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Agenda

1. Introduction to Satellite Communications

2. Link Budget Analysis

3. Future Evolutions

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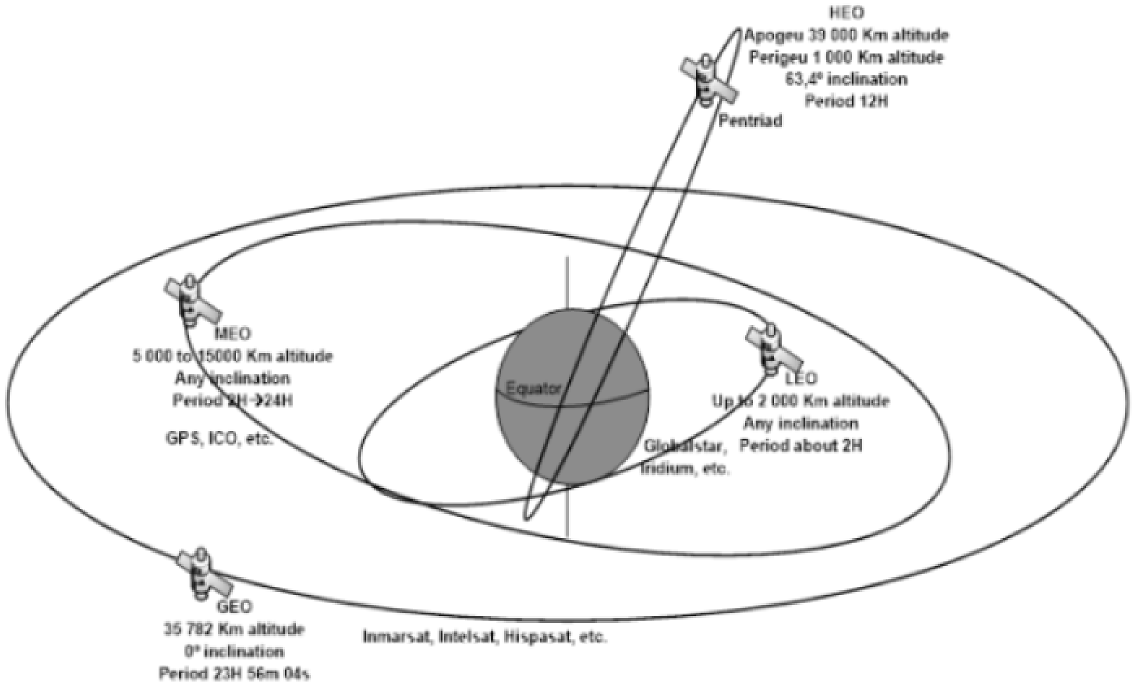
1. **Introduction to Satellite Communications**
2. Link Budget Analysis
3. Future Evolutions

Satellite Communication Systems

- One of the most important advantages of a satellite relies on its wide coverage that translates in service availability in remote areas.
- Satellites can be used for broadcast of radio or television channels, communications, imagery, or meteo.
- The Moon was the first satellite communications.
- A satellite communication has one or several transponders, each one operating in a different frequency band.
  - A transponder consists of a receiver, followed by a frequency translator, an amplifier, and a transmitter.
  - The frequency translator is necessary because the uplink and downlink frequencies are different.
- Depending on the orbit altitude and attitude, there are different orbits: GEO, MEO, LEO and HEO.



Physical Analysis of Satellite Orbits

$$f_a = G\frac{m_E \cdot m_{SAT}}{d^2}$$

$$f_C = m_{SAT} \cdot \frac{v_{SAT}^2}{r_{SAT}}$$

$$G\frac{m_E \cdot m_{SAT}}{r_{SAT}^2} = m_{SAT} \cdot \omega_{SAT}^2 \cdot r_{SAT}$$

$$\omega_{SAT} = 2\pi / T_{SAT} \longrightarrow T_{SAT}^2 = \frac{4\pi^2}{G \cdot m_E} r_{SAT}^3$$

$$r_{SAT(km)} = 5076 \cdot T_{SAT\_(hour)}^{2/3}$$

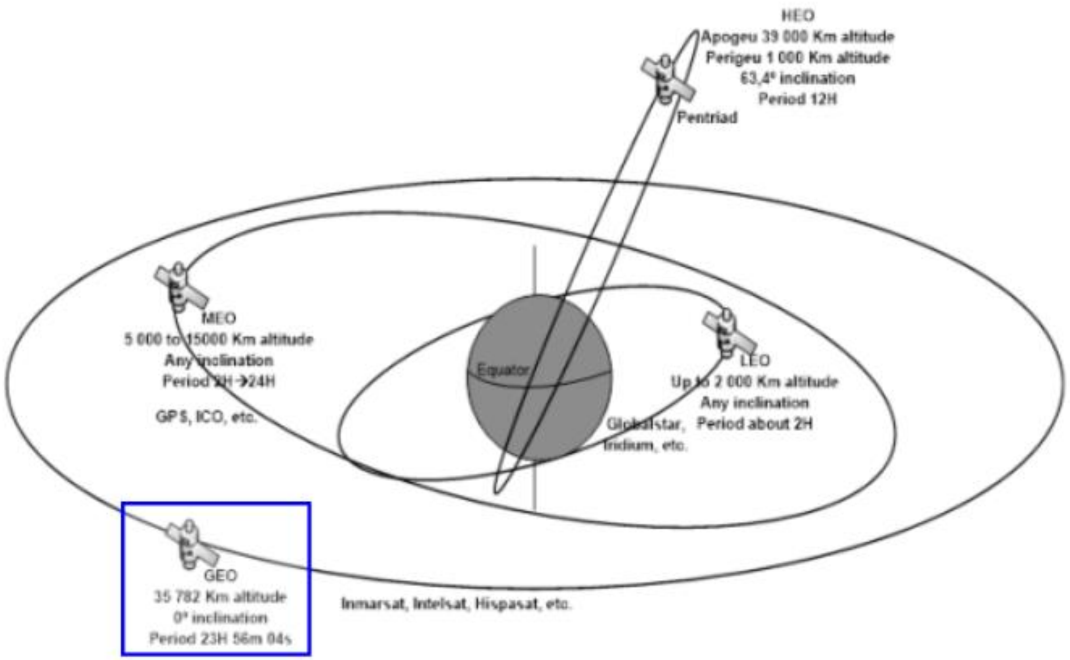
$$h_{SAT(km)} = r_{SAT(km)} - r_E = 5076 \cdot T_{SAT\_(hour)}^{2/3} - 6373$$

Orbit period as a function of orbit altitudes and radius

Altitude [km]	Orbit radius [km]	Orbit Period [hour]
0 (earth's surface)	6373	1.4068
300	6673	1.5073
2000	8373	2.1186
5000	11373	3.35
35782	42155	23.9327

GEO Orbits

- Satellite communications can be viewed as a type of cellular communications, whose coverage is much higher (due to higher altitude of the satellite).
- The GEO altitude is typically 35,782 km above the equator and, since it is geostationary, its period equals the earth rotation period (its position relative to any point in the earth is kept stationary).
  - Advantage: it covers approx. 1/3 of the earth surface.
  - Disadvantages:
    - High latency (approx. 240 ms for one hop).
    - High path loss. Typically requires a parabolic antenna at the mobile side.
    - The transponder bandwidth (typical of 72 Mbps) is split into a high amount of potential users (leaving low bandwith available to each user).



MEO and LEO Orbits

- Placed at lower altitudes, the MEO and LEO orbits overcame many of the limitations experienced by GEO.
  - LEO Orbits: 300 - 2,000 km (period around 2 hours).
  - MEO Orbits: 5,000 - 15,000 km (period around 4 hours).
- MEO and LEO orbits are not stationary.
- LEO and MEO orbits can be of any type: above the equator, above a meridian, or with any inclination.
- Requires more satellites to allow adequate area coverage.
- Facilitates advanced satellite systems: direct connection between different satellite's transponders, on board switching and routing, or advanced antenna systems.
- Advantages of MEO & LEO: can operate with low power levels and reduced antenna gains; low delays.
- Disadvantages of MEO & LEO: high doppler effect; frequent handovers; complex management of high number of satellites.

Advantages and disadvantages of different orbits

	ADVANTAGES	DISADVANTAGES
LEO	1. Can operate with low power levels and reduced antenna gains 2. Reduced delays	1. Complex control of satellites 2. Frequent handovers 3. High Doppler effect 4. High number of satellites
MEO	1. Acceptable propagation delay and link budget, but worse than in the LEO case	
GEO	1. Reduced number of satellites and, consequently, simplest solution 2. No need for handover	1. Requires high antenna gains and powers to overcome increased path loss 2. Difficult to operate with Handheld terminals 3. High delays (240 ms) 4. Reduced minimum elevation angles for high latitudes that translates in high fading effects
HEO	1. High minimum elevation angles even for high latitudes 2. Enables coverage of very specific regions	1. Requires high antenna gains and powers to overcome increased path loss 2. Extremely high delays, except in the perigee

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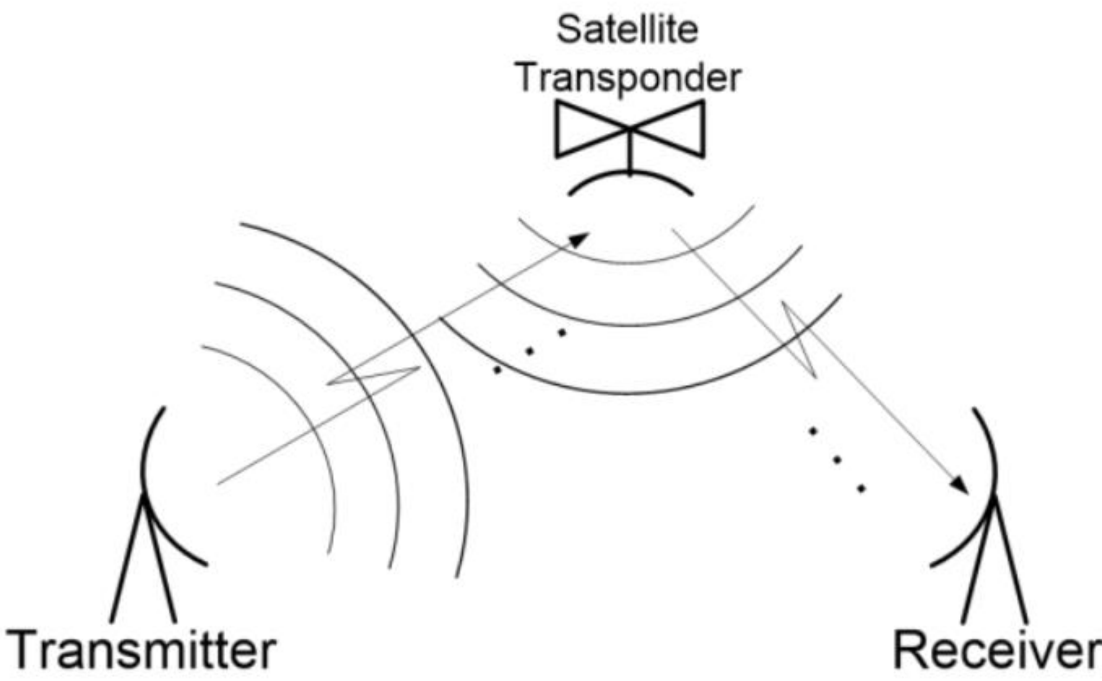
Satellite C/N Analysis

- Higher frequencies correspond to higher path attenuation levels, which may bring link budget limitations, but present higher bandwidths (higher throughputs).
- As per the Shannon capacity equation, a higher SNR allows transmitting at higher data rates.
- Frequency bands used in Satellite communications:
  - C band: uplink - 6 GHz band; downlink - 4 GHz band.
  - Since C band is saturated, Ku band is being used (higher bandwidth): uplink - 14 GHz; downlink -12 GHz.
- Uplink use higher frequencies because the higher uplink path loss and higher satellite receiver's noise (pointed towards the earth) is mitigated by the higher TX power in the uplink.
- A satellite link is typically modelled by a Rice distribution.
  - At high latitudes, as the satellite's inclination decreases, the strength of reflected waves become more predominant, and the resulting signal is more subject to fading.



Generic diagram of a Point-to-Point Satellite Communication System

Satellite C/N Analysis

$$P_{E\_D} = P_{R\_U} \cdot g_{SAT}$$

$$P_{R\_D} = P_{R\_U} \cdot g_{SAT} \cdot A_{tt\_D}$$
$$= P_{E\_D} \cdot A_{tt\_D}$$

$$N_{TOTAL} = N_U \cdot f_{SAT} \cdot g_{SAT} \cdot A_{tt\_D} + N_D$$

$$(C/N)_{TOTAL} = \frac{P_{R\_D}}{N_{TOTAL}} \qquad (C/N)_{TOTAL}^{-1} = 1/(C/N)_{TOTAL}$$

$$(C/N)_{TOTAL}^{-1} = \frac{N_{TOTAL}}{P_{R\_D}}$$
$$= \frac{N_U \cdot f_{SAT} \cdot g_{SAT} \cdot A_{tt\_D} + N_D}{P_{R\_U} \cdot g_{SAT} \cdot A_{tt\_D}}$$
$$= \frac{N_U \cdot f_{SAT}}{P_{R\_U}} + \frac{N_D}{P_{R\_D}}$$
$$= \frac{f_{SAT}}{(C/N)_U} + \frac{1}{(C/N)_D}$$
$$= \frac{f_{SAT}}{(C/N)_U} + \frac{f_{SAT}}{f_{SAT} \cdot (C/N)_D}$$

$$(C/N)_{TOTAL} = \frac{(C/N)_U + f_{SAT} \cdot (C/N)_D}{f_{SAT}}$$

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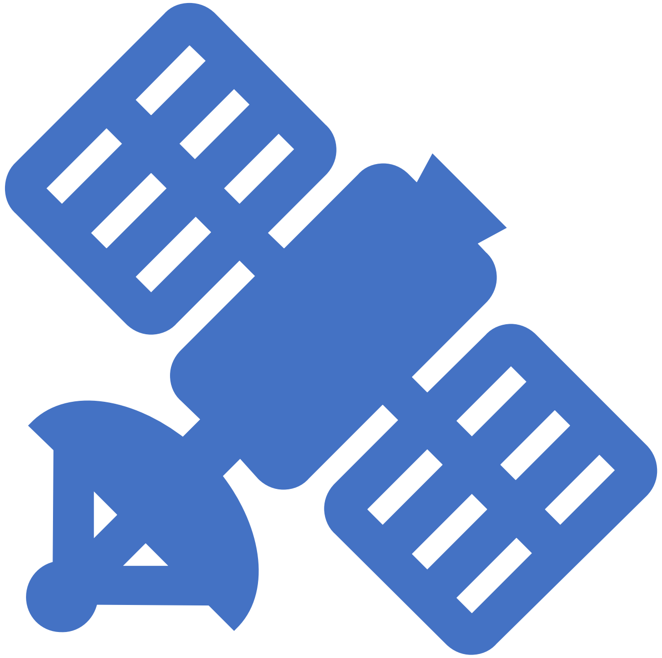
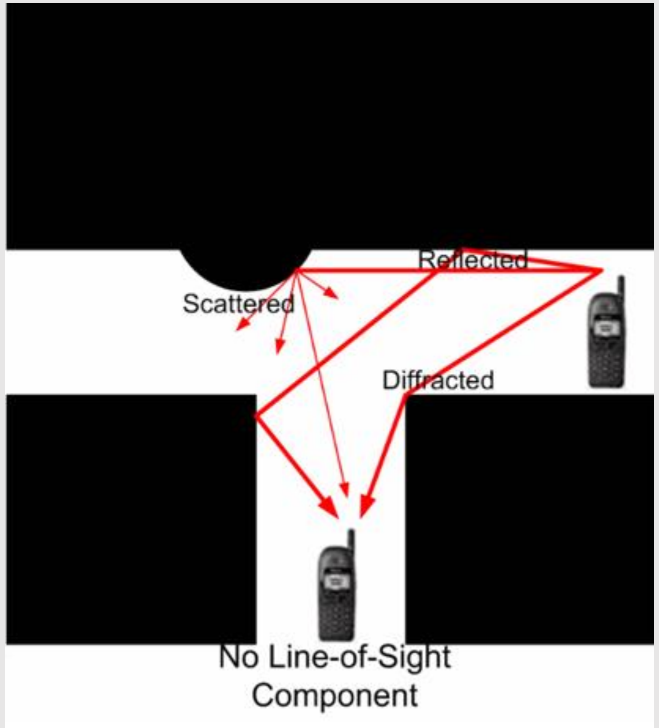
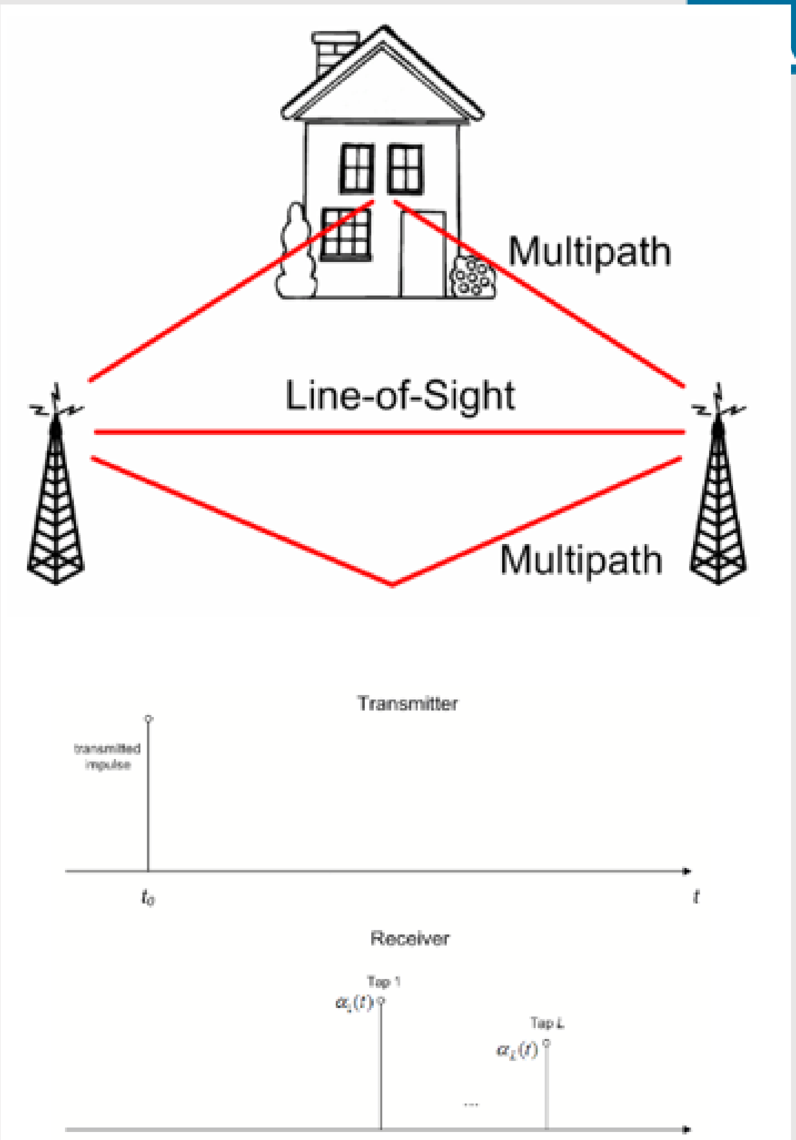


- 5G Communications can be extended through satellite communications for the following reasons:
  - Cover areas without Base Stations
  - Cover Gaps
  - Backup





- **Higher Signal Bandwidth corresponds to higher Intersymbol Interference**
- **This is not only a matter of Spectrum**

3. Future Evolutions

mm-Wave and Massive MIMO

(Large Capacity Gains)

mm-Wave communications (30-300GHz - EHF) are crucial part of 5G systems due to their **increased channel coherence bandwidth**, as compared to centimeter Wave. These systems use carrier frequencies of 30 - 70 GHz, where we have large unoccupied bandwidth. – E.g.: IEEE802.11ad uses 2.16 GHz of BW in **60 GHz band** (ISM band), supporting up to 7 Gbps.

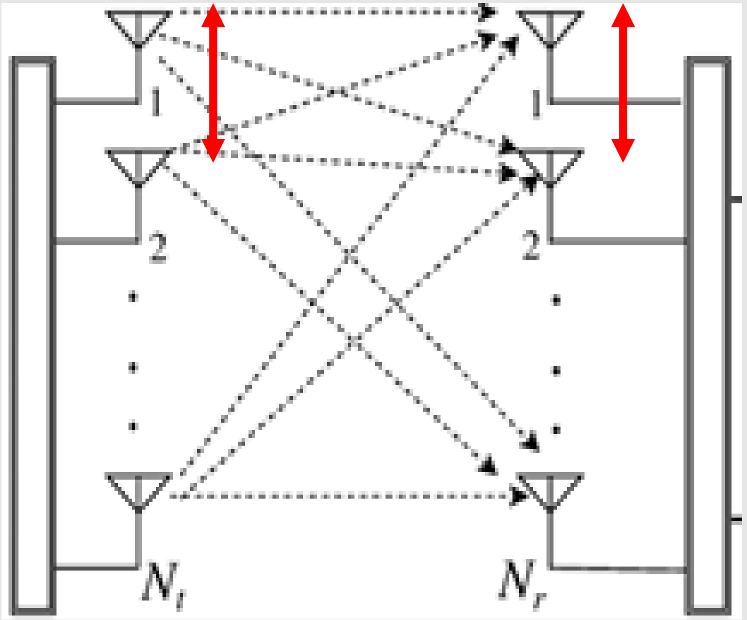
The **distance between antennas is reduced**, facilitating a higher number of antenna elements (Massive MIMO).

Moreover, antennas size are also reduced.

However, mm-Wave suffers from high path loss and rain and oxygen absorption.

Moreover, **higher frequencies present higher propagation path losses.**

This can be overcome with m-MIMO techniques, such as beamforming.



$$c = \lambda \cdot f$$

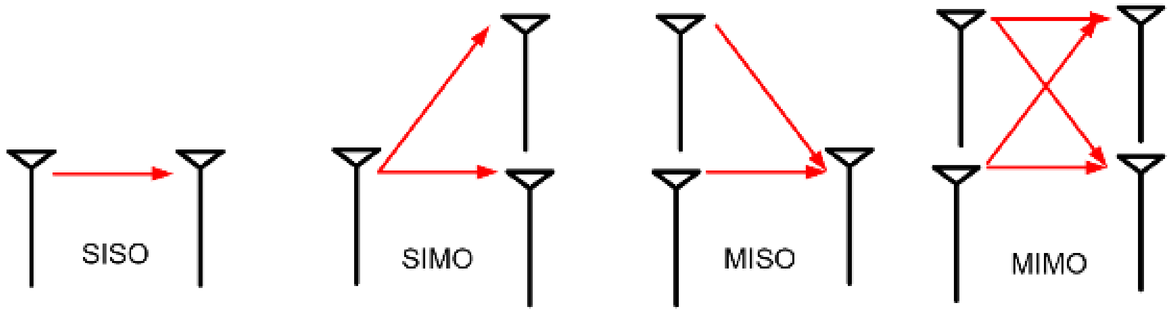
$$\lambda = c / f$$

$$with \ f = 60\ GHz$$

$$\lambda = \frac{3 \times 10^8}{60 \times 10^9} = \frac{1}{200} = 0,005\ m = 5\ mm$$

MIMO Systems

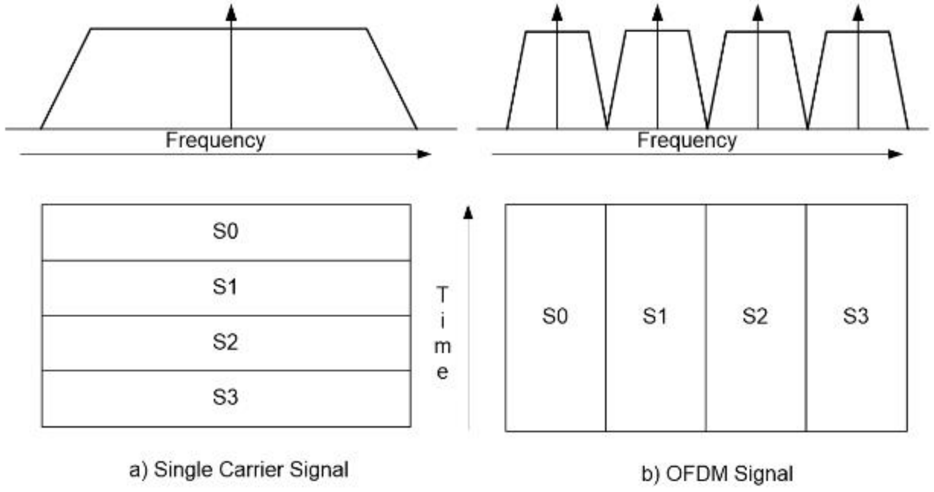
- The basic concept behind Multiple Input Multiple Output (MIMO) techniques relies on exploiting the multiple propagation paths of signals between multiple transmit (Input) and multiple receive (Output) antennas.
- In the case of frequency selective fading channel, different symbols suffer interference from each other, whose effect is usually known as Intersymbol Interference (ISI). This effect tends to increase with the increase of the symbol rate. MIMO systems can be employed to mitigate ISI. The antenna spacing must be larger than the coherence distance to ensure independent fading across different antennas.
- The various configurations are referred to as Single Input Single Output (SISO), Multiple Input Single Output (MISO), Single Input Multiple Output (SIMO) or Multiple Input Multiple Output (MIMO).
- MIMO architectures can be used for combined transmit and receive diversity (performance improvement), as well as for the parallel transmission of data or spatial multiplexing.
- MIMO schemes are implemented based on multiple-antenna techniques, which can be of different forms:
  - Space-time block coding
  - Multi-layer transmission
  - Space division multiple access
  - Beamforming



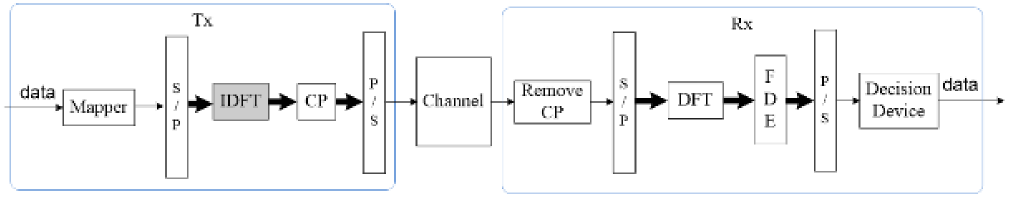
Multiple Antennas Configurations

OFDM

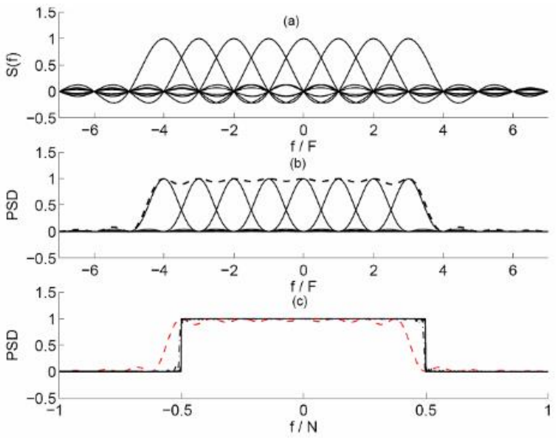
- Orthogonal Frequency Division Multiplexing (OFDM) is a transmission technique adopted by many high data rate communication systems such as IEEE 802.11n and IEEE 802.16e, being suitable for frequency selective fading channels.
- OFDM technique splits the symbols into several lower rate streams, which are then transmitted in orthogonal parallel sub-carriers. As a consequence, the symbol period is increased, making the signal less sensitive to ISI. To avoid interference between sub-carriers, the several streams are transmitted in orthogonal sub-carriers.
- To further improve the capabilities to combat ISI, it is added a cyclic prefix to each sub-stream, being removed at the receiver side, and each stream is independently subject to equalization.
- OFDM signals are commonly generated by computing the N-point IFFT, where the input of the IFFT is the frequency domain representation of OFDM signal. The output of the IFFT is the time domain representation of the OFDM signal, the N-point IFFT out is defined as a useful OFDM symbol. This "time domain" OFDM signal is composed of N sub-carriers.



Spectrum of a) Single Carrier signal versus b) OFDM signal



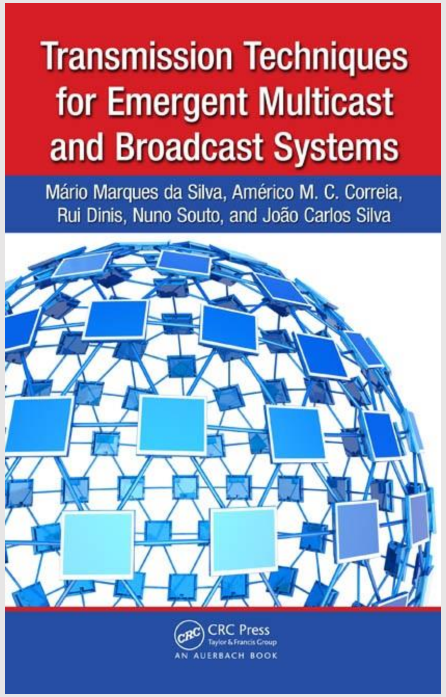
Generic transmission chain for OFDM



Transmitted OFDM signal: (a) individual sub-carriers; (b) PSD of sub-carriers and envelope; (c) PSD of envelope signal

3. Future Evolutions

- Future Evolutions:
  - LEO and MEO Orbits (ex: Starlink)
  - EHF Bands (mm-Wave Comms)
  - MIMO Systems
  - OFDM
  - On-Board Switching and Routing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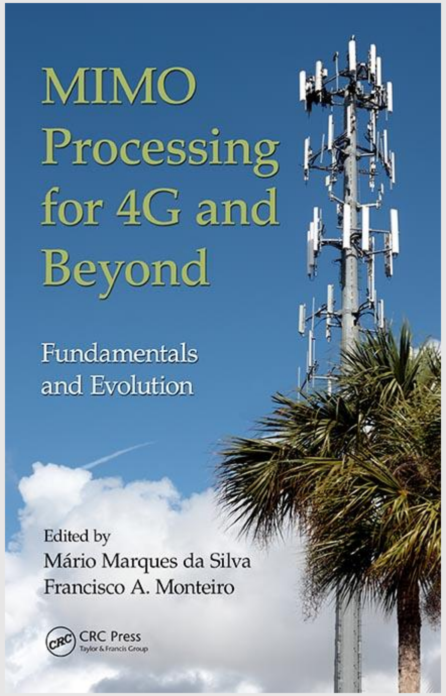
MIMO Processing for 4G and Beyond
Fundamentals and Evolution
Edited by
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Francisco A. Monteiro
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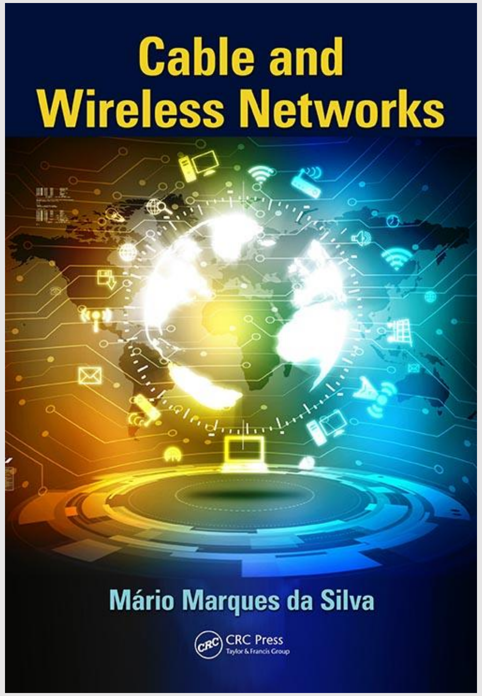
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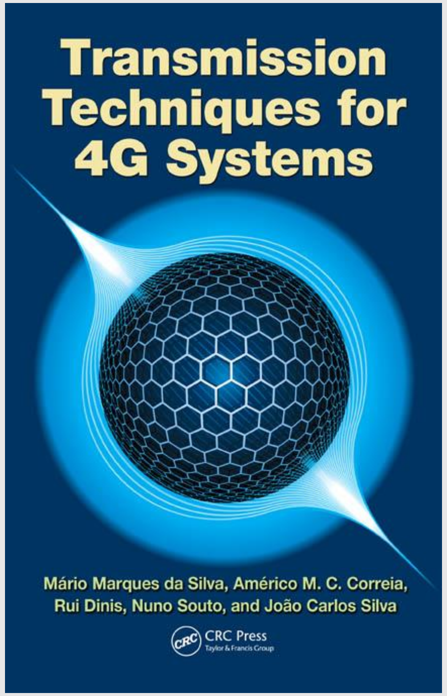
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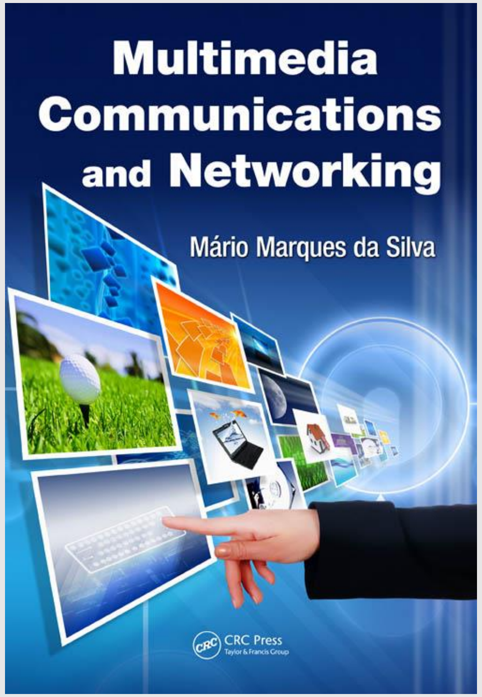
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