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Digital Telecommunications

Course Support

Developed in collaboration with NOKIA

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Section I
Introduction

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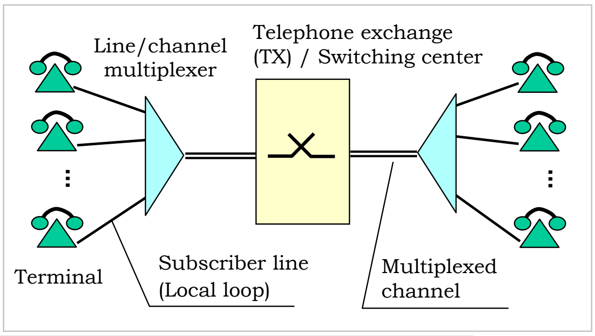
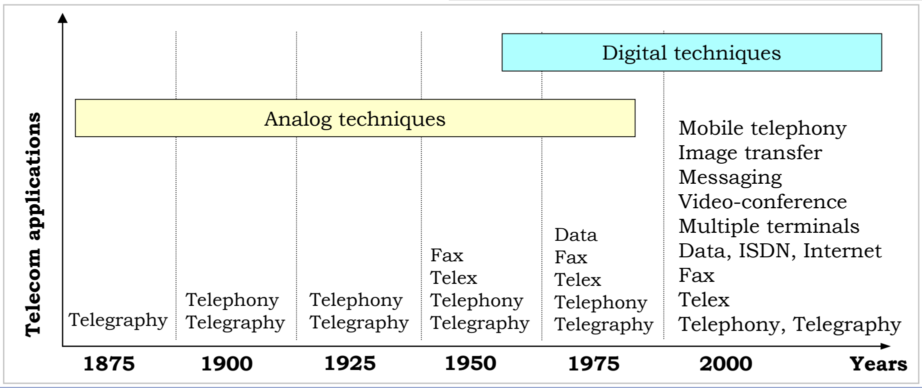
1 General Considerations

- Digital vs. analog telecommunications
  - Higher precision
  - More information
  - Easier implementation of various filters or transforms
  - Multiple solutions for multiplexing
  - Better control of telecommunications
  - Multiple switching modes (including the classical circuit switching and the modern packet switching modes)
  - Support for ISO-based implementation of communication systems and applications
  - Information compression, encoding and encryption
  - Extensive services and features

2 Model of the Telecom Channel

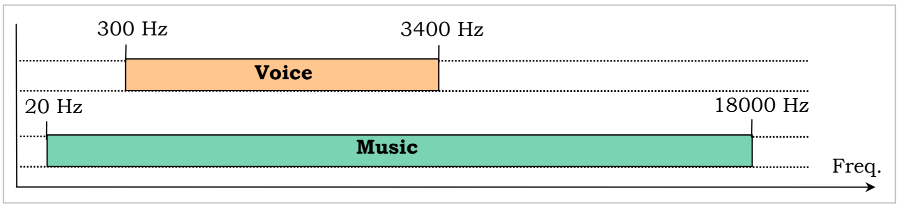
- Basic architecture
  - Information → electro-magnetic waves
  - Channel bandwidth
  - Increasing the performance and decreasing costs → multiplexing
  - Channel propagation errors → modulation, digitization
  - Digital and analogue channels





3 Analog Telecom Channels

- **Voice signal**
  - Transmission of voice: initial goal of telecom
  - Required bandwidth: 300 ÷ 3400 Hz



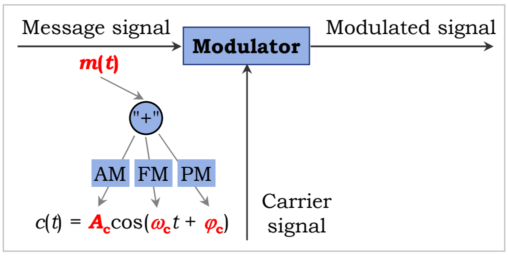
- **Baseband transmission**
  - Bandwidth of voice in telecom → **Baseband**, B_b
  - High transmission errors
  - Solutions: line repeaters

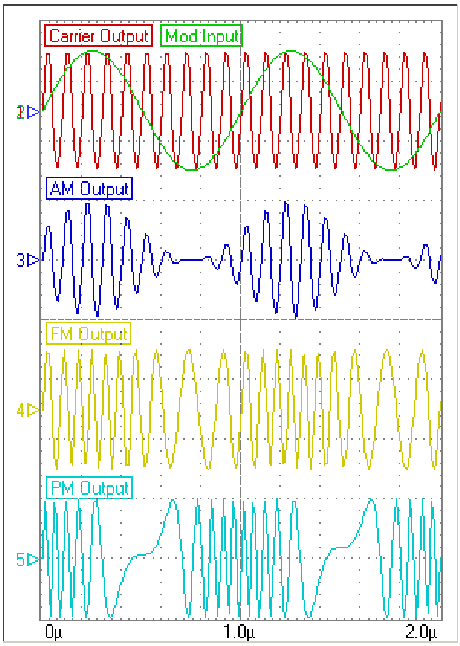
⇒ **Transmission using modulation**

3 Analog Telecom Channels

Analog modulation techniques

- Types of modulation:
  - Analog modulation: Amplitude (AM), Frequency (FM), Phase (PM)
  - Digital modulation: Amplitude Shift Keying (ASK), Frequency (FSK), Phase (PSK), Quadrature Amplitude Modulation (QAM)
  - Pulse modulation
  - Spread spectrum modulation
- A signal of higher frequency (carrier) is modulated by the user signal

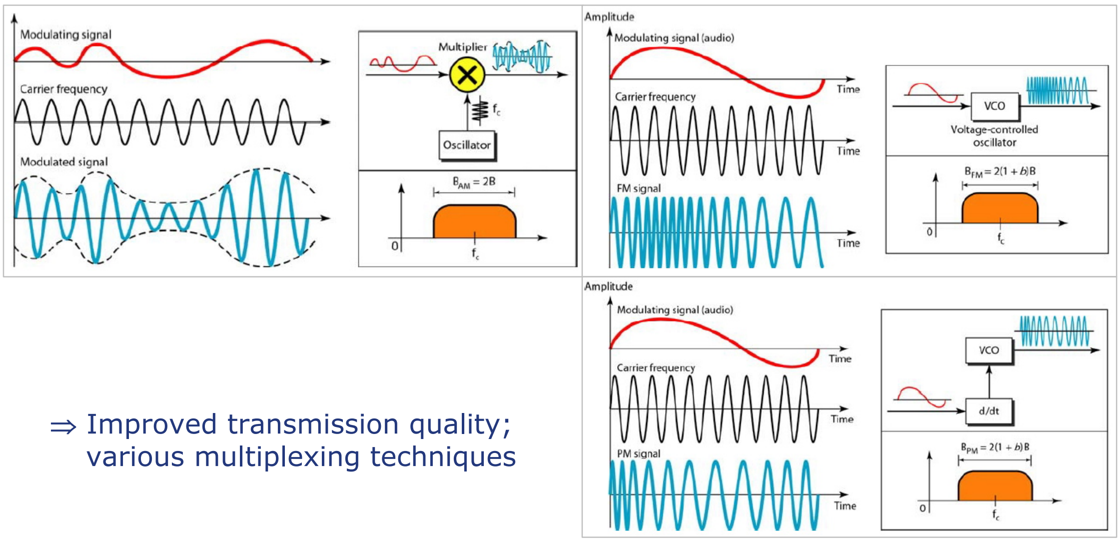




[Source: Carena Lim Yun Xian, "Communication and Network", 2011, Online: http://carenalimyunxian0302442.blogspot.com/2011/06/communication-and-network.html, Accessed: Jul. 2019]

3 Analog Telecom Channels

Analog modulation techniques (cont'd)

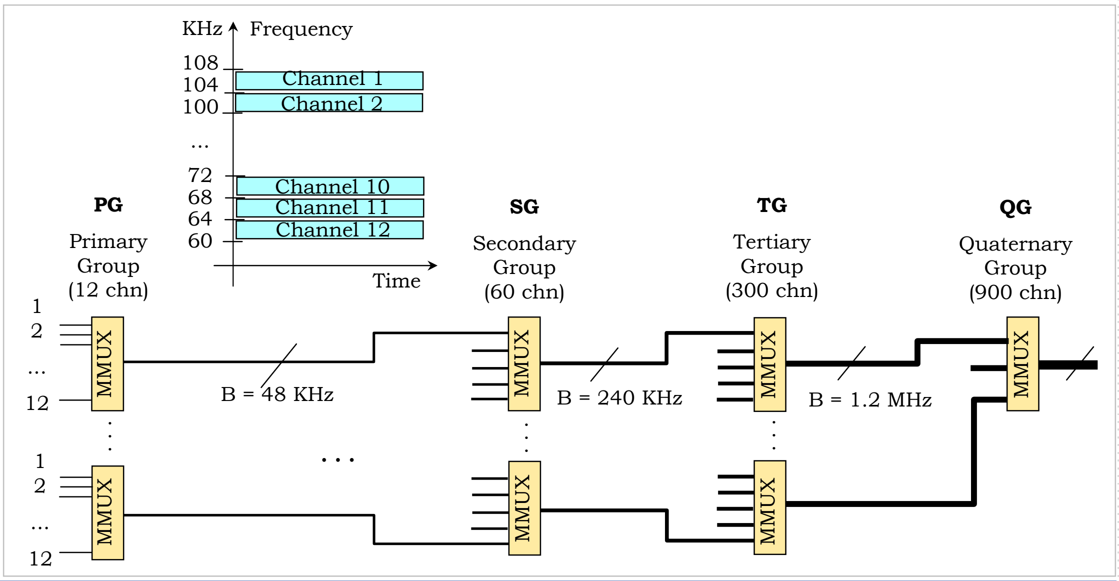


⇒ Improved transmission quality;
various multiplexing techniques

[Source: Alejandro Alcocer, "SH03 3. Signals, coding and modulation", Presentation, ICAO/ South American (SAM) Office, 2013, Online: https://www.icao.int/SAM/Documents/2010/ REDDIGRTO2010/ 03.%20Signals,%20coding%20and%20modulation.pdf, Accessed: Jul.2019]

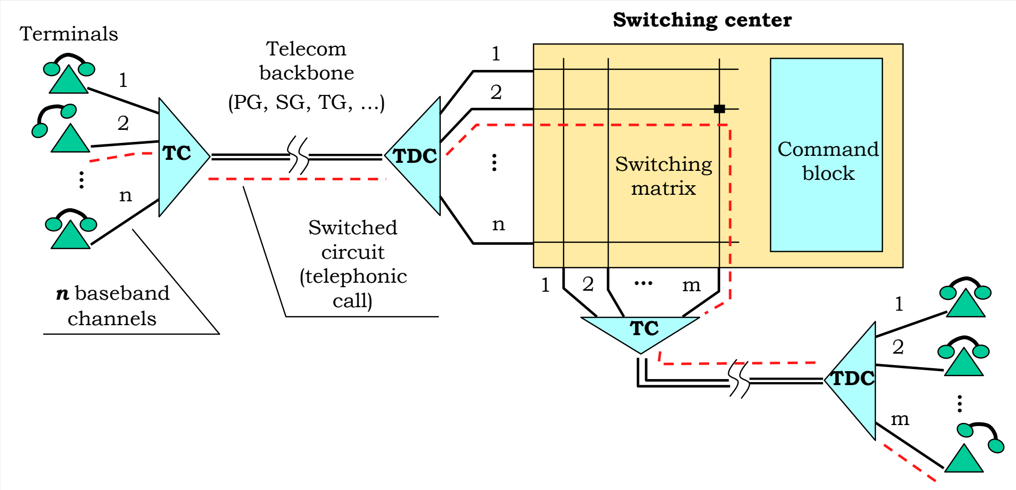
3 Analog Telecom Channels

- **Frequency Division Multiplexing (FDM)**
  - CCITT standard
  - A **Primary Group** (**PG**): 12 baseband channels, of 4 kHz each (3000 Hz for the voice and 2 guard bands of 500 Hz)



Switching of analog telecom channels

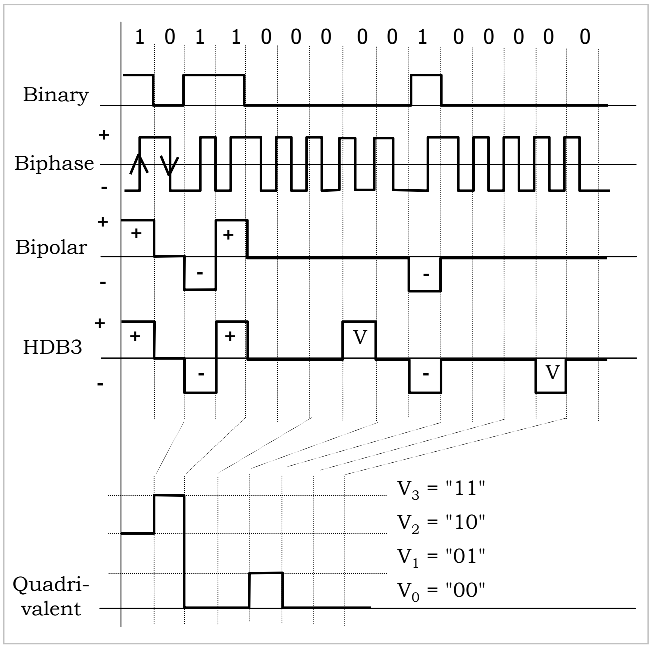
- Methods: manual (plugged cords), automatic (relays)
- Switching type: circuit switching
- Establishing a real circuit between the matrix line corresponding to source and the column corresponding to destination



4 Digital Telecom Channels

Line coding

- Type of coding: binary, biphase, bipolar, HDBn
- Decoding at reception: maintaining the line clock (synchronization)
- Communication speed over the channel:
  - **baud** or **Bd** → max number of signal (e.g. voltage) variations ("**symbols**") per second
  - **bps** (bits per sec) → describes the transfer capacity of the channel (throughput)

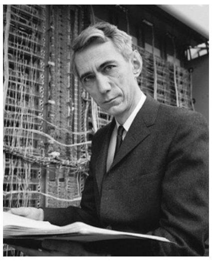


4 Digital Telecom Channels

Channel throughput

Harry Nyquist (1889 - 1976)

- Swedish born American electronic engineer
- Important contributions to communication theory
- Engineer at AT&T Department of Development and Research, later becoming the Bell Laboratories (1917 - 1954)
- Important work on thermal noise ("Johnson–Nyquist noise"), the stability of feedback amplifiers, telegraphy, facsimile, television, and other important communications problems
- Helped develop AT&T's first facsimile machines (1924), with Herbert E. Ives
- The Nyquist stability criterion can be found in all textbooks on feedback control theory
- Essential work on determining bandwidth requirements for transmitting information



Claude Elwood Shannon (1916 – 2001)

- American mathematician and engineer, known as "the father of information theory"
- Mathematician and engineer at AT&T Bell Laboratories (1941 - 1956), professor at the MIT (1956 - 1978)
- Famous for founding both digital computer and digital circuit design theory in 1937, with his master's degree Thesis at the MIT, "A Symbolic Analysis of Relay and Switching Circuits", which demonstrates that electrical applications of Boolean algebra could construct any logical, numerical relationship
- Famous for founding information theory with a landmark paper, published in 1948 in the Bell System Technical Journal: "A Mathematical Theory of Communication"
- Contributions to the field of cryptanalysis for national defense during World War II, including his basic work on code breaking and secure telecommunications

$$D \le B \cdot \log_2\left(1 + \frac{S}{N}\right)$$

4 Digital Telecom Channels

- **Voice transmission**
  - Voice: analog signal
  - Sampling: 8 ksps
  - Sample quantization
    - min bits for sufficient quality
    - logarithmic "compression" system
    - A-law (Europe) and μ-law (America)
    - PCM modulation (8 bits/sample)

Linear input code	Compressed A-Law
s 0 0 0 0 0 0 0 a b c d X	s 0 0 0 a b c d
s 0 0 0 0 0 0 1 a b c d X	s 0 0 1 a b c d
s 0 0 0 0 0 1 a b c d X X	s 0 1 0 a b c d
s 0 0 0 0 1 a b c d X X X	s 0 1 1 a b c d
s 0 0 0 1 a b c d X X X X	s 1 0 0 a b c d
s 0 0 1 a b c d X X X X X	s 1 0 1 a b c d
s 0 1 a b c d X X X X X X	s 1 1 0 a b c d
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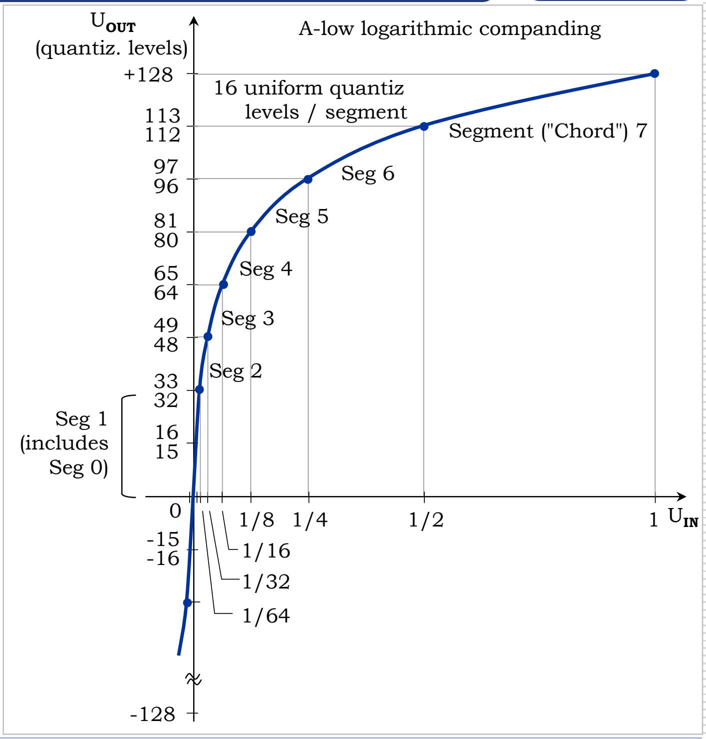
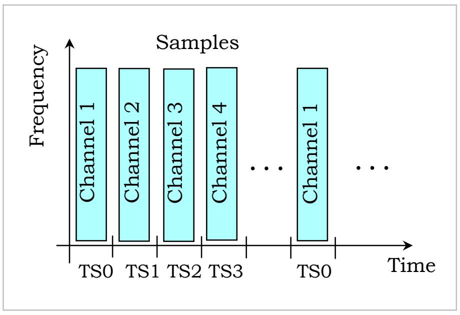
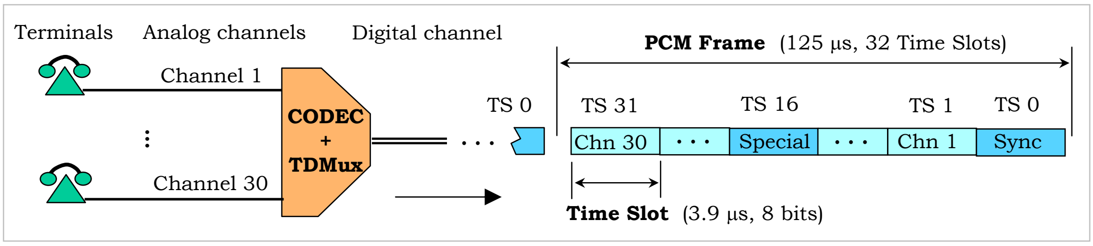


4 Digital Telecom Channels

- **Voice transmission** (cont'd)
  - Time division multiplexing (TDM)
  - Line coding: HDB3
  - ⇒ PCM frame
- **PCM frame**
  - Europe: 32 TS, 30 channels, 2 special TS
  - TS 16: reserved (formerly used in signaling)
  - TS 0: frame synchronization
    - Odd frames: FL ("9B" h)
    - Even frames: RA (bit 2)





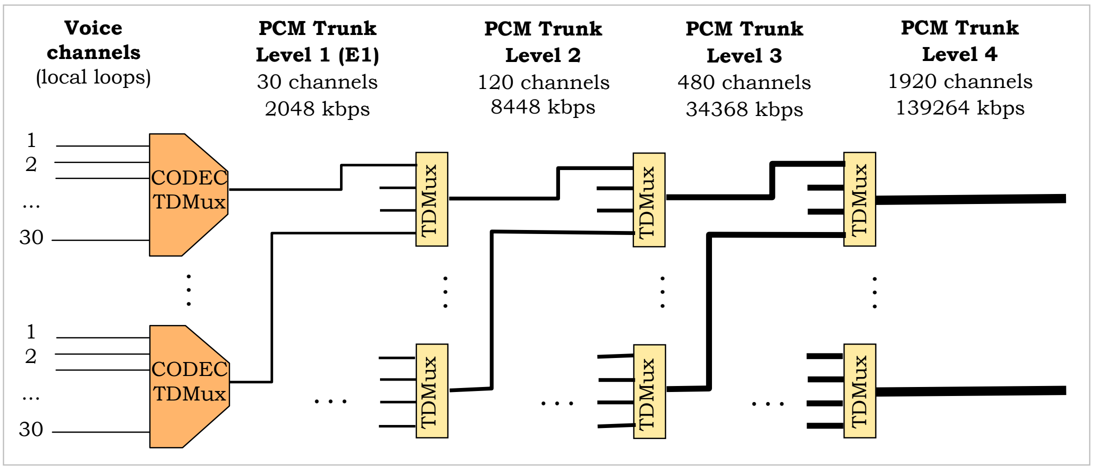
4 Digital Telecom Channels

PCM frame standards

Parameter	Europe (E1 standard)	America (T1 standard)
Companding law	A-law	μ-law
Duration of PCM frame	125 μs	125 μs
Total bits / frame	256 bits	193 bits
Time Slots / frame	32	24
Duration of TS	3.9 μs	5.2 μs
Total channels / frame	30	24
Special TS	TS 0 – frame sync TS16 – reserved (CCS)	Bit 0 / frame – frame sync Bit 7 / TS - reserved (CCS)
Channel throughput	8 bit * 8 kSps = 64 kbps	7 bit * 8 kSps = 56 kbps
Frame throughput	32 * 8 * 8 k = 2.048 Mbps	(24 * 8 + 1) * 8 k = 1.544 Mbps

4 Digital Telecom Channels

- **Plesiochronous Digital Hierarchy (PDH)**
  - CCITT → standardization of PCM channels multiplexing levels
  - Different standards for Europe and America



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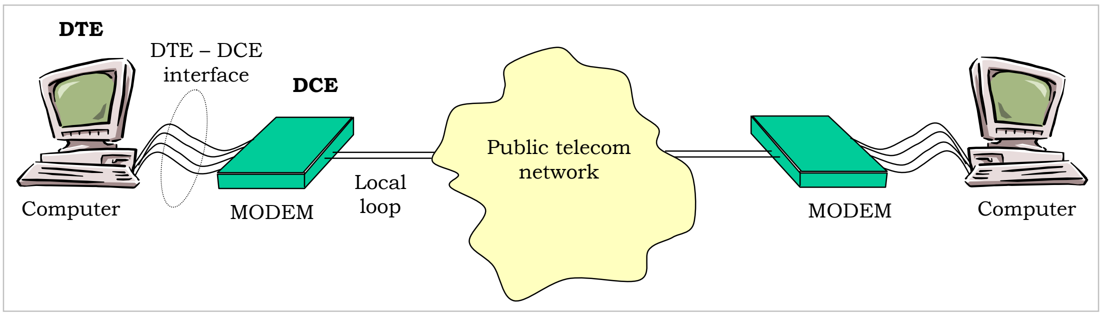
Nivelul de ierarhie	PDH Europa	PDH America
Nivelul 1	E1, 30 căi Debit: 2.048 Mbps Notaţie: 2.0 Mbps	T1, 24 căi Debit: 1.544 Mbps Notaţie: 1.5 Mbps
Nivelul 2	120 căi Debit: 8.448 Mbps Notaţie: 8.0 Mbps	96 căi Debit: 6.312 Mbps Notaţie: 6.0 Mbps
Nivelul 3	480 căi Debit: 34.368 Mbps Notaţie: 34.0 Mbps	T3, 672 căi Debit: 44.736 Mbps Notaţie: 44.5 Mbps
Nivelul 4	1920 căi Debit: 139.264 Mbps Notaţie: 140.0 Mbps	2016 căi Debit: 139.264 Mbps Notaţie: 140.0 Mbps

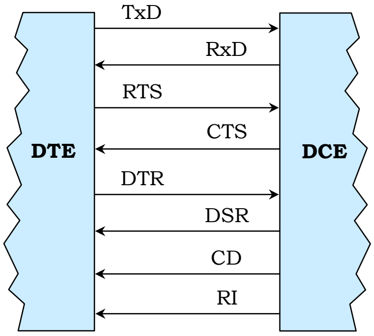
4 Digital Telecom Channels

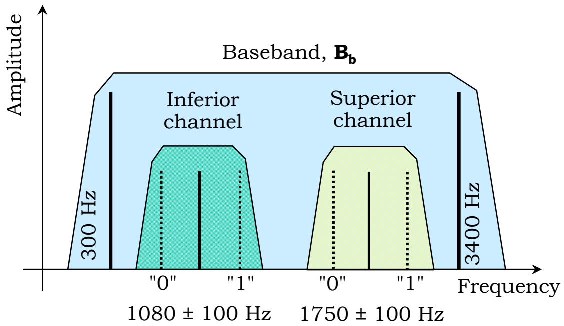
- **Transmission of digital data**
  - Problem: the local loops in telecom (analog, baseband channels)
  - Solution: special interface equipments → MODEM
  - CCITT standardization: "Recommendations V"
    - Communication between DTE – DCE
    - Communication between DCE – DCE, through the telecom network



4 Digital Telecom Channels

- Recommendation **V.24**: DTE – DCE interface (in USA: RS232-C standard)
- **V.21**: MODEM, full-duplex, asynchronous, 300 bps throughput, FSK modulation
- **V.27**: MODEM, synchronous, 1600 baud, 4800 bps, phase modulation
- **V.29**: MODEM, synchronous, 2400 baud, 9600 bps, combined modulation (phase/amplitude) with 16 states/symbol
  $\Rightarrow$ 4 bits/symbol
- **V.32**: MODEM, 2400 baud, 14400 bps, combined modulation with 6 bits/symbol
- **V.34**: MODEM, 3200 baud, 28.8 kbps, combined modulation with 9 bits/symbol
- **V.42**: MODEM, 2400 baud, 57.6 kbps, combined modulation with 6 bits/symbol and a compression factor of 4:1

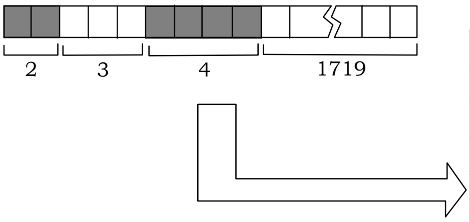




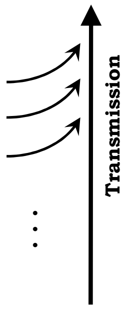
4 Digital Telecom Channels

Facsimile equipments (FAX)

- Sending the contents of printed documents and photo through the telecom network
- FAX = optical scanner + transceiver unit + thermal printer
- Operating principle
  - A4 document → raster scanning with a resolution of 1142 x 1728 points
  - Each scanned line → decomposed in white and black segments + "EOL"
  - Resulting segments → length in points, codified with the "modified Huffman" algorithm



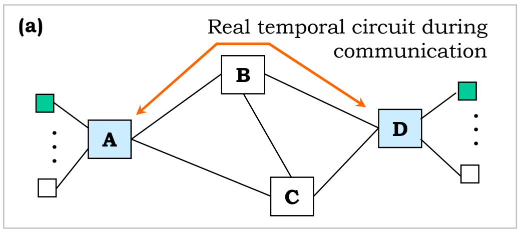
0011001	White segm., length 0
11	Black segm., length 2
1000	White segm., length 3
011	Black segm., length 4
011000	White segm., length 26x64 points
01011000	White segm., length 55 (rest)
"EOL"	"End Of Line" code

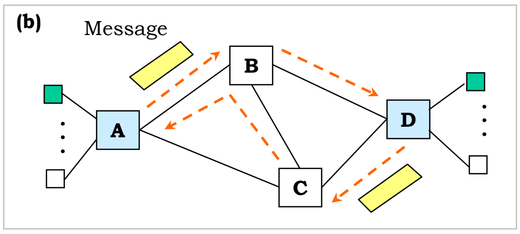


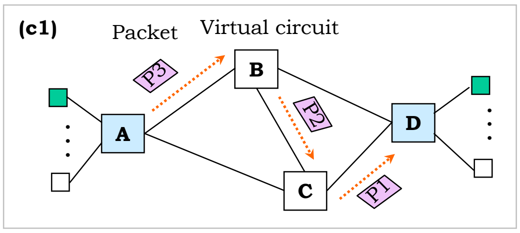
4 Digital Telecom Channels

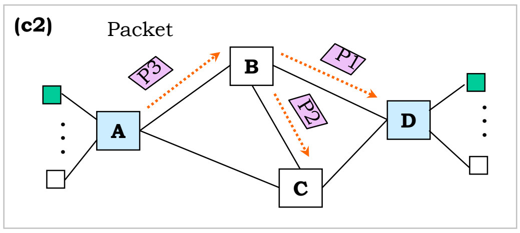
Switching of digital telecom channels

- Types of switching
  - (a) Temporal circuit switching
  - (b) Message switching
  - (c) Packet switching
    - (c1) "Virtual circuit" type
    - (c2) "Datagram" type



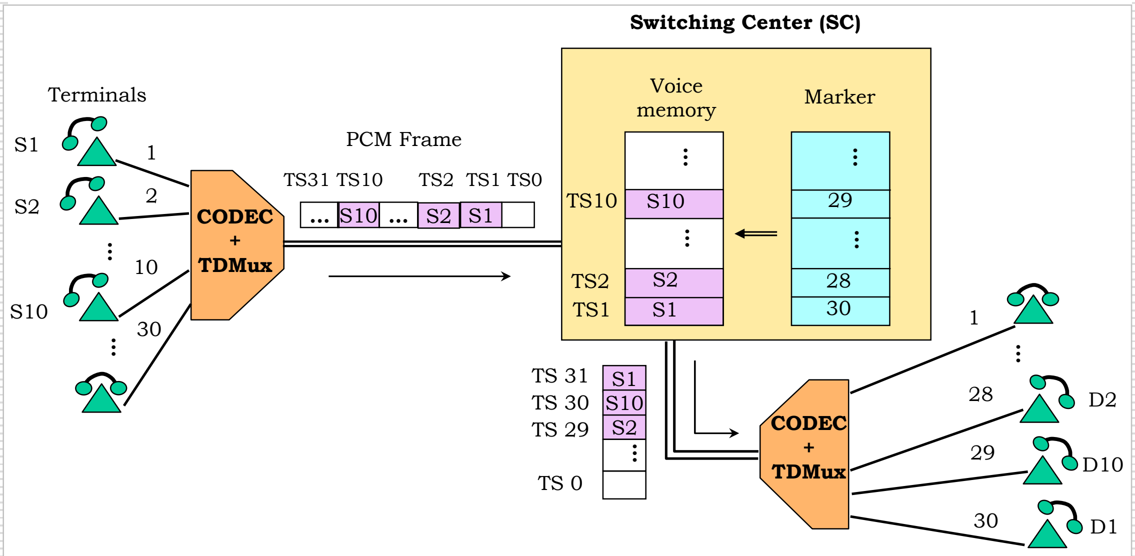






4 Digital Telecom Channels

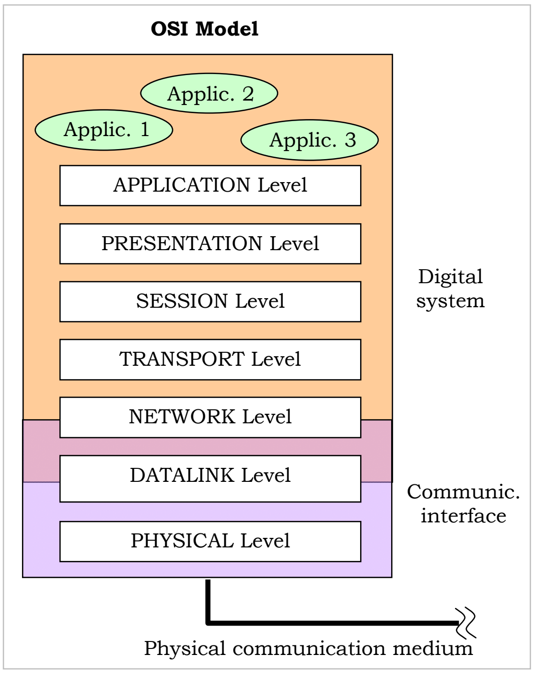
- **Switching of digital telecom channels** (cont'd)
  - Temporal circuit switching:
    - Voice memory
    - Marker: temporal addresses memory



5 OSI Model for Systems Interconnection

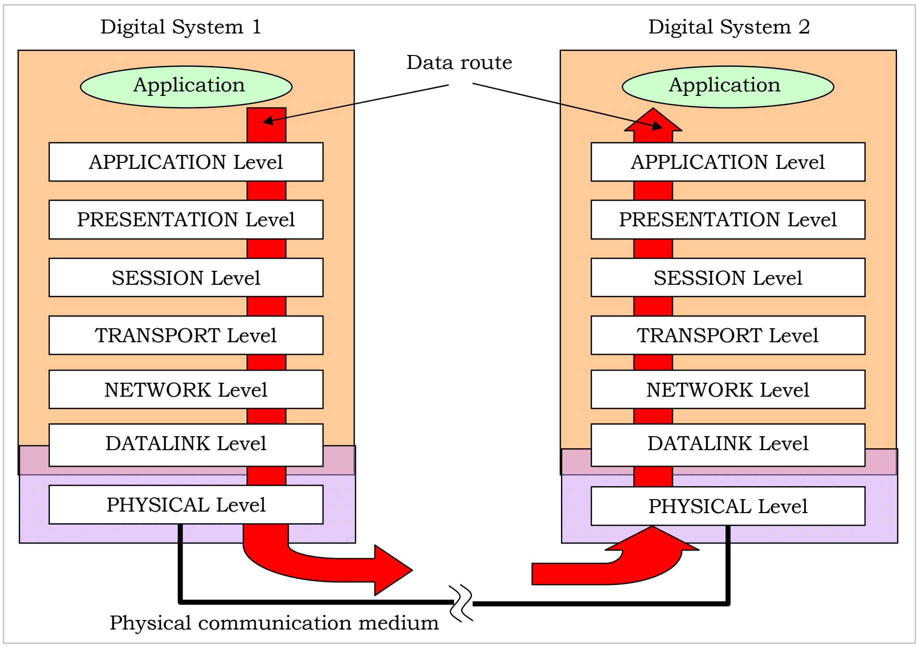
- Digital systems: high diversity
- Digital system interconnection:
  - Communication protocols
  - Communication interfaces
  - Large variety of solutions
- 1978, ISO: standardization of protocols and interfaces

⇒ OSI Reference Model
  - 7 layers of protocols
  - Physical Layer
  - Datalink Layer
  - Network Layer
  - Transport Layer
  - Session Layer
  - Presentation Layer
  - Application Layer



5 OSI Model for Systems Interconnection

- Operating principle



Section II
Introduction to Mobile Telecommunications

6. General concepts of mobile telecom
7. Radio interface
8. Specific radio communication techniques
9. History and overview of mobile telecom

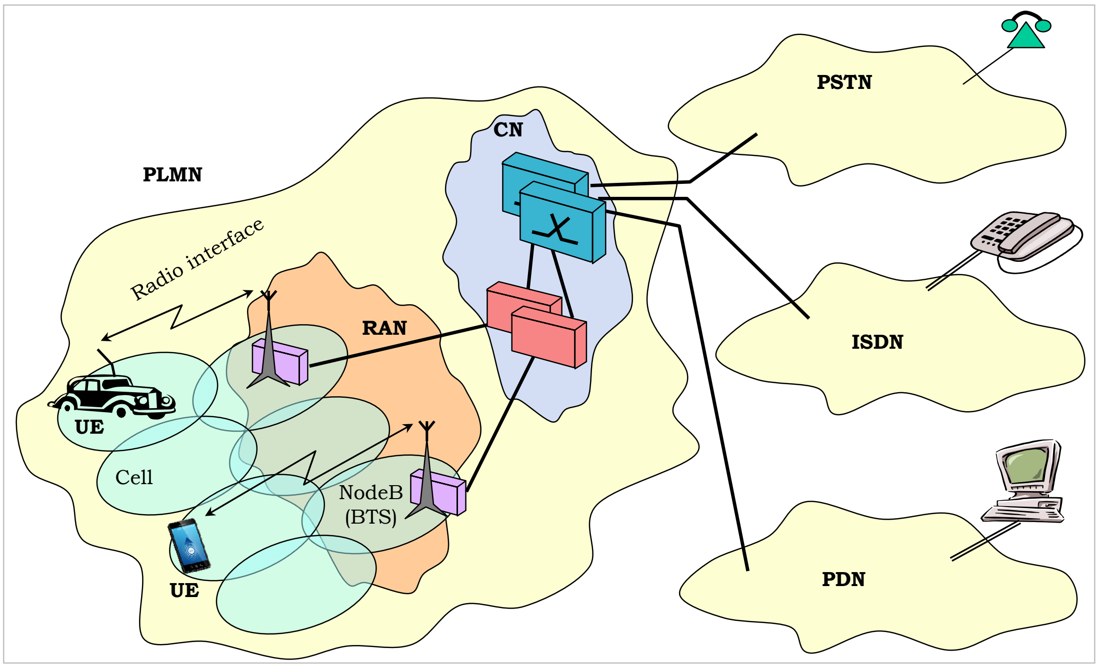
6 General Concepts of Mobile Telecom

- **Expansion of mobile devices**
  - End of 2014 → the number of mobile-connected devices exceeded the number of people in the world
  - 2019 → nearly 1.5 mobile devices per person (~11.5 Bln devices for ~7.6 Bln people)
  - Factors:
    - Explosive growth of interconnected digital devices, new application areas (IoT and smart sensors, diverless connected cars, etc.), increasingly larger mobile broadband requirements from users
    - Worldwide success of the GSM (2G) system

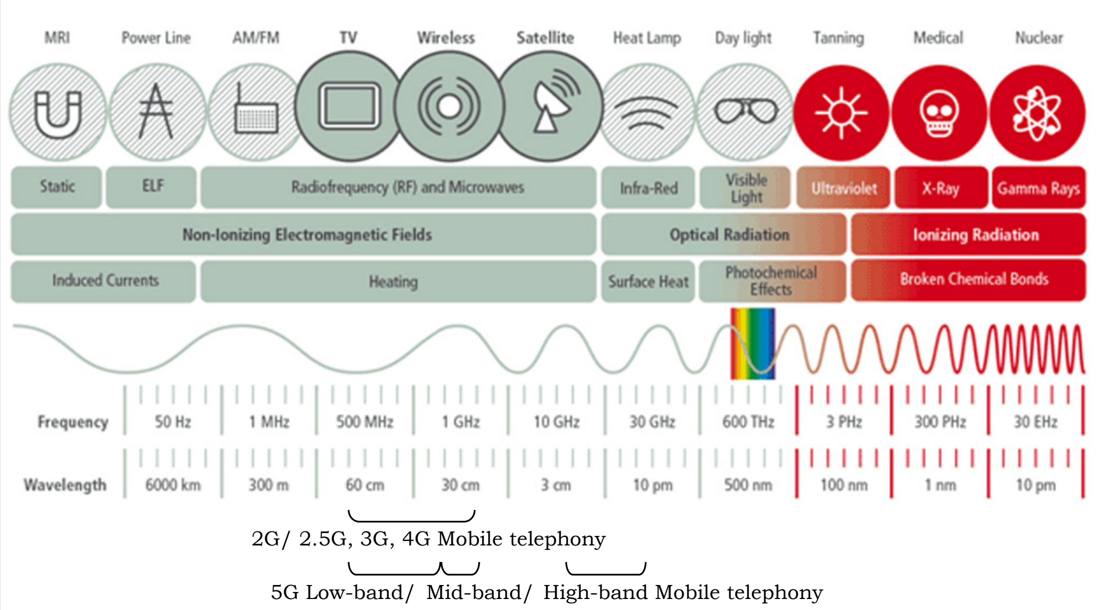
Romanian Tricolor Flag displayed on mobile devices during the February 2017 protests in Piata Victoriei, Bucharest (protests peaking over 0.5-0.6 Mil people all over the country - the largest protests in Romania's history) [Source: Meduafax.ro]

6 General Concepts of Mobile Telecom

- **General architecture of mobile telecom networks**



- **Electromagnetic spectrum**



[Source: B. Jones, J. Jones, "L8 - Wireless Transmission Research", 2018, Online: https://sites.google.com/site/mrjoneswac/yr12-information-processes-and-technology/topic-3-communication-systems/wirelesstransmissionresearch, Accessed: Aug. 2019]

Communication over radio

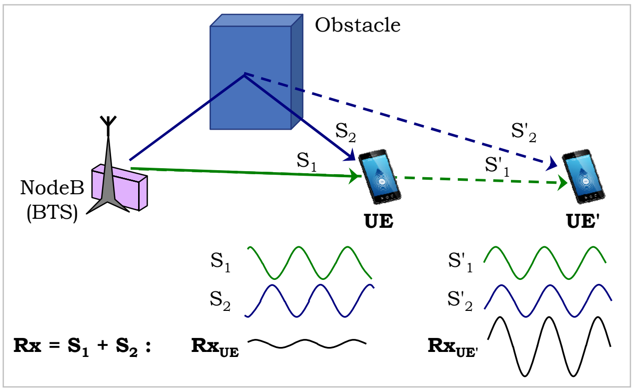
John William Strutt, 3rd Baron Rayleigh (1842 - 1919)

- British scientist with extensive contributions to theoretical and experimental physics
- Professor of Experimental Physics and Head of the Cavendish Laboratory at the University of Cambridge (following James Clerk Maxwell) (1879 - 1884) and Professor of Natural Philosophy at the Royal Institution, London (1887 - 1905)
- Received the 1904 Nobel Prize in Physics "for his investigations of the densities of the most important gases and for his discovery of argon in connection with these studies"
- Important works on:
  - wave propagation ("Rayleigh scattering" - on elastic scattering of light by particles much smaller than the light's wavelength, "Rayleigh fading" - a statistical model for the effect of a propagation environment on a radio signal), optics ("Rayleigh criterion" - angular resolution)
  - fluid dynamics ("Rayleigh number" associated with natural convection, "Rayleigh flow" on frictionless, non-Adiabatic flow through a constant area duct, the Rayleigh–Taylor instability and the Rayleigh's criterion for the stability of Taylor–Couette flow, formulated the circulation theory of aerodynamic lift)
  - acoustics ("Rayleigh waves" - on transverse surface waves in solids, "Duplex theory" - on the difference in arrival time of a sound between two ears). Rayleigh's textbook, "The Theory of Sound" (1877) is still used today by acousticians and engineers
  - quantum mechanics (derivation of the Rayleigh–Jeans law for classical black-body radiation, the Rayleigh–Schrödinger perturbation theory), other fields ("Rayleigh–Lorentz pendulum" - formed the basis for the concept of adiabatic invariants in mechanics)

- Radio propagation characteristics
  - Absorption, polarization, diffraction, reflection, refraction, dispersion and the Doppler effect ( )
  - **Different frequencies → different combinations of these phenomena**

Communication over radio (cont'd)

- Multipath propagation and Rayleigh fading
  - Position of the UE (movement)
  - Frequencies used



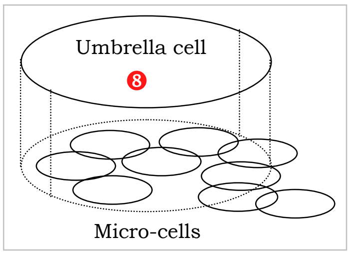
- Main challenges
  - Interference
    - ISI
    - ICI (cross-talk)
  - Limited radio resources (bandwidth)

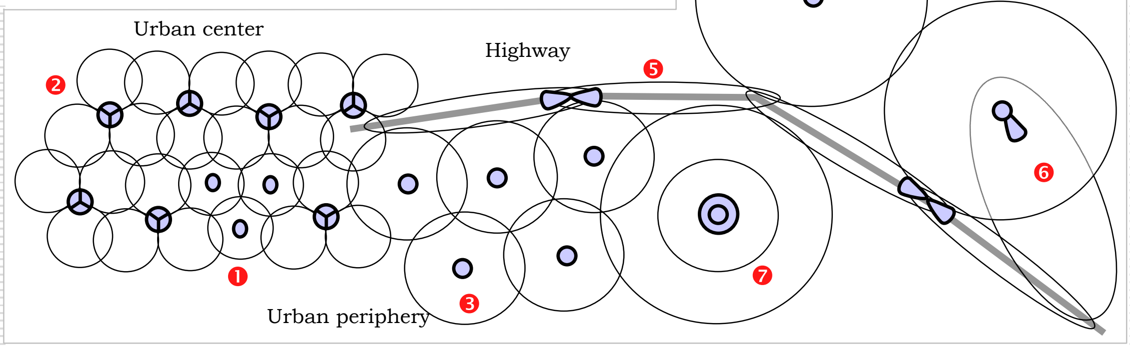
⇒ Specific techniques to reduce interference and improve the **spectral efficiency**

$$SE = \frac{N_U}{B}$$

Cell coverage

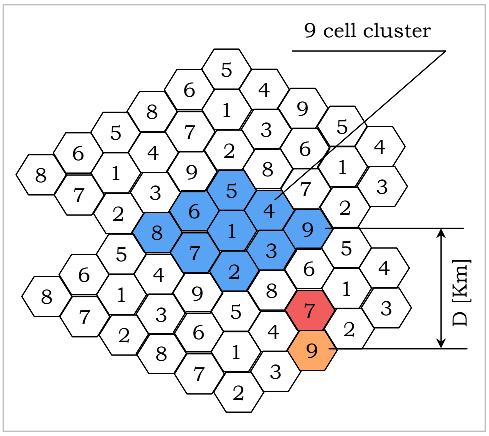
- Improving the **spectral efficiency**
- Frequency reuse
- Types of cells (due to BTS and antenna types)
  - (a) by size
  - (b) by antenna shape
  - (c) by hierarchy
  - (d) by transceiver power
  - (e) by frequency





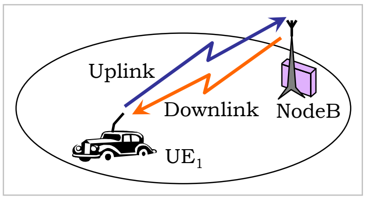
Frequency reuse

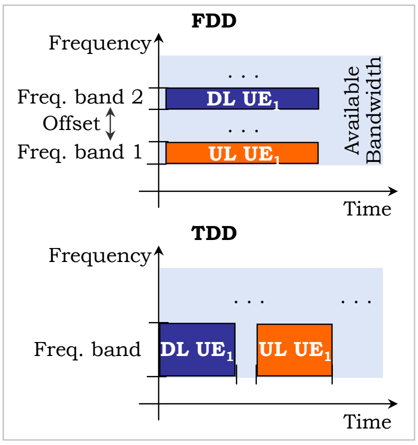
- Radio resources are limited
  - Rules for radio planning
  - Cell clustering
- Case of cell 7 → example for GSM
  - BSIC color code
    - Two 3-bit fields
    - BCC (Base Color Code)
    - NCC (National Color Code)



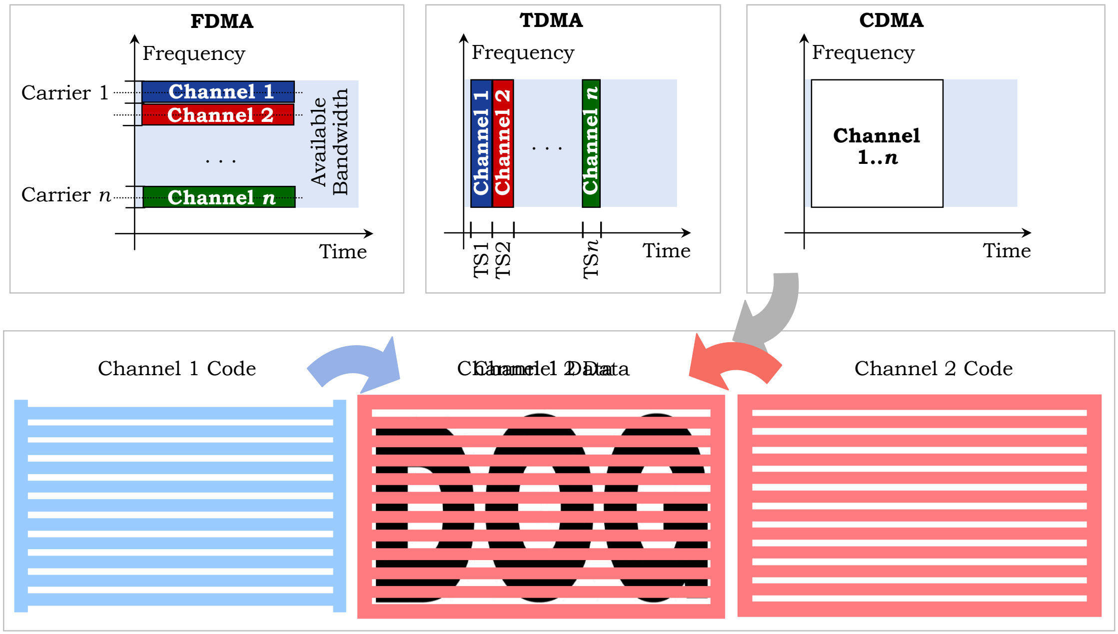
Radio duplexing (bidirectional communication)

- Downlink (DL)/ Uplink (UL)
- FDD:
  - A pair of frequencies for DL and UL
  - Distance between DL and UL frequencies → **frequency offset** (constant in most systems)
  - Simultaneous communication
  - Use of band-pass filters in case of a single antenna
  - Example: 2G (GSM)
  - ⇒ Efficient in case of symmetric traffic (same DL and UL data rates)
- TDD:
  - Same bandwidth used
  - Different time intervals for DL and UL
  - Examples: 3G–5G
  - ⇒ Flexibility in case of asymmetric traffic



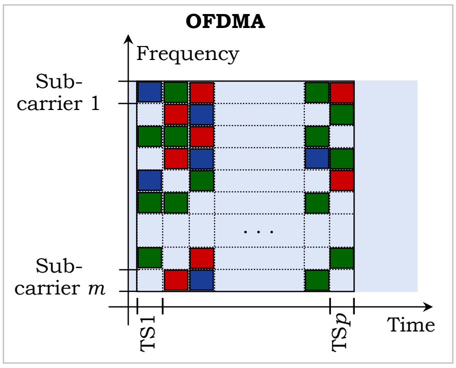


Radio channel multiplexing

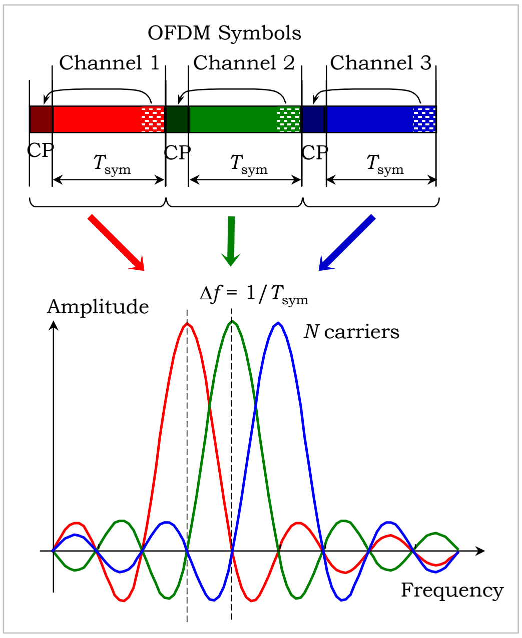


[Courtesy of Suresh Goyal & Rich Howard]

Radio channel multiplexing (cont'd)



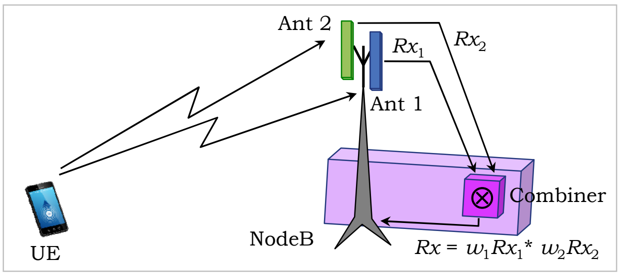
- **Orthogonal** frequency sub-carriers (Δf)
  - ⇒ FFT/ IFFT are used for Rx/ Tx, instead of BP filters
  - ⇒ eliminates ICI and the need of inter-carrier guard bands
- **Cyclic prefix (CP)**
  - copy of the last part of the symbol, as prefix
  - ⇒ eliminates ISI
  - ⇒ provides cyclic convolution and operation in frequency domain (IFFT/ FFT)
- Requires precise Rx-Tx frequency sync



8. Specific Radio Communication Techniques

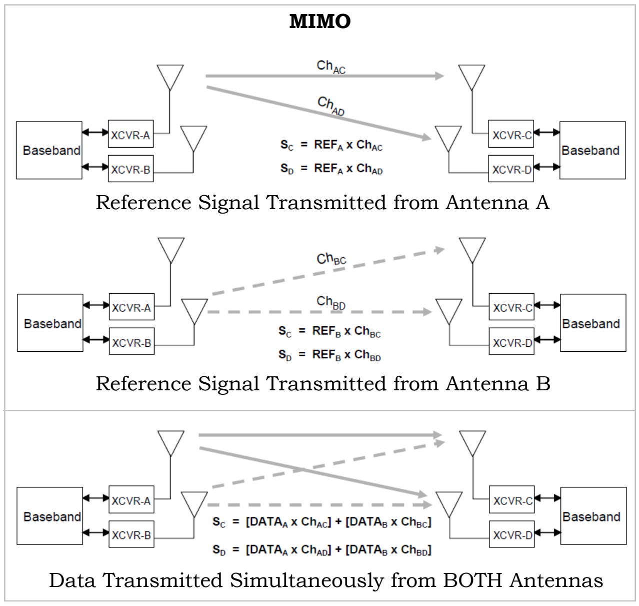
Antenna diversity

- To improve:
  - signal quality in radio multipath propagation context
  - data throughput (number of users, or data rate per user)
- Main types:
  - Space diversity
  - Frequency diversity
  - Pattern diversity



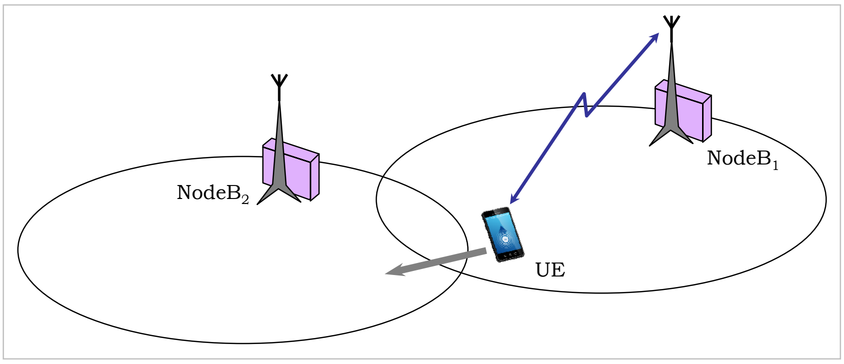
Antenna diversity (cont'd)

- Antenna arrays and MIMO



[Jim Zyren, "Overview of the 3GPP Long Term Evolution Physical Layer", White Paper, Freescale Semiconductor, 2007]

- **Specific techniques to increase spectrum efficiency**
  - Power Control
  - Discontinuous Transmission (DTx)
  - Frequency Hopping
  - Handover



9. History and Overview of Mobile Telecom

- **History of mobile telecommunications**
  - 1st Generation: analog cellular networks
    - AMPS (Chicago, 1979), NMT (Sweden, 1981), TACS (UK, 1985)
    - Cell coverage; Frequency reuse; 450 and 900 MHz radio bands; out of call mobile monitoring (roaming); cell change during call (handover)
    - No confidentiality
  - 2nd Generation: digital cellular networks ⇒ worldwide success
    - GSM 900 / 1800 (Europe, 1992), IS95/CDMA / GSM 1900 (USA, 1995)
    - Digital techniques; integrated security features; technical innovations → high traffic density; introduction of new services
    - European standards (GSM) and American standards
  - 2.5 Generation: GSM to IMT2000 evolution ⇒ packet-switched data transactions
    - GPRS / EDGE (EGPRS) (2000 / 2003)
    - Preserves GSM BSS (most expensive subsystem)
  - 3rd Generation: universal standard
    - IMT-2000, UMTS
    - Universal standards for interoperability of: systems for the general public (GSM type); private systems (PMR - DECT); shared resource systems (3RP); all cell sizes (from micro cells to satellites)
  - 3.5 Generation: increased data rates and capacity
    - HSDPA/HSPA (2002), Evolved HSPA (2008), 3GPP LTE (2010)
    - Increases data rates and capacity of UMTS systems
  - 4th Generation: mobile broadband internet access
    - LTE Advanced (2011), WiMAX rel 2 (IEEE 802.16m, 2011)
    - Transfer rates: ≤ 1 Gbps (fixed stations), ≤ 100 Mbps (mobile stations)
  - 5th Generation: mobile communications with extreme range of requirements
    - ITU-R → IMT-2020 (2012); 3GPP 5G Phase 1 Release 15 (2018); 3GPP 5G Phase 2 Release 16 (2019)
    - Support for *eMBB* (throughput), *URLLC* (latency/ reliability) and *mMTC* (# devices/ cost and power)
    - Data rates ≥ 10 Gbps; connection density: ≤ 1 Mil. devices/ km^2; latency: < 1 ms; mobility ≤ 500 km/h
    - Designed to support any spectrum between 400 MHz and 90 GHz.

Digital cellular standards

Standard	Gene-ration	Frequency bands (MHz)	Multi-plexing	Max cell size	Observations
GSM 900 (P-GSM)	2G	890 - 915 (↑) 935 - 960 (↓)	FDMA & TDMA	35 Km	* Circuit-switched * Voice or low-rate data * Frequency utilization: 200 kHz, 8 TSs (2 calls/ TS)
GSM 1800 (DCS)	2G	1710 - 1785 (↑) 1805 - 1880 (↓)	FDMA & TDMA	4 Km	
IS95	2G	1610 - 1626.5 (↑) 2483.5 - 2500 (↓)	CDMA	500 Km	
UMTS/HSPA	3G / 3.5G	880 - 915 (↑) 925 - 960 (↓)	DS-CDMA (WCDMA) FDD / TDD	+35 Km	* Circuit- and Packet-switched * Voice and data * Frequency utilization: 5 MHz/ 2 Mbps (42 Mbps with HSPA+), 1.8-12 kbps/ call
		1920 - 1980 (↑) 2110 - 2170 (↓)		~1-2 Km	
LTE	3.5G (4G)	832 - 862 (↑) 791 - 821 (↓)	OFDMA / MIMO	100 Km	* Packet switched * Data only (voice through VoLTE) * Frequency utilization: DL < 300 Mbps, UL ≤ 75 Mbps (20 MHz channel bandwidth, with 4×4 antennas)
		1710 - 1785 (↑) 1805 - 1880 (↓)		~1-5 Km	
5G NR	5G	FR1 (450 – 6000) FR2 (24250 – 52600)	OFDMA / Massive MIMO (>8)	Large (> 1 Km) Small (~100 m)	* Packet switched * Data only (voice through VoLTE) * Frequency utilization: Various carrier bandwidths

9. History and Overview of Mobile Telecom

- **Example digital cellular operators in Romania (MCC = 226)** (per 2019)

MNC	Network	Operator	Operating bands (MHz)	Notes
01	Vodafone	Vodafone Romania	GSM/GPRS 900 / 1800 (2/ 2.5G) UMTS 900 / 2100 (3/ 3.5G) LTE 800 / 1800 / 2600 (3.5/ 4G) Supernet™ 5G (activat 2019.05)	Formerly: Connex
03	Telecom	Telekom Romania	GSM/GPRS 900 / 1800 (2/ 2.5G) UMTS 900 / 2100 (3G/ 3.5G) LTE 800 / 900 / 1800 / 2600 (3.5/ 4G)	Formerly: Cosmote
05	Digi.Mobil	RCS & RDS	UMTS 900 / 2100 (3/ 3.5G) LTE 2600 (3.5/ 4G) TDD 5G 3700 (5G, activat 2019.06)	
06	Telekom/Zapp	Telekom Romania	UMTS 900 / 2100 (3G)	
10	Orange	Orange Romania	GSM/GPRS 900 / 1800 (2/ 2.5G) UMTS 900 / 2100 (3/ 3.5G) LTE 800 / 1800 / 2600 (3.5/ 4G)	Formerly: Dialog
11	*Enigma-System*	?	?	MVNO
15	Idilis	Idilis	LTE 2600 (3.5/ 4G)	Since 2018.12: Cloudsys Telecom
16	*Lycamobile*	Lycamobile Romania	GSM/GPRS 900 / 1800 (2/ 2.5G) UMTS 900 / 2100 (3/ 3.5G) LTE 800 / 900 / 1800 / 2600 (3.5/ 4G)	MVNO Uses Telekom infrastructure
(03)	*Akta*	Acta Telecom S.A./ Digital Cable Systems S.A.	GPRS (2.5G) UMTS (3/ 3.5G)	MVNO Uses Telekom infrastructure

Section III
GSM System

10. Short history
11. System architecture
12. Radio interface
13. System security
14. Interchanges over the network

Digital Telecommunications

10 Short History

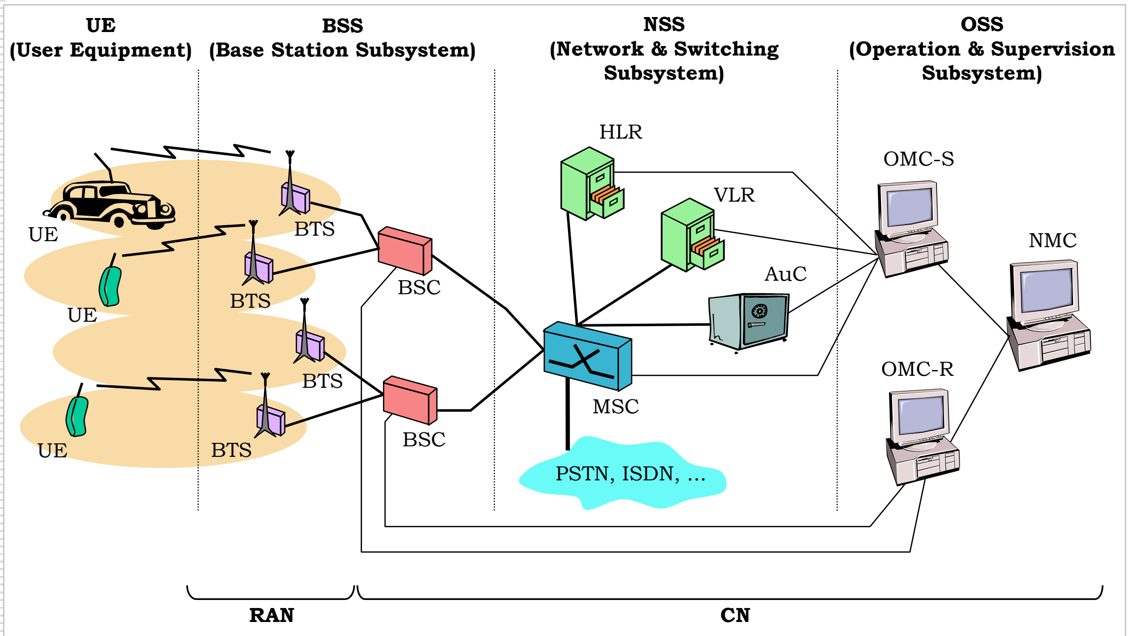
- GSM – Global System for Mobile communication
  - 1979-00 World Administrative Radio-communications Conference (WARC) → 900 MHz band reserved
  - 1982 Stockholm → founding of "Groupe Special Mobile"
  - 1987 Main GSM techniques chosen: frequency band pair, digital transmission (rate < 16 kbps), FDMA, 8*TDMA (future increase to 16), slow Frequency Hopping (FH)

    "Memorandum of Understanding" (MoU) signoff, between European operators: system development schedule, routing and numbering plan compatibility, joint introduction of new services, similar billing procedures
  - 1988-89 GSM taken over by ETSI (European Telecom. Standards Institute)

    First publication of "Recommendations" (draft)
  - 1990 Upon UK's requests → studies to adapt GSM for the 1800 MHz freqency band (DCS – Digital Communication System)
  - 1991 "Recommendations, Phase 1" published. First GSM prototypes in service (Telecom'91, Geneva)

    Hong Kong, Australia, New Zealand, United Arab Emirates sign the GSM MoU
  - 1992 First commercial GSM networks in service.
  - 1995 "Recommendations, Phase 2" published

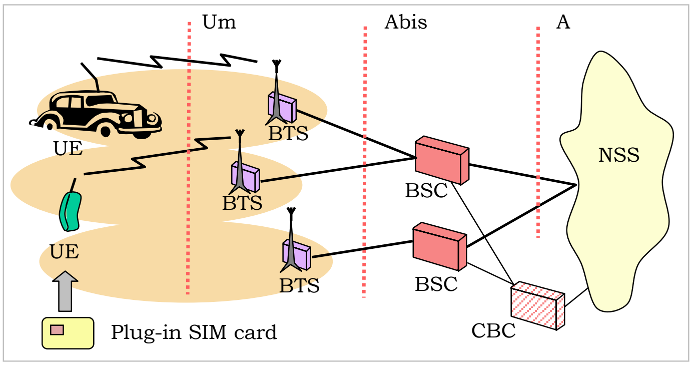
PLMN general architecture



11 System Architecture

UE and BSS

- Equipments (UE) are standardized
- SIM card - Subscriber Identity Module
- BTS (Base Station Transceiver)
- BSC (Base Station Controller)
- CBC (Cell Broadcast Center)
- Interfaces:
  - "Um" (MS - BTS)
  - "Abis" (BTS - BSC)
  - "A" (BSC - NSS)

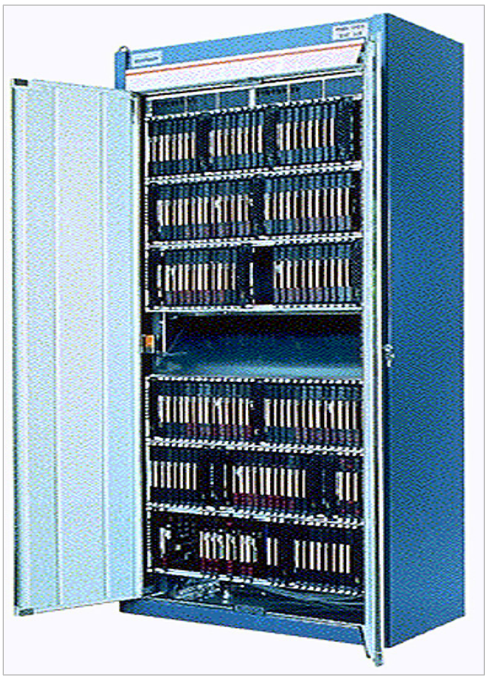


11 System Architecture

- **UE and BSS (cont'd)**

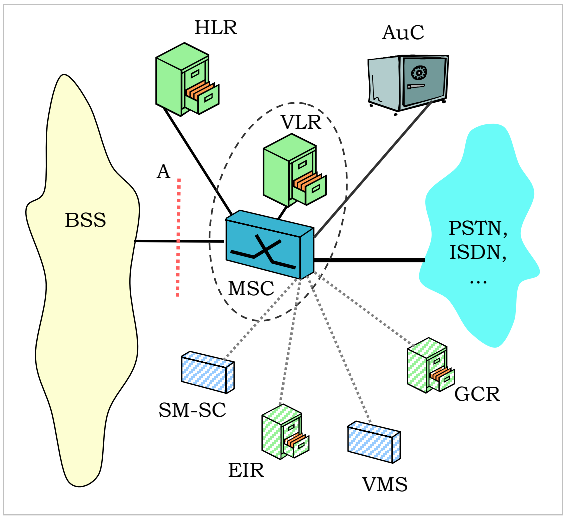
11 System Architecture

- **UE and BSS (cont'd)**



Network & Switching Subsystem (NSS)

- Basic configuration
  - MSC (Mobile Switching Center)
  - HLR (Home Location Register)
  - VLR (Visitors Location Register)
  - AuC (Authentication Center)
- Optional equipments
  - EIR
  - GCR
  - SM-SC
  - VMS



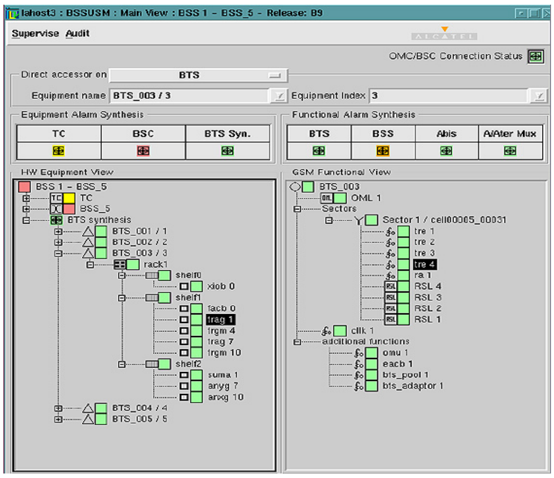
11 System Architecture

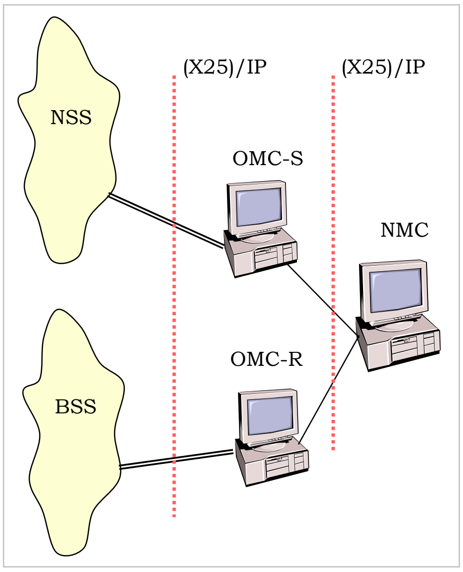
- **Network & Switching Subsystem (NSS) (cont'd)**

11 System Architecture

Operation & Supervision Subsystem (OSS)

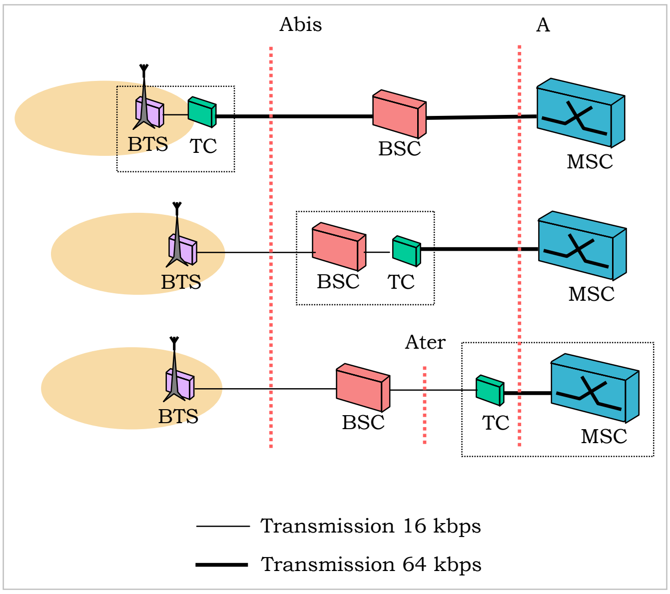
- OMC (Operation & Maintenance Center):
  - OMC-R (OMC-Radio) → BSS
  - OMC-S (OMC-Switching) → NSS
- NMC (Network Management Center) - optional





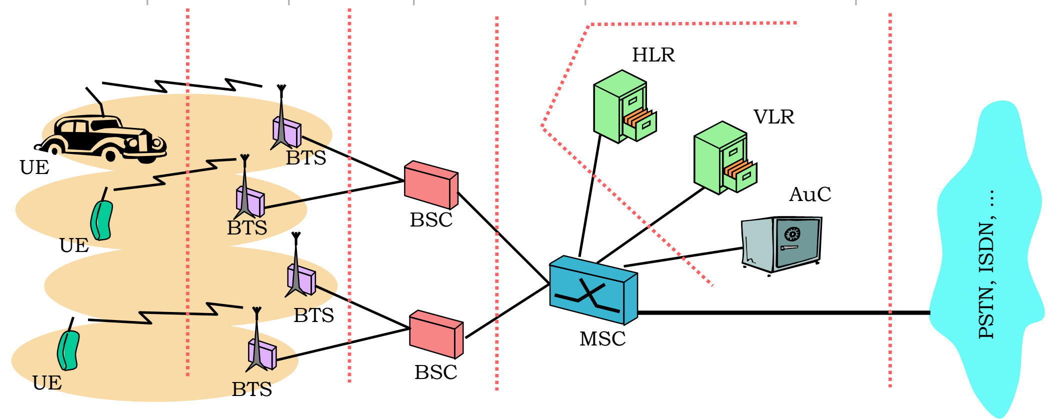
11 System Architecture

Transcoding unit (TC)



Interfaces and protocols

Protocols:	LAPDm	LAPD	SS7 + BSSAP	SS7 + MAP	SS7 + TUP, ISUP
Interfaces:	Um	Abis	A	B, C, D, E, F, G, H, I	PSTN, ISDN

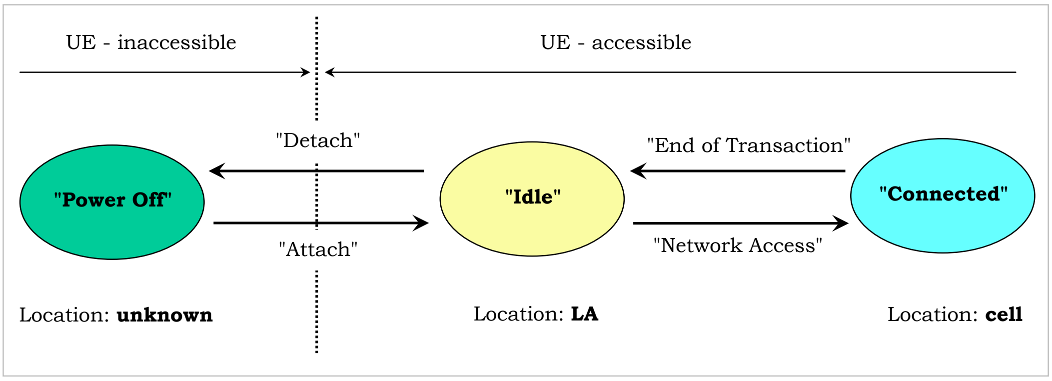


Introduction

- Radio interface (Um) → essential part of GSM specifications
  - MS – PLMN compatibility
  - Optimized usage of radio resources
  - Minimization of radio interferences
- **Traffic** resources
  - Allocation of dedicated radio resources
  - Two types: **voice/speech** and **data**
- **Signaling** resources
  - **Out of call** type
  - **During a call** type

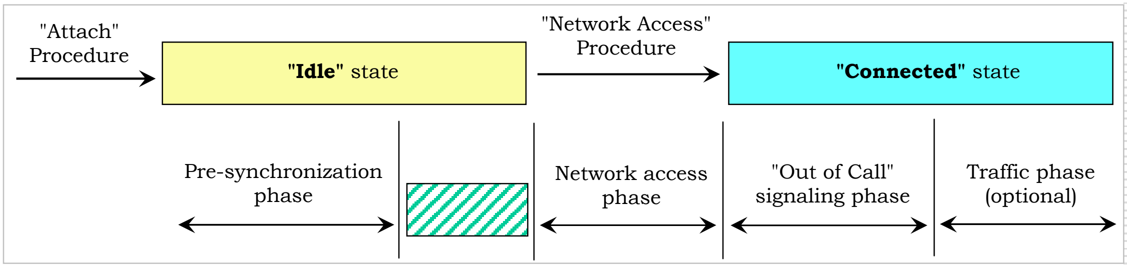
Typical UE states

- **"Power Off"** → UE is powered off
- **"Idle"** → UE is powered on, attached to the network, but unused
- **"Connected"** → UE is exchanging information with the network (sending and receiving)



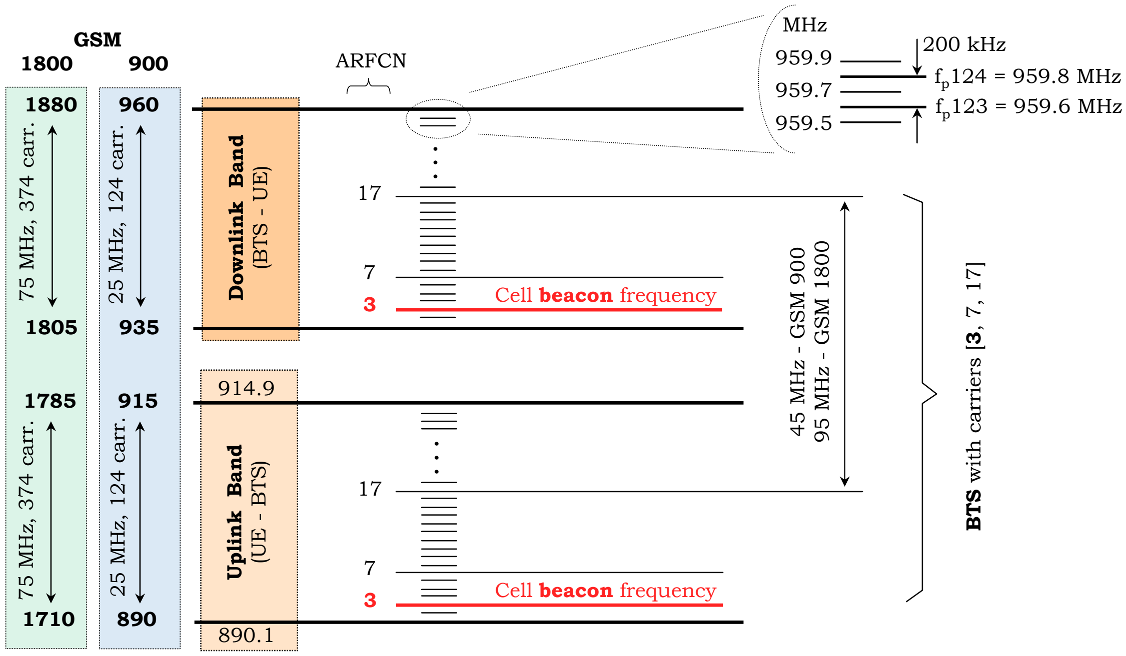
12 Radio Interface

Radio resources in a typical UE-network transaction

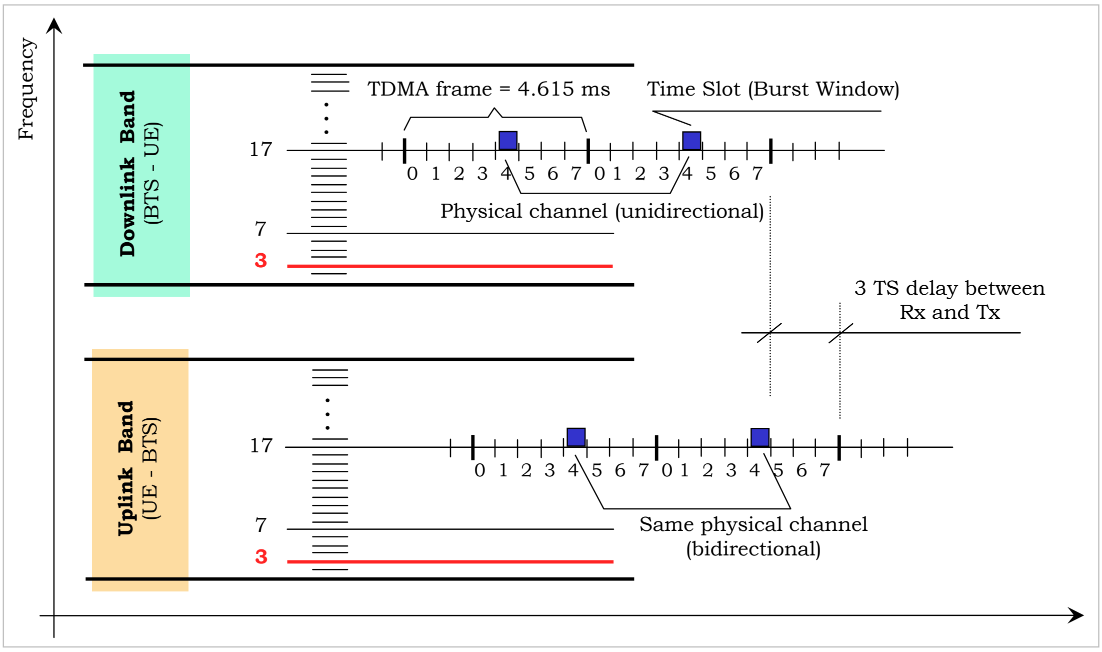


Logical channels used	Common Broadcast Channels		Common Access Channels	Dedicated Signaling Channels	Dedicated Traffic Channels
Types of procedures and transactions	Frequency Search Timing Synchro System Parameters Analysis	Frequency Monitoring	(Paging) Access Request Dedicated Channel Assignment	Authentication Location Updating SMS (Traffic Channel Assignment)	Traffic Signaling

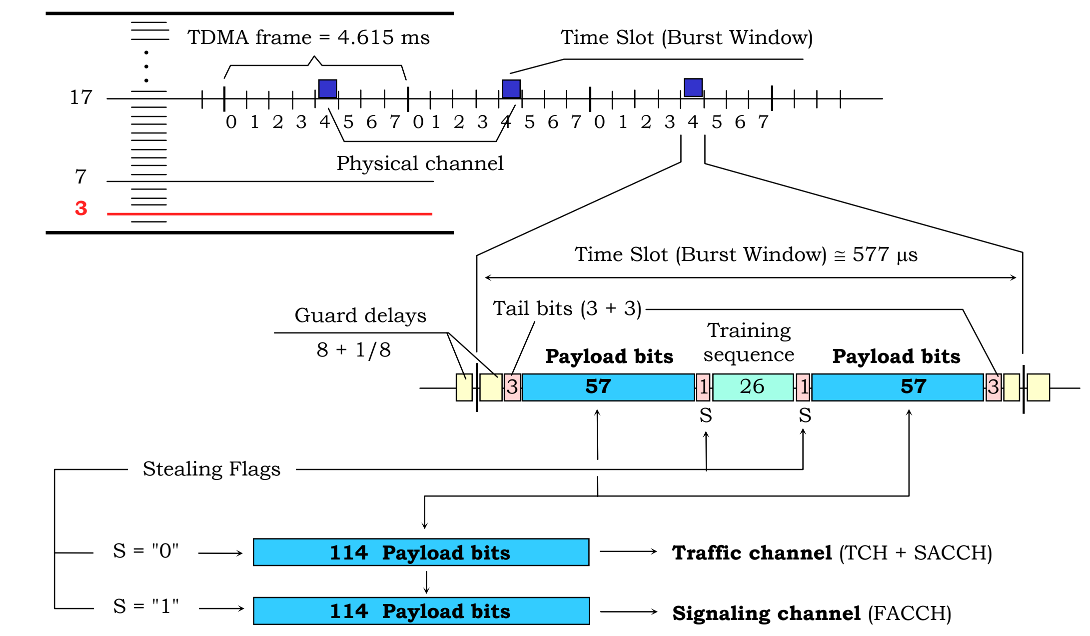
GSM frequency spectrum



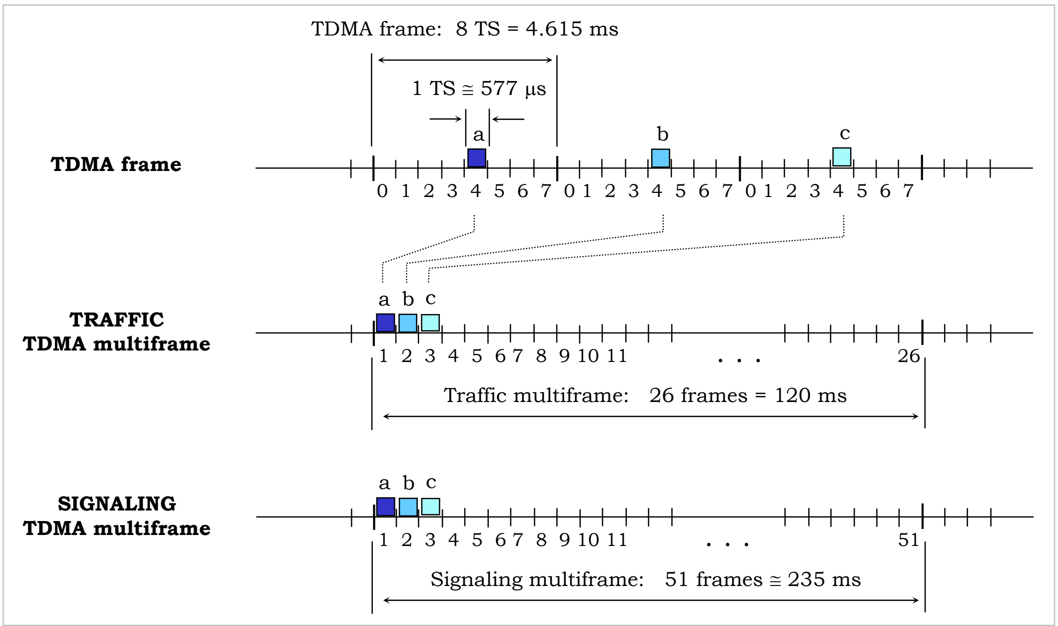
Physical channels: TDMA frame



Physical channels: Normal burst structure (TS)



Physical channels: TDMA multiframes



Logical channels: General presentation

Family	Abbr.	Name	Type		Description	Format
Broadcast	FCCH	Frequency Correction Ch.	MP	→ UE	Identifies the beacon freq.	Frequency
	SCH	Synchronization Ch.	MP	→ UE	UE reception sync.	Synchro
	BCCH	Broadcast Common Ch.	MP	→ UE	System info from network	Normal
CCCH	RACH	Random Access Ch.	PP	← UE	Network access req. from UE	Access
	PCH	Paging Ch.	MP	→ UE	Search of UE within network	Normal
	AGCH	Access Grant Ch.	PP	→ UE	Dedicated channel assignment	Normal
	CBCH	Cell Broadcast Control Ch.	MP	→ UE	Broadcast SMS	Normal
	NCH	Notification Ch.	MP	→ UE	Netwk. access & extra info for UE	Normal
Dedicated signaling (Out of call)	SDCCH	Standalone Dedicated Ctrl. Ch.	PP	← →	Signaling with a particular UE	Normal
	SACCH	Slow Associated Control Ch.	PP	← →	Pwr. ctrl., timing adv., SMS	Normal
Dedicated Traffic + Signaling (During a call)	TCH/F	Traffic / Full Rate Ch.	PP	← →	Traffic speech: 13 kbps; data	Normal
	TCH/H	Traffic / Half Rate Ch.	PP	← →	Traffic speech: 5.6 kbps; data	Normal
	SACCH	Slow Associated Control Ch.	PP	← →	Pwr. ctrl., timing advance	Normal
	FACCH	Fast Associated Control Ch.	PP	← →	Handover, FAX/data	Normal

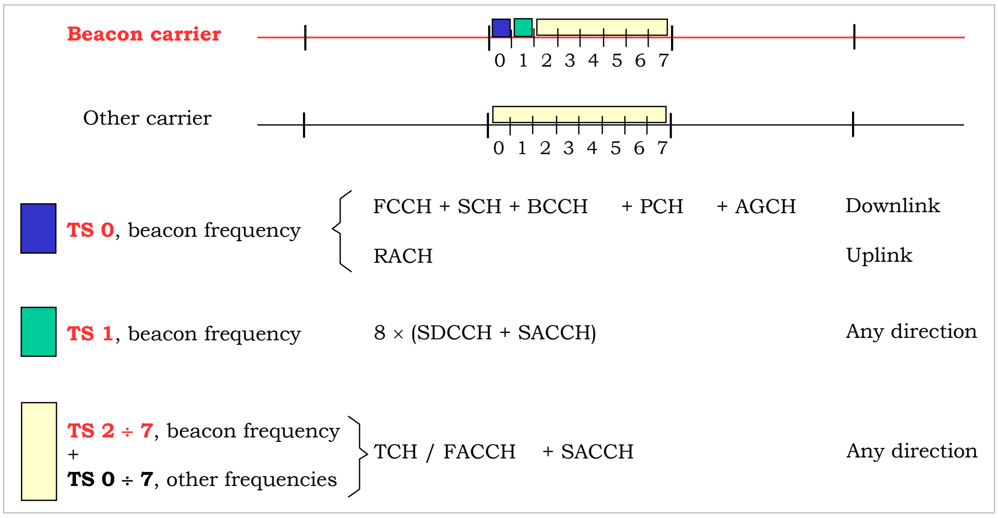
Logical channels: Usage in a typical UE-network transaction

Power Off → **Attach** → **Idle** → **Access** → **Connected** (Out of call) → **Connected** (During a call)

Attach	Idle	Access	Connected (Out of call)	Connected (During a call)
Synchronization: **FCCH + SCH**	Access info, extra info, SMS Broadcast: **NCH, CBCH**	(Paging): **(PCH)**	Dedicated signaling channel: **SDCCH + SACCH**	Dedicated traffic speech / data channel: **TCH + SACCH**
System Information: **BCCH**		Network access request: **RACH**		(Dedicated fast signaling channel): **(FACCH + SACCH)**
		Access acknowledge: **AGCH**		

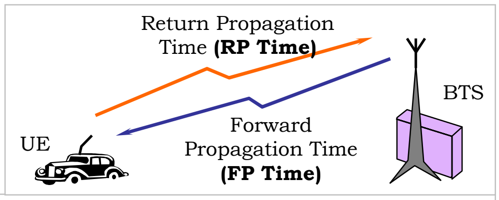
Logical channels: Mapping over physical channels

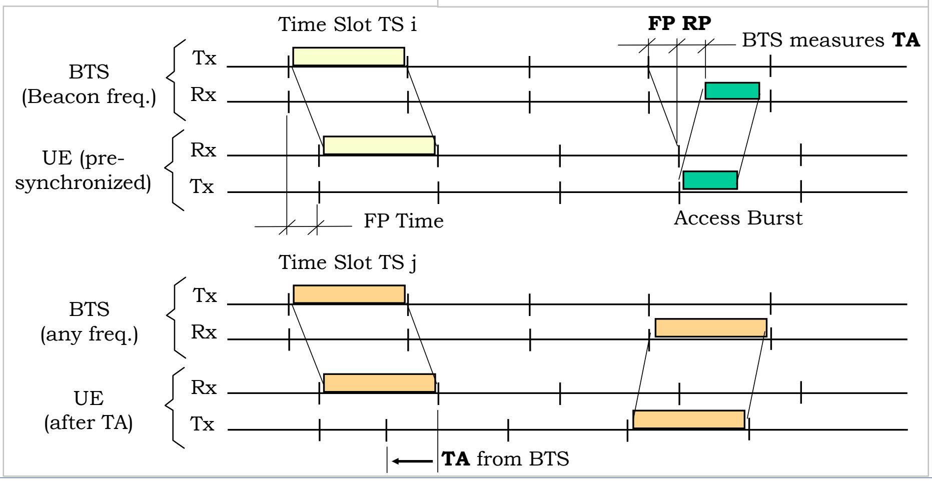
- Multiple logical channels are mapped over a single physical channel, during a time interval, at multiframe level



Specific procedures: Timing Advance

- Pre-synchronized UE ⇒ **FP** time
- During UE **Access Bursts** → BTS measures **TA = FP + RP**
- BTS → measures **TA** and reports to BSC
- BSC → commands UE with the **TA** over SACCH
- "Access Bursts" → **short**, to fit the BTS reception window





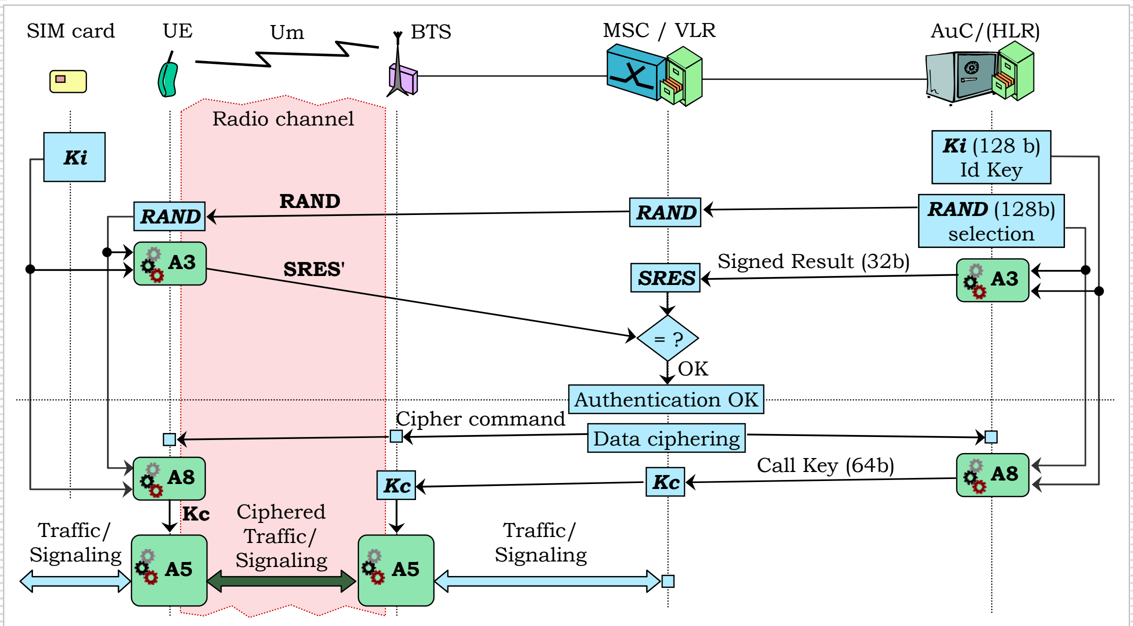
GSM identities

- Subscriber identities
  - IMSI
    - uniquely identifies a subscriber
    - stored in SIM and AuC
  - TMSI
    - temporarily assigned to a subscriber
    - changed during each LU procedure
  - MS-ISDN
    - "phone number" of the subscriber
- UE identities
  - IMEI
    - stored in UE and EIR
    - used by EIR for the 3 lists
    - replaces IMSI or TMSI in some cases
- Geographical identities
  - LAI
    - identifies a LA within the network (at operator's discretion, 1 ÷ 65536)
    - Paging: network searches a UE in a corresponding LA
    - LU: UE moves to another LA
    - Authentication and security: TMSI contains the LAI
  - CGI (Cell Global Id)
    - Uniquely identifies a cell within a LA (at operator's discretion, 1 ÷ 65536)

Code	IMSI		
Format	MCC	MNC	MSIN
N° digits	3	2	max 10
Meaning	Mobile Country Code	Mobile National Code	Mobile Subscriber Id Number
		NMSI (national identity)	
Examples	226 (RO)	01 10	Vodafone Orange

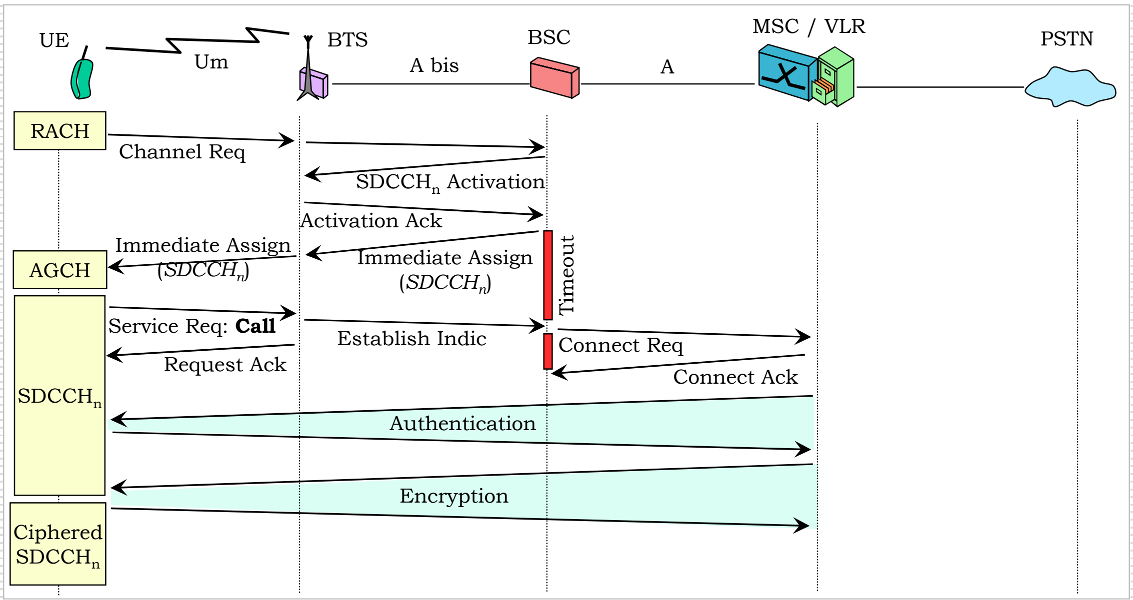
Code	MS - ISDN		
Format	CC	NDC	SN
N° digits	1 ÷ 3	2 ÷ 4	max 15
Meaning	Country Code	National Destination Code	Subscriber Number (national identity)
Examples	40 (RO)	72, 73 74, 75	Vodafone Orange

Authentication and encryption



Mobile Originated Call

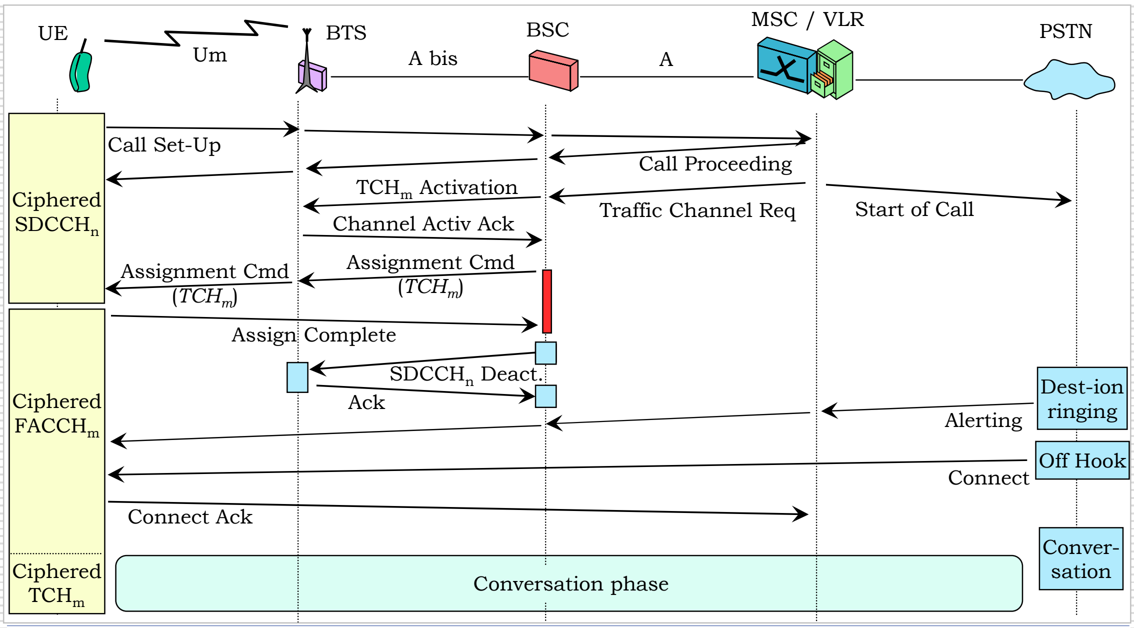
(1) Radio connection setup, service request, security functions



14. Interchanges Over the Network

Mobile Originated Call (cont'd)

(2) Call setup

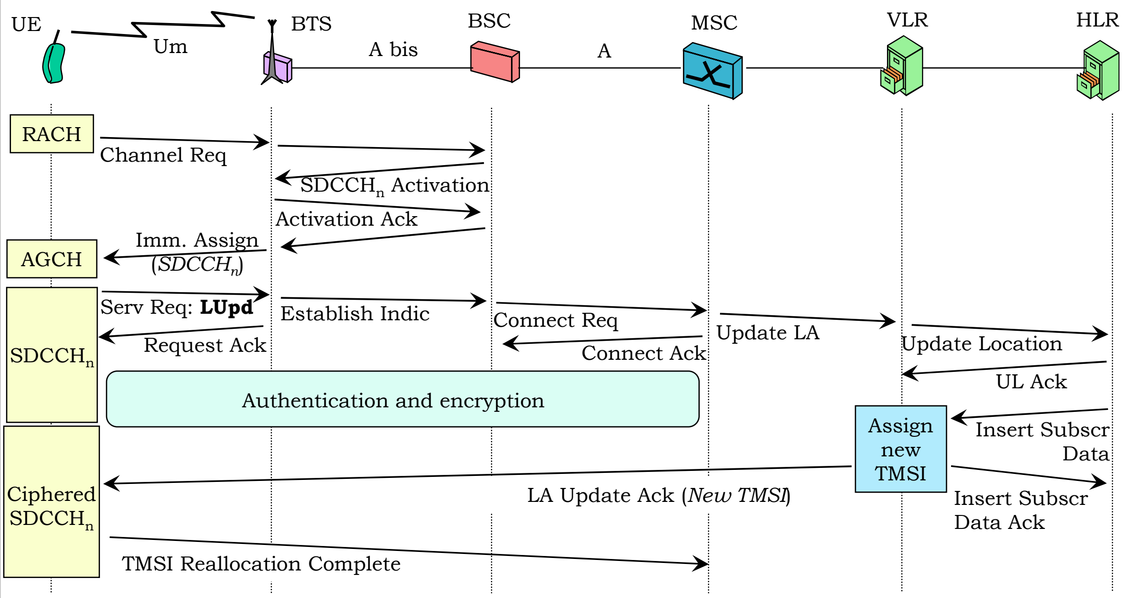


Location Update

- Always initiated by UE in **"Idle" state (pre-synchronized)**
- Updates the following
  - VLR with current LA of the UE
  - HLR with address of current VLR
  - SIM of UE with current LA and new TMSI
    - Current LAI code → stored in non-volatile SIM memory
- Normal Location Update
  - Initialization of a new SIM in UE (does not contain any LAI)
  - When UE is powered on in another LA as the one stored in SIM
  - When Idle (pre-synchronized) UE moves into another LA
- Periodic Location Update
  - When corresponding timer in UE SIM expires (configured by operator → one or more days, usually)
- Location Update ⇒ UE receives a new TMSI

14. Interchanges Over the Network

Location Update (cont'd)



14. Interchanges Over the Network

Handover

- Always initiated by the current BSC (controlling the originating cell)
- Performed only when the UE uses dedicated channels (SDCCH, TCH/FACCH)
  - UE is in the "Connected" status
  - If UE uses TCH, it changes into fast signaling channel, FCCH, through "cycle stealing" (the "Stealing flags" are set from "0" to "1")
- UE involvement
  - Continuous power monitoring for current cell (Rx signal power and quality)
  - Continuous power monitoring of adjacent cells
  - Periodic measurement reports sent to BSC (through BTS, over SACCH, every 0.5s)
- GSM network involvement
  - Continuous power monitoring of entire cell (Rx signal from all UEs in cell)
  - BSC executes the handover algorithms and controls the procedure
- Handover phases: **(1)** Identification of requirement, **(2)** Selection of new cell, and **(3)** Procedure execution

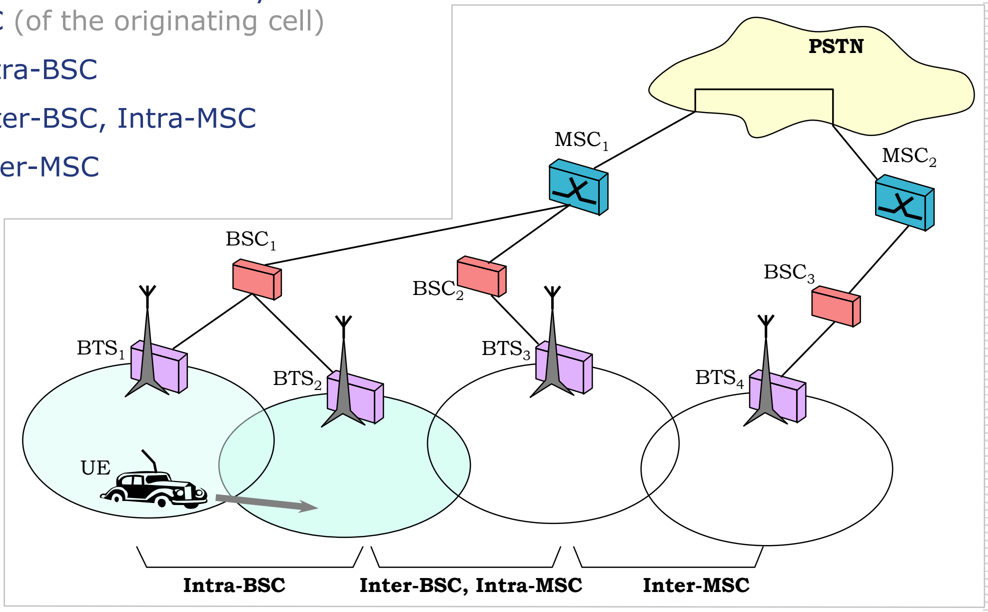
Handover (cont'd)

- Procedure controlled by the current BSC (of the originating cell)

(a) Intra-BSC

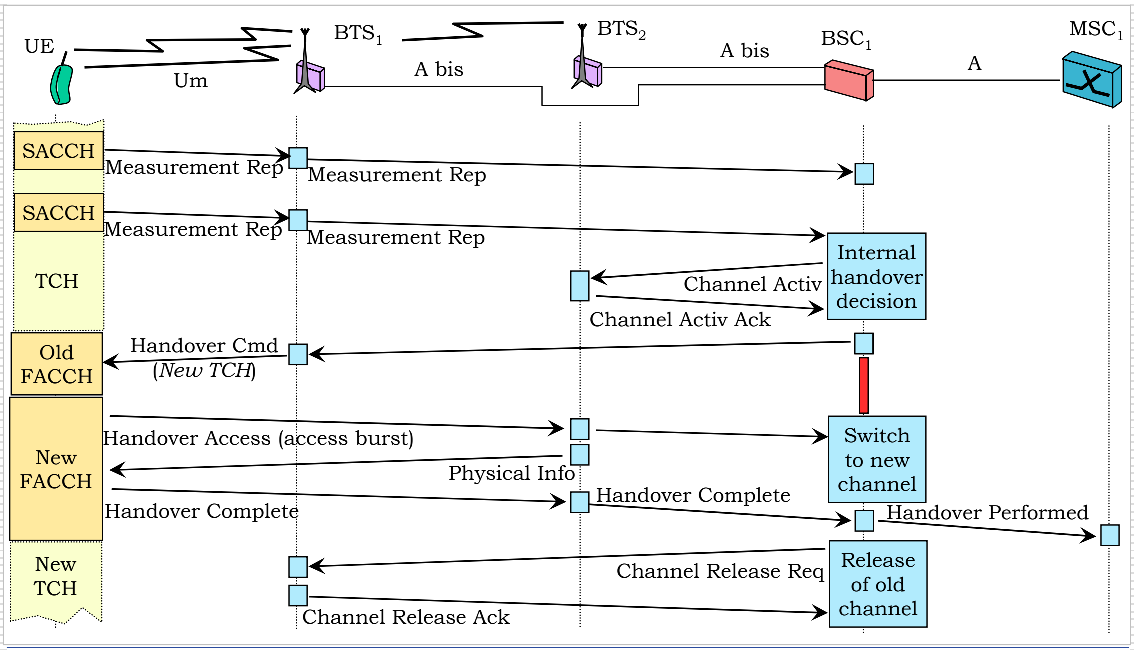
(b) Inter-BSC, Intra-MSC

(c) Inter-MSC



14. Interchanges Over the Network

Handover (cont'd)



Section IV
GPRS System

15. Introduction
16. General architecture

What is GPRS

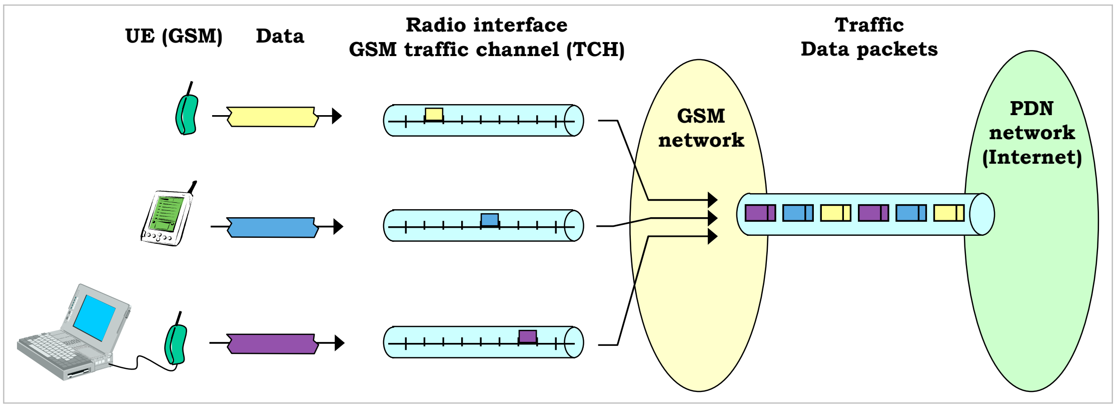
- GSM → **circuit switched** mobile telecommunications standard (real temporal circuit)
- **GPRS: "General Packet Radio Service"**
- ETSI standard, as GSM
- Purpose: providing the subscribers with the means of directly communicating with packet switched data networks (**PDN**)
- Definition

  GPRS is a communication network architecture which provides full support for packet switched data transfer for subscribers connected to the system through a radio interface
- GPRS → convergence of two highly popular technologies: mobile telecommunications (GSM) and Internet (IP networks)

What is GPRS (cont'd)

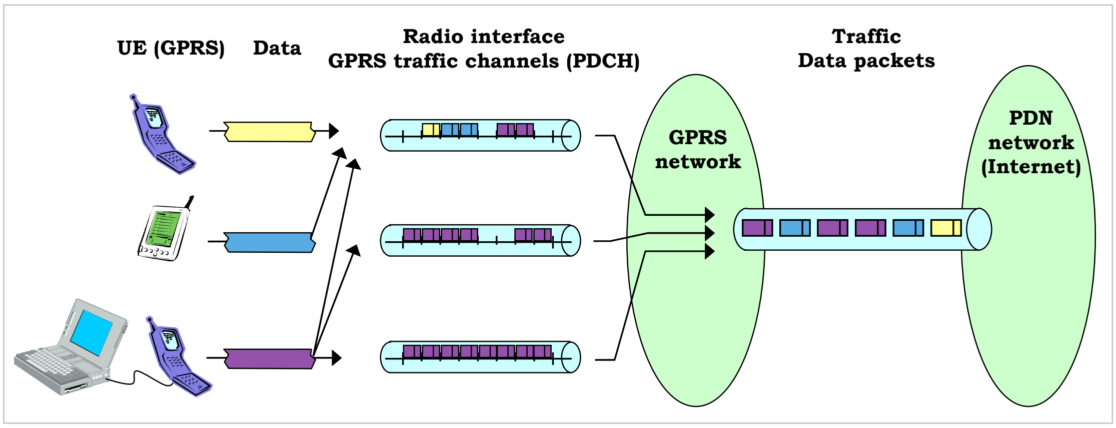
- Data communication over the radio interface
  (a) Circuit switched
  (b) Packet switched

(a) Circuit switched



What is GPRS (cont'd)

(b) Packet switched



15 Introduction

Use of the radio interface

- **Radio resource** → assigned upon requirements
  - GPRS resource allocation unit → **Radio Block**: same TS from 4 consecutive TDMA frames
  - **Temporary Block Flow** (**TBF**)
    - Established between the network and the UE
    - Only when data needs to be transferred over the radio interface
    - ⇔ Temporary micro-connections
  - Dynamic sharing: a same TS is shared between multiple UEs, according to **dynamic (statistical) multiplexing** algorithms (implemented in BSS)
  - Uplink and Downlink resources → assigned and managed separately
  - Resource assignment depends on
    - Configuration (cell parameters)
    - Type of equipment (UE)
    - Momentary data transfer requirements
    - (QoS parameters, as integrated component of GPRS subscription packages)

15 Introduction

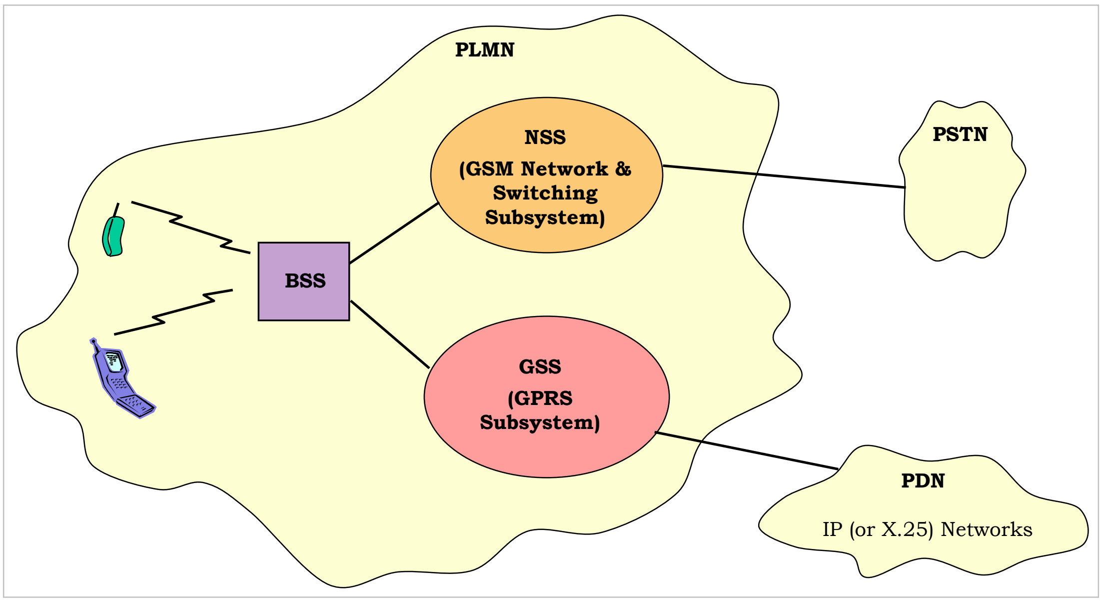
GPRS equipment classes

- **Class A**
  - Capable of simultaneous GSM calls and GPRS data transactions
- **Class B**
  - GPRS data transactions are suspended during a GSM call
  - Simultaneous GSM and GPRS "standby" mode
- **Class C**
  - Manual selection for exclusive GSM or GPRS "standby"

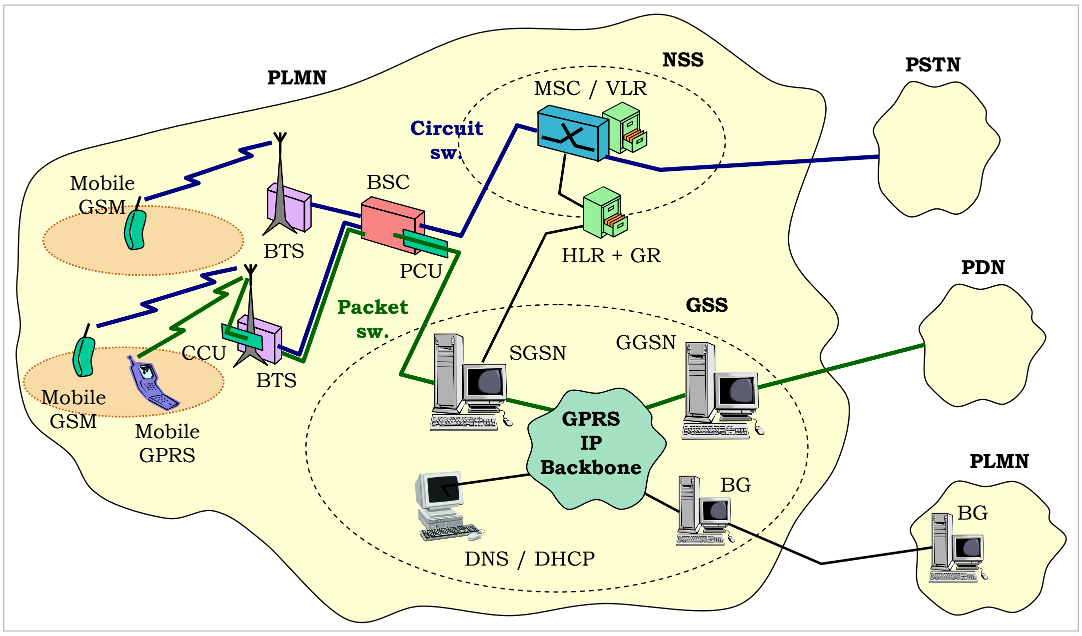
- Additional **multi-slot class** for each MS
  - Number of channels which can be simultaneously managed by the MS for each direction (UL / DL)

16 General Architecture

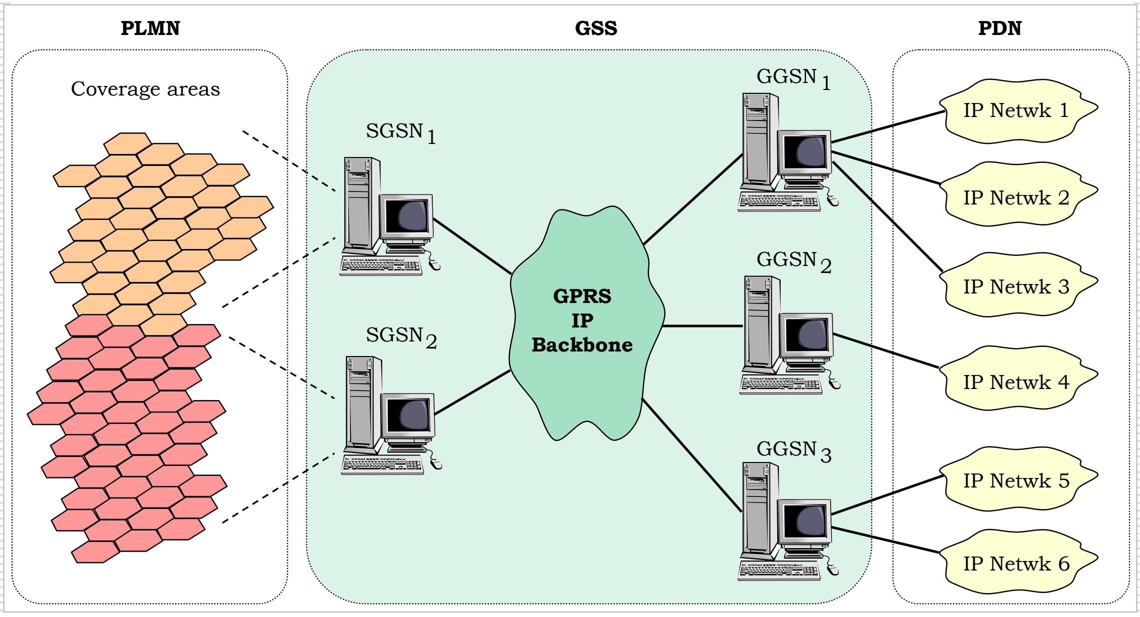
- ## System overview



Main GPRS entities



SGSN and GGSN



- **GPRS equipments**



Section V
5G System

17. Introduction
18. System architecture
19. 5G-NR radio interface

17 Introduction

Prospects of mobile communication

- Past → "**connecting people**"; future → "**connecting things**"
  - Fixed internet: 1 Bln places connected by 2005
  - Mobile internet: 5 Bln people connected by 2020
  - "Programmable World": 50 Bln things connected by 2025
- "**More of everything**":
  - Number of mobile users by 2020: 9 Bln
  - Increase of mobile devices number, over 2014-2018: 57%
  - More tablets sold in 2014, than laptops and desktop PCs combined: 320 Mil more
  - Increase of cloud and data center traffic, over 2012-2017: 440%
  - Traffic needs per 2019: 24.3 exabytes/month

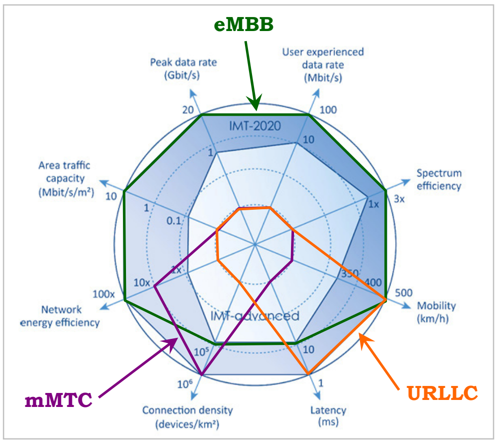
[Multiple sources: Bell Labs Consulting report, Statista, Radicati, Cisco Internet Business Solutions Group]

⇒ Current approaches of networking (legacy blueprints, cycles of expensive upgrades) → unsustainable

⇒ **Change needed** in the way networks will be built

System requirements and use cases

- ITU-R **IMT-2020** specifications → 8 key capabilities identified as potential targets
  - Peak data rate: achievable data rate per user/ device (ideal conditions)
  - User experienced data rate: minimum data rate per user, achievable anytime, anywhere
  - Spectrum efficiency: avg. data throughput per unit spectrum resource and per cell [bit/s/Hz]
  - Mobility: maximum speed at which a defined QoS can be achieved
  - (Over-the-air) Latency: time latency introduced by the network during the packet transfer
  - Connection density: total # of connected/ accessible devices per km^2
  - Network energy efficiency: quantity of information received/ transmitted by users, per energy consumption unit at RAN level [bit/J]
  - Area traffic capacity: total traffic throughput served per area unit

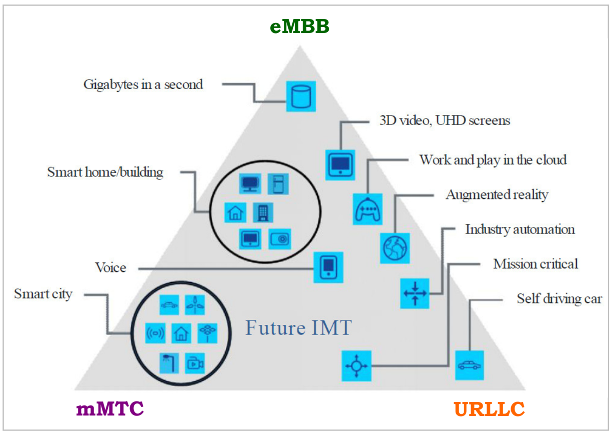


[Source: ETSI, https://www.etsi.org/technologies/5g, Accessed: Aug. 2019]

- 3 main use-case categories:
  - **eMBB** - Extreme Mobile Broadband communications
  - **URLLC** - Ultra-Reliable and Low Latency Communications
  - **mMTC** - Massive Machine-Type Communications

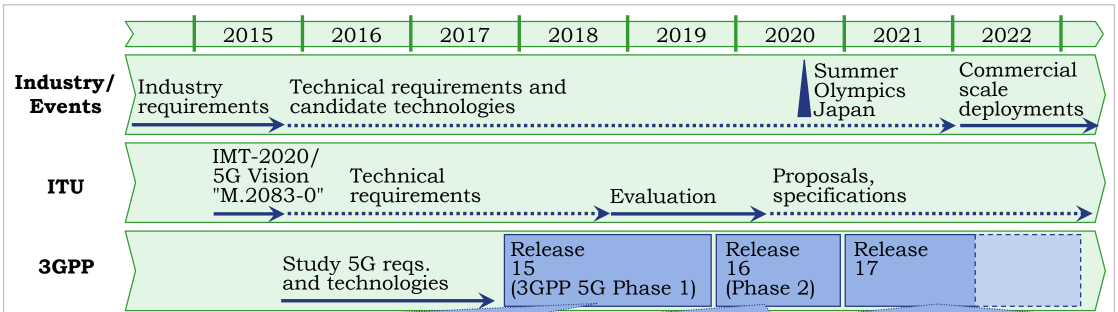
System requirements and use cases (cont'd)

- **eMBB** - Extreme Mobile Broadband communications
  - Addresses human-centric use cases
  - Access to multi-media content, services and data
  - High user density & very high traffic capacity for hotspot scenarios
  - Seamless coverage & medium to high mobility, with much improved user data, for wide area coverage scenarios
- **URLLC** - Ultra-Reliable and Low Latency Communications
  - Wireless control of industrial processes, smart manufacturing, industry robots
  - Remote medical surgery, Tactile Internet
  - Drone control
  - Vehicle-to-X communication, driverless connected cars
- **mMTC** - Massive Machine-Type Communications
  - Wireless control of industrial processes
  - e-health
  - Smart energy networks, smart grids
  - Environmental monitoring, WSNs
  - Smart agriculture, smart retail



[Source: ITU-R, "Recommendation M.2083-0", Sep. 2015, https://www.itu.int/rec/R-REC-M.2083-0-201509-I/en, Accessed: Aug. 2019]

System standardization



3GPP Release 15

- NR
- The 5G System – Phase 1
- Massive MTC and Internet of Things (IoT)
- Vehicle-to-Everything Communications (V2x) Phase 2
- Mission Critical (MC) interworking with legacy systems
- WLAN and unlicensed spectrum use
- Slicing – logical end-2-end networks
- API Exposure – 3rd party access to 5G services
- Service Based Architecture (SBA)
- Further LTE improvements
- Mobile Communication System for Railways (FRMCS)

3GPP Release 16

- The 5G System – Phase 2
- V2x Phase 3: Platooning, extended sensors, automated driving, remote driving
- Industrial IoT
- Ultra-Reliable and Low Latency Communication (URLLC) enhancements
- NR-based access to unlicensed spectrum
- 5G Efficiency: Interference Mitigation, SON, eMIMO, Location and positioning, Power Consumption, eDual Connectivity, Device capabilities exchange, Mobility enhancements
- Enhancements for Common API Framework for 3GPP Northbound APIs (eCAPIF)
- FRMCS Phase 2

3GPP Release 17 Content Approval*

TSG SA Work Areas under discussion at SA#85 (September 2019):

- 5G System Enhancement for Advanced Interactive Services (5G_AIS)
- Cellular IoT enhancement for the 5G System (5G_MCIoT)
- System enhancement for Proximity based Services in 5GS (5G_ProSe)
- Enhancement of support for 5G LAN-type service (5GLAN_enh)
- Integration of Satellite in 5G Systems (5GSAT_ARCH)
- Architectural enhancements for 5G multicast-broadcast services (5MBS)
- Study on enhancement of support for 5G Wireless and Wireline Convergence (5WWC_enh)
- Application Awareness Interworking between LTE and NR (AAI_LTE_NR)
- Extended Access Traffic Steering, Switch and Splitting support in the 5G system architecture (eATSSS)
- 5G Enhancement for unmanned aerial vehicles - UAVs (EAV)
- Enhanced IMS to 5GC Integration (eIMS5G)
- Enhancement to the 5GC LoCation Services-Phase 2 (eLCS_ph2)
- Enablers for Network Automation for 5G - phase 2 (eNA_Ph2)
- Enhancement of support for Edge Computing in 5GC (enh_EC)
- Enhanced support of Non-Public Networks (eNPN)
- Enhancement of Network Slicing Phase 2 (eNS_Ph2)
- Enhancement of 5G UE Policy (eUEPO)
- Architecture enhancements for 3GPP support of advanced V2X services - Phase 2 (eV2XARC_Ph2)
- Supporting Flexible Local Area Data Network (FLADN)
- Supporting Unmanned Aerial Systems Connectivity, Identification and Tracking (ID-UAS)
- Enhanced support of Industrial IoT - TSC/URLLC enhancements (IIoT)
- Support for Minimization of service Interruption (MINT)
- Multimedia Priority Service Phase 2 (MPS2)
- Support for Multi-USIM Devices (MUSIM)
- System architecture for next generation real time communication services (NG_RTC)
- Service-based support for SMS in 5GC (SB_SMS)
- Smarter User Plane (SUP)
- UPF enhancement for control and Service Based Architecture (UPCAS)
- Usage of User Identifiers in the 5G System (UUI5)

TSG RAN Work Areas under discussion For final decision at RAN#86 (December 2019):

- NR Light
- Small data transfer optimization
- Sidelink enhancements
- NR above 52.6 GHz (inlc 60GHz unlicensed)
- Multi SIM operation
- NR multicast broadcast
- Coverage enhancements
- NB-IoT and eMTC enhancements
- Industrial IoT & URLLC enhancements
- MIMO enhancements
- NR for Non Terrestrial Networks
- Integrated Access and Backhaul enhancements
- Generic enhancements to NR-U
- Power saving enhancements
- RAN data collection enhancements
- Positioning enhancements

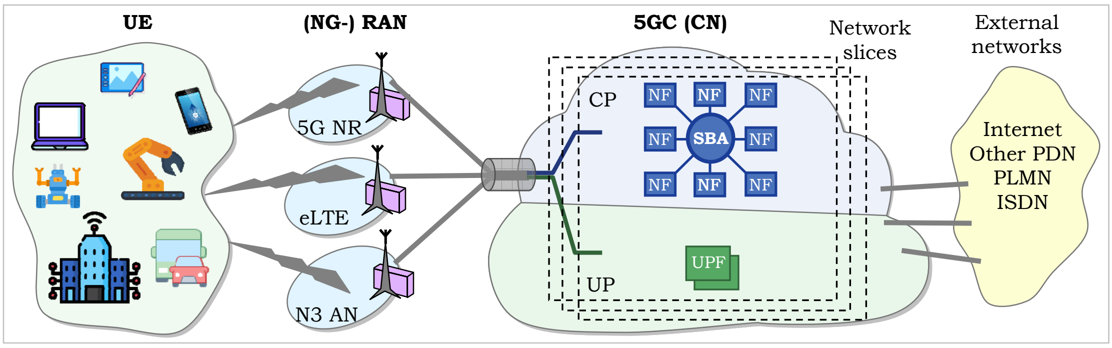
** Mainstream Rel-17 specification work will start at the beginning of 2020, with the functional freeze of physical layer aspects scheduled for the second quarter of 2021.*

The ASN.1 freeze should follow in September 2021.

There are a large number of work areas to be discussed. Realistically, we will only be able to take on board a sub-set of them within Rel-17.

18. System Architecture

General architecture and key principles

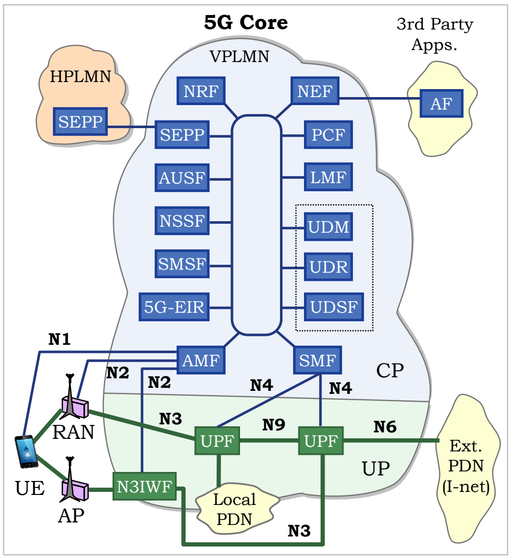


- Common AN-CN interface
- Flexible, cloud-native CN infrastructure
- SDN capabilities
- Separate UP and CP
- NFV/ SBA
- Network slicing

18. System Architecture

5G Core network functions: overview

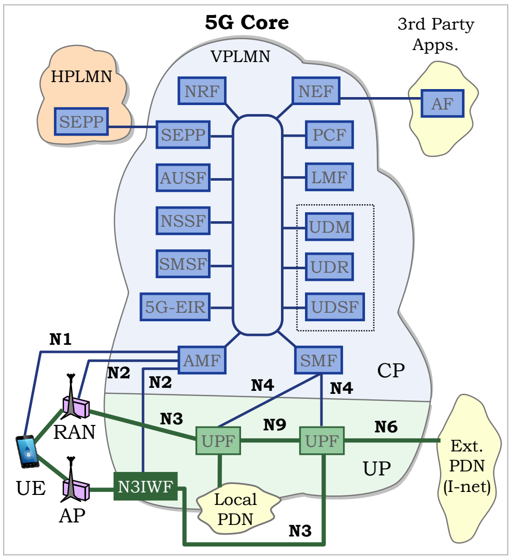
N3IWF	Non-3GPP Inter-Working Function
UPF	User Plane Function
AMF	Access and Mobility management Function
SMF	Session Management Function
NRF	Network Repository Function
NEF	Network Exposure Function
PCF	Policy Control Function
LMF	Location Management Function
UDM	Unified Data Management
UDR	Unified Data Repository
UDSF	Unstructured Data Storage Function
SEPP	Security Edge Protection Proxy
AUSF	Authentication Server Function
NSSF	Network Slice Selection Function
SMSF	SMS Function
5G-EIR	5G Equipment Identity Register



18. System Architecture

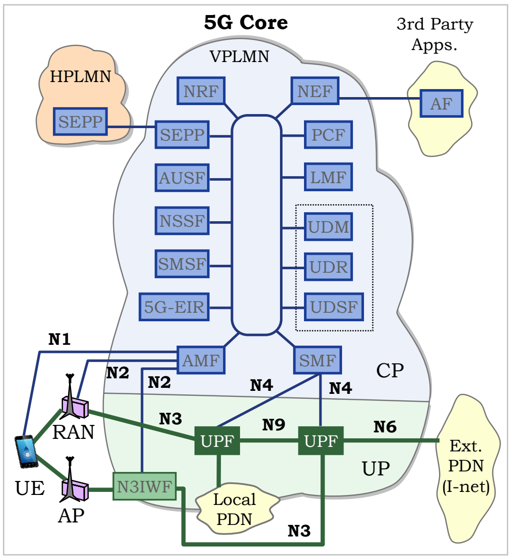
5G Core network functions: N3IWF

- **Non-3GPP Inter-Working Function**
- **Integrates stand-alone untrusted non-3GPP access to the 5G Core**
- Termination of IPsec (Internet Protocol Security) tunnel with UE
- Termination of N2 (for the CP) and N3 (for the UP) interfaces with 5G Core
- Handling of N2 signaling related to packet (PDU) sessions and QoS, from SMF (relayed by AMF)
- Relaying (over N2) of N1 signaling related to authentication and access authorization, between UE and AMF
- Relaying user-plane packets between UE and UPF (packet encapsulation/ decapsulation for IPsec, N3 tunneling)



5G Core network functions: UPF

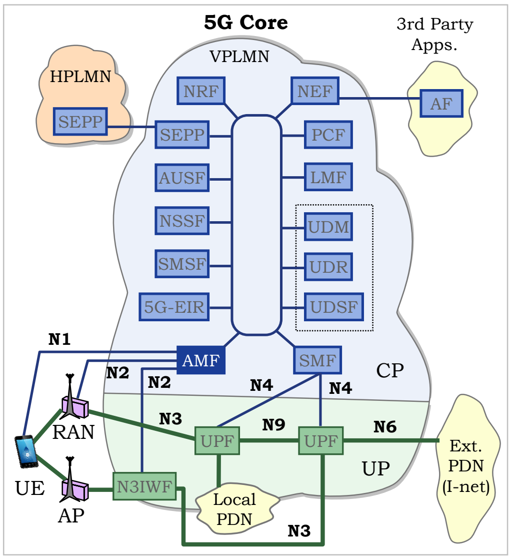
- **User Plane Function**
- **Equivalent to G4 serving/ packet gateway, or GPRS S/G GSNs**
- One or multiple instances are possible
- Packet routing and forwarding
- Downlink data buffering and notification triggering
- Uplink traffic verification
- Branching point for multi-homed packet session
- Packet inspection and UP-part of policy rule enforcement
- Traffic usage reporting
- Lawful intercept (UP part)



18. System Architecture

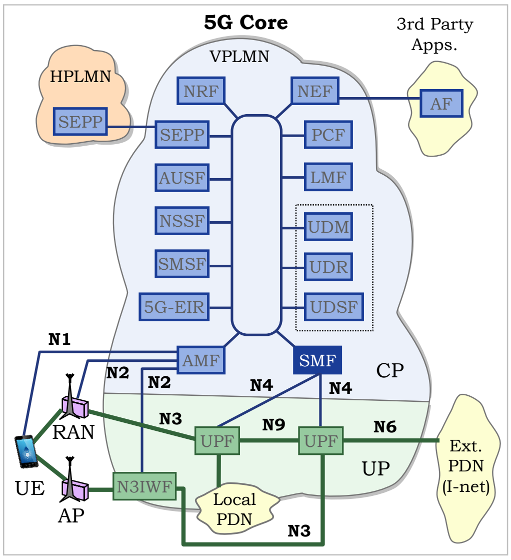
5G Core network functions: AMF

- **Access and Mobility management Function**
- **The single CP component which:**
  - **terminates the N1 (NAS – Non-Access Stratum) interface**
  - **terminates the RAN control interface (N2)**
  - **access authentication and authorization**
  - **registration, connection, reachability and mobility management**
  - **key role in network slicing → serving all slices accessed by UE**
- Transport and proxy of session management messages between UE and SMF
- Transport SMS between UE and SMSF
- Lawful intercept



5G Core network functions: SMF

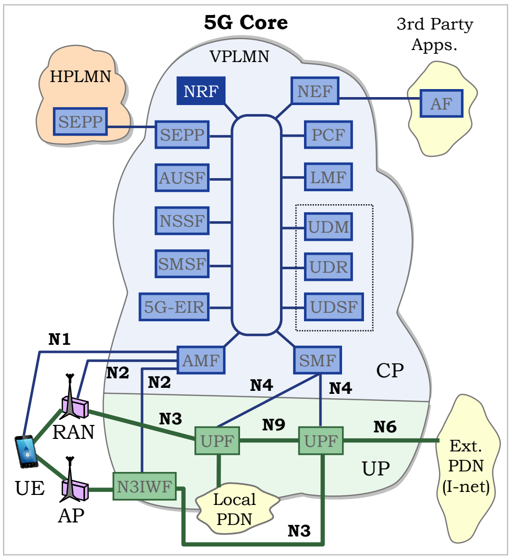
- **Session Management Function**
- **The single function which establishes, manages and releases sessions for all access types according to the network policy**
- UE IP address allocation and management
- Selection and control of UPFs
- UPF traffic steering configuration to proper destination
- Determines the SSC (Session and Service Continuity) mode of a session
- Control part of policy enforcement and QoS
- Charging data collection and support of charging interfaces
- Control and coordination of charging data collection at UPF
- Termination of SM (Session Management) parts of NAS (N1) messages
- Roaming functionality (local QoS, charging)
- Lawful intercept



18. System Architecture

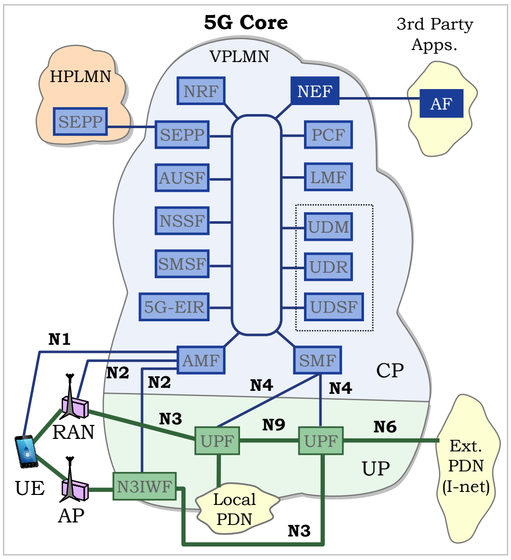
5G Core network functions: NRF

- **Network Repository Function**
- **Provides registration and discovery functionality to enable other network functions/services to discover and communicate with each other**
- All network functions interact with NRF
- Maintains the NF (Network Function) profile of available NF instances and their supported services (e.g. ID, Type, PLMN, Slice, capabilities, authorization information, service names)
- Receives NF Discovery Request from a NF instance and provides the information of the available (discovered) NF instances
- Multiple NRFs can be deployed in network slicing per PLMN, per group of slices, or slice specific



5G Core network functions: NEF

- **Network Exposure Function**
- **Supports internal and external exposure of NF services and capabilities**
- **External exposure:**
  - Supports secure exposure of the 5G Core functionalities to 3rd party Application Functions, and vice-versa
  - Translates between information exchanged with the AF and the internal NF
- **Internal exposure:**
  - Receives information from other NFs (based on their exposed capabilities)
  - The stored information can be accessed and "re-exposed" by the NEF to other NFs and AFs

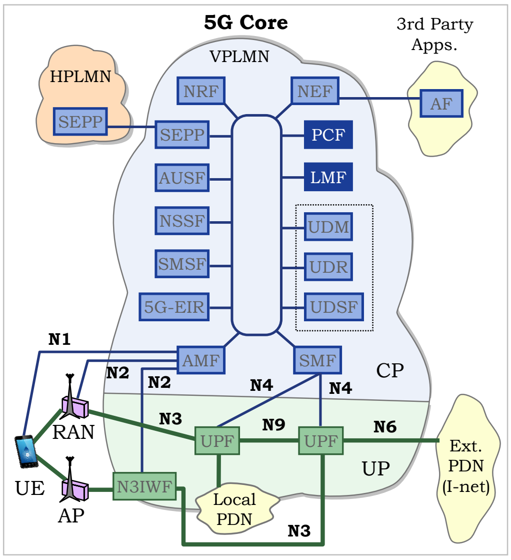


18. System Architecture

5G Core network functions: PCF, LMF

- **Policy Control Function**
- **Unified policy framework to govern network behavior**
- Exposes policy rules as a service for any authorized client (CP NFs)
- Supports network slicing, roaming and mobility policies, QoS and charging

- **Location Management Function**
- **Determines and manages UE location**
- Receives DL location measurements or a location estimate from the UE
- Receives UL location measurements from the NG-RAN
- Receives non-UE associated assistance data from the NG-RAN



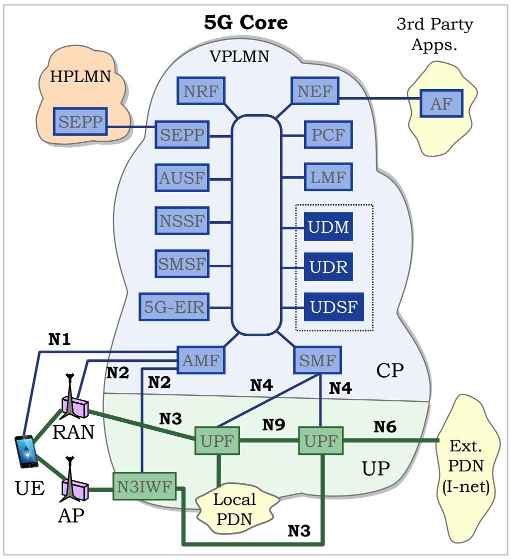
18. System Architecture

5G Core network functions: UDM, UDR, UDSF

- **Unified** (user) **Data Management**
- **Functionality similar to Home Subscriber Server (HSS) or Home Location Register (HLR)**
- Stores subscriber data and profiles
- Manages user identification, registration, access authorization, user subscription

- **Unified Data Repository**
- **Common backend** (data storage) **for the UDM, NEF and PCF**
- Subscription data for UDM; policy data for PCF; application data and structured data for exposure for NEF
- Can be collocated with the UDSF

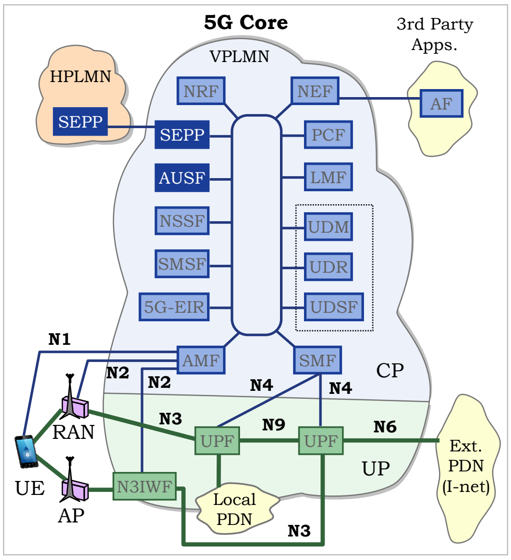
- **Unified Data Storage Function**
- **New functionality supporting CP NFs to store their session and data** (e.g. context, state, session)**, to become session stateless**
- Can be shared by multiple NFs or some NFs can have their own UDSF
- Can be collocated with UDR



5G Core network functions: SEPP, AUSF

- **Security Edge Protection Proxy**
- **Non-transparent proxy which protects the interactions between PLMNs**
- Used in roaming
- Inter-PLMN CP interface, message filtering and service relay
- Topology hiding

- **Authentication Server Function**
- **Common authentication framework for all access types** (3GPP and untrusted non-3GPP accesses)

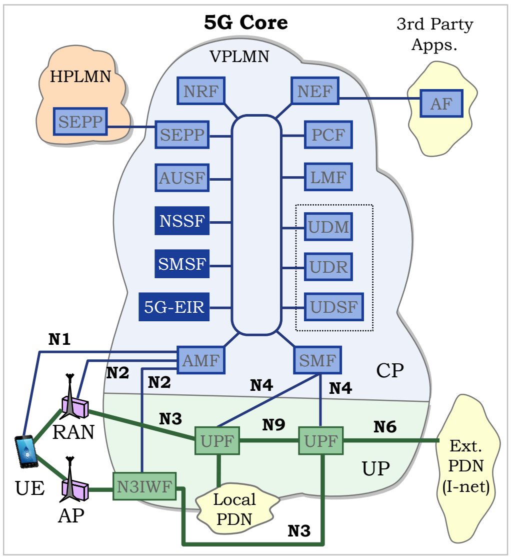


5G Core network functions: NSSF, SMSF, 5G-EIR

- **Network Slice Selection Function**
- **Assigns network slice instances to UEs**
- Established the AMF to serve the UE/ a list of candidate AMFs (based on configuration), possibly by querying the NRF

- **SMS Function**
- **SMS management and gateway**
- SMS subscription data checking
- Lawful interception

- **5G Equipment Identity Register**
- **Checks the status of Permanent Equipment Identifier (e.g. whether it has been blacklisted)**
- Optional function



19. 5G-NR radio interface

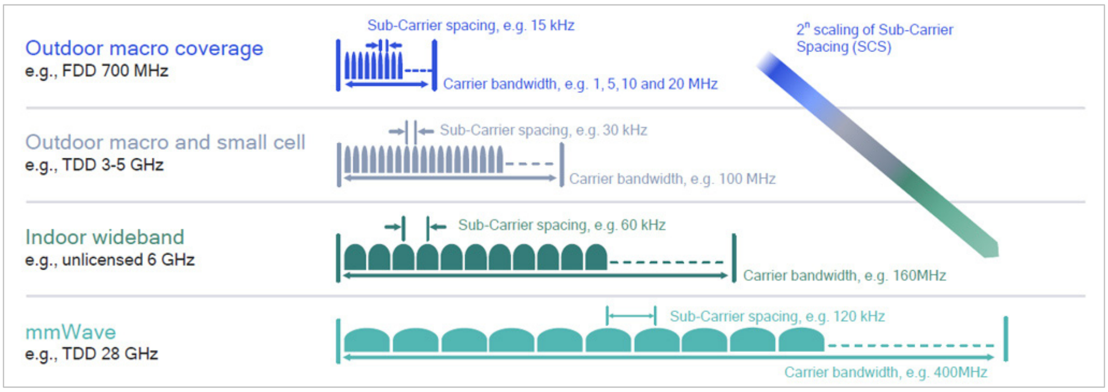
5G radio spectrum

Frequency range	Cell size	Coverage	Peak data rates	Example freq. band	Bandwidth/ Duplexing
FR1 0.45 – 6.00 GHz ("sub-6")	Macro	Deep indoor > 1km	~100 Mbps	600 MHz (n71) 900 MHz (n8) 1500 MHz (n75) 1700 MHz (n86) 1800 MHz (n3) 2600 MHz (n7) 3700 MHz (n77) 4700 MHz (n79)	5(+)→20 MHz/ FDD idem 5(+)→20 MHz/ SDL 5(+)→20,40 MHz/SUL 5(+)→30 MHz / FDD 5(+)→30,40,50 MHz/ FDD 10÷100 MHz/ TDD 40÷100 MHz/ TDD
("cmW")	Small	~ 1km	~ 1 Gbps	Not defined yet	
FR2 24.25 – 52.60 GHz ("mmW")	Ultra small	Line of sight ~ 100m Hot spots	~ 10 Gbps	26 GHz (n257) 28 GHz (n258) 39 GHz (n260)	50,100,200,400 MHz/ TDD idem idem

19. 5G-NR radio interface

Sub-carrier spacing

- Scalable SCS (or "numerology")
  - 15, 30, 60, 120 and 240 kHz

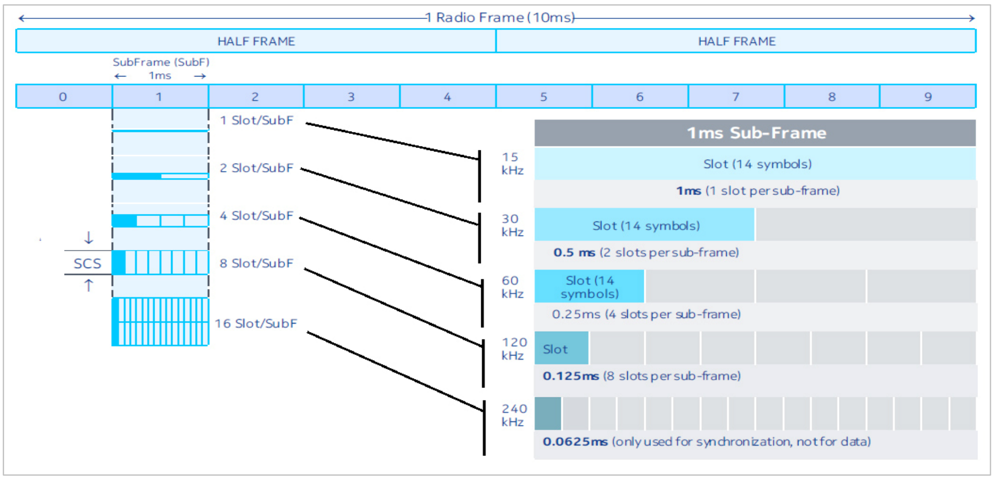


[Source: Qualcomm, "Making 5G NR a Commercial Reality", Mar. 2019, https://www.qualcomm.com/documents/making-5g-nr-commercial-reality-0, Accessed: Oct. 2019]

19. 5G-NR radio interface

Radio frame structure

- Radio frames:
  - 10 ms duration
  - divided into 10 subframes (SubF), 1ms each
- Slot:
  - basic transmission and scheduling unit
  - number of slots per SubF depends on the SCS

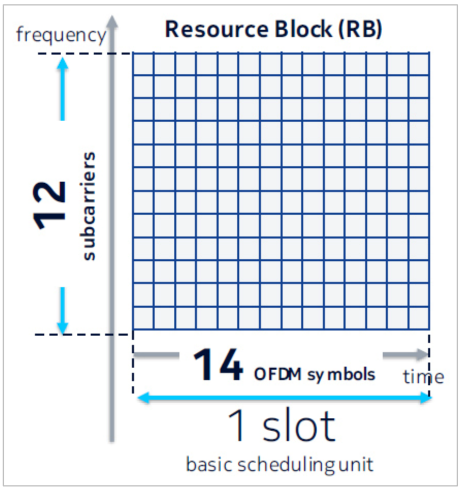


[Source: Nokia, "Understanding 5G System Fundamentals", Student Guide, Nokia internal documentation, 2018.]

19. 5G-NR radio interface

Multiple access and Radio RB

- CP-OFDMA (Cyclic Prefix OFDMA)
  - Granularity in frequency/ time:
    12 subcarriers/ 14 symbols (1 slot)
  - ⇒ Radio **Resource Block** (**RB**)
- TDMA:
  - transmission to/ from different UEs → separated in time
  - Granularity:
    - 1 slot (14 symbols), or
    - 1 **mini-slot** (2, 4 or 7 symbols) → provides fast transmission opportunities, e.g. URLLC traffic
- SDMA (Space Division Multiple Access)
  - also known as **MU-MIMO** (Multi-User MIMO)
  - part of the 5G-NR advanced-antenna capabilities
  - transmission to/ from multiple users (having different positions in space) on the same frequency-time resource



[Source: Nokia, "Understanding 5G System Fundamentals", Student Guide, Nokia internal documentation, 2018.]

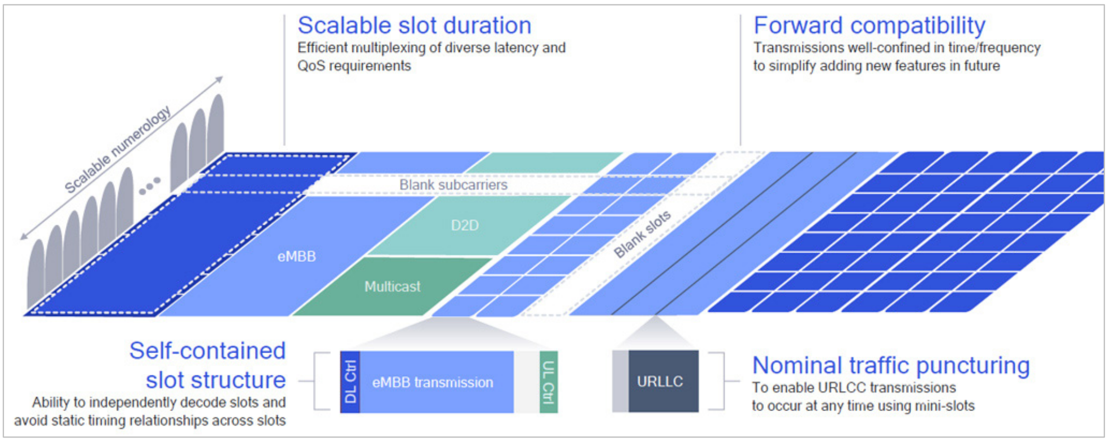
19. 5G-NR radio interface

Flexible slot-based framework

- Regular transmission slots can be complemented by mini-slot transmissions

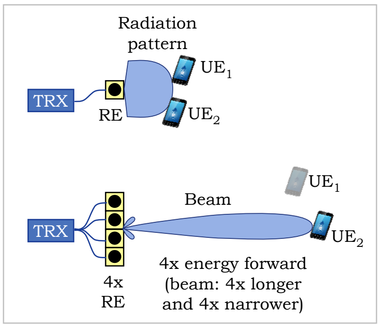
⇒ "**Punctured scheduling**"

- Enables low latency and multiplexing of eMBB and URLLC traffic

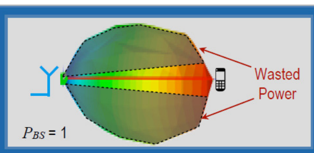


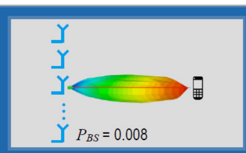
[Source: Qualcomm, "Making 5G NR a Commercial Reality", Mar. 2019, https://www.qualcomm.com/documents/making-5g-nr-commercial-reality-0, Accessed: Oct. 2019]

Massive MIMO and beamforming: principles



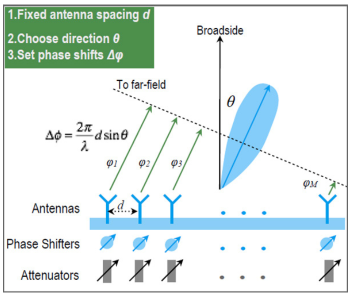
Beam forming

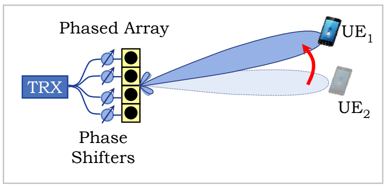




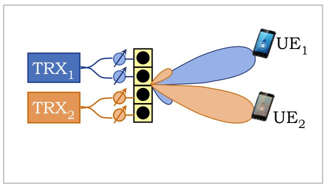
	Number of Antennas = 1	Number of UEs: 1 120 antennas per UE
Number of BS Transmit Antennas	1	120
Normalized Output Power of Antennas	$P_{ant} = \frac{1}{M_t} = 1$	$P_{ant} = \frac{1}{M_t^2}$
Normalized Output Power of Base Station	$P_{total} = \sum_{i=1}^{M_t} P_{ant}^i = 1$	$P_{total} = \sum_{i=1}^{M_t} P_{ant}^i = 0.008$

Source: IEEE Signal Processing Magazine, Jan 2013





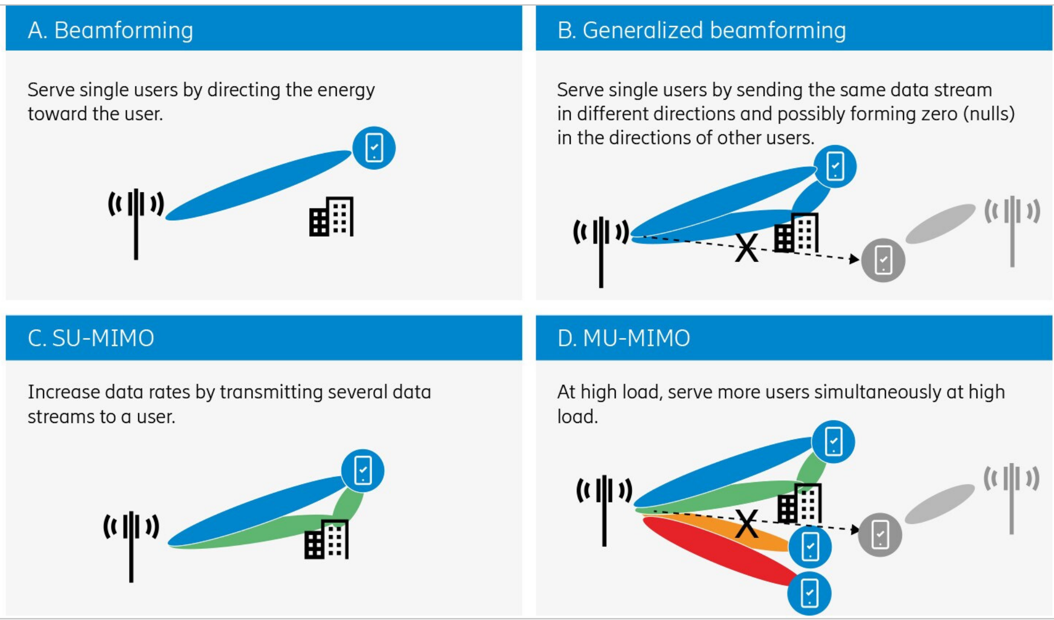
Beam steering



Multiple beamforming

19. 5G-NR radio interface

mMIMO and beamforming: types and usage



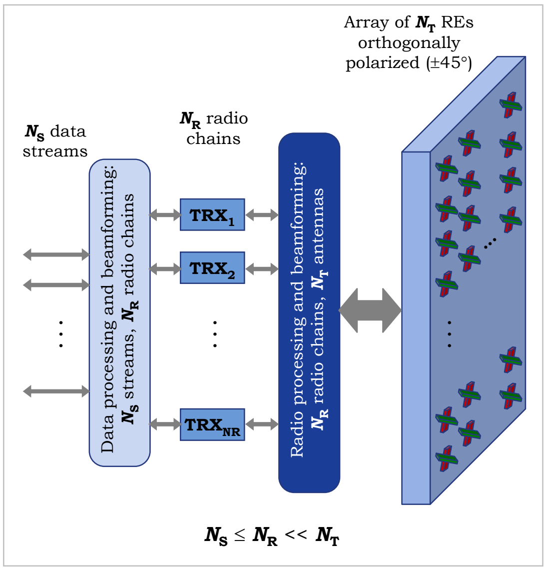
[Source: Ericsson, "Advanced antenna systems for 5G networks", White paper, Nov. 2018, https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks, Accessed: Nov. 2019]

19. 5G-NR radio interface

mMIMO and beamforming: AAS and MAA

- Passive antenna
  - Radiating Elements (RE) + Phase Shifters (enabling remote tilting)
  - No data or radio processing
- Active Antenna Systems (**AAS**)
  - (also Advanced Antenna Systems, Adaptive Antenna Systems)
  - Integrates: antenna + data/ radio processing elements
  - Dynamically adapts its pattern in response to operating radio environment
- Massive Antenna Arrays (**MAA**)
  - AAS having a large number of controllable antennas (>> 8) as a 2D array
  - Typical number of controllable antennas: 32, 64 or 128

⇒ 3D beamforming:
  – vertical beam steering (elevation)
  – horizontal beam steering (azimuth)



mMIMO and beamforming: devices