Department of Computer Engineering & Informatics

Signal Processing and Communications Lab

Wireless and Mobile Communications

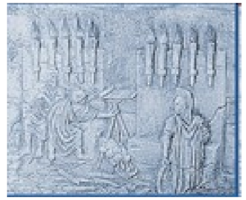
Introduction

Presentation Outline

- Basic concepts regarding «wireless» and «mobile» communications
- Main historical milestones of wireless communications
- Evolution of main wireless standards
- New challenges and goals (5G, B5G, 6G)
- Basic architecture of a Cellular network
- The main components of a wireless digital com system
- Course syllabus and other useful information

Wireless and Mobile Communications

- Wireless communications refers to any system transmitting information from a transmitter to a receiver, through the air or water without requiring any cable or wires or other electronic conductors.
- When the transmitter or/and the receiver are not static (e.g., a moving person, car, etc.) wireless communications can also be referred as mobile communications (or cellular com).
- Some types of wireless communications:
  - Radio and Television
  - Microwave links and Repeaters
  - Cellular Communications
  - Wireless radio
  - Radar
  - Satellite Communications
  - Wi-Fi and other LANs
  - Sensor networks



Historical milestones of wireless communications (1/5)

- 1820: Hans Christian Oersted discovered that electric currents create magnetic fields
- 1831: Michael Faraday demonstrated that an electric current can be induced by moving a magnet
    - that is, a changing magnetic field creates an electric field
- 1867: Based on previous work, James Maxwell predicted the existence of electromagnetic waves and established the basic theory (a set of coupled partial differential equations plus the Lorentz force law)
- 1887: Heinrich Rudolf Hertz proved the existence of electromagnetic waves (wireless signal transmission)
- 1890: O Edouard Branly demonstrated the first sensitive device for detecting radio waves, named the coherer

Historical milestones of wireless communications (2/5)

- 1896: Guglielmo Marconi developed a wireless telegraph system
- 1897: Marconi filed a patent wireless telegraph system
- 1897: The first “Marconi station” was established (between the Needles islands and English coast)
- 1898: Wireless telegraphic connection between England and France
- 1901: Marconi succeeds in sending the first radio transmission across the Atlantic Ocean (from Cornwall to Newfoundland)
- 1902: Transatlantic bidirectional connection
- 1909: Marconi was awarded with the Nobel prize in Physics

Historical milestones of wireless communications (3/5)

Voice over Radio

- 1914: First voice over radio transmission
- 1920s: Mobile receivers installed in police cars in Detroit
- 1930s: Mobile transmitters developed (radio equipment occupied most of police car trunk)
- 1935: Frequency modulation (FM) system demonstrated by Edwin Howard Armstrong
- Major developments in electronics (vacuum tube, transistor, IC) and in telecommunications theory

Historical milestones of wireless communications (4/5)

Cellular Mobile Telephony

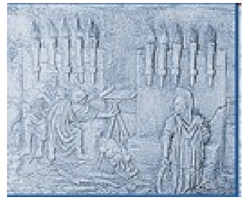
- 1979: H NTT/Japan deployed the first cellular communication system
- 1983: The so-called Advanced Mobile Phone System (AMPS) was deployed in US (in 900 MHz band, supporting 666 duplex channels)
- 1989: Groupe Spècial Mobile – GSM in Europe defined the first ever digital cellular standard
- 1991: The Digital Cellular phone system (IS-54) was introduced in US
- 1993: IS-95 code-division multiple-access (CDMA-based) spread-spectrum digital cellular system deployed in US

Historical milestones of wireless communications (5/5)

PCS and Beyond

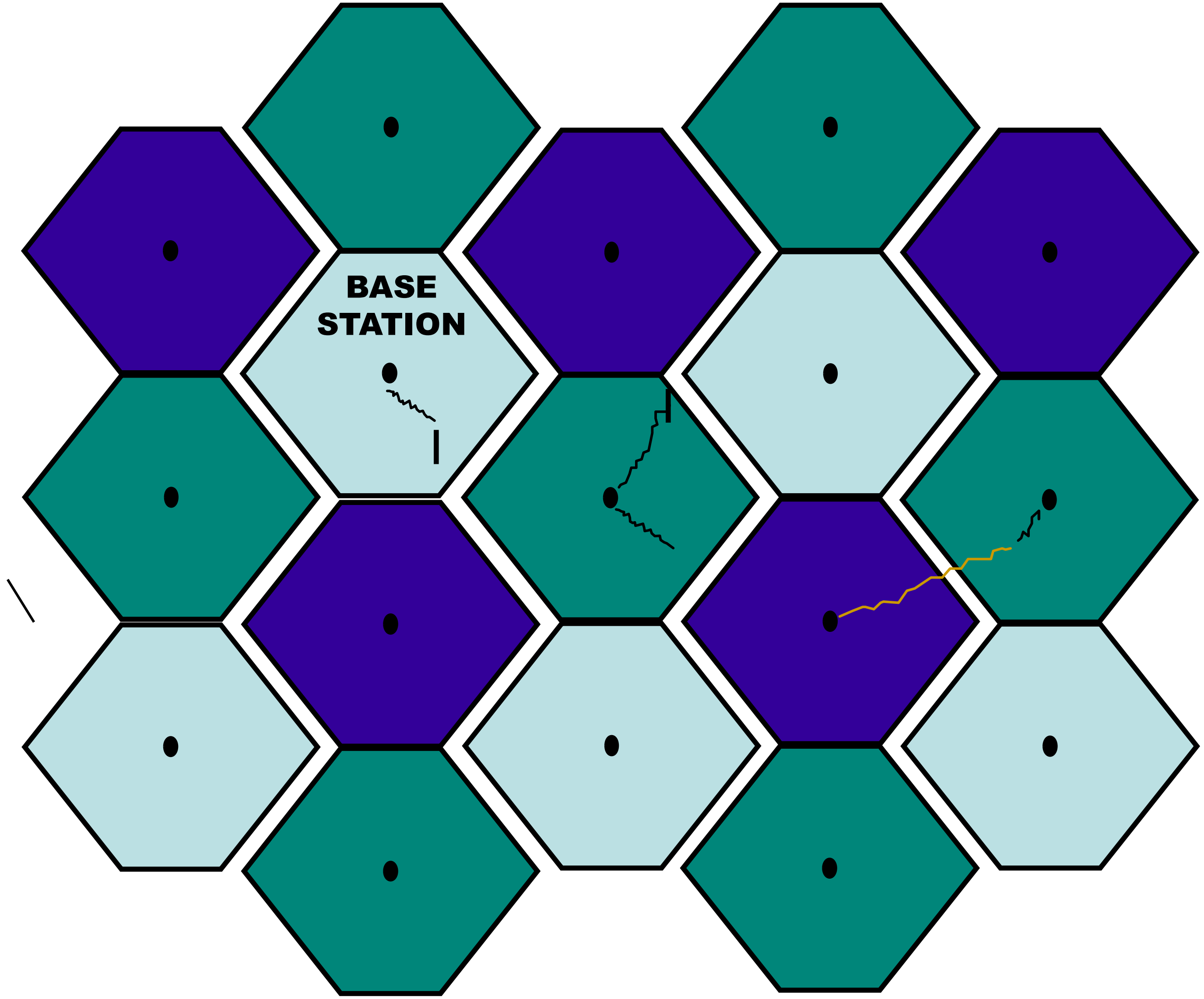
- 1995: International and national level boards auctioned off new frequency bands for Personal Communications Systems (PCS) at 1.8 GHz
- 2000: Third generation cellular system standards (CDMA2000, UMTS)
- 2005: Number of cellular telephone users more than 2B worldwide (10M in 1990)
- 2009: Pre-4G systems (e.g., WiMax, LTE)
- Today: 4G Networks (True 4G, LTE-A, WiMAX-R2) in use, 5G first deployed in 2019, intensive research towards 6G
- Meanwhile the number of cellular telephone users > 15B

Mobile Communications: Overview

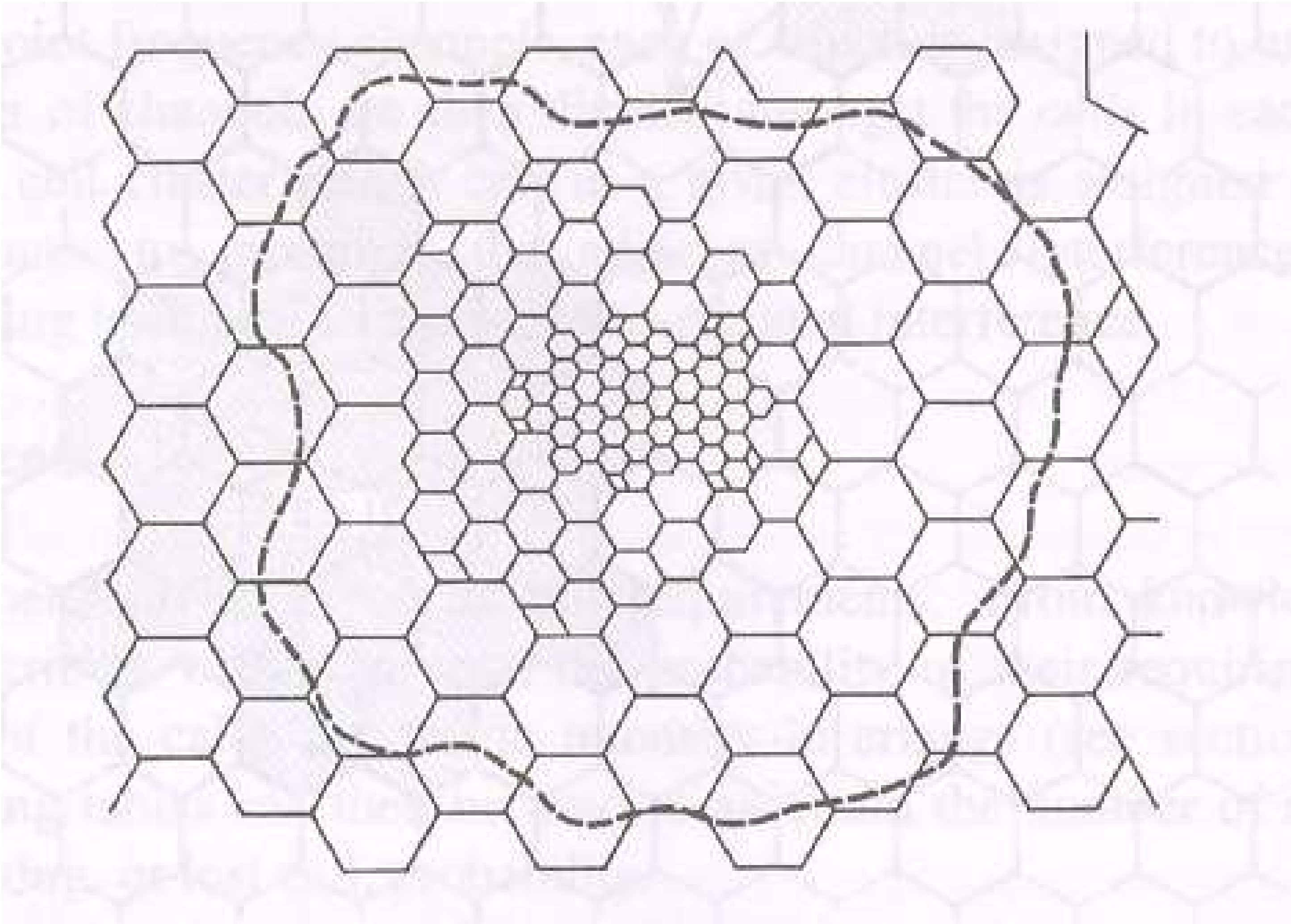


- Multiple relays are involved with low (up to very low) power transmitters
- The network is spatially distributed over areas called "cells"
- Each cell has a corresponding base station that includes a transmitter, a receiver and a controller
- Each of these cells is assigned with multiple frequencies. The group of frequencies can be reused in other cells, provided that the same frequencies are not reused in adjacent cells (not such a stringent constraint any more)
- Alternatively, all base stations use all frequencies but work together to deal with interference (Cellular → COMP → Cell-Free)

Overview cont. : The “Cell” concept



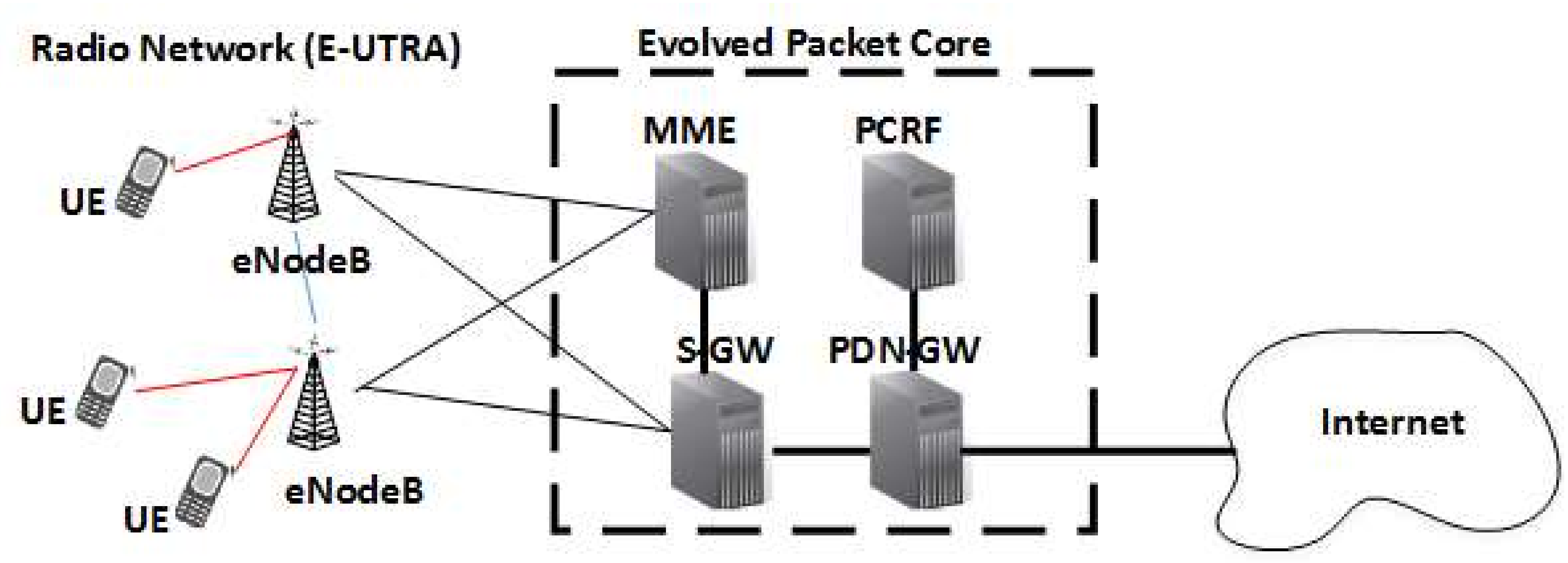
Overview cont. : Cellular networks in urban centers



Overview cont. : Handoff (Handover)

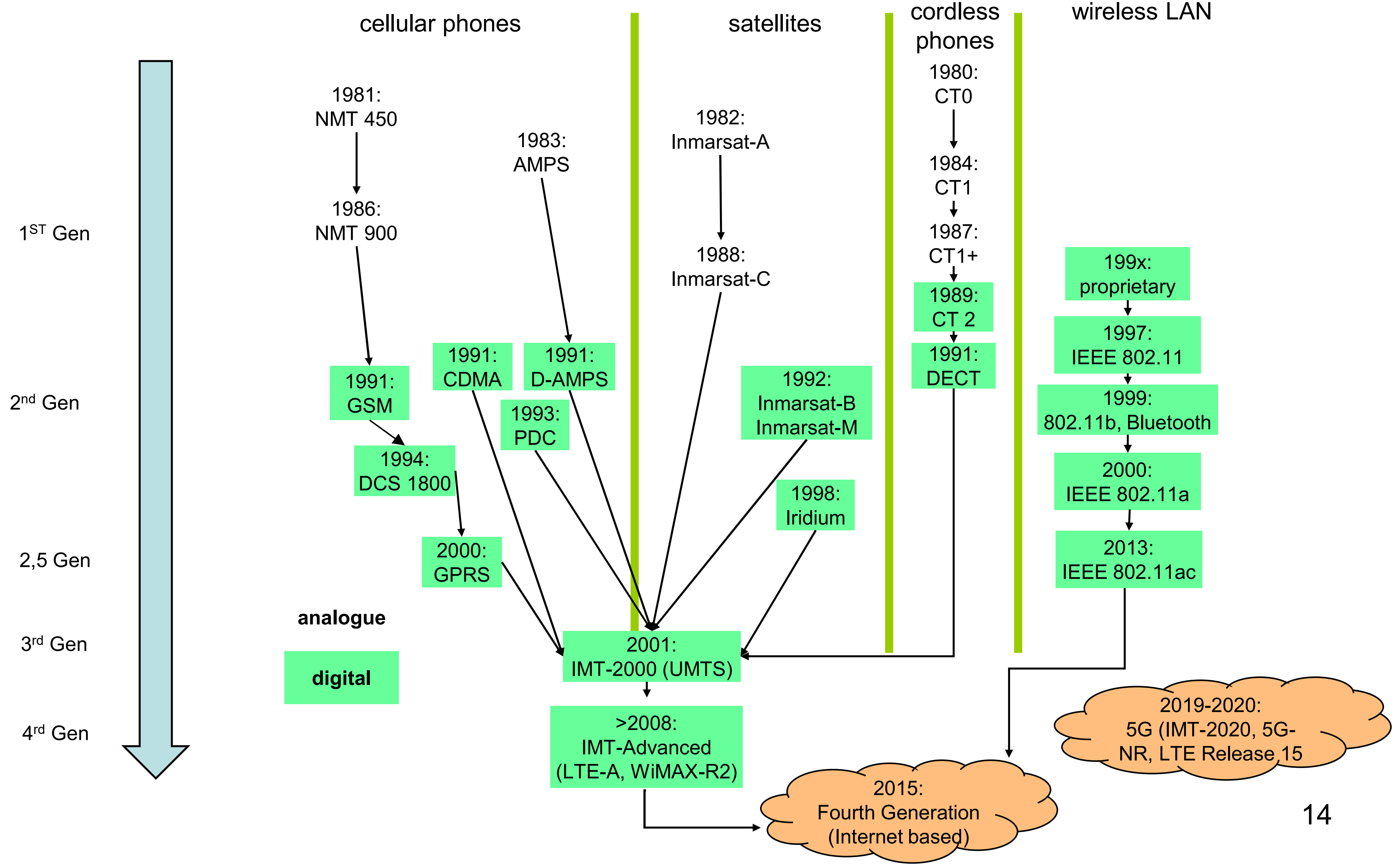
- What happens when a user moves from one cell to another during a call?
  - The neighboring base station takes over its service.
- This process is called handoff (or handover).
- Issues to be considered:
  - Who decides whether handoff should take place or not (mobile device, BS, or both)?
  - How frequently should handover take place; Frequent and pointless handover must be avoided.
  - How will the mobile, the previous BS and the next BS be notified?
  - Could it be served by multiple stations at the same time?

Overview cont. : Architecture of Long Term Evolution (LTE)

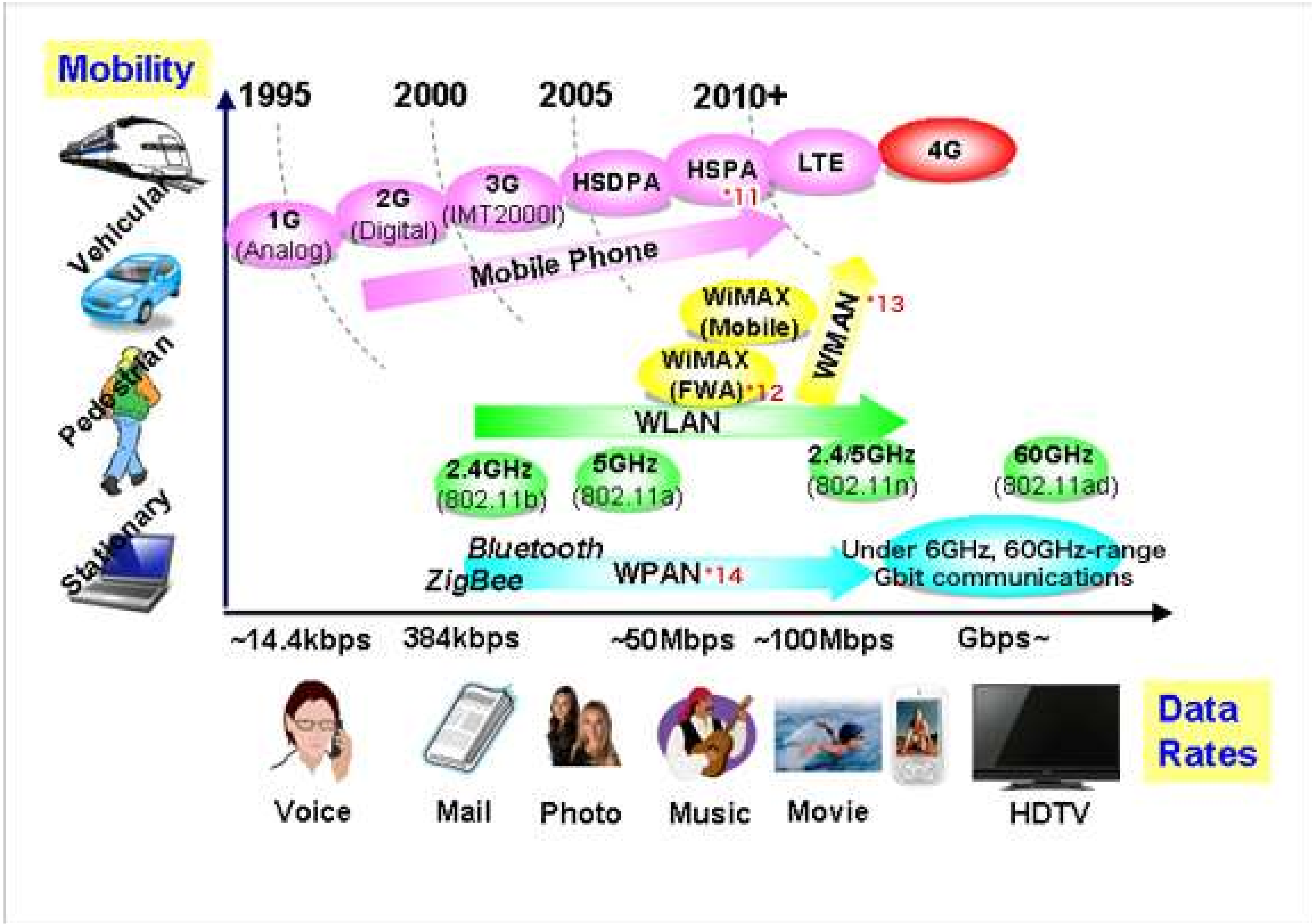


MME: Mobility Management Entity
S-GW: Serving GateWay
PDN-GW: Packet Data Network GateWay
PCRF: Policy and Charging Rules Function
E-UTRA: Evolved Universal Terrestrial Radio Access

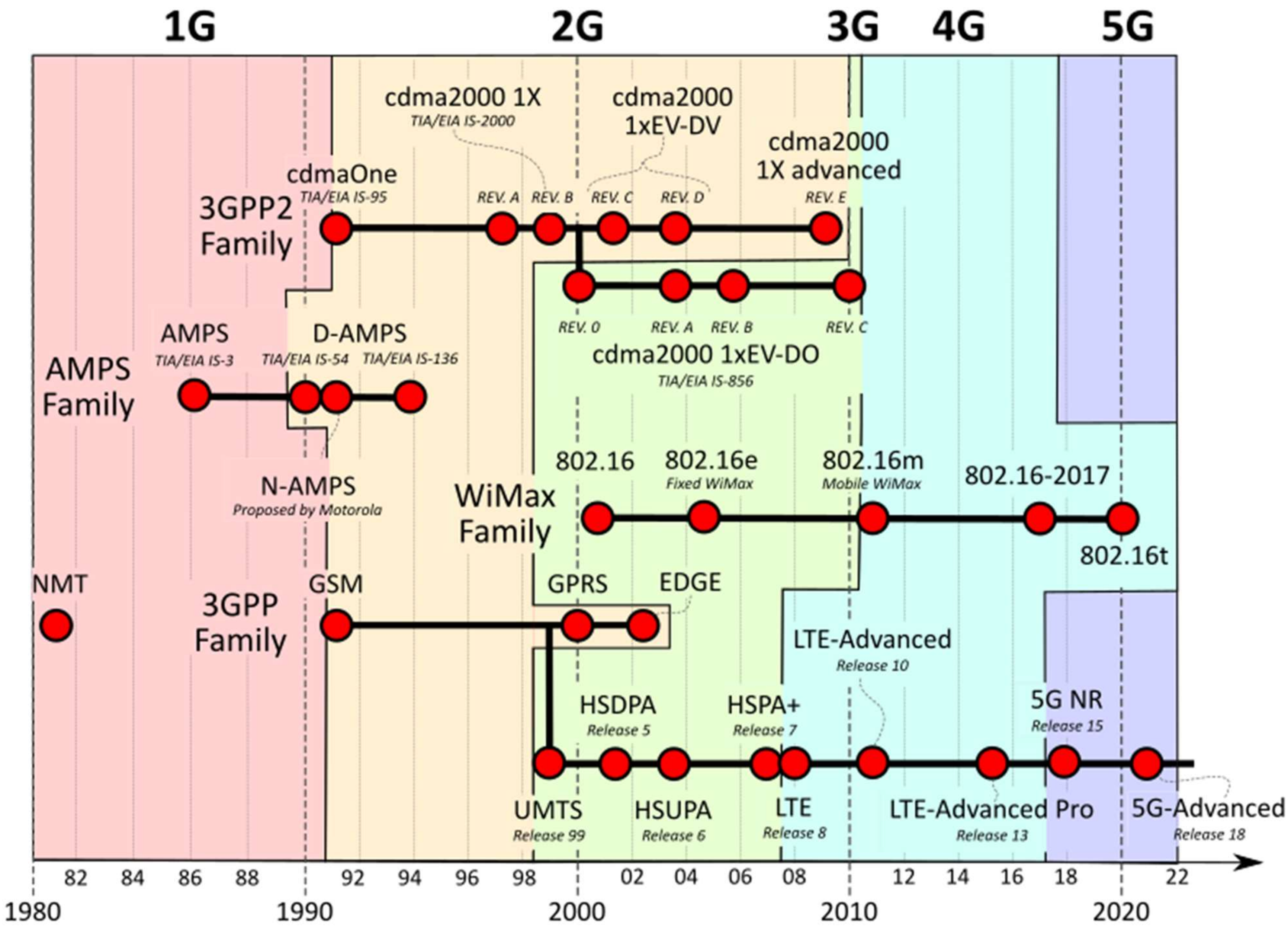
Evolution of standards until 4G (1/3)



Evolution of standards until 4G (2/3)

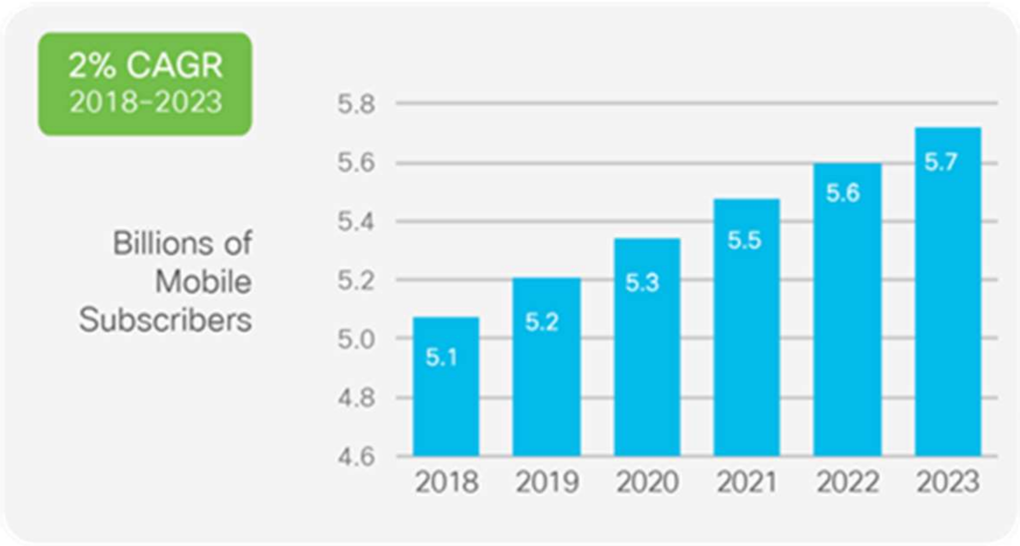


Evolution of standards until 4G (3/3)

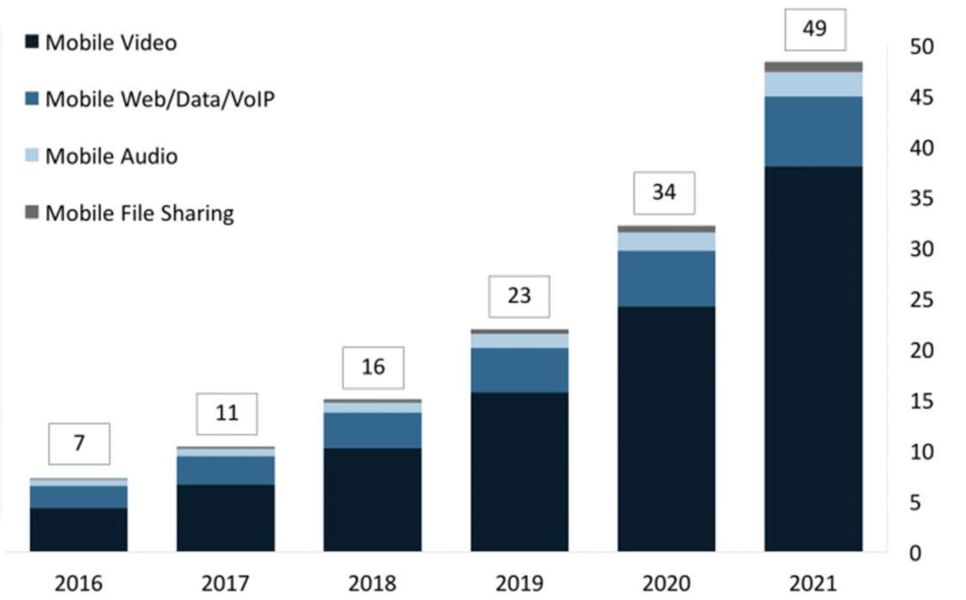


From 4G to 5G and beyond (1/5)

- Wireless networks have gained popularity due to:
  - New services (data transfer/ multimedia content, cloud, etc.), usage cost reduction, etc..
- The number of users (humans or not), the amount of data and the number of interconnected devices are growing rapidly and give rise to new challenges



Global Monthly Mobile Data Traffic, By Type
In exabytes



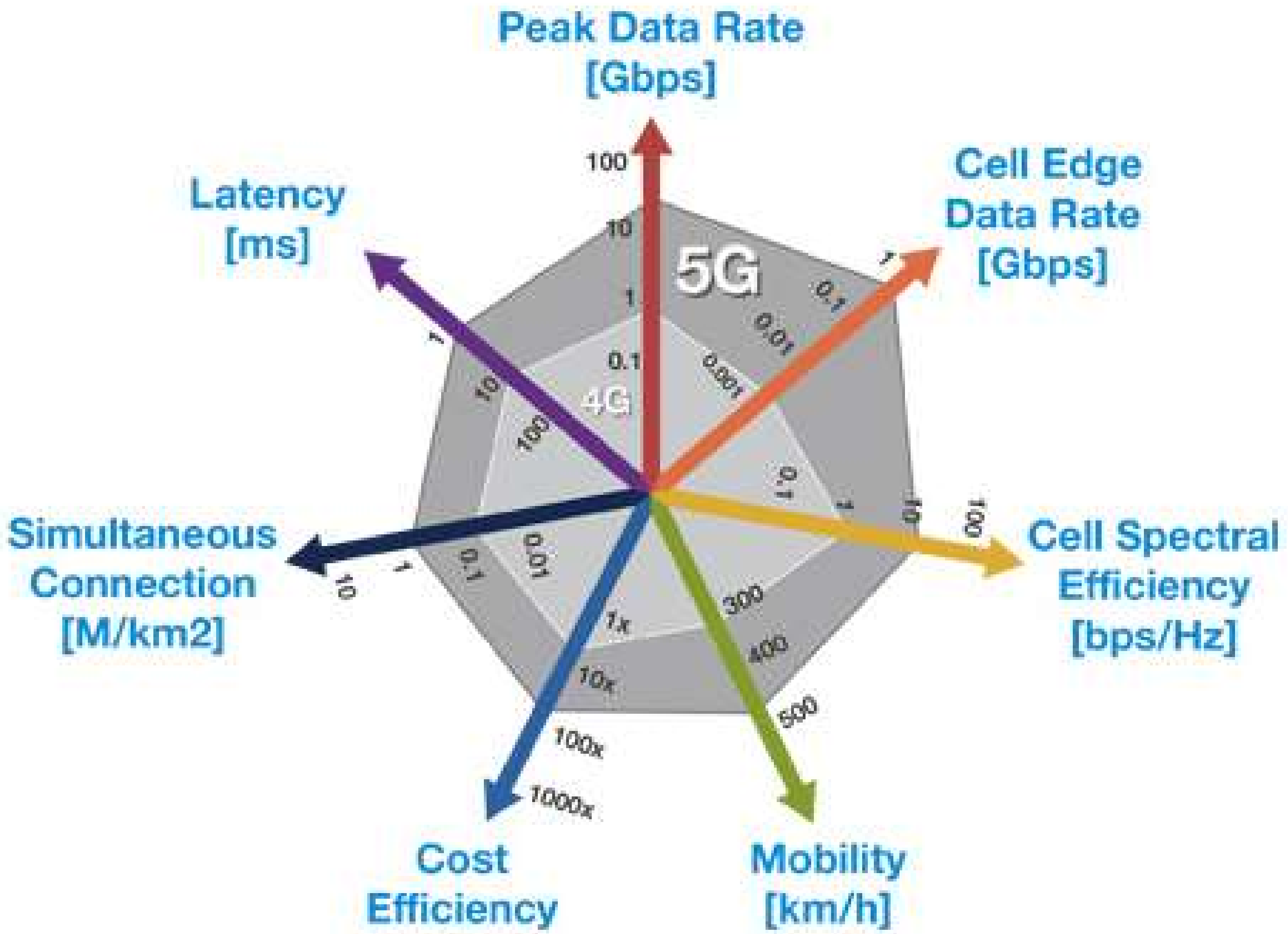
Source: Cisco, BI Intelligence calculations, 2017

BI INTELLIGENCE

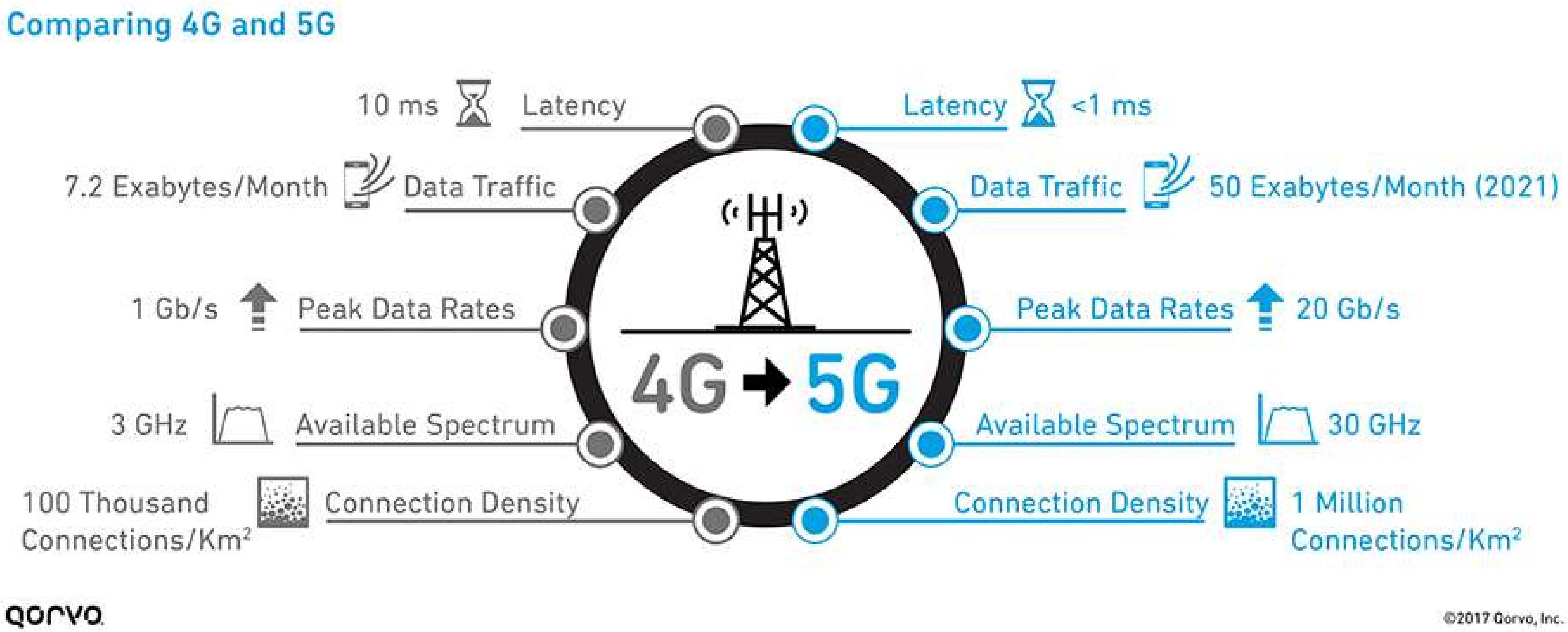
From 4G to 5G and beyond (2/5)

- Existing 4G networks and technologies were unable to cover the new demands for wireless networking
- 5G Networks have been designed to overcome these challenges and promising:
  - 1000x growth in the amount of data per region
  - 10x to 100x growth in the amount of interconnected devices
  - 10x to 100x higher data rates
  - 10x growth in battery’s autonomy for low power transmition between engines
  - 5x reduction of communication delay
- Supported scenarios and applications :
  - Device to device communication , communication between multiple devices, mobile networks, high density user networks, communications with high reliability requirements .
  - Increased / virtual reality, telemedicine, infrastructure security, IoT, autonomous cars, etc..

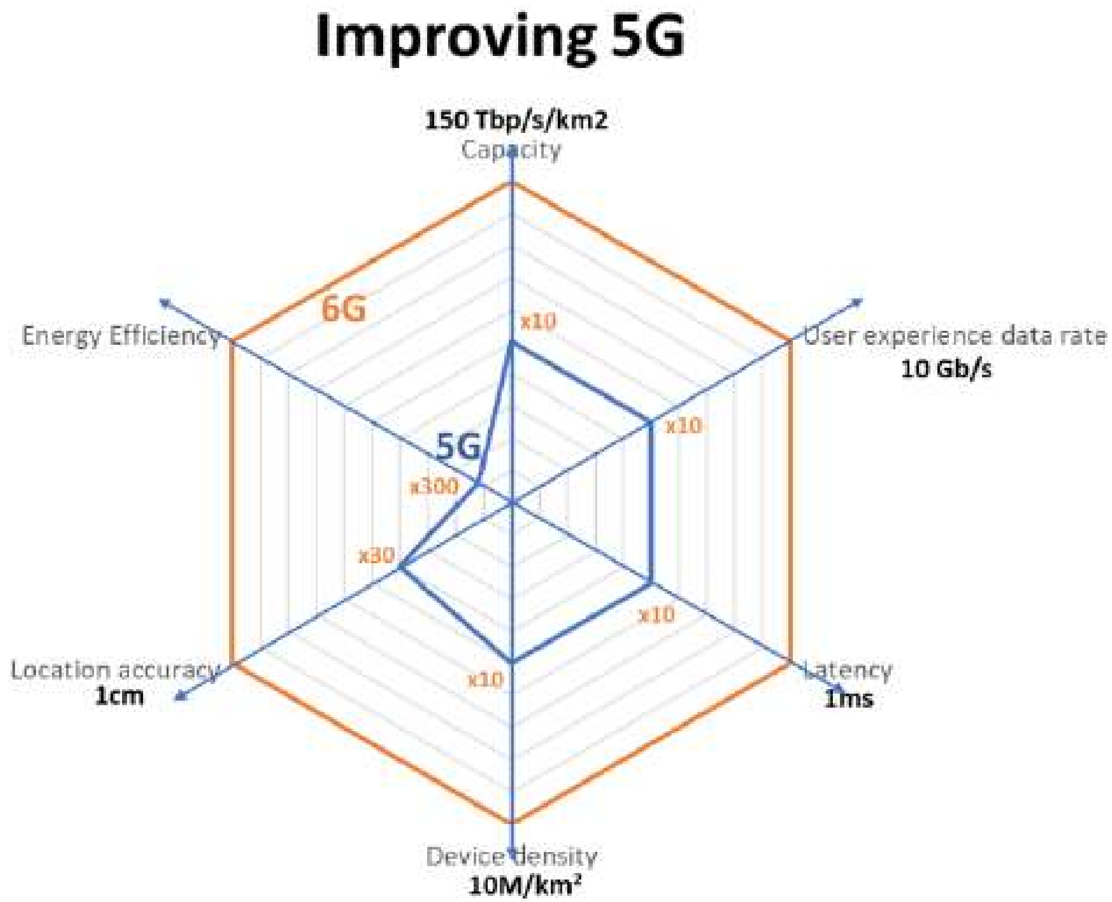
From 4G to 5G and beyond (3/5)



From 4G to 5G and beyond (4/5)



From 4G to 5G and beyond (5/5)



Key Performance Indicators (KPIs)

Target KPI	5G NR (Rel.16) 2020	Short-term Evo. ~2025	Medium-term Evo ~2028	Long-term Evo. ~2030
Spectrum	<52.6 GHz	<150 GHz	<300 GHz	<500 GHz
Bandwidth	<0.5 GHz	<2.5 GHz	<5 GHz	<10 GHz
Peak Data Rate	DL: >20 Gbps UL: >10 Gbps	DL: >100 Gbps UL: >50 Gbps	DL: >200 Gbps UL: >100 Gbps	DL: >400 Gbps UL: >200 Gbps
User Data Rate	DL: >100 Mbps UL: >50 Mbps	DL: >500 Mbps UL: >250 Mbps	DL: >1 Gbps UL: >0.5 Gbps	DL:>2 Gbps UL: >1 Gbps
Density	>1 device/sqm	>1.5 device/sqm	>2 device/sqm	>5 device/sqm
Reliability [BLER]	URLLC: $>1\text{-}10^{-5}$	$>1\text{-}10^{-6}$	$>1\text{-}10^{-7}$	$>1\text{-}10^{-8}$
U-Plane Latency	URLLC: <1 ms	<0.5 ms	<0.2 ms	<0.1 ms
C-Plane Latency	<20 ms	<10 ms	<4 ms	<2 ms
Energy Efficiency (Network/Terminal)	Qualitative	>30 % gain vs IMT-2020	>70 % gain vs IMT-2020	>100% gain vs IMT-2020
Mobility	<500 Km/h	<500 Km/h	<500 Km/h	<1000 Km/h
Positioning accuracy	NA (<1 m)	<30 cm	<10 cm	<1 cm

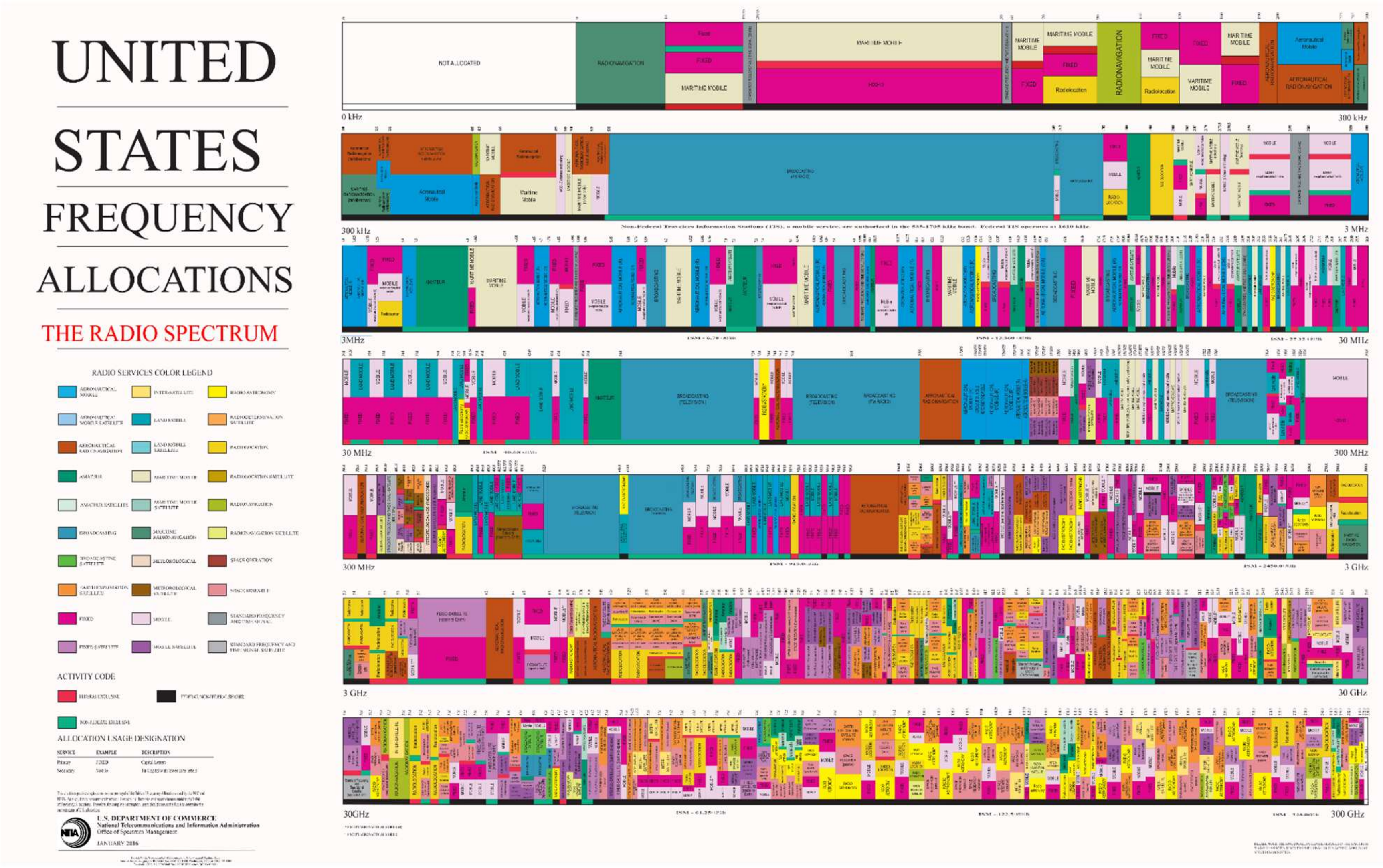
Current research challenges (1/3)

1) Spectrum re-farming and reutilisation, as well as co-existence;
2) Millimetre wave systems;
3) Optical wireless communications (OWC), especially VLC;
4) Terahertz communications including new materials (graphene);
5) Massive and ultra-massive MIMO including intelligent reflecting surface;
6) Waveform, non-orthogonal multiple access and full-duplex;
7) Enhanced modulation and coding;
8) Integrated positioning and sensing including radar;
9) Random access for massive connections;
10) Wireless edge caching for further increased spectrum and energy efficiency.

Technological Areas	Indicative list of promising research areas
ubiquitous availability	Integrated fixed mobile architecture Satellite communications
infinite network capacity	Spectrum re-farming and Reutilization mmWave, Terahertz, VLC communicati Satellite communications Ultra-massive MIMO Flexible capacity scaling
Throughput	Ultra-massive MIMO Enhanced modulation and coding Optical wireless integration
Ultra-low e2e latency	Media access control Edge/fog computing
Security	Software defined security Network wide security Slice-specific and convergence on common software defined patterns Distributed trust systems
Energy efficiency	extended bandwidth adaptation improved RF
Massive IoT Service management	Scalable management of massive deployment Distributed autonomous and cooperative computing

Current research challenges (2/3)

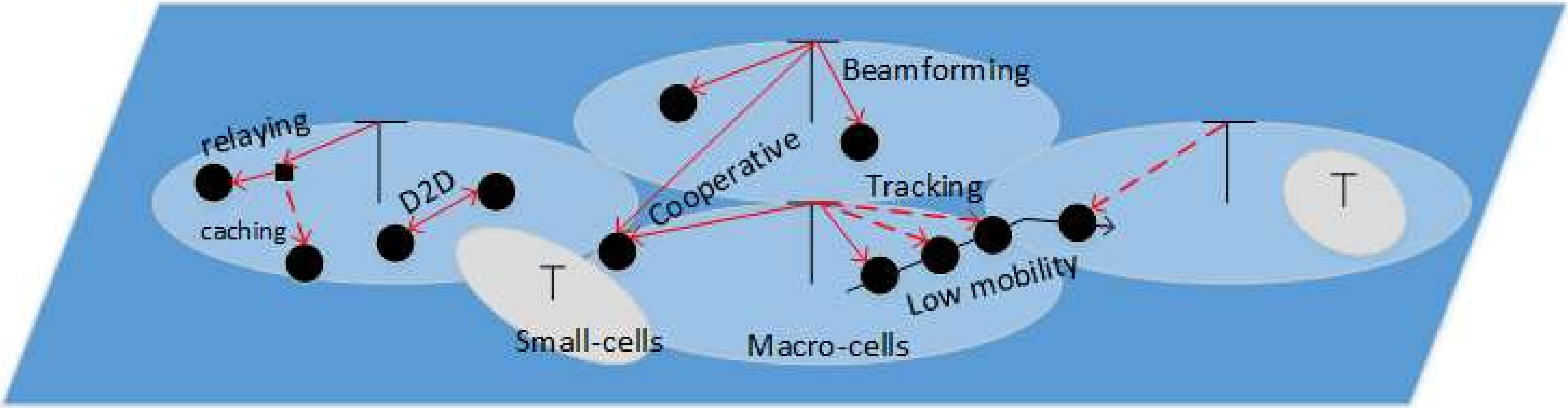
Συχνοτικές περιοχές: Φαινομενικά υπερπλήρεις



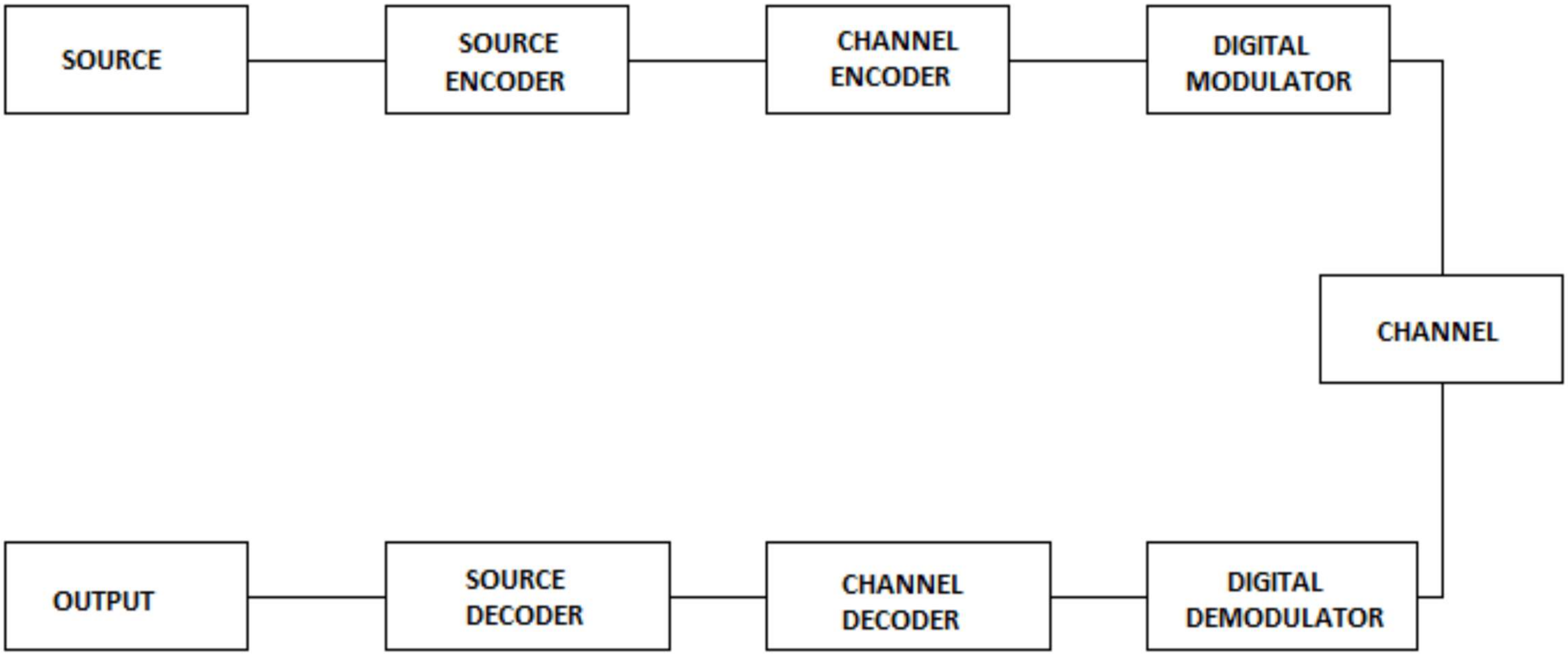
Current research challenges (3/3)

– Massive MIMO systems
– mmWave communications
– Non-Orthogonal Multiple Access and Full Duplex
– Integrated Communications & Sensing (& Computing)
– Reconfigurable Intelligent Surfaces
– Wireless Edge Cashing
– Cooperative Communications (D2D, M2M, …)
– Cognitive Radio Networks
– ML & AI in Communications (Edge ML)
– ML for COM & COM for ML

5G Networks: Integrating some of the new technologies



Digital Telecommunication System: Basic Structure (1/6)



Digital Telecommunication System (2/6)

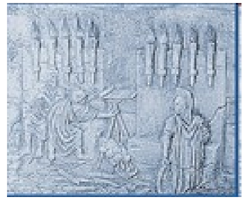
- **Source:**
  - Analog signal (e.g., sound, video)
  - Digital (discrete time– discrete values)
  - An analog signal can be transmitted directly using analog modulation techniques such as FM, AM, PM etc.
  - For digital transmission it must be sampled and quantized
  - Advantages of Digital vs Analog Transmission:
    - Digital signal processing offers signal reconstruction over long distances, less noise, distortion, and interference.
    - Redundant information is being discarded
    - Digital systems are generally more flexible, scalable and cheaper
    - Information transmission is by far more secure and privacy preserving

Digital Telecommunication System (3/6)

- **Source Encoding – Decoding**
  - The output of the source is a digital sequence
  - It must be represented with as few bits as possible
  - Redundant information must be discarded

- Much of the information circulated is multimedia data
  - Encoders with high compression (low Bit rate) and good quality after decompression are preferred

Digital Telecommunication System (4/6)



- **Channel Encoding - Decoding**
  - Redundant information is being added in a controlled and systematic manner
  - These bits do not convey information, but enable the decoder to detect or even correct errors

- Random Error Correction Codes – Burst Error-Correcting Codes
  - Block Codes – Convolutional Codes

- Block codes:
  - Block *k bits* of information correspond to *n bits (n>k)*
  - The amount of redundant information is calculated by the ratio *n/k*.
  - E.g., Hamming, Hadamard, Golay, Cyclic Codes, BCH, Reed-Solomon

- Convolutional Codes:
  - The continuous information sequence corresponds to a continuous sequence of encoded bits
  - Encoder: its structure consists of shift registers
  - Decoder: Viterbi Algorithm is often used

Digital Telecommunication System (5/6)

- **Digital Modulation - Demodulation**
  - Only (properly designed) continuous waveforms can be transmitted through physical channels
  - Modulation is the process of converting an input sequence of bits into a waveform suitable for transmission:

    ‘0’ → $s_0(t)$, $0<t<T_s$

    ‘1’ → $s_1(t)$, $0<t<T_s$
  - *This process in called Binary Modulation*
  - A group of b bits corresponds to $M=2^b$ waveforms:

    ‘0’ → $s_0(t)$, $0<t<T_s$

    ‘1’ → $s_1(t)$, $0<t<T_s$

    … …

    ‘M-1’ → $s_{M-1}(t)$, $0<t<T_s$
  - *This process in called M-ary Modulation*

- Advances in VLSI and DSP have contributed to making digital configuration more efficient than analog

Digital Telecommunication System (6/6)

- **Advantages:**
  - More robust against channel distortions (noise)
  - Easy multiplexing of different information
  - Stronger Security
  - Digital signal processing (detection codes, compression, encryption, equalization) improves channel performance
  - Flexible S/W implementations

Channel (1/2)

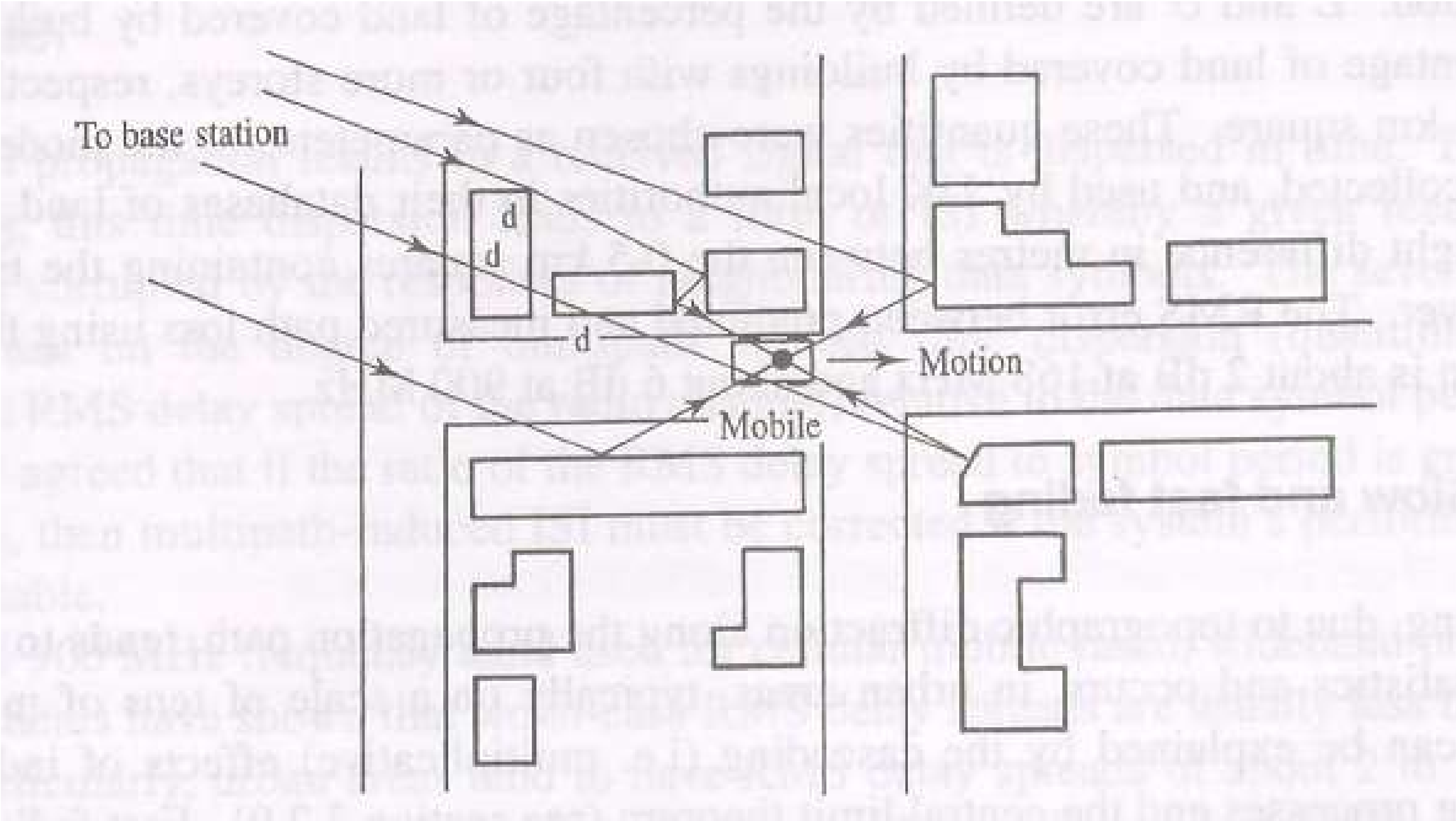
- **Channel:**
  - The physical transmission medium from a transmitter to a receiver
  - Atmosphere, water (underwater communications), wire, optical fiber

Degradations:
  - Added noise, white, Gaussian.
    - Introduced at the receiver input due to the amplifier.
    - Noise sources: thermal noise in the physical medium and in the emission-reception systems, radio-radiations, etc.
  - Impulsive noise
    - Consists of large quiet intervals and short-duration, high-amplitude burst of noise energy
  - InterSymbol Interference - ISI
  - Other types of Interference (intercarrier, between users, etc)

Channel (2/2)

- **Wired channel:**
  - Relatively stationary and predictable
- **Wireless channel:**
  - random, hard to analyze
  - a transmission path can differ significantly from LOS to the case where it is obstructed by mountains, buildings, etc.
  - Analysis is being done statistically and based on measurements
- **The mobile channel:** Particularly difficult, with significant and varied degradations
- Transmission types: LOS, Reflection, Diffraction, Scattering

Mobile Communications: Means of Transmit



LOS, Reflection, Diffraction, Scattering

Multiple Access Mechanisms

- Multiple access mechanisms
- Spectrum sharing to increase the capacity of a system
- Some of the basic techniques:
  - FDMA (Frequency Division Multiple Access)
  - TDMA (Time Division Multiple Access)
  - CDMA (Code Division Multiple Access)
  - OFDMA (Orthogonal Frequency Division Multiple Access)
  - SDMA (Space Division Multiple Access)
  - NOMA (Non Orthogonal Multiple Access)
- Multiple Access Techniques should not be confused with Duplexing Techniques (ability to simultaneously transmit and receive) which are:
  - Simplex
  - Half-Duplex
  - Full-Duplex
    - FDD (Frequency Division Duplexing)
    - TDD (Time Division Duplexing)

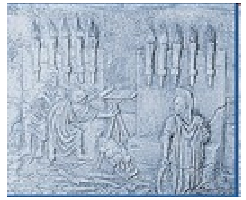
  - Combinations are also possible, e.g., π.χ. TDMA/FDD

Synchronization

- Carrier – Phase Tracking
  - Coherent copy of the carrier on the receiver is needed
  - Implementation based on PLL

- Symbol Synchronization
  - The output of the receiver filter is sampled per $t_m=mT_s+\tau_0$
  - The period of the symbol T_s must be known
  - As well as the exact time τ_0

- Symbol Synchronization Techniques:
  - Master Clock
  - The timing signal is transmitted along with the data
  - The timing signal is extracted from the data

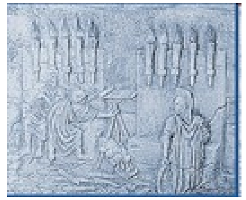


Equalization

- Due to channel distortions the signal at the receiver end suffers from (usually severe) intersymbol interference - ISI
- The symbols are intertwined
- Each symbol affects its next and previous ones
- The equalizer aims to mitigate ISI and restore original sequence
- In wireless communications, the equalizer often needs to be adaptive, since the channel is unknown and time-varying.

Topics to be covered in this course

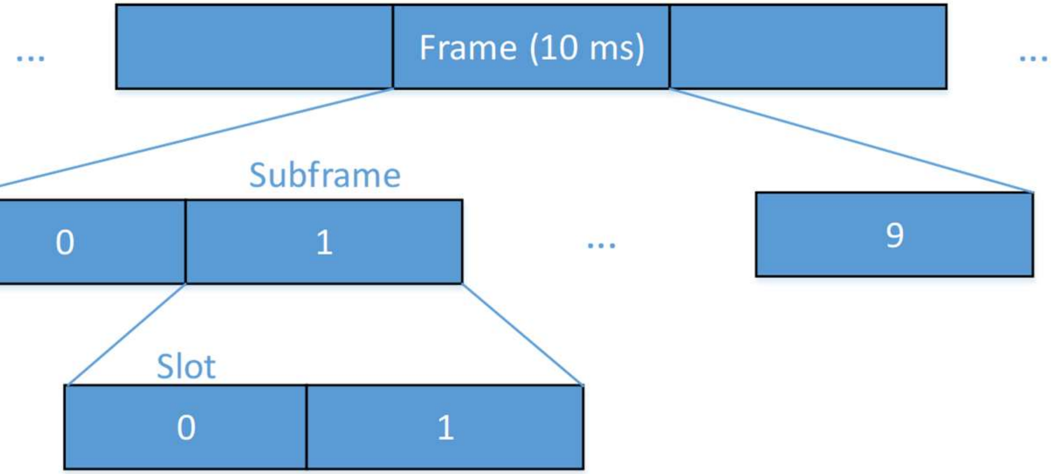
- Mobile Communication Channels:
  - Characteristics, Modeling
- Key technologies in Wireless & Mobile Com
  - Multicarrier transmission (OFDM)
  - Multiple Input Multiple Output (MIMO) com
  - Massive MIMO
  - Interference Management
  - Reconfigurable Intelligent Surfaces
  - mmWave Com
  - From Cellular to Cell-free Com
  - Multiple Access Mechanisms
  - Cognitive Radio Networks
- Machine Learning and Wireless Com
  - Edge ML and Federated Learning
  - Case studies



END OF INTRODUCTION

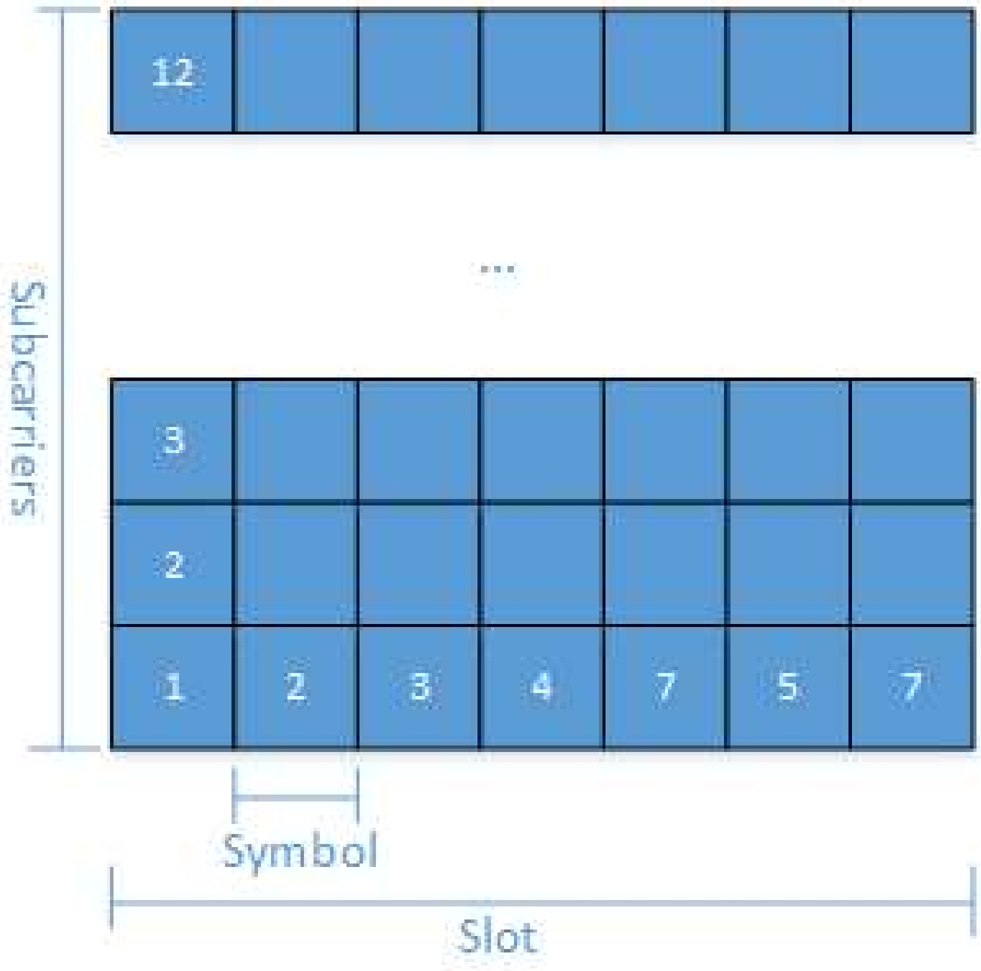
LTE as an example (1/3) (OXI)

- Scalable bandwidth up to 20 MHz. Specifically, the bands 1.4, 2.5, 5, 10, 15 and 20 MHz can be used.
- Transmissions using up to 8 antennas are supported.
- The downlink system offers peak data rates up to 326 Mbps when bandwidth equal to 20 MHz is used
- In the uplink, the corresponding rate reaches ~ 87 Mbps again when the bandwidth is 20 MHz
- The downlink uses OFDM and the uplink SC-FDMA.
- The structure of the transmission in time is:



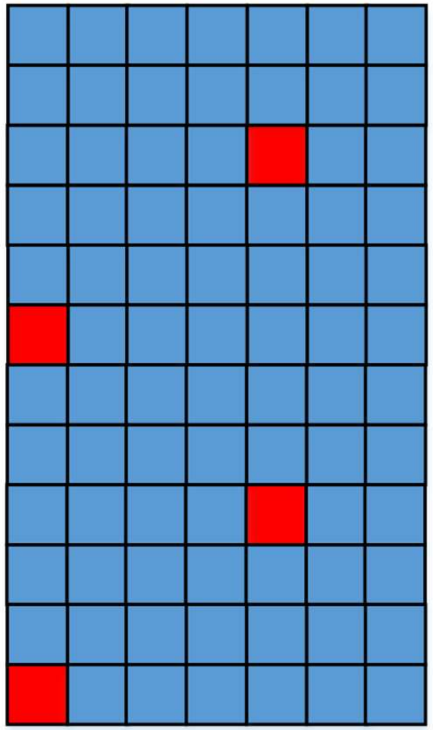
LTE as an example (2/3) (OXI)

- In LTE there is the so-called minimum resource block that can be assigned to a slot. Specifically:



LTE as an example (3/3) (OXI)

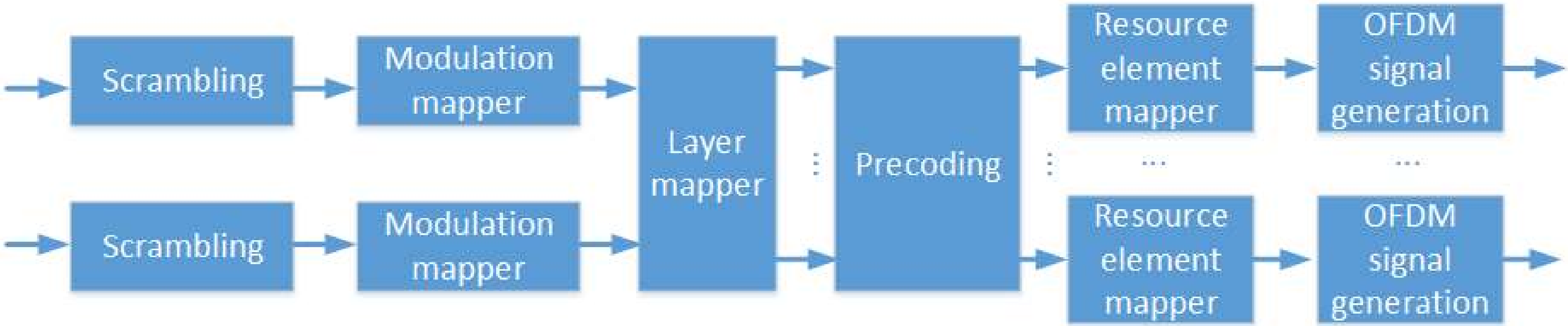
- The subcarrier spacing is 15 KHz.
- The 12 subcarriers of the resource block correspond to a bandwidth of 180 KHz.
- In transmission, in the frequency field, the resource blocks can be placed from 6^{th} position up to 110^{th}



- For the operation of the system, the so-called reference signals are defined, which are used, for example, in channel estimation or equalization tasks. For example, cell-specific reference signals have the structure shown in the figure.

LTE – Transmission Systems (OXI)

The transmission system in uplink



The transmission system in downlink

New technological trends (1/2) (OXI)

- **MIMO** systems (Multiple-Input Multiple-Output)
- Uniform treatment of procedures: Configuration – Equalization – Channel Encoding
- Adaptive Configurations. Dealing with non- linearity
- Implementation issues (real time requirements, limited consumption)
- Using frequencies above 6 GHz
  - E.g., 60/70/80/90 GHz

New technological trends (2/2) (OXI)

- Optimizations with level collaboration (increase of total capacity, position finding, etc.)
- Opportunistic and cooperative communications
- Interference Management
- Software radio (reconfigurable transceiver)
- Software Defined Radio / Cloud RAN
- Cognitive Radio / Green Radio
- AI/Edge computing