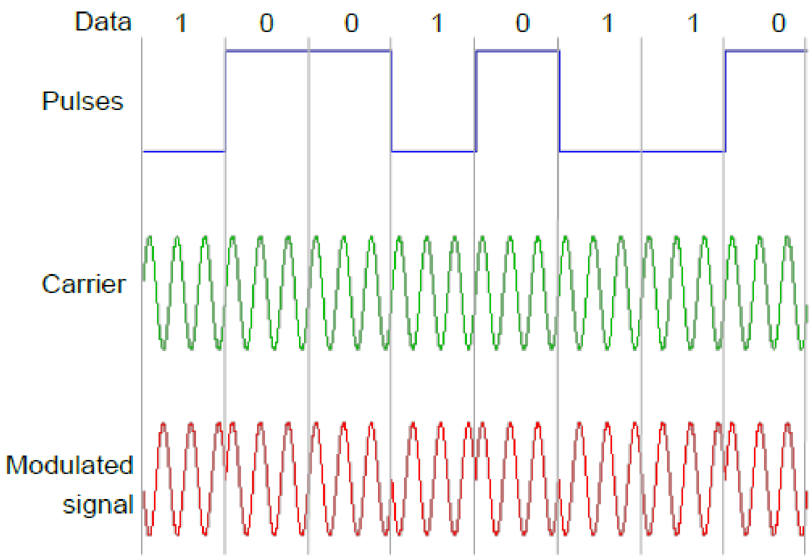
- Third way to represent signals (in addition to time and frequency domain)
- Shows the amplitude M of a signal and its phase φ in polar coordinates
- X-axis is called **In-Phase(I), y-axis is called Quadrature-Phase(Q)**



Phase Shift Keying (PSK)

Two binary values are represented by shift the phase of the carrier signal.

This simple scheme, shifting the phase by 180 degree each time the value of data changes is called BPSK



Advantage :

✓PSK requires less bandwidth than FSK

✓PSK is less susceptible to errors than ASK

✓Suitable for long distance communication

Disadvantage :

✓Decoding is complex as phase changes needs to be tracked

Application :

✓Used for Wireless radio transmission such as UMTS, WLAN

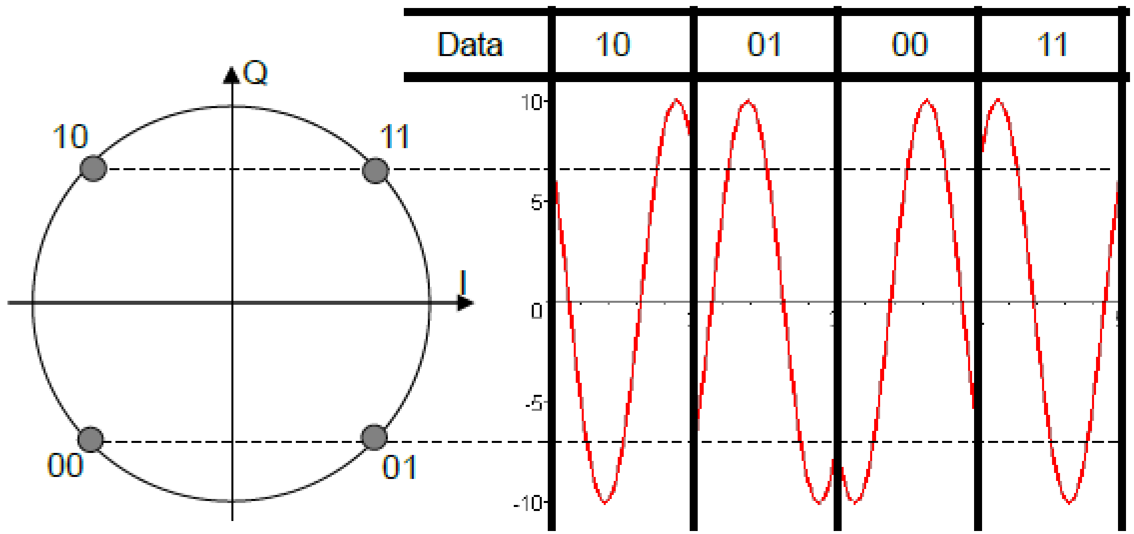
PSK with Multiple Signal States

So far: each kind of shift keying defines two signal states for representing binary 0 or 1

But: a shift keying scheme can fix an arbitrary number of signal states (in theory) to increase the number of bits transferred in a single modulation step

Example: Quadrature Phase Shift Keying (QPSK)

- Four signal states. two bits are transmitted in a single step
- Used in UMTS and IEEE 802.11 (WLAN)

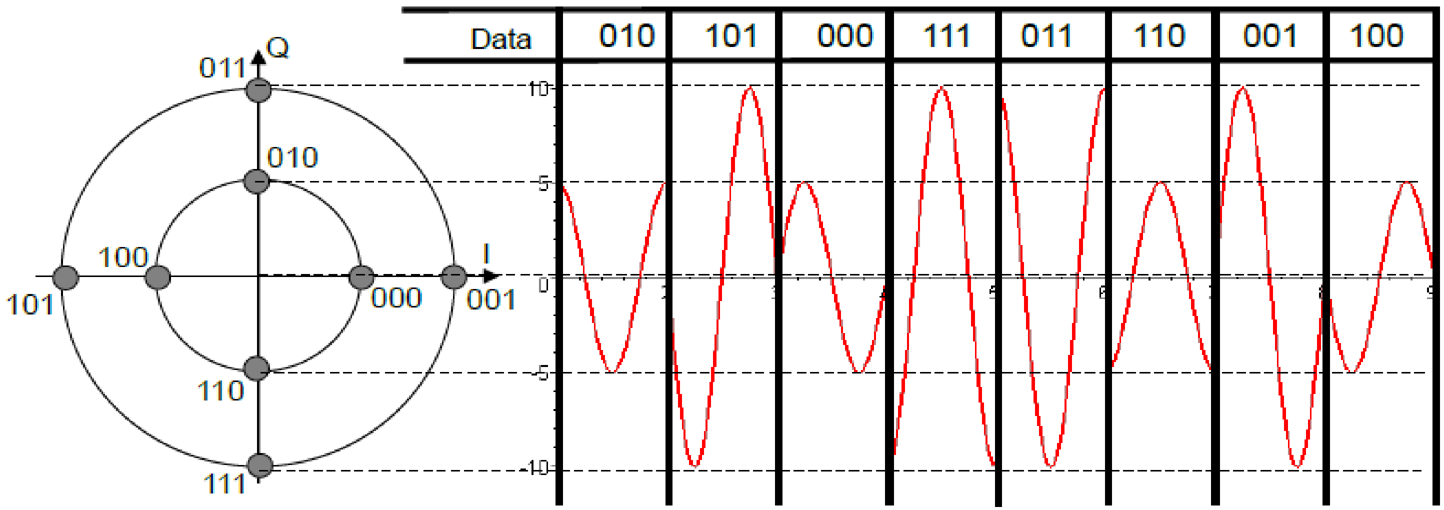


Mixing of Shift Keying Methods

It is also possible to mix different types of shift keying schemes

Example: Quadrature Amplitude Modulation (QAM)

- Combination of ASK and QPSK
- Eight signal states, three bits are transmitted in a single step
- Used as one alternative for IEEE 802.11 (WLAN)



Relationship between data rate and signal rate

- The **data rate** defines the number of bits sent per sec - bps. It is often referred to the bit rate.
- The **signal rate** is the number of signal elements sent in a second and is measured in bauds. It is also referred to as the modulation rate.
- Goal is to increase the data rate whilst reducing the baud rate.
- The baud or signal rate can be expressed as:

$$S = c \times N \times 1/r \text{ bauds}$$

where N is data rate

c is the case factor (worst, best & avg.)

r is the ratio between data element & signal element

Line codeing

Digital data to digital signals

- A digital signal is sequence of discrete, discontinuous voltage pulses. Each pulses a signal element.

- Encoding scheme is an important factor in how successfully the receiver interprets the incoming signal.

- Considerations for choosing a good signal element referred to as line encoding
  - Baseline wandering
  - DC components
  - Self synchronization
  - Error detection
  - Noise and interference

Line encoding challenges

- Baseline wandering - a receiver will evaluate the average power of the received signal (called the baseline) and use that to determine the value of the incoming data elements. If the incoming signal does not vary over a long period of time, the baseline will drift and thus cause errors in detection of incoming data elements.

  - A good line encoding scheme will prevent long runs of fixed amplitude.

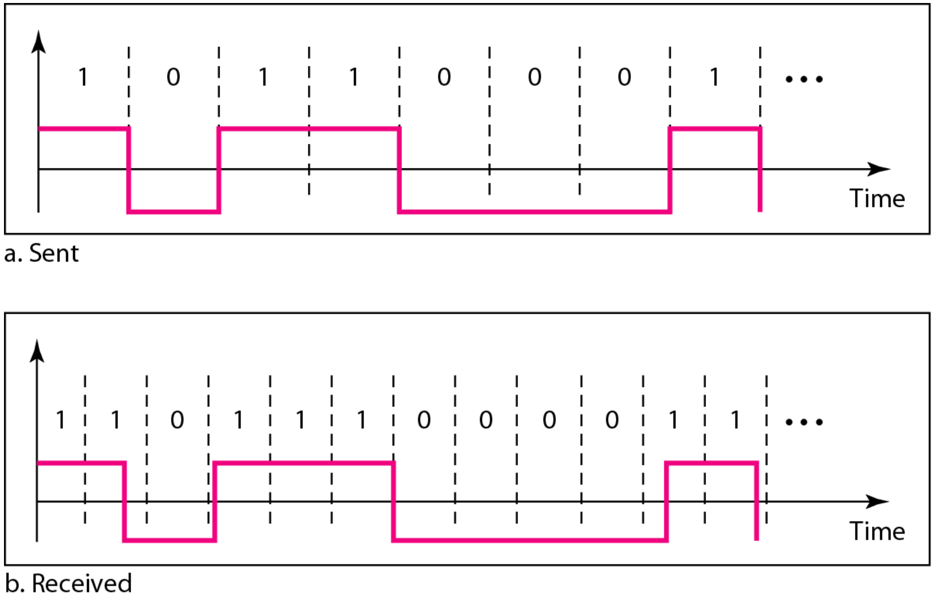
- DC components - when the voltage level remains constant for long periods of time, there is an increase in the low frequencies (around ZERO, called DC component) of the signal. Most channels are bandpass and may not support the low frequencies.

  - This will require the removal of the DC component of a transmitted signal.

Line encoding challenges (contd.)

- Self synchronization - the clocks at the sender and the receiver must have the same bit interval.
  - If the receiver clock is faster or slower it will misinterpret the incoming bit stream.

Effect of lack of synchronization

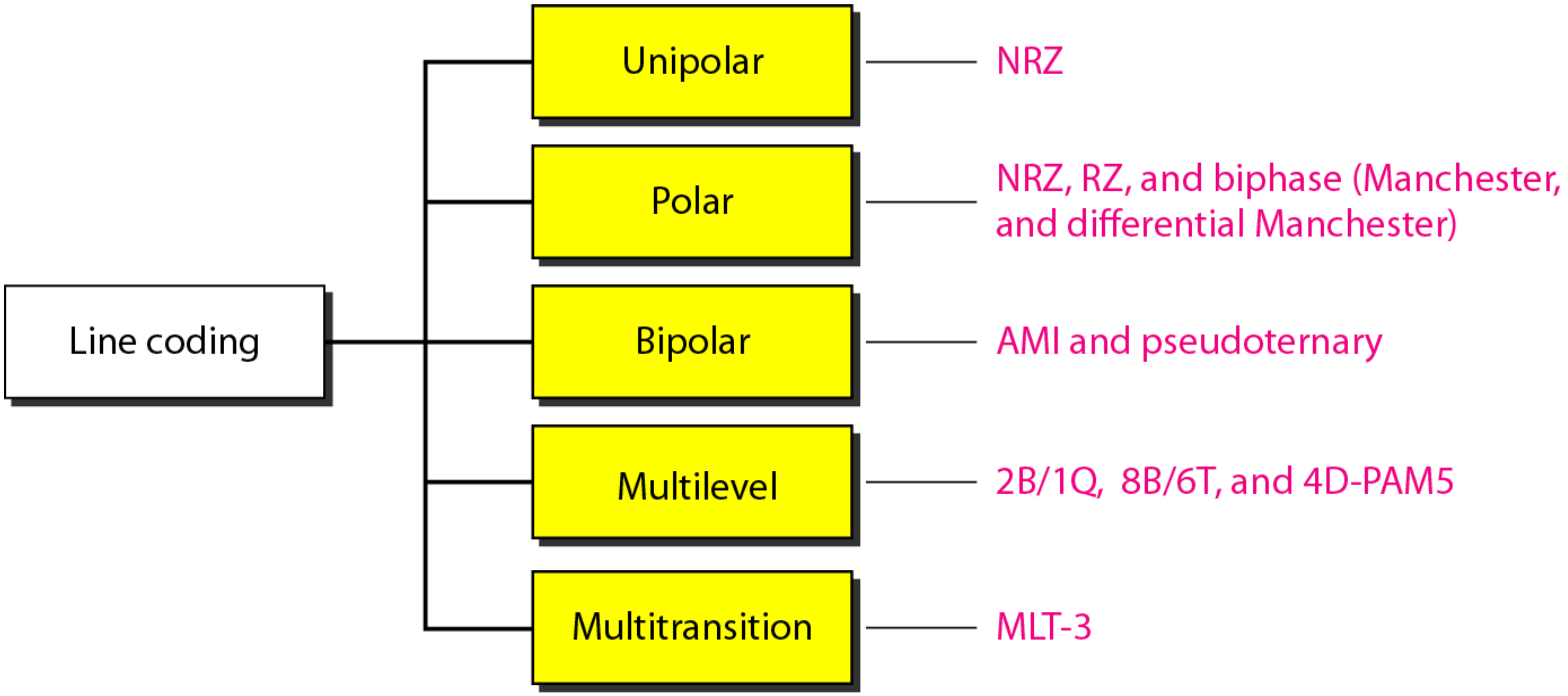


Line encoding challenges (contd. II)

- Error detection - errors occur during transmission due to line impairments.
  - Some codes are constructed such that when an error occurs it can be detected.
    - For example: a particular signal transition is not part of the code. When it occurs, the receiver will know that a symbol error has occurred.

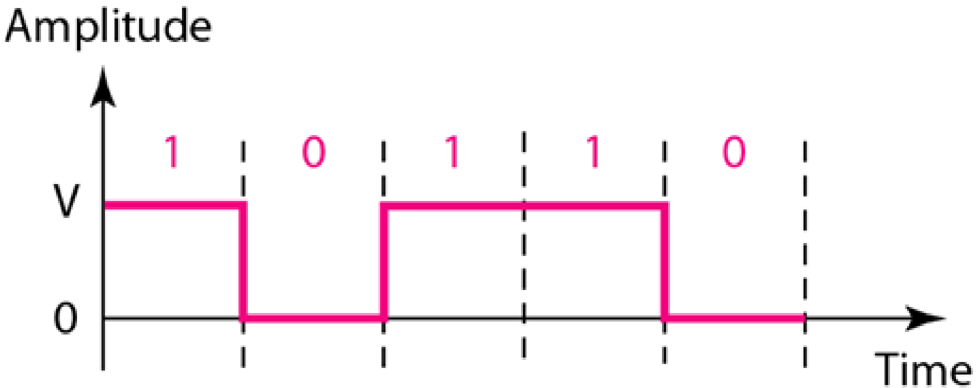
- Noise and interference - there are line encoding techniques that make the transmitted signal "immune" to noise and interference.
  - This means that the signal cannot be corrupted, it is stronger than error detection.

Line coding schemes

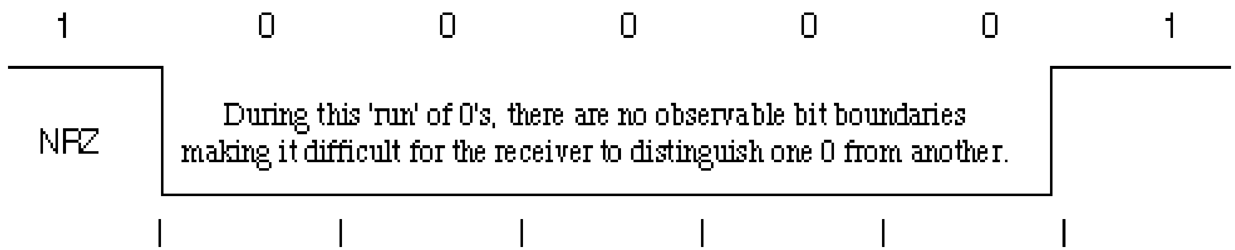


Unipolar

- All signal levels are on one side of the time axis - either above or below
- Voltage held constant during each bit interval
- NRZ - Non Return to Zero scheme is an example of this code. The signal level does not return to zero during a symbol transmission.



Non Return to Zero(NRZ) problem



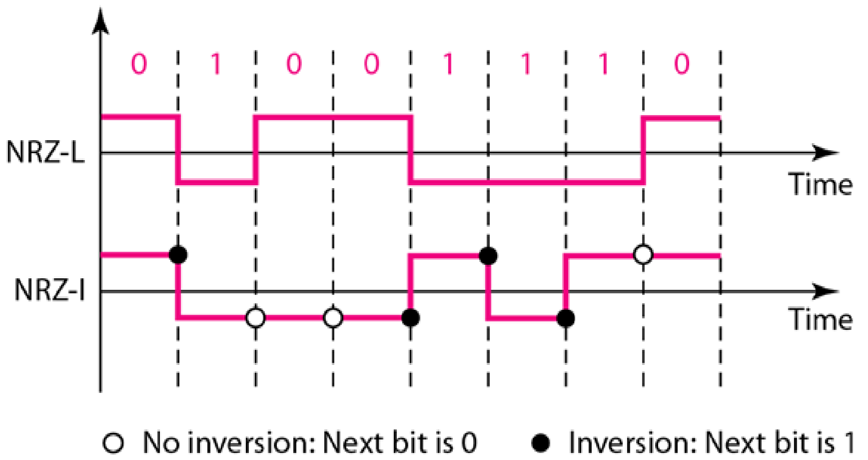
- ✓ Problem arises when there is a long sequence of 0s or 1s and the voltage level is maintained at the same value for a long time.
- ✓ This creates a problem on the receiving end because now, the clock synchronization is lost due to lack of any transitions and hence, it is difficult to determine the exact number of 0s or 1s in this sequence
- ✓ separate clock line need to be provided.
- ✓ Problem of DC component

Polar - NRZ

- The voltages are on both sides of the time axis.
- Polar NRZ scheme can be implemented with two voltages. E.g. +V for 1 and -V for 0.
- There are two versions:
  - NZR - Level (NRZ-L)
  - NRZ - Inversion (NRZ-I)
- Problem of long sequence of 0s or 1s persists - baseline wandering and DC component problem
- Relatively simple to implement.

Polar – NRZ (contd.)

- NRZ-Level
  - Binary 1 → negative voltage
  - Binary 0 → positive voltage (or vice versa)
- NRZ-Inverted: Nonreturn to zero, invert on ones
  - Binary 1 → transition (low-to-high or high-to-low) at the beginning of a bit interval
  - Binary 0 → no transition
  - An example of differential encoding (data represented by changes rather than levels)



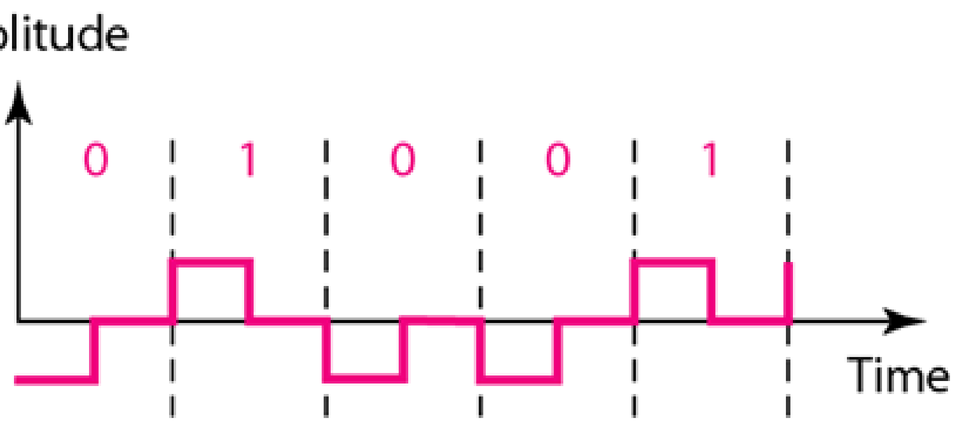
Disadvantages

✓NRZ-L and NRZ-I both have a DC component problem and baseline wandering, it is worse for NRZ-L.

✓Both have no self synchronization & no error detection.

Polar - RZ

- The Return to Zero (RZ) scheme uses three voltage values. +, 0, -.
- Each symbol has a transition in the middle of each bit-period. Either from high to zero or from low to zero.
- Voltage level NOT constant over an entire bit-interval

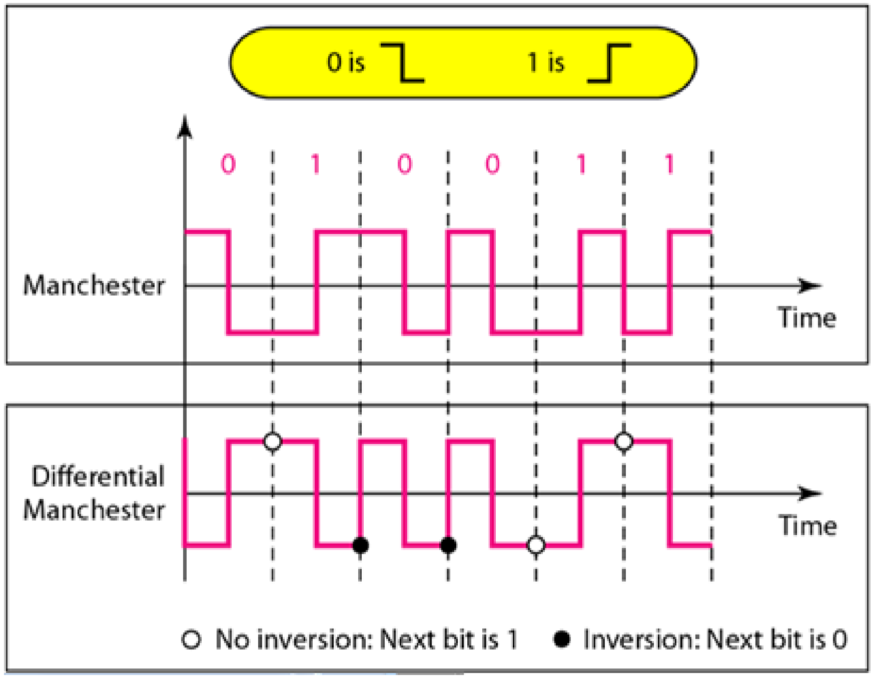


- Advantages
  - ✓ No DC components or baseline wandering.
  - ✓ Self synchronization - transition indicates symbol value.
- Disadvantage
  - ✓ More complex as it uses three voltage level.

Polar - Biphase: Manchester and Differential Manchester

- Manchester coding consists of combining the NRZ-L and RZ schemes.
  - Every symbol has a level transition in the middle: from high to low or low to high. Uses only two voltage levels.

- Differential Manchester coding consists of combining the NRZ-I and RZ schemes.
  - Every symbol has a level transition in the middle. But the level at the beginning of the symbol is determined by the symbol value. One symbol causes a level change the other does not.

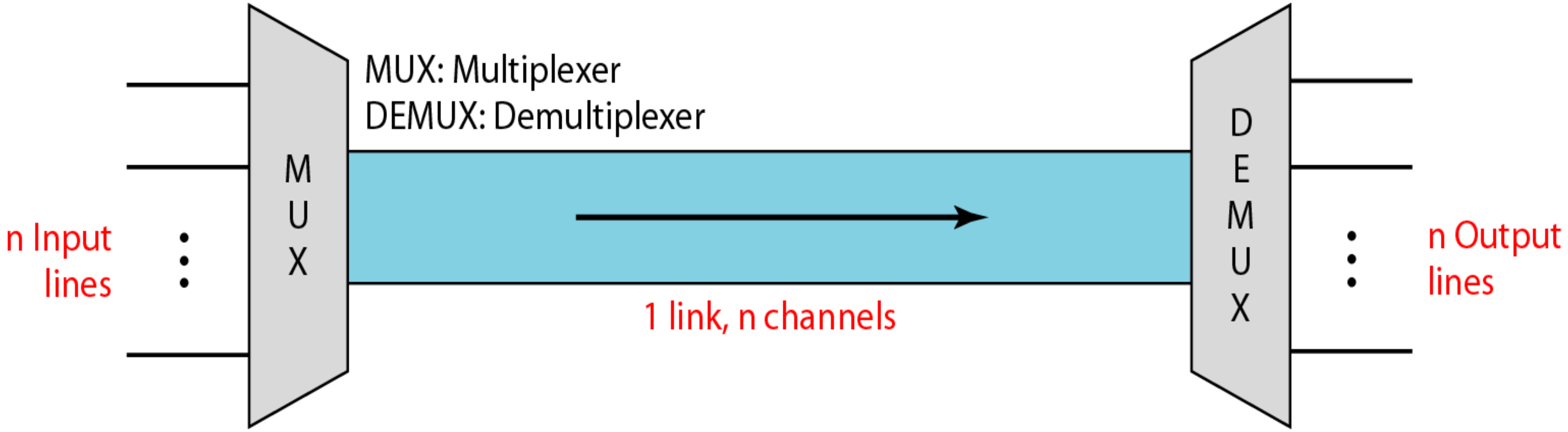


Multiplexing

Multiplexing

- Whenever the bandwidth of a medium linking two devices is greater than the bandwidth needs of the devices, the link can be shared.

- Multiplexing is the set of techniques that allows the (simultaneous) transmission of multiple signals across a single data link. As data and telecommunications use increases, so does traffic.



Multiplexing

Motivation

Task of multiplexing is to assign space, time, frequency, and code to each communication channel with a minimum of interference and a maximum of medium utilization

Communication channel refers to an association of sender(s) and receiver(s) that want to exchange data

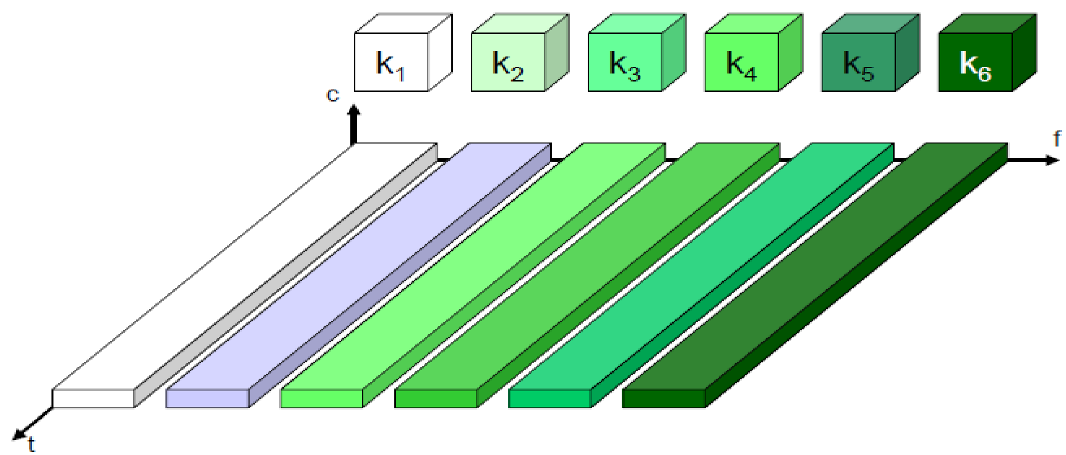
Classification of multiplexing

Four types :

- Frequency
- Time
- Code
- Wavelength

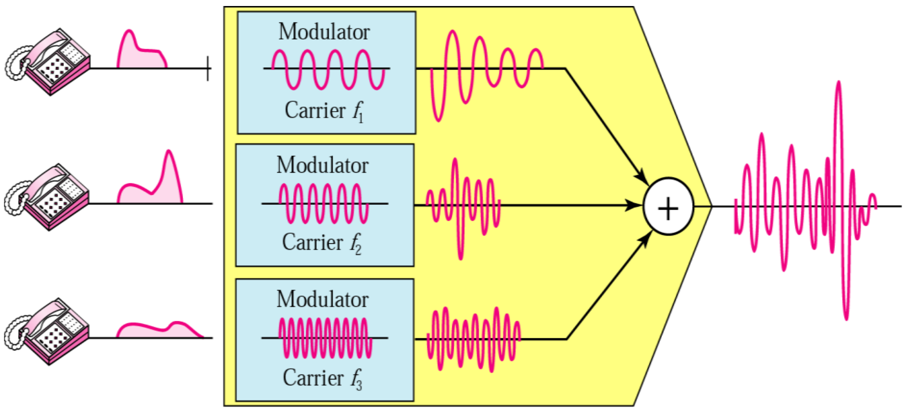
Frequency Division Multiplexing (FDM)

- Subdivision of the frequency dimension into several non-overlapping frequency bands, each continuously carrying one channel
- Guard spaces between frequency bands to avoid overlapping (adjacent channel interference)
- Permanent assignment of a frequency to a sender makes it advantageous for radio transmission (24 hours a day), but inapplicable for mobile communication (assignment of a permanent frequency band for each mobile device would result in a tremendous waste of scarce frequency resources)
- Simultaneously and continuously transmitting
- One circuit per channel

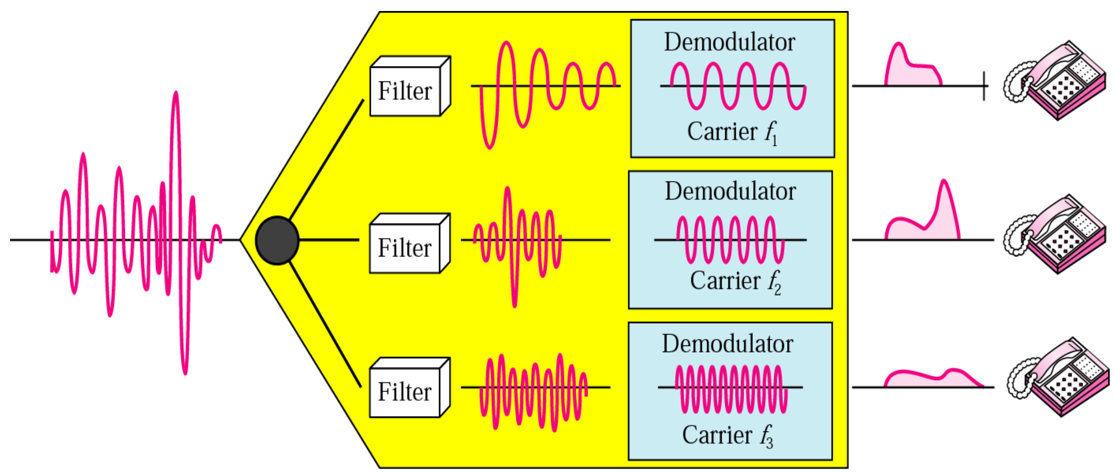


Frequency Division Multiplexing (FDM) contd

Multiplexing

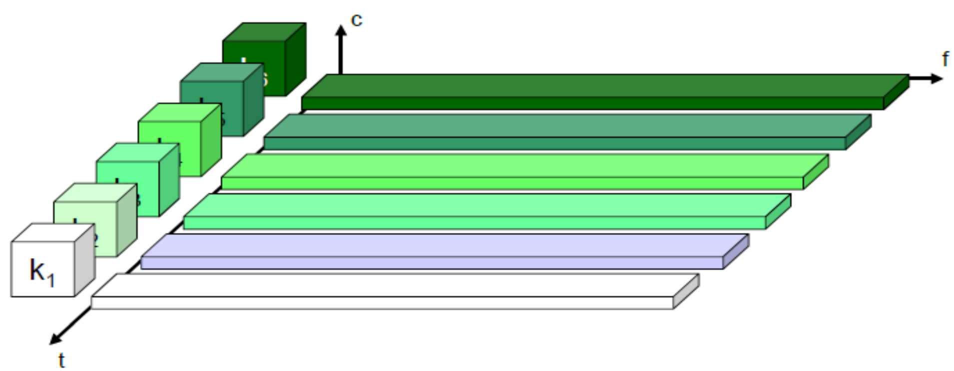


Demultiplexing

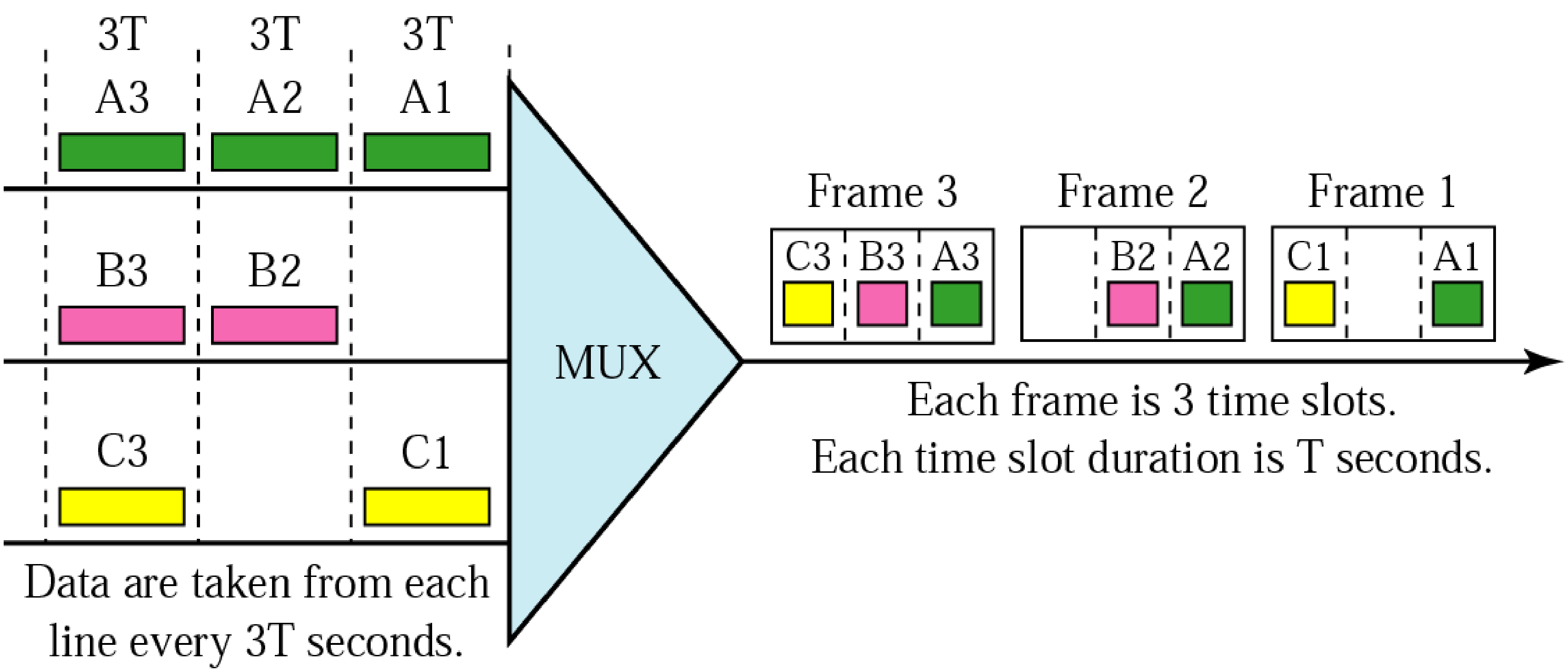


Time Division Multiplexing (TDM)

- All senders alternately use the same frequency at different points in time – a single carrier frequency for several users
- Avoidance of transmission overlaps (co-channel interference) by time gaps (guard spaces)
- Requires precise synchronization between senders (either by a precise clock or by a dedicated synchronization signal accessible for all senders)
- Flexible, as senders with heavy load can be assigned more sending time and senders with light load less sending time
- Transmission in bursts for each user, low battery consumption
- High synchronization overhead – stations has to be time synchronized



Time Division Multiplexing (TDM) example



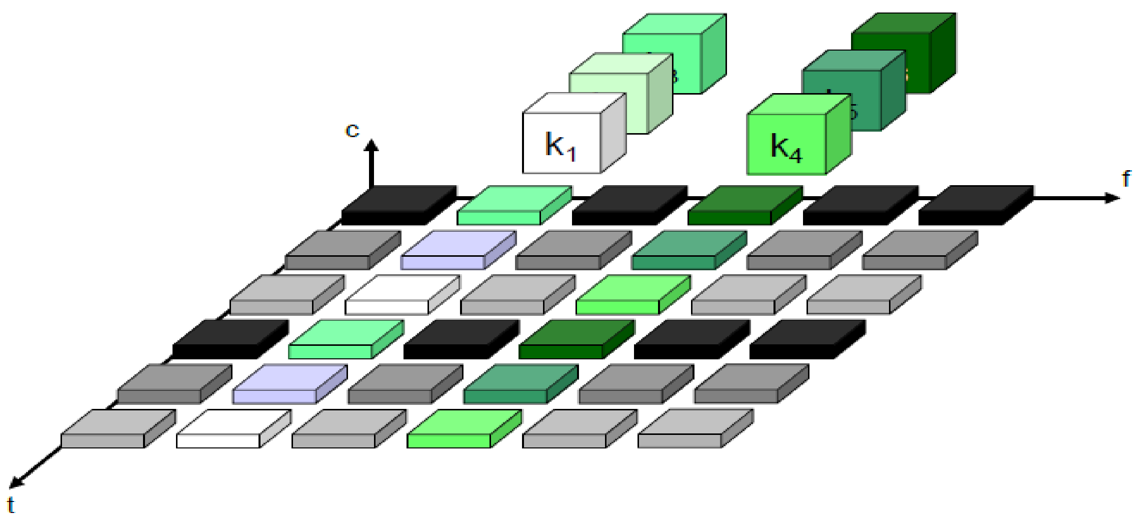
TDM Types

- **Synchronous** : Fixed number of time slots allocated for each source
  - May leave empty slots in a TDM frame (if one or more sources is not sending data)
  - To synchronize demux (in Rx) with mux (in Tx), extra framing bit transmitted with each TDM frame:
    - ✓ Framing bits define a control channel: similar to an additional channel having 1 bit per frame (say, alternate 101010…)
  - Many slots within a TDM frame may be wasted

- **Statistical** : Allocates time slots dynamically based on demand of the sources

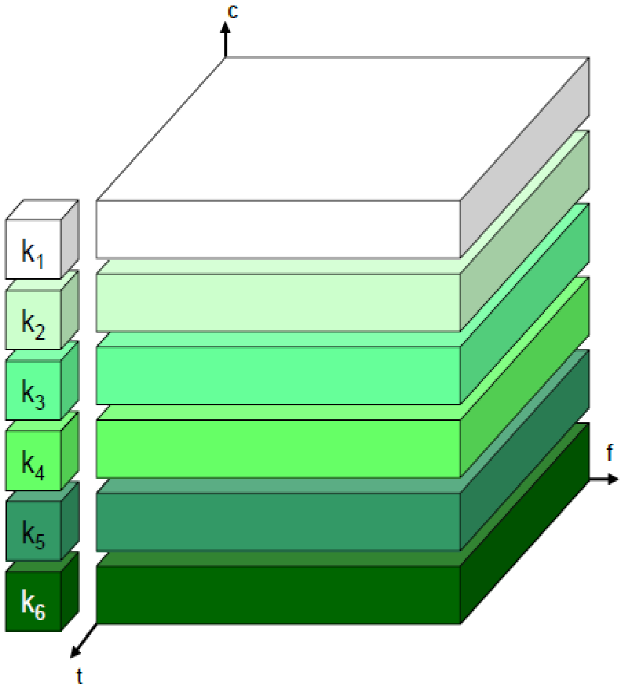
Combination of FDM and TDM

- Channel can use a certain frequency band for a certain amount of time
- Guard spaces in the time and in the frequency dimension
- Robust against small-scale fading by using frequency hopping(fast change of frequency bands)
- Deployed in GSM



Code Division Multiplexing (CDM)

- All channels use the same frequency band at the same time
- Separation by codes, guard spaces corresponds to the distance between codes (orthogonal codes)
- Good protection against interference and tapping (i.e., signals are spread on a broad frequency band, and interpretation of a signal is only possible with matching code)
- High complexity of the receivers
- Precise synchronization between sender and receiver
- Multiplexing technique for WLAN/UMTS



Principle of Spread Spectrum to be discussed later

CDM Analogy

All people are in the same room together. They can all be talking the same time.

Provided -

- ✓ Each of the person talk and understand exactly one language
- ✓ Every one talk almost in same loudness (amplitude)

CDMA transmission and reception analogy

Tx 1 : Information Signal **S1**, Spreading Code **C1**. Transmits (**S1.C1**) over the air

Tx 2 : Information Signal **S2**, Spreading Code **C2**. Transmits (**S2.C2**) over the air

From Spreading code's auto-correlation and orthogonal property -

C1.C1 = 1

C2.C2 = 1

C1.C2 = 0

When signal transmitted from two source, over the air it becomes -

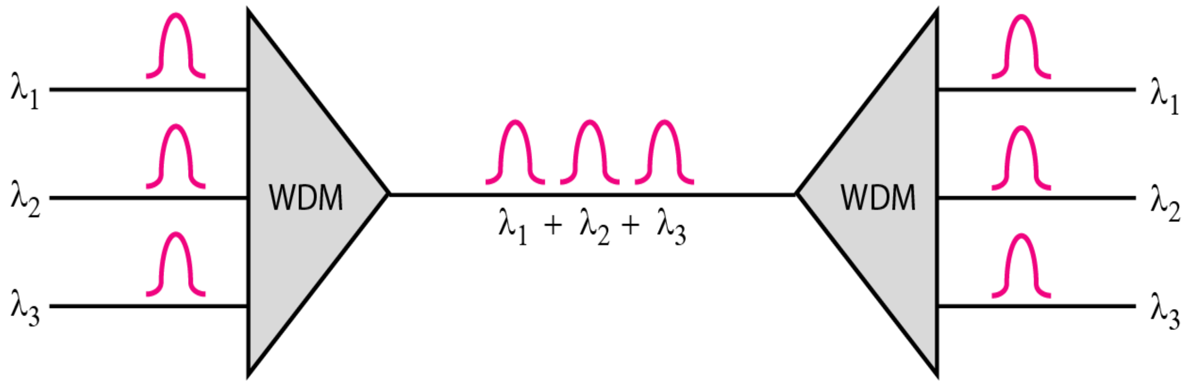
(S1.C1 + S2.C2)

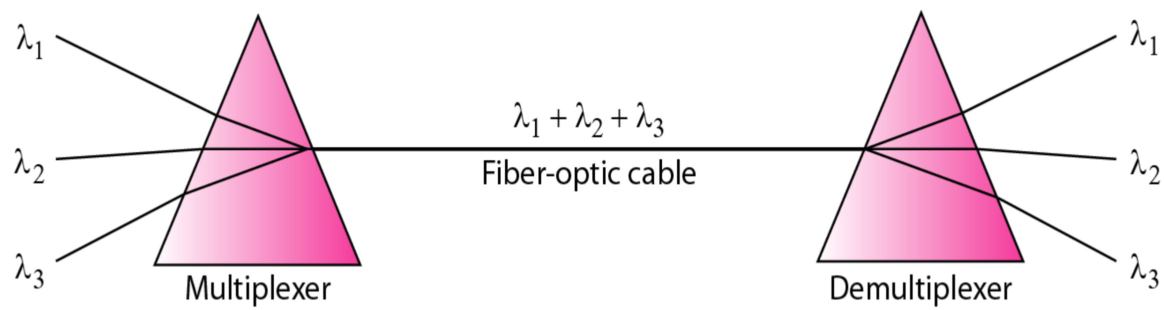
Rx 1 : Despreading on reception **(S1.C1 + S2.C2).C1 = S1.C1.C1 + S2.C2.C1 = S1**

Rx 2 : Despreading on reception **(S1.C1 + S2.C2).C2 = S1.C1.C2 + S2.C2.C2 = S2**

Wavelength-division multiplexing (WDM)

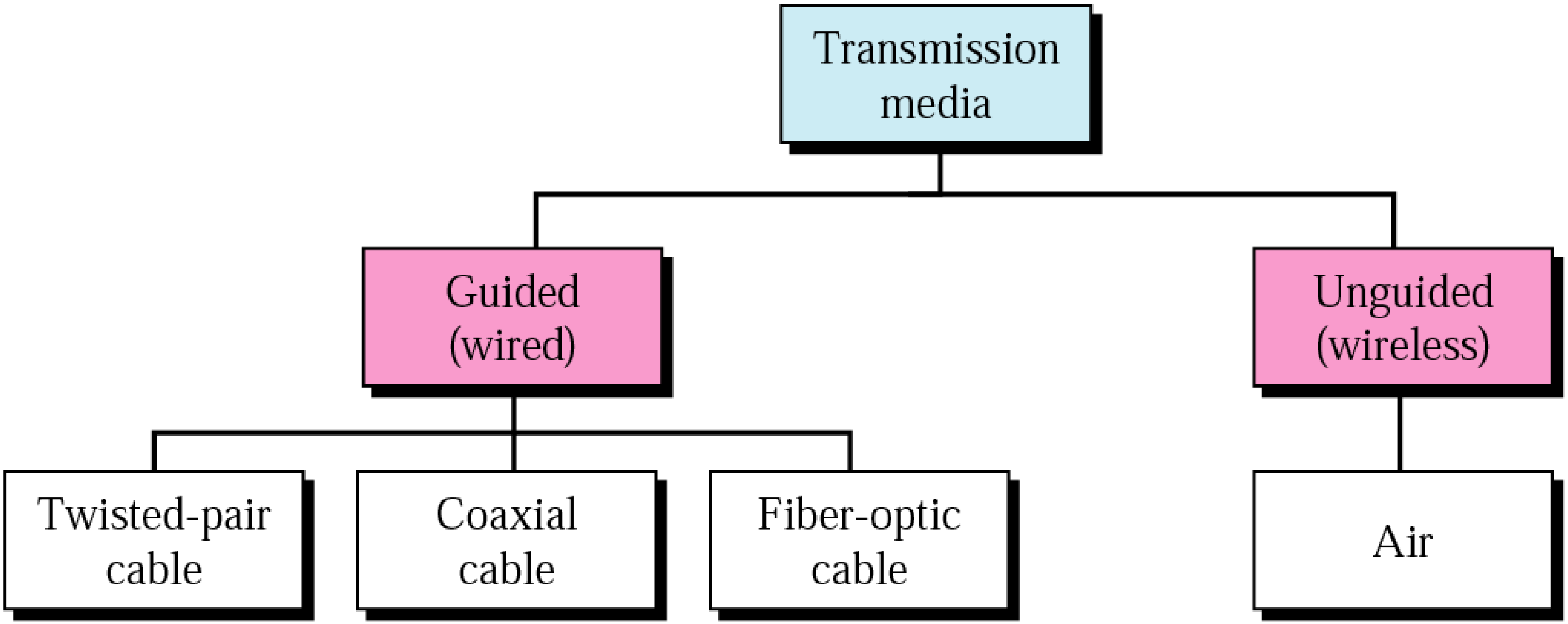
- WDM is an analog multiplexing technique to combine optical signals.





Transmission Media

Types of media



Guided (Wired)

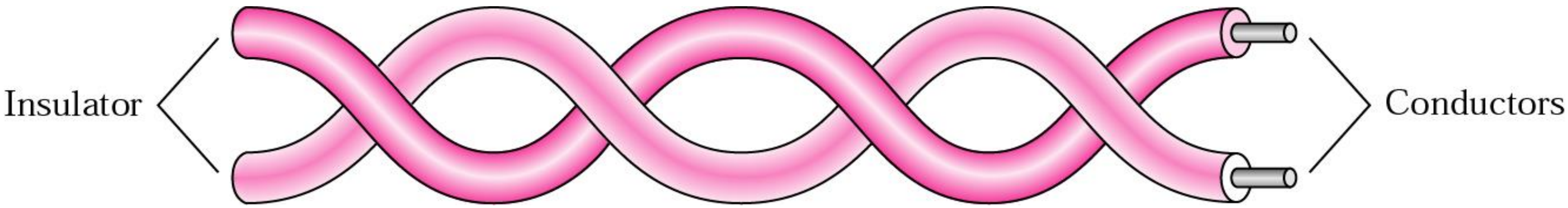
Twisted Pair

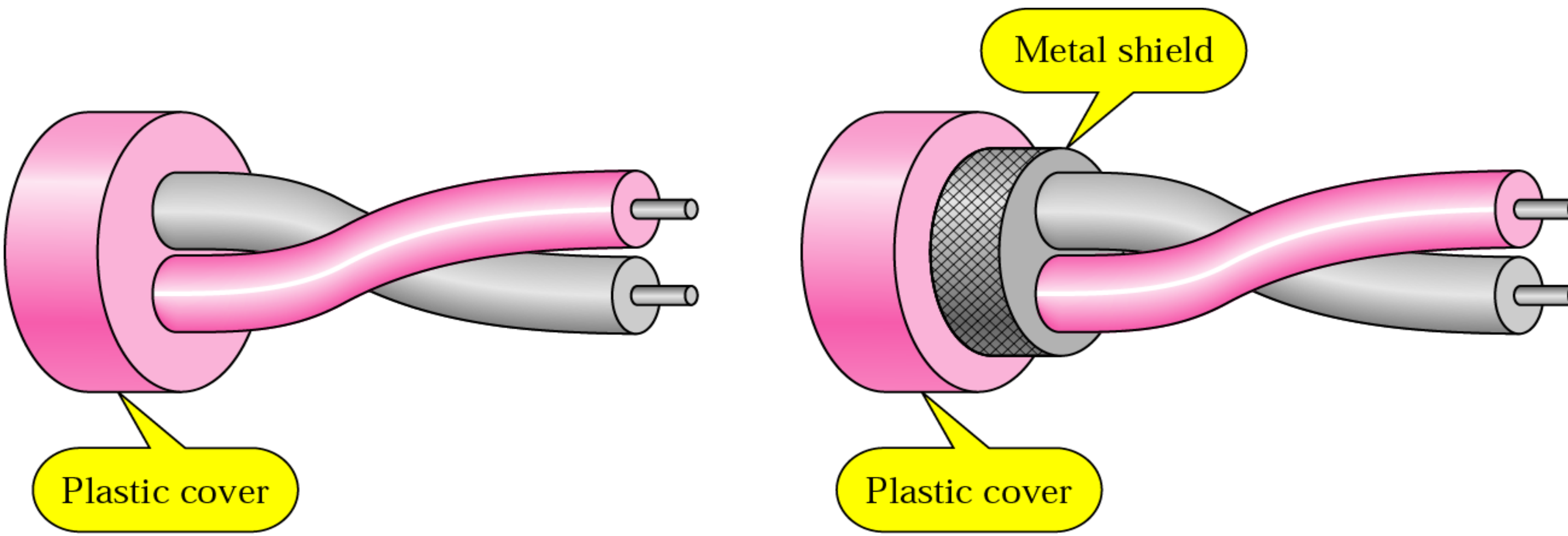
- consists of two insulated copper wires
- arranged in a regular spiral pattern to minimize the electromagnetic interference (EMI) between adjacent pairs
- Carries signals in lower frequency ranges
- Advantage – cheap, lightweight
- Disadvantage
  - relatively low bandwidth
  - more susceptible to interference/noise
  - Repeaters needed every 5-6 km for analog signal, every 2-3 km for digital signal

Unshielded and Shielded Twisted Pair

- UTP
  - Cheapest, easiest to install
  - Ordinary telephone wire
  - Suffers relatively more from external EMI
- STP
  - The pair is wrapped with metallic foil to insulate the pair from EMI
  - More expensive

Twisted pair





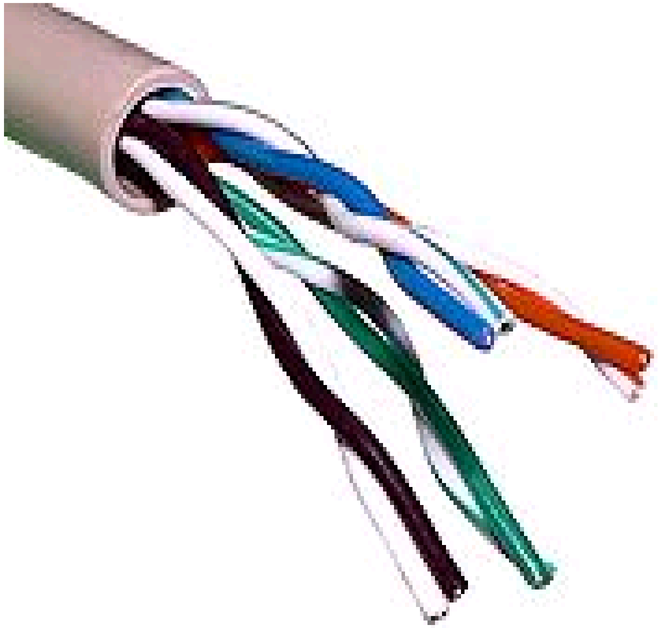
a. UTP

b. STP

Important UTP Categories

- Seven categories of UTP determined by cable quality: cat 1 (lowest quality) to cat 7

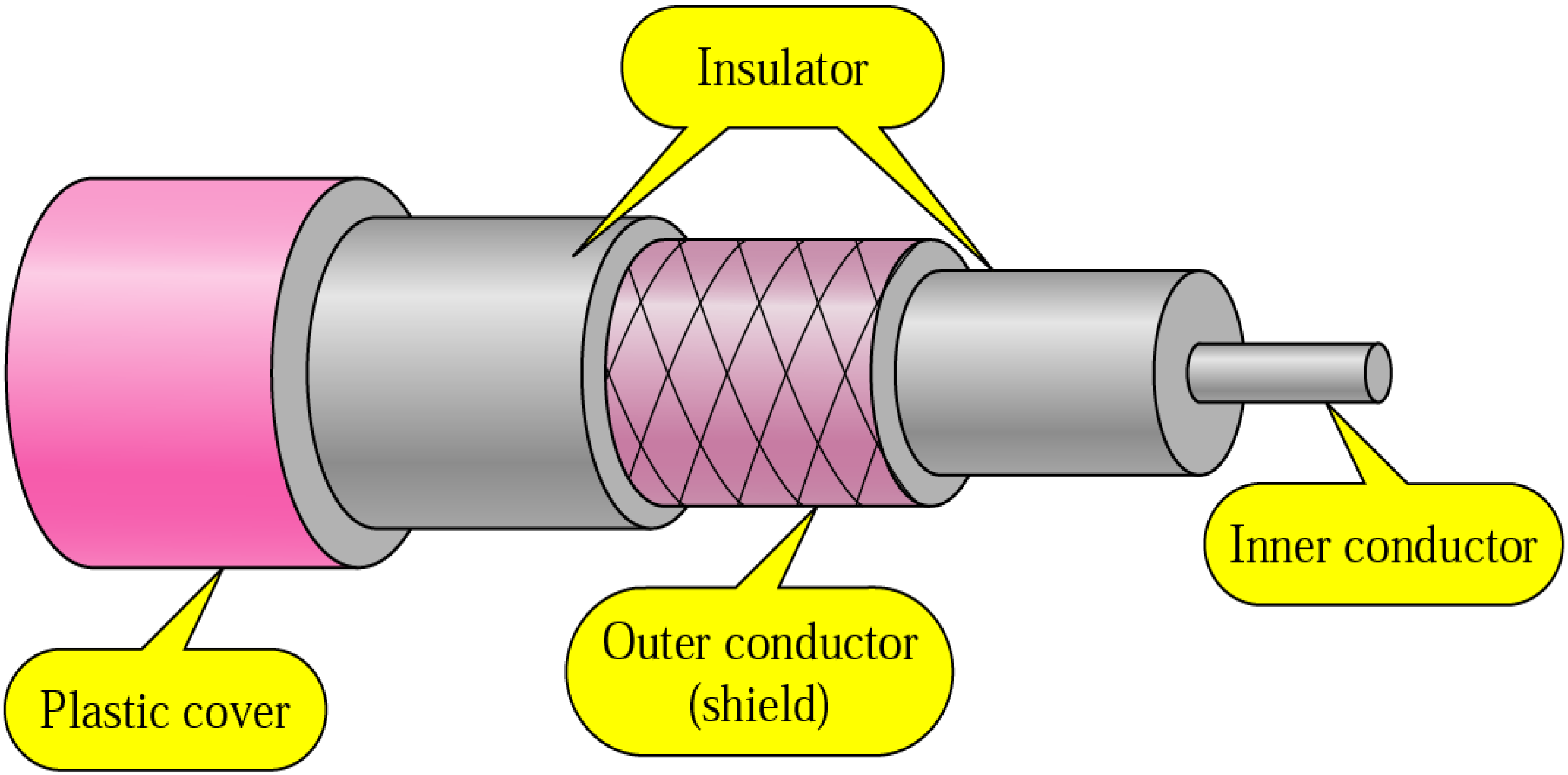
- Cat 5
  - Upto 100 Mbps
  - Commonly used in LANs



Coaxial Cable

- Carries signals of higher frequency ranges (compared to twisted pairs)
- Central core conductor of solid or stranded wire (usually copper)
- Enclosed in an insulating sheath
- Encased in an outer conductor of metal foil
- Outer conductor also enclosed in an insulating sheath, and the whole cable protected by a plastic cover
- Application: cable tv

Coaxial Cable

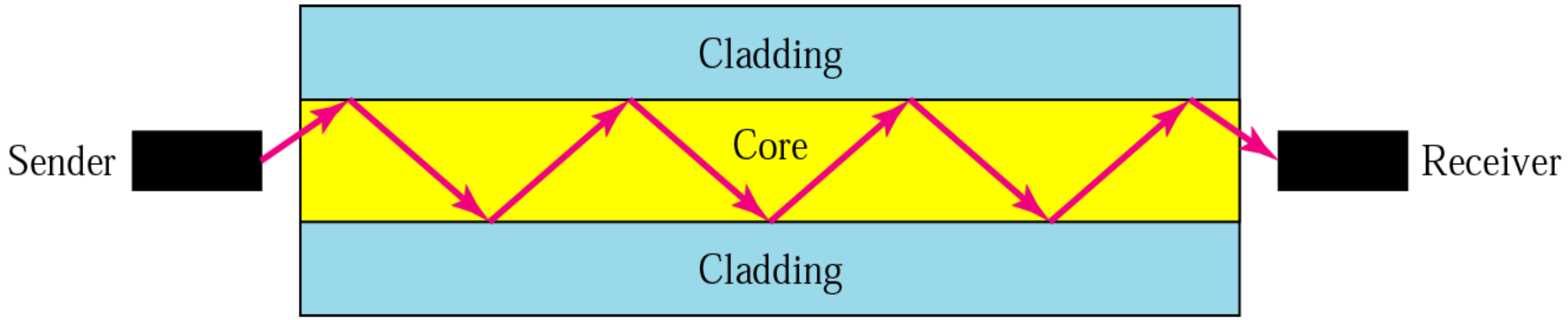


Optical Fiber

- Thin (2-125 micrometer), flexible medium capable of conducting an optical ray
- Cylindrical shape with three concentric sections: the ***core***, the ***cladding***, and the ***jacket***
- Greater data rates
- Smaller size & weight
- Lower attenuation
- Greater repeater spacing – tens of kilometres
- Highly secure
  - Difficult to tap into
  - Lack of signal radiation

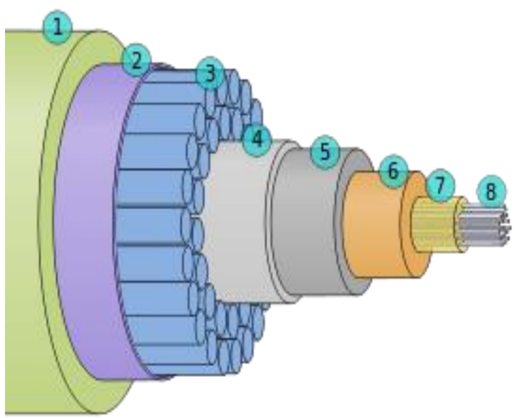
Optical Fiber

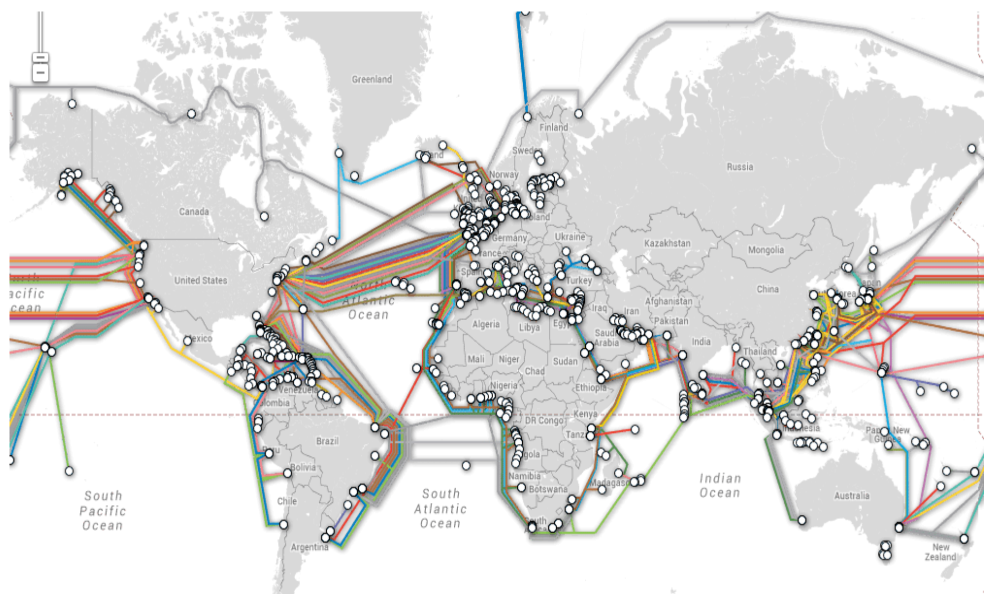
- A glass or plastic **Core** is surrounded by a **cladding** of less dense glass or plastic
- Difference of density of the two materials must be such that a beam of light moving through the core is reflected off the cladding instead being refracted into it



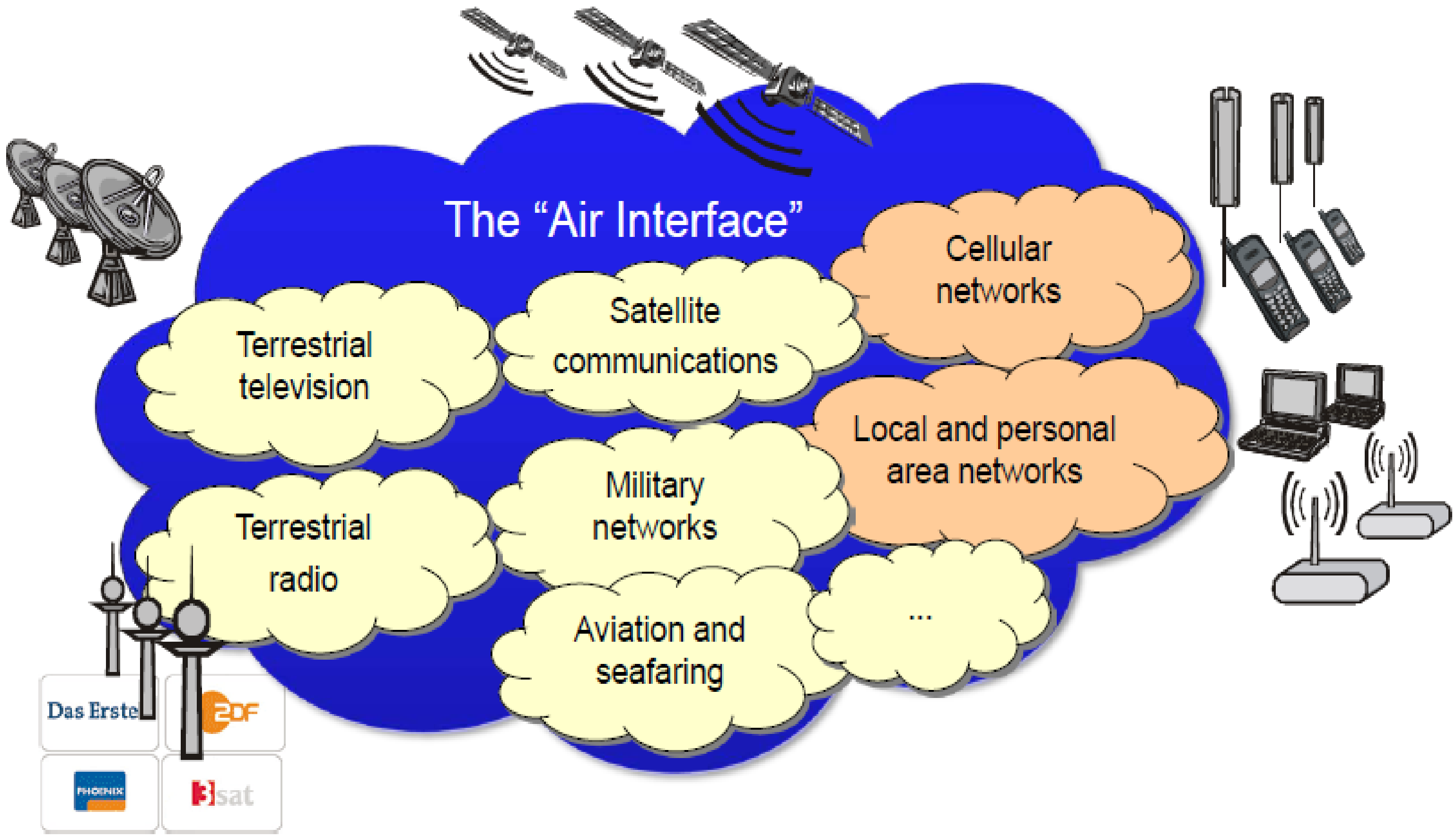
Submarine communications cable (undersea optical fibre cables)

- **cable** laid on the sea bed between land-based stations to carry telecommunication signals across stretches of ocean
- connected all the world's continents except Antarctica



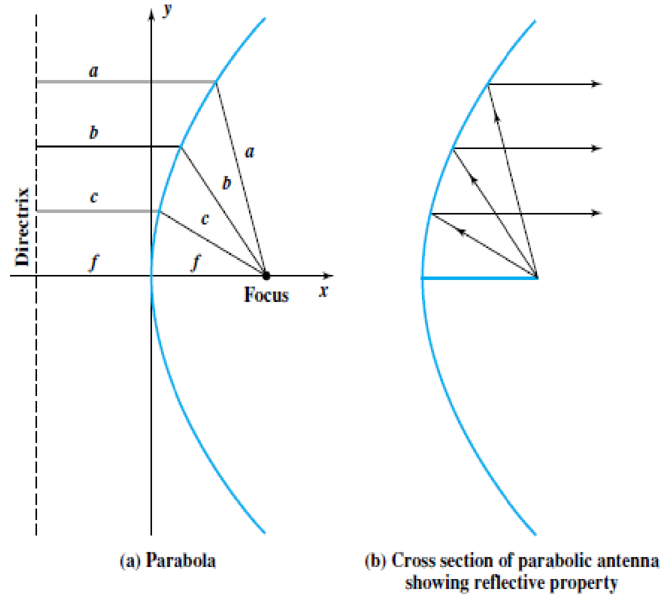


Un-guided (Wireless)



Wireless Transmission

- Unguided media, transmission and reception via antenna



Parabolic Reflective Antenna

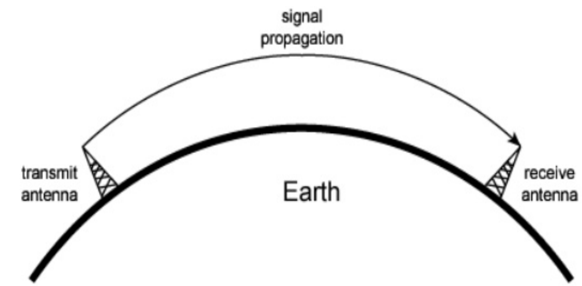
- Directional
  - Signal transmitted as a focused beam
  - Careful alignment of antennae required

- Omnidirectional
  - Signal spreads in all directions
  - Can be received by many antennae

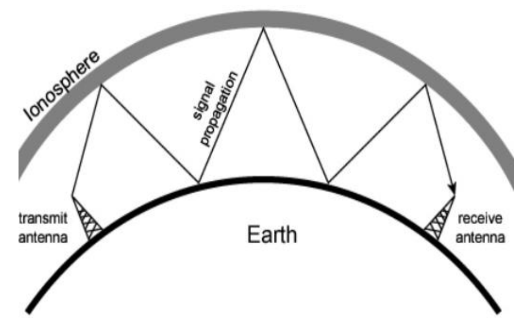
- Examples of wireless transmission
  - Terrestrial microwave transmission
  - Satellite transmission
  - Broadcast radio

Radio Wave Propagation

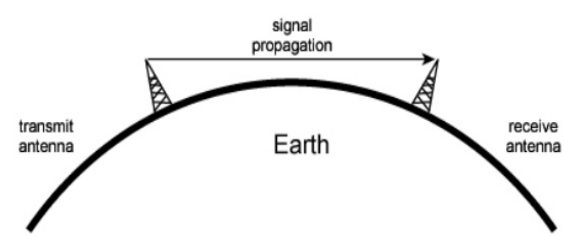
- Ground Wave Propagation
  - Follows contour of earth



- Sky Wave Propagation
  - Signal reflected from ionosphere layer of upper atmosphere



- Line-of-sight Propagation
  - High frequency signal transmitted in straight line



Band & Radio Wave Propagation

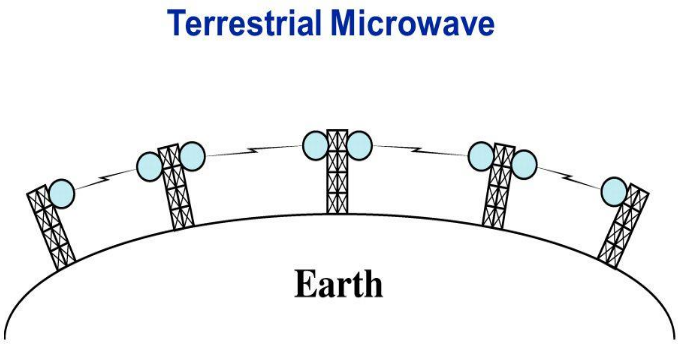
Band	*Range*	*Propagation*	*Application*
VLF (very low frequency)	3-30 kHz	Ground	Long-range radio navigation
LF (low frequency)	30-300 kHz	Ground	Radio beacons and navigational locators
MF (middle frequency)	300 kHz-3 MHz	Sky	AM radio
HF (high frequency)	3-30 MHz	Sky	Citizens band (CB), ship/aircraft communication
VHF (very high frequency)	30-300 MHz	Sky and line-of-sight	VHF TV, FM radio
UHF (ultrahigh frequency)	300 MHz-3 GHz	Line-of-sight	UHF TV, cellular phones, paging, satellite
SHF (superhigh frequency)	3-30 GHz	Line-of-sight	Satellite communication
EHF (extremely high frequency)	30-300 GHz	Line-of-sight	Radar, satellite

Terrestrial Microwave

- Uses the radio frequency spectrum, commonly from 2 to 40 Ghz
- Transmitter is a parabolic dish antenna, mounted as high as possible
- Requires unobstructed line of sight between source and receiver
- Curvature of the earth requires stations (called repeaters) to be ~30 miles apart
- Applications
  - Long-haul voice and television transmission service

Terrestrial Microwave (contd.)

- ❑ Advantages
  - ➢ No cabling needed between sites
  - ➢ Wide bandwidth
  - ➢ Multi-channel transmissions possible



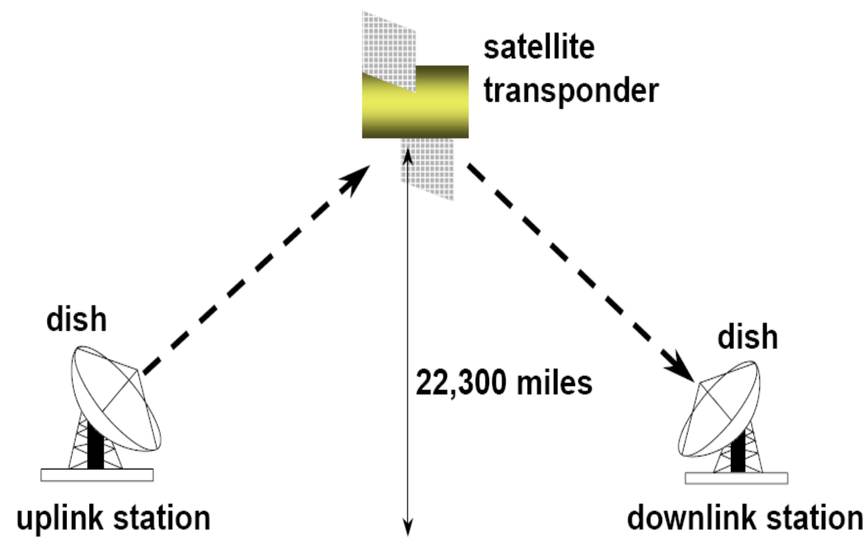
- ❑ Disadvantages
  - ➢ line of sight requirement
  - ➢ expensive towers and repeaters
  - ➢ subject to interference such as passing airplanes and rain

Satellite Microwave

- Satellite: a microwave relay station in space
- Satellite receives signal from earth stations on one frequency (uplink)
- Amplifies or repeats signal and transmits on another frequency (downlink)
- The broadcast nature of the downlink makes it attractive for services such as the distribution of television programming
- Geostationary satellites used

Satellite Microwave (contd.)

- Applications
  - Satellite television distribution
  - Long-distance telephone transmission



- Advantages
  - Can reach a large geographical area
  - High bandwidth, high data rates
  - Cheaper over long distances
- Disadvantage
  - High initial cost
  - Susceptible to noise and interference
  - Propagation delay

Why don't we use satellites more than undersea optical fibre cables for Internet ?

- Large communications satellites cost huge amounts of money but they can deliver coverage over wide areas pretty much irrespective of geography

- The problem with fibre is that it is point-to-point, a satellite can broadcast information to millions of people in parallel with no more effort than to deliver to one person.

- But for fibre to reach millions of people it must be physically dragged to each person.

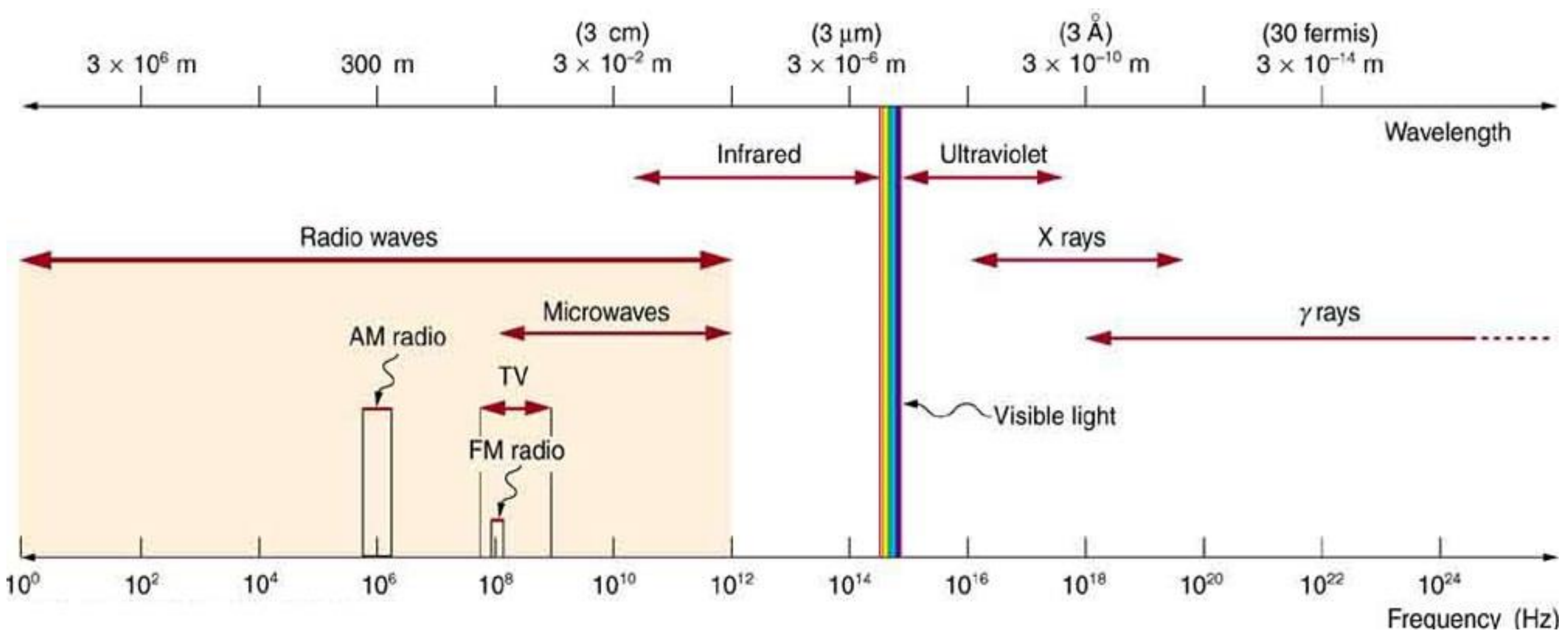
- A fibre roll-out to a population is hugely expensive but the investment once made is more flexible and powerful than satellite → **How ???**

Why don't we use satellites more than undersea optical fibre cables for Internet ? (contd)

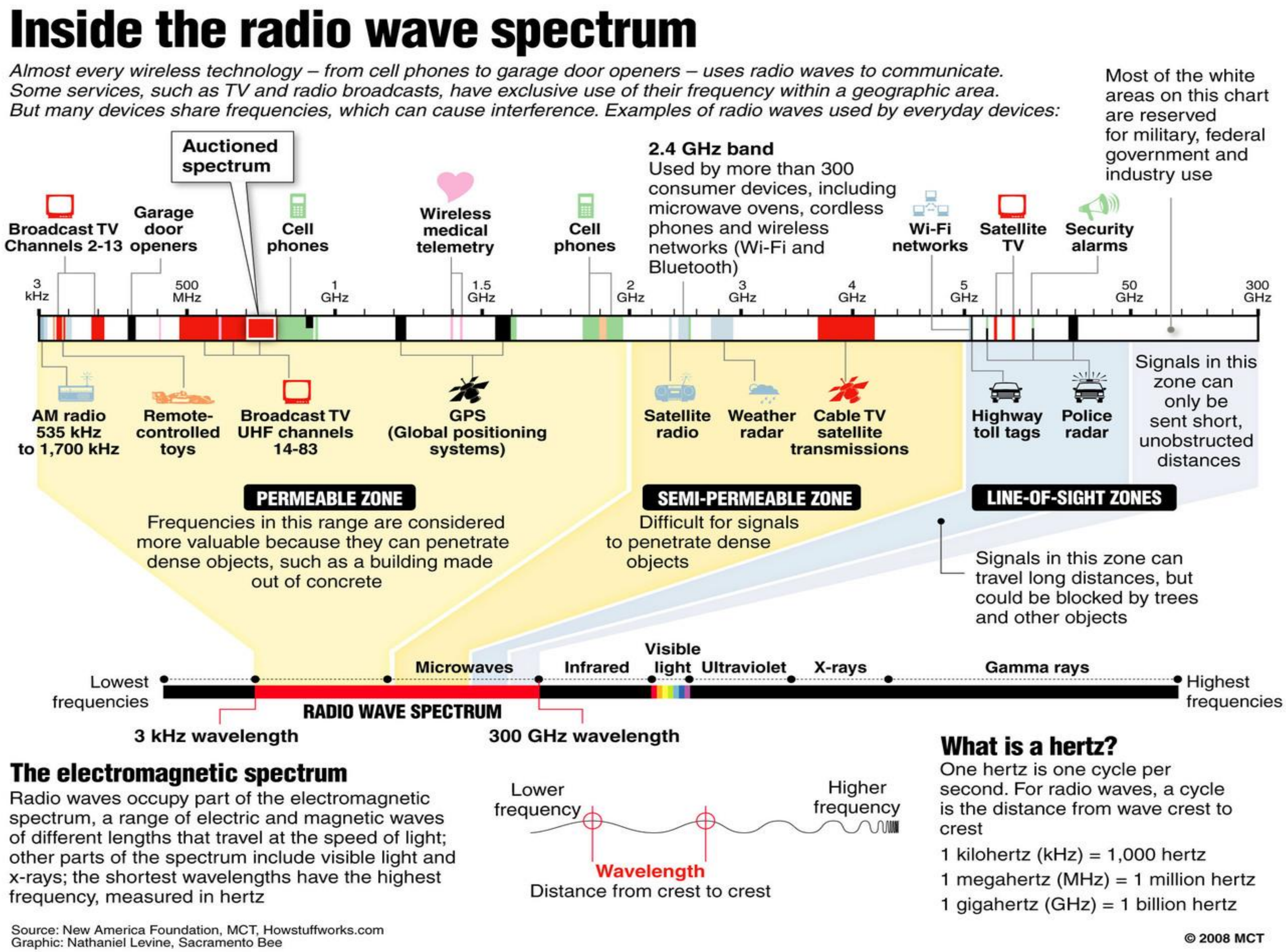
- Compared to fibre is that satellite have a very limited bandwidth in comparison
  - Satellite may only occupy a couple of GHz of radio spectrum, one fibre with DWDM(Dense WDM) could deliver the equivalent of all the bandwidth of every traditional satellite in operation

- Another concern is latency
  - The distance from Earth to the satellite and back creates delays which make real-time communication more difficult than by fibre.

Appendix 1 : Electromagnetic Spectrum



Appendix 2 : Electromagnetic Spectrum (detail)



References

- *Data Communications & Networking, 5th Edition, Behrouz A. Forouzan*
- *Data and Computer Communication, William Stallings*
- *Computer Networks, Andrew S. Tanenbaum and David J. Wetherall*
- *Mobile Communication, Jochen Schiller*
- *Wikipedia / Internet Resources*