IT 601: Mobile Computing

Session 2

Wireless Transmission Basics

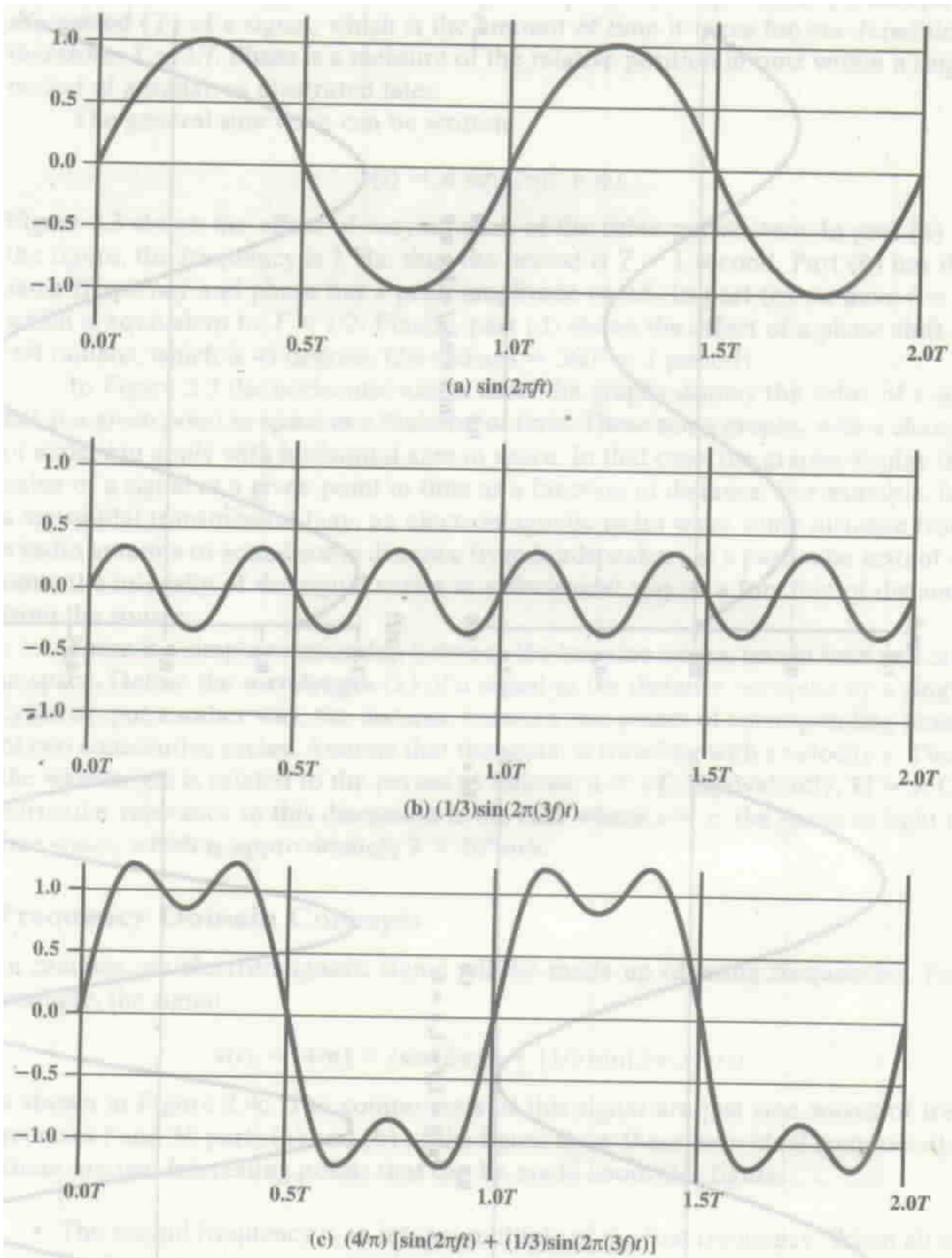
Prof. Anirudha Sahoo
IIT Bombay

Spectrum and bandwidth

- Electromagnetic signals are made up of many frequencies
- Shown in the next example

$$s(t) = (4/\pi)\,[\sin(2\pi ft) + 1/3(\sin 2\pi(3f)t)]$$

FIG 1



Source: Stallings

Spectrum and bandwidth

- The 2nd frequency is an integer multiple of the first frequency
  - When all of the frequency components of a signal are integer multiples of one frequency, the latter frequency is called *fundamental frequency* (f)
  - *period* of the resultant signal is equal to the period of the fundamental frequency
    - Period of s(t) is T=1/f

Fourier Analysis

- Any signal is made up of components at various frequencies, in which each component is a sinusoid.
  - Adding enough sinusoidal signals with appropriate amplitude, frequency and phase, any electromagnetic signal can be constructed

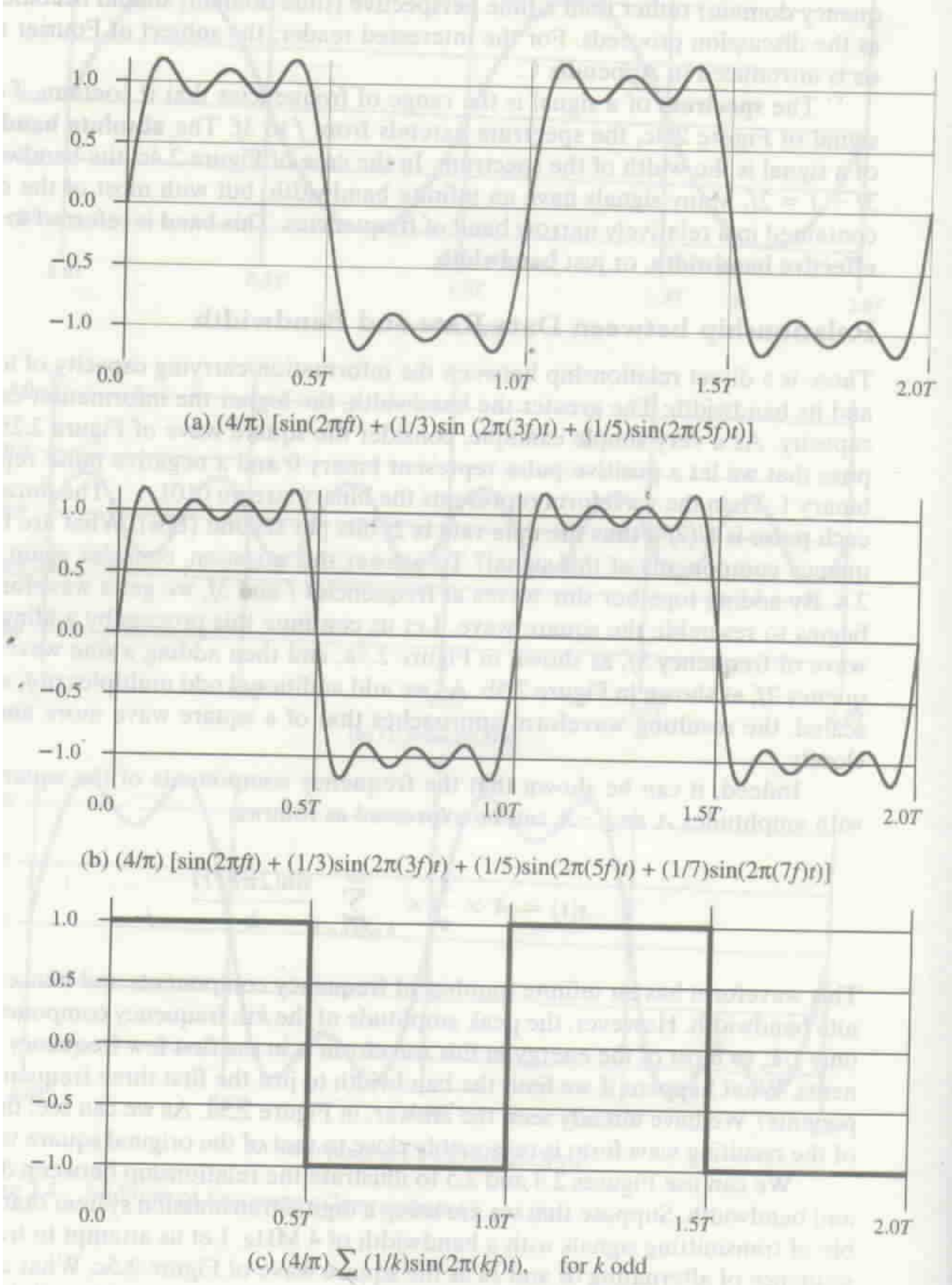
Spectrum and bandwidth

- It is the range of frequencies that a signal contains (among its components)
  - In the example, *spectrum is from f to 3f*
  - absolute bandwidth is the width of the spectrum
    - 3f-f = 2f

Data Rate and bandwidth

- There is a direct relationship between data rate (or signal carrying capacity) and bandwidth
- Suppose we let a positive pulse represent 1 and negative pulse represent 0
  - Then the waveform (next slide) represents 1010..
  - Duration of each pulse is t_{bit} = (1/2) (1/f)
  - Thus data rate is 1/ t_{bit} = 2f bits/sec
- As we add more and more frequencies the wave looks more like a square wave

FIG 2



(a) $(4/\pi)\,[\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t) + (1/5)\sin(2\pi(5f)t)]$

(b) $(4/\pi)\,[\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t) + (1/5)\sin(2\pi(5f)t) + (1/7)\sin(2\pi(7f)t)]$

(c) $(4/\pi)\sum (1/k)\sin(2\pi(kf)t)$, for k odd

Source: Stallings

Example

- Looking at FIG 2(a) the bandwidth = 5f-f = 4f
  - If f=1MHz = 10^6 cycles/sec, then bandwidth = 4MHz
  - The period of the fundamental frequency = T = 1/f = 1 μs
  - So each bit takes up 0.5 μs i.e. data rate is 1/0.5 Mbps = 2 Mbps

Example

- Looking at FIG 1(c) the bandwidth = 3f-f = 2f
  - If f=2MHz = 2×10^6 cycles/sec, then bandwidth = 4MHz
  - The period of the fundamental frequency = T = 1/f = 0.5 μs
  - So each bit takes up 0.25 μs i.e. data rate is 1/0.25 Mbps = 4 Mbps

Example

- Thus a given bandwidth can support different data rate, depending on the ability of the receiver to discern the difference between 0 and 1 in the presence of noise and interference

Gain and Loss

- Ratio between power levels of two signals is referred to as Gain
  - gain (dB) = 10 $\log_{10} (P_{out}/P_{in})$
  - loss (dB) = -10 $\log_{10} (P_{out}/P_{in})$ = 10 $\log_{10} (P_{in}/P_{out})$
  - P_{out} is output power level and P_{in} is input power level
- Signal of power 10mw transmitted over wireless channel, and receiver receives the signal with 2mw power:
  - gain (db) = 10 $\log_{10}$ (2/10) = -10 (0.698) = -6.98 dB
  - loss (db) = 6.98 dB

dBW power

- dB-Watt
  - power in dB transmitted with respect to a base power of 1 Watt
    - $dBW = 10 \log_{10} P$
      - P is power transmitted in Watt
  - if power transmitted is 1 Watt
    - $dBW = 10 \log_{10} 1 = 0$ dBW
  - 1000 watt transmission is 30 dBW

dBm power

- dB-milliwatt
  - better metric in wireless network
  - power in dB transmitted with respect to a base power of 1 milliwatt
    - $dBm = 10 \log_{10} P$
      - P is power transmitted in milliwatt
  - if power transmitted is 1 milliwatt
    - $dBm = 10 \log_{10} 1 = 0$ dBm
  - 10 milliwatt transmission is 10 dBm
  - 802.11b can transmit at a maximum power of 100mw = 20 dBm

Channel Capacity

Four concepts :

- Data Rate : rate (in bps) at which data can be communicated
- Bandwidth: bandwidth of the transmitted signal as constrained by the transmitter and the medium, expressed in Hz
- Noise : interfering electromagnetic signal that tend to reduce the integrity of data signal
- Error rate : rate at which receiver receives bits in error i.e. it receives a 0 when actually a 1 was sent and vice-versa

Nyquist Bandwidth

- Given a bandwidth of B, the highest signal rate that can be carried is 2B (when signal transmitted is binary (two voltage levels))
  - When M voltage levels are used, then each signal level can represent $\log_2 M$ bits. Hence the Nyquist bandwidth (capacity) is given by

$$C = 2\,B\,\log_2 M$$

Shannon's Capacity Formula

- When there is noise in the medium, capacity is given by
  - $C <= B \log_2 (1 + SNR)$
    - SNR = signal power/noise power
  - $SNR_{dB} = 10 \log_{10} SNR$

Bandwidth Allocation

- Necessary to avoid interference between different radio devices
  - Microwave woven should not interfere with TV transmission
  - Generally a radio transmitter is limited to a certain bandwidth
    - 802.11channel has 30MHz bandwidth
  - Power and placement of transmitter are regulated by authority
    - Consumer devices are generally limited to less than 1W power

ISM and UNII Band

- Industrial, Scientific and Medical (ISM) band
  - 902-928 MHz in the USA
  - 433 and 868 MHz in Europe
  - 2400 MHz – 2483.5 MHz (license-free almost everywhere)
  - Peak power 1W (30dBm)
    - but most devices operate at 100mW or less
  - 802.11 uses the ISM band of 2.4GHz
- Unlicensed National Information Infrastructure (UNII) bands
  - 5.725 – 5.875 GHz

Antenna

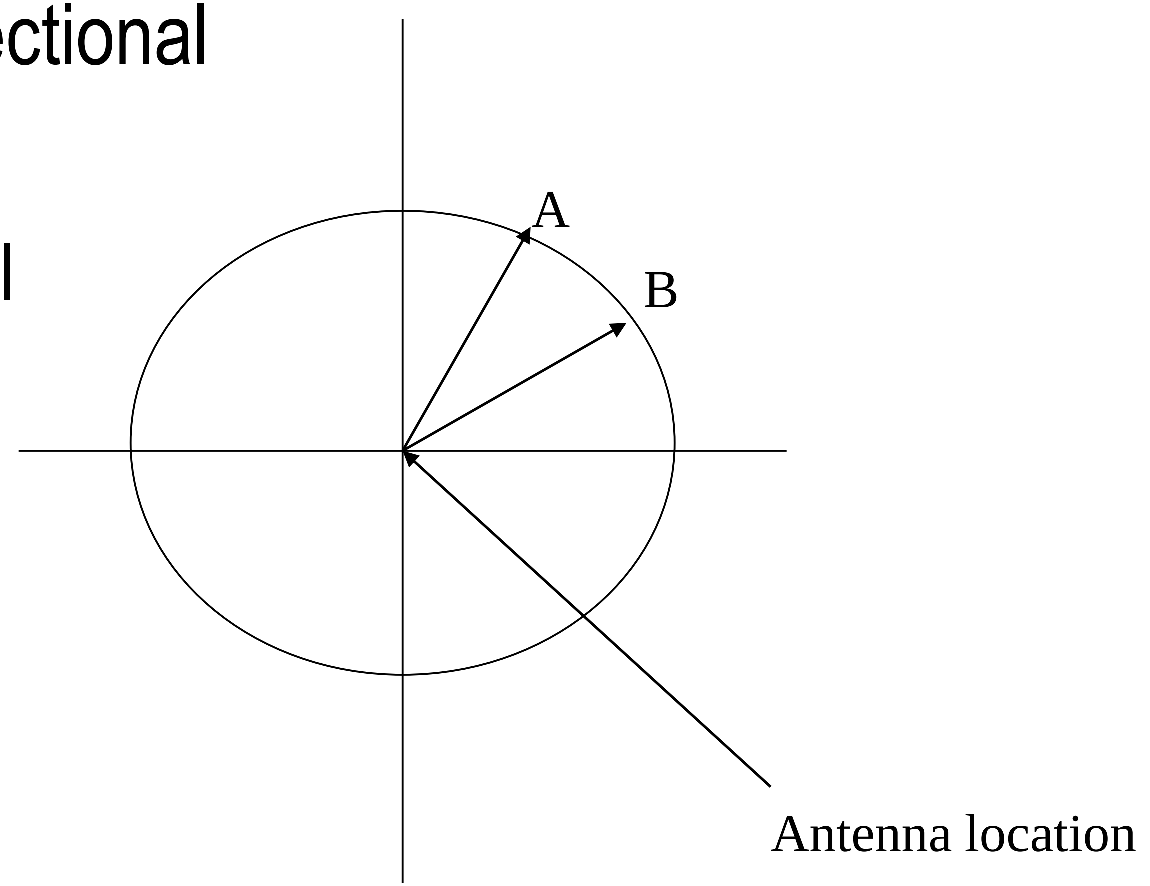
- An electrical conductor or system of conductors used for radiating electromagnetic energy into space or for collecting electromagnetic energy from the space
  - An integral part of a wireless system

Radiation Patterns

- Antenna radiates power in all directions
  - but typically does not radiate equally in all directions
- Ideal antenna is one that radiates equal power in all direction
  - called an isotropic antenna
  - all points with equal power are located on a sphere with the antenna as its center

Omnidirectional Antenna

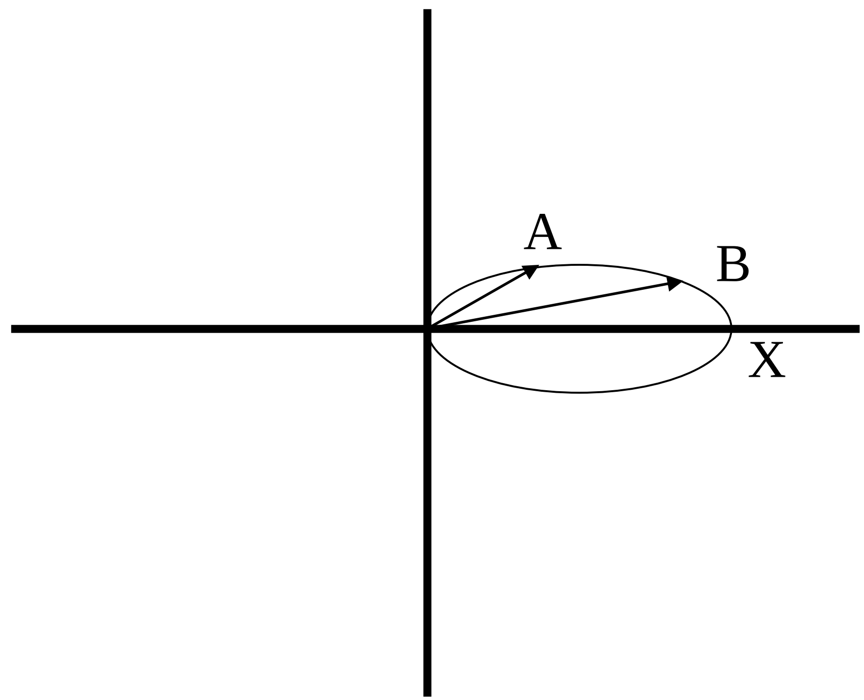
- Produces omnidirectional radiation pattern of equal strength in all directions
- Vector A and B are of equal length



Omnidirectional Antenna

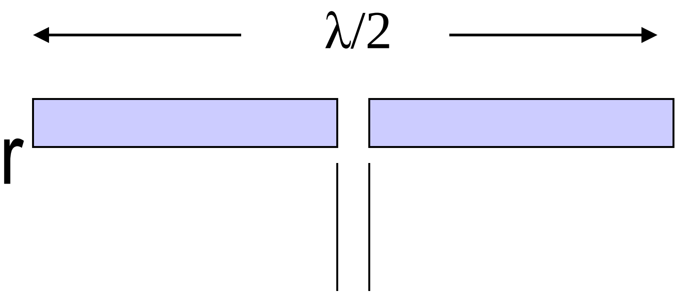
Directional Antenna

- Radiates most power in one axis (direction)
  - radiates less in other direction
  - vector B is longer than vector A : more power radiated along B than A
  - directional along X



Dipole Antenna

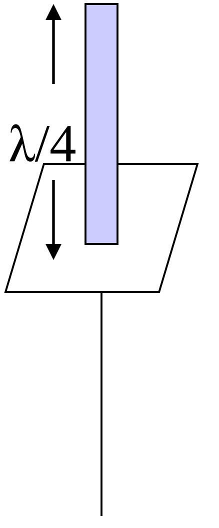
- Half-wave dipole or Hertz antenna consists of two straight collinear conductor of equal length
- Length of the antenna is half the wavelength of the signal.



Half-wave dipole

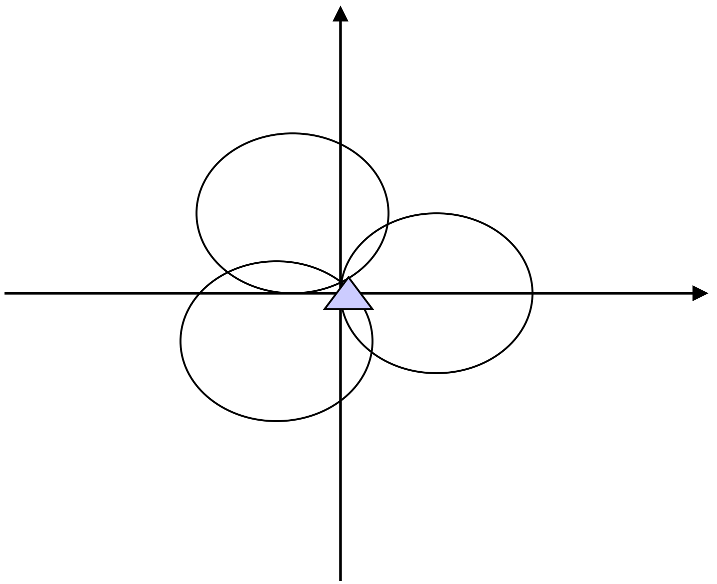
Quarter-wave antenna

- Quarter-wave or marconi antenna has a veritcal conductor of length quarter of the wavelength of the signal



Sectorized Antenna

- Several directional antenna combined on a single pole to provide sectorized antenna
- each sector serves receivers listening it its direction



3 sector antenna

Antenna Gain

- A measure of the directionality of an antenna
- Defined as the power output, in a particular direction, compared to that produced in any direction by a perfect isotropic antenna
  - Example: if an antenna has a gain of 3dB, the antenna is better (in that direction) than isotropic antenna by a factor of 2

Antenna Gain

- Antenna gain is dependent on *effective area* of an antenna.
  - effective area is related to the physical size of the antenna and its shape
  - Antenna Gain is given by

$$G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f^2 A_e}{c^2}$$

where

G = antenna gain

A_e = effective area

f = carrier frequency

c = speed of light

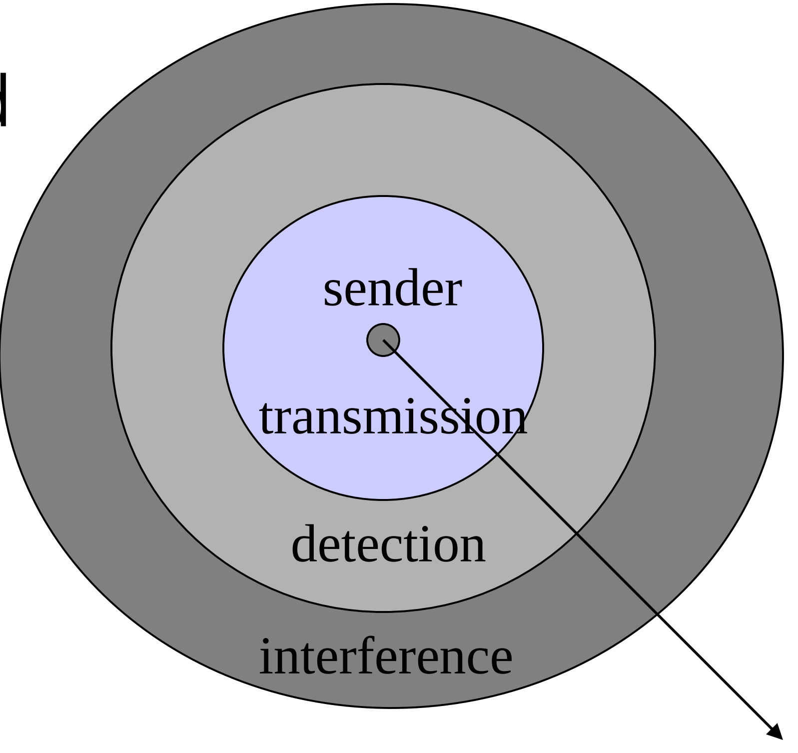
λ = carrier wavelength

Signal Propagation

- Transmission range:

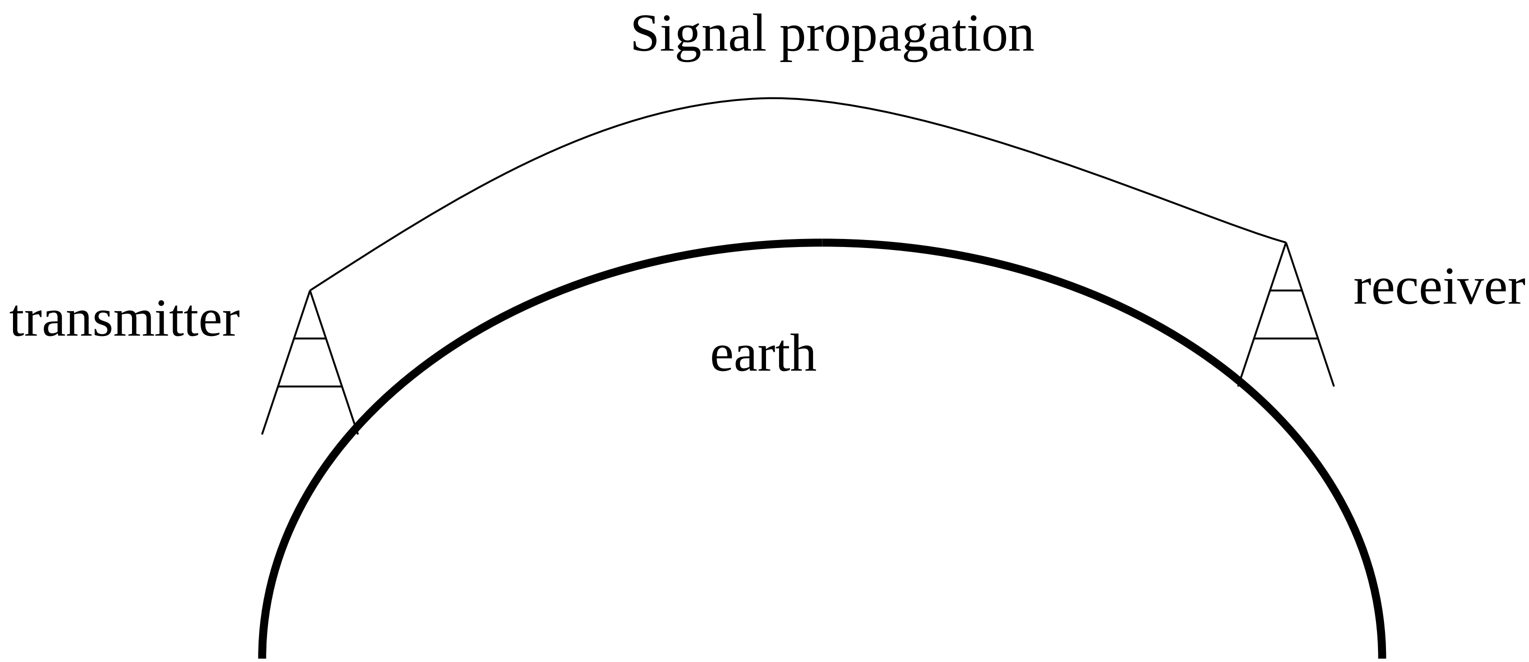
receiver receives signal with an error rate low enough to be able to communicate

- Detection range: transmitted power is high enough to detect the transmitter, but high error rate forbids communication
- Interference range: sender interferes with other transmissions by adding to the noise

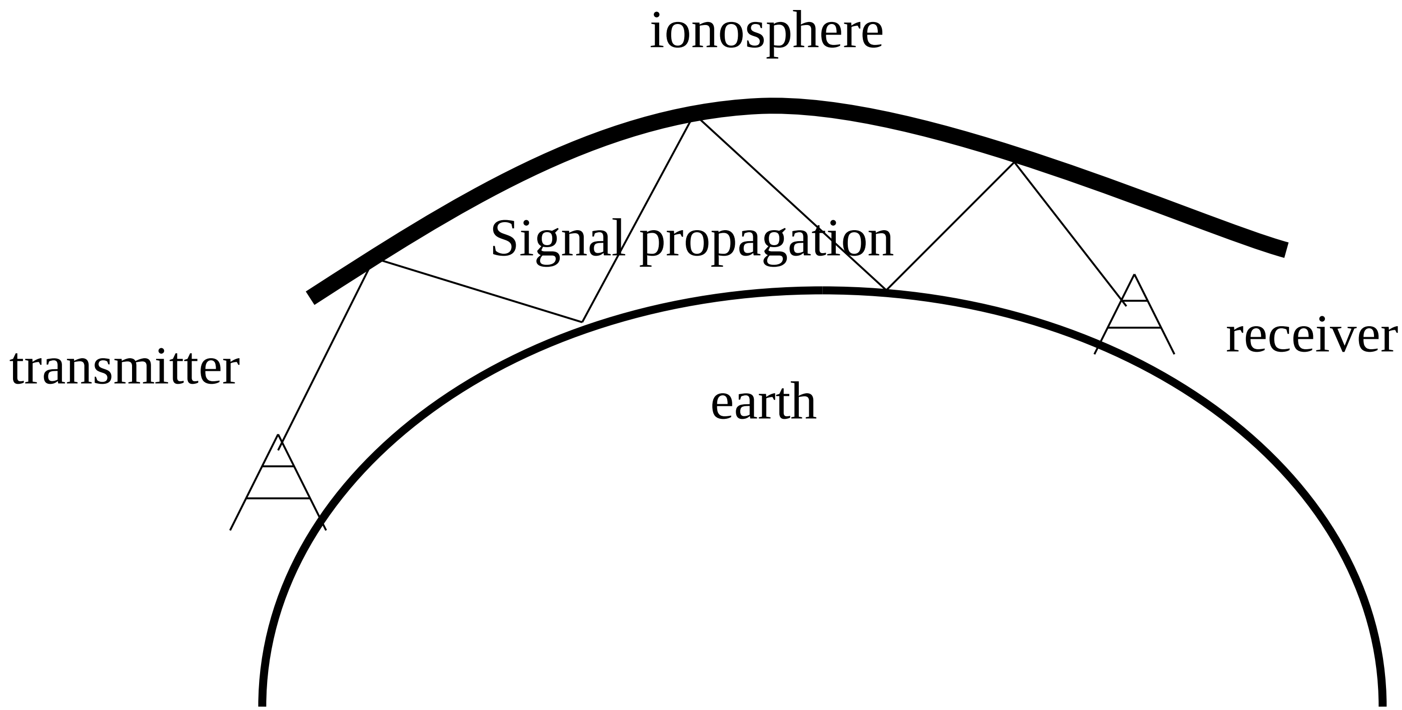


Signal Propagation

- Radio waves exhibit three fundamental propagation behavior
  - Ground wave (< 2 MHz) : waves with low frequency follow earth's surface
    - can propagate long distances
    - Used for submarine communication or AM radio
  - Sky wave (2-30 MHz) : waves reflect at the ionosphere and bounce back and forth between ionosphere and earth , travelling around the world
    - Used by international broadcast and amateur radio



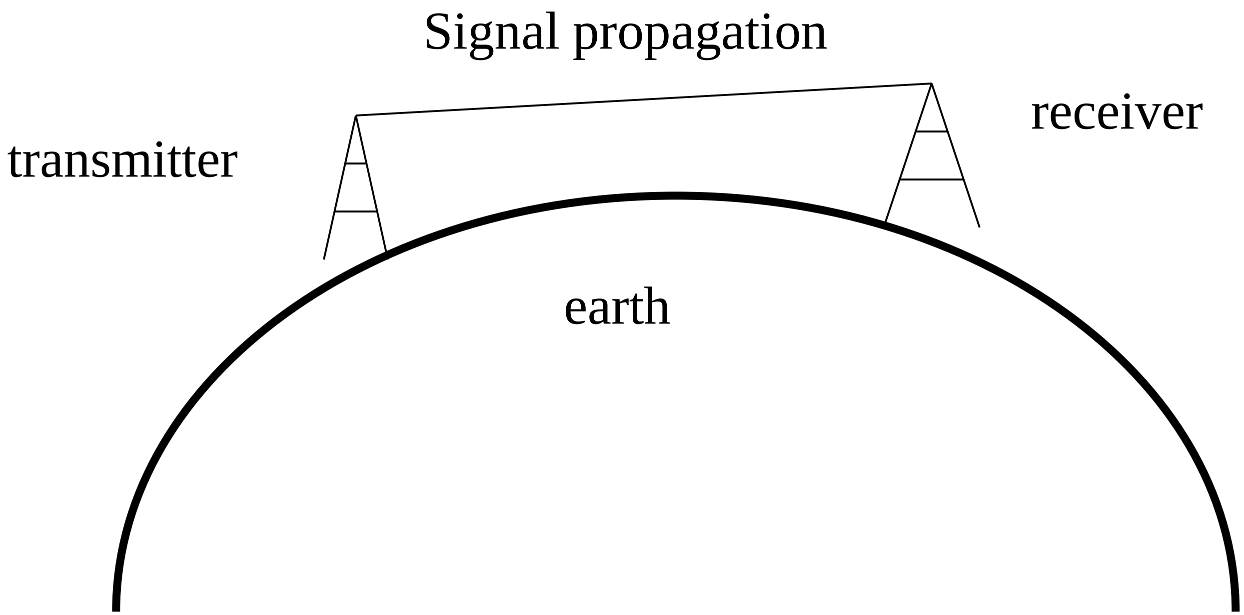
Ground wave propagation (< 2 MHz)



sky wave propagation (2 - 30MHz)

Signal Propagation

- Line of Sight (> 30 MHz) : emitted waves follow a straight line of sight
  - allows straight communication with satellites or microwave links on the ground
  - used by mobile phone system, satellite systems



Line of Sight (LOS) propagation (> 30 MHz)

Free Space loss

- Transmitted signal attenuates over distance because it is spread over larger and larger area
  - This is known as free space loss and for isotropic antennas

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2}$$

P_t = power at the transmitting antenna

P_r = power at the receiving antenna

λ = carrier wavelength

d = propagation distance between the antennas

c = speed of light

Free Space loss

– For other antennas

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{G_r G_t \lambda^2} = \frac{(\lambda d)^2}{A_r A_t}$$

G_t = Gain of transmitting antenna

G_r = Gain of receiving antenna

A_t = effective area of transmitting antenna

A_r = effective area of receiving antenna

Thermal Noise

- Thermal noise is introduced due to thermal agitation of electrons
  - Present in all transmission media and all electronic devices
  - a function of temperature
  - uniformly distributed across the frequency spectrum and hence is often referred to as *white noise*
  - amount of noise found in a bandwidth of 1 Hz is

$$N_0 = k\,T$$

N_0 = noise power density in watts per 1 Hz of bandwidth

k = Boltzman's constant = 1.3803×10^{-23} J/K

T = temperature, in Kelvins

N = thermal noise in watts present in a bandwidth of B

= kTB where

Data rate and error rate

- A parameter related to SNR that is more convenient for determining digital data rates and error rates
  - ratio of signal energy per bit to noise power density per Hertz, E_b/N_0
  - R = bit rate of transmission, S= power of the signal,

  T_b = time required to send 1 bit. Then $R = 1/T_b$

$E_b = S\,T_b$

so

$$\frac{E_b}{N_0} = \frac{S/R}{N_0} = \frac{S}{kTR}$$

Data rate and error rate

- Bit error rate is a decreasing function of E_b/N_0
  - If bit rate R is to increase, then to keep bit error rate (or E_b/N_0) same, the transmitted signal power must increase, relative to noise
- E_b/N_0 is related to SNR as follows

$$\frac{E_b}{N_0} = \frac{S}{N}\frac{B}{R}$$

B = signal bandwidth

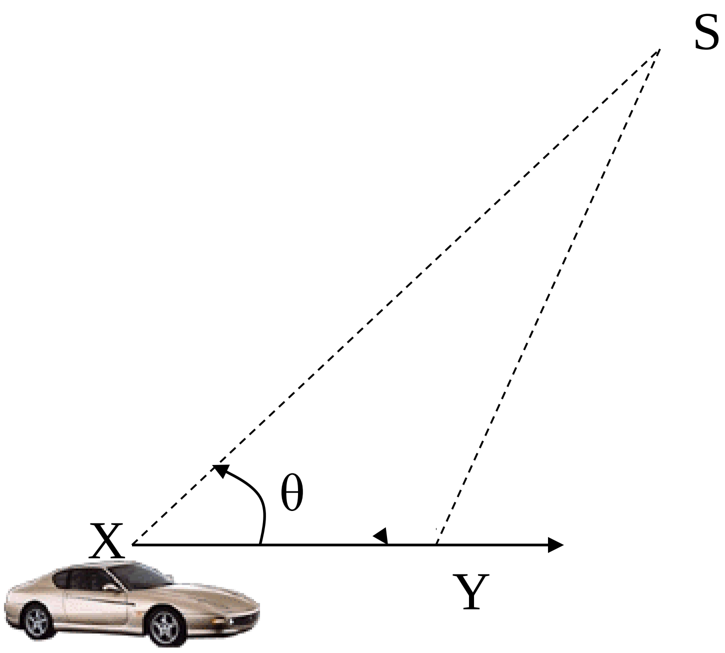
(since $N = N_0 B$)

Doppler’s Shift

- When a client is mobile, the frequency of received signal could be less or more than that of the transmitted signal due to Doppler’s effect
- If the mobile is moving towards the direction of arrival of the wave, the Doppler’s shift is positive
- If the mobile is moving away from the direction of arrival of the wave, the Doppler’s shift is negative

Doppler's Shift

$$f_d = \frac{v}{\lambda}\cos\theta$$



where

f_d =change in frequency

due to Doppler's shift

v = constant velocity of the

mobile receiver

λ = wavelength of the transmission

Doppler's shift

$f = f_c + f_d$

where

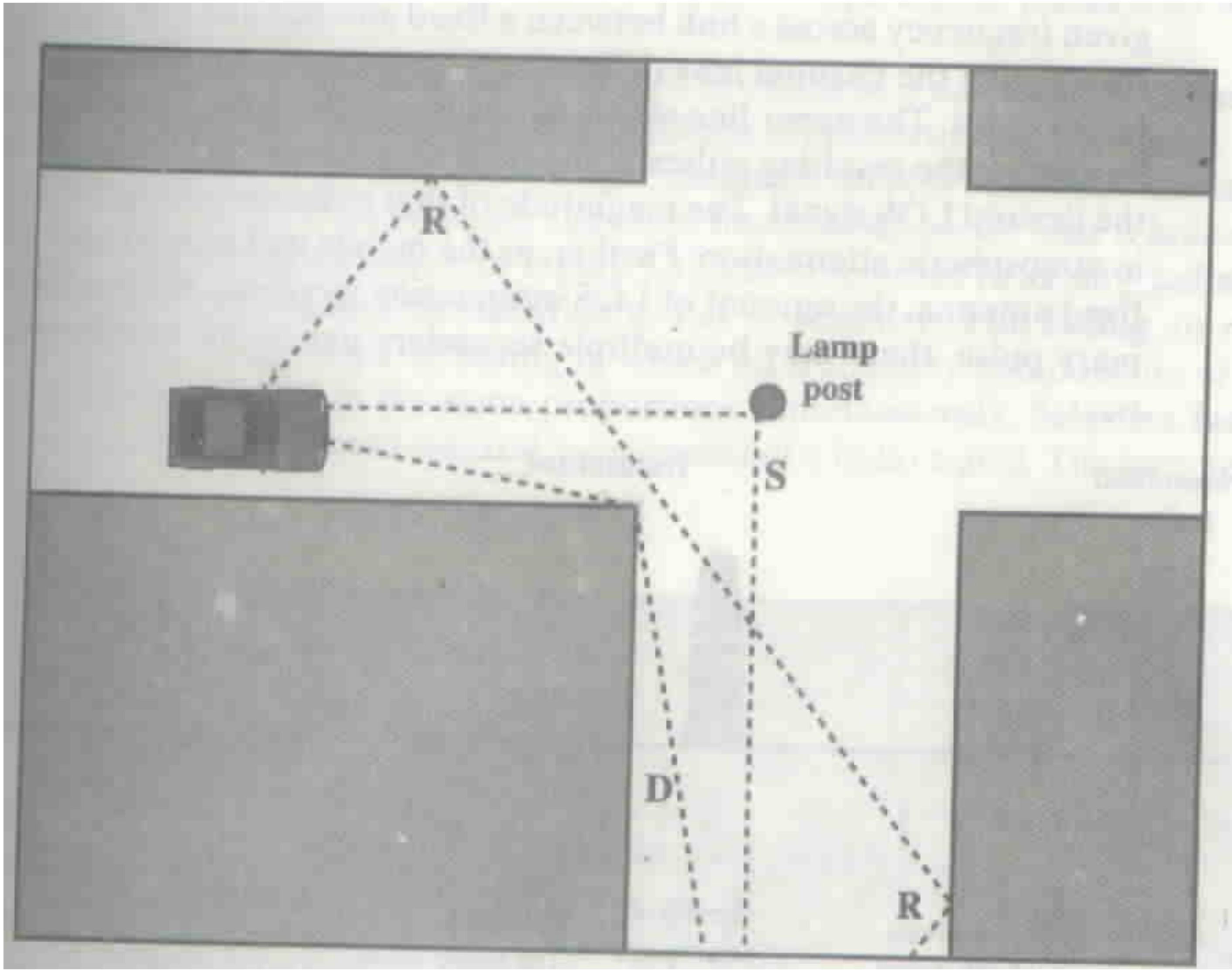
f = the received carrier frequency

f_c = carrier frequency being transmitted

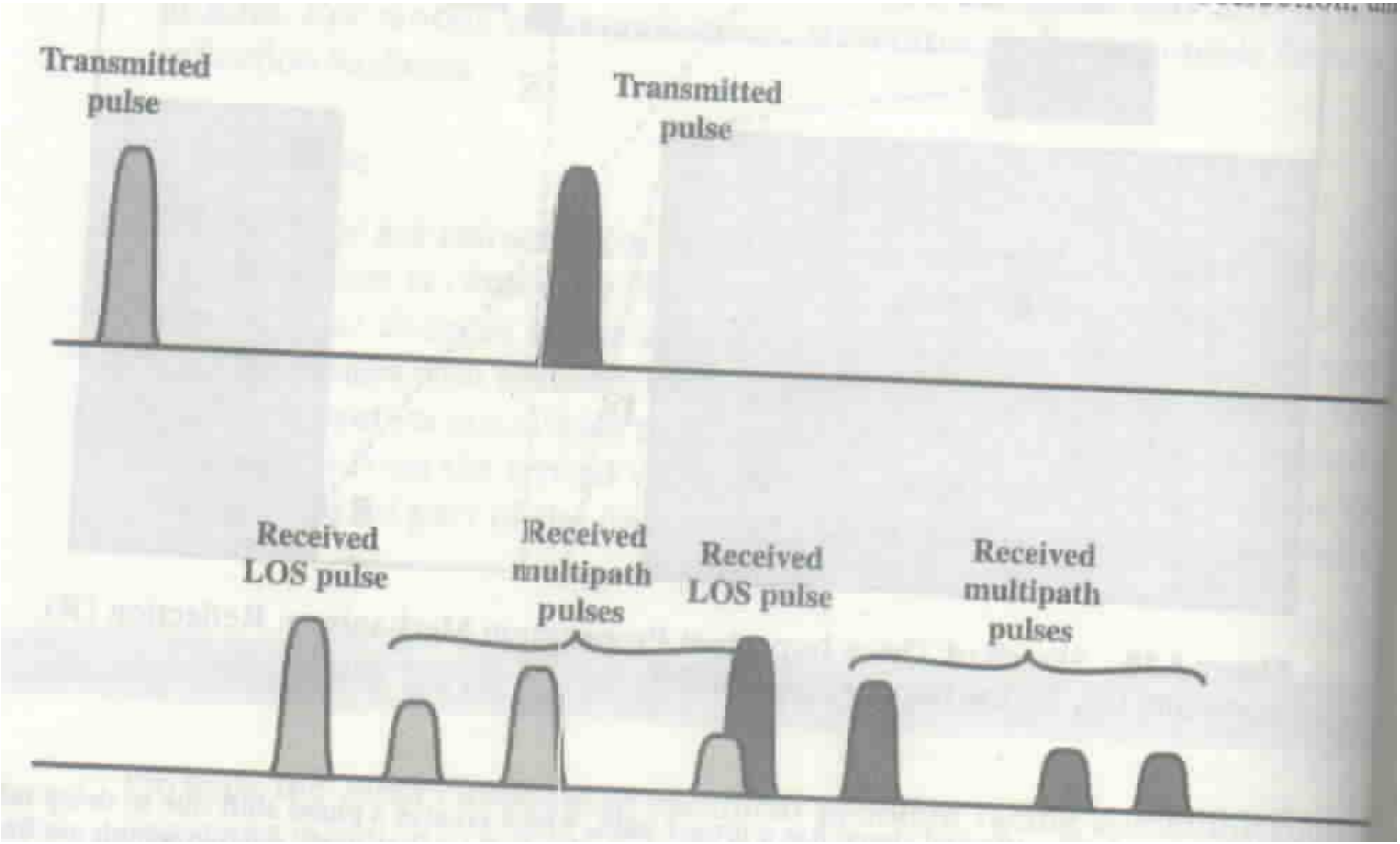
f_d = Doppler's shift as per the formula in the prev slide

Multipath Propagation

- Wireless signal can arrive at the receiver through different pahs
  - LOS
  - Reflections from objects
  - Diffraction
    - Occurs at the edge of an impenetrable body that is large compared to the wavelength of the signal



Multipath Propagation (source: Stallings)



Inter Symbol Interference (ISI) in multipath (source: Stallings)

Effect of Multipath Propagation

- Multiple copies of the signal may arrive with different phases. If the phases add destructively, the signal level reduces relative to noise.
- Inter Symbol Interference (ISI)

Multiplexing

- A fundamental mechanism in communication system and networks
- Enables multiple users to share a medium
- For wireless communication, multiplexing can be carried out in four dimensions: space, time, frequency and code

Space division multiplexing

- Channels are assigned on the basis of “space” (but operate on same frequency)
- The assignment makes sure that the transmission do not interfere with each (with a guard band in between)

Space division multiplexing

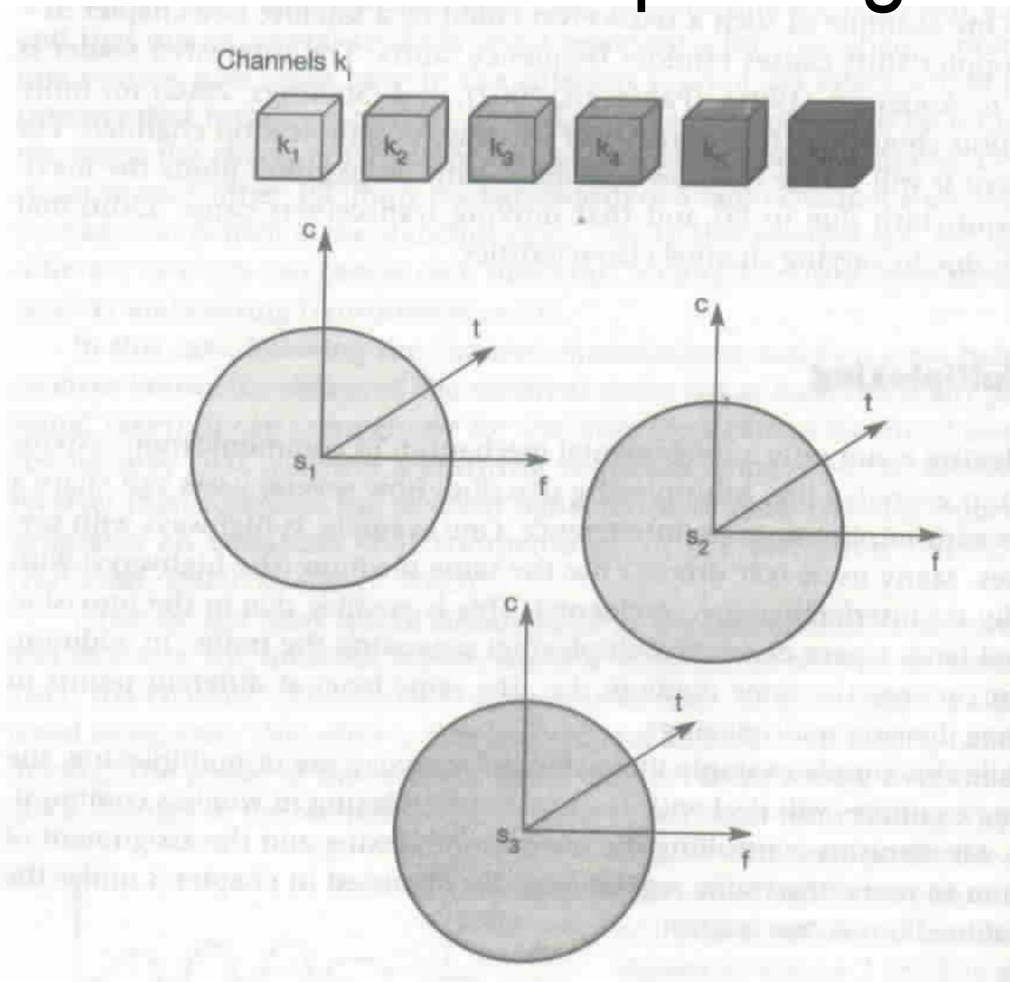


Figure 2.16 Space division multiplexing (SDM)

Source: Schiller

Frequency Division Multiplexing

- Frequency domain is subdivided into several non-overlapping frequency bands
- Each channel is assigned its own frequency band (with guard spaces in between)

Frequency Division Multiplexing

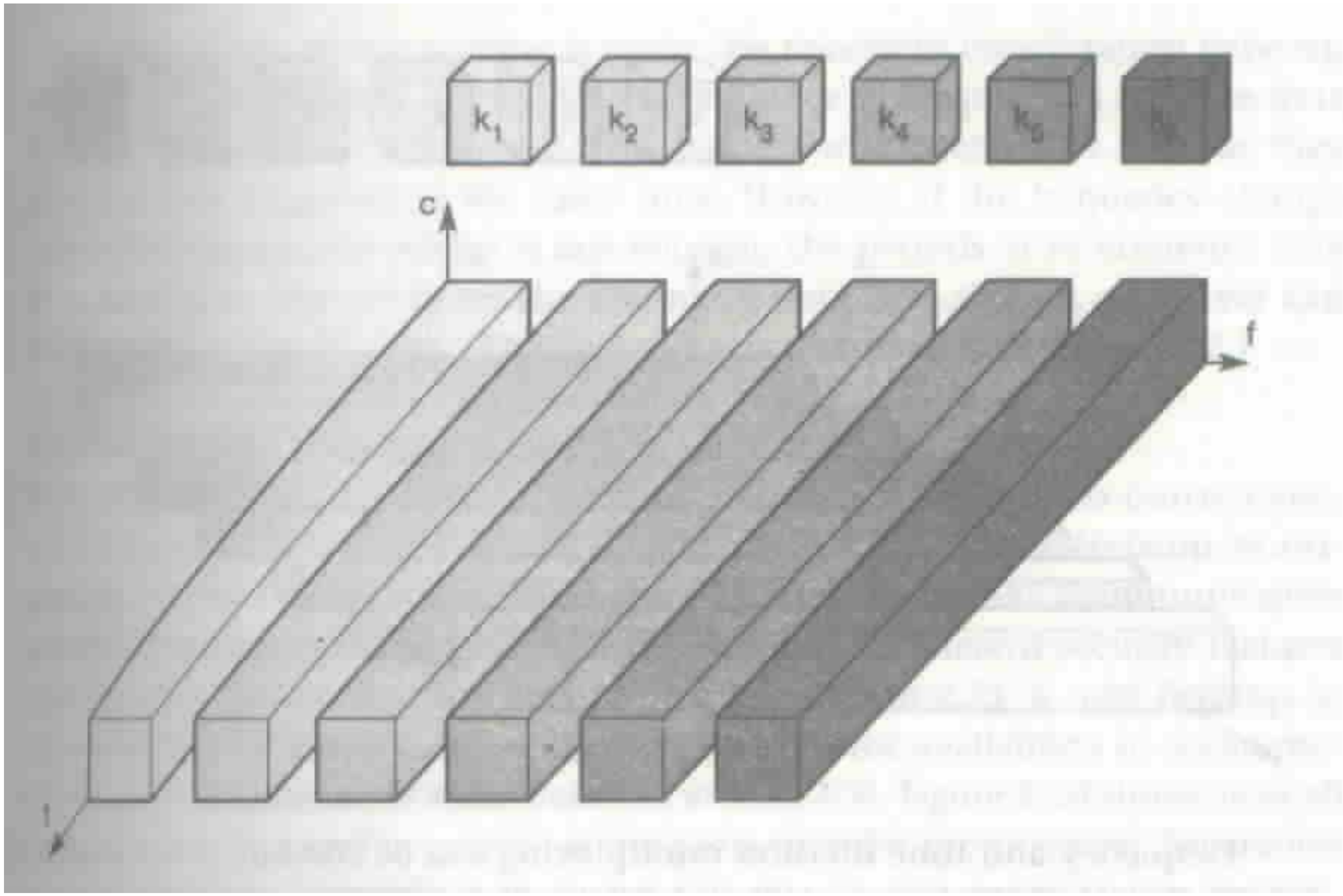


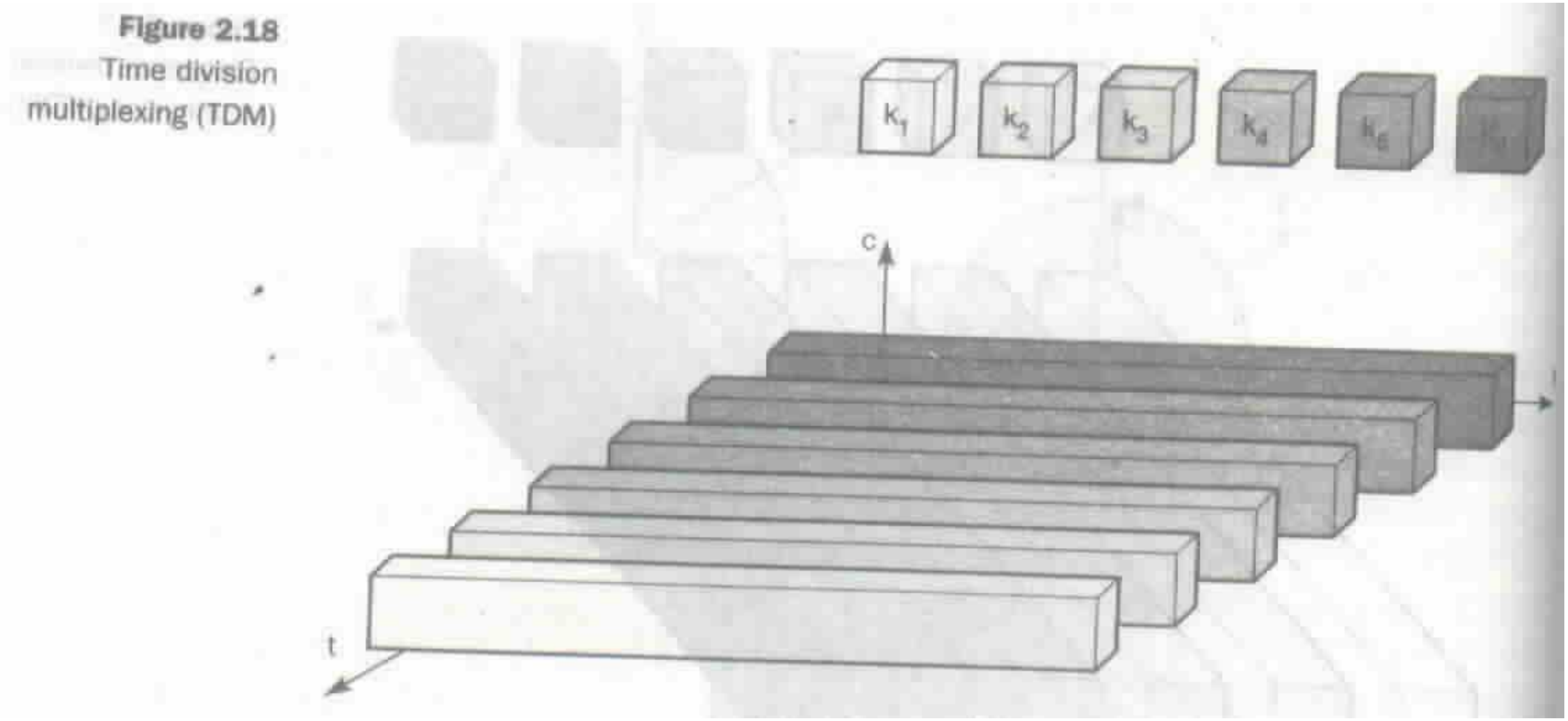
Figure 2.17
Frequency division multiplexing (FDM)

Source : Schiller

Time Division Multiplexing

- A channel is given the whole bandwidth for a certain amount of time
  - All senders use the same frequency, but at different point of time

Time Division Multiplexing



Source : Schiller

Frequency and time division multiplexing

- A channel use a certain frequency for a certain amount of time and then uses a different frequency at some other time
  - Used in GSM systems

Frequency and time division multiplexing

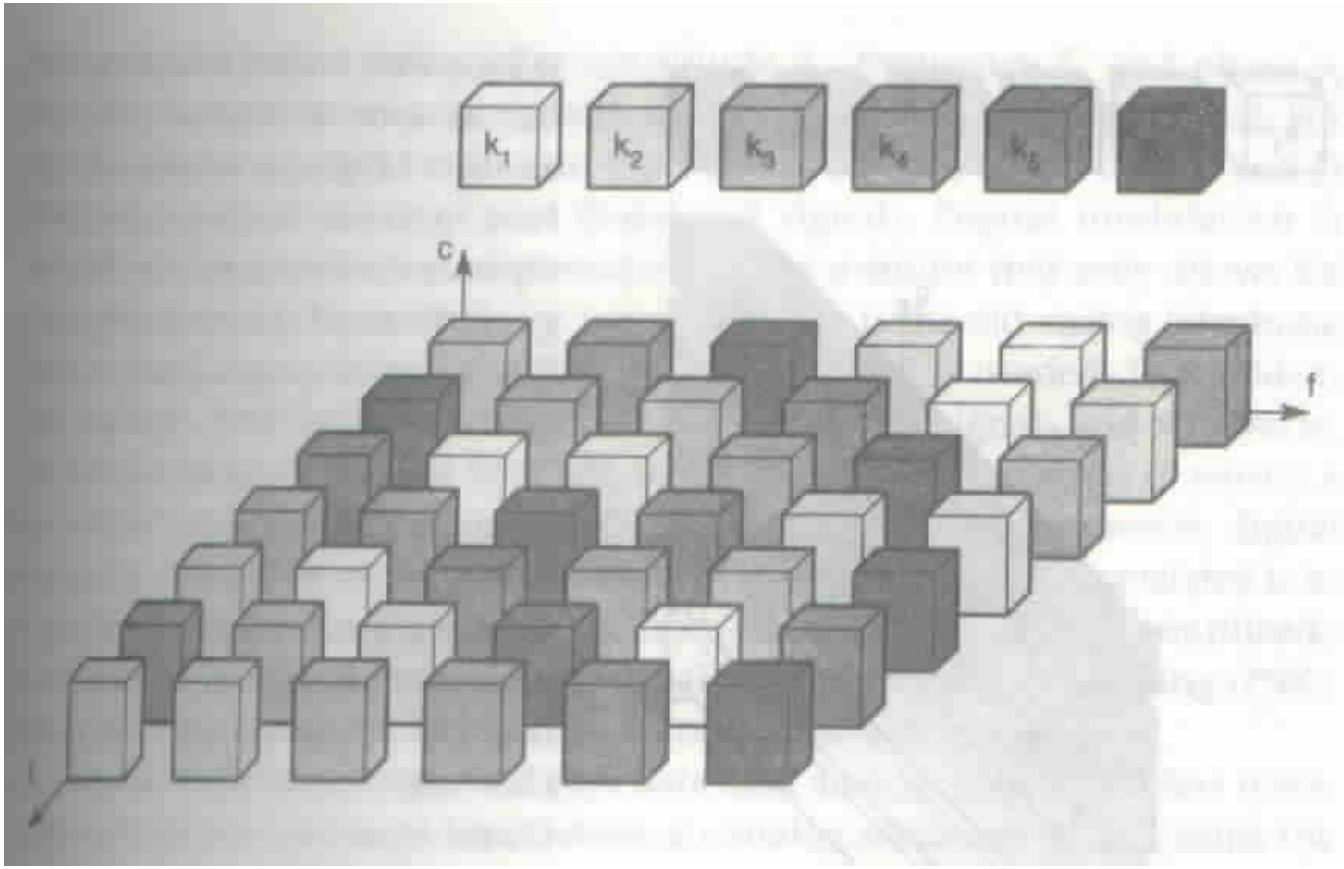


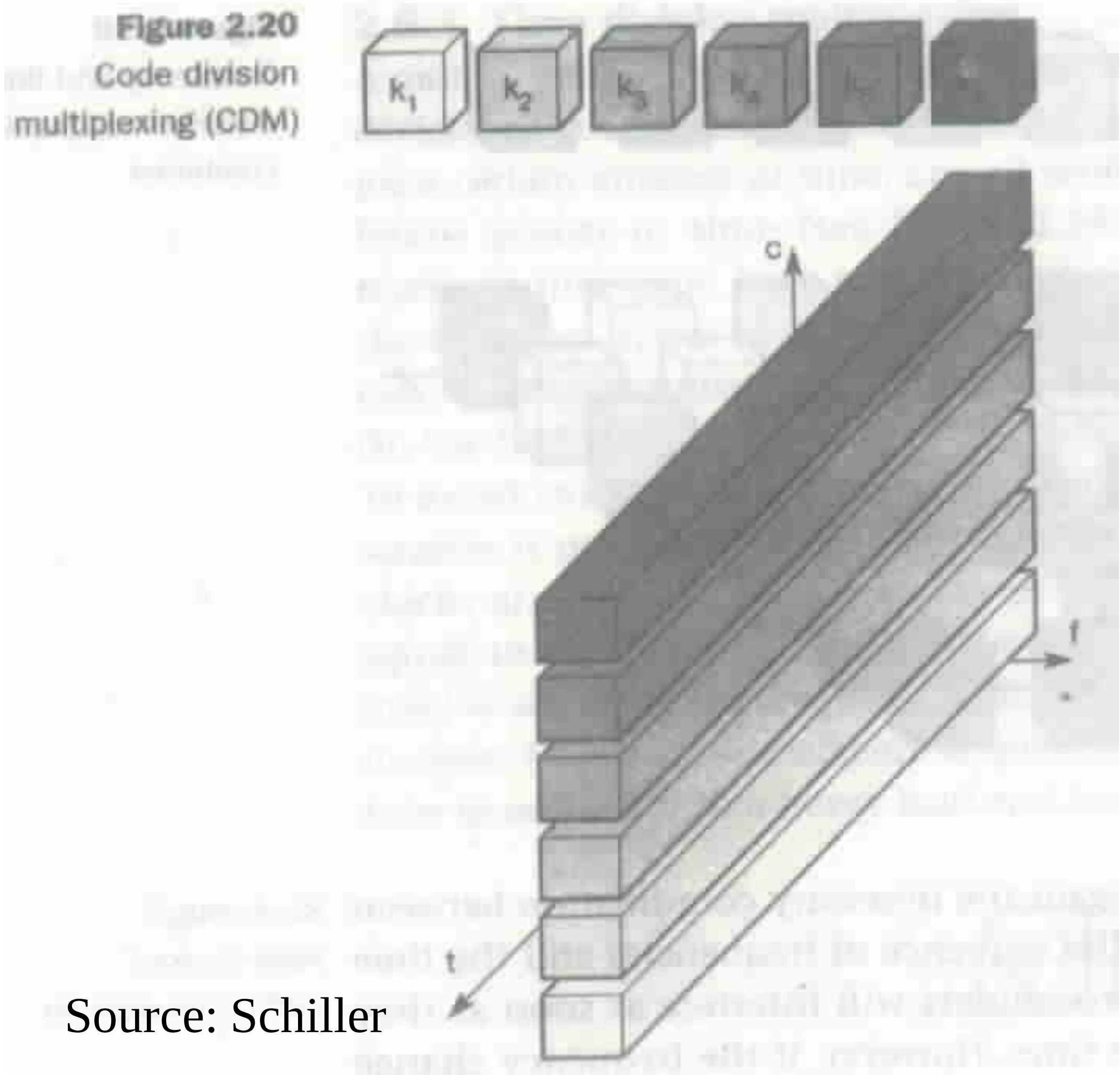
Figure 2.19 Frequenoy and time division multiplexing combined

Source : Schiller

Code division multiplexing

- separation of channels achieved by assigning each channel its own *code*
- guard spaces are realized by having *distance* in code space (e.g. orthogonal codes)
- transmitter can transmit in the same frequency band at the same time, but have to use different code
- Provides good protection against interference and tapping
- but the receivers have relatively high complexity
  - has to know the code and must separate the channel with user data from the noise composed of other transmission
  - has to be synchronized with the transmitter

Code division multiplexing



Source: Schiller

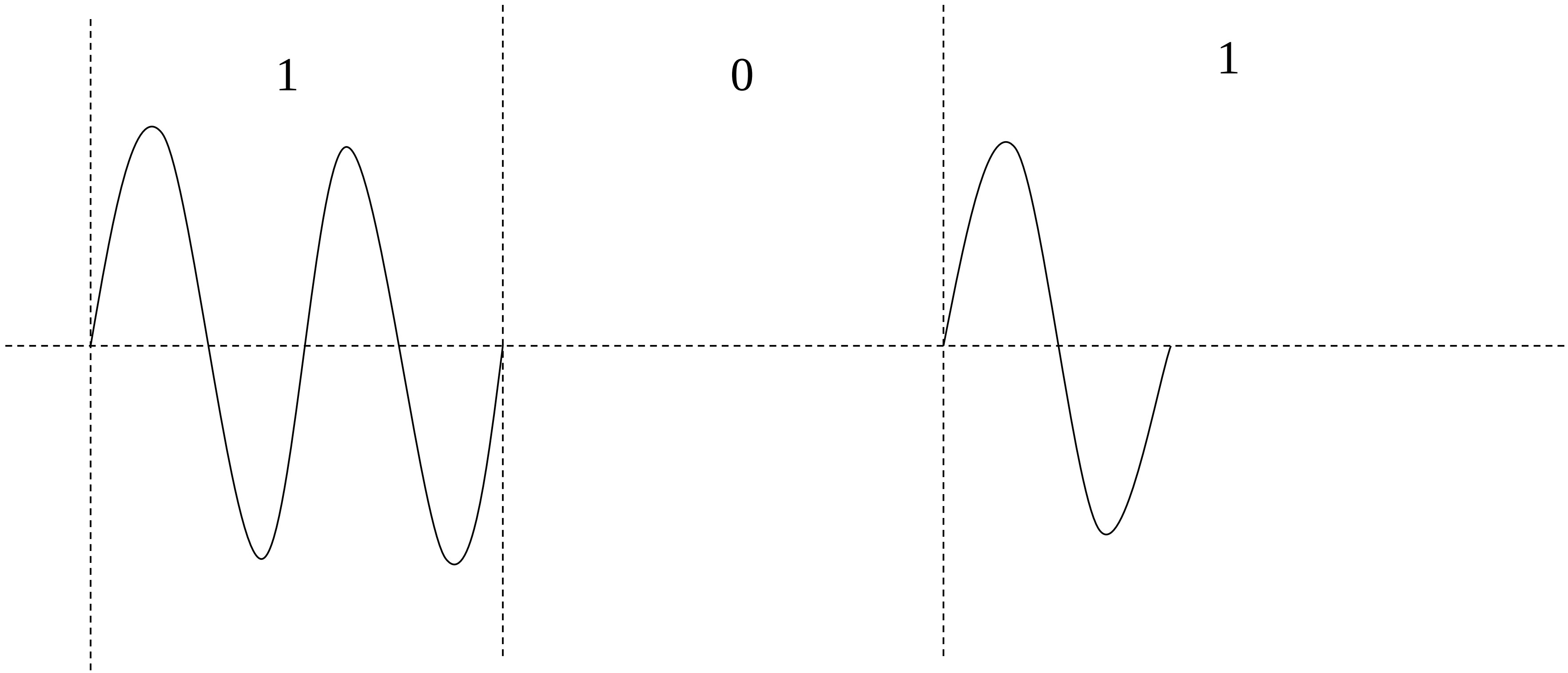
Modulation

- Process of combining input signal and a carrier frequency at the transmitter
- Digital to analog modulation
  - necessary if the medium only carries analog signal
- Analog to analog modulation
  - needed to have effective transmission (otherwise the antenna needed to transmit original signal could be large)
  - permits frequency division multiplexing

Amplitude Shift Keying (ASK)

- ASK is the most simple digital modulation scheme
- Two binary values, 0 and 1, are represented by two different amplitude
- In wireless, a constant amplitude cannot be guaranteed, so ASK is typically not used

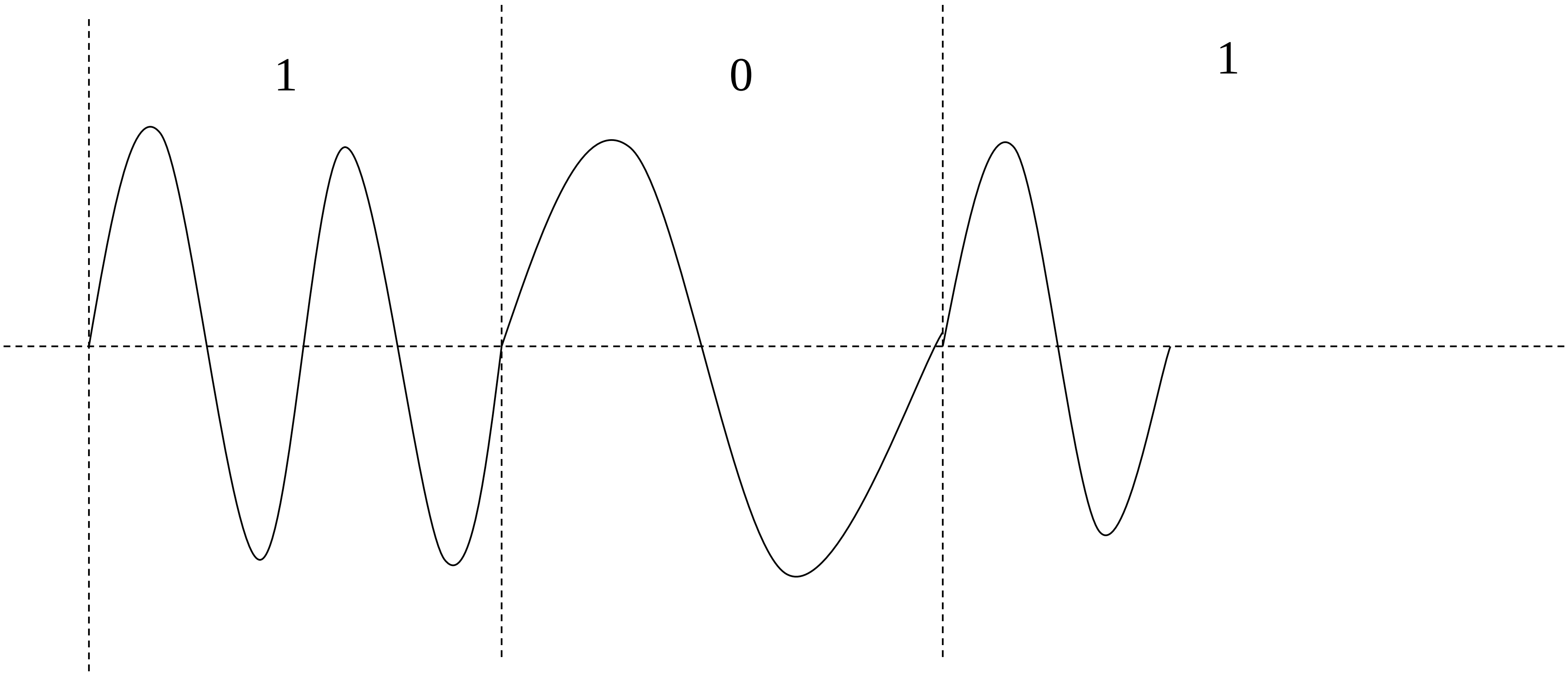
Amplitude Shift Keying (ASK)



Frequency Shift Keying (FSK)

- The simplest form of FSK is binary FSK
  - assigns one frequency f_1 to binary 1 and another frequency f_2 binary 0
- Simple way to implement is to switch between two oscillators one with f_1 and the other with f_2
- The receiver can demodulate by having two bandpass filter

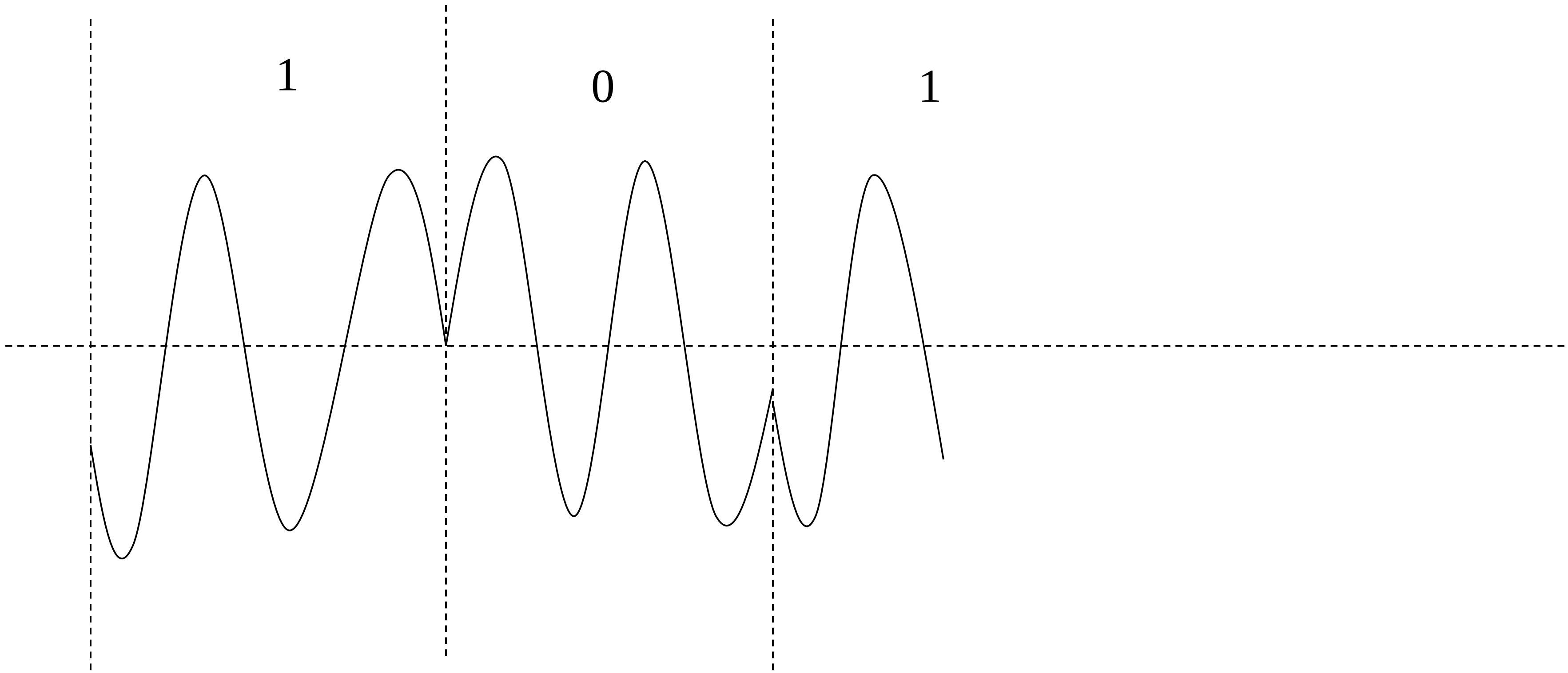
Frequency Shift Keying (FSK)



Phase Shift Keying (PSK)

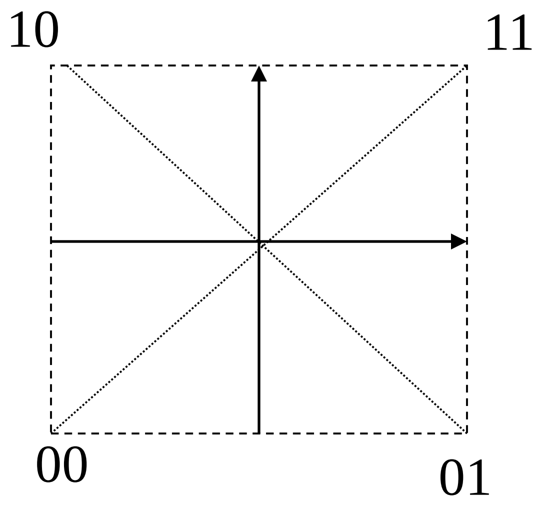
- Uses shifts in the phase of a signal to represent data
- Shifting the phase by 180^0 each time data changes: called binary PSK
- The receiver must synchronize in frequency and phase with the transmitter

Phase Shift Keying (PSK)



Quadrature Phase Shift Keying (Q-PSK)

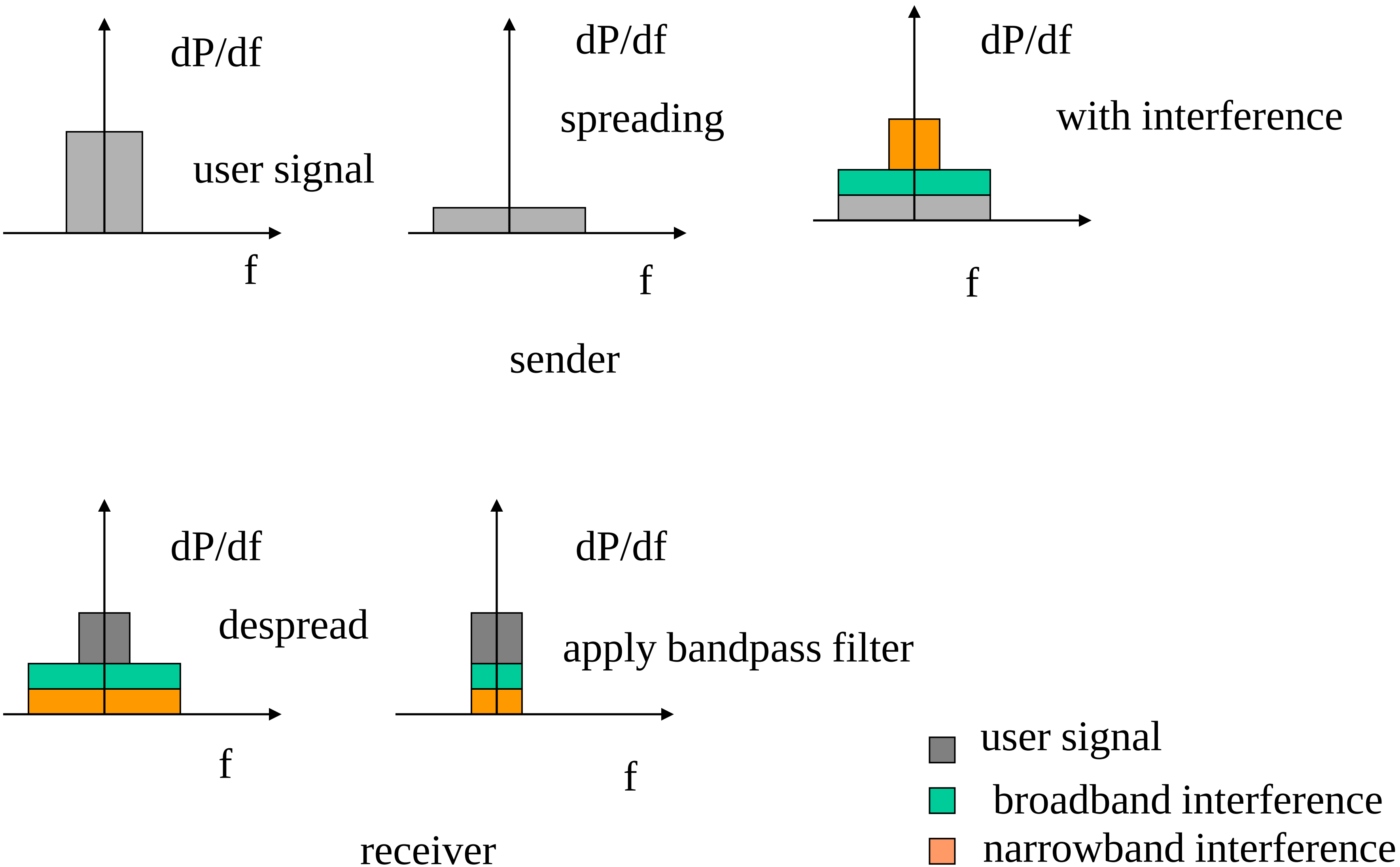
- Higher bit rate can be achieved for the same bandwidth by coding two bits into one phase shift.
- 45^0 for data 11
- 135^0 for data 10
- 225^0 for data 00
- 315^0 for data 01



Spread Spectrum

- Spreading the bandwidth needed to transmit data
  - Spread signal has the same energy as the original signal, but is spread over a larger frequency range
  - provides resistance to narrowband interference

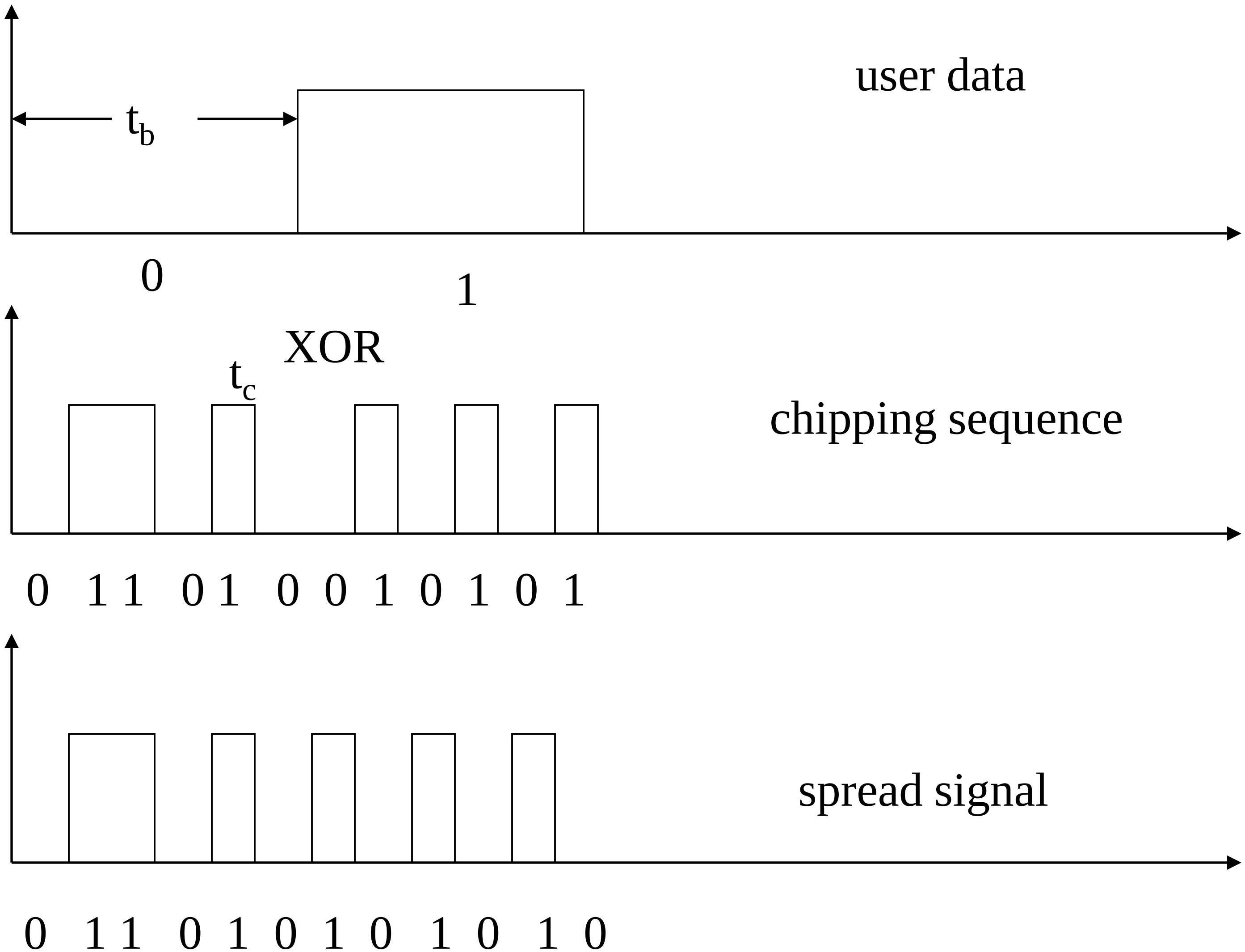
Spread Spectrum



Direct Sequence Spread Spectrum

- Takes a user bit sequence and performs an XOR with, what is known as, *chipping sequence*
- Each user bit duration t_b
- chipping sequence has smaller pulses t_c
- If chipping sequence is generated properly it may appear as random noise
  - sometimes called pseudo-noise (PN)
- t_b/t_c is known as the *spreading factor*
  - determines the bandwidth of the resultant signal
- Used by 802.11b

Direct Sequence Spread Spectrum



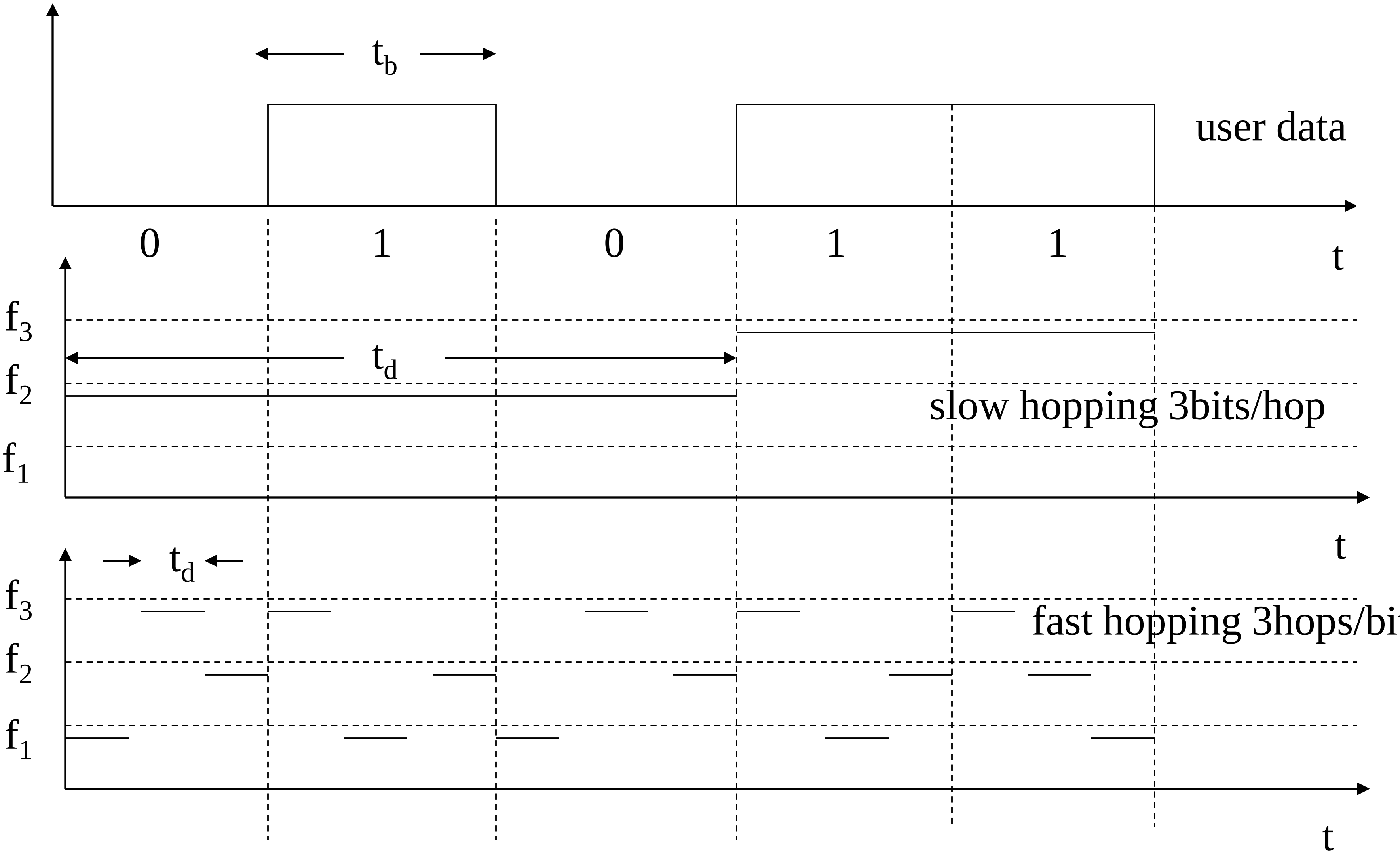
Frequency Hopping Spread Spectrum

- Total available bandwidth is split into many channels of smaller bandwidth and guard spaces
- Transmitter and receiver stay on one of these channels for a certain time and then hop to another channel
- Implements FDM and TDM
- Pattern of channel usage : *hopping sequence*
- Time spent on a particular channel: *dwell time*

Frequency Hopping Spread Spectrum

- Slow hopping
  - Transmitter uses one frequency for several bit period
  - systems are cheaper, but are prone to narrow band interference
- Fast hopping
  - Transmitter changes frequency several times in one bit period
  - Transmitter and receivers have to stay synchronized within smaller tolerances
  - Better immuned to narrow band interference as they stick to one frequency for a very short period
- Receiver must know the hopping sequence and stay synchronized with the transmitter
- Used by bluetooth

Frequency hopping spread spectrum



t_d = dwel time