Computer Networks

Physical Layer

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Physical Layer

- It is the lowest layer in the OSI model.
- It is the foundation on which other layers build
- It defines how to transmit raw bits of logical data frames that it gets from the Data Link layer
- These bits can be grouped into bit words (**codes**)
- Properties of wires, fiber, wireless limit what the network can do
- Key problem is to send (digital) bits using only (analog) signals. Physical Layer defines the shape of the signal to be transmitted over the medium and its frequency (**modulation**)

The Theoretical Basis for Data Communication

- ❑ Fourier Analysis
- ❑ Bandwidth-Limited Signals
- ❑ Maximum Data Rate of a Channel
- ❑ Modulation
- ❑ Digital Modulation and Multiplexing
- ❑ Physical media

Fourier Analysis

- French mathematician Jean Baptiste Fourier (19^{th}) proved that any periodic function can be constructed as sum of sines and cosines

$$f(x) = a_0(f) + \sum_{n=1}^{\infty} \left(a_n(f) \cdot \cos\left(nx\frac{2\pi}{T}\right) + b_n(f) \cdot \sin\left(nx\frac{2\pi}{T}\right)\right)$$

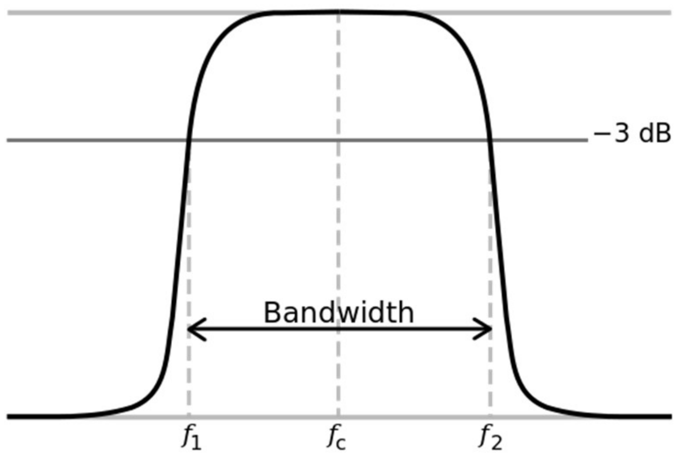
- X_n(rms) corresponds the energy transmitted on the corresponding frequency

$$\chi_n^2 = a_n(f)^2 + b_n(f)^2$$

- Signal transmission
  - > Power loss.
- Different Fourier components are diminished non uniformly.
  - > Distortion
- Each wire is characterized by a cutoff frequency

What does Bandwidth refer to?

- **Bandwidth** is the difference between the upper and lower frequencies in a continuous set of frequencies. It is typically measured in hertz (Hz)
- Bandwidth : **channel size** for electrical engineers (analog)
- **Maximum data rate** for computer science engineers (digital). Data or bite rate is typically measured in bps.
- **Bandwidth is a physical property of the medium**. It is function of its construction, thickness, length…
- Typically in electronic systems such as communication channels, **cutoff frequency** applies to an edge in a lowpass, highpass, bandpass, or band-stop characteristic – a frequency characterizing a boundary between a passband and a stopband

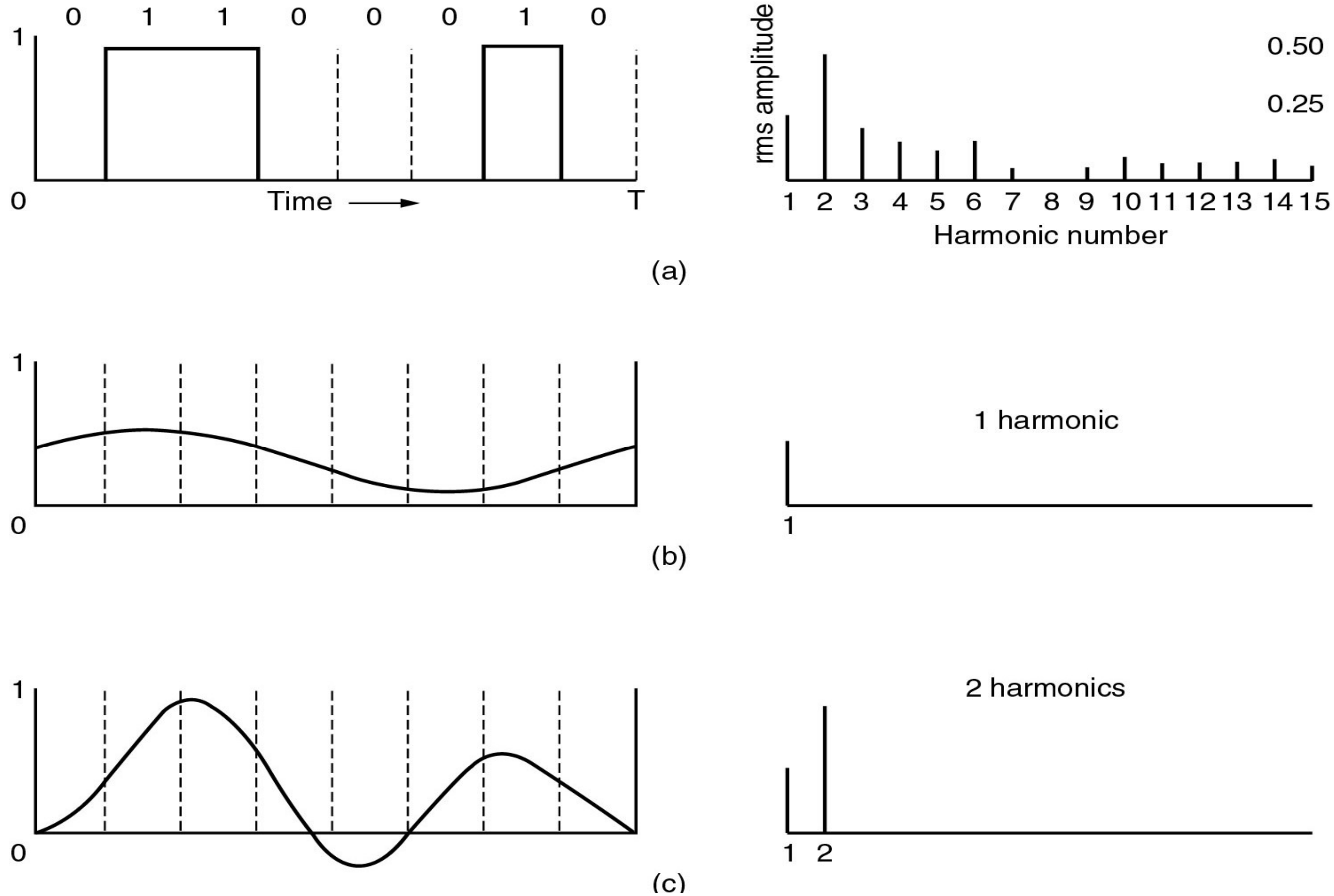


Magnitude transfer function of a bandpass filter with lower 3 dB cutoff frequency f1 and upper 3 dB cutoff frequency f2

Bandwidth examples:

- TV channels → 6 MHz
- 802.11 → 20 MHz
- ADSL → 1 MHz

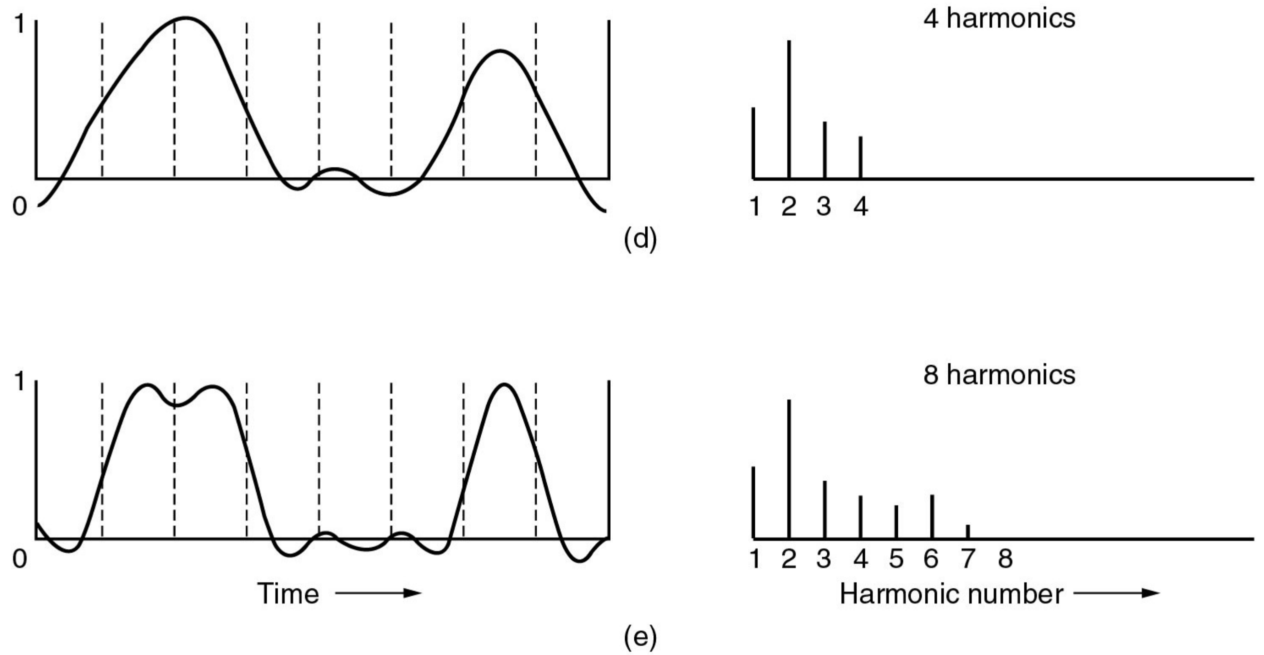
Bandwidth-Limited Signals



A binary signal (ASCII of letter **b**)and its root-mean-square Fourier amplitudes.

(b) – (c) Successive approximations to the original signal.

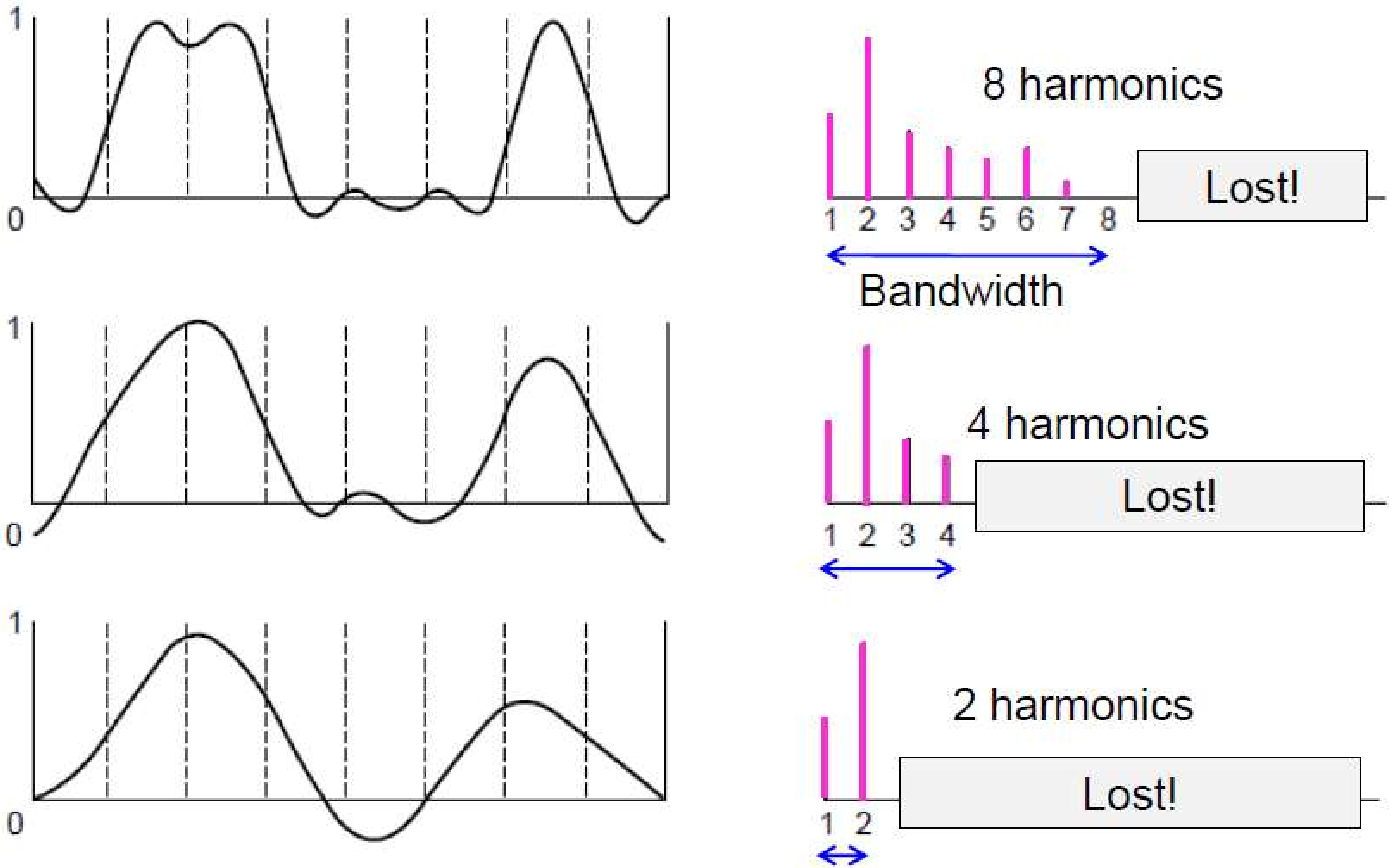
Bandwidth-Limited Signals



(d) – (e) Successive approximations to the original signal.

Bandwidth-Limited Signals

Having less bandwidth (harmonics) degrades the signal



Bandwidth-Limited Signals

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

Number of harmonics that can be obtained over an ordinary telephone line (3000 Hz) to send 8 bits words.

Bit Rate and Symbol (Baud) Rate

Baud rate refers to the number of signal or symbol changes that occur per second. A symbol is one of several voltage, frequency, or phase changes

Baud rate:

$$R = \frac{1}{\Delta}$$

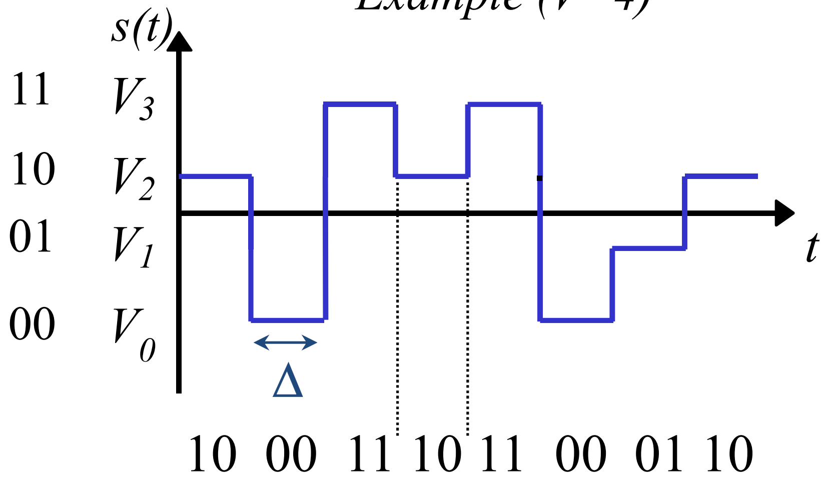
Bit rate:

$$D = \frac{1}{T_b}$$

T_b is the bit duration,

Δ Is the symbol duration

Example (V=4)



$$D = \frac{1}{T_b}$$

If n bits per state, then

$$\boxed{V = 2^n}$$

Then

$$\boxed{D = nR}$$

$$\boxed{D = R \log_2 V}$$

Maximum Data Rate of a Channel

- Henry **Nyquist**, an AT&T engineer (1924) had proven that even a perfect Channel has a finite transmission capacity
- B: bandwidth in Hertz / V: number of discrete symbols

$$Max.-data-rate(D) = 2B * \log_2 V \ bits/s$$

Claude **Shannon** (1948) extends Nyquist's work to channels subject to random thermo dynamic noise. Shannon's theorem relates the data rate to the bandwidth (B) and signal strength (S) relative to the noise (N)

$$Max-data-rate(D) = B * \log_2 (1 + S/N) bits/s$$

Maximum Data Rate of a Channel

S/N or SNR = Signal ratio / Noise ratio

Usually represented in decibels (dB)

$$S/N_{dB} = 10\log_{10}\frac{S}{N}$$

e.g. S/N = 100 is 20 dB, 1000 is 30 dB

Maximum Data Rate of a Channel

Example [data rate over telephone line]

What is the theoretical highest bit rate of a regular telephone line?
A telephone line normally has a bandwidth of 3000 Hz (300 Hz to 3300 Hz). The signal-to-noise ratio is usually 35 dB (3162) on up-link channel (user-to-network).

Maximum Data Rate of a Channel

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Solution:

We can calculate the theoretical highest bit rate of a regular telephone line as

$$C = B \log_2 (1 + SNR) =$$
$$= 3000 \log_2 (1 + 3162) =$$
$$= 3000 \log_2 (3163)$$

$$\boxed{C = 3000 \times 11.62 = 34{,}860 \text{ bps}}$$

Maximum Data Rate of a Channel

Example [data rate / number of levels]

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

Maximum Data Rate of a Channel

Example **[data rate / number of levels]**

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Solution:

First use Shannon formula to find the upper limit on the channel's data-rate

$$C = B \log_2 (1 + SNR) = 10^6 \log_2 (1 + 63) = 10^6 \log_2 (64) = 6 \text{ Mbps}$$

Although the Shannon formula gives us 6 Mbps, this is the upper limit. For better performance choose something lower, e.g. 4 Mbps.

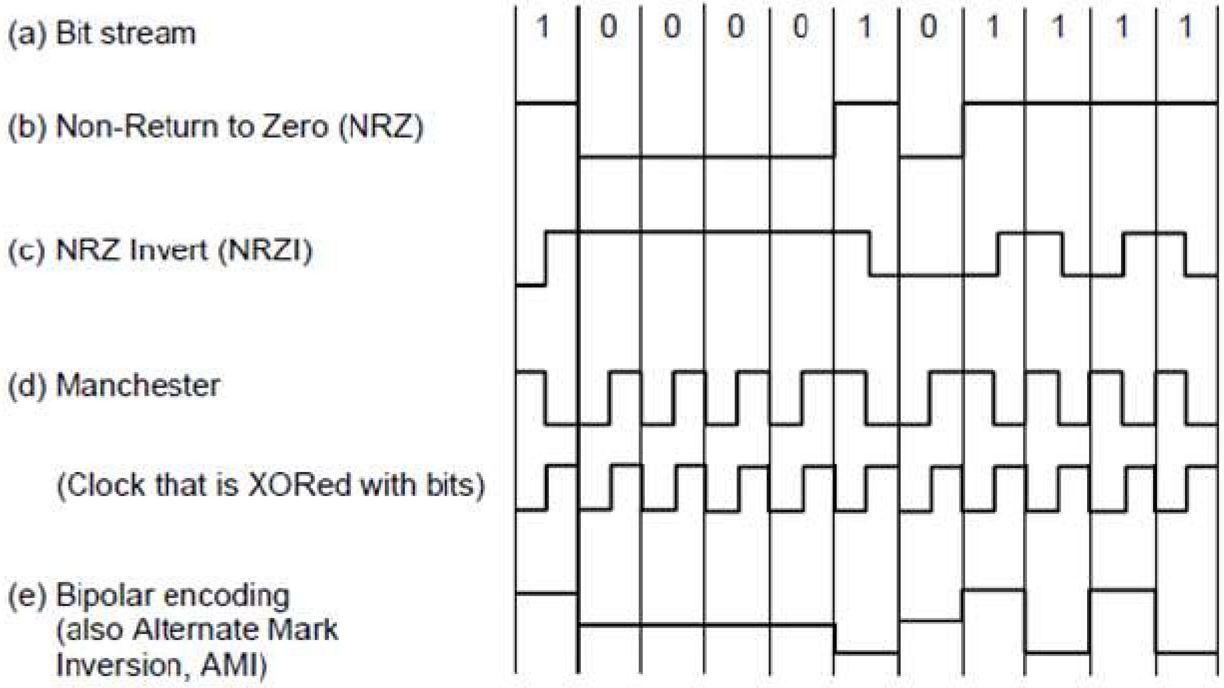
Then use the Nyquist formula to find the number of signal levels.

$$C = 2 \cdot B \cdot \log_2 M \ \ [\text{bps}]$$

$$4 \text{ Mbps} = 2 \times 1 \text{ MHz} \times \log_2 L \ \rightarrow \ L = 4$$

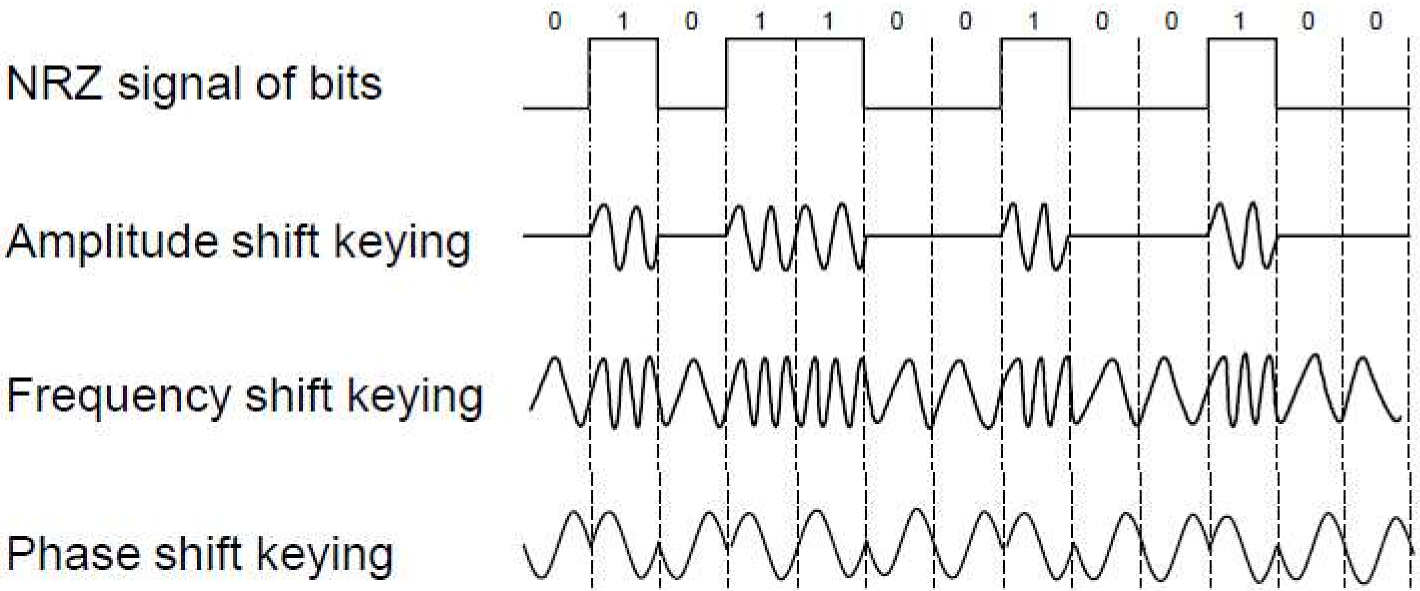
Baseband Transmission

- Line codes send symbols that represent one or more bits
- NRZ is the simplest, literal line code (+1V="1", -1V="0")
- Other codes tradeoff bandwidth and signal transitions
- MANCHESTER stay synchronized because there are enough transitions



Passband Transmission

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



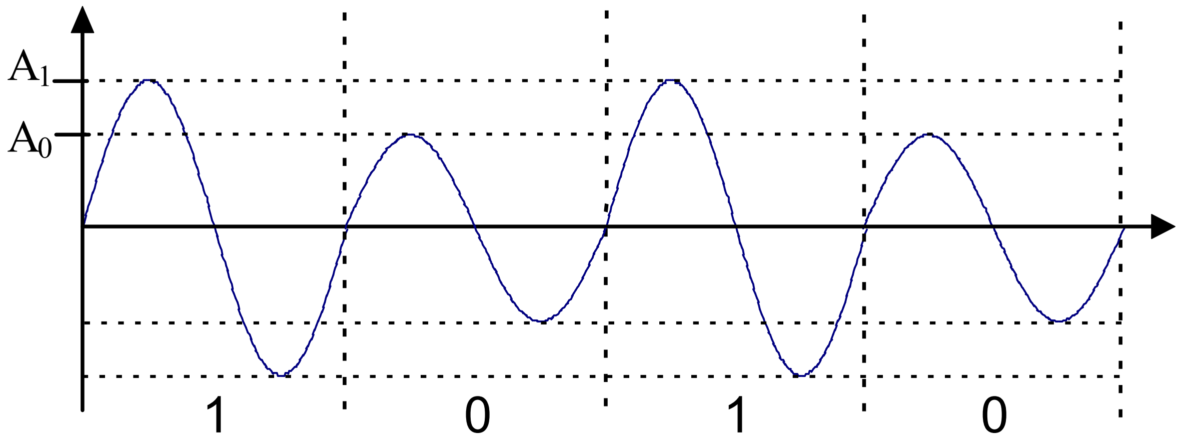
Modulation

- Modulation/demodulation : **modem**
- Modulation is the process of varying one or more properties of a periodic waveform called **carrier signal**, with a modulating signal that contains the information to be transmitted:

$$A_0 \sin(2\pi \quad f_0 \quad t + \phi_0)$$

Amplitude modulation	Frequency modulation	Phase Modulation

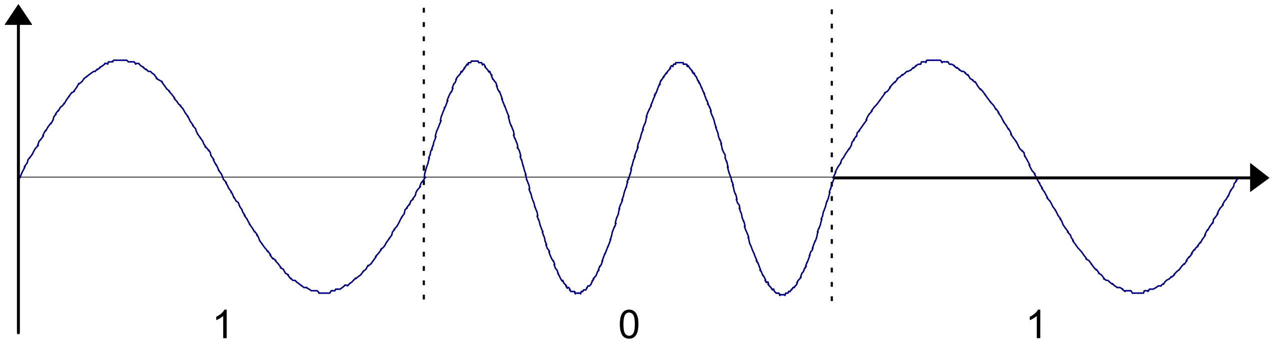
AMPLITUDE MODULATION (AM or ASK)



Two amplitudes : A_0 and A_1

ASK: Amplitude Shift Keying

Frequency Modulation
(FM or FSK)

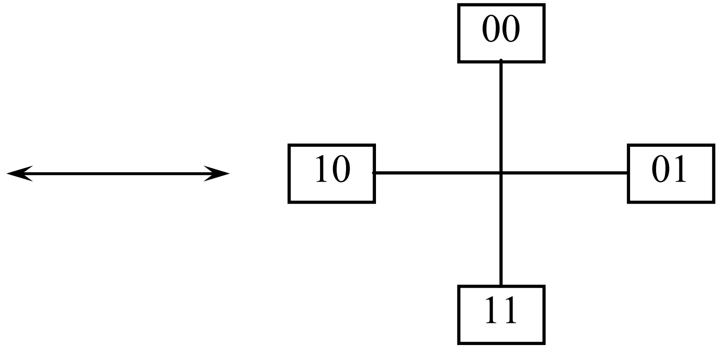


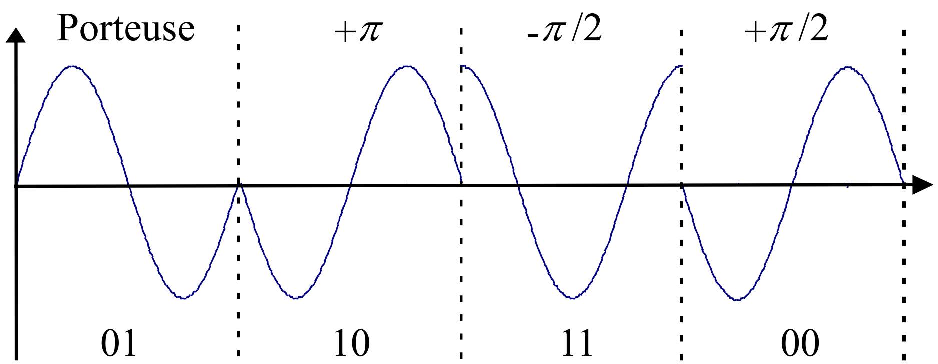
Two frequencies: $f_0 - f_1$ et $f_0 + f_1$

FSK: Frequency Shift Keying

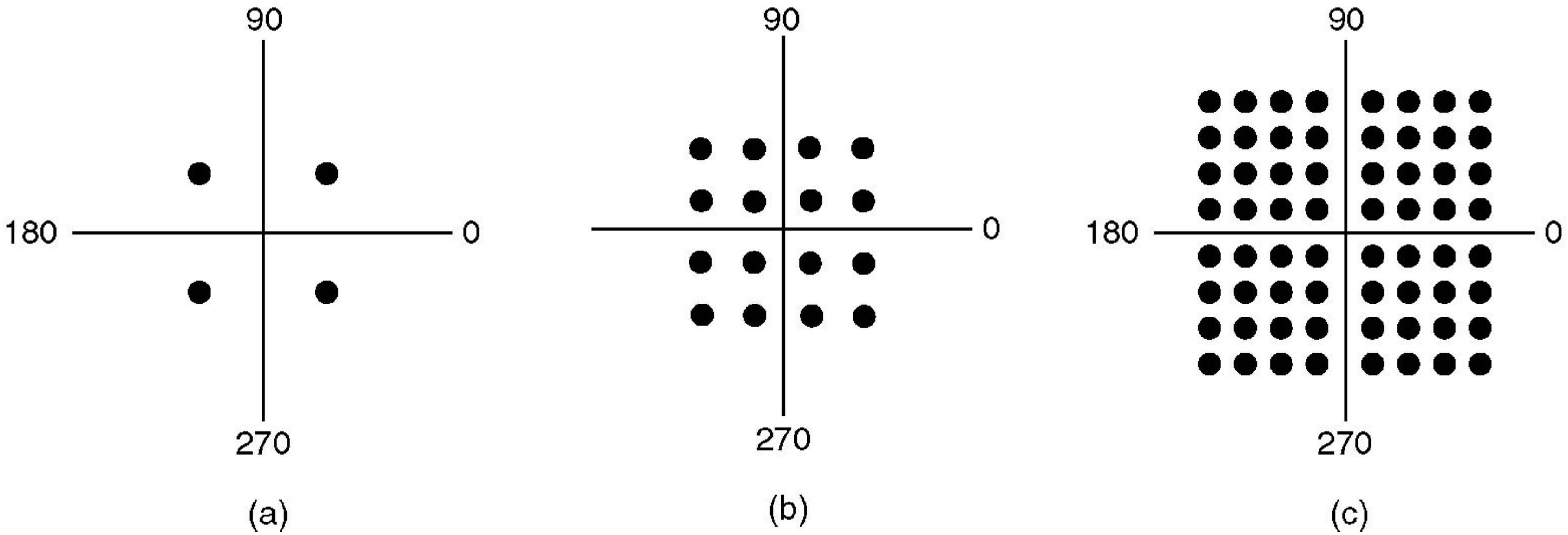
Modulation DPSK

01 $\rightarrow$ phase= 0
00 $\rightarrow$ phase= $+\pi/2$
11 $\rightarrow$ phase= $-\pi/2$
10 $\rightarrow$ phase= π





More Modems



(a) QPSK.

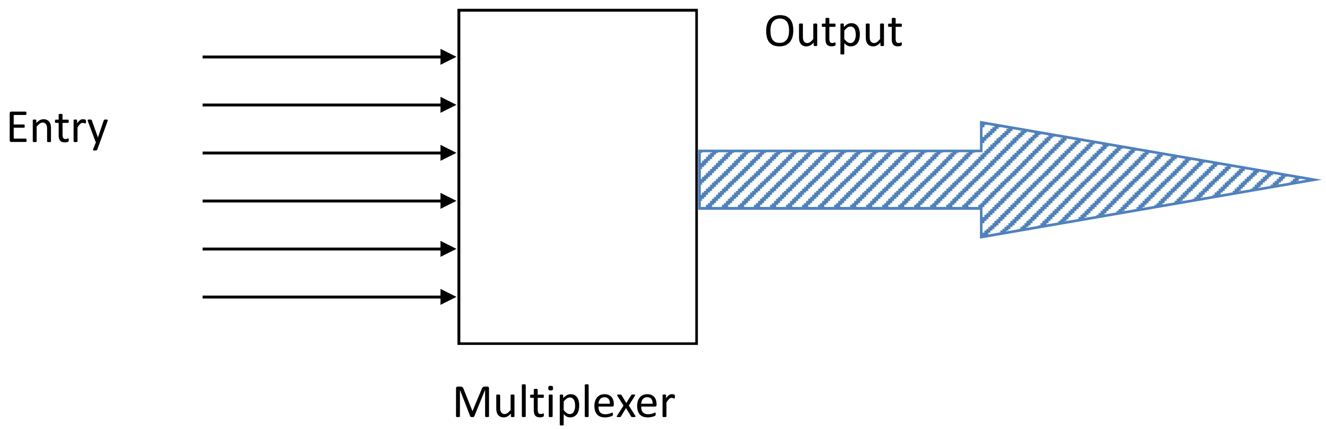
(b) QAM-16.

(c) QAM-64.

Line Sharing

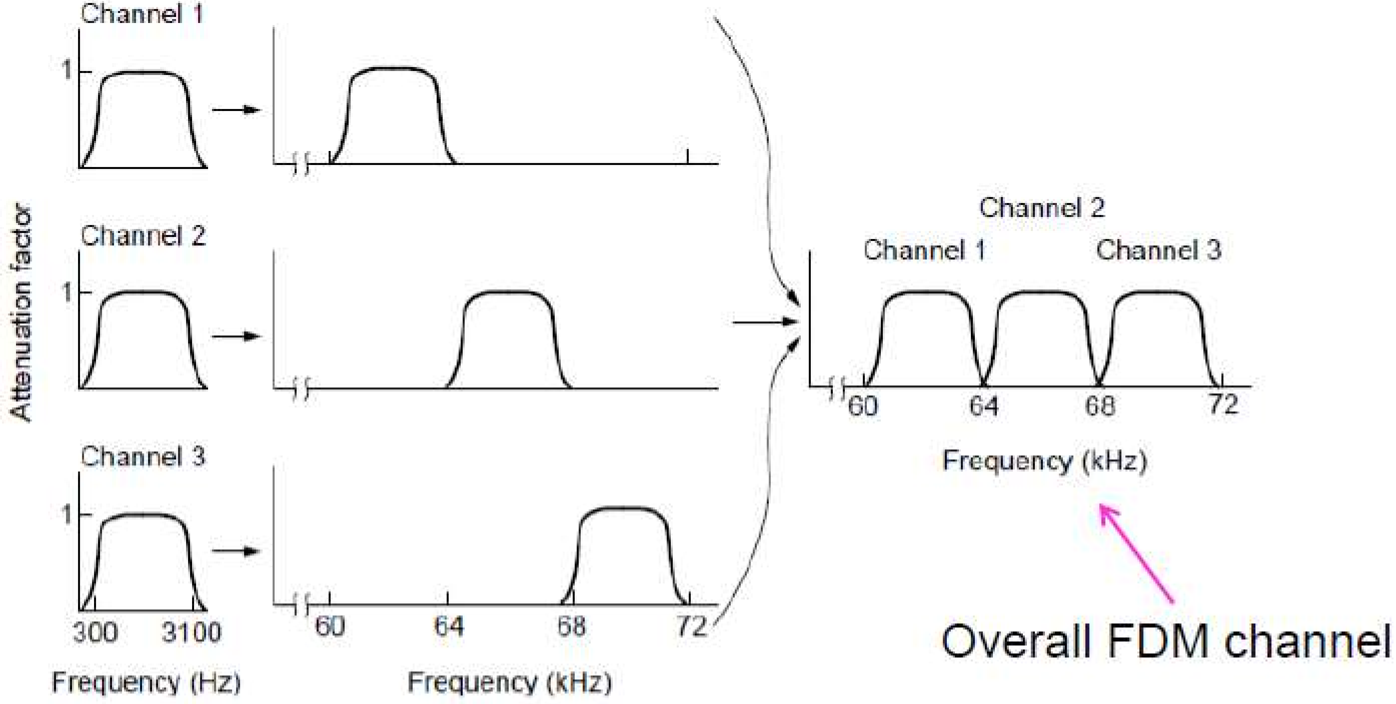
Why?

One medium supports several users



Frequency Division Multiplexing

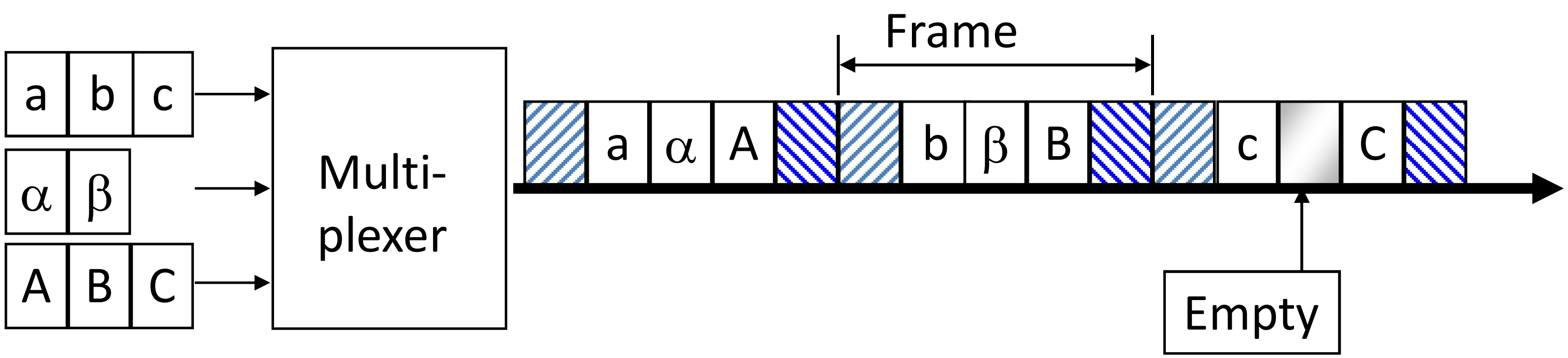
FDM (Frequency Division Multiplexing) shares the channel by placing users on different frequencies:



Overall FDM channel

TDMA : Time Division Multiplexing Access

- The line is shared between users in a round robin.
- Each user periodically gets the entire bandwidth
- Is widely used in telephone and cellular networks

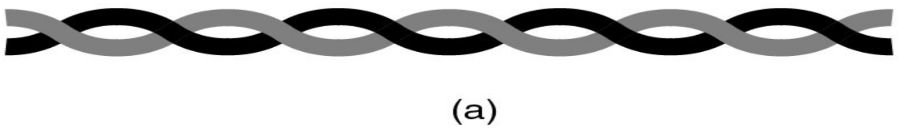


Physical media

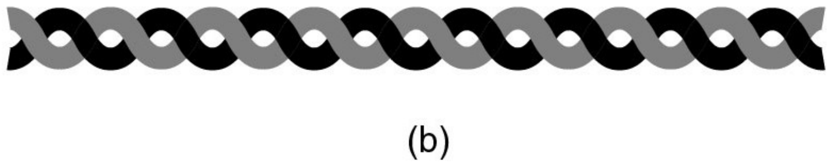
- Twisted Pair
- Coaxial Cable
- Fiber cables
- Wireless Transmission

Twisted Pair

- Signal is carried on difference of voltage between different wires of a pair
- In cat 5, 2 pairs are used in 100 Mbps Ethernet
- 4 pairs are used in 1Gbps Ethernet
- Cat 5 provides better quality over long distances than Cat 3
- Cat 6: 500 Mhz BW, 10 Gbps, **UTP (Unshielded Twisted Pair)**
- Cat 7: STP further reduction of interference



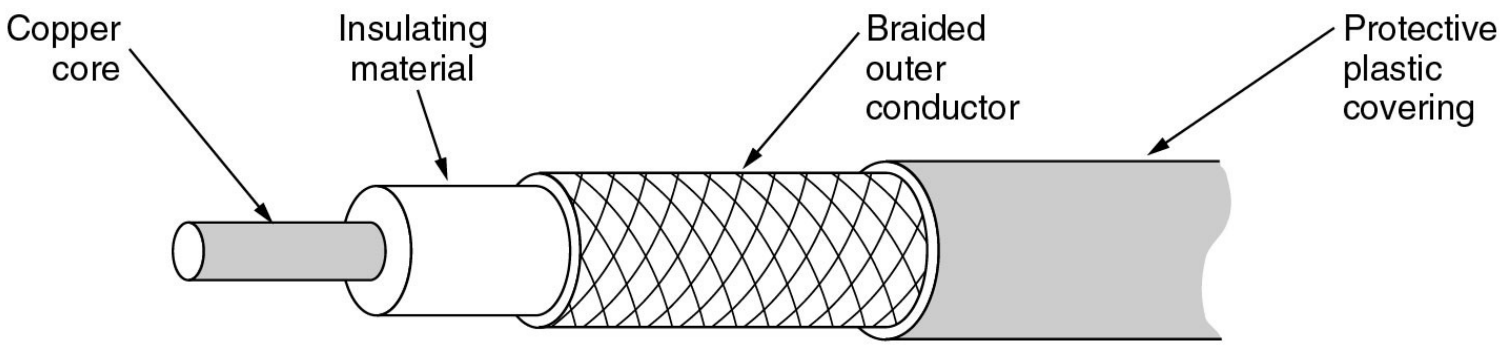
(a) Category 3 UTP



(a) Category 5 UTP.

Coaxial Cable

- ❑ Higher BW than twisted pairs
- ❑ Offers higher data rates until several Gbps
- ❑ Was largely used in telephone systems for connecting long distances
- ❑ Now replaced by Fiber
- ❑ Still used in cable TV and MANs

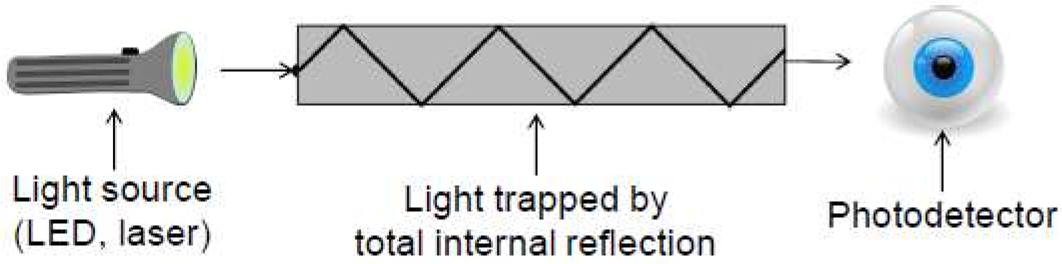


Fiber Cable

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

Common for high rates and long distances

- Long distance ISP links, Fiber-to-the-Home
- Light carried in very long, thin strand of glass



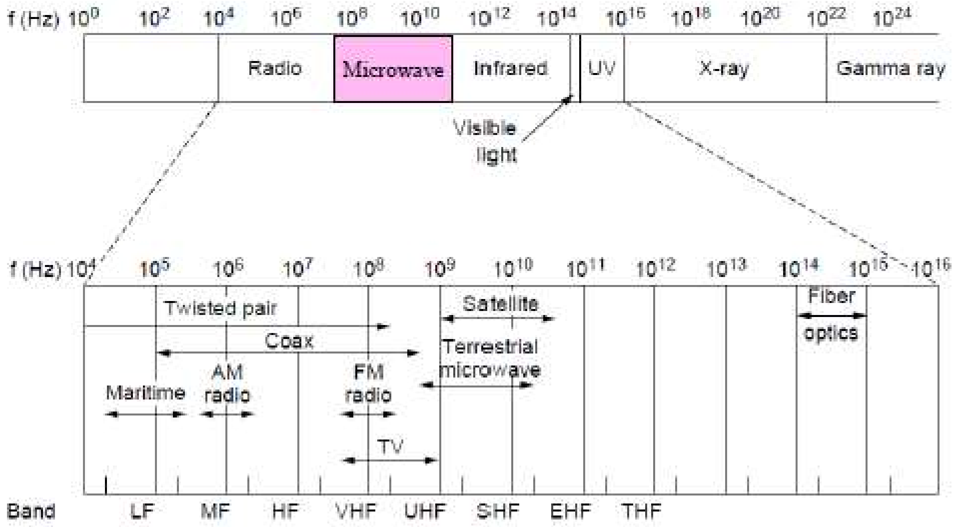
Wireless Transmission

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

The Electromagnetic Spectrum

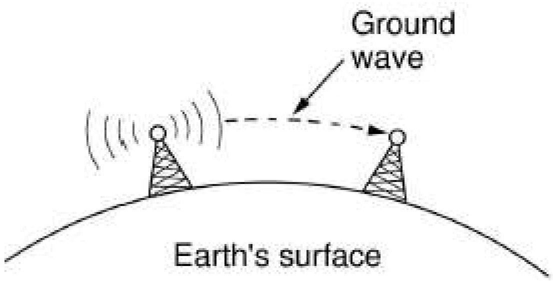
Different bands have different uses:

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

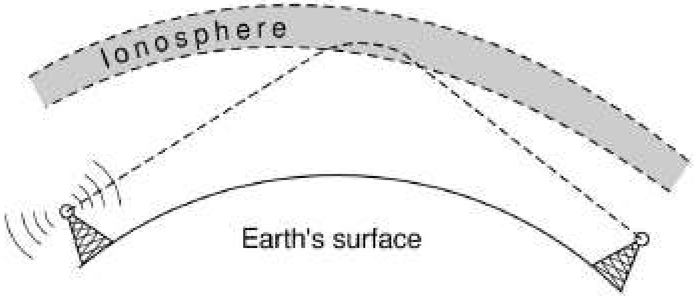


Radio Transmission

Radio signals penetrate buildings well and propagate for long distances with path loss



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

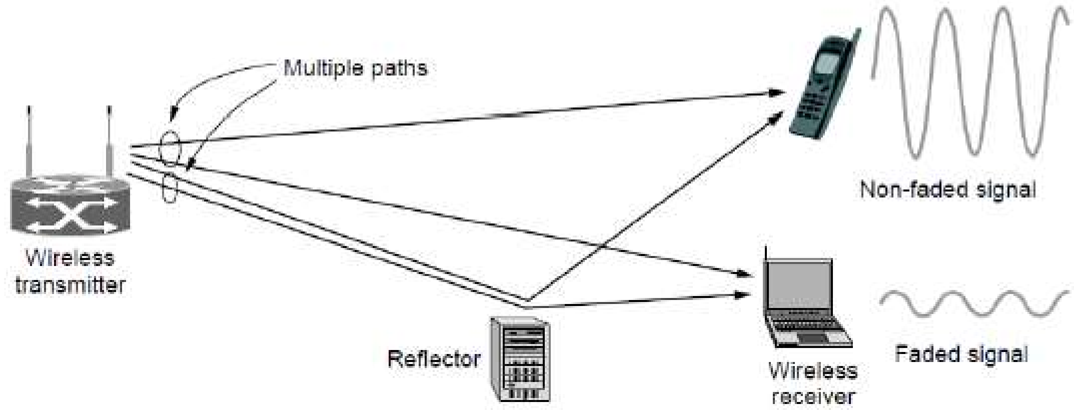


In the HF band, radio waves bounce off the ionosphere.

Microwave Transmission

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

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



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

References

[1] Andrew S. Tanenbaum, David J. Wetherall, *Computer Network*

[2] Doughlas E. Comer, Computer Networks and Internet

[3] Salim NAHLE and Naceur MALOUCH, “Fast-Converging Scheduling and Routing Algorithms for WiMAX Mesh Networks”, proceedings of Networking 2011.