Universidad del País Vasco Euskal Herriko Unibertsitatea

Bsc Degree on Telecommunication 2023-2024

Dpt. Communication Engineering

Bilbao Faculty of Engineering

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2. Applications
3. Technological Evolution
4. Frequency Bands
5. Mobile Coverage Calculations

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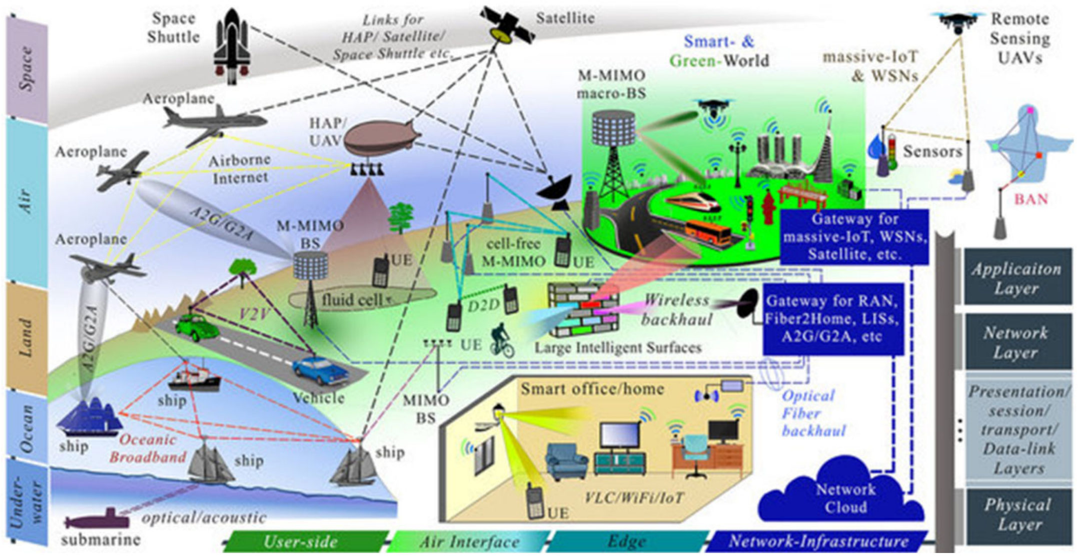
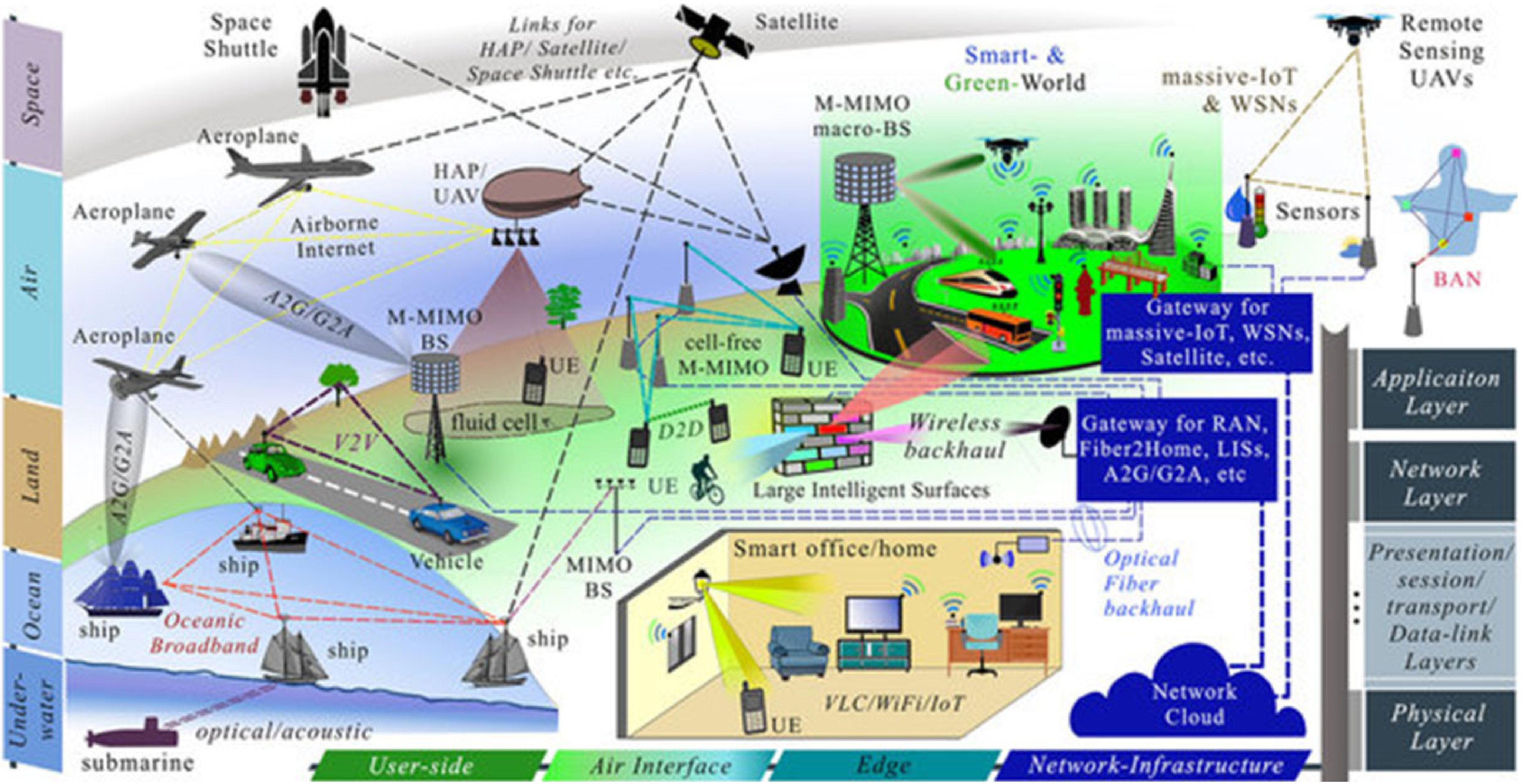
Basics

Definitions - ITU Radio Regulations – Article 1:

- Mobile service: A radio-communication service between mobile and land stations, or between mobile stations
- Mobile-satellite service: A radio-communication service
  - between mobile earth stations and one or more space stations, or between space stations used by this service; or
  - between mobile earth stations by means of one or more space stations. This service may also include feeder links necessary for its operation.



- **Land mobile service: A mobile service between base stations and land mobile stations, or between land mobile stations.**
- Maritime mobile service: A mobile service between coast stations and ship stations, or between ship stations.
- Aeronautical mobile service: A mobile service between aeronautical stations and aircraft stations, or between aircraft stations



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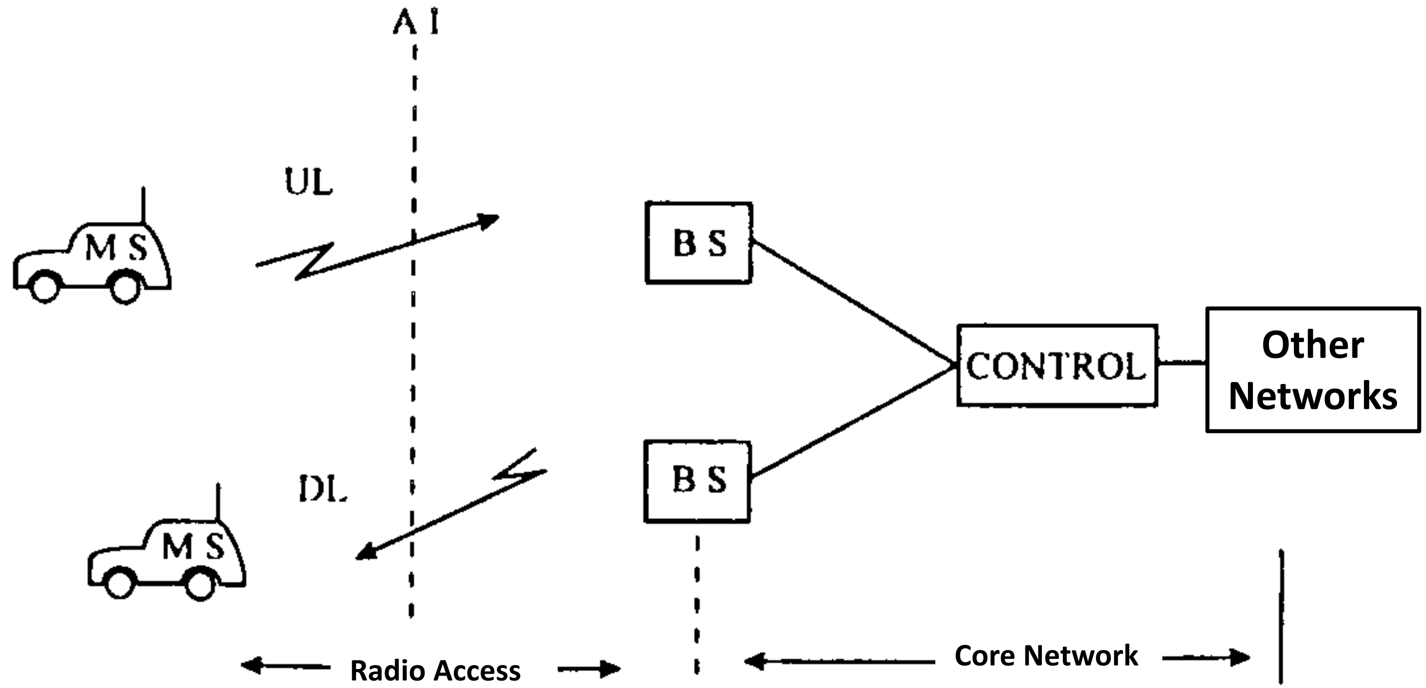
Basics

Basic Components:



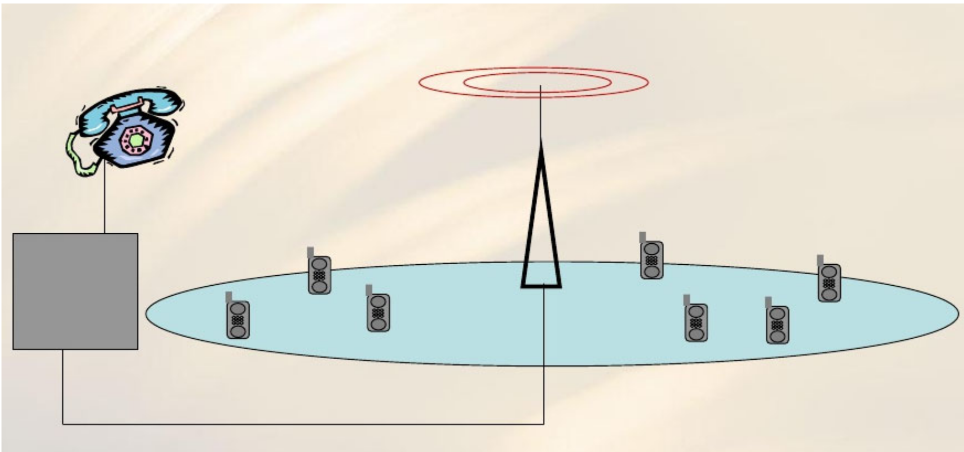
- MS (UE): Mobile transceiver Station (User Equipment)
- AI: Air Interface
- UL: Uplink
- DL: Downlink

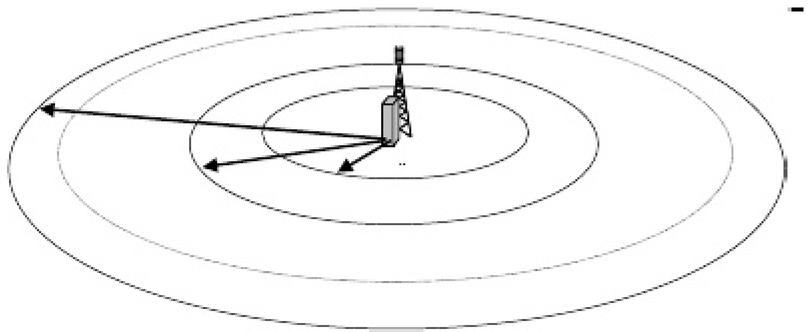
- BS (BTS): Base Station (BaseTransceiver Station): fixed-location transceiver

Basics

Coverage. Concept:

- A base station provides radio coverage to mobile users
- Coverage area of the base station: geographic area around the BS where the strength of the signal has a value exceeding a certain threshold of operation .
- Users outside the coverage area are very low signals below the threshold.





- Topology from base station to the mobile stations: point to area. Area size can be very different in different applications

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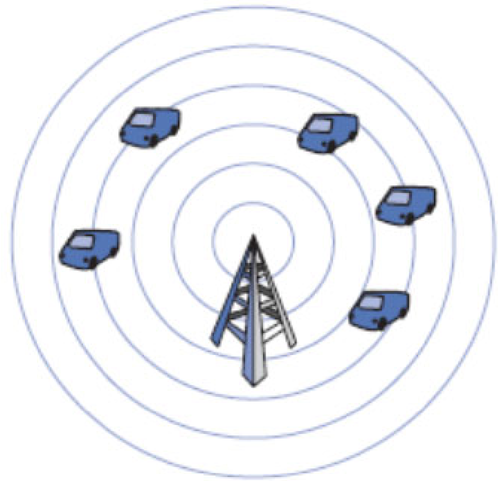
Basics

Coverage. Types:

- Single transmitter with no frequency reuse: A single base station provides radio coverage to mobile users

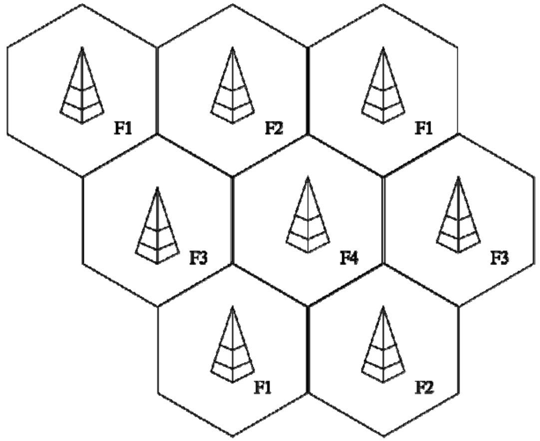


- Cellular network: A wireless network distributed over land areas called cells, each providing a coverage to only a small portion of the service area by one fixed-location transceiver, known as a cell site or base station. Cellular network reuses frequencies in cells separated from one another to avoid any interference.

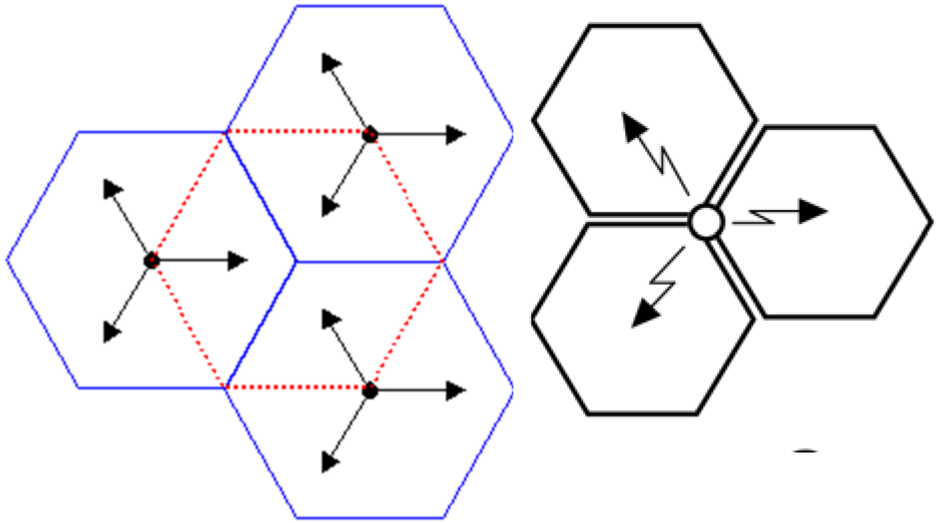
Basics

Coverage. Cellular Networks:

- Center-excited cells with omnidirectional antennas located in the center of the cell.

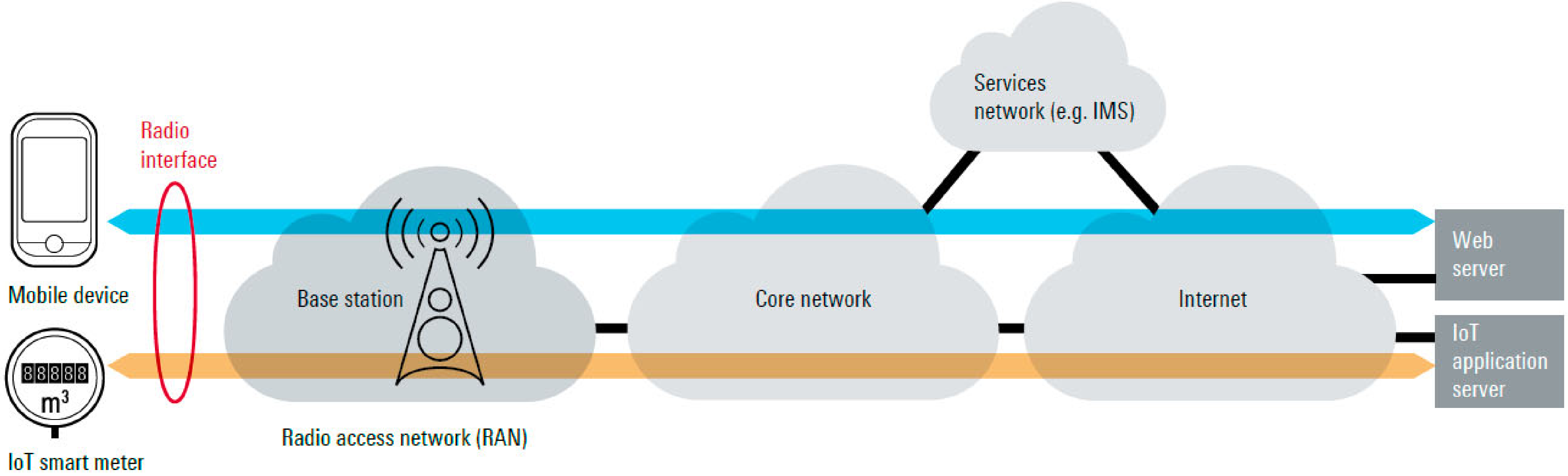


- Corner-excited cells or sectored cells: directional antennas are used in a cell site. It is common to use three sectors by site (three-sectored cells) or six



Basics

Cellular network: a high-level view:



Basics

Coverage. Cellular Networks:

- Macrocell: provides radio coverage served by a high power cellular base station (tower). The antennae for macrocells are mounted on ground-based masts, rooftops and other existing structures, at a height that provides a clear view over the surrounding buildings and terrain. Macrocell base stations have power outputs of typically tens of watts

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Basics

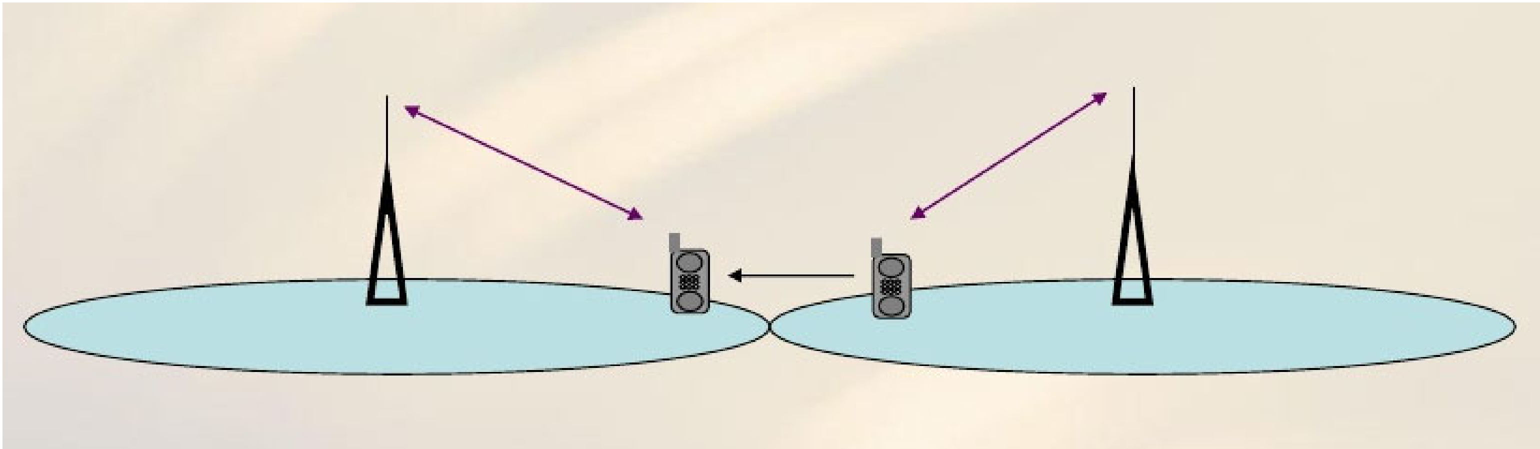
Coverage. Cellular Networks:

- Small cells: are low-powered radio access nodes that have a small range compared to a mobile macrocell. Small cells encompass femtocells, picocells, and microcells. Small cells can be used to provide in-building and outdoor wireless service. Mobile operators use small cells to extend their service coverage and/or increase network capacity.

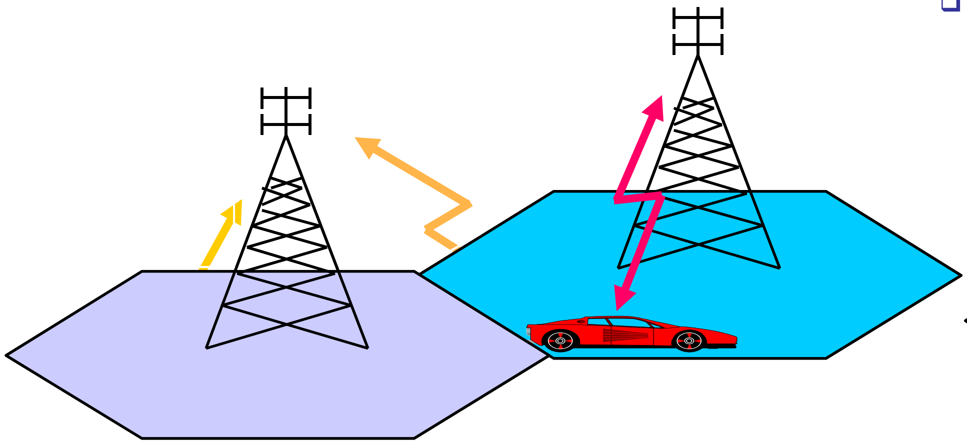
Basics

Coverage. Cellular Networks:

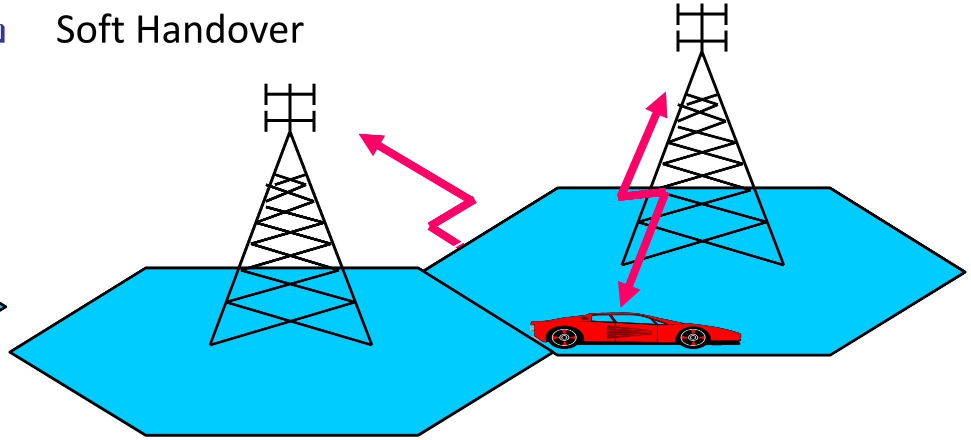
- Handover. Process of transferring an ongoing call or data session from one channel connected to a BS to another channel connected to an another BS.



- Hard Handover



- Soft Handover



Basics

Coverage. Cellular Networks:

- Roaming: ability for a cellular customer to automatically make and receive voice calls, send and receive data, or access other services, when travelling outside the geographical coverage area of the home network, by means of using a visited network.

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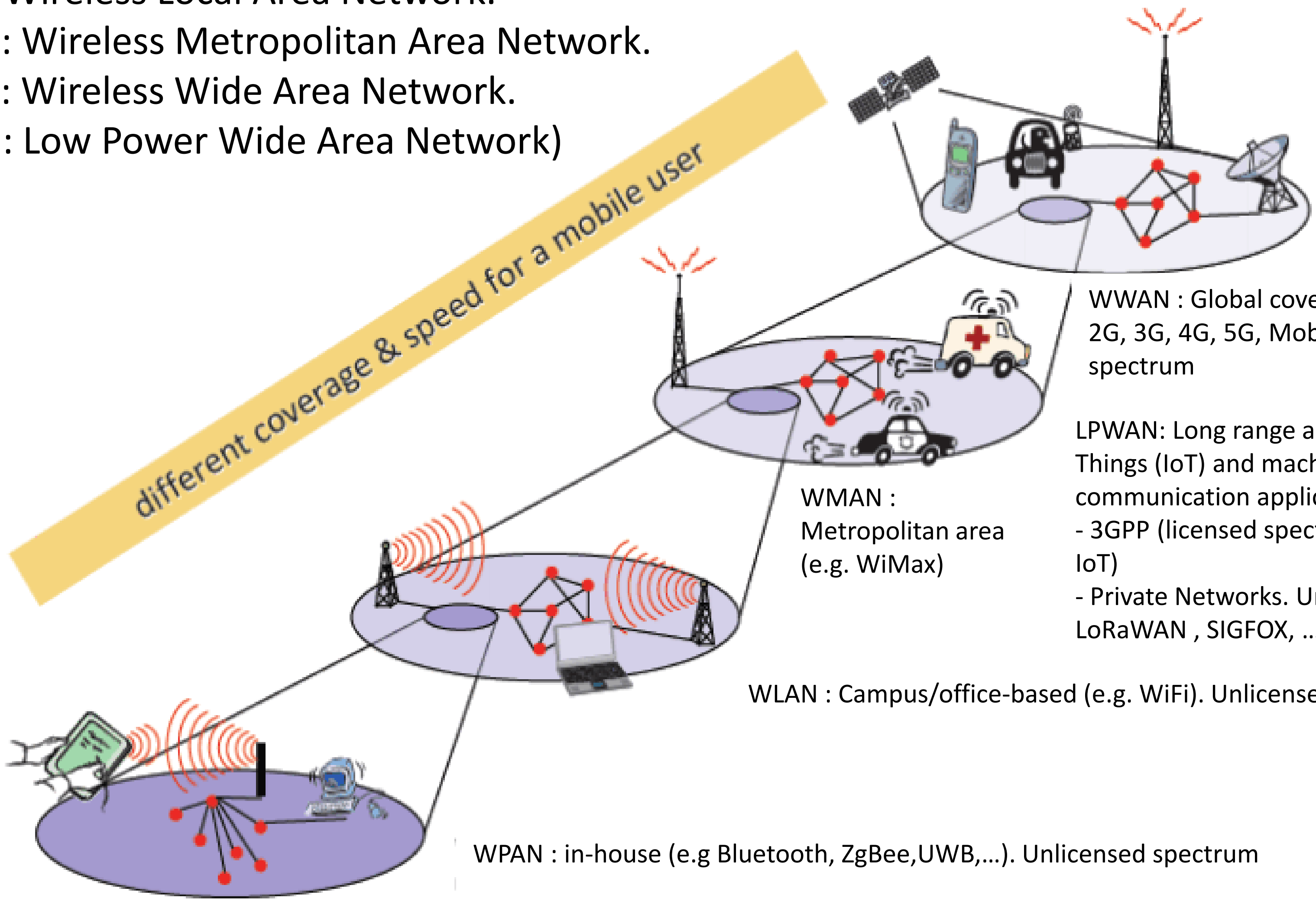
Applications

WPAN: Wireless Personal Area Network.
WLAN: Wireless Local Area Network.
WMAN: Wireless Metropolitan Area Network.
WWAN: Wireless Wide Area Network.
LPWAN: Low Power Wide Area Network)



WWAN : Global coverage. Cellular Technologies (e.g. 2G, 3G, 4G, 5G, Mobile-satellite,). Licensed spectrum

LPWAN: Long range and Low Power Internet of Things (IoT) and machine to machine (M2M) communication applications:
- 3GPP (licensed spectrum) (e.g. NB-IoT, NarrowBand IoT)
- Private Networks. Unlicensed spectrum (e.g. LoRaWAN , SIGFOX, …)

WMAN : Metropolitan area (e.g. WiMax)

WLAN : Campus/office-based (e.g. WiFi). Unlicensed spectrum

WPAN : in-house (e.g Bluetooth, ZgBee,UWB,…). Unlicensed spectrum

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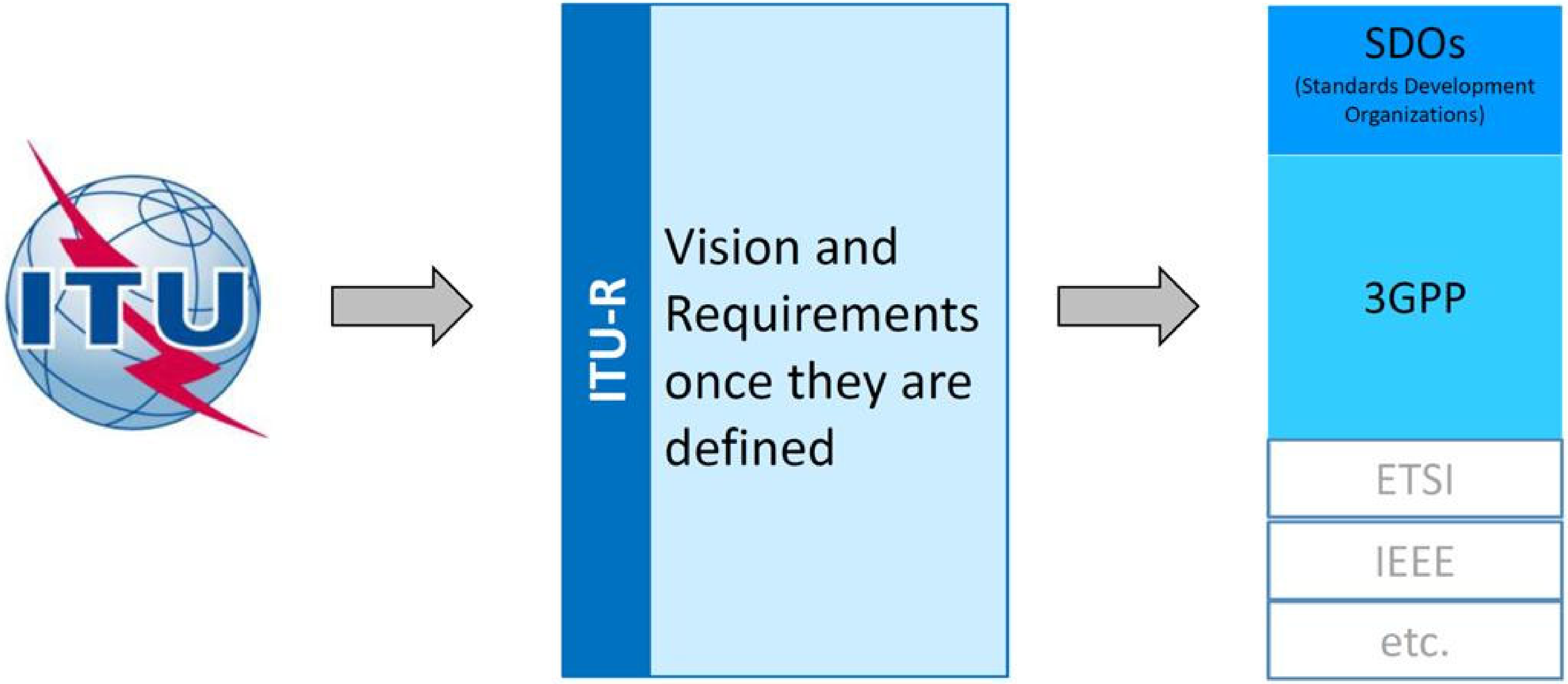
Technological Evolution

- Standardisation Process.

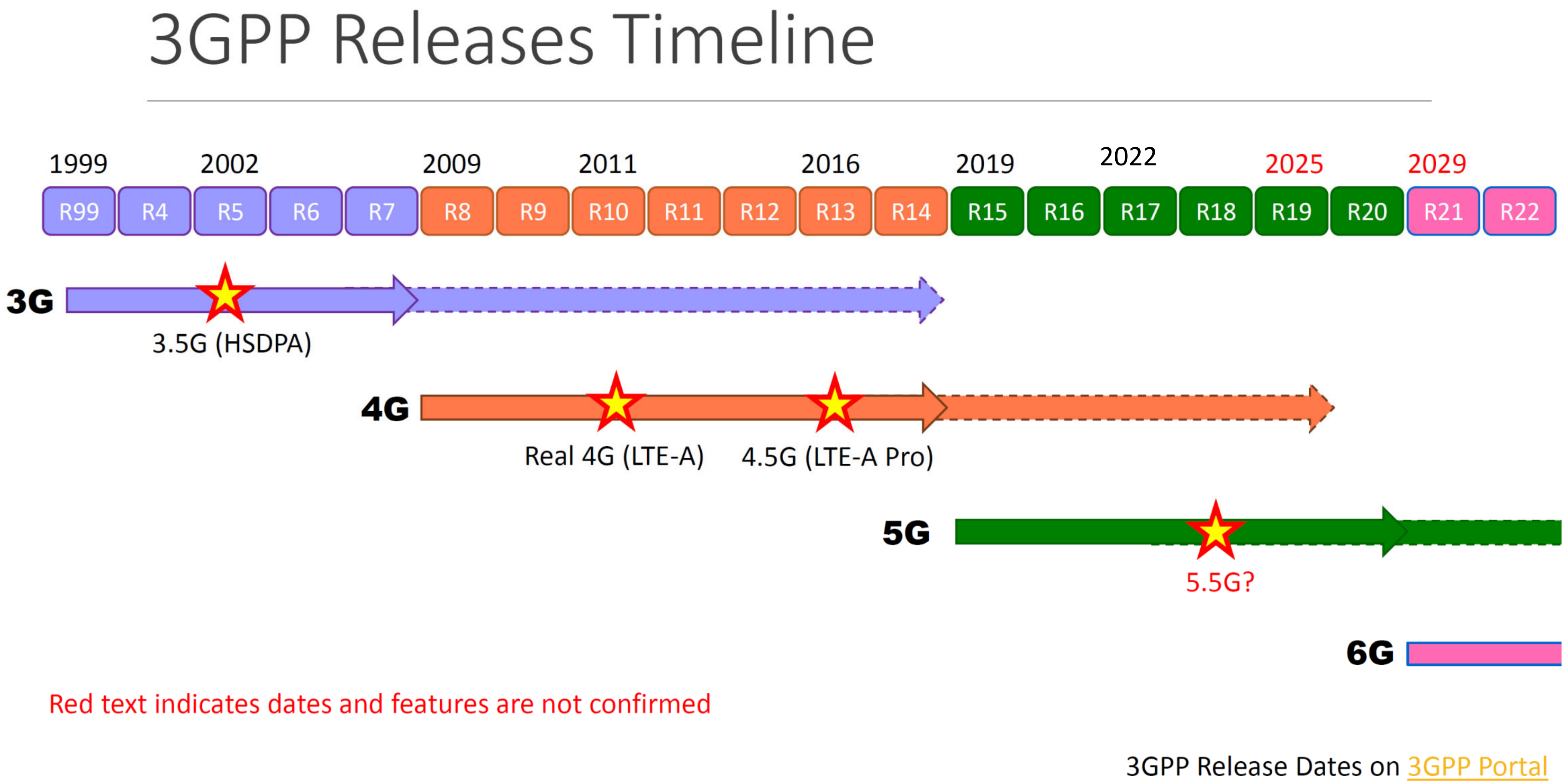


ITU: International Telecommunication Union
3GPP: 3rd Generation Partnership Project

Technological Evolution

	1G	2G	3G	4G	5G	6G
Marketing name	1G	2G	3G	4G	5G	6G
	1980	1991	1999	2009	2019	2029
	1G Launch	2G Launch	3G Launch	4G Launch	5G Launch	6G Launch
Features:	Analog Voice Unable to transmit any data	Digital voice Can send text or SMS Can use data (less than 0.5 Mbps)	Emphasis on high speed wireless conection Can: •Calling •Video calling •Playing games	Faster than 3G Upgrade video quality to be full HD Making the streaming more smooth	All devices will be able to connect to the Internet Low latency Higher data traffic, peak data rate, availaable spectrum and connection density	High Precision Communications (Throughput and latency) Dense Networks Beyond AR/VR ¿?
Commercial name:	Advanced Mobile Phone Service (AMPS) Total Access Communication System (TACS)	GSM (Global System for Mobile) GPRS (General Packet Radio Service) EDGE (Enhanced Data for GSM Evolution)	UMTS (Universal Mobile Telecommunications Service HSPA (High Speed Packet Access)	LTE (Long Term Evolution) LTE-A (LTE Advanced) LTE Advanced Pro	5G NSA (5G Non-Stand Alone) 5G SA (5G Stand Alone)	
ETSI name:		GSM				
ITU name:			IMT – 2000 (International Mobile Telecommunications)	IMT – Advanced (International Mobile Telecommunications)	IMT – 2020 (International Mobile Telecommunications)	IMT – 2030 (International Mobile Telecommunications)
3GPP name			UMTS (Universal Mobile Telecommunications System)	LTE – Advanced (Long Term Evolution)	5G (International Mobile Telecommunications)	6G (International Mobile Telecommunications)

Technological Evolution



https://www.3gpp.org/specifications-technologies/releases

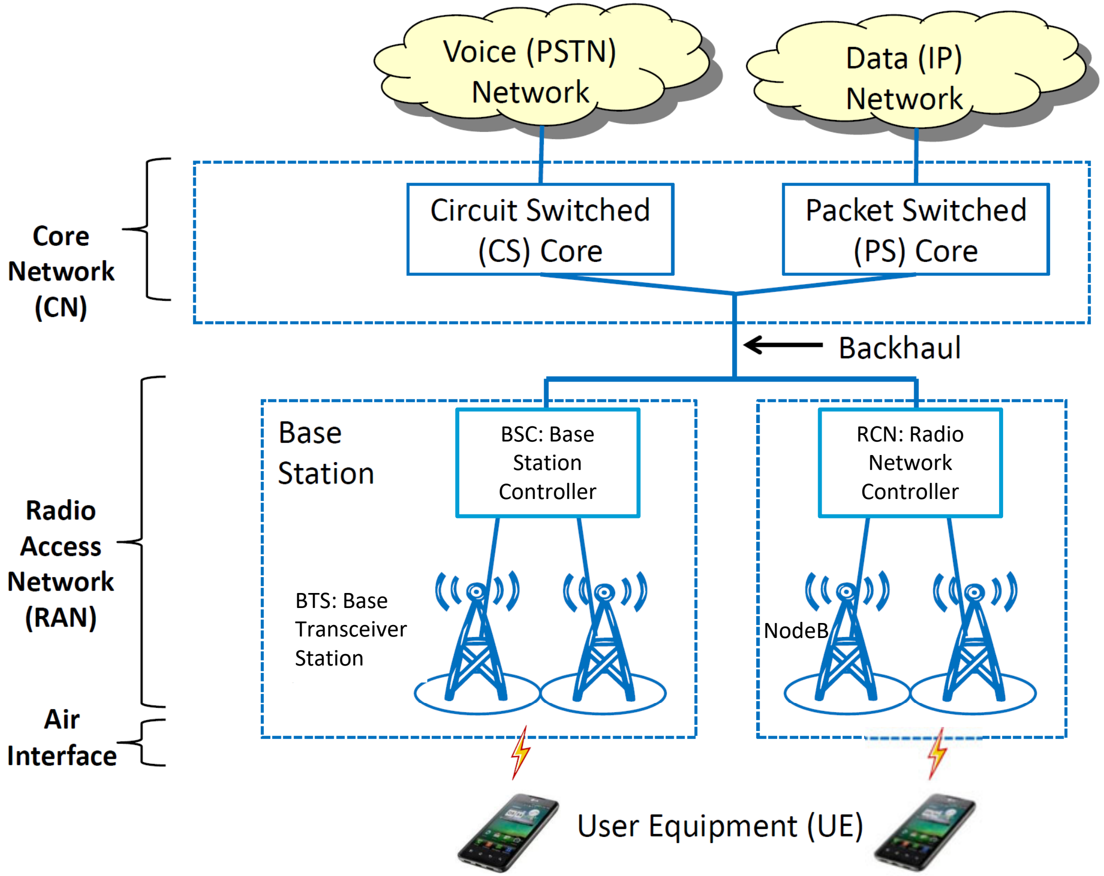
Technological Evolution

Comparison* of different Technology Generations

	2G	3G (HSPA+)	4G	5G	6G**
Year	1990	2000	2010	2020	2030
Max DL Speed (theoretical)	473.6 Kbps	42 Mbps	3 Gbps	20 Gbps	1 Tbps
Avg DL Speed (practical)	50 Kbps	8 Mbps	100 Mbps	300 Mbps	1 Gbps
Max UL Speed (theoretical)	473.6 Kbps	11.5 Mbps	1.5 Gbps	10 Gbps	10 Gbps
Avg UL Speed (practical)	50 Kbps	2 Mbps	50 Mbps	100 Mbps	1 Gbps
E2E Latency (practical)	600 ms	120 ms	30 ms	10 ms	1 ms
Reliability	99%	99.9%	99.99%	99.999%	99.99999%
Connection Density	N/a	N/a	10^5 devices/km^2	10^6 devices/km^2	10^7 devices/km^2
Mobility	150 km/h	300 km/h	350 km/h	500 km/h	1000 km/h

* Approximate values to show comparisons. **Subject to change when standards process starts.

2G / 3G Mobile Network Architecture



Core Network

- Connects to voice and data networks
- Provides Security and Authentication
- Billing / Charging
- Roaming

Backhaul

- Connects access network with core network
- Example: Fiber, microwave, satellite, mesh, etc.

Access Network

- Connects devices over the air
- Allows mobility and handovers
- GERAN: GPRS/EDGE Radio Access Network
- UTRAN: UMTS Terrestrial Radio Access Network

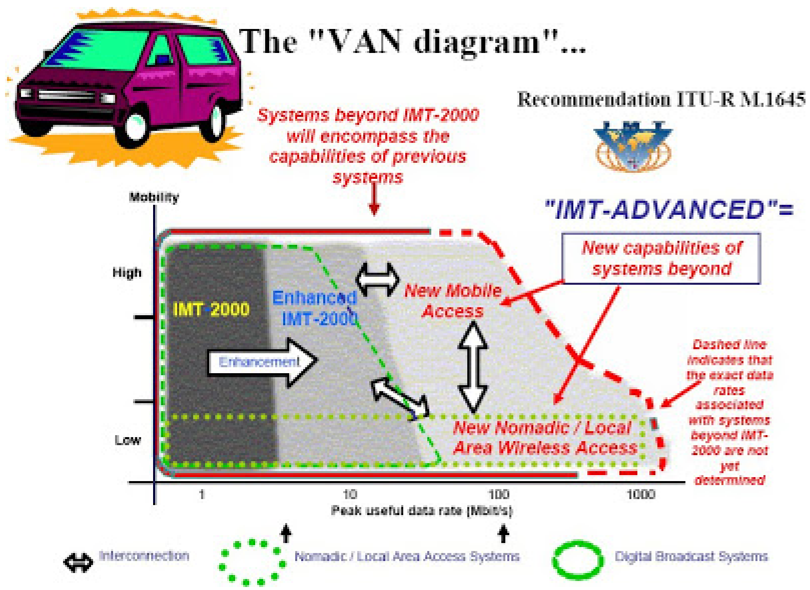
Technological Evolution

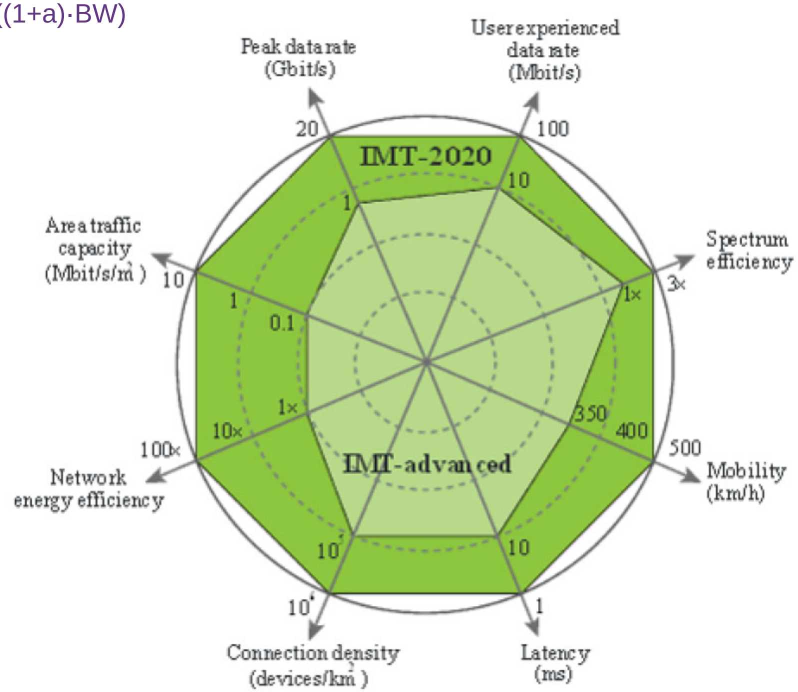
4G:

- IMT-Advanced (International Mobile Telecommunications Advanced): a set of requirements for 4G standards, defined by the International Telecommunication Union(ITU).

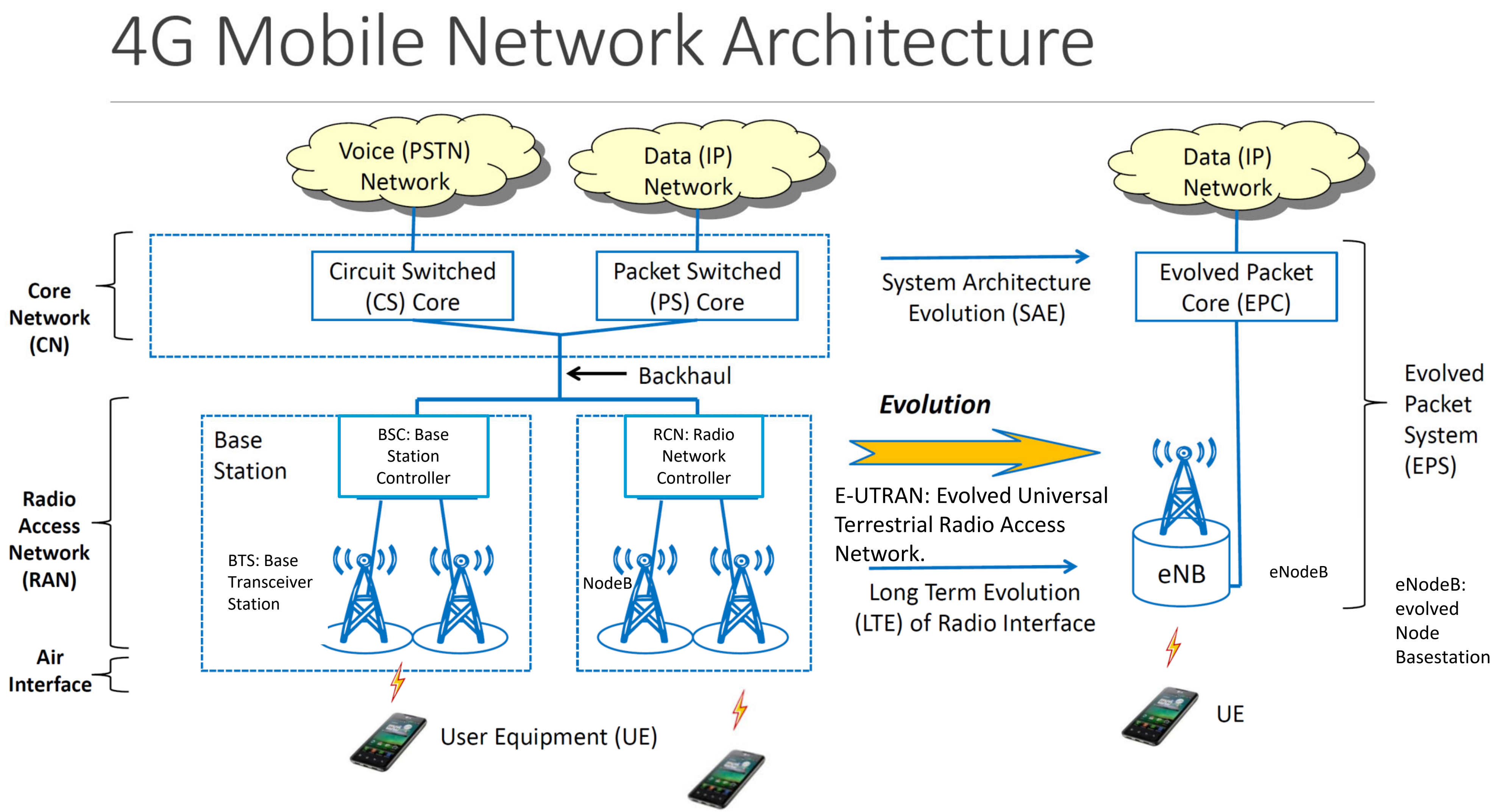
BW = BW_Nyquist(1+a)
a = rolloff faktorea

Efizientzia espektrala: (BW·m)/((1+a)·BW)





Technological Evolution



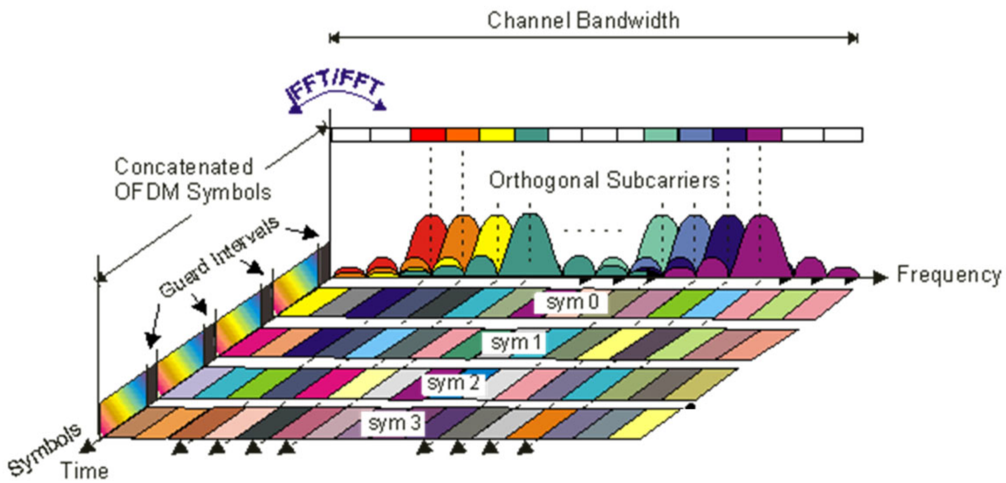
Technological Evolution

❑ LTE Air Interface Characteristics:

A carrier can sometimes be dedicated entirely to a single user/device.

- Multiple Access Schemes
  - DL: OFDM (Orthogonal Frequency Division Multiple Access)

    Tu =
  - UL: SC-FDMA (Single Carrier Frequency Division Multiple Access). It can be interpreted as a linearly precoded OFDMA scheme, withn lower peak-to-average power ratio (PAPR)

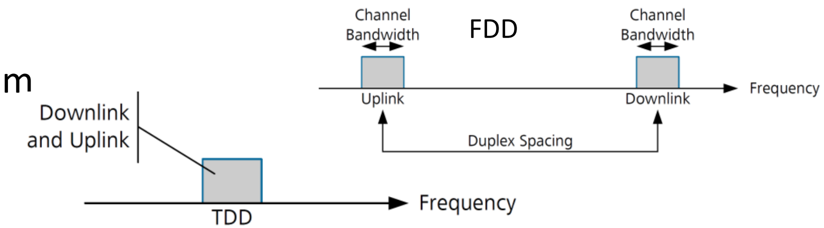


f =

- Subcarrier spacing = 15 kHz IKASTEKO!
- Modulation Schemes:
  - QPSK, 16QAM, 64QAM
- OFDM symbol duration (T_U) = 1 /subcarrier spacing = 1/15 kHz
- Guard interval = Cyclic Prefix (CP). Two different cyclic prefix sizes:
  - “Normal”: 7 ODFM symbols per Interval Time (IT)
  - “Extended”: 6 ODFM symbols per Interval Time (IT)

Bit kopurua kalku

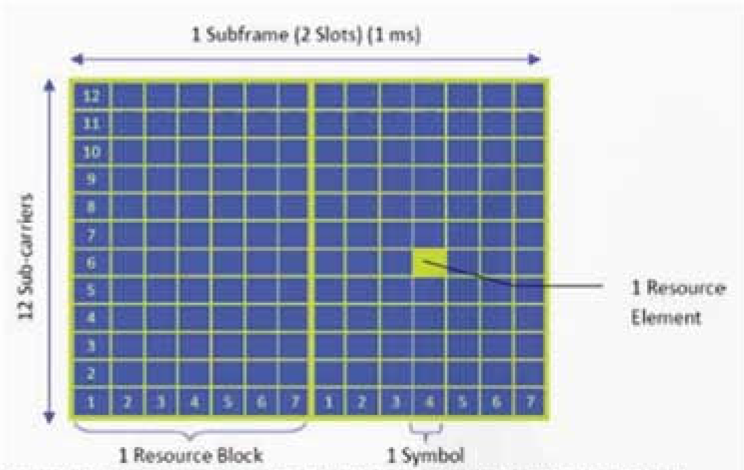
- Dupolex Modes:
  - FDD (Frequency Division Duplex) for paired spectrum
  - TDD (Time Divison Duplex) for unpaired spectrum



- Channel Coding: Turbo encoder is used with 1/3 code rate. In fact coding rate range is 0.0762 - 0.9258.

Technological Evolution

- LTE Air Interface Characteristics:
  - Time and Frequency Resources

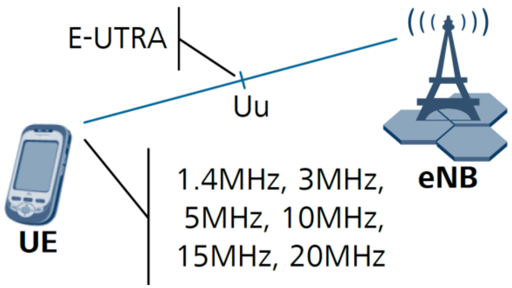


RESOURCE BLOCK AND RESOURCE ELEMENT DEFINITION (NORMAL CP MODE)

- Frame: 10 ms
- Subframe 1 ms
- Slot 0.5 ms
- Symbol:
  - (0.5 ms) / 7 for normal CP
  - (0.5 ms) / 6 for extended CP
- Bits per symbol:
  - QPSK: 2
  - 16QAM: 4
  - 64QAM: 6

- Resource element (RE) = 1 subcarrier x 1 symbol
- Resource block (RB) is the smallest unit of resources that can be allocated to a user. The resource block is 12 subcarriers (wide in frequency = 180 kHz = 12 x 15 kHz) and 1 slot long in time

- Bandwidths:
  - The bandwidths defined by the standard are 1.4, 3, 5, 10, 15, and 20 MHz.



Bandwidth	Resource Blocks
1.4 MHz	6
3 MHz	15
5 MHz	25
10 MHz	50
15 MHz	75
20 MHz	100

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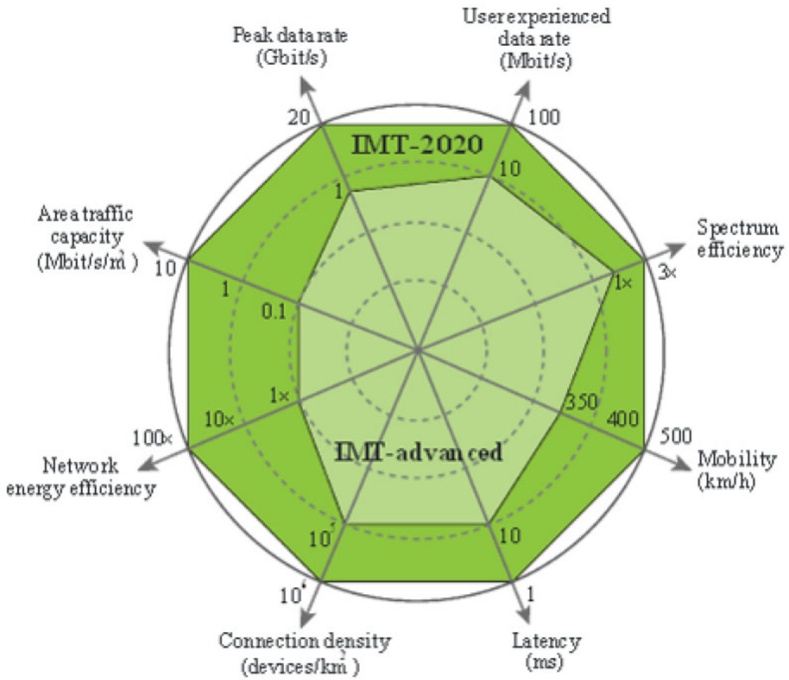
Technological Evolution

5G:

- IMT- 2020 (International Mobile Telecommunications 2020): a set of requirements for 5G standards in International Telecommunication Union(ITU)

Metric	Requirement	Comments
Peak Data Rate	DL: 20 Gb/s UL: 10 Gb/s	Single eMBB mobile in ideal scenarios assuming all resources utilized
Peak Spectral Efficiency	DL: 30 b/s/Hz (assuming 8 streams) UL: 15 b/s/Hz (assuming 4 streams)	Single eMBB mobile in ideal scenarios assuming all resources utilized
User Experienced Data Rate	DL: 100 Mb/s UL: 50 Mb/s	5% CDF of the eMBB user throughput
Area Traffic Capacity	Indoor hotspot DL: 10 Mb/s/m^2	eMBB
User Plane Latency	eMBB: 4 ms URLLC: 1 ms	Single user for small IP packets, for both DL and UL (eMBB and URLLC)
Control Plane Latency	20 ms (encouraged to consider 10 ms)	Transition from Idle to Active (eMBB and URLLC)
Connection Density	1M devices per km^2	For mMTC
Reliability	99.9999% success prob.	32 L2 bytes within 1 ms at cell edge
Bandwidth	>100 MHz; up to 1 GHz in > 6 GHz	Carrier aggregation allowed

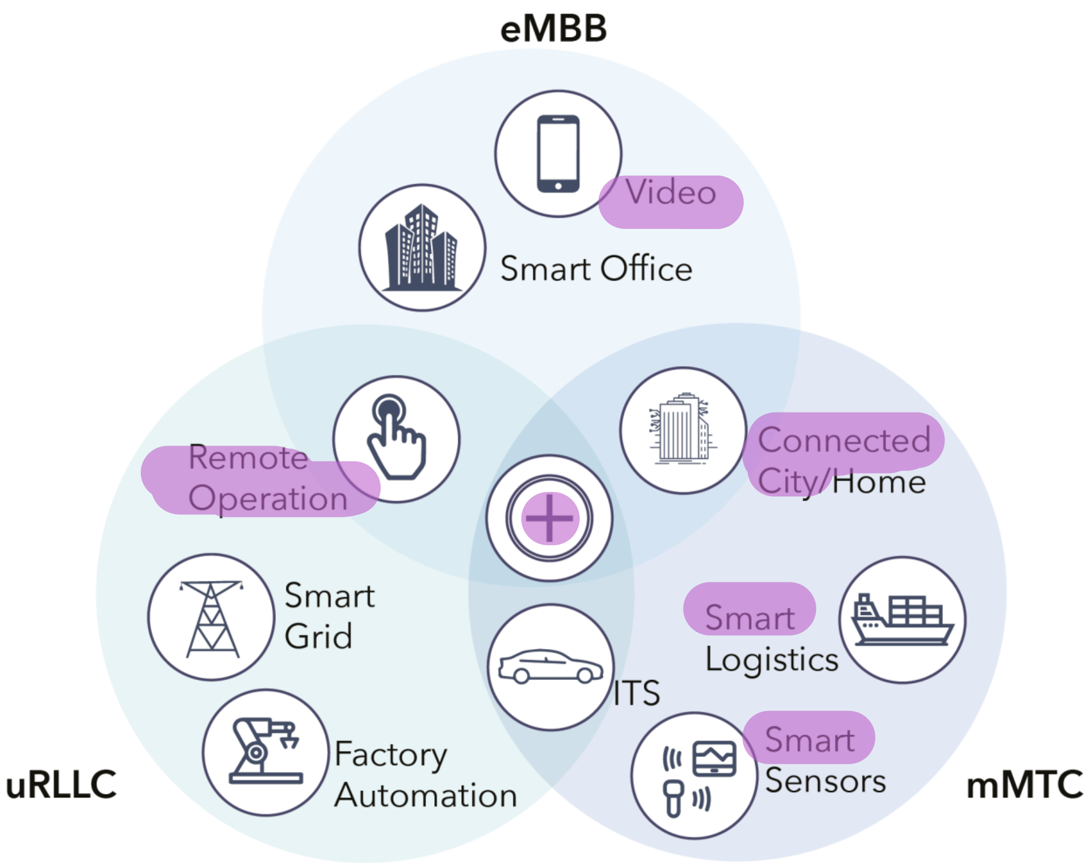


Enhancement of Key Capabilities from IMT-Advanced to IMT-2020

Technological Evolution

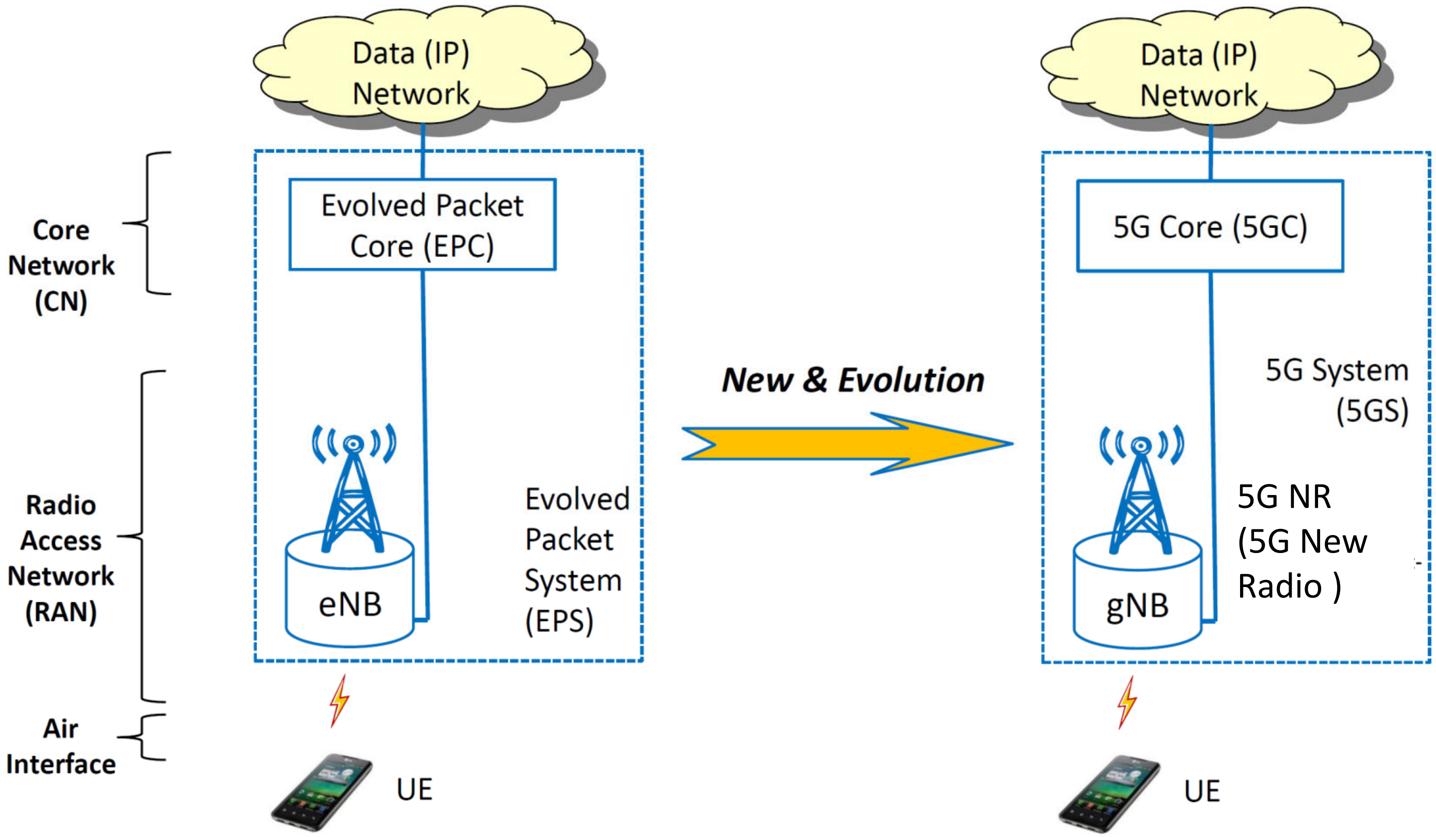
5G:

- 5G major use cases with service categorization:
  - Enhanced mobile broadband services (eMBB services)
  - Massive machine-type communications (mMTC services)
  - Ultra-reliable low latency communications (uRLLC services)



Technological Evolution

5G Mobile Network Architecture



5G System (5GS) is defined as 3GPP system consisting of:
- 5G Core Network (5GC)
- 5G Radio Access Network (RAN)
- User Equipment (UE)
- Next Gen Node Basestation (gNB)

Technological Evolution

5G NR Air Interface Characteristics:

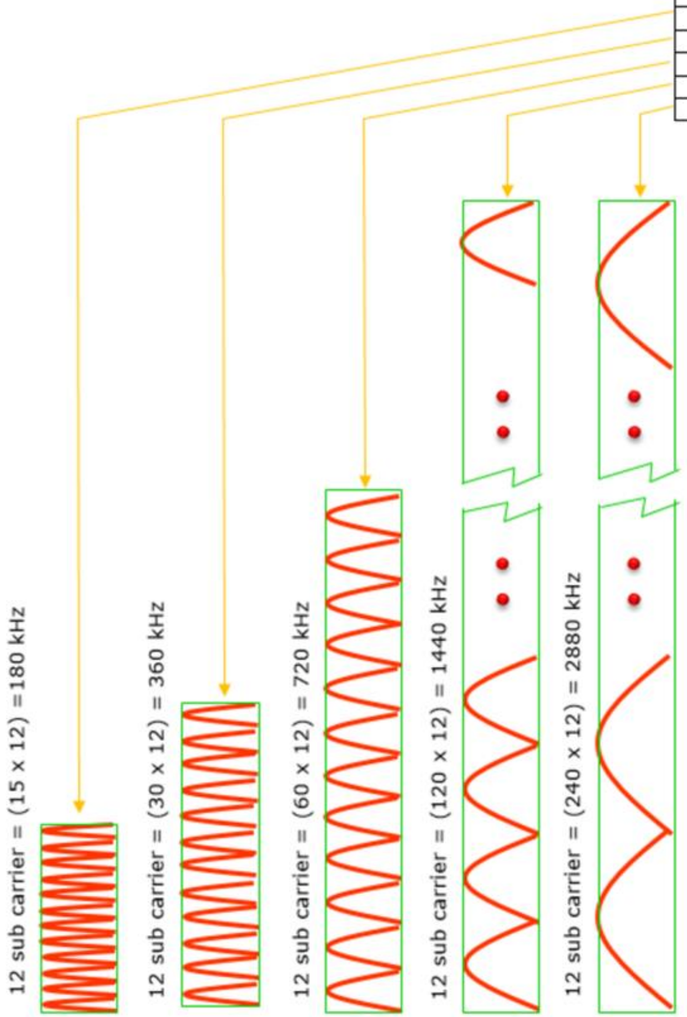
- Multiple Access Scheme: F-OFDMA, Filter or Flexible OFDMA: Flexible numerology:
- Numerology Parameter μ, Subcarrier spacing Δf and Cyclic Prefix

μ	$\Delta f = 2^{\mu} \cdot 15\,[\text{kHz}]$	Cyclic prefix
0	15	Normal
1	30	Normal
2	60	Normal, Extended
3	120	Normal
4	240	Normal

- NR support multiple different types of subcarrier spacing (15 kHz to 240 kHz) (in LTE there is only one type of subcarrier spacing, 15 Khz).

- Each numerology is labled as a parameter μ.
- The numerology (u = 0) represents 15 kHz which is same as LTE.
- The subcarrier spacing of other u is derived from (u=0) by scaling up in the power of 2.

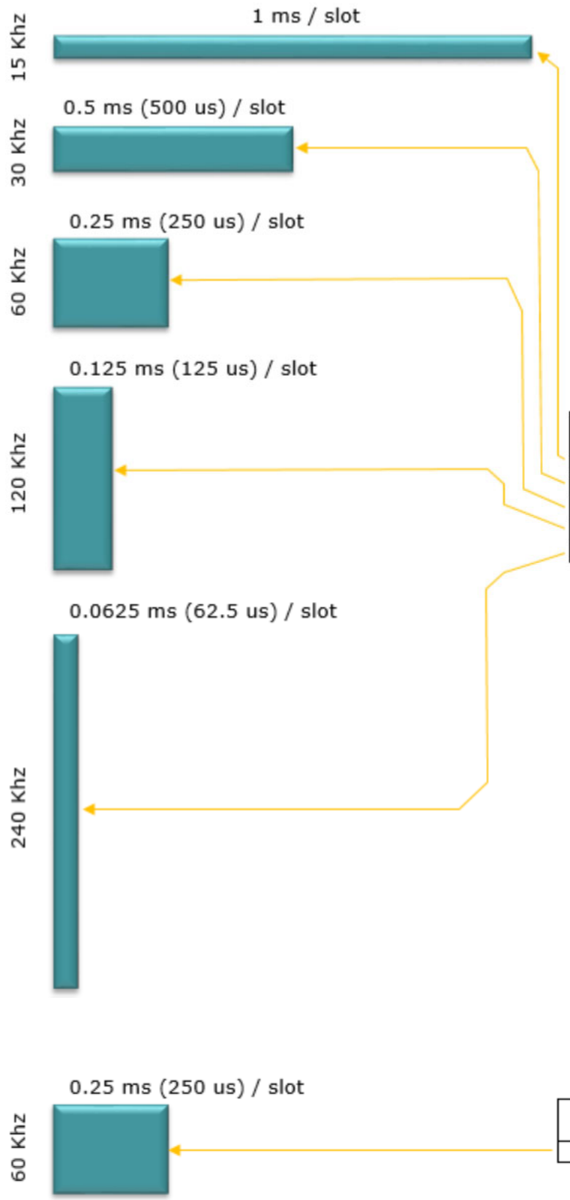
RB = Resource Block = 12 Garraiatzaile
(LTE-n bezala!)



Technological Evolution

- 5G NR Air Interface Characteristics:
  - Numerology and Slot Length

    - Slot length gets different depending on numerology.
    - The general tendancy is that slot length gets shorter as subcarrier spacing gets wider. Actually this tendancy comes from the nature of OFDM.
    - OFDM symbol duration (T_U) = 1 /subcarrier spacing
    - CP length depends on:
      - CP Type (Normal or Extended)
      - Index number of the symbol in the Time Slot



CP Normal:

< 38.211 – Table 4.3.2-1 >

μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
0	14	10	1
1	14	20	2
2	14	40	4
3	14	80	8
4	14	160	16

CP Extended:

< 38.211 – v2.0.0 Table 4.3.2-w >

μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
2	12	40	4

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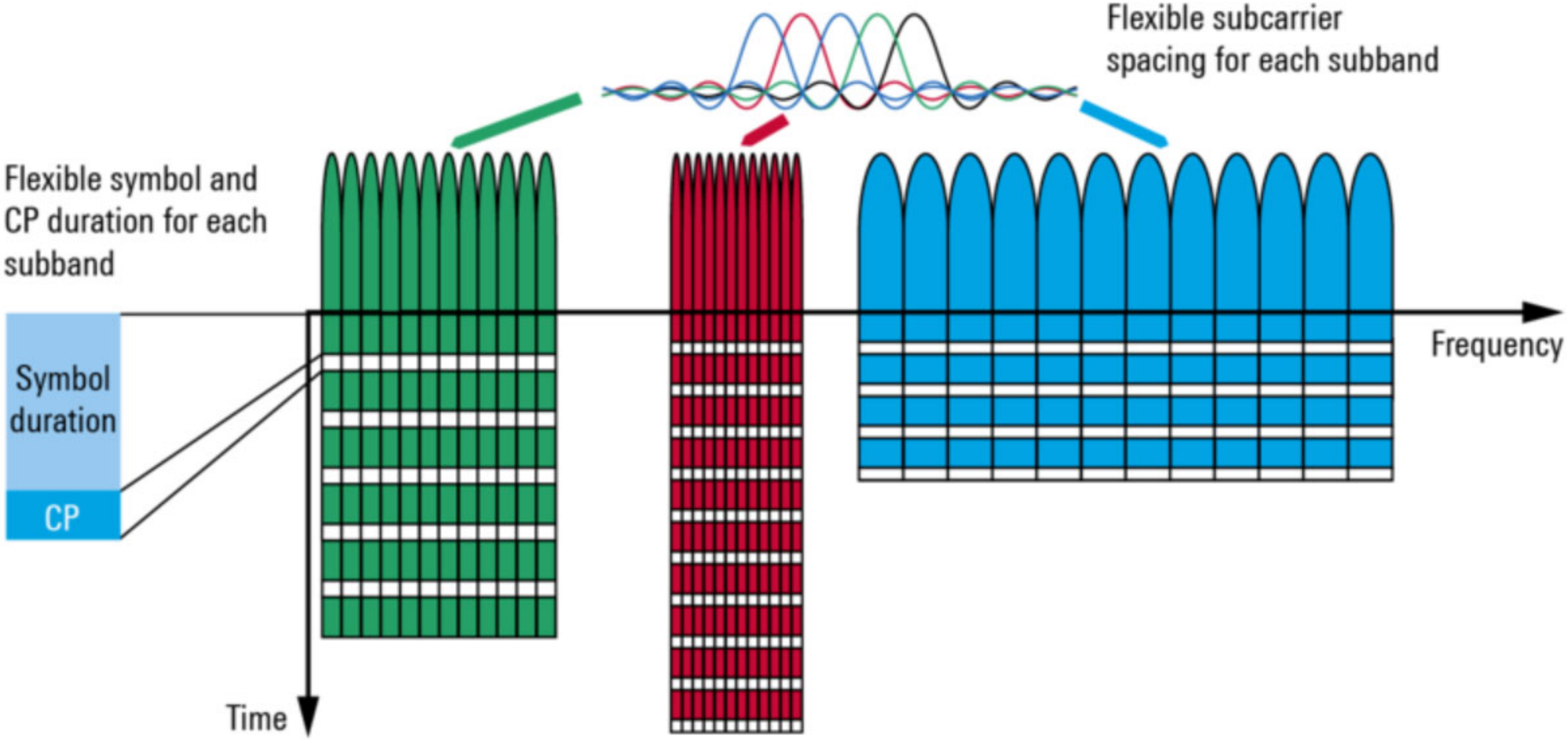
Technological Evolution

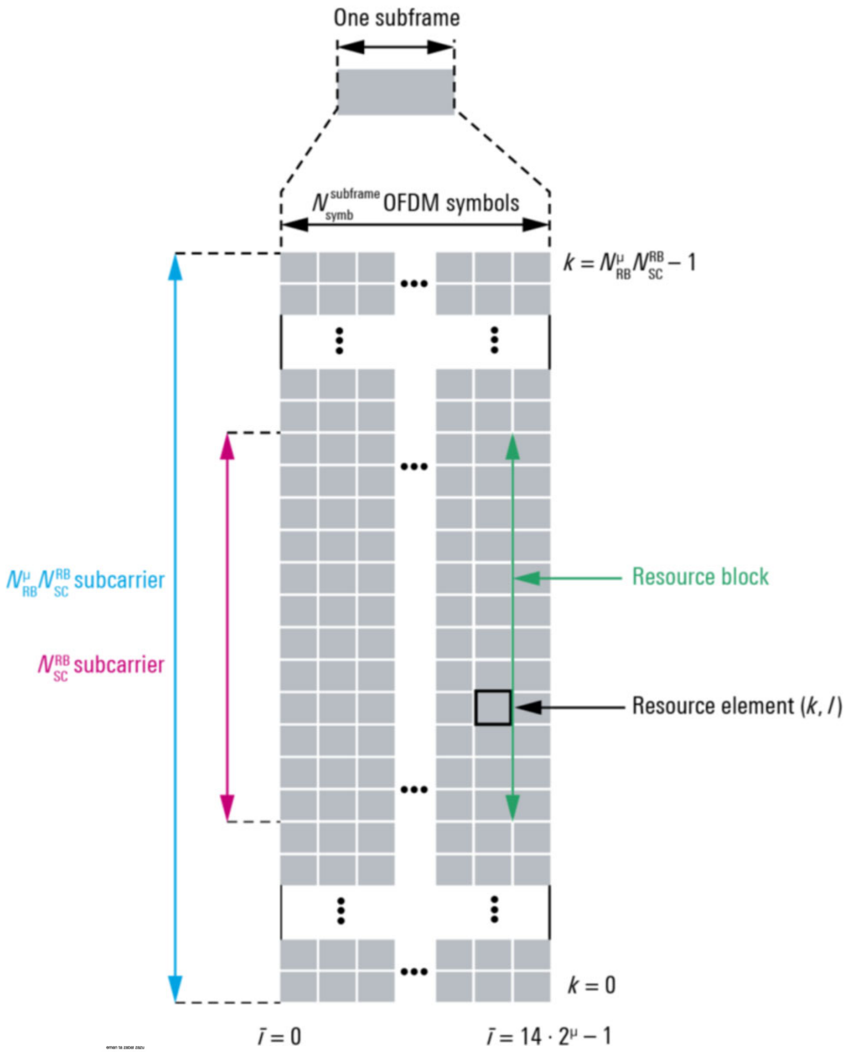
- 5G NR Air Interface Characteristics:
  - Numerology and OFDM Symbol Duration

Parameter / Numerlogy (u)	0	1	2	3	4
Subcarrier Spacing (Khz)	15	30	60	120	240
OFDM Symbol Duration (us)	66.67	33.33	16.67	8.33	4.17
Cyclic Prefix Duration (us)	4.69	2.34	1.17	0.57	0.29
OFDM Symbol including CP (us)	71.35	35.68	17.84	8.92	4.46



Technological Evolution

- 5G NR Air Interface Characteristics:
  - 5G NR Resource Block and Resource Elements



- Resource Element : This is same as LTE. It is the smallest unit of the resource grid made up of one subcarrier in frequency domain and one OFDM symbol in time domain.

- Resource Block:
  - In 5G NR, Resource Block is defined only for frequency domain.
    - 38.211-4.4.4.1 states 'A resource block is defined as 12(N_RB_sc) consecutive subcarriers in the frequency domain'.
  - Time domain definition of resource block is a little bit ambiguous.
    - Minimum time domain length in a resource block can be one OFDM symbol, but exact time domain length vary depending SLIV (Start and Length Indicator).

- Resource Grid and Antenna port and Numerology:
  - Basically one resource grid is created for one antenna port and numerology. 38.211-4.2.2 states as follows:
    - There is one set of resource grids per transmission direction (uplink or downlink) with the subscript set to DL and UL for downlink and uplink
    - There is one resource grid for a given antenna port p , subcarrier spacing configuration u, and transmission direction (downlink or uplink).

Technological Evolution

5G: Release 16:

- Increasing support of vertical industries such as non-terrestrial networks (NTN), vehicle to everything (V2X), public safety, and Industrial Internet of Things (IoT).
- Unlicensed access (NR-U)
- Enhanced Massive MIMO (in particular >6 GHz)
- Integrated access and backhaul (IAB)
- Non-orthogonal multiple access (NOMA) waveforms.

Technological Evolution

Comparison of 5G and expected 6G KPIs (Key Performance Indicators)

Key Performance Indicator (KPI)	5G	6G
Peak data rate	20 Gb/s	1 Tb/s
Experienced data rate	0.1Gb/s	1 Gb/s
Peak spectral efficiency	30 b/s/Hz	60 b/s/Hz
Experienced spectral efficiency	0.3 b/s/Hz	3 b/s/Hz
Maximum bandwidth	1 GHz	100 GHz
Area traffic capacity	10 Mb/s/m2	1 Gb/s/m2
Connection density	10^6 devices/km2	10^7 devices/km2
Energy Efficiency	not given	1 Tb/Joule
Latency	1 milli sec	100 micro sec
Jitter	not given	1 micro sec
Reliability	1-10^ -5	1-10^-9
Mobility	500 km/h	1000 km/h

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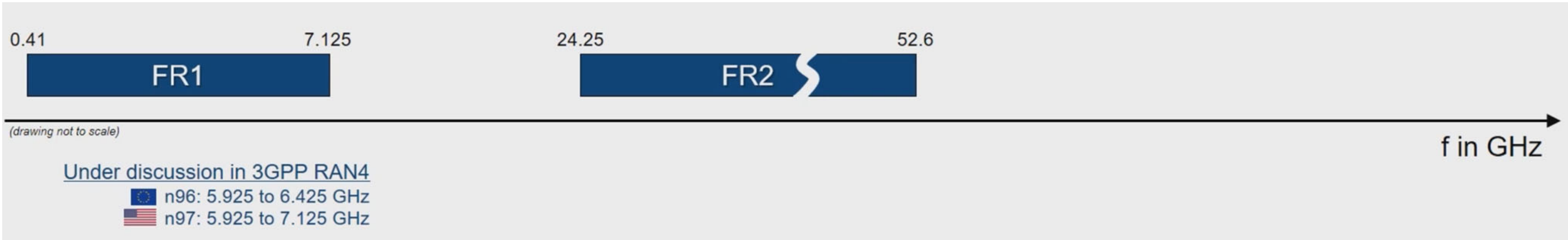
Frequency Bands

- 3GPP Frequency bands :
  - In R15, 3GPP initially defined FR1 to cover 450 MHz to 6 GHz and FR2 to cover 24.250 GHz to 52.6 GHz.
  - FR1 was later extended in R15 to cover 410 MHz to 7.125 GHz to include the 6 GHz unlicensed spectrum in the higher frequencies and any available spectrum around 400 MHz (e.g. T-GSM 410 or GSM trunking system from about 410 MHz to about 430 MHz).



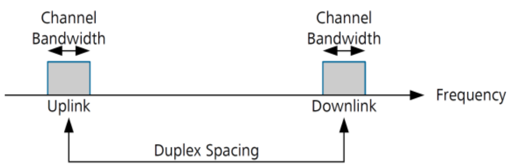
Sistemas 5G

❑ **Espectro 5G.** 5G NR Release-15 Operating Bands

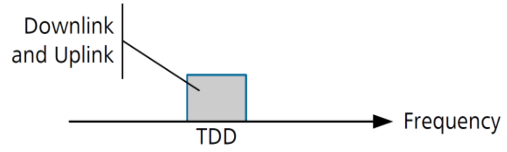
Frequency Range 1 (FR1) - 410 MHz to 7.125 GHz

OPERATING BAND	UPLINK (UL) BS RECEIVE/UE TRANSMIT	DOWNLINK (DL) BS TRANSMIT/UE RECEIVE	DUPLEX MODE
n1	1920 – 1980 MHz	2110 – 2170 MHz	FDD
n2	1850 – 1910 MHz	1930 – 1990 MHz	FDD
n3	1710 – 1785 MHz	1805 – 1880 MHz	FDD
n5	824 – 849 MHz	869 – 894 MHz	FDD
n7	2500 – 2570 MHz	2620 – 2690 MHz	FDD
n8	880 – 915 MHz	925 – 960 MHz	FDD
n12	699 – 716 MHz	729 – 746 MHz	FDD
n20	832 – 862 MHz	791 – 821 MHz	FDD
n25	1850 – 1915 MHz	1930 – 1995 MHz	FDD
n28	703 – 748 MHz	758 – 803 MHz	FDD
n34	2010 – 2025 MHz	2010 – 2025 MHz	TDD
n38	2570 – 2620 MHz	2570 – 2620 MHz	TDD
n39	1880 – 1920 MHz	1880 – 1920 MHz	TDD
n40	2300 – 2400 MHz	2300 – 2400 MHz	TDD
n41	2496 – 2690 MHz	2496 – 2690 MHz	TDD
n50	1432 – 1517 MHz	1432 – 1517 MHz	TDD
n51	1427 – 1432 MHz	1427 – 1432 MHz	TDD
n66	1710 – 1780 MHz	2110 – 2200 MHz	FDD
n70	1695 -1710 MHz	1995 – 2020 MHz	FDD
n71	663 – 698 MHz	617 – 652 MHz	FDD
n74	1427 – 1470 MHz	1475 – 1518 MHz	FDD
n75	N/A	1432 – 1517 MHz	SDL
n76	N/A	1427 – 1432 MHz	SDL
n77	3300 – 4200 MHz	3300 – 4200 MHz	TDD
n78	3300 – 3800 MHz	3300 – 3800 MHz	TDD
n79	4400 – 5000 MHz	4400 – 5000 MHz	TDD
n80	1710 – 1785 MHz	N/A	SUL
n81	880 – 915 MHz	N/A	SUL
n82	832 – 862 MHz	N/A	SUL
n83	703 – 748 MHz	N/A	SUL
n84	1920 – 1980 MHz	N/A	SUL
n86	1710 – 1780 MHz	N/A	SUL

- FDD (Frequency Division Duplex) for paired spectrum



- TDD (Time Divison Duplex) for unpaired spectrum



- SDL: Supplementary Downlink

- SUL: Supplementary Uplink

In FR1, 5G allows bandwidths from 5 MHz to 100 MHz. In FR2 (24.25 GHz - 52.6 GHz), 5G offers

For each bandwidth, the maximum number of RBs depends on the numerology

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Sistemas 5G

- **Espectro 5G.** 5G NR Release-15 Operating Bands

Frequency Range 2 (FR2) - 24.25 GHz to 52.6 GHz

OPERATING BAND	UPLINK (UL) BS RECEIVE/UE TRANSMIT	DOWNLINK (DL) BS TRANSMIT/UE RECEIVE	DUPLEX MODE
n257	26.5 – 29.5 GHz	26.5 – 29.5 GHz	TDD
n258	24.25 – 27.5 GHz	24.25 – 27.5 GHz	TDD
n260	37 – 40 GHz	37 – 40 GHz	TDD
n261	27.5 – 28.35 GHz	27.5 – 28.35 GHz	TDD

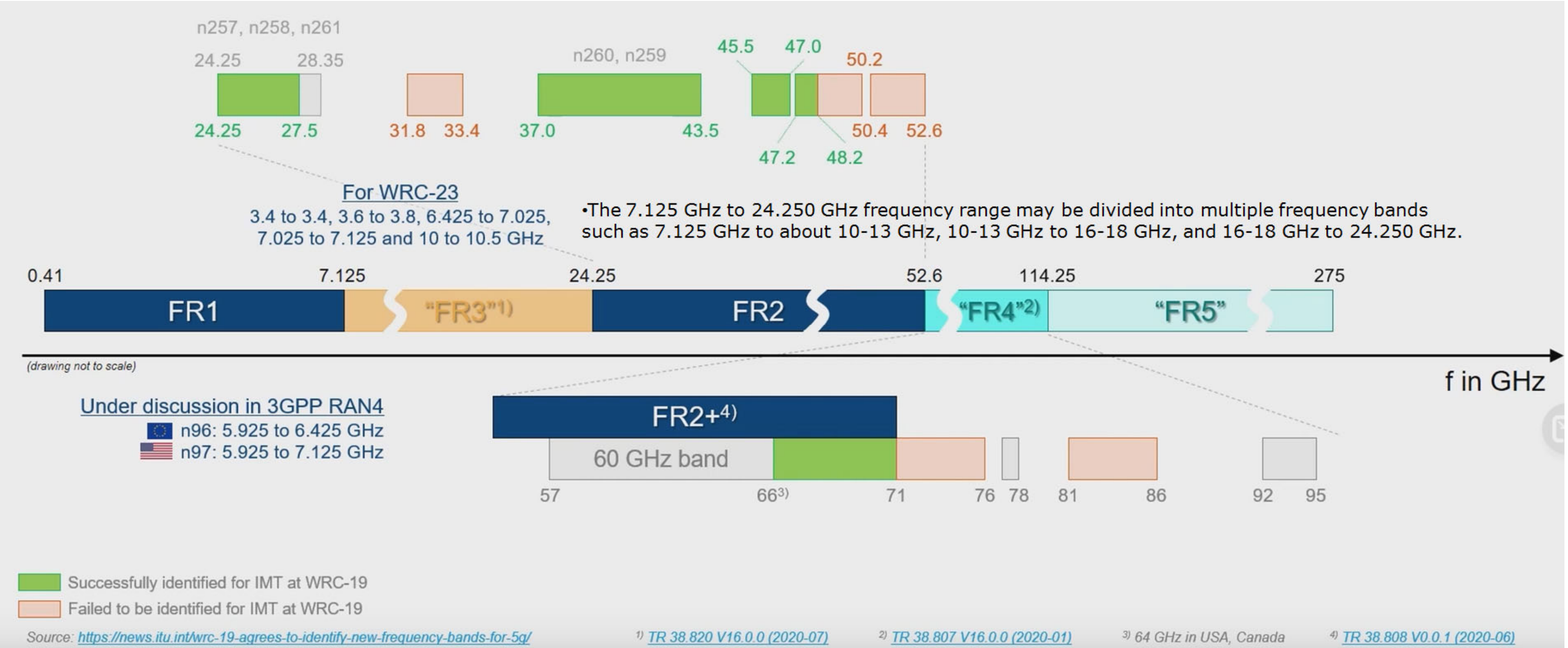
3GPP TS 38.101-1/2, 38.104-1/2

In FR2, 5G allows bandwidths from 50 MHz to 400 MHz

For each bandwidth, the maximum number of RBs depends on the numerology

Frequency Bands

- 3GPP Frequency bands:
  - The existing FR1/FR2 may be extended or new FRs may be defined.
  - 3GPP is exploring further frequency band increases in the 7.125 GHz to 24.250 GHz range and above 52.6 GHz.



Frequency Bands

- Unlicensed spectrum :
  - In recent years ISM (Industrial, Scientific, and Medical) bands have also been shared with (non-ISM) license-free error-tolerant communications applications such as:
    - Wireless sensor and IoT devices networks in the 915 MHz and 2.450 GHz bands
    - Wireless LANs and cordless phones in the 915 MHz, 2.450 GHz, and 5.800 GHz bands.

Table of Contents

1. Basics
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3. Technological Evolution
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5. **Mobile Coverage Calculations**
   - **Relevant propagation phenomena for system design**
   - **Statistical description of the wireless channel**
   - **Channel models**
   - **Link budgets of wireless noise-limited systems**
   - **Interference-limited systems**

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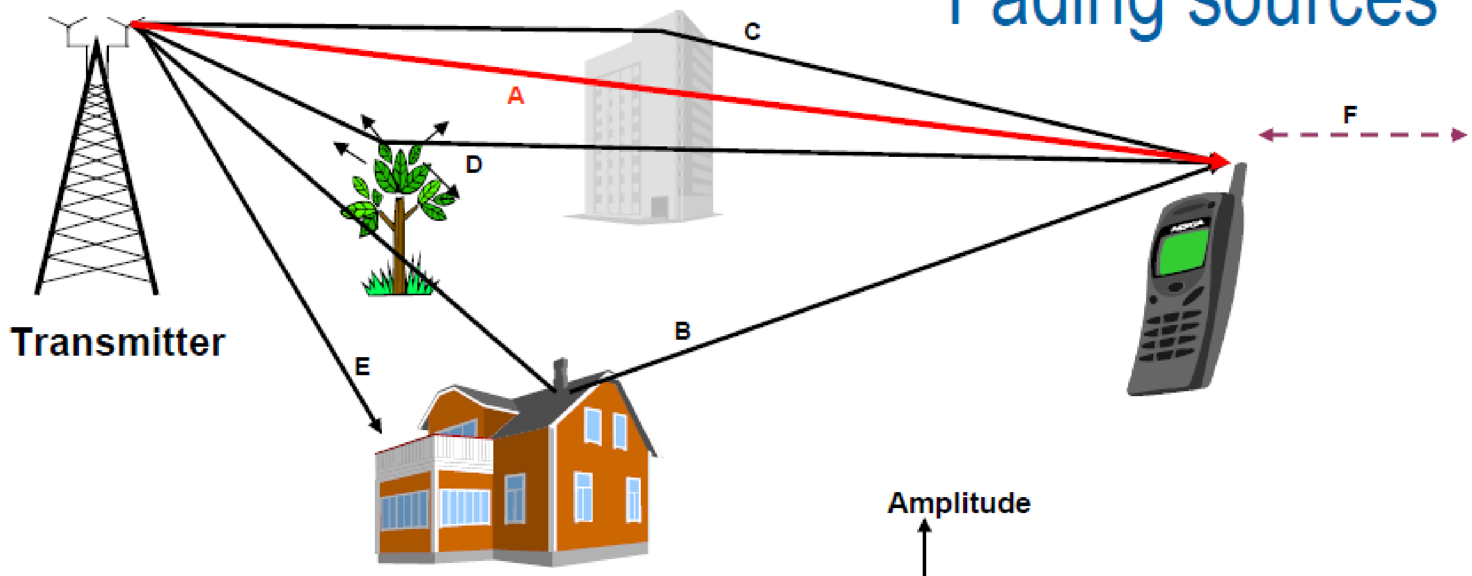
Relevant propagation phenomena for system design

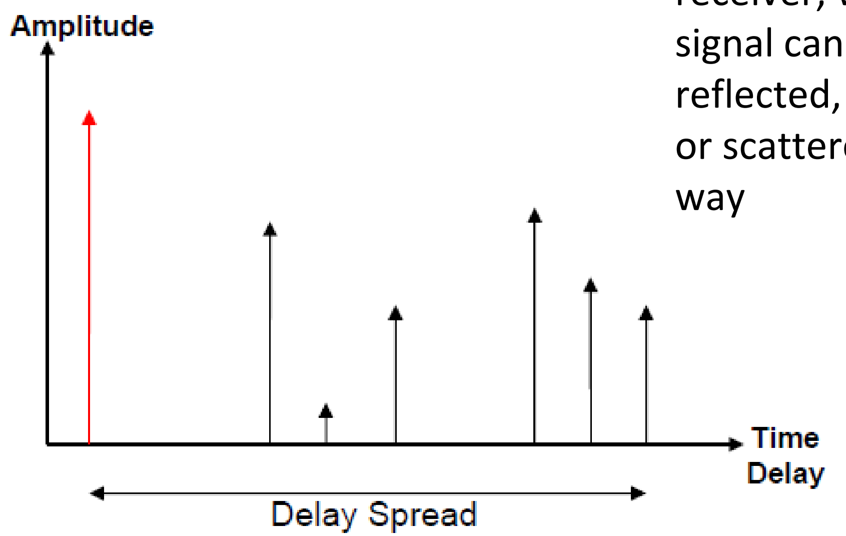
- Mobile systems usually:
  - Have low height antennas on one of the receiving ends (user equipment)
  - Have moderate height antennas on the other side, not always higher than surrounding clutter (buildings, vegetation, etc)
  - The frequencies involved range from dozens of MHz up to a few GHz
  - Other portable/mobile systems in 5 GHz band (WLAN)
  - ITU has also identified additional spectrum above 6 GHz for mobile broadband services 5G. A focus will be on bands above 24 GHz:
    - 24 GHz and/or 28 GHz bands
    - Millimeter wave band: 60 GHz – 90 GHz
- In most cases in an outdoor environment, electromagnetic signals can travel from the transmitter to the mobile receiver along many paths

Relevant propagation phenomena for system design

Fading sources



A: free space
B: reflection
(object is large compared to wavelength)
C: diffraction
D: scattering
(object is small or its surface irregular)
E: shadowing (birth death)
F: doppler



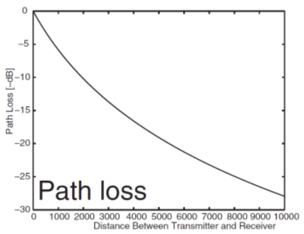
- Wireless channels differ from wired channels by multipath propagation: the existence of a multitude of propagation paths from transmitter and receiver, where the signal can be reflected, diffracted, or scattered along its way

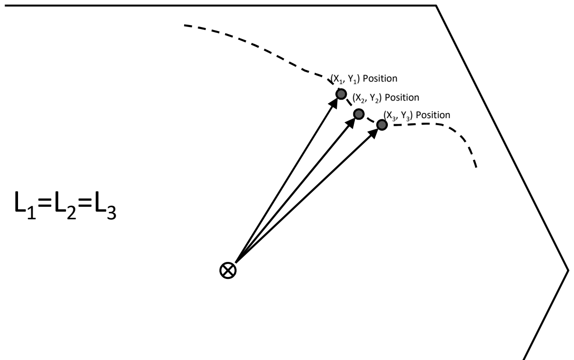
Statistical description of the wireless channel

- In a mobile system, the received signal is usually divided into three components: Path Loss (l), Shadowing (slow fading) (g) and Fast Fading (r)

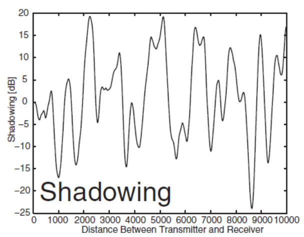
$$l_b(d)=l(d)\cdot g(x,y)\cdot r(t,f)\Rightarrow L_b(d)=L(d)+G(x,y)+R(t,f)$$

- Path Loss:
  - Depends on the tx-rx distance (higher distance means higher loss) and other factors: ie. frequency
  - Depends on the tx-rx profile
  - Relevant for network planning
  - Usually empirical/deterministic value

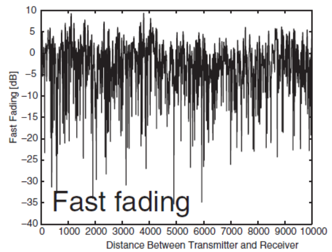




- Shadowing:
  - Depends on the service area characteristics
  - Depends on the specific location where the mobile is located (shadowing by trees, buildings, etc. (x_i, y_i)
  - Independent on the tx-rx distance
  - Statistical (slow varying). Accounts for variations along distances longer than 40λ
  - Relevant for equipment design and network planning



- Fast Fading:
  - Depends on multipath on close elements
  - Time and frequency dependent
  - Statistical (fast varying), changes in a few wavelength distance
  - Independent of tx-rx distance and specific position
  - Relevant for equipment design



Channel models

Channel Model:

- Mathematical representation of the effects of a communication channel through which wireless signals are propagated.
- In a more general case, the channel model is the impulse response of the channel medium in the time domain or its Fourier transform in the frequency domain. The channel impulse response of a wireless communication system typically varies randomly over time.
- Channel models can be classified in four categories:
  - Purely stochastic
  - Path loss
  - Spatial
  - Ray tracing

Channel models

- Purely stochastic Models:
  - Purely stochastic channel models address thermal noise generation and multipath fading channels. They do not require any knowledge of the geometry of the link being modeled:
    - AWGN (Additive White Gaussian Noise) Channel Model: The only impairment to communication is a linear addition of wideband or white noise with a constant spectral density (expressed as watts per hertz of bandwidth) and a Gaussian distribution of amplitude.
    - Multipath Fading Channel Models: Exhibit delay spread, in which multiple copies of the transmitted signal arrive at the receiver. These copies typically are attenuated and phase shifted relative to the original. This channel can be modeled with an impulse response. (e.g. ITU Channel Models)
      - The delay spread of a channel is the time duration between the first and last multipath components with significant energy. If the reciprocal of the delay spread is much greater than the signal bandwidth, then the fading is called frequency flat. If that reciprocal is comparable to or less than the signal bandwidth, then the fading is called frequency selective

Channel models

- ITU Channel Models:
  - The multipath fading is modeled as a tapped-delay line with 6 taps with non-uniform delays. The gain associated with each tap is characterized by a distribution (Ricean with a K-factor>0, or Rayleigh with K-factor=0) and the maximum Doppler frequency.

Outdoor to Indoor and Pedestrian Test Environment Tapped-Delay-Line Parameters

Tap	Channel A		Channel B		Doppler Spectrum
	Relative Delay (ns)	Average Power (dB)	Relative Delay (ns)	Average Power (dB)	
1	0	0	0	0	Classic
2	110	-9.7	200	-0.9	Classic
3	190	-19.2	800	-4.9	Classic
4	410	-22.8	1200	-8.0	Classic
5	ºTM ºTM	ºTM ºTM	2300	-7.8	Classic
6	ºTM ºTM	ºTM ºTM	3700	-23.9	Classic

Vehicular Test Environment Tapped-Delay-Line Parameters

Tap	Channel A		Channel B		Doppler Spectrum
	Relative Delay (ns)	Average Power (dB)	Relative Delay (ns)	Average Power (dB)	
1	0	0.0	0	-2.5	Classic
2	310	-1.0	300	0	Classic
3	710	-9.0	8900	-12.8	Classic
4	1090	-10.0	12900	-10.0	Classic
5	1730	-15.0	17100	-25.2	Classic
6	2510	-20.0	20000	-16.0	Classic

Channel models

Path loss Models:

- Path loss channel models represent the power reduction (attenuation) of a transmitted signal as it traverses the wireless medium.
- Path loss average and median receiver power are calculated, taking into account coverage scenario such as indoor or outdoor, and propagation phenomena.
- Traditional Log-distance (Power exponent) Path loss models are accurate enough to plan for the 2G/3G/4G technologies outdoor scenarios and basic radio coverage plan for bands below 6 GHz (FR1 5G NR systems) (e.g. Hata & COST231-Hata, Breakpoint distance, …)
- Many methods have been proposed to predict path loss with high accuracy and precision in 5G-NR, taking into account high speed data communication and propagation characteristics of the millimeter wave (mm-wave) for FR2 5G NR. (e.g. METIS and COST2100 channel models)

Channel models

- **Log-distance pathloss models** (Power exponent models) :
  - Empirical mathematical formulation for the characterization of radio wave propagation as a function of frequency, distance and other conditions.
  - In general, the average pathloss for a given transmitter and receiver distance d (Km) is given by:

$$L_B = Pathloss = K_1 + 10log(d)^{n}$$

  - Usually n range from 1.5 - 5.5:
    - For free space n = 2.
    - For standard urban environment n = 4.

Channel models

- **Log-distance pathloss models**:
  - Okumura-Hata Model: $L_B = Pathloss = K_1 + K_2 x Log_{10}(d)$

Azterketetan hau ERABILTZEN jakin behar da!

$$k_1 = 69{,}55 + 26{,}16 * \log_{10} \text{f}\ (MHz) - 13{,}82 * \log_{10} H_B - a(hm)$$

$$k_2 = 44{,}9 - 6{,}55 * \log_{10} H_B$$

f: Frequency of transmission (MHz)
H_B: Height of base station antenna (m)
h_m: Height of mobile station antenna (m)
d : Distance between the base and mobile stations (Km).

The Okumura-Hata model is restricted to the following limits:
f: 150 to 1500 MHz
H_B: 30 to 200 m
h_m: 1 to 10 m
d: 1 to 20 km

where $a(h_m)$ is the correction factor for mobile antenna height and is computed as follows:

1) for urban areas:

a) for a small or medium-sized city:

$$a(h_m) = (1.1 \log f - 0.7) h_m - (1.56 \log f - 0.8)$$

where $1 \le h_m \le 10$ m

b) for a large city:

$$a(h_m) = \begin{cases} 8.29(\log 1.54 h_m)^2 - 1.1 & f \le 200\ MHz \\ 3.2(\log 11.75 h_m)^2 - 4.97 & f \ge 400\ MHz \end{cases}$$

2) for suburban areas:

$$L_b = L_b(urban) - 2[\log(f/28)]^2 - 5.4$$

3) for rural areas:

$$L_b = L_b(urban) - 4.78 \log(f)^2 + 18.33 \log f - 40.94$$

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Channel models

- **Log-distance pathloss models**:
  - COST-231 Hata Model: $L_B = Pathloss = K_1 + K_2 x Log_{10}(d)$

$$k_1 = 46{,}3 + 33{,}9 * \log_{10} f\,(MHz) - 13{,}82 * \log_{10} H_B - a(Hm)$$

$$k_2 = 44{,}9 - 6{,}55 * \log_{10} H_B$$

f: Frequency of transmission (MHz)
H_B: Height of base station antenna (m)
h_m: Height of mobile station antenna (m)
d : Distance between the base and mobile stations (Km).

The Cost-231-Hata model is restricted to the following limits:
f: Up to 2600 MHz

where $a(h_m)$ is the correction factor for mobile antenna height and is computed as follows:

1) for urban areas:

a) for a small or medium-sized city:

$$a(h_m) = (1.1 \log f - 0.7) h_m - (1.56 \log f - 0.8)$$

where $1 \leq h_m \leq 10$ m

b) for a large city:

$$a(h_m) = \begin{cases} 8.29(\log 1.54 h_m)^2 - 1.1 & f \leq 200\ MHz \\ 3.2(\log 11.75 h_m)^2 - 4.97 & f \geq 400\ MHz \end{cases}$$

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3) for rural areas:

$$L_b = L_b(urban) - 4.78 \log(f)^2 + 18.33 \log f - 40.94$$

Channel models

- **Log-distance pathloss models**:
  - Breakpoint distance Model: Metodo modernoago-bat edo
    - The received signal power (median power) is assumed that decays as d^{-2} (Friis' law remains approximately valid) until a breakpoint, d_{break}, and from there with d^{-n}.

BEFORE BREAKPOINT

$$p_{RX}(d) = eirp \cdot g_{RX}\left(\frac{\lambda}{4\pi d}\right)^2 \quad for\ d \le d_{break}$$

AFTER BREAKPOINT

$$p_{RX}(d) = p_{RX}(d_{break})\left(\frac{d}{d_{break}}\right)^{-n} = eirp \cdot g_{RX}\left(\frac{\lambda}{4\pi d_{break}}\right)^2\left(\frac{d}{d_{break}}\right)^{-n} \quad for\ d > d_{break}$$

$$d_{break} = \frac{4h_{TX}h_{RX}}{\lambda}$$

h_{TX}, h_{RX}: antennas heights

Puntu bateraino metodo bat, puntu batetik aurrera beste bat.

- 1.5 < n < 5.5, and the actual value strongly depends on the surrounding environment. It can be obtained by regression techniques.

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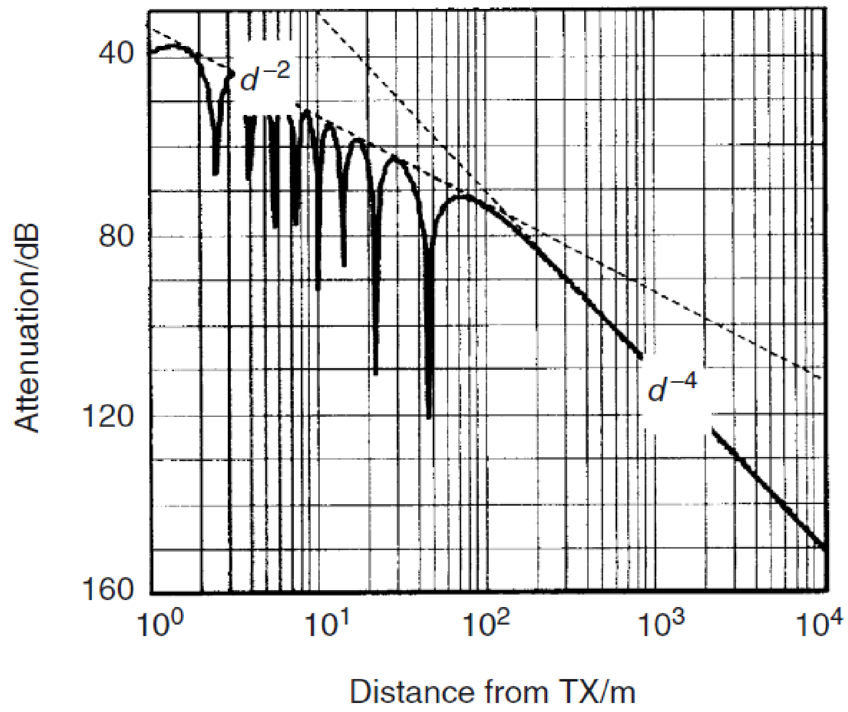
Channel models

- **Log-distance pathloss models**:
  - Breakpoint distance Model :
  - The value of n = 4 is, at best, a mean value of various environments. This d^{-4} law is justified by computing the received power for the case that only a direct (Line Of Sight, LOS) wave, plus a ground-reflected wave, exists.



  - Path loss (inverse of the Path Gain) is then calculated as:

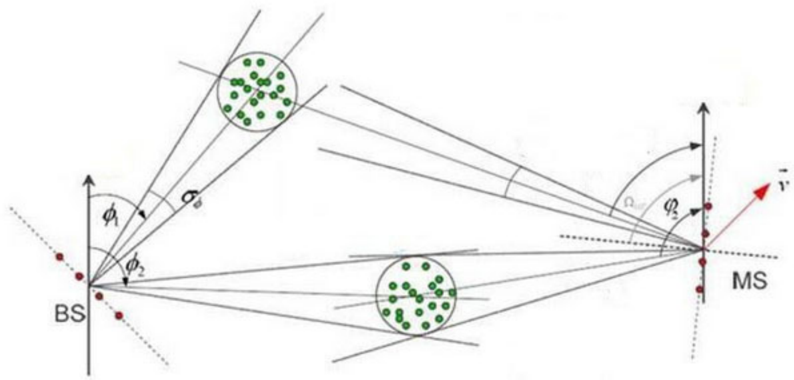
$$l_{PATH}(d) = \frac{eirp \cdot g_{RX}}{p_{RX}(d)} = \left(\frac{4\pi d_{break}}{\lambda}\right)^2 \left(\frac{d}{d_{break}}\right)^n$$

Channel models

- **Log-distance pathloss models**:
  - UMa (Urban Macrocell), UMi (Urban Microcell), and RMa (Rural Macrocell) models:
  - 5G use 3D propagation models defined in 3GPP 36.873
  - The UMa, UMi, and RMa models are applicable to frequency bands 2–6 GHz and then are extended to 0.5–100 GHz in 3GPP 38.901.
  - For example and if we consider the UMa model for Line Of Sight (LOS) case, the path loss formula is given as following :
    - Path loss =28.0+22*log10(d)+20 log10(fc)
      - "d" which is the distance between the transmitter and receiver (cell radius) and the center frequency (fc).
      - If the cell radius correspond to max cell range, then the path loss will correspond to maximum allowed path loss (MAPL).

Channel models

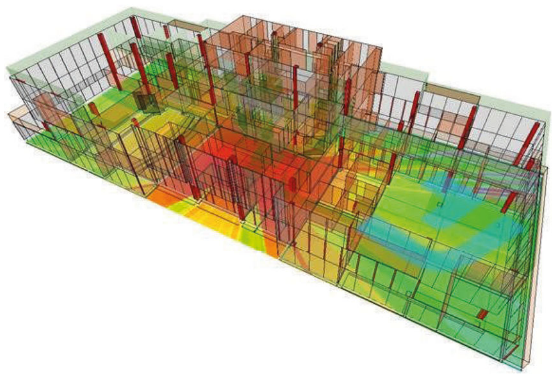
- Spatial Models:
  - Modern wireless systems typically use beamforming to direct energy toward desired receivers and away from interferers. Beamforming requires a transceiver to use antenna arrays, giving rise to multiple-input multiple-output (MIMO) systems
  - Spatial channel models were developed to better represent MIMO links, since previously developed channel models did not account for array geometries and array responses. (e.g. WINNER II channel model)
  - These channel models enable the prediction of the angles of departure (AoD) and arrival (AoA) of signals in a wireless system. These models typically define scatterers that reflect transmitted signals to a receiver.

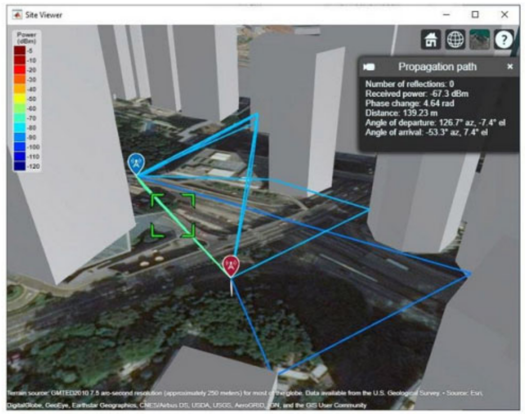


Scatterers between a transmitter and receiver.

Channel models

- Ray Tracing Models:
- RayTracing models computes multiple propagation paths and determine the path loss and phase shift of each ray using electromagnetic analysis, including tracing the horizontal and vertical polarizations of a signal through the propagation path.
- They useprecise building location information to generate outdoor channel models, and precise room information to generate indoor models
- The path loss calculations include free-space loss, reflection losses, and diffraction losses. For each reflection and diffraction, the model calculates losses on the horizontal and vertical polarizations by using the Fresnel equation, the Uniform Theory of Diffraction (UTD), the geometric angle, and the complex permittivity of the interface materials.





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Link budgets of wireless noise-limited systems

- The link budget is the calculation of total gain and loss in the system to conclude the received signal level (P_{Rx}) at the receiver.
- We calculate the link budgets of uplinks and downlinks (the link budgets of uplinks and downlinks are different)
- Usually the limiting link is the uplink and it is recommended to calculate downlink and uplink link budget separately and then consider the worst link.

Link budgets of wireless noise-limited systems

- The following formula is used to calculate the link budget received signal level in the Downlink:

$$P_{Rx}(dBm) = EIRP(dBm) - L_{PATH}(d)(dB) - L_{Other\ Propagation}\,(dB) - MARGIN(dB) + G_{RX}(dBi) - L_{Other\ Rx}(dB)$$

  - P_{Rx}: Received Signal Level at UE receiver, over the channel bandwidth
  - EIRP: Basestation transmit EIRP, over the channel bandwidth
  - $L_{PATH}(d)$: Path Loss. It is obtained from any Path Loss model as function of outdoor distance between the transmitter and receiver (cell radius), "*d*". Average path loss at a given distance.
  - $L_{other\ Propagation}(d)$: Propagation losses additional to the average losses given by the Propagation Model. The most important ones are: penetration loss (dB), foliage loss (dB) and body block loss (dB)
  - MARGIN: To take into account some interactions between different effects, in addition to the averaged path losses. For example, interference margin (dB), rain/ice margin (dB), slow fading margin (dB) and body block loss (dB)
  - G_{RX}: Receiver antenna gain (UE antenna gain)
  - $L_{Other\ Rx}$ = Losses between the receiving antenna and the receiver, due to cables, connectors, passive elements,..

Link budgets of wireless noise-limited systems

- We set up link budgets for noise-limited systems:
  - When the spectrum is regulated and the network operator can control the interference.
  - In absence of interference (WLANs and even any cellular network if the user density is low)
- The transmission quality is often described in terms of the Bit Error Rate (BER) probability
- Depending on the modulation scheme, coding, and a range of other factors there is a relationship between SINR and BER for each digital communications systems. The required transmission quality requires a minimum Signal-to-Interference and Noise (SINR) at the receiver
- SINR ($\text{SINR}_{\text{Minimum required}}$) are vendor specific values which depend mainly on hardware performance and Modulation Coding Scheme decoding performance

Link budgets of wireless noise-limited systems

- $SINR_{Minimum\ required}$ (dB) = Receiver sensitivity (dBm) - Interference margin (dB) - Noise power (dBm): SINR_MIN = P_MIN(dBm) - [N(dBm) + I(dB)]
  - The noise that disturbs the signal can consist of several components: Thermal noise, Man-made noise, and Receiver noise. It is defined by Noise Power at the receiver (N): $N = 10\log(KTBW_N)$
  - Receiver sensitivity (S) corresponds to the received power to provide a certain minimum transmission quality (minimum required Signal-to-Interference and Noise Ratio (SINR)).
  - Interference margin: The effect of interference is modeled as a margin on the thermal noise level that quantifies the effect of interference from neighboring cells. According to some bibliographical references, this margin varies between 1 and 4 dB depending on the environment, the layout of the network and the distance between neighboring cells.

Link budgets of wireless noise-limited systems

- The goal of the planning methods is:
  - To calculate the Receiver sensitivity as: S (dBm) = $SINR_{Minimum\ required}$ (dB) + Interference margin (dB) + Noise power (dBm)
  - To calculate the L_{PATH} at a given EIRP using the link budget
  - To Calculate the coverage distance d from a Propagation Model for calculated L_{PATH} .
- At any point in the coverage area you can compare the received signal level (Rx) to the receiver sensitivity (S) to check if the channel status is pass or fail. The channel status is "Pass" if the received signal level is better than the reception sensitivity, else it is "Fail".
- Shanon's theorem can be used to relate the theoretical maximum transmitted bit rate to the SINR required for a given channel bandwidth.

Link budgets of wireless noise-limited systems

- SNR required for different type of LTE signal:

Required Base Band SNR		
SNR Requirements Versus Coding Rate and Modulation Scheme		
Modulation	**Code Rate**	**SNR [dB]**
QPSK	1/8	-5.1
	1/5	-2.9
	1/4	-1.7
	1/3	-1.0
	1/2	2.0
	2/3	4.3
	3/4	5.5
	4/5	6.2
16 QAM	1/2	7.9
	2/3	**11.3**
	3/4	12.2
	4/5	12.8
64 QAM	2/3	15.3
	3/4	17.5
	4/5	18.6

Link budgets of wireless noise-limited systems

- Shannon Theorem:
  - The Shannon limit or Shannon capacity establishes the maximum bitrate of error-free data that can theoretically be transmitted over a communications channel of a specified bandwidth in the presence of noise.

$$R = BW \times log_2(1 + SINR) \qquad Spectral\,Efficiency = \frac{R}{BW}$$

    - R is the channel capacity (Bit Rate) in bits per second, that can theoretically be transmitted, in bits/s.
    - BW is the bandwidth of the channel in Hz
    - SINR is the required signal-to-interference and noise ratio at the receiver, expressed as a linear power ratio, not as logarithmic decibels, necessary to transmit the Bit Rate R.

Interference-limited systems

- Case that the interference is so strong that it completely dominates the performance, so that the noise can be neglected.
- The complex computations follow the link budget computations of the previous section.
- One difference between interference and noise lies in the fact that interference suffers from fading, while the noise power is typically constant (averaged over a short time interval).