

Physical Layer

Gianfranco Nencioni



Outline

- Signal Propagation
- Antenna
- Encoding and Modulation
- Duplexing
- Channel Correction Mechanisms

Signal Propagation

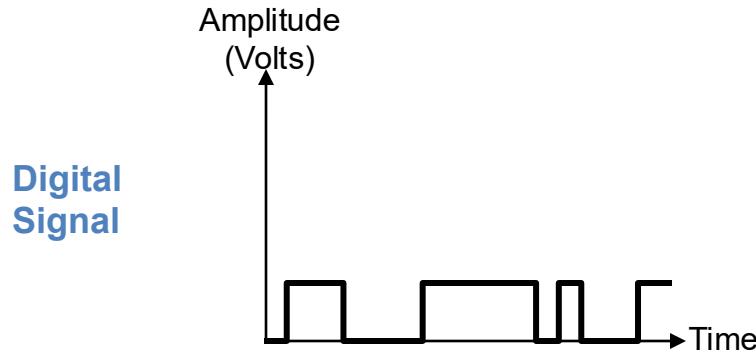
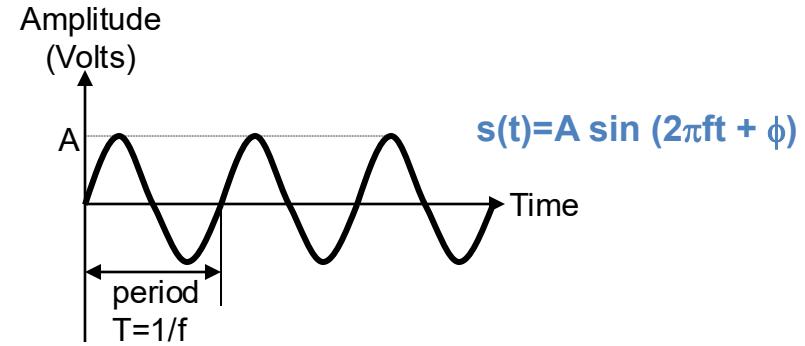
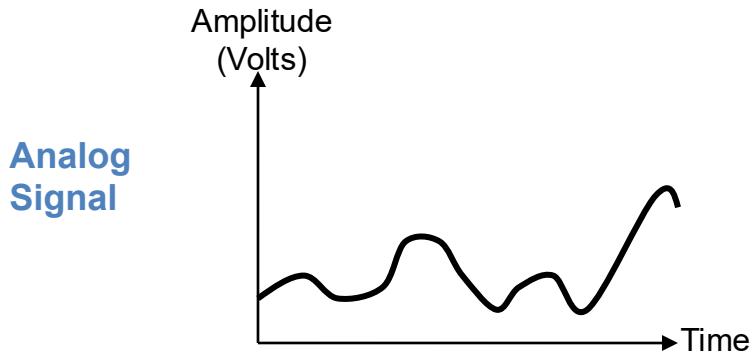
Signal

An electromagnetic signal is a **function** of time,
which can be also expressed in function of frequency.

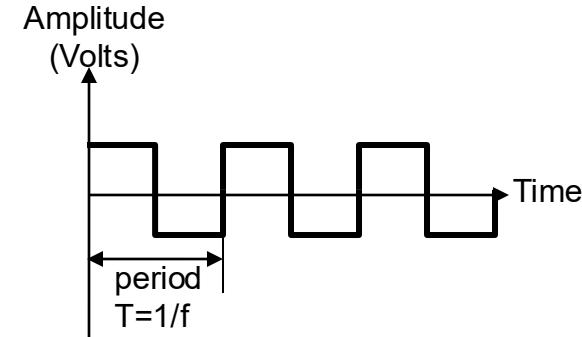
Signal representation:

- Time domain
- Frequency domain More “unnatural”, but more important

Time Domain

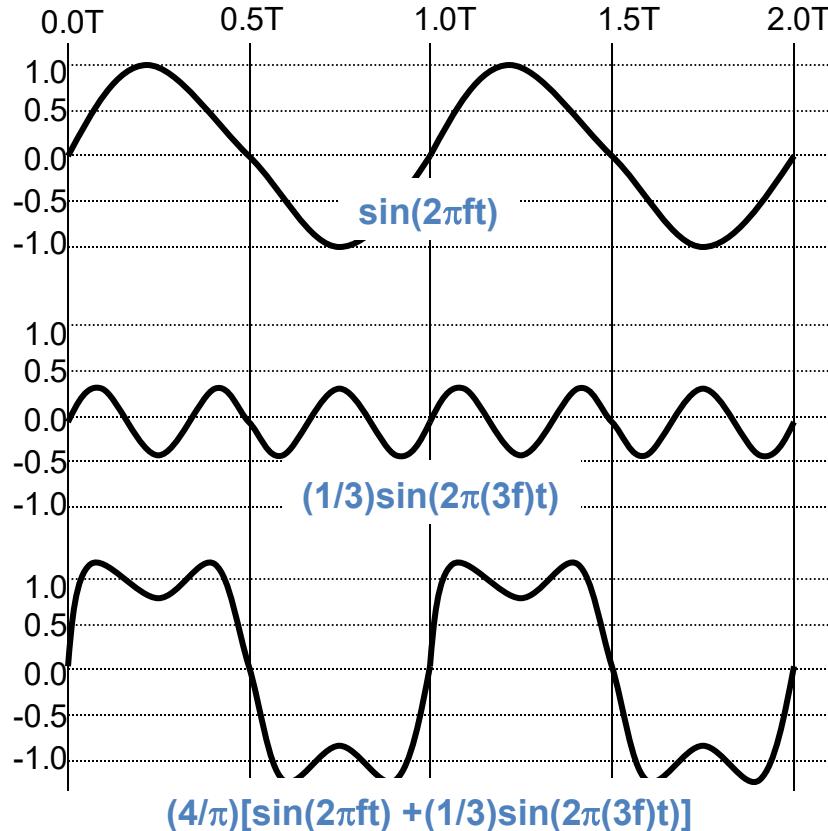


Aperiodic Signal



Periodic Signal $s(t+T)=s(t)$

Frequency Domain



Spectrum of the signal extends from f to $3f$.

Absolute bandwidth is the width of the spectrum.

$$3f - f = 2f$$

Many signals have infinite bandwidth.

The band where the most of the energy contained is called **effective bandwidth** or bandwidth.

Transmission Media

Guided

- Copper cable
- Twisted pair
- Coaxial cable
- Optical fiber

Unguided

- Broadcast radio
- Terrestrial microwave
- Satellite microwave
- Aqueous
- Infrared

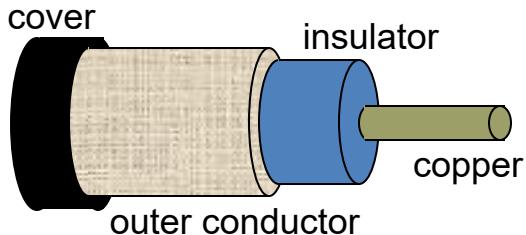
Guided Media



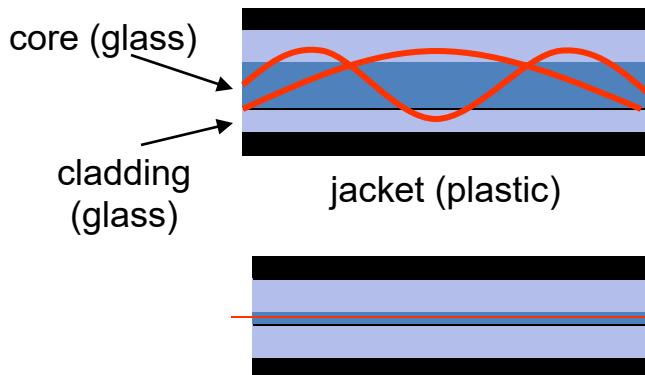
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Unshielded Twisted Pair (UTP), CAT3, CAT5
Shielded Twisted Pair (STP), CAT6, CAT7, CAT8



Coaxial Cable



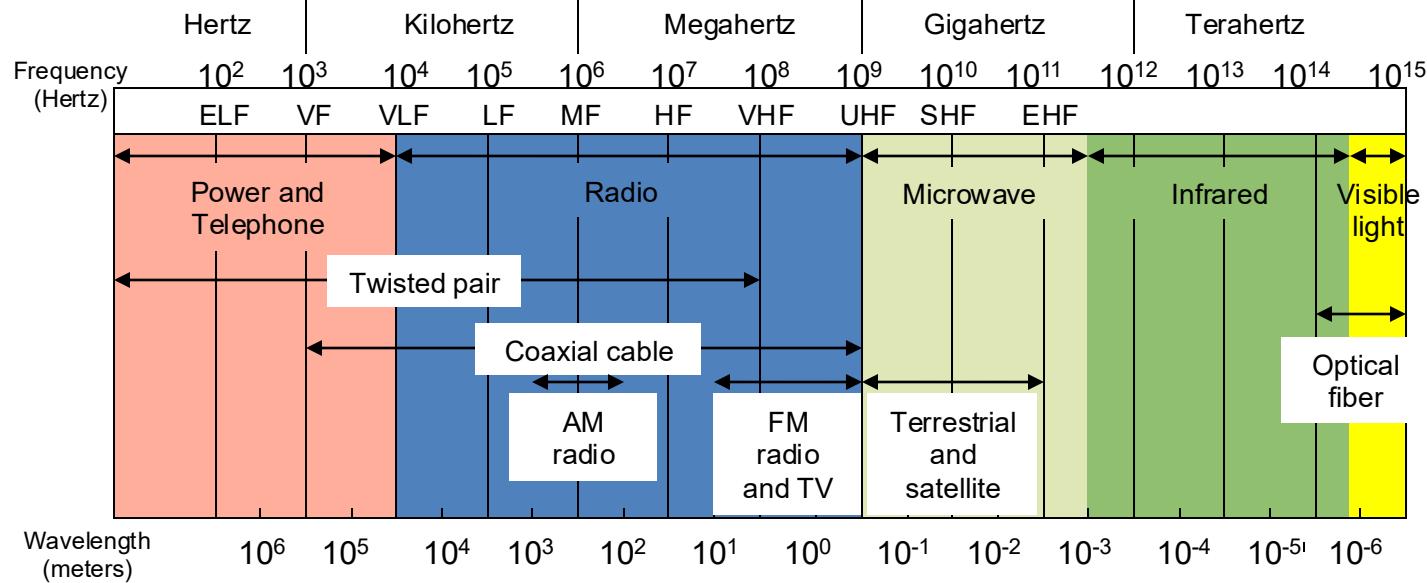
core = 50 microns

Multimode optical fiber

core = 8-10 microns

Single-mode optical fiber

Unguided Media: Electromagnetic Spectrum

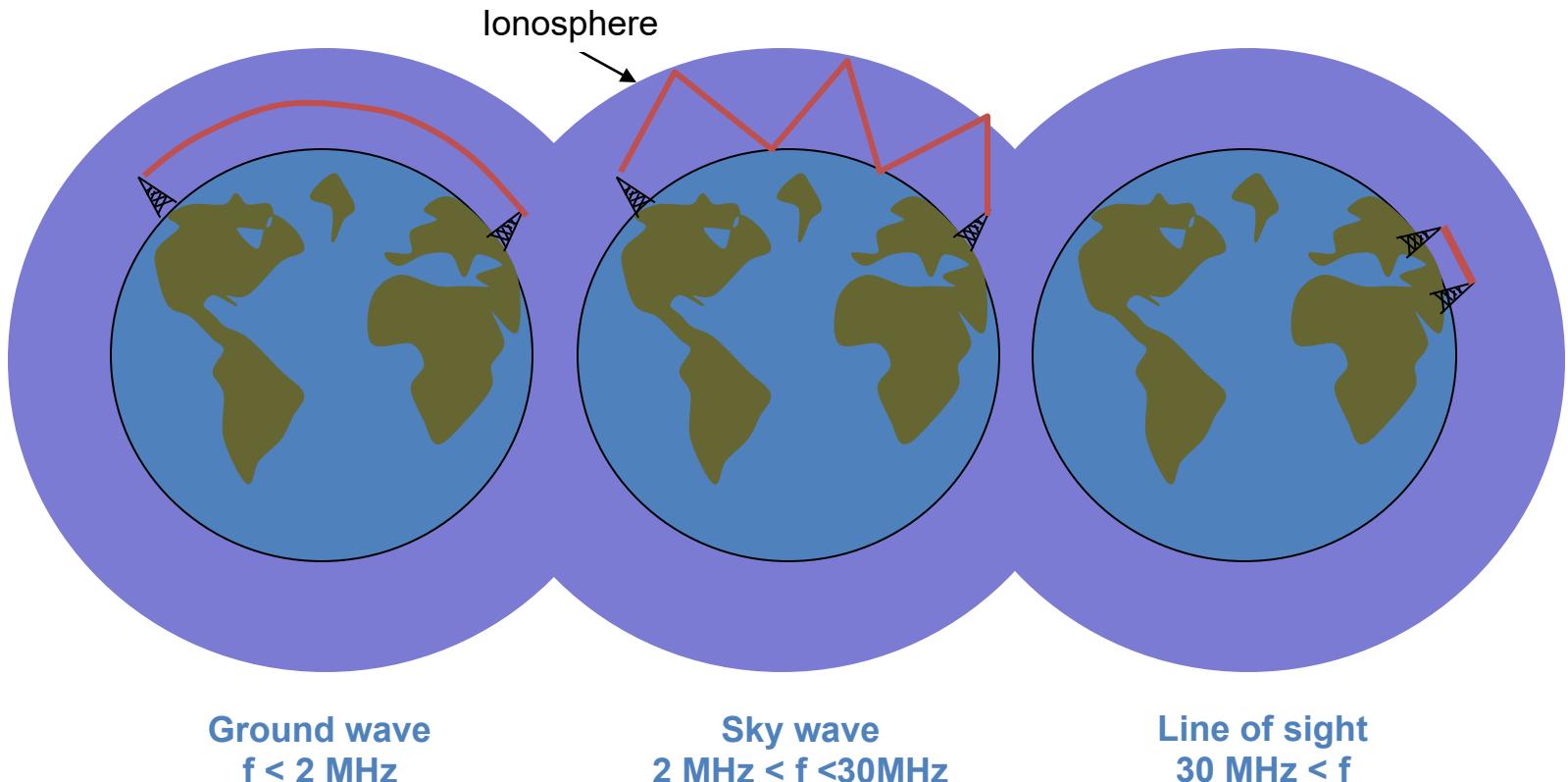


$$\text{Wavelength } \lambda = c / f$$

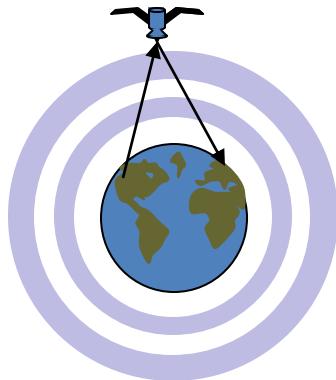
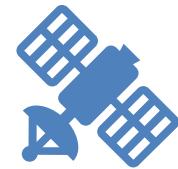
5G Frequency Range 1 & 2

- Defined by 3GPP
 - "[TS 38.101-1: NR; User Equipment \(UE\) radio transmission and reception; Part 1: Range 1 Standalone](#)" (18.2.0 ed.). 3GPP.
 - "[TS 38.101-2: NR; User Equipment \(UE\) radio transmission and reception; Part 2: Range 2 Standalone](#)" (18.2.0 ed.). 3GPP.
- FR1
 - From 410 MHz to 7125 MHz
- FR2
 - From 24.25 GHz to 71.0 GHz
- Definition of the operating bands (uplink/downlink) and duplex mode

Propagation Modes

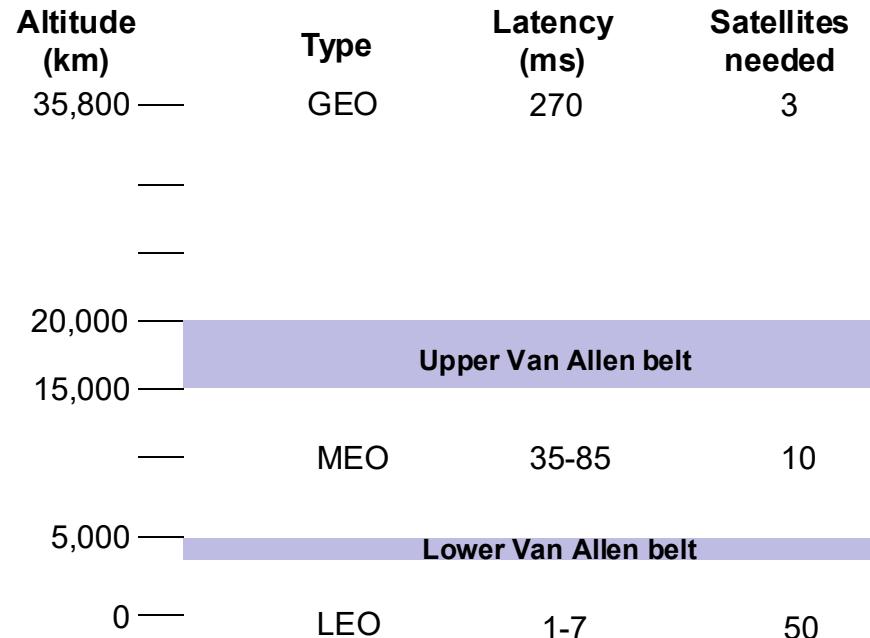


Satellite Orbits

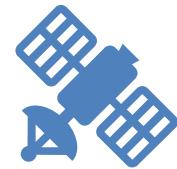


Van Allen belts

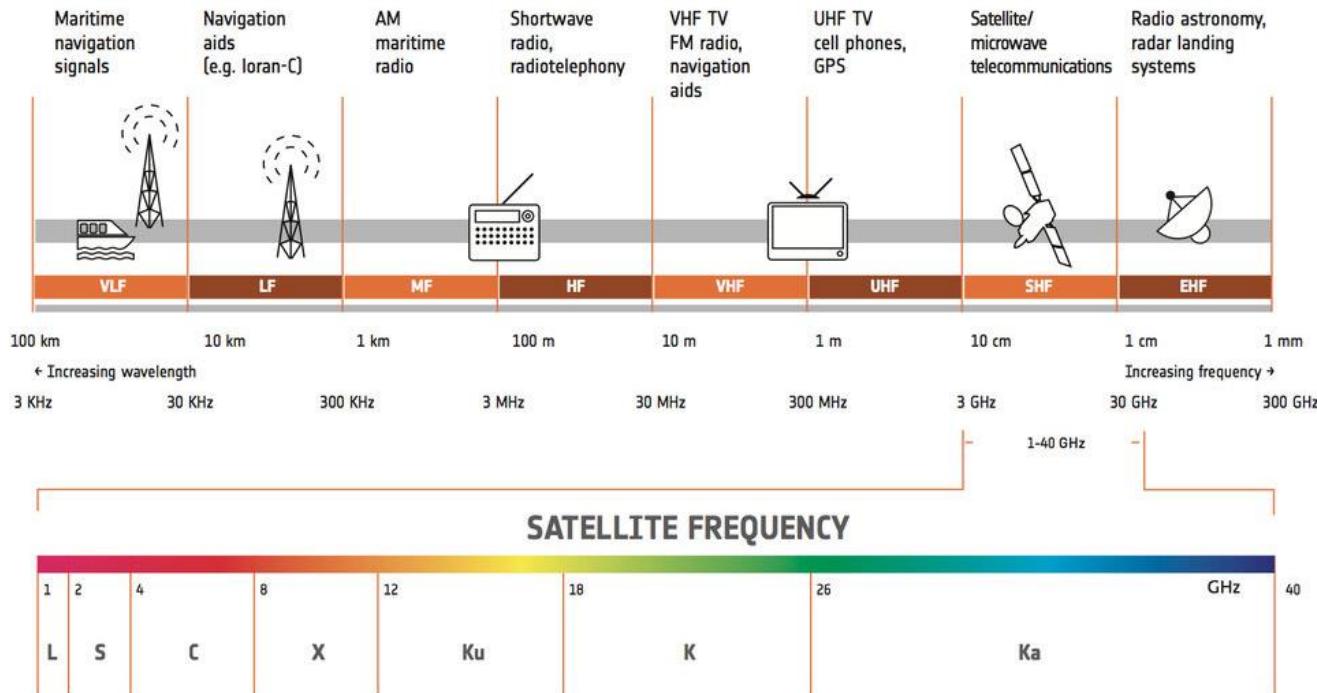
*Energetic charged
particles*



Principal Satellite Bands

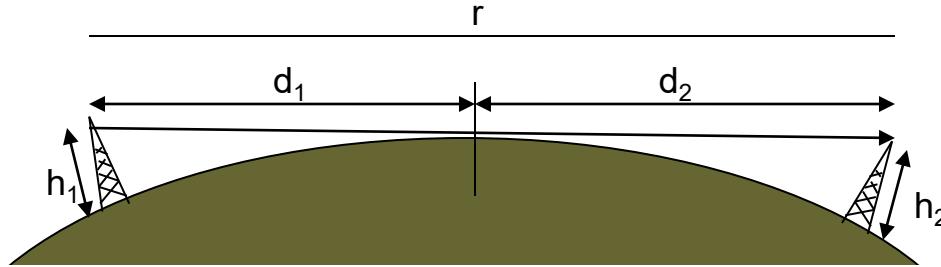


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Source: https://www.esa.int/Applications/Connectivity_and_Secure_Communications/Satellite_frequency_bands

Line of Sight



$$d_1 = 3.57 \sqrt{kh_1}$$

where k is an adjustment factor and generally assumed to be 4/3

$$r = 3.57 \left(\sqrt{kh_1} + \sqrt{kh_2} \right)$$

Light-of-Sight Transmission Impairments

- Free-space loss
- Attenuation
- Refraction
- Atmospheric absorption
- Multipath
- Noise

Free-Space Path Loss



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

where

P_t = signal power at the transmitting antenna

P_r = signal power at the receiving antenna

λ = carrier wavelength

d = propagation distance between antennas

c = speed of light (3×10^8 m/s)

$$L_{dB} = 10 \log \frac{P_t}{P_r} = 20 \log \left(\frac{4\pi f d}{c} \right) = \underline{\underline{20 \log(f) + 20 \log(d) - 147.56 \quad dB}}$$

Attenuation



- The strength of the **signal degrades** with distance over any transmission medium
- Higher at higher frequencies, causing **distortion**
- Receiver must be able to **detect and interpret** the signal

Indoor Path Loss (ITU-R Model)



$$L_{dB} = 20 \log(f) + 10n \log(d) + L_{floor} - 28 \quad dB$$

f frequency

d distance

n propagation factor

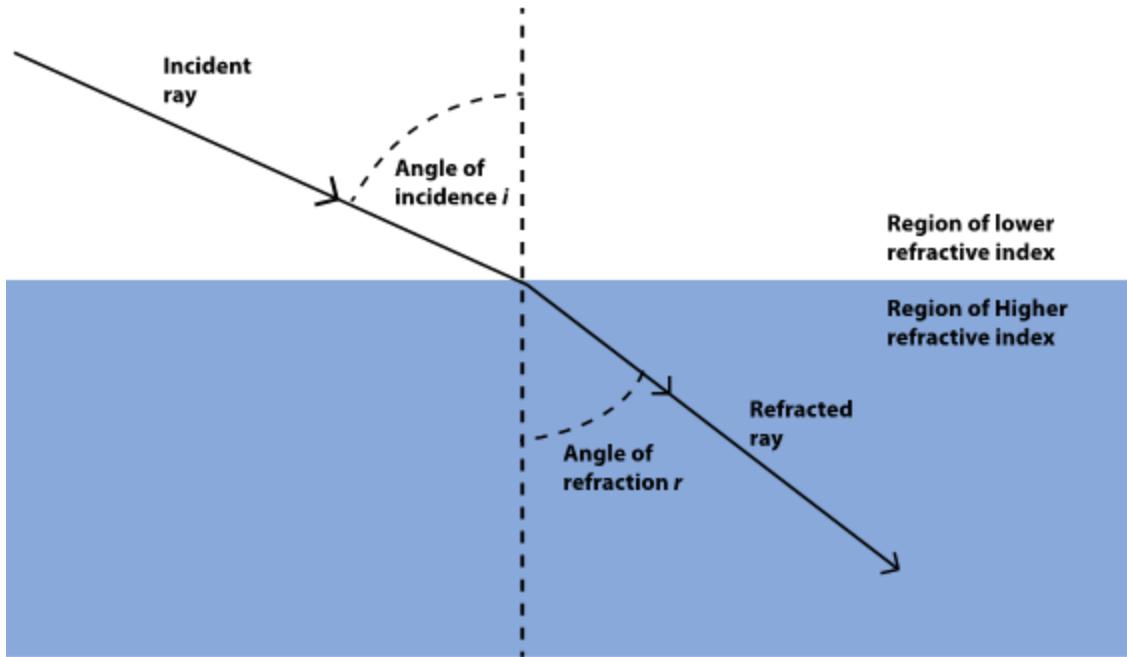
L_{floor} is loss due to penetration of floor

$$n = \begin{cases} 3.3 & f = 900MHz \text{ Dwelling building and office} \\ 2.0 & f = 900MHz \text{ Commercial building} \\ 3.2 & f = 1.2 - 1.3GHz \text{ Dwelling building and office} \\ 2.2 & f = 1.2 - 1.3GHz \text{ Commercial building} \\ 3.0 & f = 1.8 - 2.0GHz \text{ Office} \\ 2.8 & f = 1.8 - 2.0GHz \text{ Dwelling house} \\ 2.2 & f = 1.8 - 2.0GHz \text{ Commercial building} \end{cases}$$

$$L_{floor} = \begin{cases} 9 & f = 900MHz \text{ Dwelling, office, commercial } m = 1 \\ 19 & f = 900MHz \text{ Dwelling, office, commercial } m = 2 \\ 24 & f = 900MHz \text{ Dwelling, office, commercial } m = 3 \\ 4m & f = 1.8 - 2.0GHz \text{ Dwelling} \\ 15 + 4(m-1) & f = 1.8 - 2.0GHz \text{ Office} \\ 6 + 3(m-1) & f = 1.8 - 2.0GHz \text{ Office} \end{cases}$$

m number of floors

Refraction

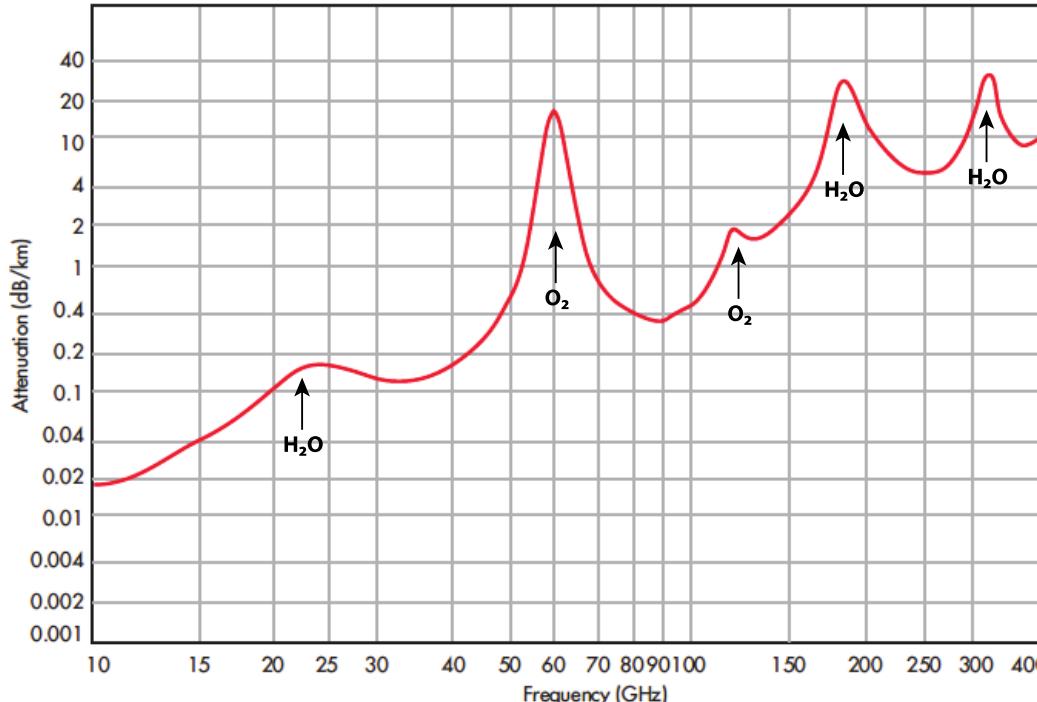


Atmospheric Absorption

- Water vapour and oxygen contribute to attenuation.
- A **peak attenuation** occurs **in the vicinity of 22 GHz**.
- At frequencies **less than 15 GHz**, the attenuation is **less**.
- Rain and fog cause scattering.



Atmospheric Absorption



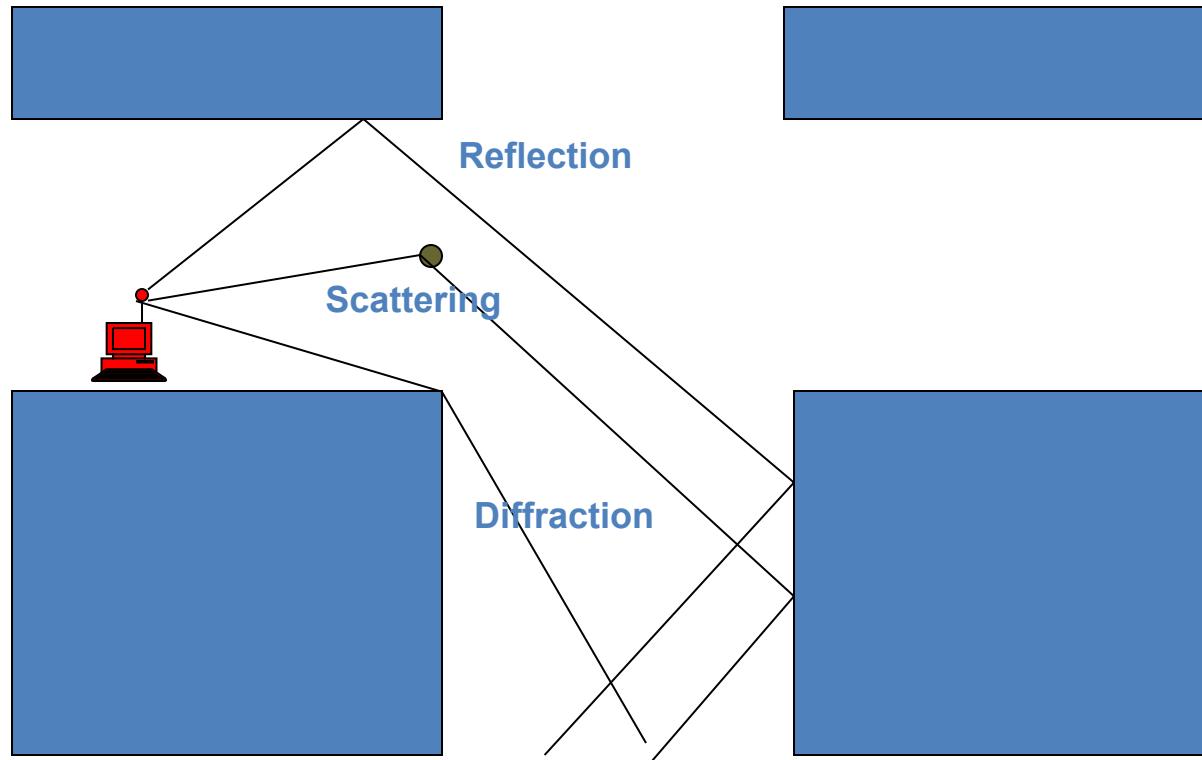
Sea level

$T = 20^\circ C$

$P = 760 \text{ mm}$

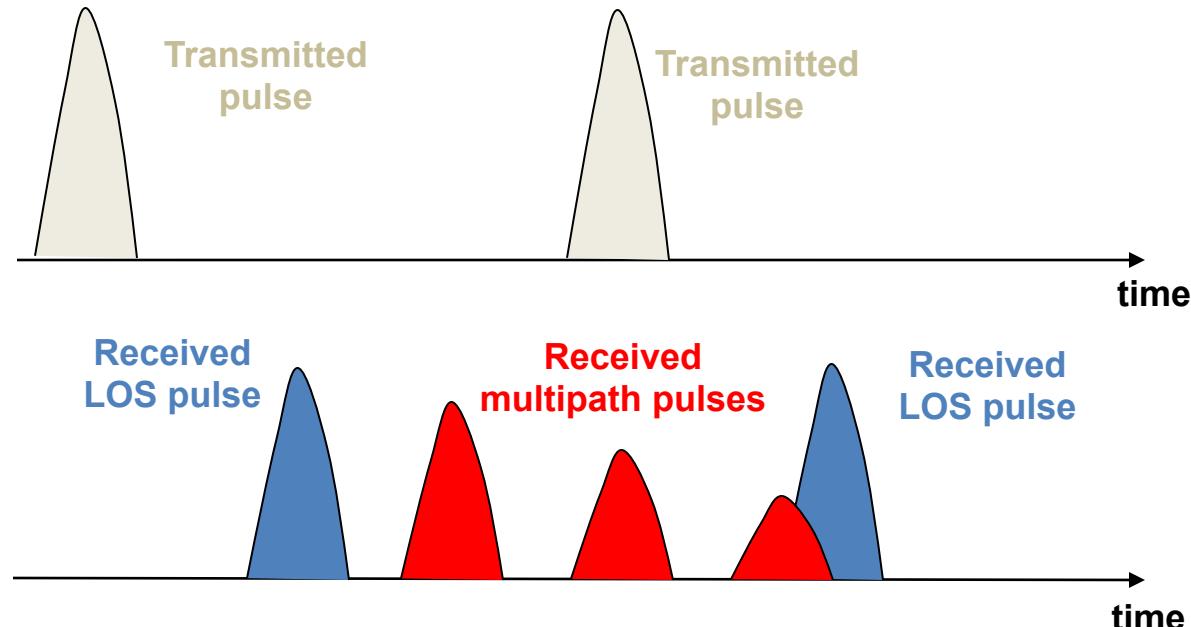
$H_2O = 7/5 \text{ gr/mm}^2$

Multipath



Intersymbol Interference (ISI)

Unwanted effect of multipath propagation. Multiple secondary copies of a pulse may arrive at the receiver.

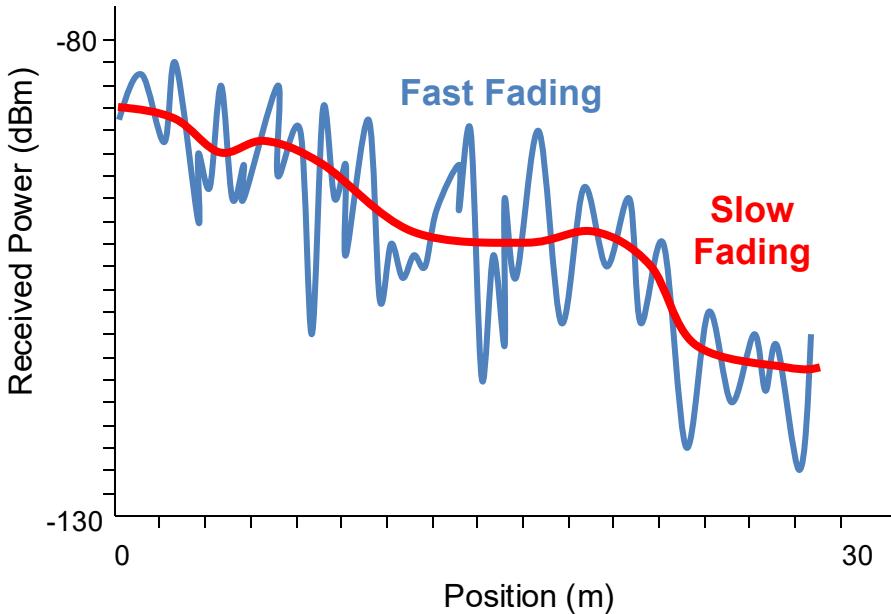


Fading in a Mobile Environment

Time variation of received signal power caused by changes in the transmission medium or path(s).

- Multipath propagation
 - Reflection
 - Diffraction
 - Scattering
- Effects of multipath propagation
 - ISI

Types of Fading



In **flat (nonselective) fading**, the fading effects equally the different spectral components.

Selective fading effects unequally.

Figure related to Urban Mobile Environment.

Large-Scale Fading, slowly changing waveform

Small-Scale Fading, changes also over distance of half of the wavelength 0.33 m (i.e. $f=900$ MHz).

Coherence time, T_c , time over which the channel stays relatively constant.

Examples:

- for pedestrians 70 ms;
- for cars 5 ms.

In **slow fading**, the coherence time is much longer than the time for transferring a bit.

Otherwise, it is **fast fading**.

Fading Channels

Additive White Gaussian Noise (AWGN) channel: The signal is degraded by thermal noise as well as electronics. It is accurate for cases such as space communications and coaxial cable but not for terrestrial wireless.

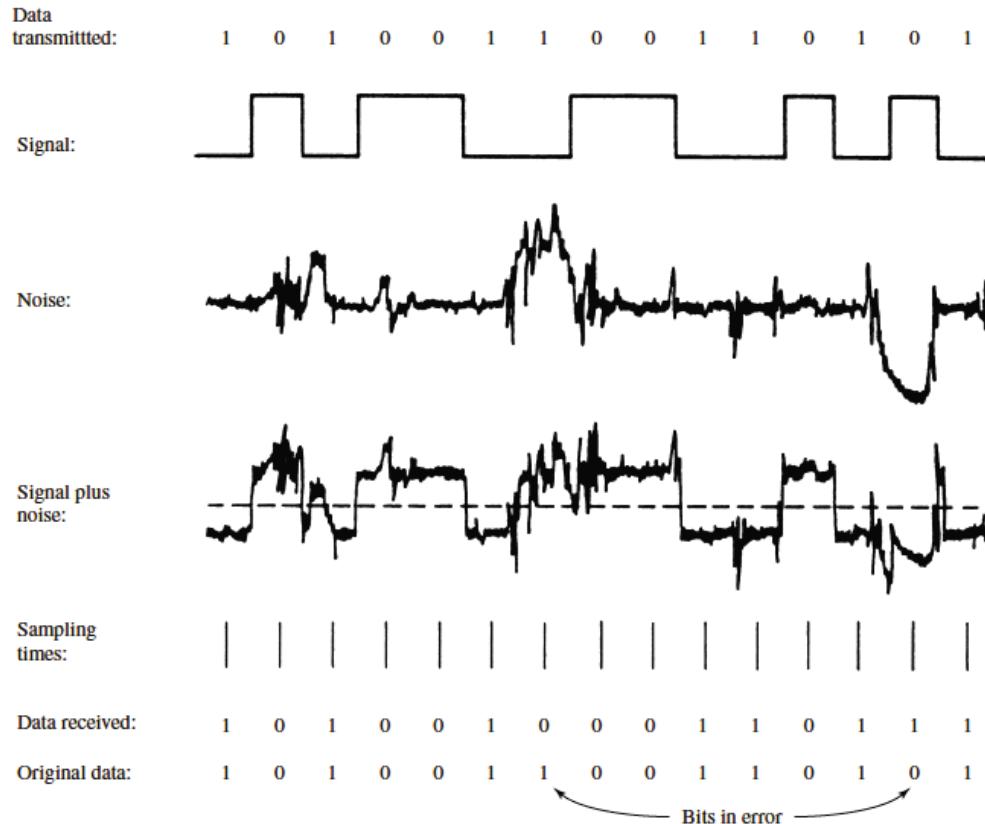
Rayleigh channel: The model is for the case when there are multiple indirect paths but not a LOS. It is a good model for dense urban areas for outdoor applications.

Rician channel: The model is for the case when there are multiple indirect paths as well as a LOS component. It is a good model for indoor applications.

Noise

- Thermal noise *Thermal agitation of electrons*
 - $N_0 = kT$ (W/Hz)
 - where
 - k is Boltzman's constant (1.3803×10^{-23} J/K),
 - T is absolute temperature in Kelvins.
 - $N = kTB$
 - $N_{dBW} = -228.6 \text{ dBW} + 10\log T + 10\log B$
 - Intermodulation noise *Nonlinearity in transmitter, receiver, or transmission*
 - Crosstalk *Electrical coupling*
 - Impulse noise *Various causes, limited in time*

Effect of Noise on a Digital Signal



Signal-to-Noise Ratio (SNR)

$$\text{SNR}_{dB} = 10 \log_{10} \frac{S}{N}$$

S signal power

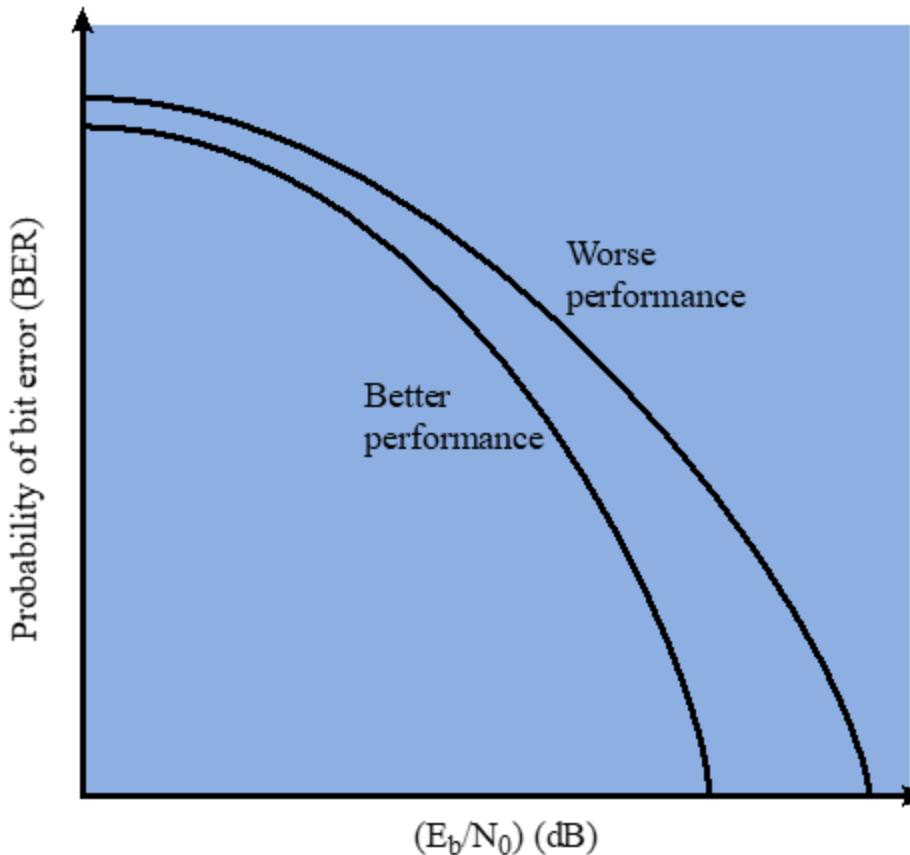
- For digital communication systems:

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

E_b signal energy per bit
R bit rate

$$\left(\frac{E_b}{N_0} \right)_{dB} = S_{dBW} + 10 \log R + 228.6 - 10 \log T$$

BER and SNR



Channel Capacity

Nyquist Bandwidth

$$C = 2B \log_2 M$$

where

C is capacity in bit per second (bps),

B is bandwidth in hertz (Hz),

M is discrete signal levels.

Shannon Capacity Formula

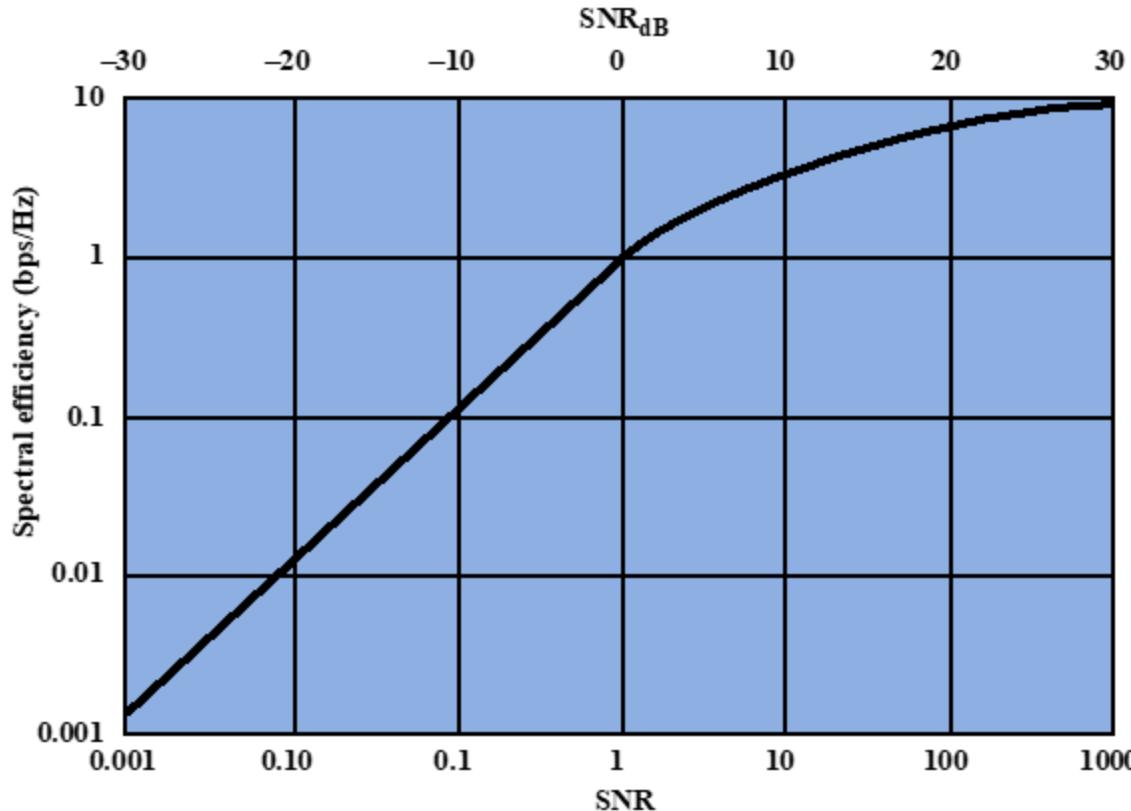
$$C = B \log_2 (1 + SNR)$$

Feasible number of signal levels

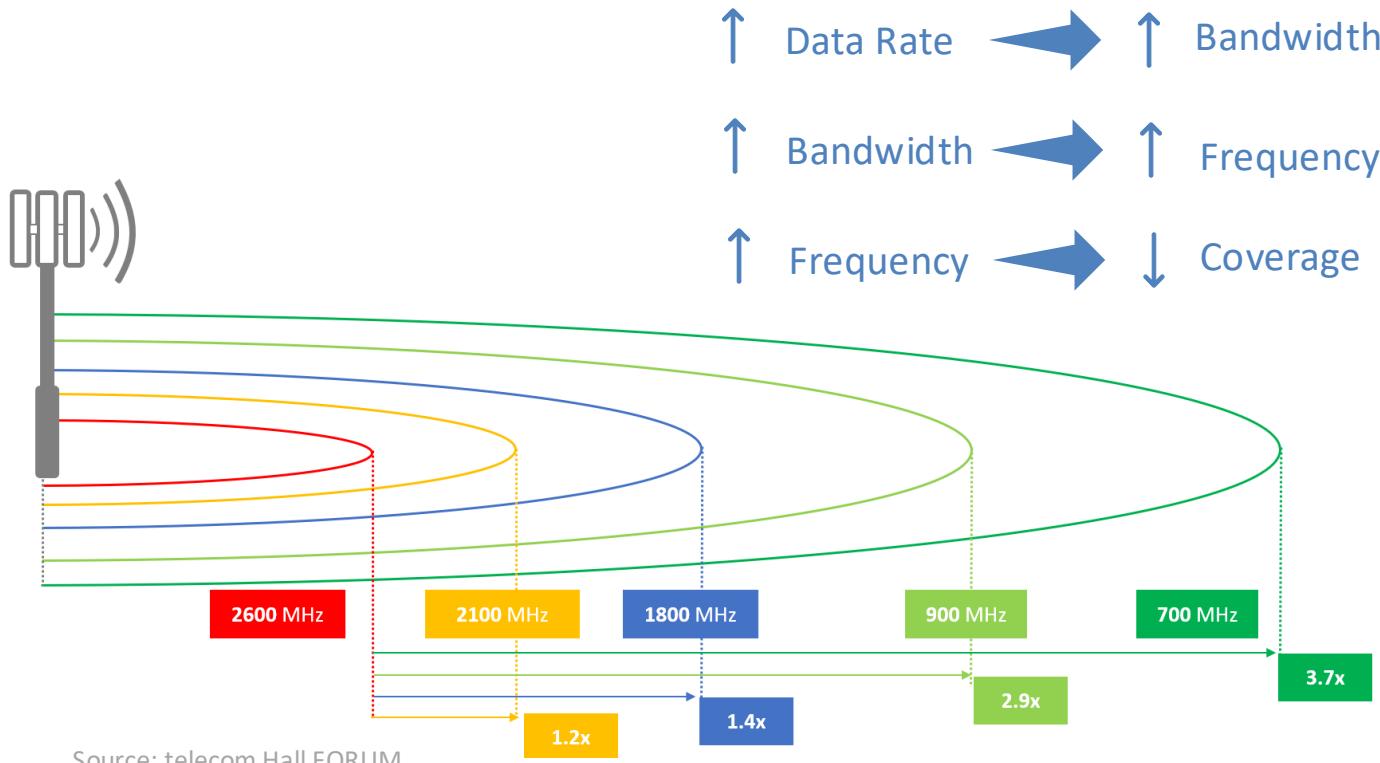
$$2B \log_2 M = B \log_2 (1 + SNR)$$

$$M = \sqrt{1+SNR}$$

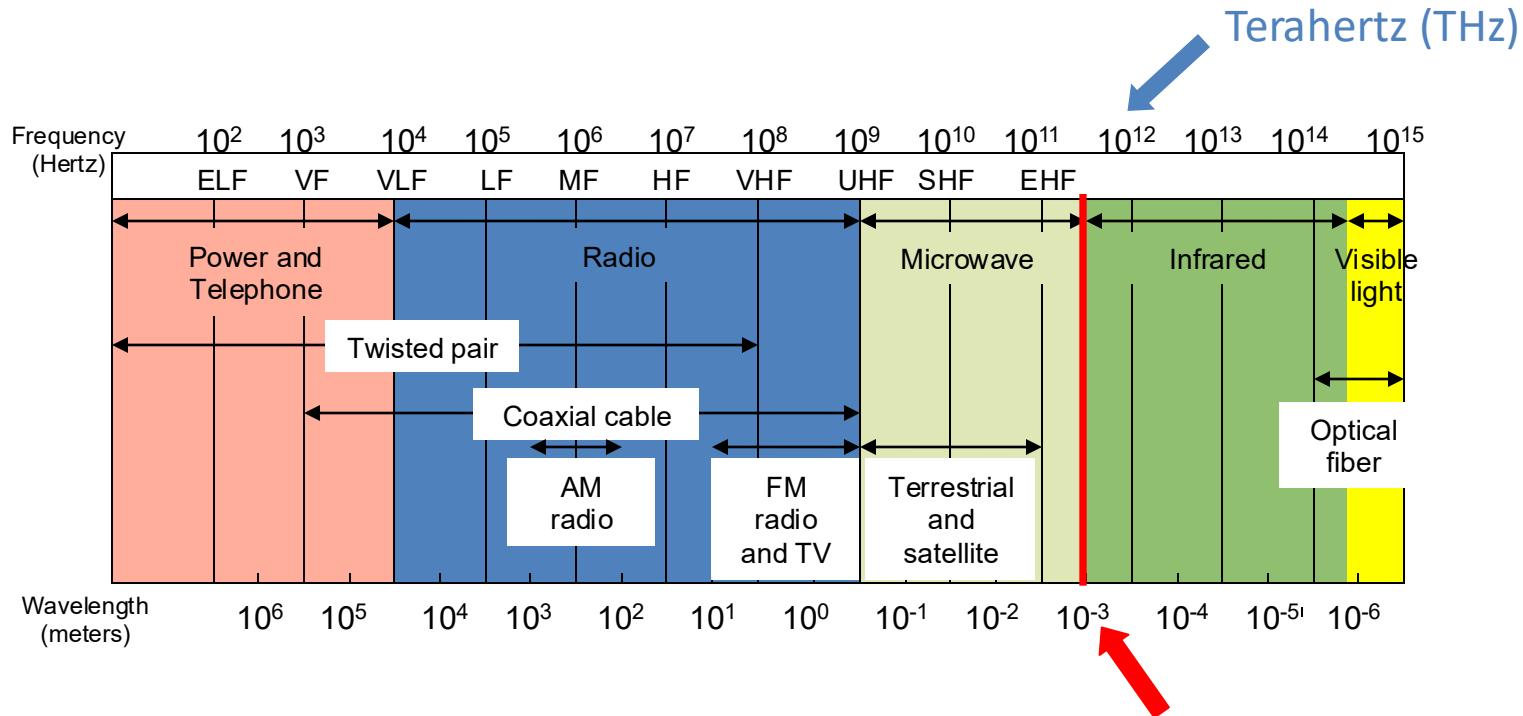
Spectral or Bandwidth Efficiency



Coverage vs Data Rate



Millimeter Wave (mmWave)



Millimeter Wave (mmWave)



- Susceptible to propagation impairments
- Challenges:
 - Limited coverage
 - Path loss
 - Difficulties with non-line-of-sight
 - Blockage from solid object in LOS
 - Difficulties with mobile use
 - Blockage
 - Large from factor
 - Power consumption due to higher bandwidth

Antenna

Antenna



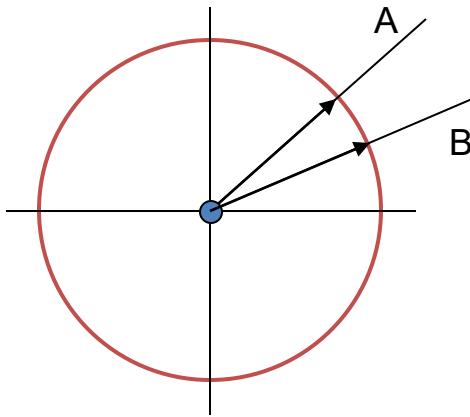
An electrical conductor (or a system of conductors) used for radiating (and/or collecting) electromagnetic energy.

The **radiation pattern** is a geographical representation of the radiation properties of an antenna as function of space coordinates.

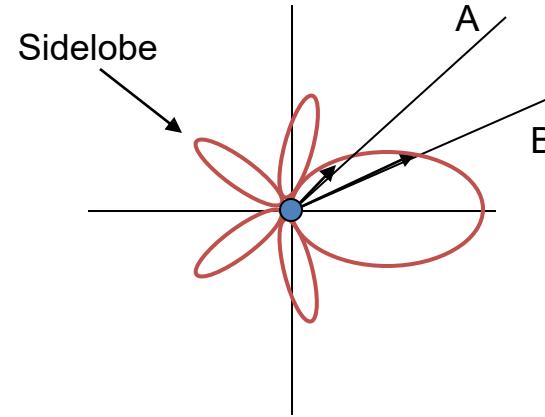
Categories of pattern:

- Isotropic (omnidirectional)
- Directional

Isotropic vs Directional Antennas

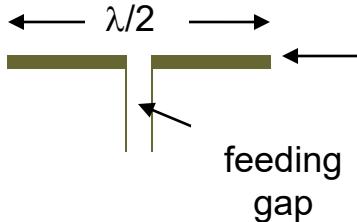


Isotropic Antenna

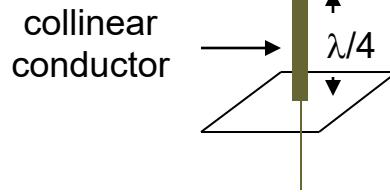


Directional Antenna

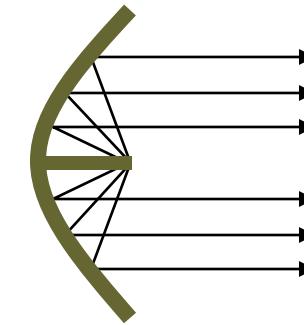
Types of Antenna



Half-wave dipole
(Hertz antenna)



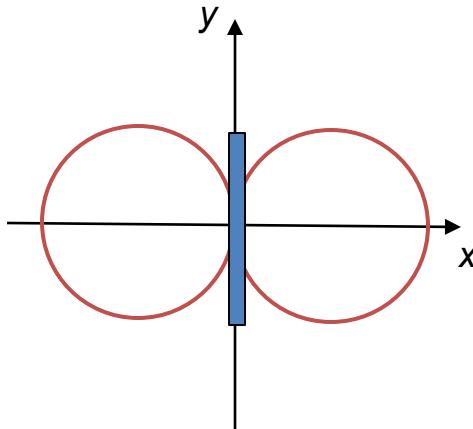
Quarter-wave dipole
(Marconi antenna)



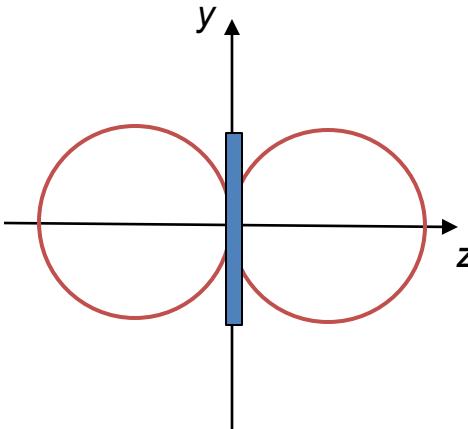
Parabolic reflective
antenna

Radiation Pattern is 3D

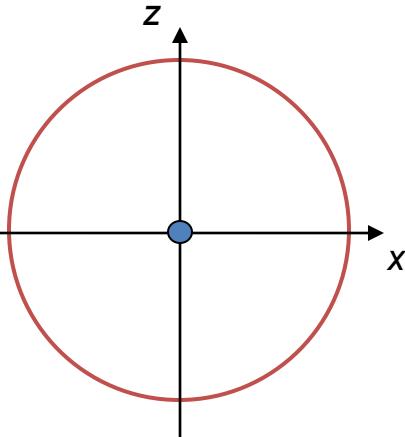
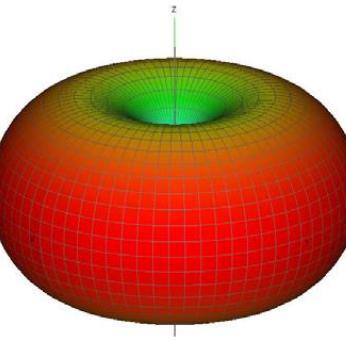
Radiation pattern of a simple dipole



Side view (xy plane)



Side view (zy plane)



Top view (xz plane)

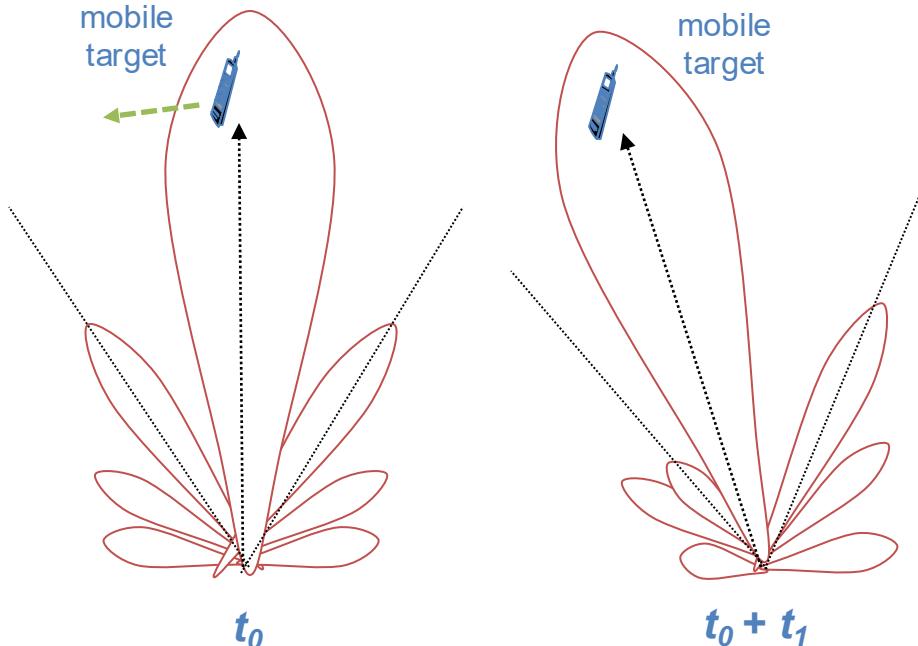
Directionality Measures

Beam width is the angle within which the power radiated by the antenna is at least half of what it is in the most preferred direction. It can be determined by the radiation pattern.

Antenna gain is the ratio of the radiation intensity in a given direction to the radiation intensity that would be produced in any direction by a perfect isotropic antenna.

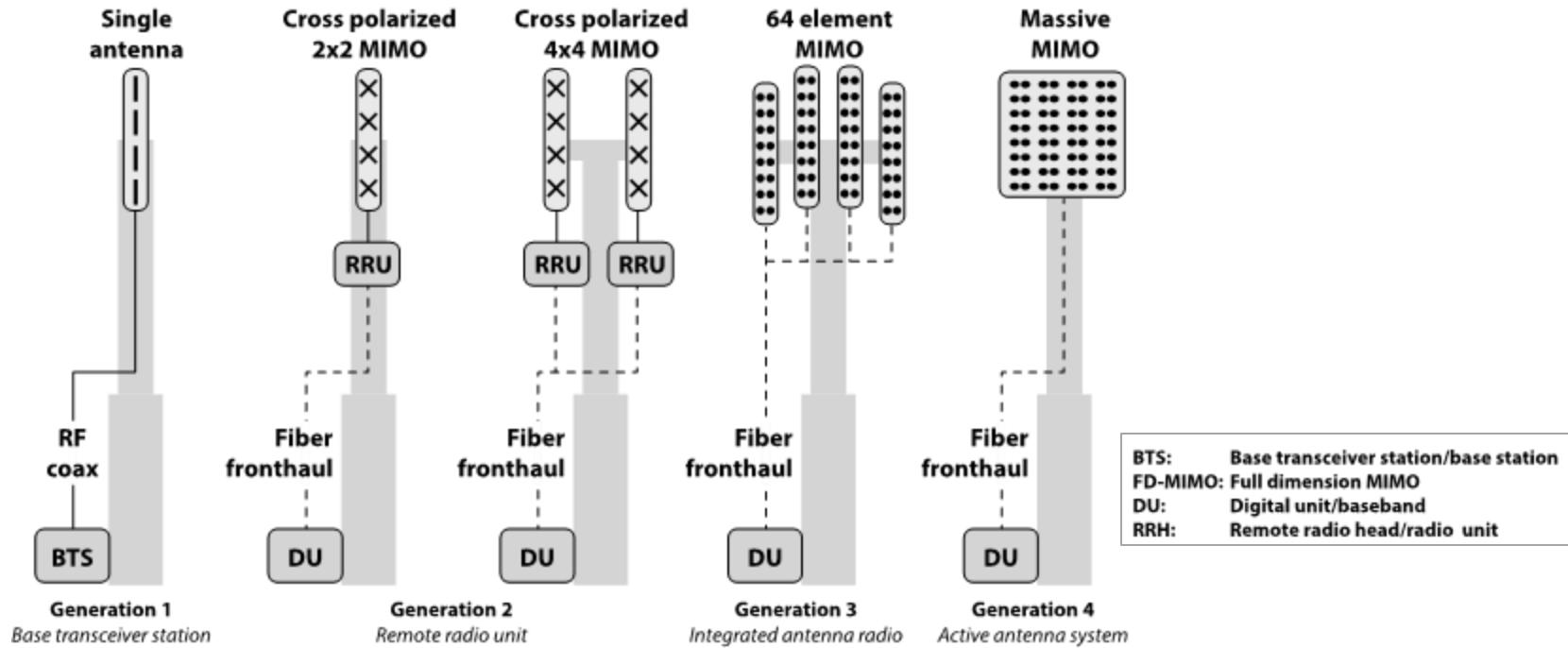
Smart Antennas

Smart antennas are antenna arrays with smart signal processing algorithms used to track and locate the antenna beam on the mobile target.



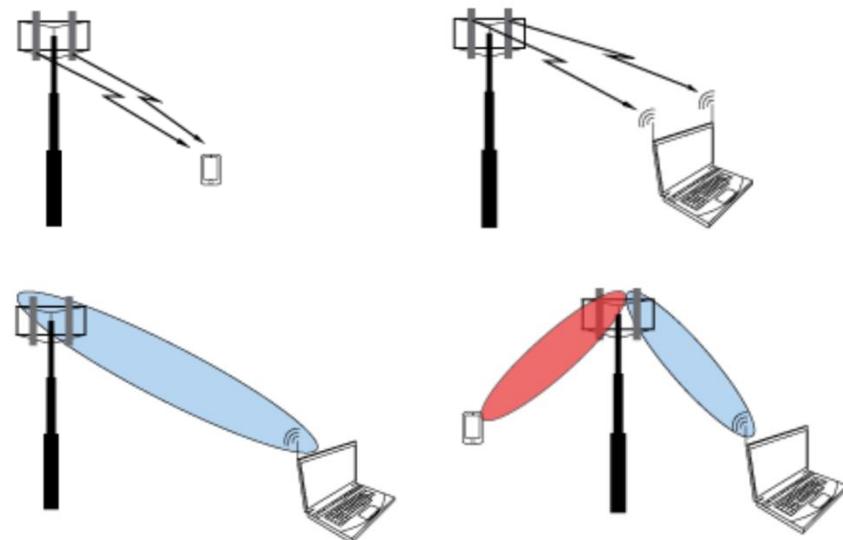
- Types of smart antennas:
- Switched beam
 - Adaptive array

Advanced Cellular Antennas



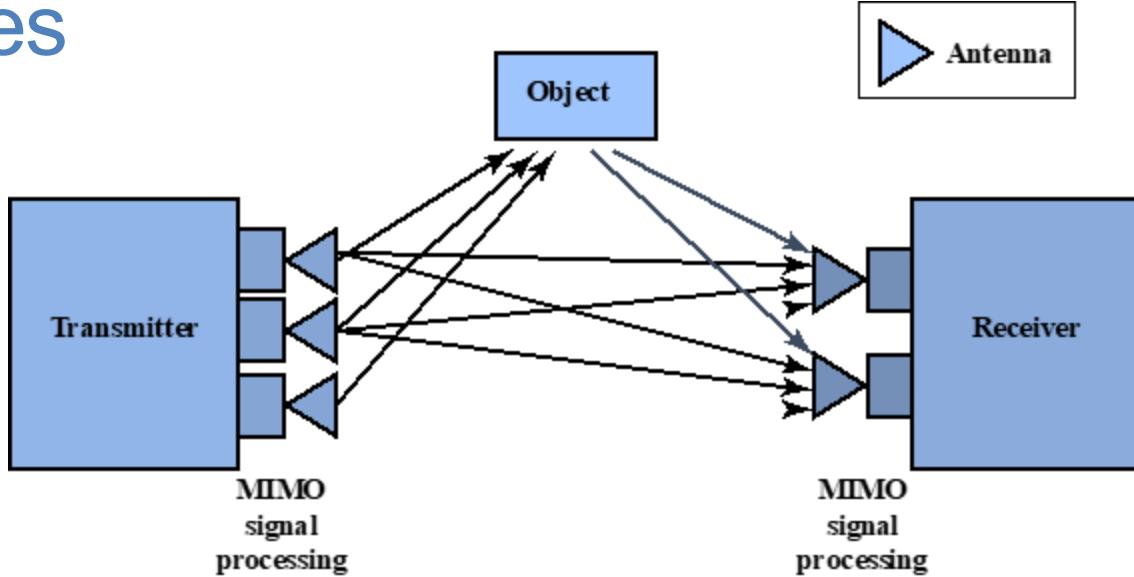
Multiple-Input Multiple-Output (MIMO)

- Transmitter and receiver implement a system with multiple antennas
- Four important uses:
 - Diversity
 - Multiple streams
 - Beamforming
 - Multi-User MIMO (MU-MIMO)



MIMO Principles

- Original data stream divided in n substreams
 - One for each of the n transmitting antennas
 - LOS and multipath signals received by m receiving antennas
- Output signals from the m antennas are combined
- Resulting in a **much better receive signal**
- $n \times m$ MIMO



Types of MIMO transmission schemes:

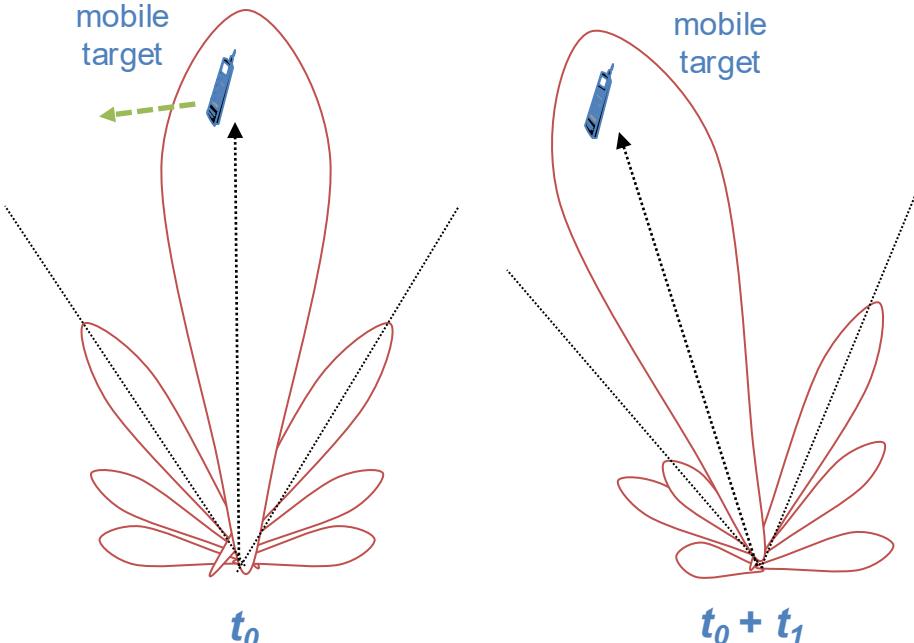
- Spatial diversity:** Same data in each substream
 - Benefit from the different “views”
- Spatial multiplexing:** Different data from the original stream in each substream
 - Profitable in a good channel and short distances

Multi-User MIMO (MU-MIMO)

- Extension to multiple endpoints
- Previous was Single-User MIMO (SU-MIMO)
- Two applications:
 - **Uplink – Multiple Access Channel**: multiple end users transmit to a single base station
 - Better than SU-MIMO, especially if $m \gg n$
 - **Downlink – Broadcast Channel**: a base station transmits different data streams to multiple independent users
 - More challenging

Beamforming

An antenna arrays with smart signal processing algorithms is used to **track** and **locate** the (narrow) antenna beam on the **mobile target**.

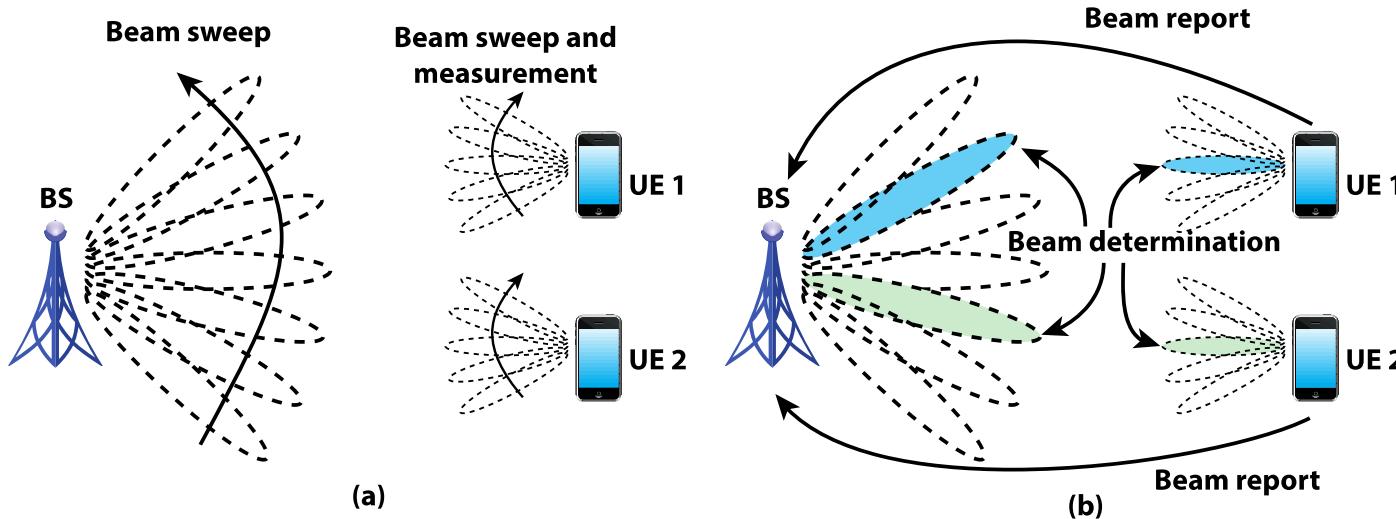


Advantages:

- Higher SNR
 - Directional transmission
- Interference prevention and rejection
 - Spatial properties
- Higher network efficiency
 - Denser deployments

Beam Management

- Important for 5G if working on mmWave

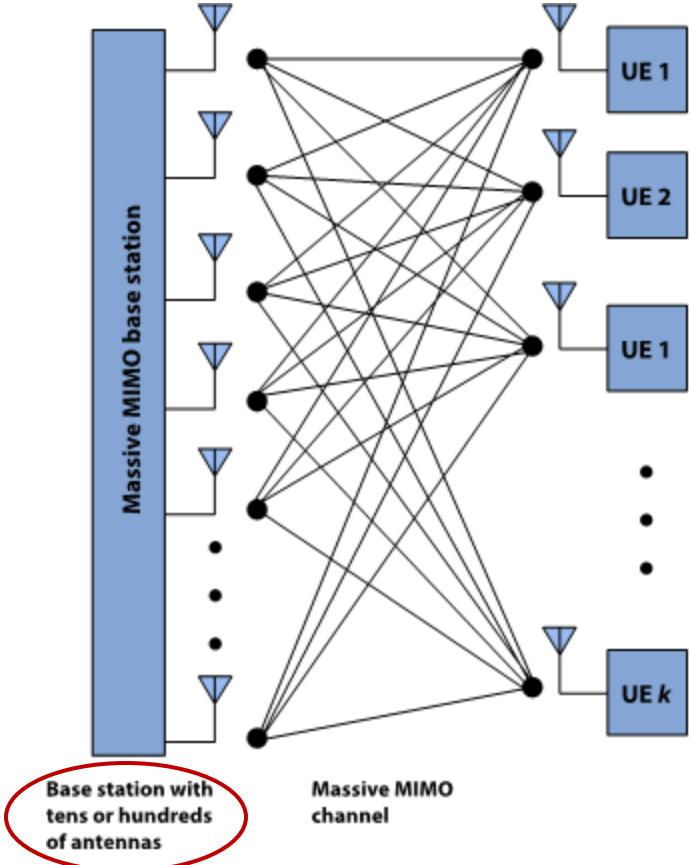


Full-Dimension MIMO (FD-MIMO)

- The antenna system is able to vary the beam in both horizontal (azimuth) and vertical (elevation)
 - Also called 3D-MIMO
 - Enabled by high number of antennas
 - Important in dense urban scenario
 - Indoor deployments in high-rise buildings



Massive MIMO



- Number of User Equipment (UE) is much less than the **number of antennas** in the base station
- UEs may have a single antenna
- The base station's antennas serve simultaneously multiple UEs
- Benefits:
 - Antenna gain
 - Diversity gain
 - Multiplexing gain
- Challenges:
 - Computational complexity
 - Channel estimation: pilot subframe used to determine the channel status information
 - Pilot contamination: interference from pilots in adjacent cells

Benefits and Challenges

Antenna technology	SISO	SU-MIMO	MU-MIMO	mMIMO
Diversity gain	N	P	PP	PPP
Multiplexing gain	N	PP	PPP	PPP
Array gain	N	PP	PP	PPP
mmWave bandwidth	N	N	N	N
Computational complexity	N	NN	NNN	NNNN
Channel estimation challenge	N	NN	NNN	NNNN
Pilot contamination issue	N	NN	NNN	NNNN

N= challenge

P= benefit

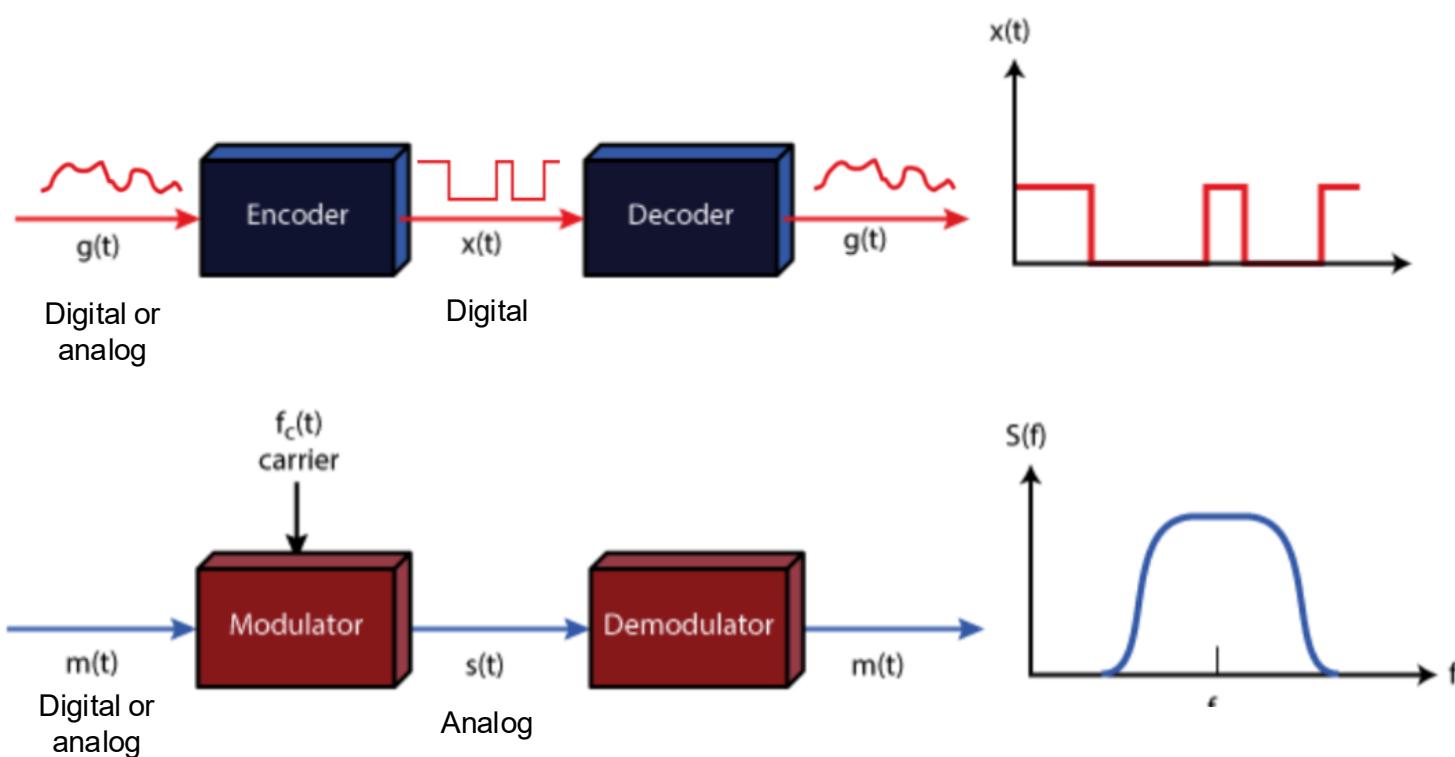
The number of symbols signifies normalized quantity relative to SISO

Encoding and Modulation

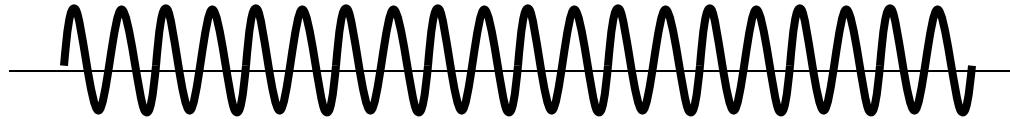
Encoding and Modulation



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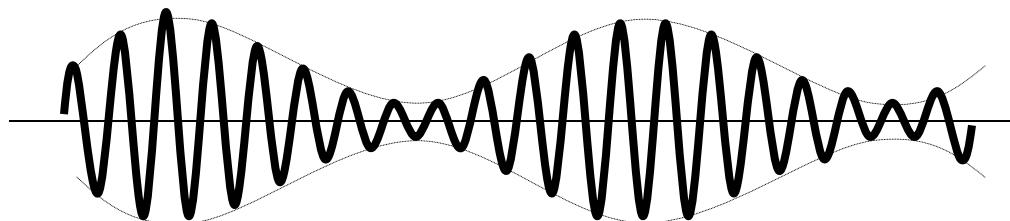
Modulation: Analog Data – Analog Signals



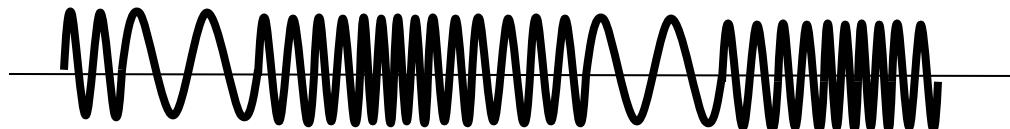
Carrier



Modulating signal

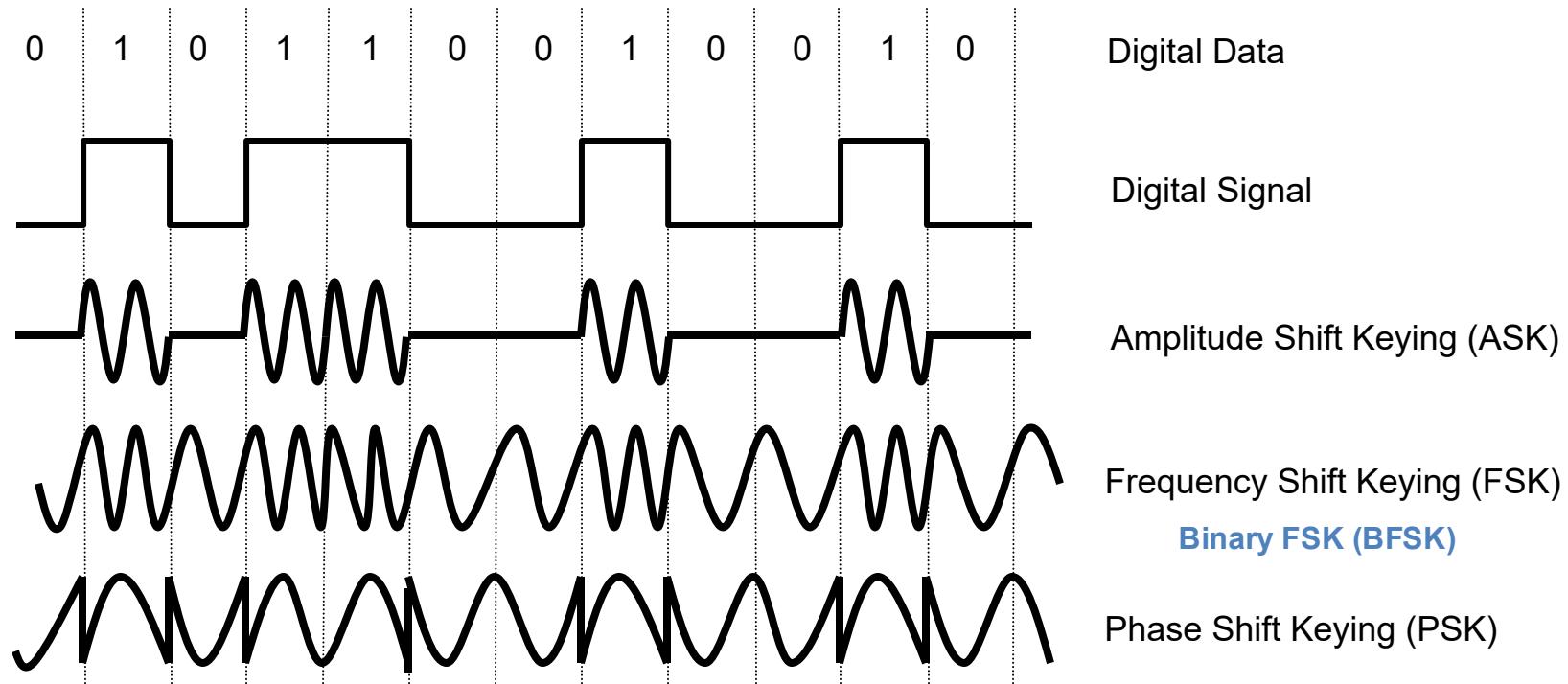


Amplitude Modulation (AM)

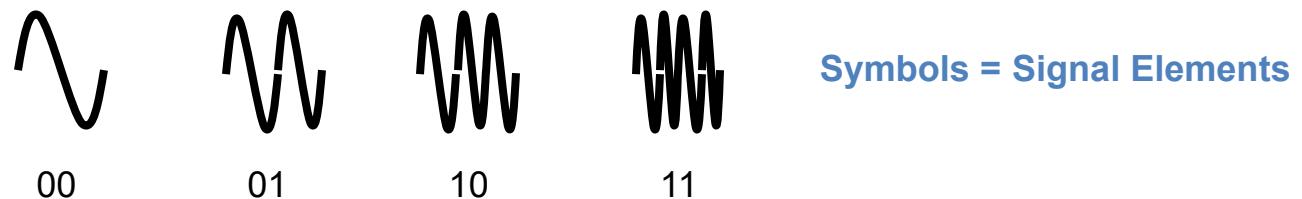
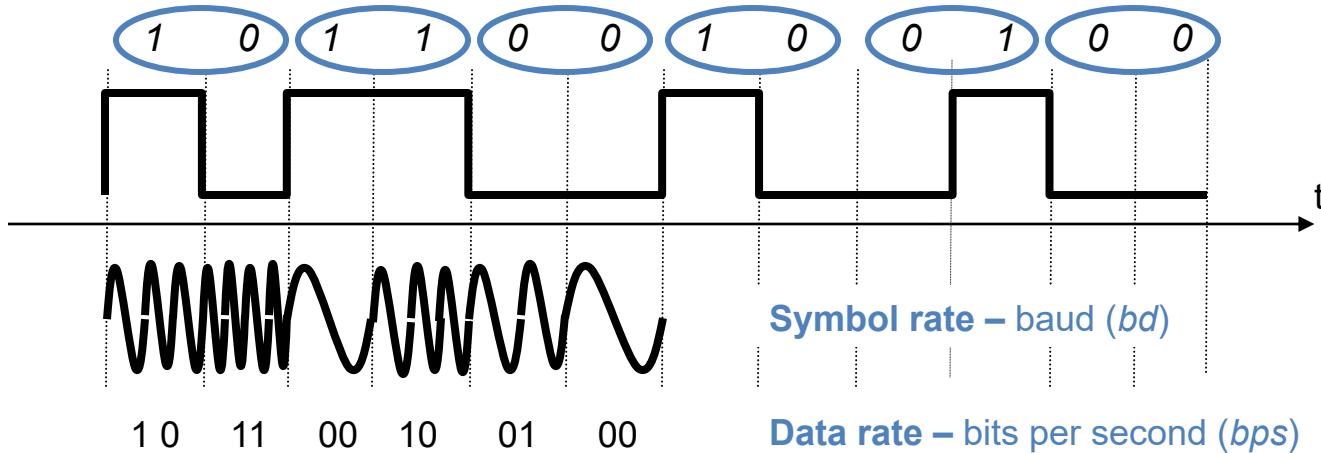


Frequency Modulation (FM)

Modulation: Digital Data – Analog Signals

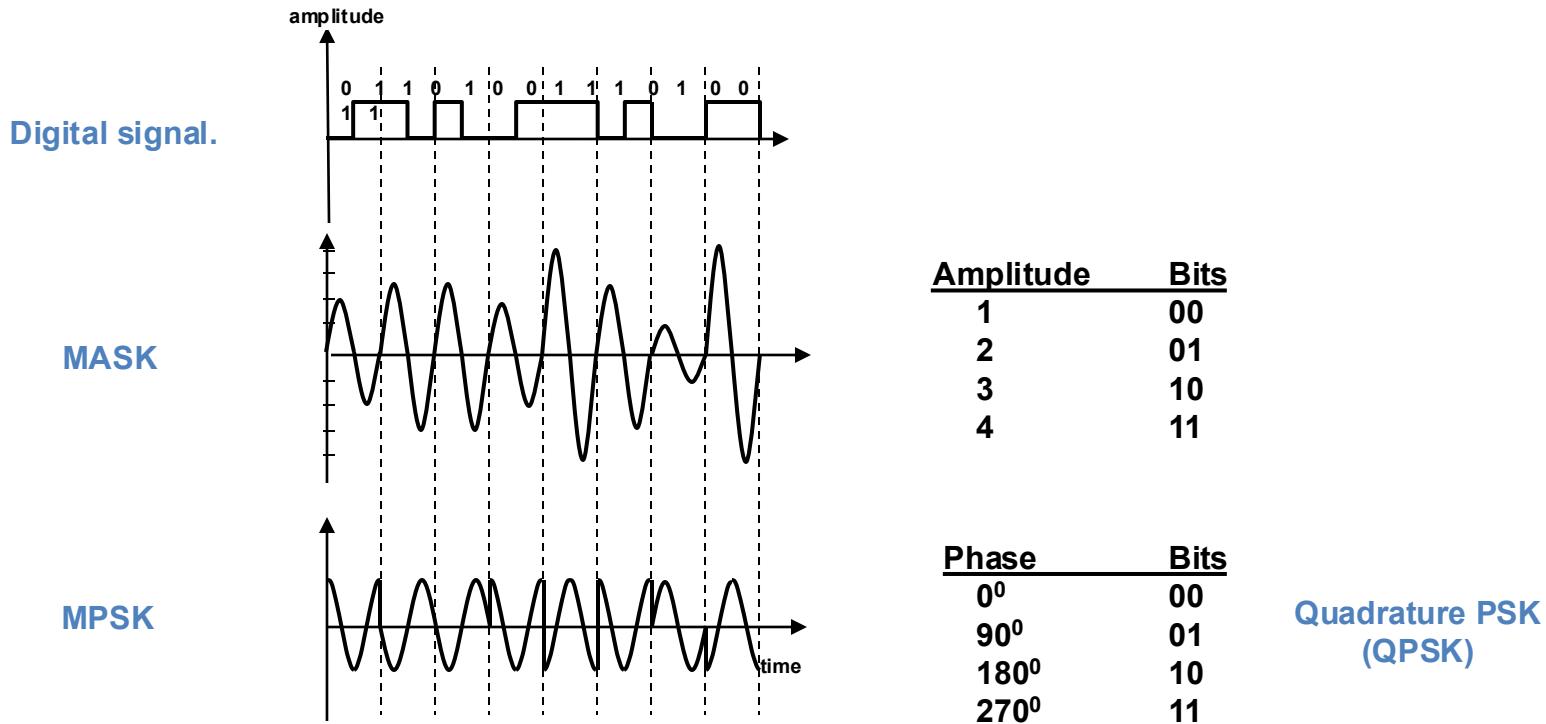


Multilevel Modulation: FSK

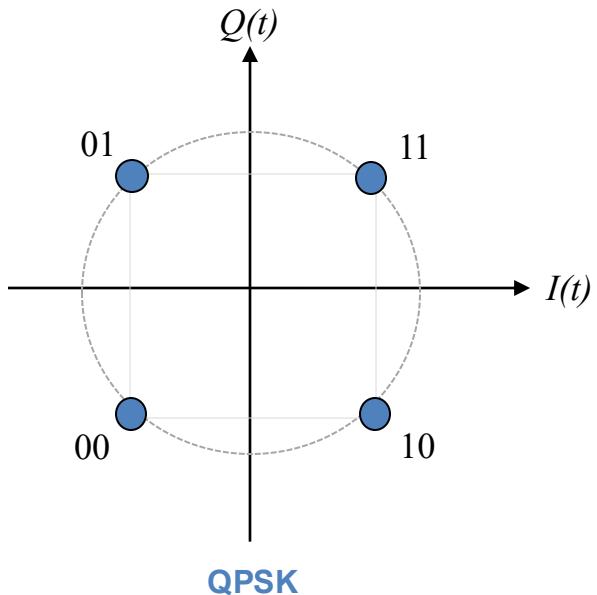


Example: 1 symbol = 2 bits therefore data rate = $2 \times$ symbol rate

Multilevel Modulation: ASK - PSK



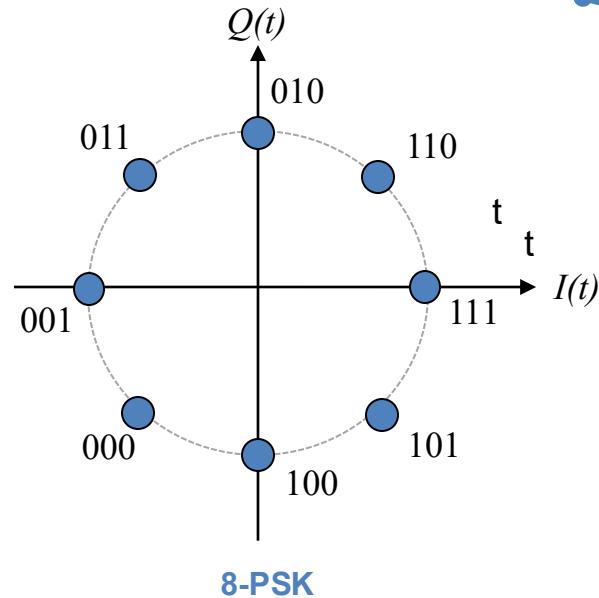
Constellation Diagram



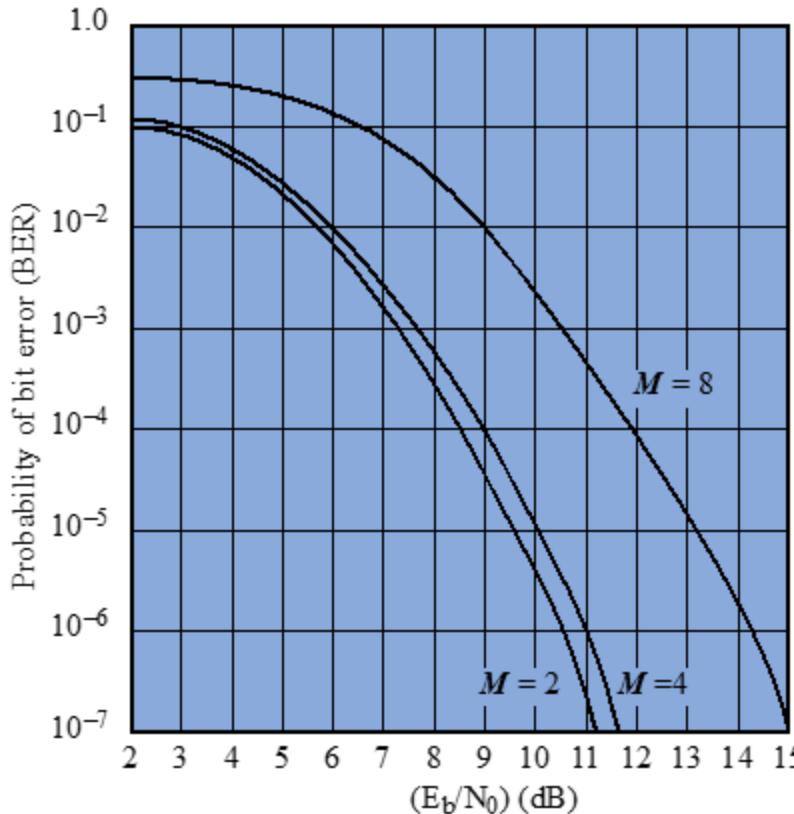
$$s(t) = \frac{1}{\sqrt{2}} I(t) \cos 2\pi f_c t - \frac{1}{\sqrt{2}} Q(t) \sin 2\pi f_c t$$

*In-phase
component*

*Quadrature
component*



Multilevel PSK



Modulation Performance

Bandwidth Efficiency

Ratio of the data rate to transmission bandwidth
 (R/B_t)

Bandwidth Efficiency

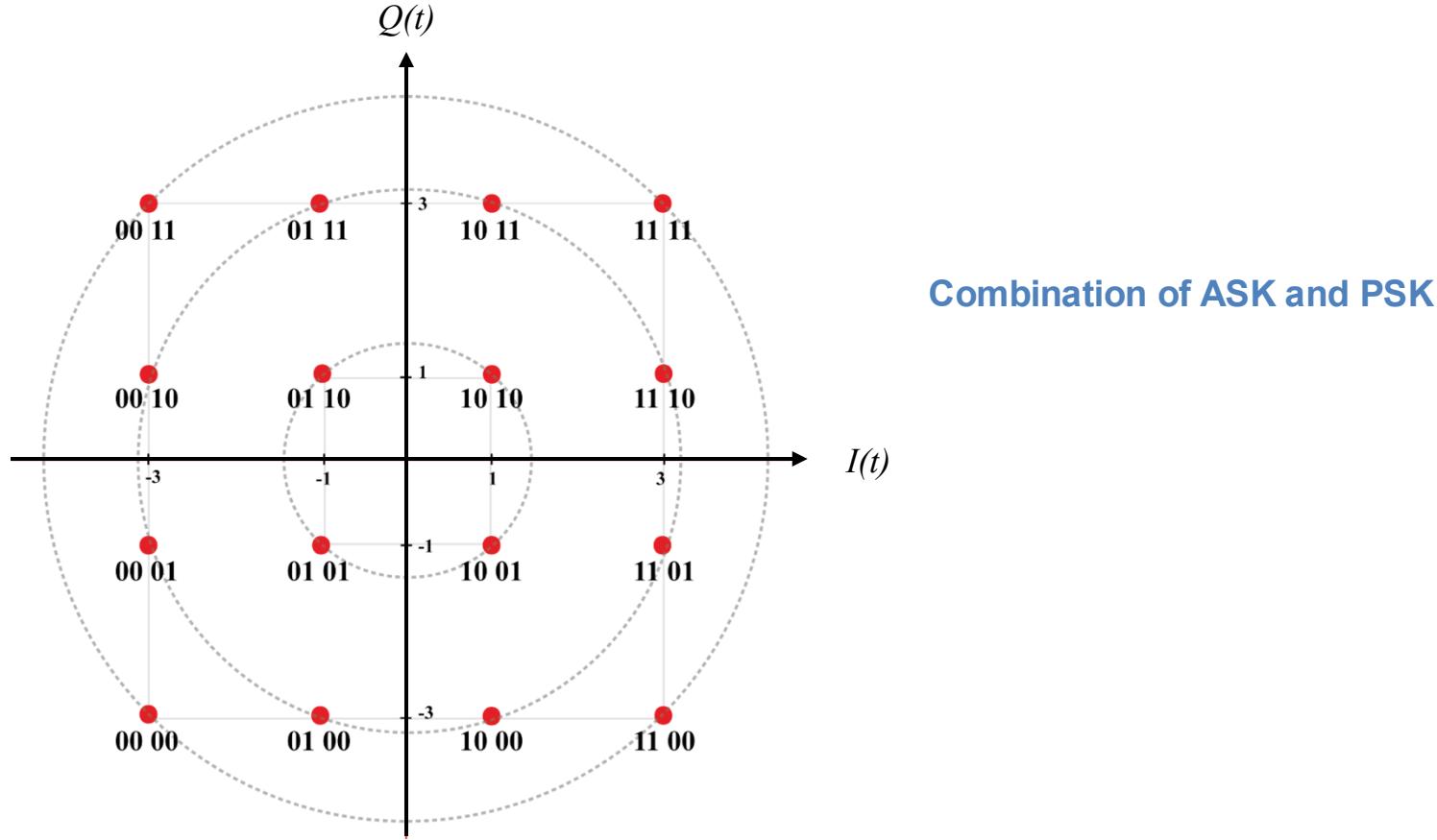
	$r = 0$	$r = 0.5$	$r = 1$
ASK	1.0	0.67	0.5
PSK	1.0	0.67	0.5
Multilevel PSK			
$M = 4, L = 2$	2.00	1.33	1.00
$M = 8, L = 3$	3.00	2.00	1.50
$M = 16, L = 4$	4.00	2.67	2.00
$M = 32, L = 5$	5.00	3.33	2.50

M : number of different symbols

L : number of bits per symbol

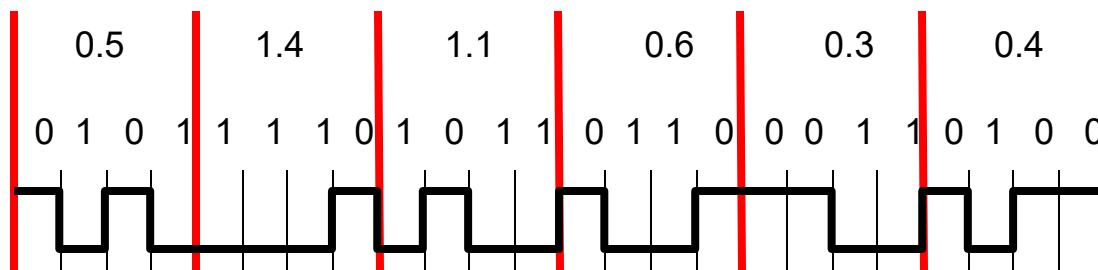
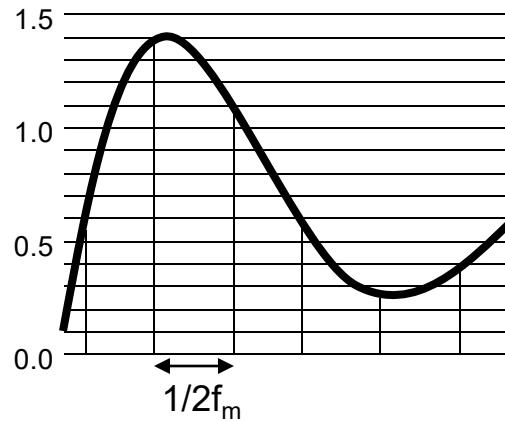
r : depends on the technique to filter the signal

Quadrature Amplitude Modulation (QAM)



Encoding: Analog Data – Digital Signals

Pulse Code Modulation (PCM)



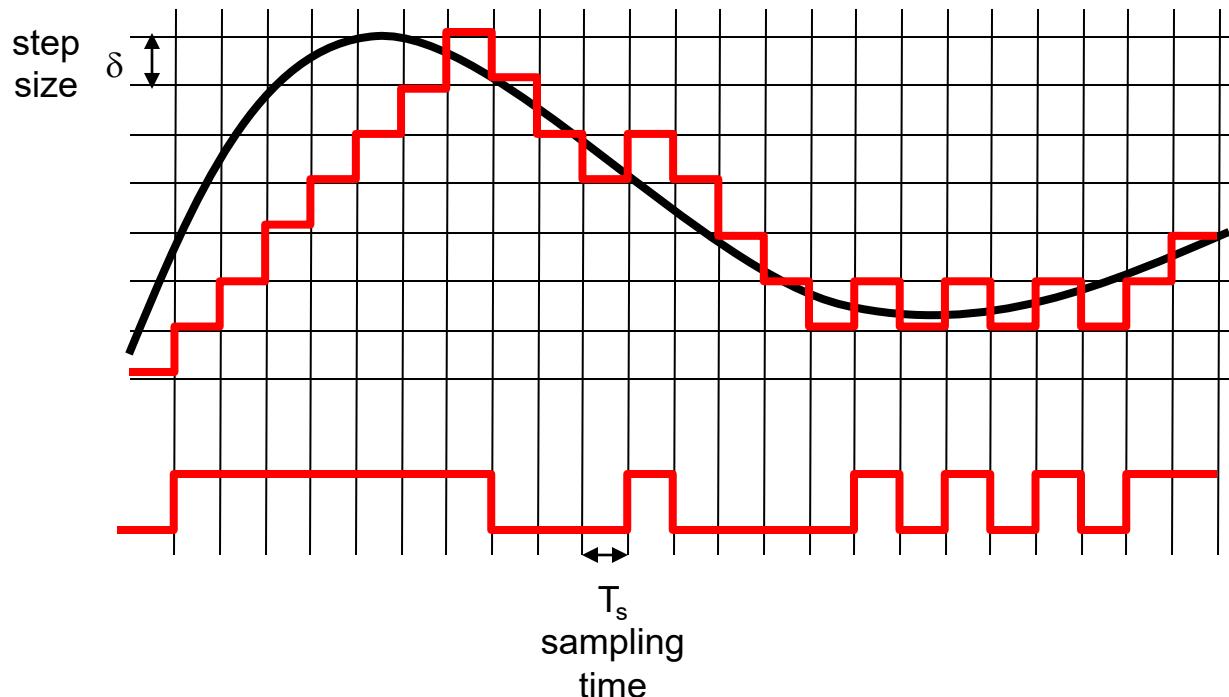
Sampling Theorem

If a signal is sampled at regular intervals of time and at a rate higher than **twice the highest signal frequency**, than the samples contain all the information of the original signal.

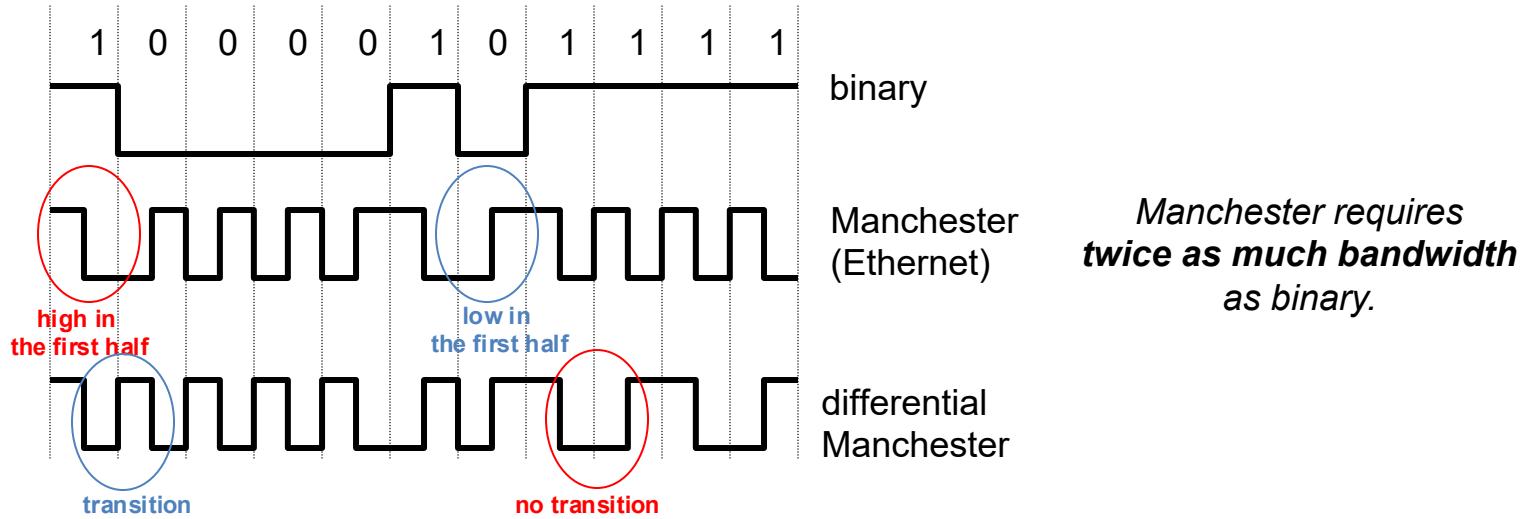
Encoding: Analog Data – Digital Signals

Delta Modulation

*Staircase-function
approximation*



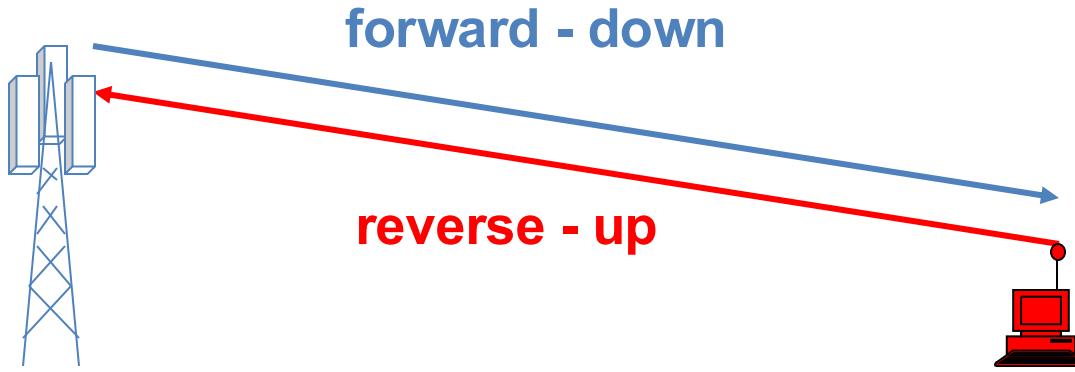
Encoding: Digital Data – Digital Signals



If one station sends 0001000, the others may interpret it as 1000000 or 0100000 because they cannot tell the difference between an idle sender (0 Volts) and a 0 bit (0 Volts).

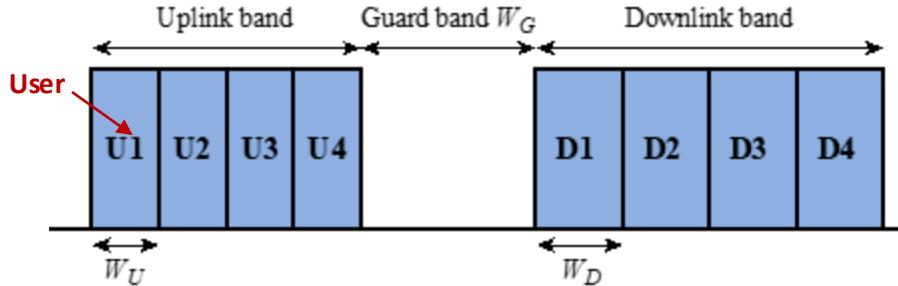
Duplexing

Duplexing



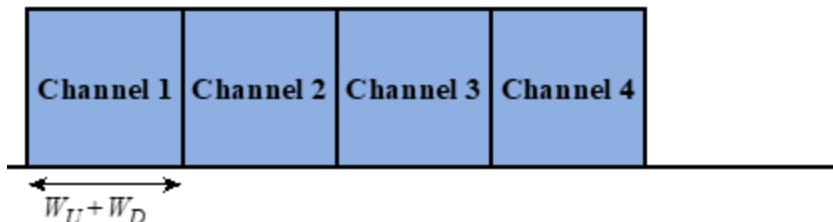
- Time Division Duplexing (TDD)
- Frequency Division Duplexing (FDD)

Spectrum Allocation



FDD

- Different frequency bands for uplink and downlink transmissions
- Two blocks of contiguous channels (**paired spectrum**) separated by a **guard band**



TDD

- **Same band** but different time domain
- More **flexible**

Characteristics

Defined for LTE-A

PARAMETER	LTE-TDD	LTE-FDD
Paired spectrum	Does not require paired spectrum as both transmit and receive occur on the same channel.	Requires paired spectrum with sufficient frequency separation to allow simultaneous transmission and reception.
Hardware cost	Lower cost as no diplexer is needed to isolate the transmitter and receiver. As cost of the UEs is of major importance because of the vast numbers that are produced, this is a key aspect.	Diplexer is needed and cost is higher.
Channel reciprocity	Channel propagation is the same in both directions which enables transmit and receive to use one set of parameters.	Channel characteristics are different in the two directions as a result of the use of different frequencies.
UL / DL asymmetry	It is possible to dynamically change the UL and DL capacity ratio to match demand.	UL / DL capacity is determined by frequency allocation set out by the regulatory authorities. It is therefore not possible to make dynamic changes to match capacity. Regulatory changes would normally be required and capacity is normally allocated so that it is the same in either direction.
Guard period / guard band	Guard period required to ensure uplink and downlink transmissions do not clash. Large guard period will limit capacity. Larger guard period normally required if distances are increased to accommodate larger propagation times.	Guard band required to provide sufficient isolation between uplink and downlink. Large guard band does not impact capacity.
Discontinuous transmission	Discontinuous transmission is required to allow both uplink and downlink transmissions. This can degrade the performance of the RF power amplifier in the transmitter. Base stations need to be synchronized with respect to the uplink and downlink transmission times. If neighboring base stations use different uplink and downlink assignments and share the same channel, then interference may occur between cells.	Continuous transmission is required.
Cross slot interference		Not applicable

Why are they both needed?

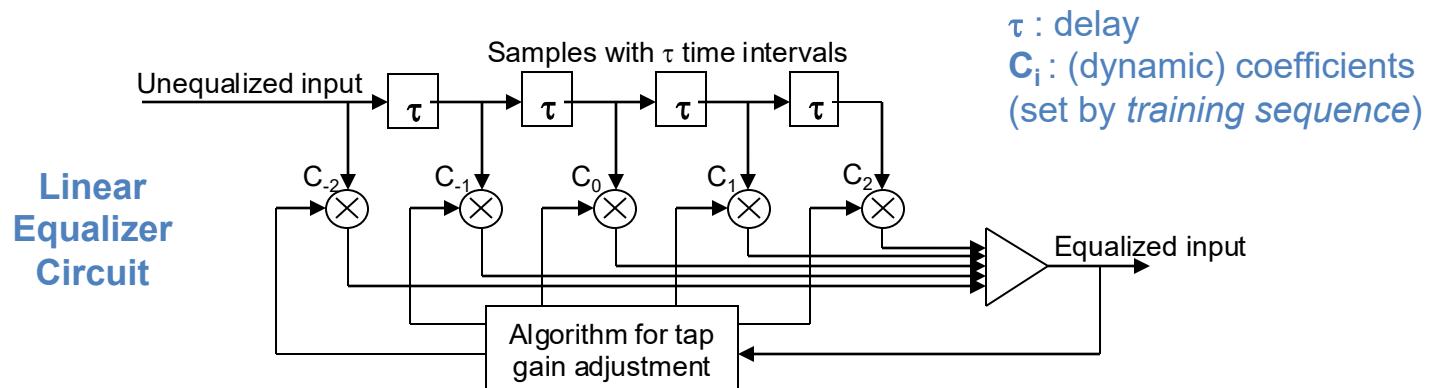
Feature	5G FDD	5G TDD
Application	FDD is used where uplink and downlink are symmetrical	TDD is used where uplink and downlink is asymmetrical.
Interference with neighboring Base Stations	Less	More
Deployment type	Best for rural and suburban areas.	Best for urban areas with low-power nodes.
Beamforming	Explicit Beamforming Only	Explicit Beamforming Only
Frequency bands	Low frequency bands below 10 GHz	High frequency bands above 10 GHz.
Channel response	Downlink and uplink uses different channels, so they can't match perfectly.	Using one channel means that downlink and uplink match perfectly, making it better for MIMO and beamforming .

Source: <https://www.signalboosters.com/blog/fdd-vs-tdd-explained-/>

Channel Correction Mechanisms

Channel Correction Mechanisms

- Forward Error Correction Receiver corrects bit errors in the data
- Adaptive Equalization For combating ISI



Channel Correction Mechanisms

- Adaptive Modulation and Coding (AMC)

Example: switch between QPSK and 16QAM depending on the channel condition

- Diversity Provide multiple logical channels to exploit the fact that individual channels experience independent fading events.

- Space diversity
- Frequency diversity
- Time diversity

Outline

- Signal Propagation 2.1, 2.3, 2.4, 5.1-5.3, 6.2-6.4 11.1-11.4
- Antenna 5.1, 5.2, 6.1 12.2-12.4
- Encoding and Modulation 5.5, 7.1-7.4 13.1
- Duplexing 2.5 1.6, 12.4
- Channel Correction Mechanisms 5.4, 6.5 12.1