3GPP LONG TERM EVOLUTION NETWORKING ASPECTS ON RADIO ACCESS

MOBSYS, FALL 2023

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EURECOM

RECAP FROM PREVIOUS SESSION

- WHAT IS RAN ARCHITECTUE?
- WHAT IS RAN PROTOCOL STACK?
- WHAT ARE TWO MAIN RAN EVOLUTIONS?

OUTLINE

- Introduction
- 4G and 5G RAN architecture
- 4G and 5G internetworking and deployment scenarios
- 4G and 5G functional Split
- 4G and 5G RAN/CN QoS
- 4G and 5G Functions and Protocol Stack
  - Packet Data flow in RAN
  - L2 Architecture and Channels
  - RAN identities
  - Connection procedures
  - Protocol Stack
  - Procedures – MAC and RRC
  - Advanced Features

RAN FUNCTIONS AND PROTOCOL

5GC SPECS

- 5G System:
  - TS23.501 - System Architecture for the 5G System
  - TS23.502 - Procedures for 5G System
  - TS29.500 - 5G System, Technical Realization of Service Based Architecture
  - TS29.501 - 5G System, Principles and Guidelines for Services Definition
  - TS 33.501: "Security Architecture and Procedures for 5G System".
  - **TS 38.300: "NR and NG-RAN Overall description"**

- 5GC components
  - AMF: - TS29.518 - Access and Mobility Management Services
  - NRF: TS29.510 - Network Function Repository Services
  - SMF: TS29.502 - Session Management Services, TS29.508 - Session Management Event Exposure Service
  - UDM: TS29.503 - Unified Data Management Services
  - AUSF: TS29.509 - Authentication Server Services, PCF: TS29.507 - Access and Mobility Policy Control Service, TS29.512 - Session Management Policy Control Service, TS29.571 - Common Data Types for Service Based Interfaces

- Others:
  - TS 24.501: Non-Access-Stratum (NAS) protocol for 5G System (5GS)
  - TS 38.413: NG-RAN; NG Application Protocol (NGAP)

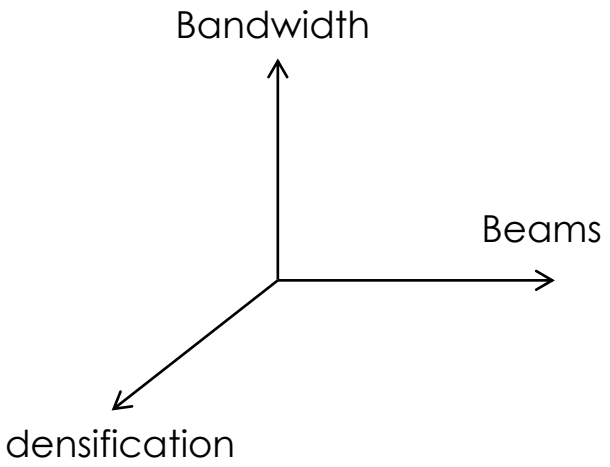
5G RAN SPECS

- RAN:
  - **3GPP TS 38.300: “NR and NG-RAN Overall description”**
  - **3GPP TS 38.401: "NG-RAN; Architecture description".**
  - 3GPP TS 37.340: "NR; Multi-connectivity; Overall description; Stage-2".
  - 3GPP TS 38.321: "NR; Medium Access Control (MAC) protocol specification".
  - 3GPP TS 38.322: "NR; Radio Link Control (RLC) protocol specification".
  - 3GPP TS 38.323: "NR; Packet Data Convergence Protocol (PDCP) specification".
  - 3GPP TS 37.324: "NR; Service Data Protocol (SDAP) specification".
  - 3GPP TS 38.331: "NR; Radio Resource Control (RRC); Protocol specification".
  - 3GPP TS 38.133: "NR; Requirements for support of radio resource management".

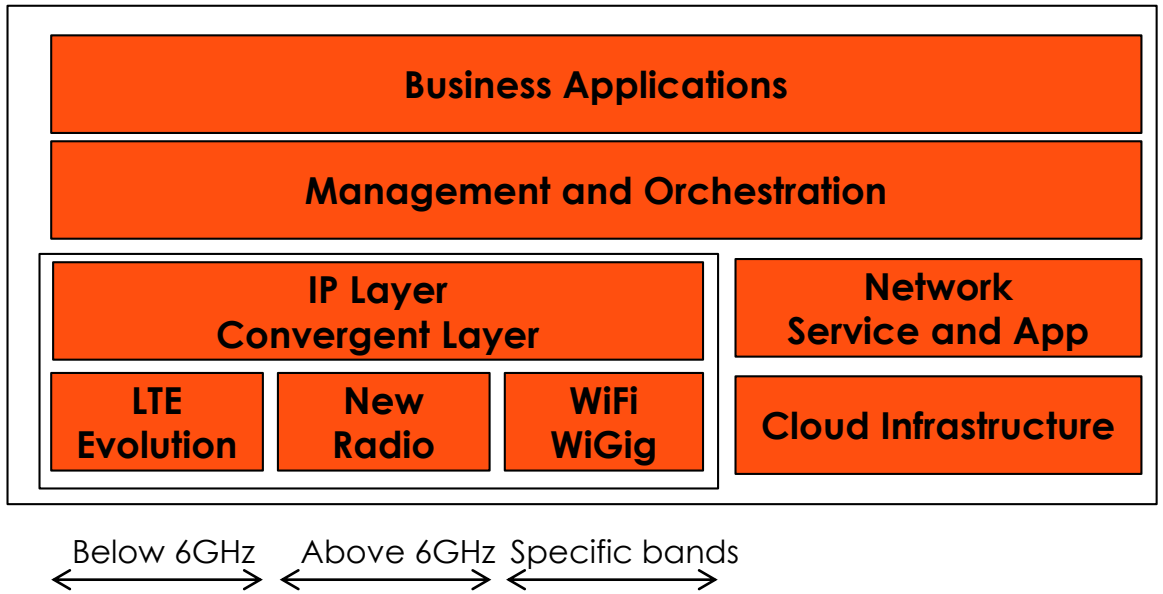
- UE:
  - 3GPP TS 38.304: "NR; User Equipment (UE) procedures in idle mode".
  - 3GPP TS 38.306: "NR; User Equipment (UE) radio access capabilities".

5G : A PARADIGM SHIFT

Dimension in increasing capacity



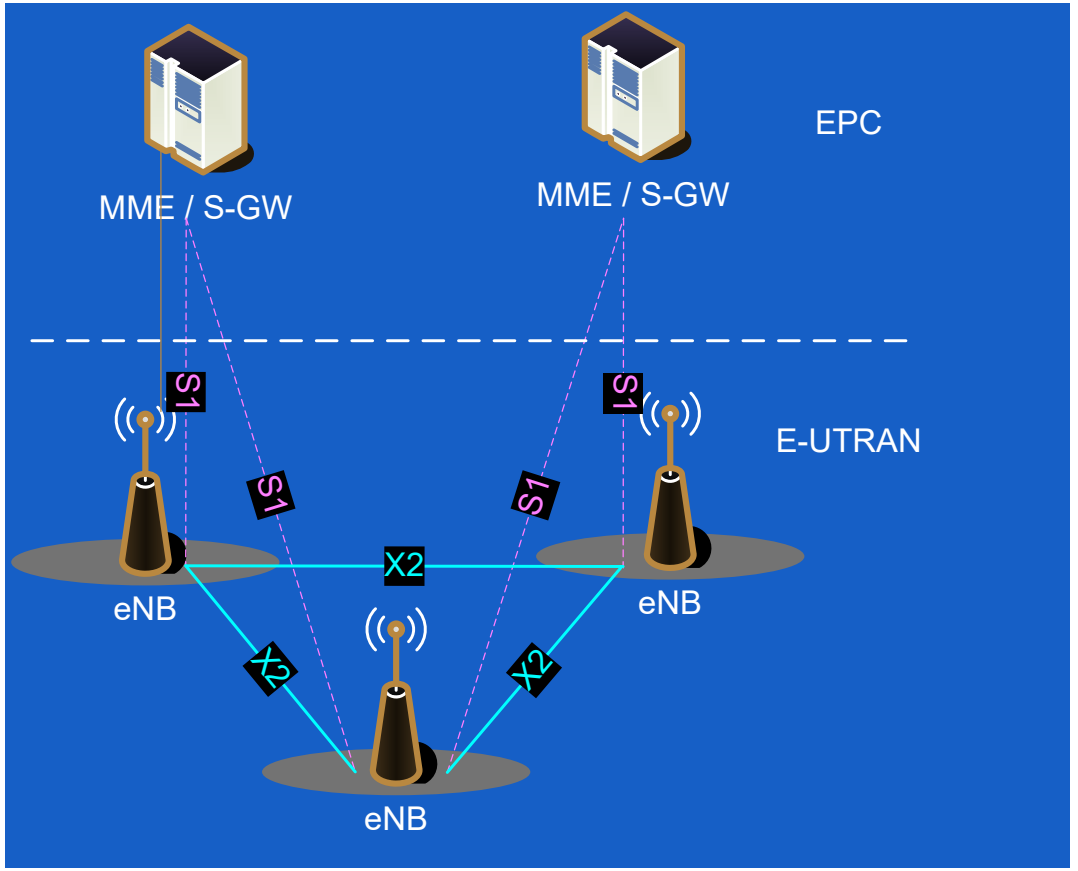
Overall 5G Components



5G is not just new radio/spectrum, but also a new architecture and business helper

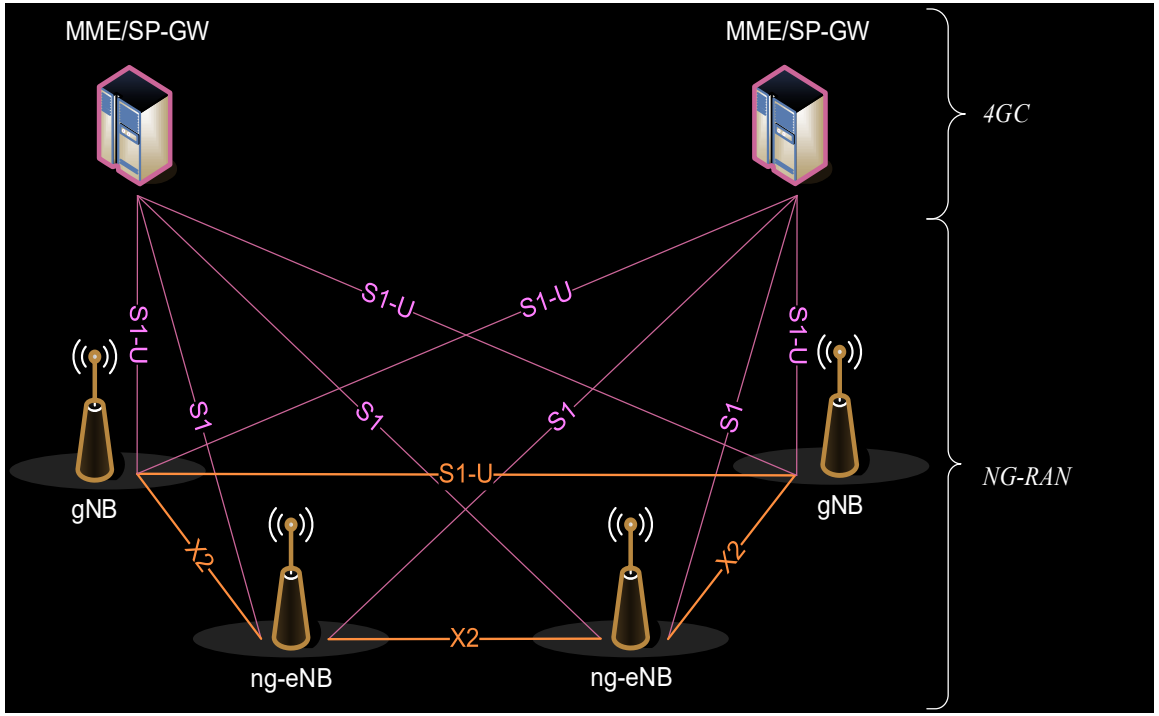
4G ARCHITECTURE

- **COMMUNICATION-ORIENTED SYSTEM** DESIGNED FOR A LIMITED NUMBER OF UCS
  - THROUGHPUT-OPTIMIZED
  - FIXED
  - RIGID

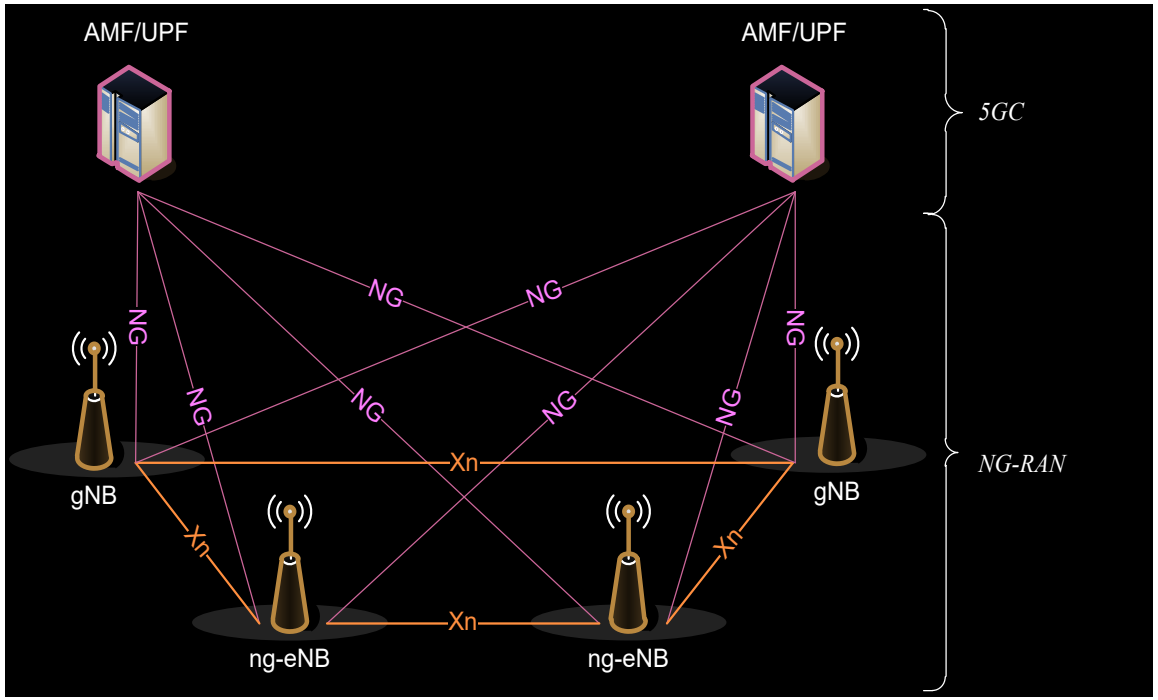


5G ARCHITECTURE MODE

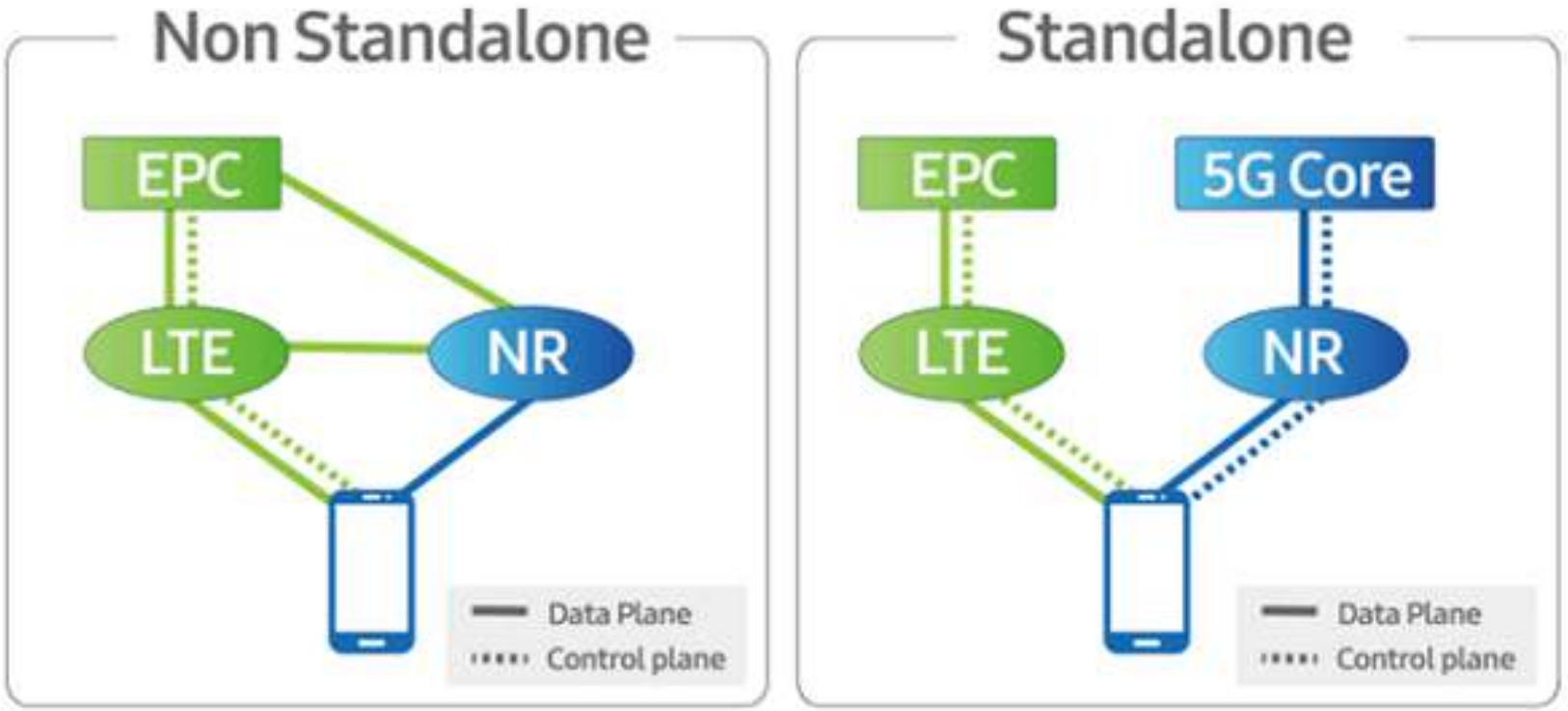
5G NSA



5G SA



5G ARCHITECTURE

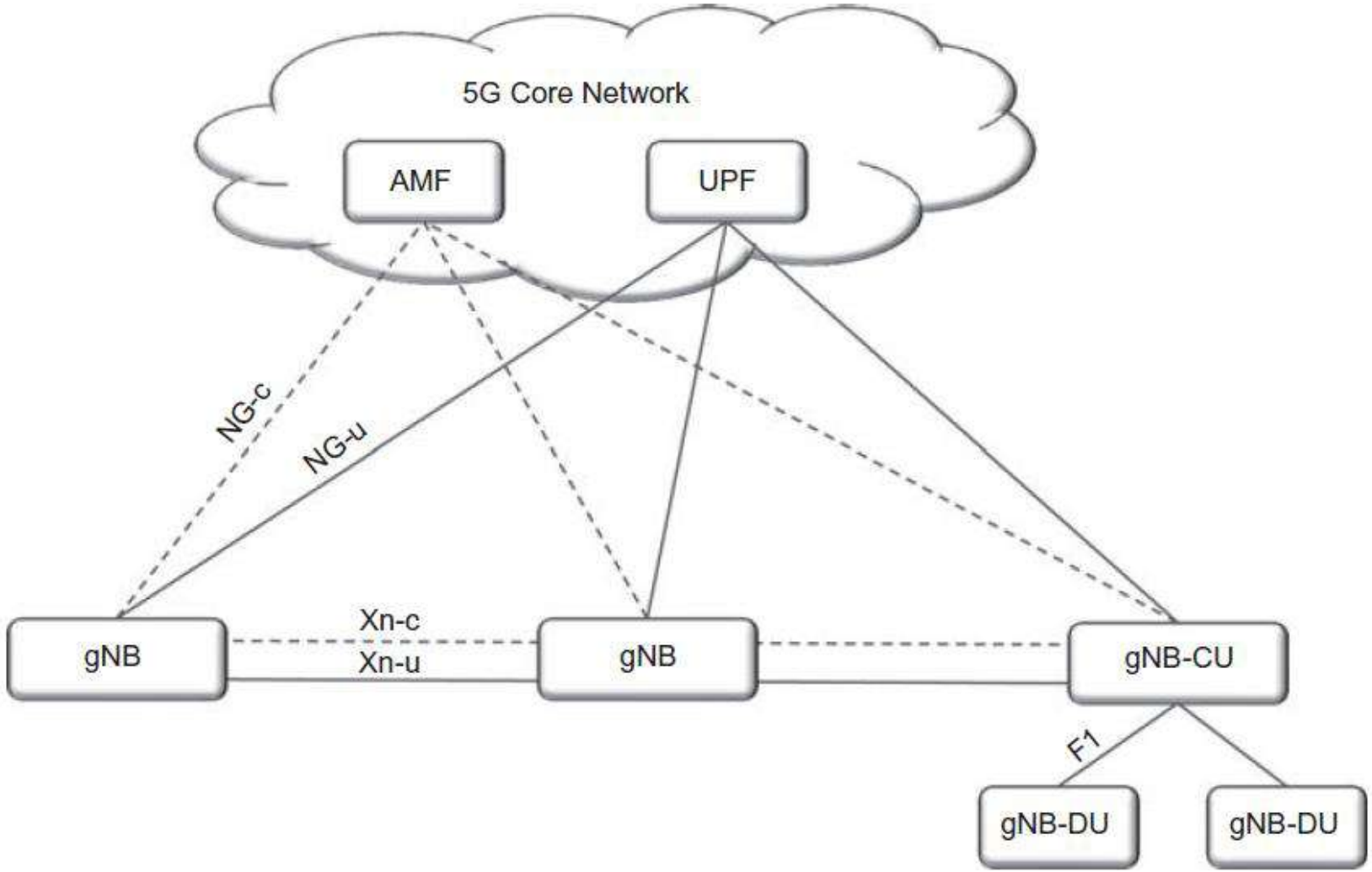


5G ARCHITECTURE OPTIONS

Option	SA/NSA	Core network	CP/UP	Additional UP	Comment
1	SA	4G-EPC	LTE	-	E-UTRAN
2	SA	5G-CN	NR	-	NR
3/3a/3x	**NSA**	**4G-EPC**	**LTE**	**NR**	**EN-DC**
4/4a	NSA	5G-CN	NR	LTE	
5	SA	5G-CN	LTE	-	
6	SA	4G-EPC	NR	-	EPC
7/7a	NSA	5G-CN	LTE	NR	Validation
8/8a	NSA	4G-EPC	NR	LTE	EPC ext: CUPS,
?	SA	5G-CN	NR	NR	NR-DC

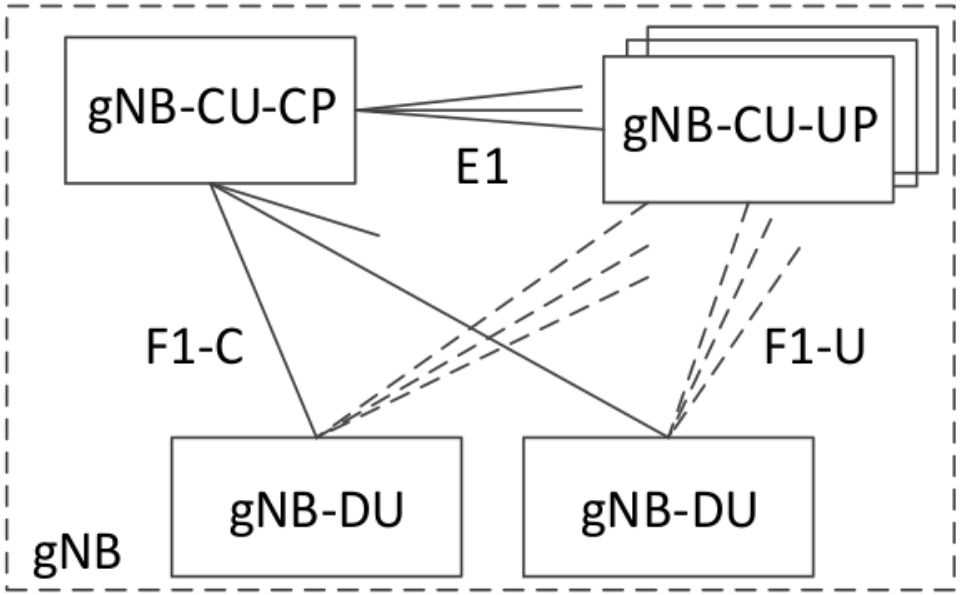
https://blog.3g4g.co.uk/2018/10/5g-network-architecture-options-updated.html
https://www.gsma.com/futurenetworks/wp-content/uploads/2018/04/Road-to-5G-Introduction-and-Migratior

OVERALL ARCH WITH INTERFACES REVISITED



DISAGGREGATED GNB CU-DU

- ONE CU-UP CAN AGGREGATE MULTIPLE DUS
  - N:M, AS 1 CU-UP AGGREGATES MULTIPLE DUS (MULTIPLEXING GAIN), BUT ONE DU CAN ALSO CONNECT TO MULTIPLE CU-UPS (E.G., SERVICE CUSTOMIZATION WITH SPECIAL CU-UP



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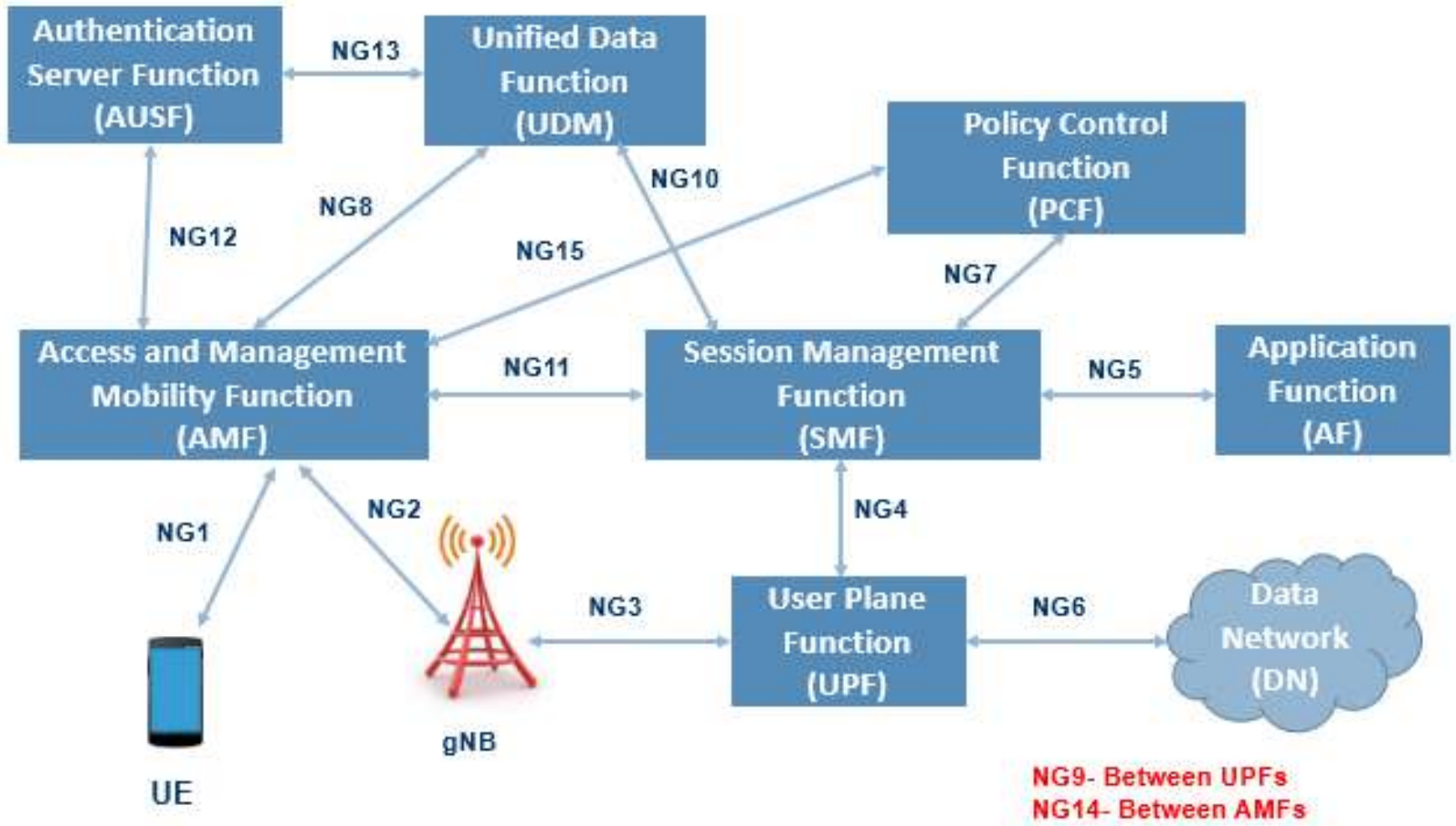

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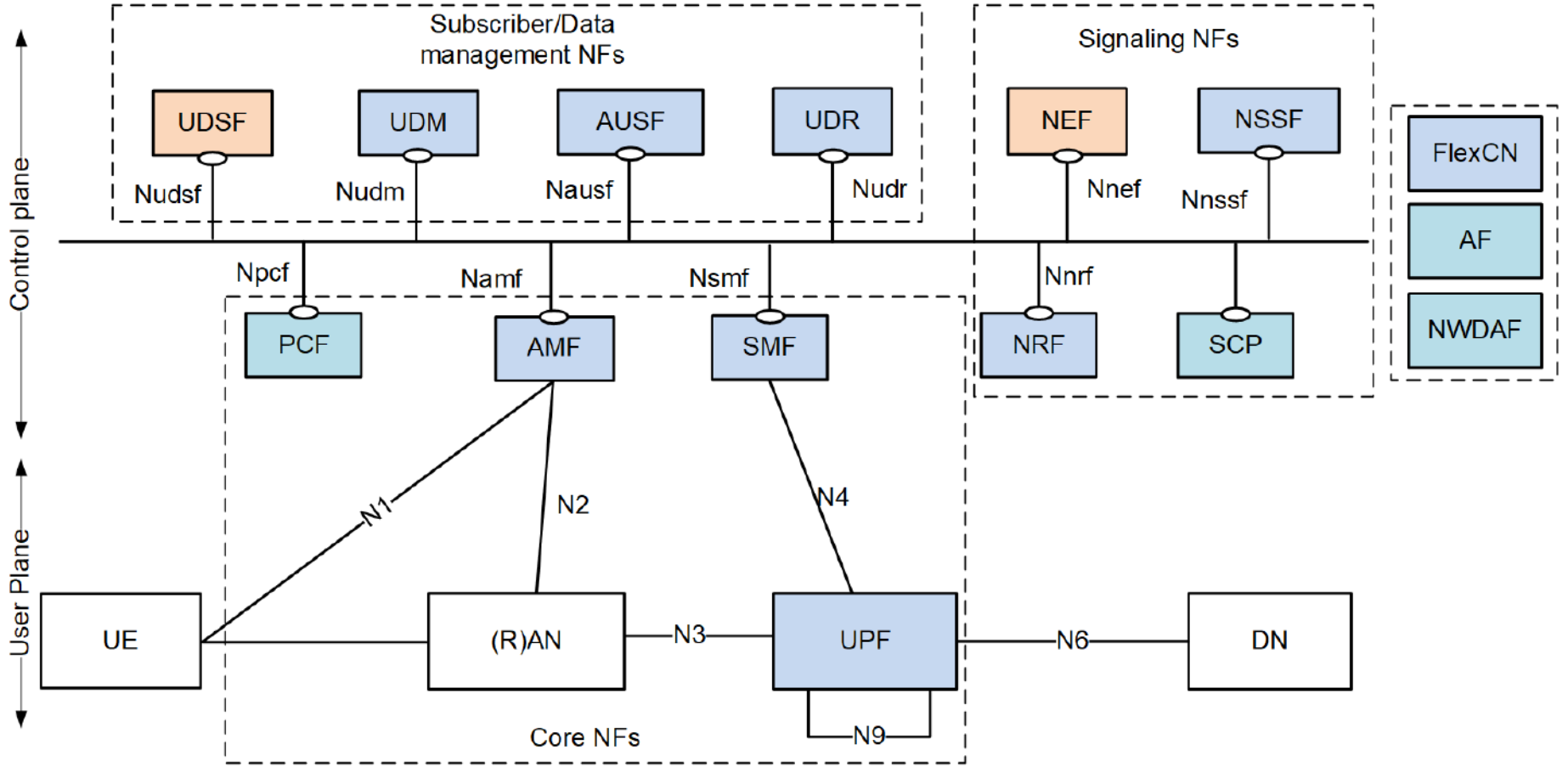
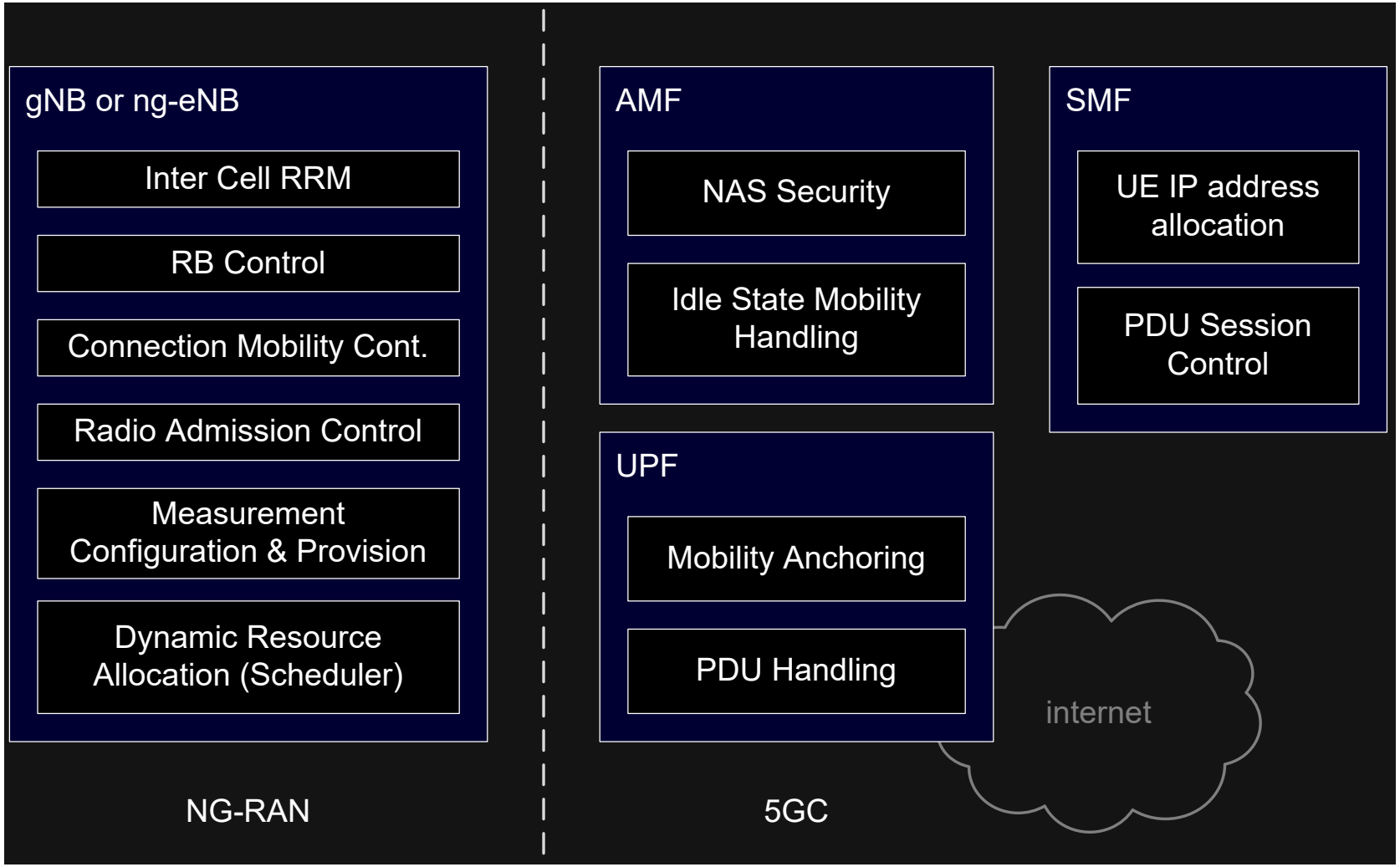
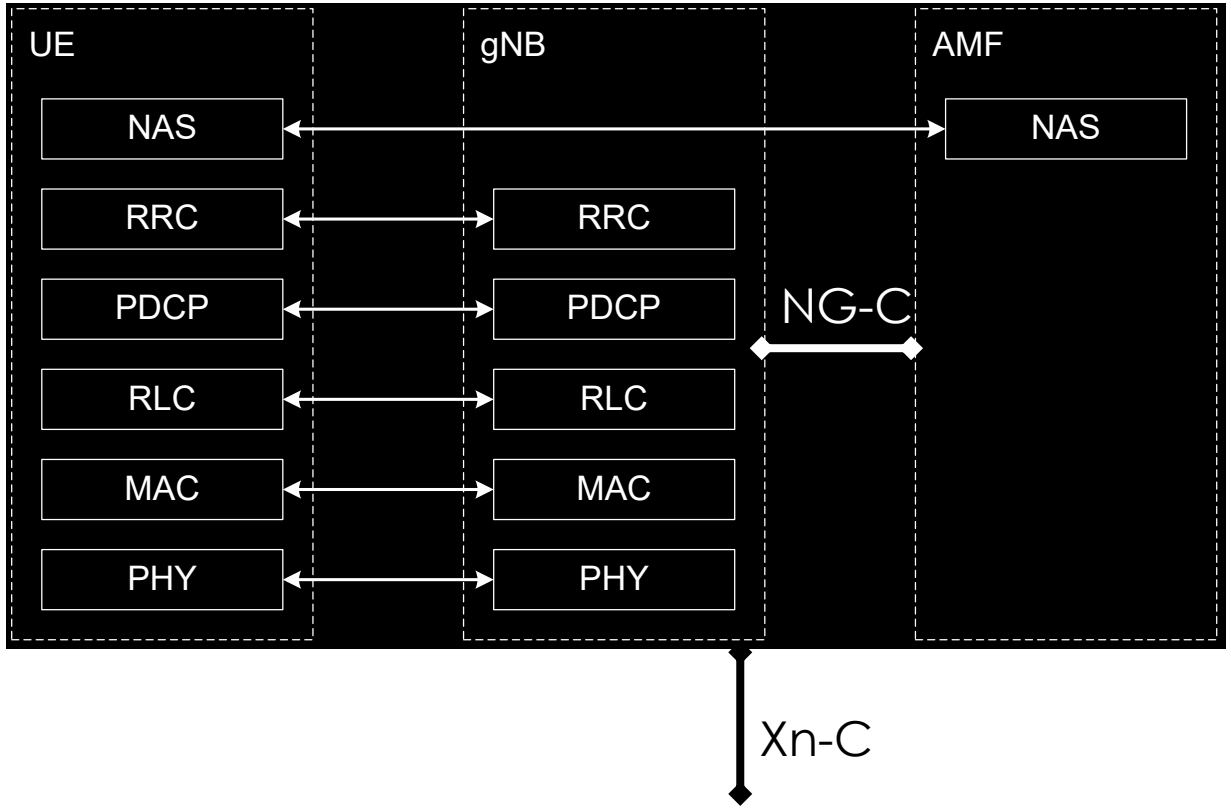


RAN AND 5GC MAIN FUNCTIONS

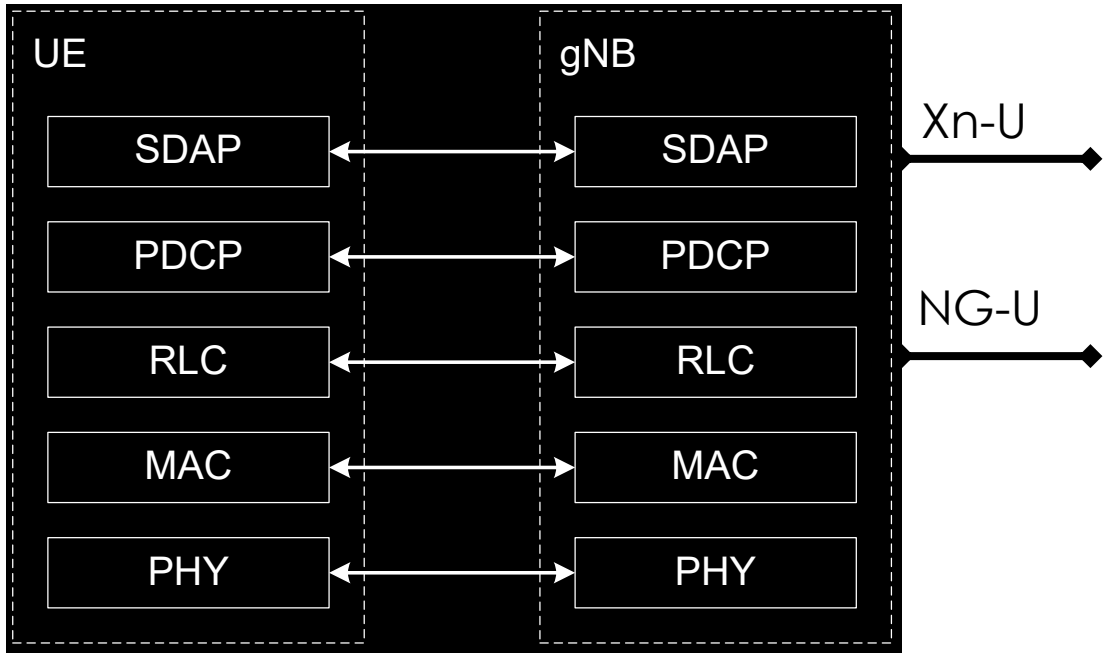


RAN PROTOCOLS

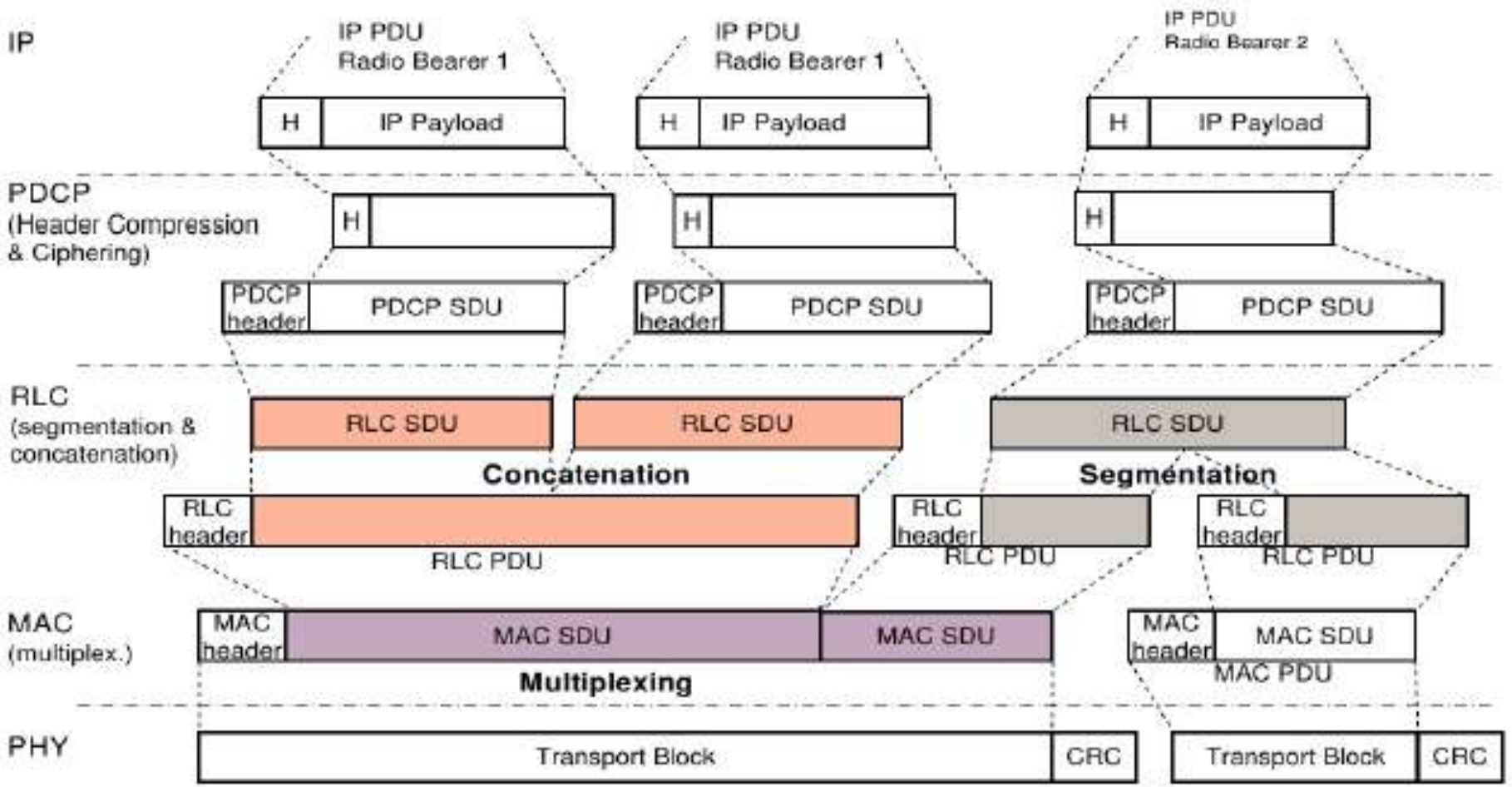
CP PROTOCOL STACK



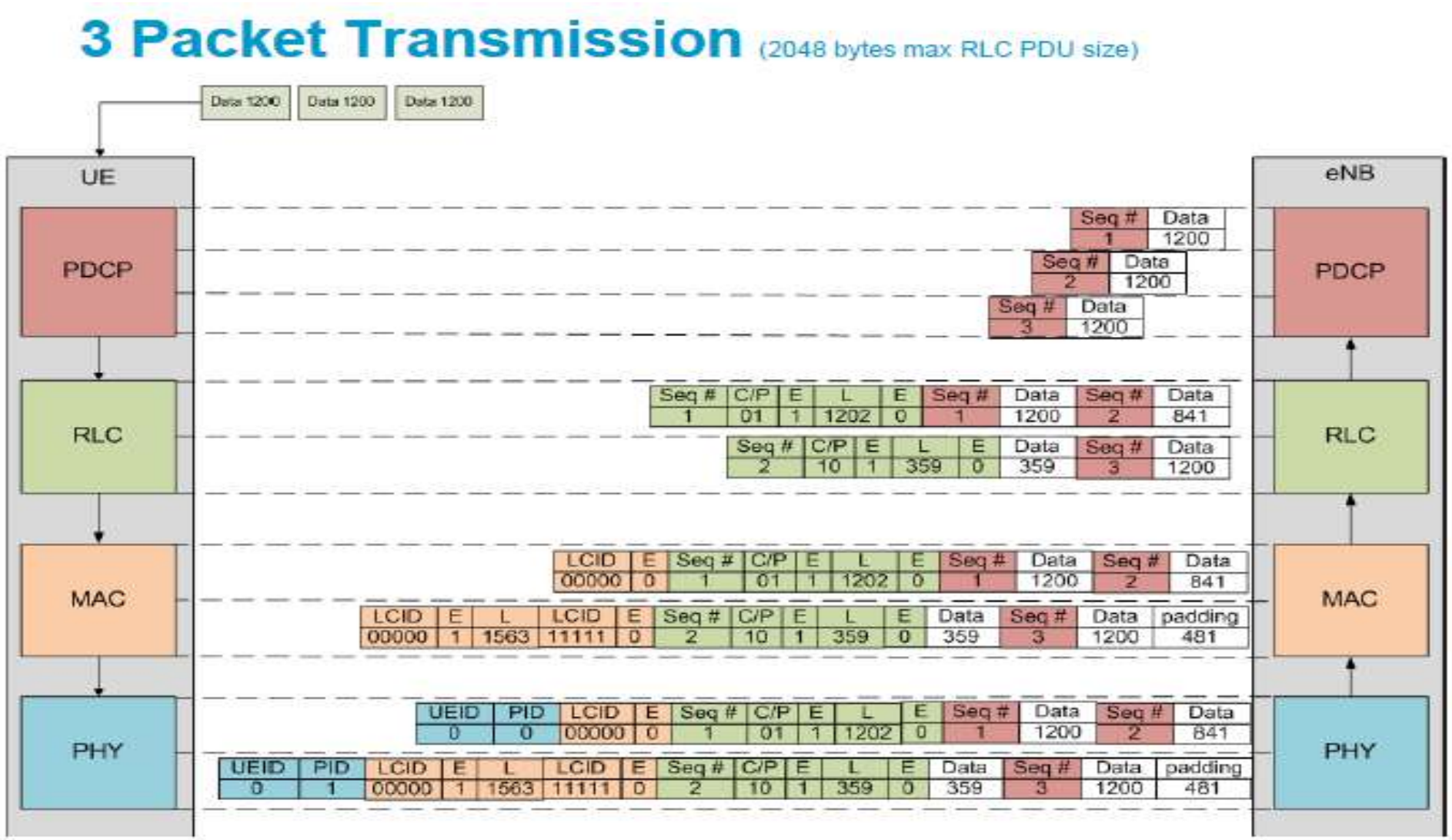
UP PROTOCOL STACK



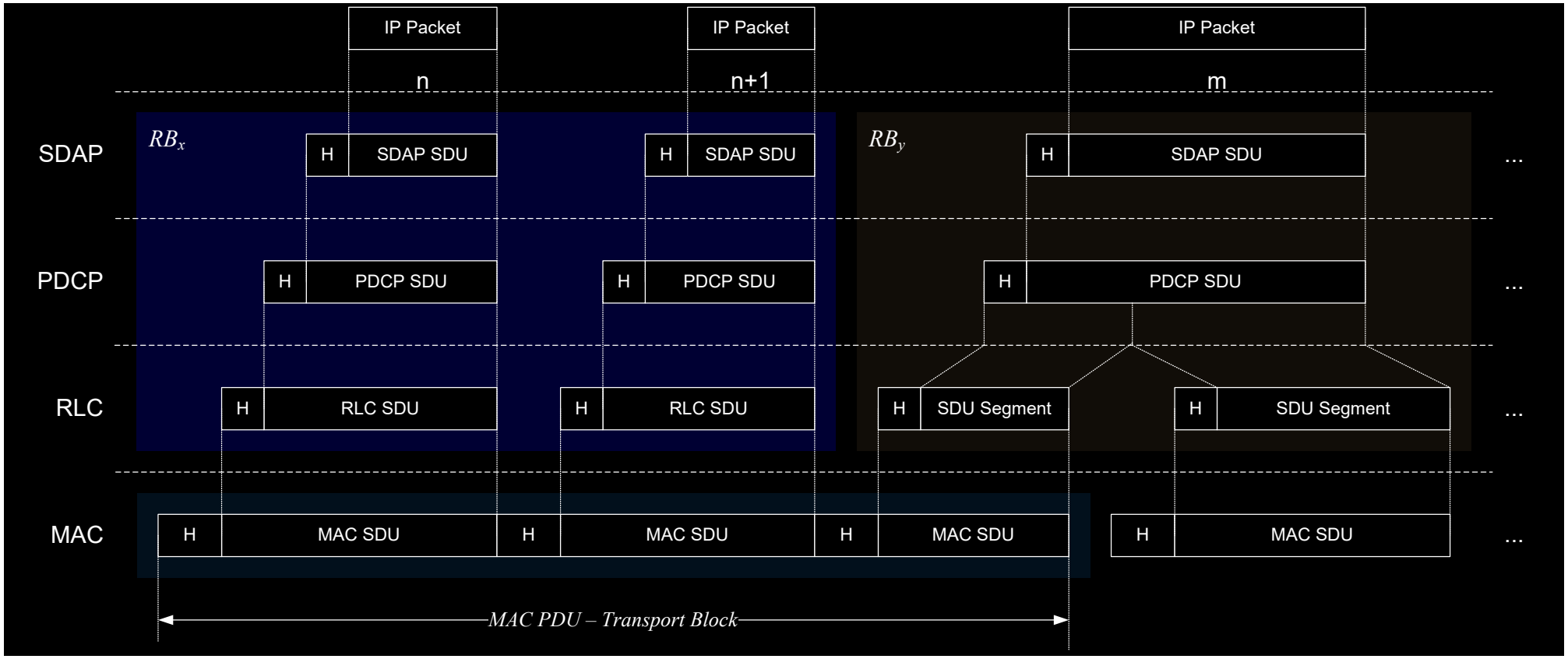
4G RAN DATA FLOW: WHAT HAPPENS TO IP?



4G RAN – 3 PACKET TRANSMISSION EXAMPLE



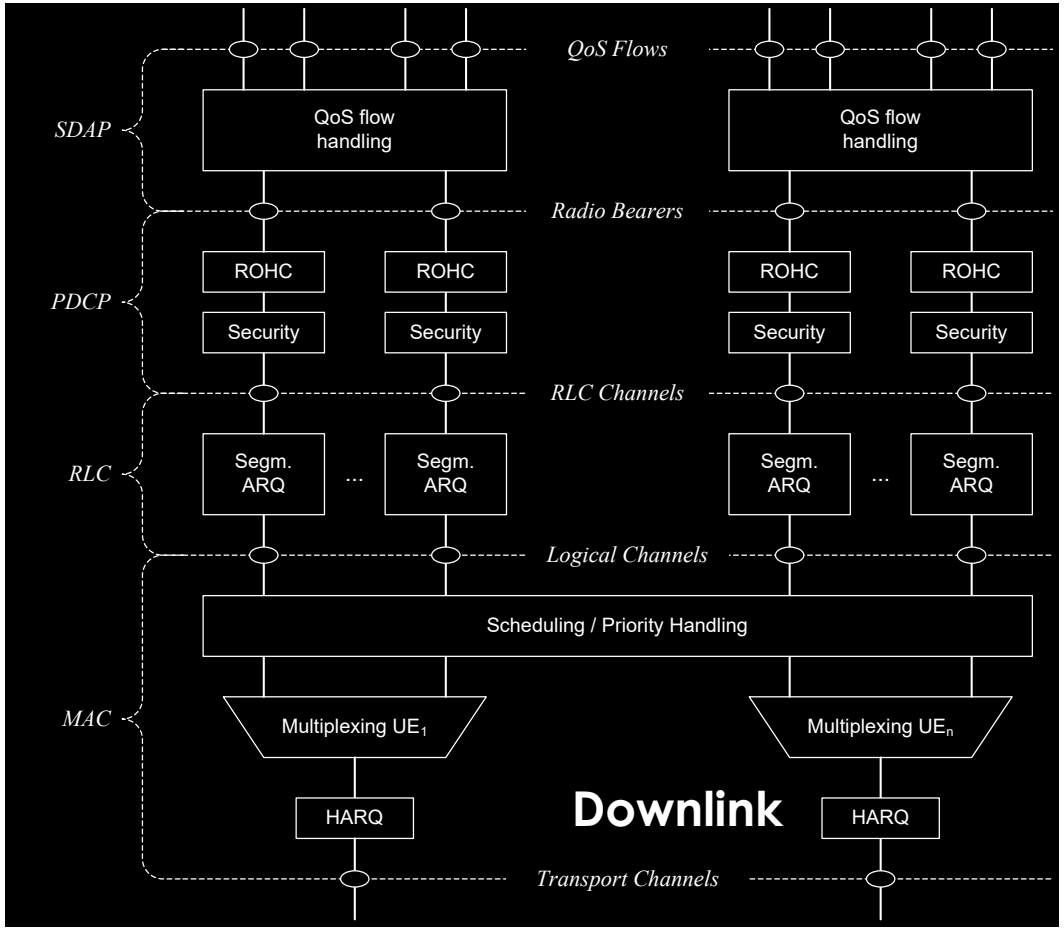
5G RAN DATA FLOW: WHAT HAPPENS TO IP?

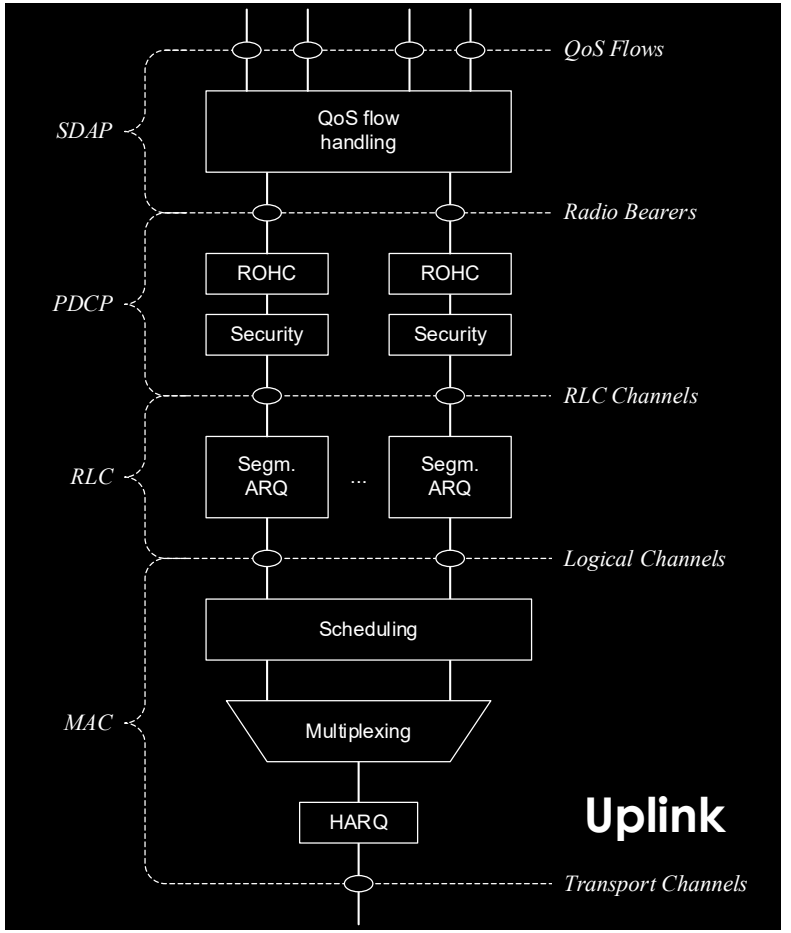


- Mapping of IP packets: the principles are actually easier than 4G!
- RLC Segmentation and Reassembly
- MAC concatenation across different radio bearer ($RB_{x,\ \&}\ RB_y$)
- MAC Transport Block → PHY Transport UNIT

LAYER 2 ARCHITECTURE

- Flows/bearers/channels refer to data exchange between specific layers, each with its own configura
- Each layer has a number of specific tasks that is applied between the channel(s)





DOWNLINK COMMON LOGICAL CHANNELS

THE MAC PROVIDES SERVICES TO RLC VIA LOGICAL CHANNELS CHARACTERIZED BY **TYPE** OF INFORMATION

- **BROADCAST CONTROL CHANNEL (BCCH)**
  - TRANSMISSION OF SYSTEM INFORMATION
  - ONLY IN SA (IN NSA, LTE CELL FORWARDS THIS INFORMATION)
- **PAGING CONTROL CHANNEL (PCCH)**
  - PAGING OF DEVICES (I.E., WHEN THEIR LOCATION IS UNKNOWN, TRANSMITTED IN MULTIPLE CELLS)
  - SYSTEM INFORMATION UPDATES
  - ONLY IN SA (IN NSA, LTE DOES PAGING)
- **COMMON CONTROL CHANNEL (CCCH)**
  - CONTROL INFORMATION FOR RANDOM ACCESS

DOWNLINK DEDICATED LOGICAL CHANNELS

- **DEDICATED CONTROL CHANNEL (DCCH)**
  - CONTROL INFORMATION TO INDIVIDUAL UES
- **DEDICATED TRAFFIC CHANNEL (DTCH)**
  - TRANSMITS USER DATA DEDICATED TO ONE UE
  - BULK OF DATA IS USED BY THIS CHANNEL

- NOTES :
  - IN LTE, ALL THE ABOVE CHANNELS EXIST AND HAVE THE SAME TASK
  - IN LTE, THERE ARE MORE CHANNELS THAT ARE **NOT NEEDED** IN NR OR (NOT YET) STANDARDIZED

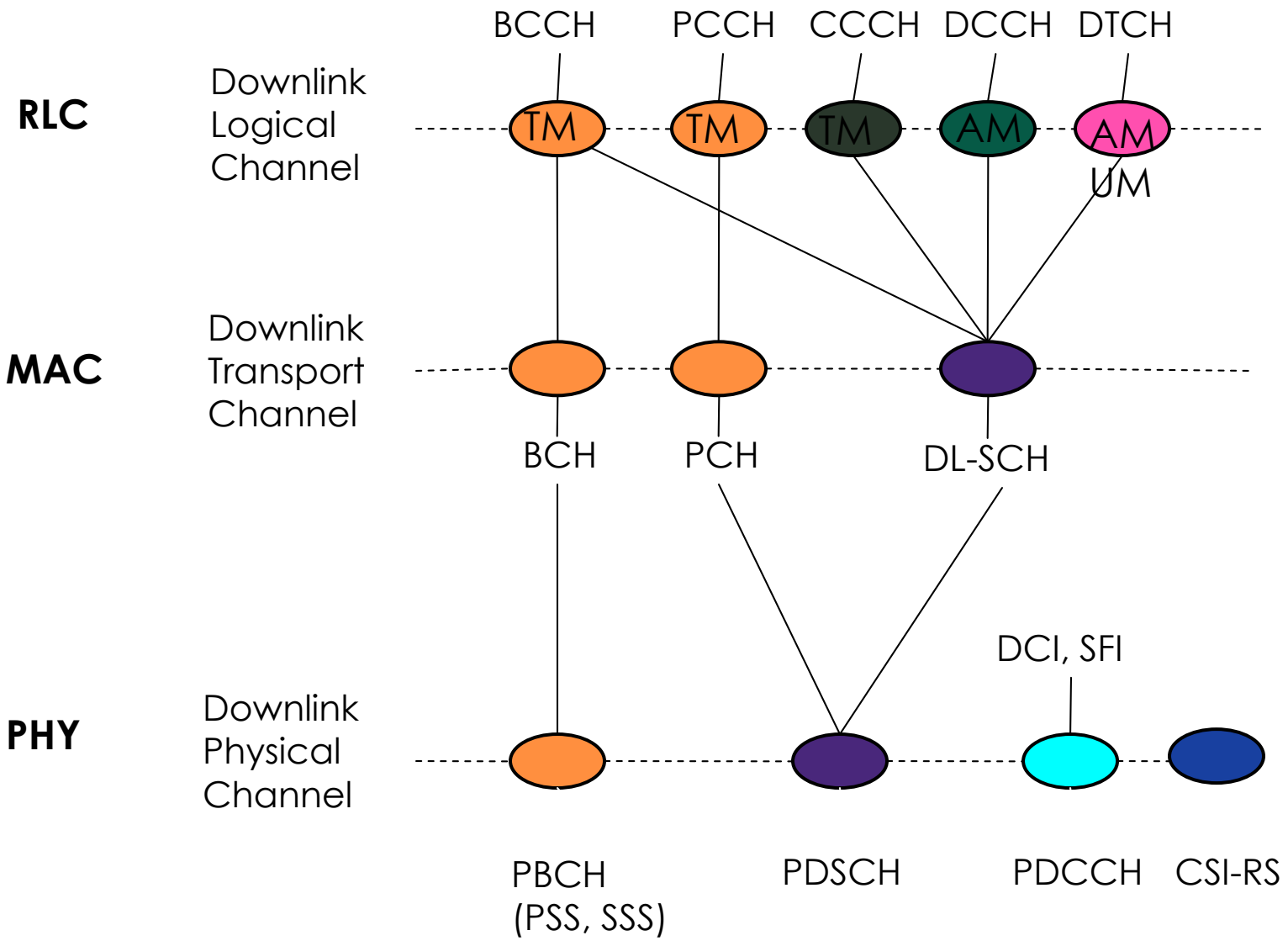
DOWNLINK TRANSPORT CHANNELS

THE MAC LAYER USES PHY TRANSPORT CHANNELS CHARACTERIZED BY **HOW** AND **WITH WHAT CHARACTERISTICS** INFORMATION IS CONVEYED

- DATA IS ORGANIZED IN TRANSPORT BLOCKS (REMEMBER FROM THE L1 PART OF THE LECTURE!)
- A TRANSPORT BLOCK HAS A TRANSPORT FORMAT (SIZE, MODULATION AND CODING SCHEME, ANTENNA MAPPING, …)

- **BROADCAST CHANNEL (BCH)**
  - USED TO SEND BCCH SYSTEM INFORMATION
  - FIXED TRANSPORT FORMAT
- **PAGING CHANNEL (PCH)**
  - TRANSMISSION OF THE PCCH
- **DOWNLINK SHARED CHANNEL (DL-SCH)**
  - MAIN TRANSPORT CHANNEL FOR DOWNLINK DATA
  - SUPPORTS RATE ADAPTATION, CHANNEL-DEPENDENT SCHEDULING, RETRANSMISSIONS, SPATIAL MULTIPLEXING…

DOWNLINK CHANNELS



❑ **Logical Channels**
- PCCH: paging control channel
- BCCH: broadcast control channel
- CCCH: common control channel
- DCCH: dedicated control channel
- DTCH: dedicated traffic channel

❑ **Transport Channels**
- PCH: paging channel
- BCH: broadcast channel
- DL-SCH: downlink shared channel

❑ **Physical Channels**
- PBCH: phy. broadcast channel
- PDSCH: phy. downlink shared channel
- PDCCH: phy. downlink control channel

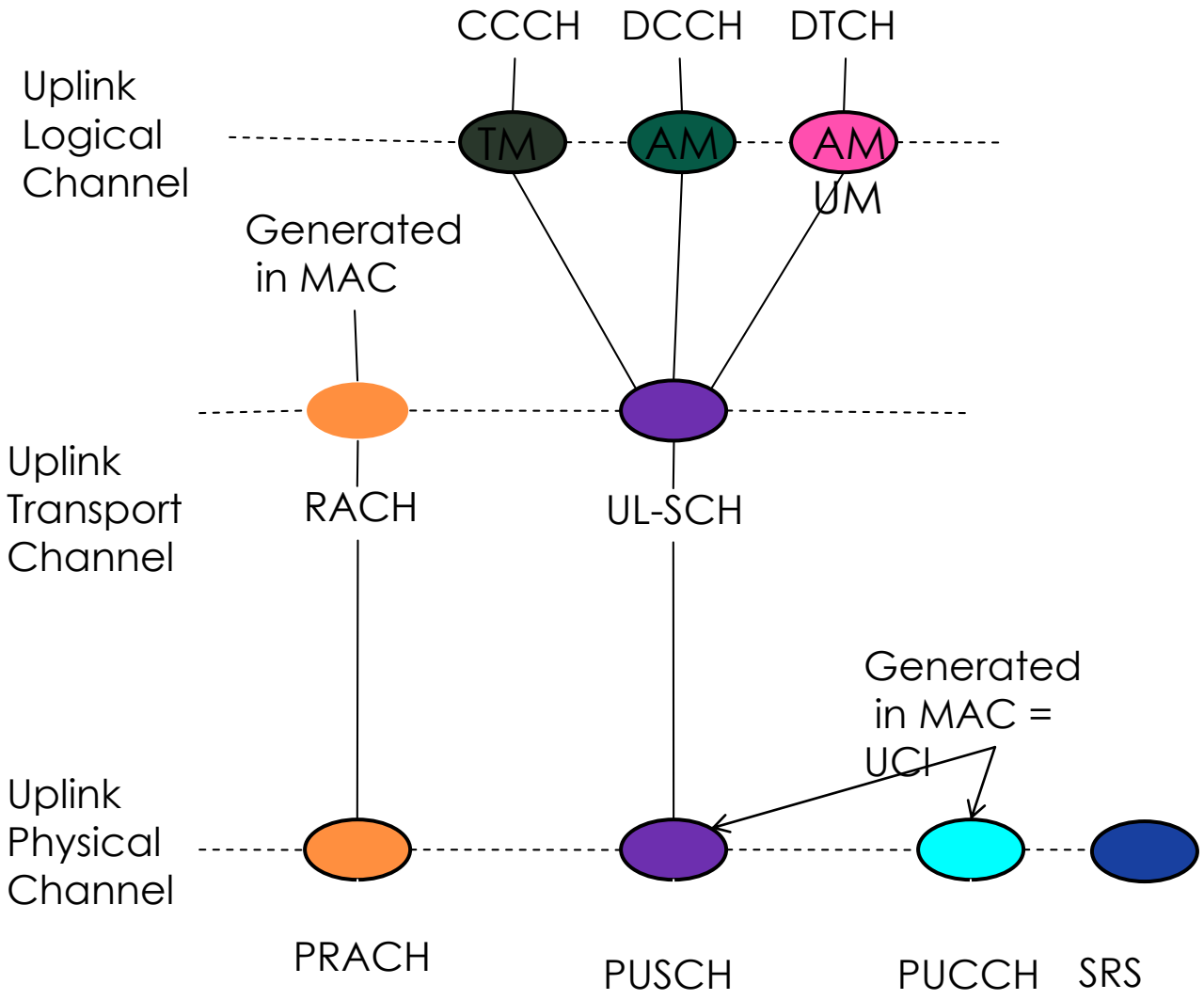
UPLINK CHANNELS

- The logical channels in uplink are as in downlink

The transport channels in uplink are:

- **Uplink Shared Channel (UL-SCH)**
  - Main Transport channel in the uplink
  - Counterpart to DL-SCH with similar features
- **Random-Access Channel (RACH)**
  - Handles the random access
  - Has no corresponding logical channel (so the layers above MAC "do not participate")

UPLINK CHANNELS



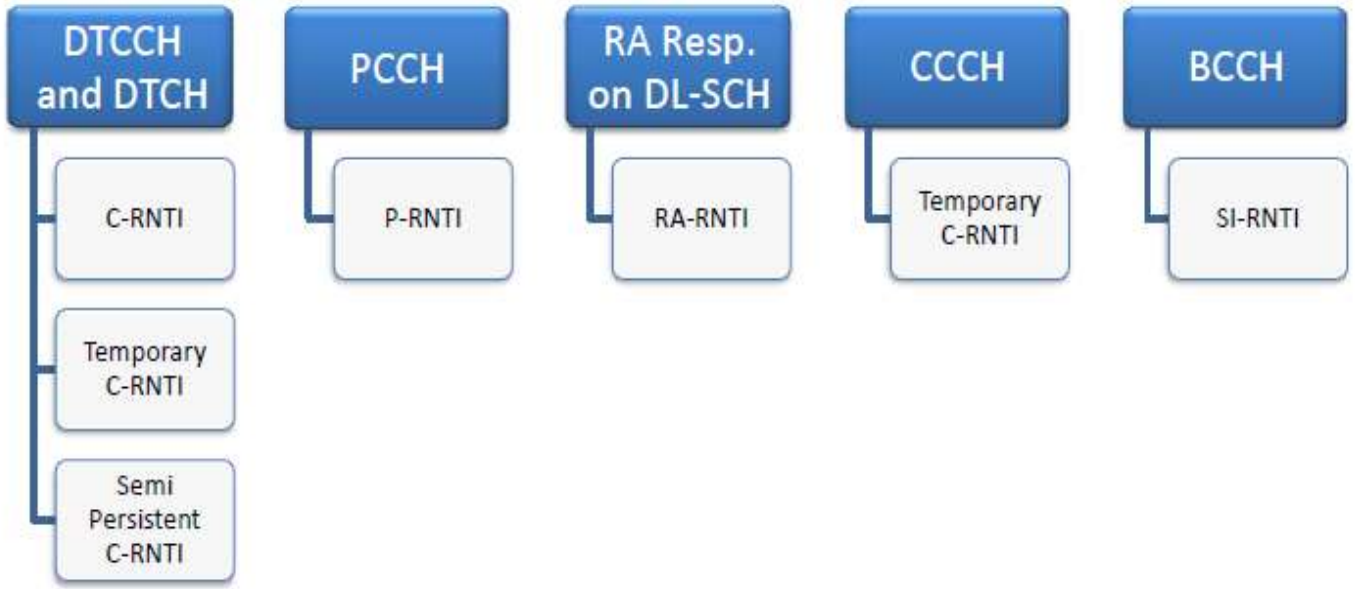
❑ **Logical Channels**
- CCCH: common control channel
- DCCH: dedicated control channel
- DTCH: dedicated traffic channel

❑ **Transport Channels**
- RACH: random access control
- UL-SCH: Uplink shared channel
- UCI : Uplink Control Information

❑ **Physical Channels**
- PRACH: phy. random access channel
- PUSCH: phy. uplink shared channel
- PUCCH: phy. uplink control channel

RAN IDENTIFIERS

- In LTE/NR C-RNTI (Cell Radio Network Temporary Identifier) is indirectly allocated by MAC layer.
- During random access procedure MAC Layer provides T-CRNTI (Temporary C-RNTI) to the UE
- UE uses this T-CRNTI as a C-RNTI after successfully completion of the RRC Connection establishment procedure.
- Example
  - MAC indicates radio resource allocation using PCCCH, and RNTI is mapped on PDCCH depending on logical channel type



RAN IDENTITY USAGES

RNTI	Usage	Transport Channel	Logical Channel
P-RNTI	Paging and System Information change notification	PCH	PCCH
SI-RNTI	Broadcast of System Information	DL-SCH	BCCH
RA-RNTI	Random Access Response	DL-SCH	N/A
Temporary C-RNTI	Contention Resolution (when no valid C-RNTI is available)	DL-SCH	CCCH
Temporary C-RNTI	Msg3 transmission	UL-SCH	CCCH, DCCH, DTCH
C-RNTI	Dynamically scheduled unicast transmission	DL-SCH, UL-SCH	DCCH, DTCH
C-RNTI	Triggering of PDCCH ordered random access	N/A	N/A
Semi-Persistent Scheduling C-RNTI	Semi-Persistently scheduled unicast transmission (activation, reactivation and retransmission)	DL-SCH, UL-SCH	DCCH, DTCH
Semi-Persistent Scheduling C-RNTI	Semi-Persistently scheduled unicast transmission (deactivation)	N/A	N/A
TPC-PUCCH-RNTI	Physical layer Uplink power control	N/A	N/A
TPC-PUSCH-RNTI	Physical layer Uplink power control	N/A	N/A

UE IDENTITIES

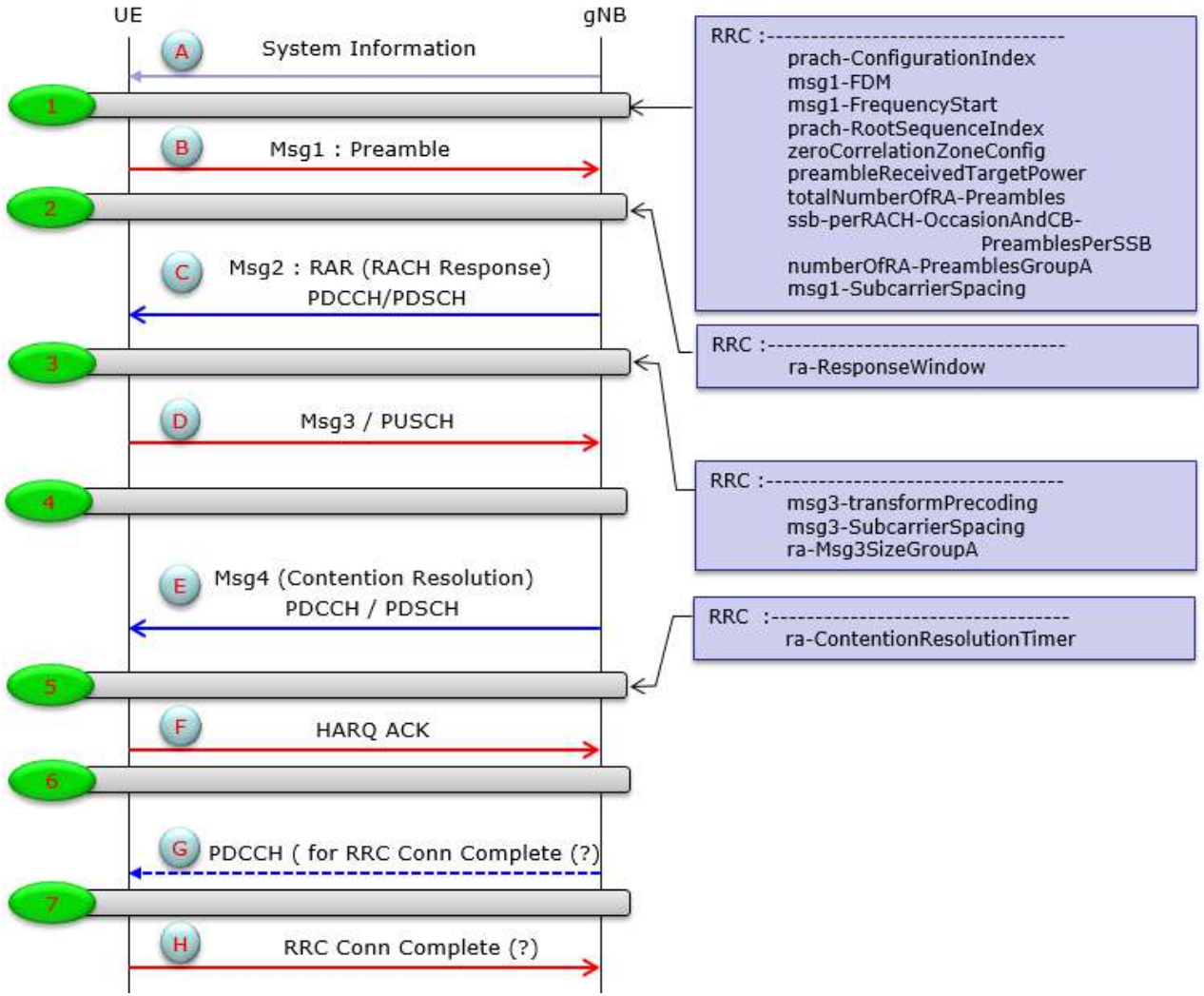
- For NR connected to 5GC, the following UE identities are used at cell level:
  - C-RNTI: unique identification, which is used as an identifier of the RRC Connection and for scheduling;
  - Temporary C-RNTI: identification used for the random access procedure;
  - Random value for contention resolution: during some transient states, the UE is temporarily identified with a random value used for contention resolution purposes.
- In DC, two C-RNTIs are independently allocated to the UE: one for MCG, and one for SCG.
- For NR connected to 5GC, the following UE identities are used at NG-RAN level:
  - I-RNTI: unique identification used to identify the UE context for RRC_INACTIVE.

CONNECTION SETUP PROCEDURES

OVERALL CONNECTION/REGISTRATION STEPS

- Scan and Synchronize
- Receive Master information blocks (MIB) and System information blocks
- Cell selection and Random Access
- RRC Connection Procedures (Control-plane)
- NAS Registration Procedures (Control-plane)
- Send / Receive data (User-plane)
  - Mobility and handover (Control-plane and User-plane)

RANDOM ACCESS: SA/CONTENTION-BASED

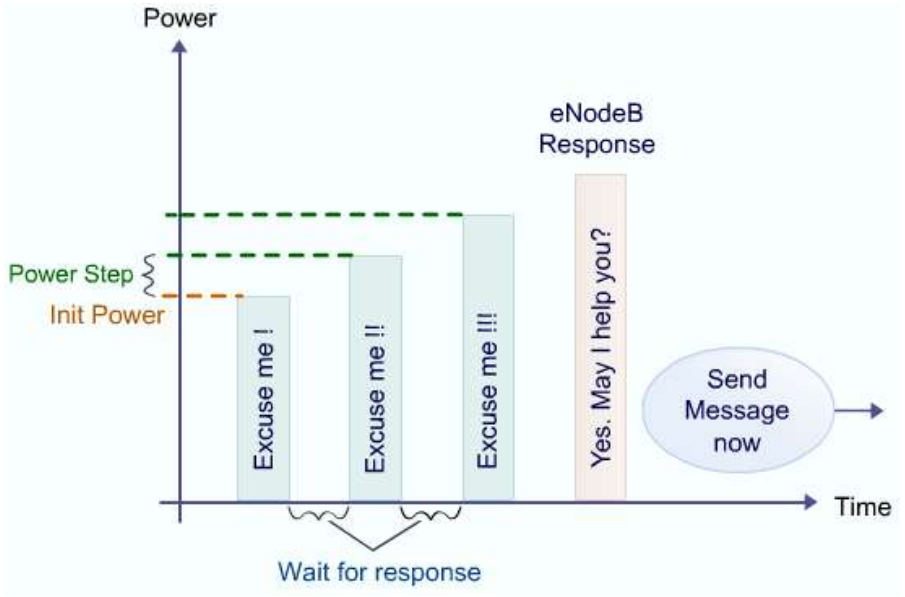


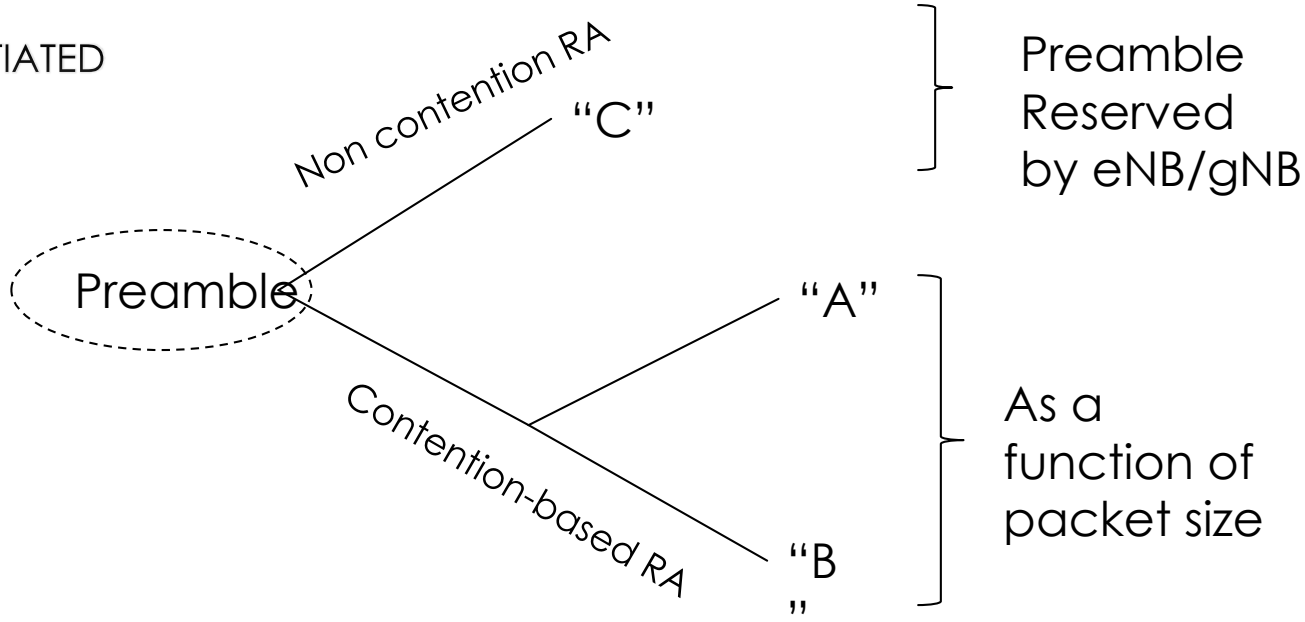
- This is Contention-Based Random Access (CB-RA)
- Used by UE to synchronize to cell and to get resources for attach at network
- Note: there is also Contention-Free RA (CF-RA)

http://www.sharetechnote.com/html/5G/5G_RACH.html

RANDOM ACCESS: SA/CONTENTION-BASED

- CONTENTION-BASED PROCEDURE INITIATED BY UE
- NON CONTENTION-BASED PROCEDURE INITIATED BY ENB

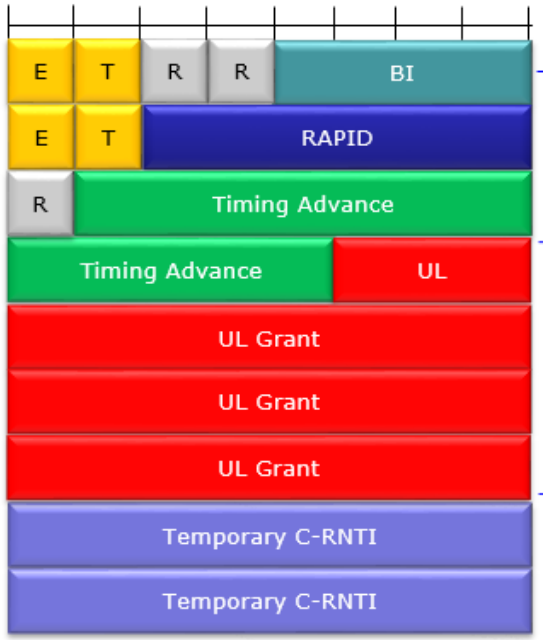




http://www.sharetechnote.com/html/5G/5G_RACH.html

RANDOM ACCESS: SA/CONTENTION-BASED

< 38.321 v15.3.0 - 6.2.2,6.2.3 >



< 38.321 v15.3.0 - Table 7.2-1>

Index	Backoff Parameter value (ms)
0	5
1	10
2	20
3	30
4	40
5	60
6	80
7	120
8	160
9	240
10	320
11	480
12	960
13	1920
14	Reserved
15	Reserved

< 38.213 v15.3.0 - Table 8.2-2>

TPC Command	Value (in dB)
0	-6
1	-4
2	-2
3	0
4	2
5	4
6	6
7	8

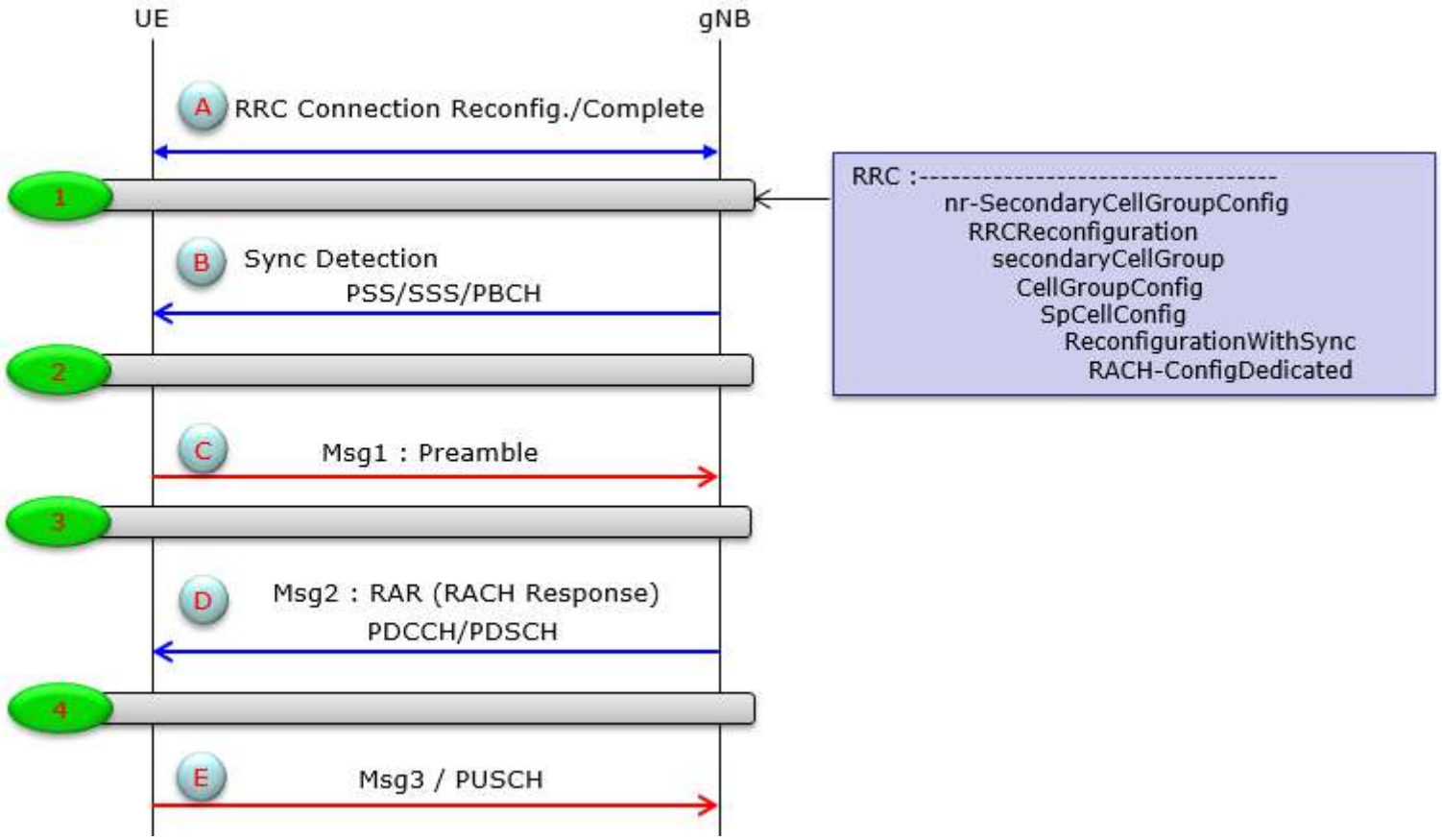
< 38.213 v15.3.0 - Table 8.2-1>

RAR grant field	Number of bits
Frequency hopping flag	1
Msg3 PUSCH frequency resource allocation	14
Msg3 PUSCH time resource allocation	4
MCS	4
TPC command for Msg3 PUSCH	3
CSI request	1
Total	27 bits

- RAR is Msg. 2 (DL)
- gNB sends DCI
- UE will compare RAPID to determine whether this Msg.2 belongs to itself
- Includes UL Grant for Msg. 3 (For contention resolution)

http://www.sharetechnote.com/html/5G/5G_RACH.html

RANDOM ACCESS: NSA/CONTENTION-FREE

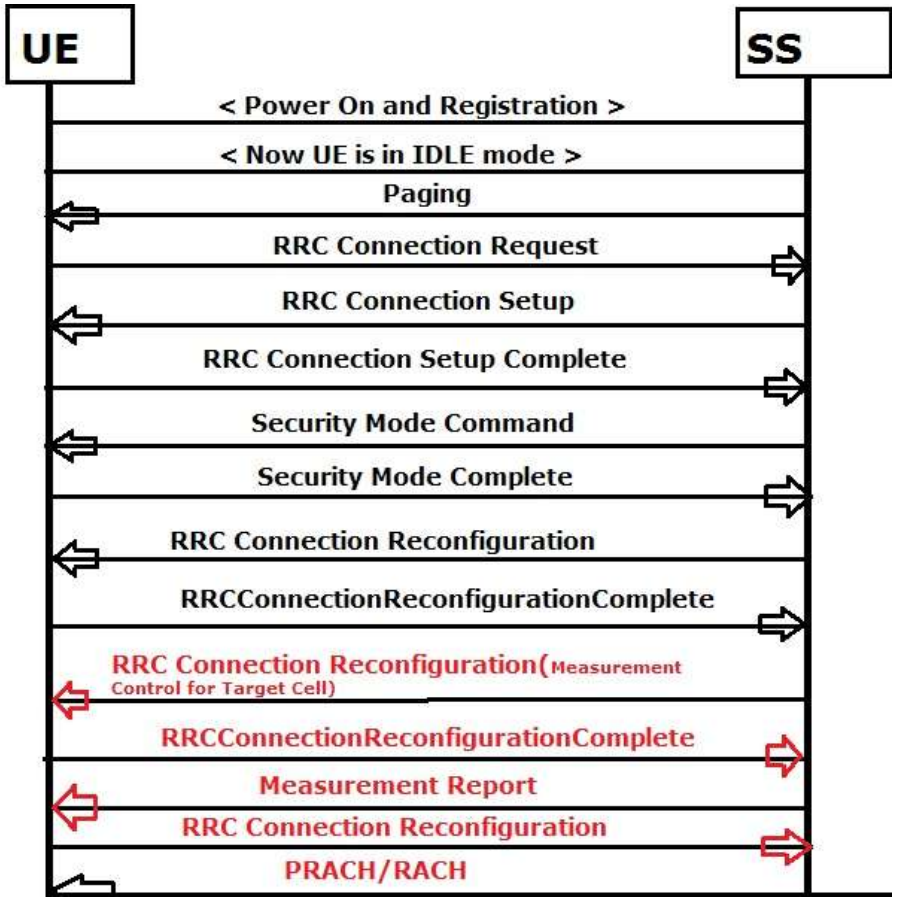


- This is Msg. 2 (DL)
- gNB sends DCI
- UE will compare RAPID to determine whether this Msg.2 belongs to itself
- Includes UL Grant for Msg. 3 (For contention resolution)

http://www.sharetechnote.com/html/5G/5G_RACH.html

INITIAL ATTACH /DETACH 4G – REVISITED

- REFER TO THE MOBSYS-LTE-EPC-LEC2.PDF LECTURE



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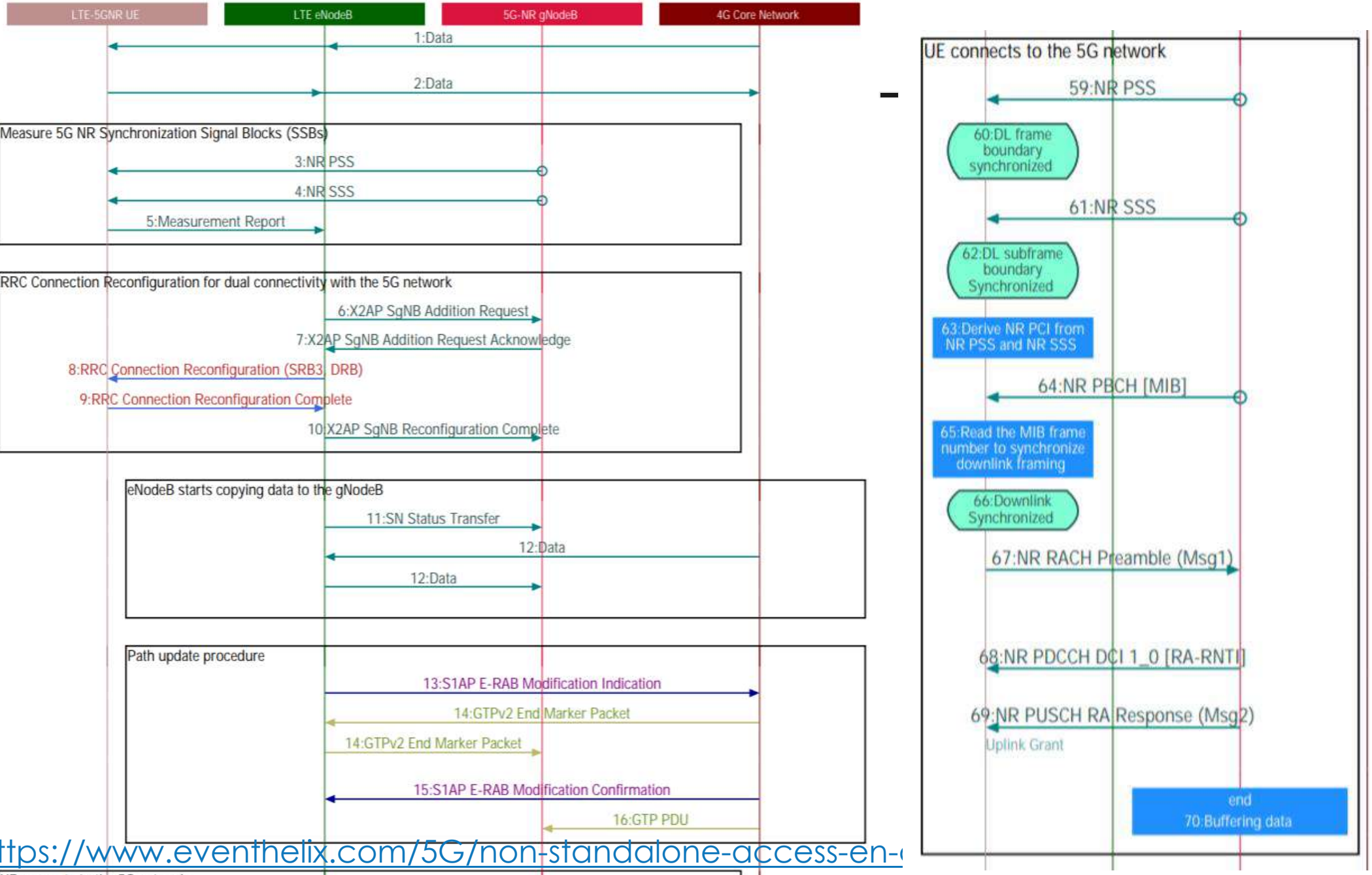
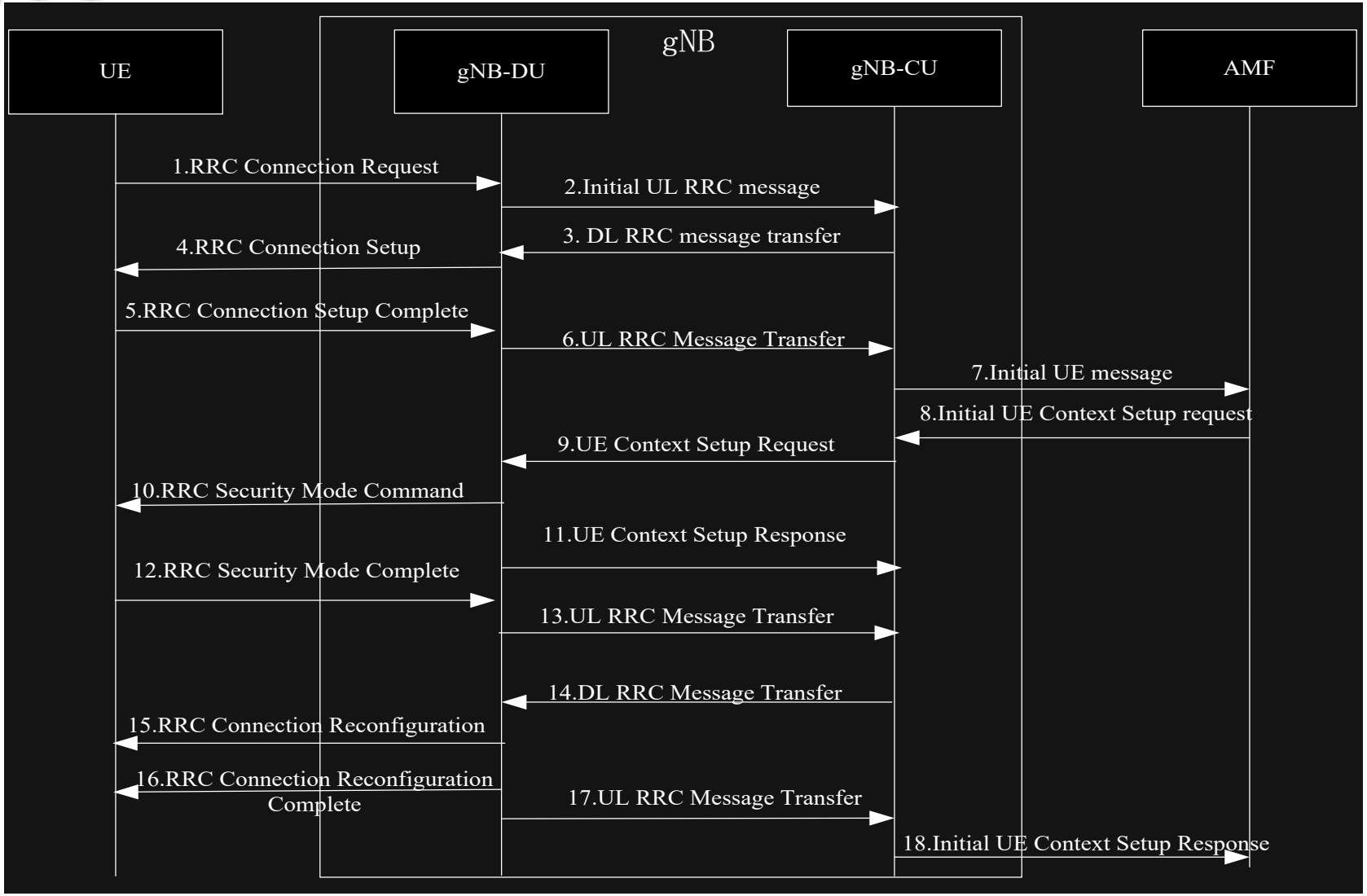


https://www.eventhelix.com/5G/non-standalone-access-en-[illegible]lition.pdf

INITIAL ATTACH – DISAGGREGATED GNB FOR SA/5G



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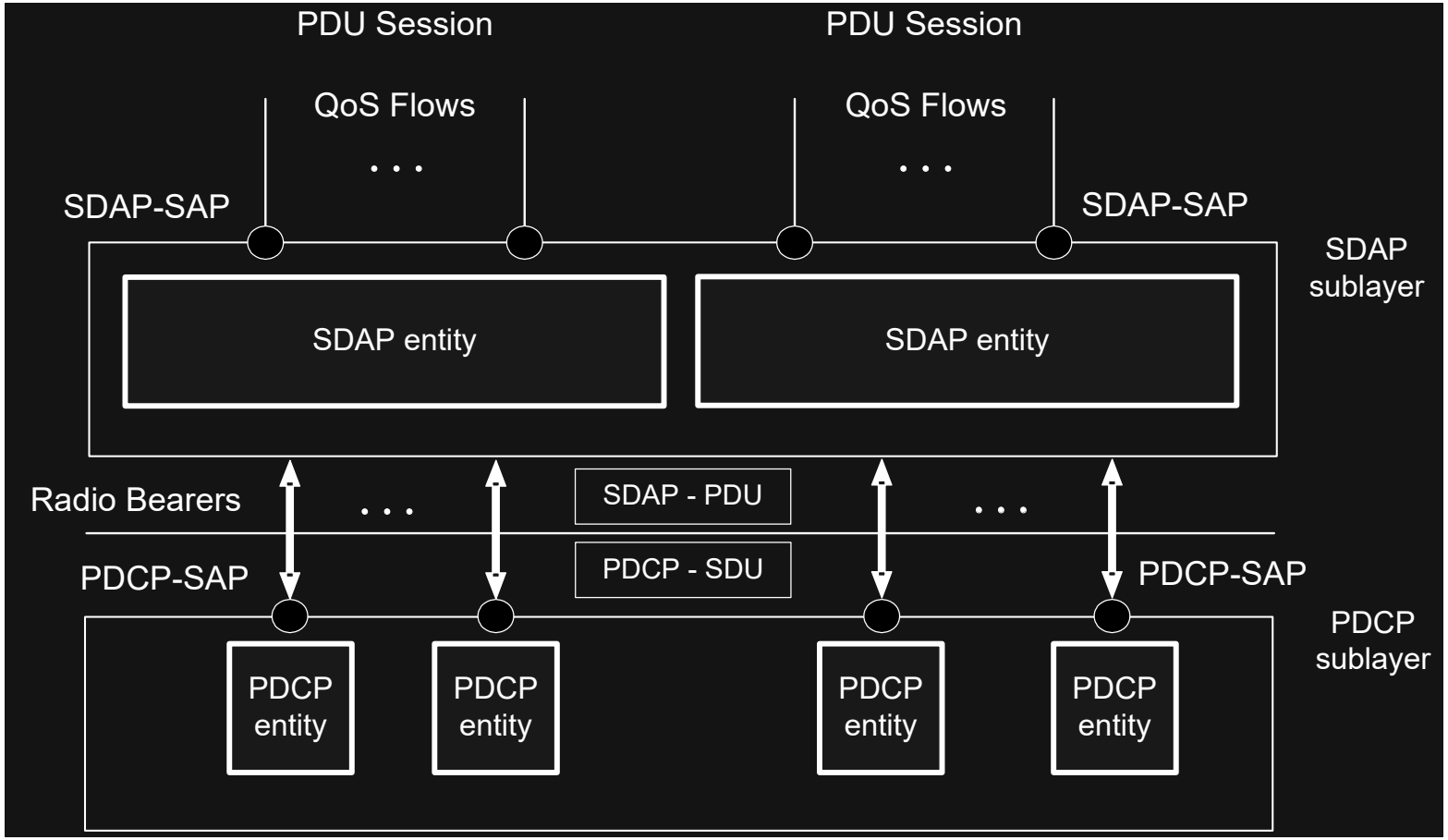
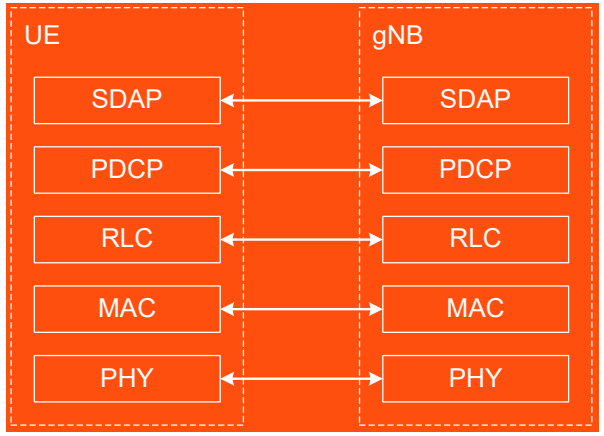
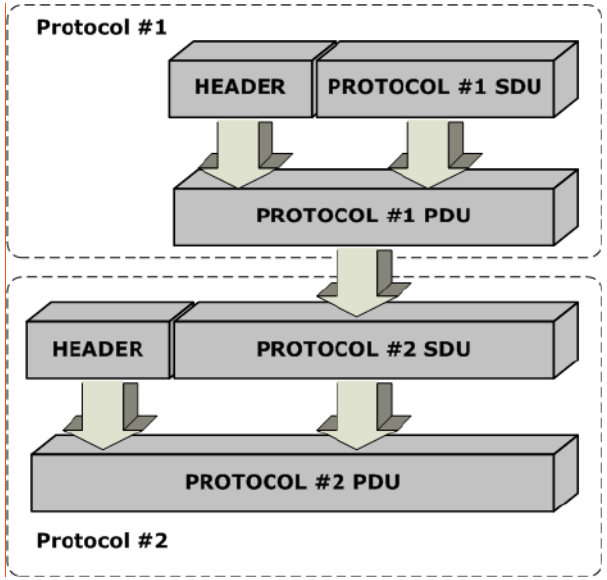
PROTOCOL STACK

SDAP - SERVICE DATA ADAPTATION PROTOCOL ARCHITECTURE

- HANDLES QOS-FLOWS
- MAPS TO RADIO BEARERS
- ONLY USED WITH A 5GC (NO EPC)

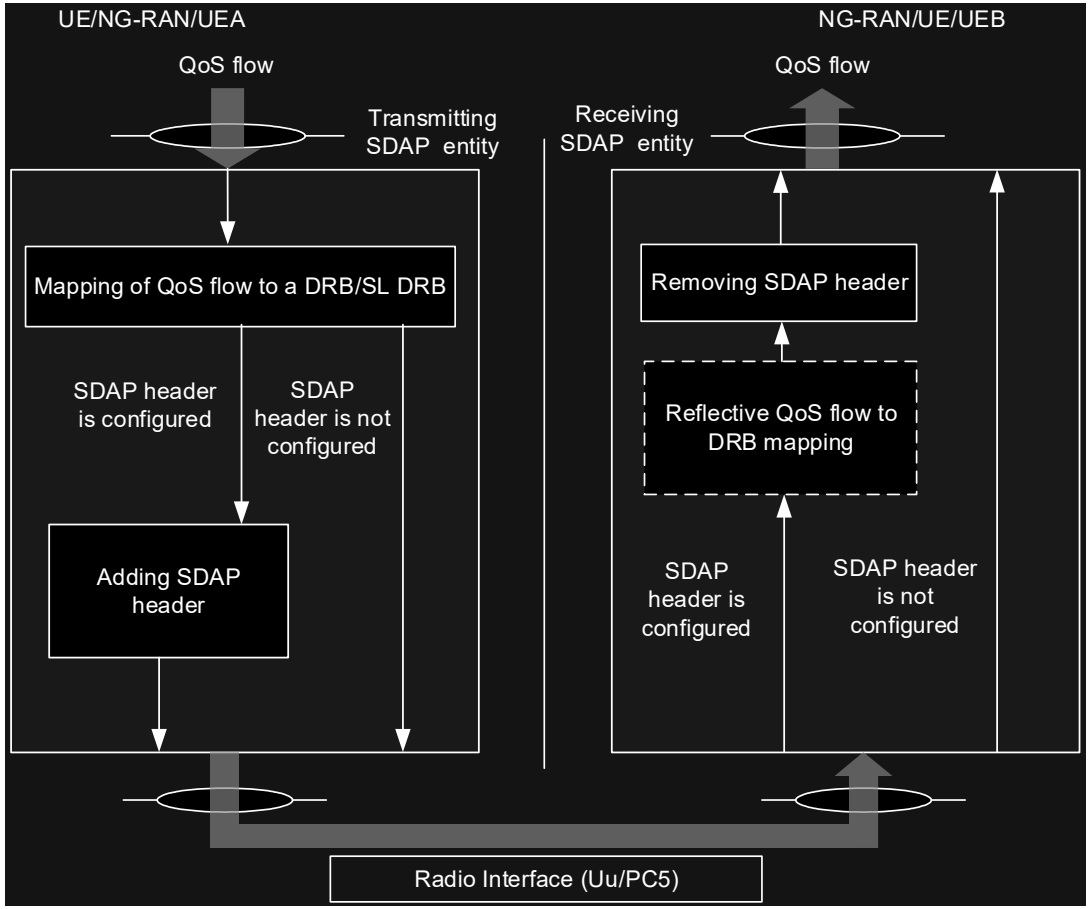






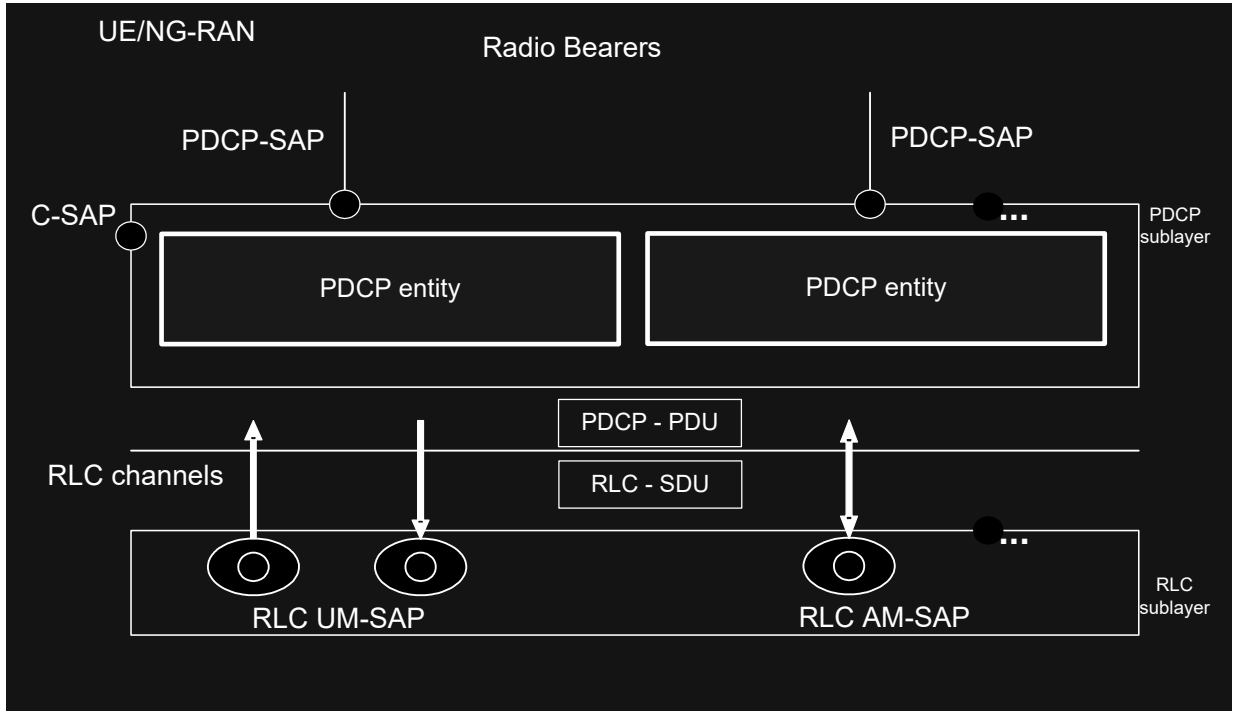
SDAP FUNCTIONAL VIEW

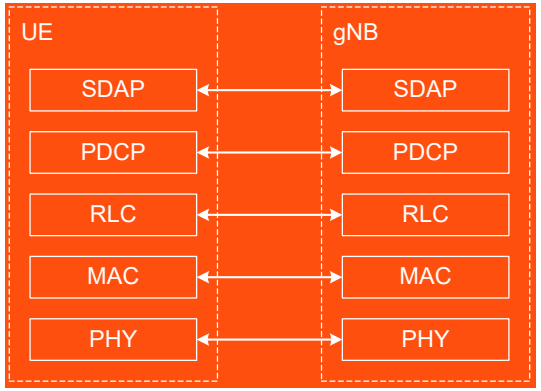
- Mapping between a QoS flow and a data radio bearer
- Marking QoS flow ID in both DL and UL packets
  - reflective QoS
    - NG-RAN marks downlink packets over Uu with QoS flow ID
    - UE monitors the QoS flow ID(s) and PDU sessions of the downlink packets and applies the same mapping in the uplink.
  - Explict QoS Configuration signaled by RRC (QoS Flow to DRB mapping)
- Optionally: Packet scheduling and active Queue management

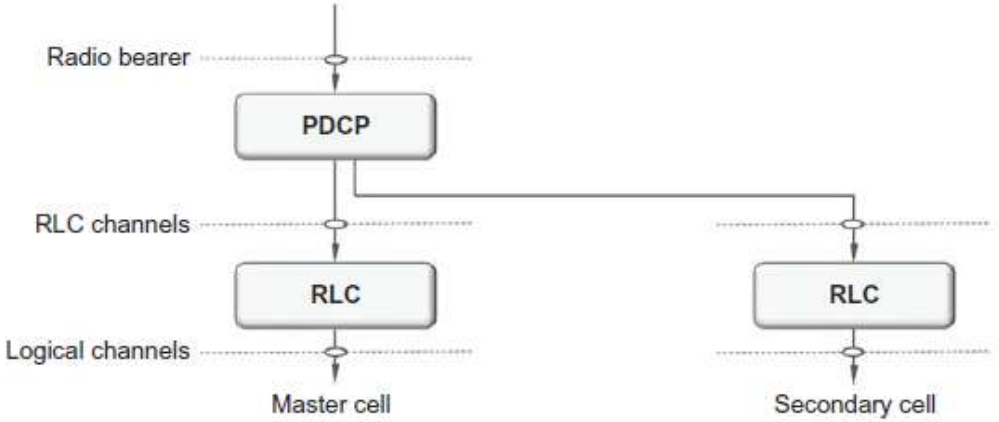


PDCP - PACKET-DATA CONVERGENCE PROTOCOL

- HANDLES DATA FORWARDING, SEQUENCE NUMBERING, INTEGRITY PROTECTION, …
- MAPS RADIO BEARERS TO RLC CHANNELS
- RELATIVELY SIMILAR TO LTE

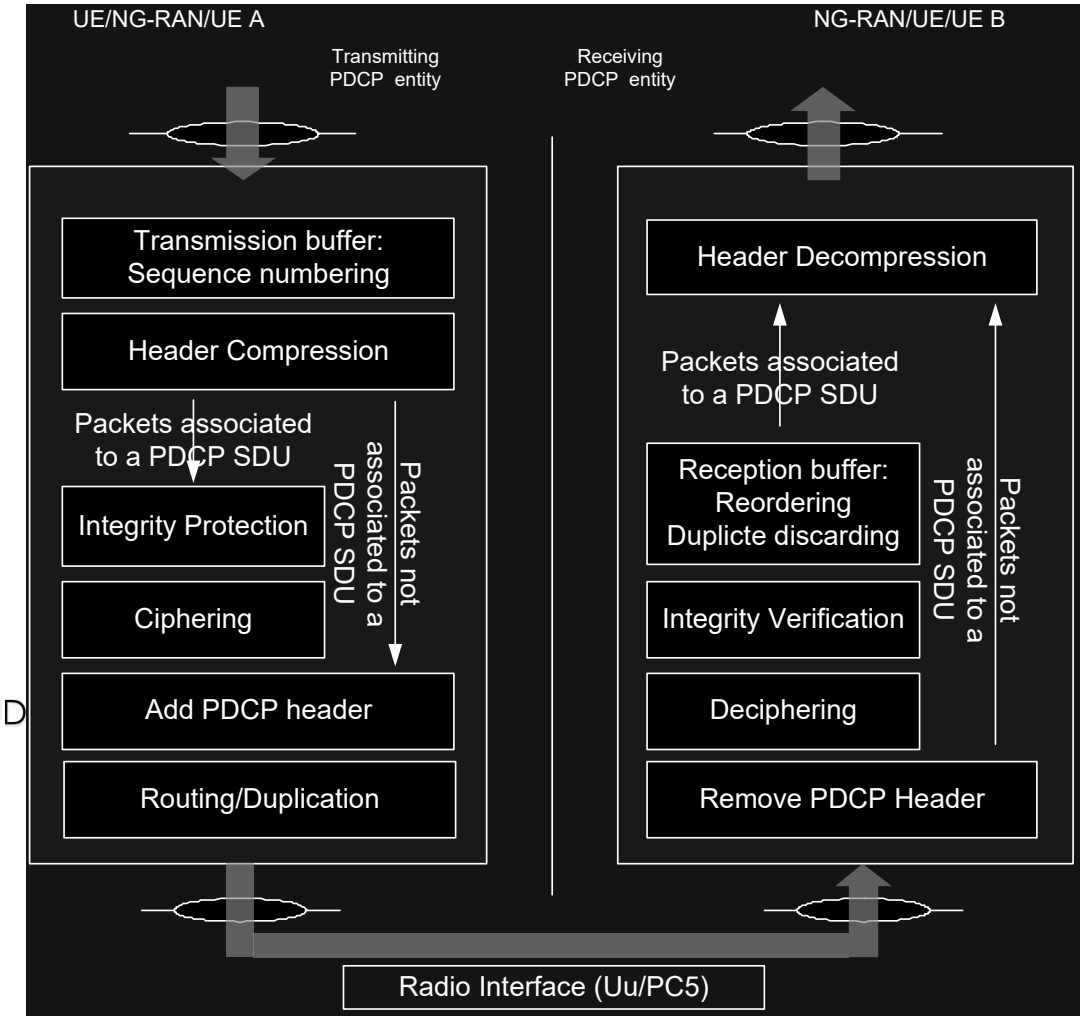






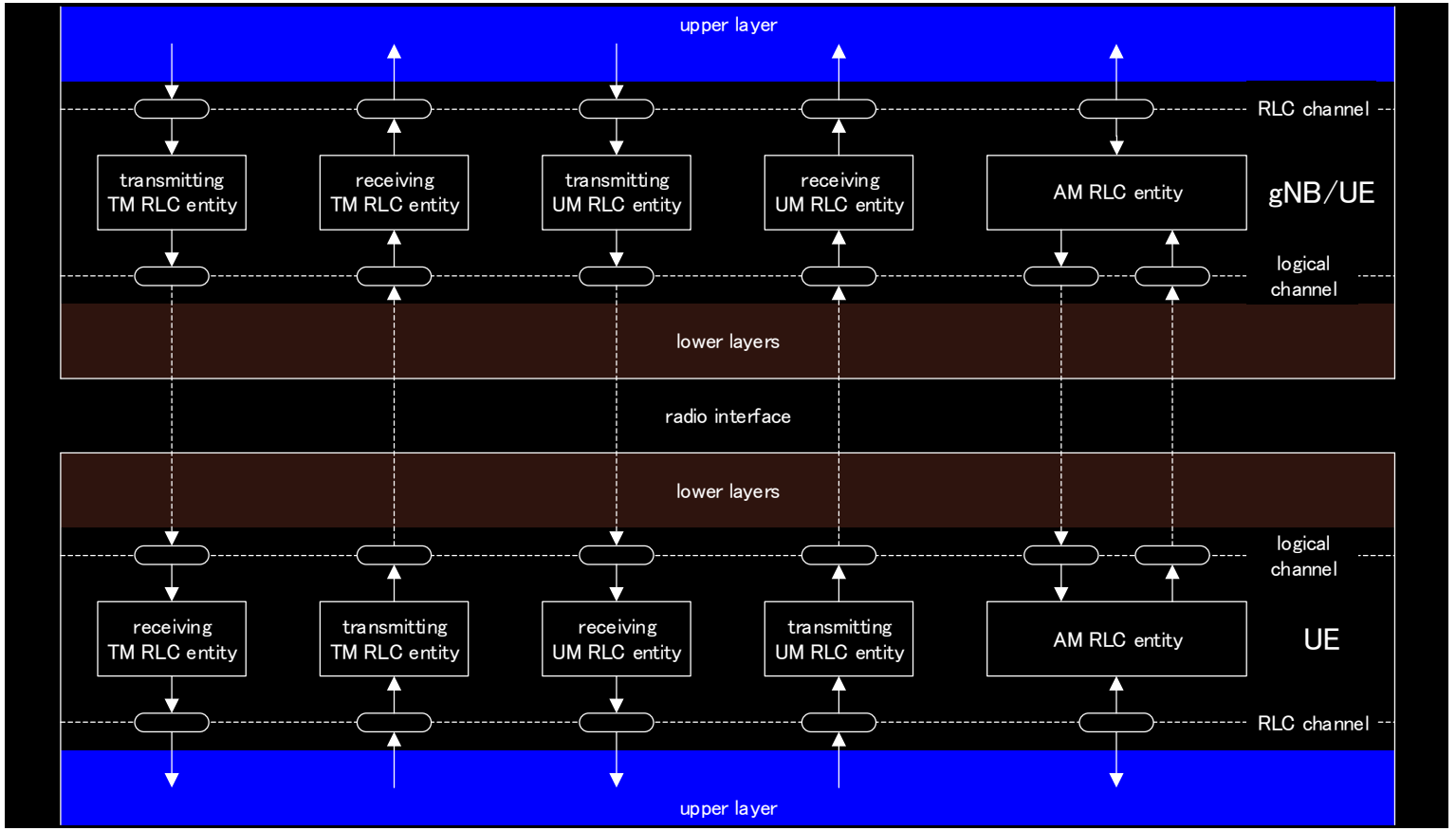
PDCP SERVICES AND FUNCTIONS

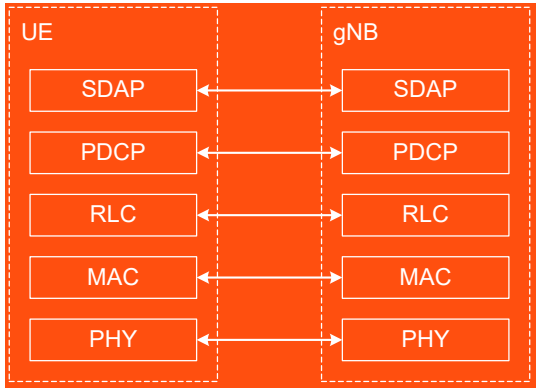
- The main services and functions for the user plane include:
  - **Sequence Numbering;**
  - Header compression and decompression: ROHC only;
  - **Transfer of user data;**
  - Reordering and duplicate detection;
  - PDCP PDU routing (in case of split bearers);
  - Retransmission of PDCP SDUs;
  - Ciphering, deciphering and **integrity protection**;
  - PDCP SDU discard;
  - PDCP re-establishment and data recovery for RLC AM;
  - Duplication of PDCP PDUs.
- The main services and functions for the control plane includ
  - **Sequence Numbering;**
  - Ciphering, deciphering and **integrity protection**;
  - **Transfer of control plane data;**
  - Reordering and duplicate detection;
  - Duplication of PDCP PDUs (see subclause 16.1.3).

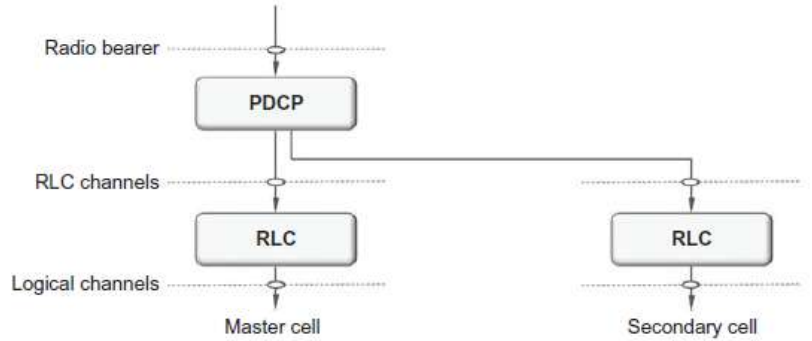


RLC - RADIO LINK CONTROL

- HANDLES DATA BUFFERING AND FORWARDING, SEQUENCE NUMBERING, SEGMENTATION, RETRANSMISSIONS, …
- RELATIVELY SIMILAR TO LTE, BUT NO CONCATENATION

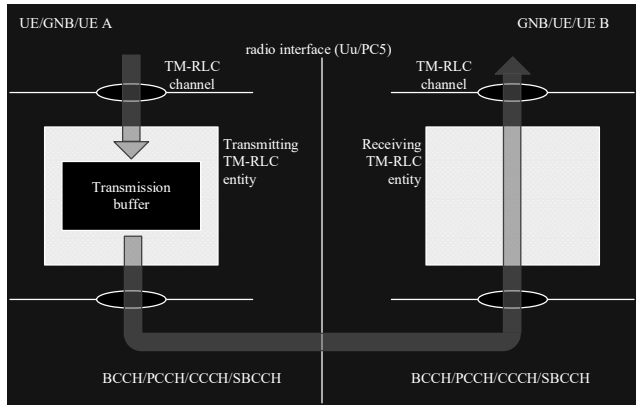


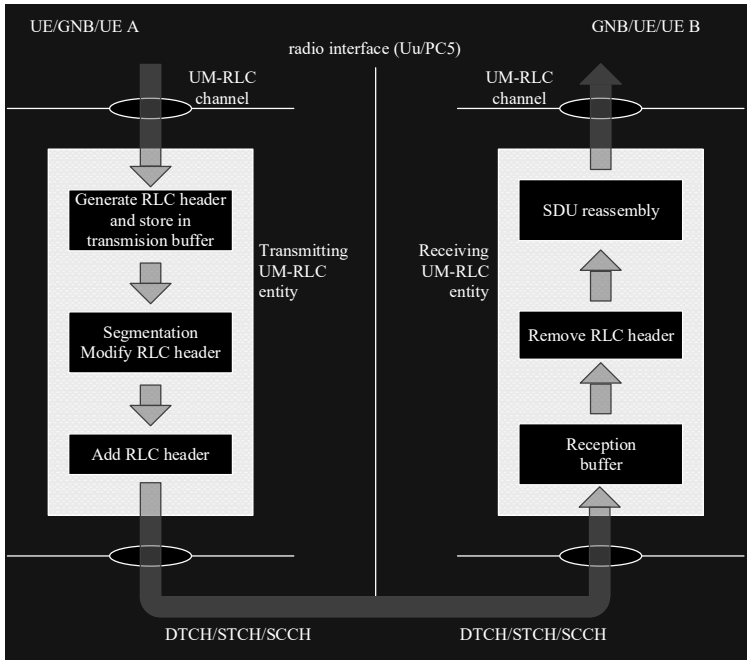


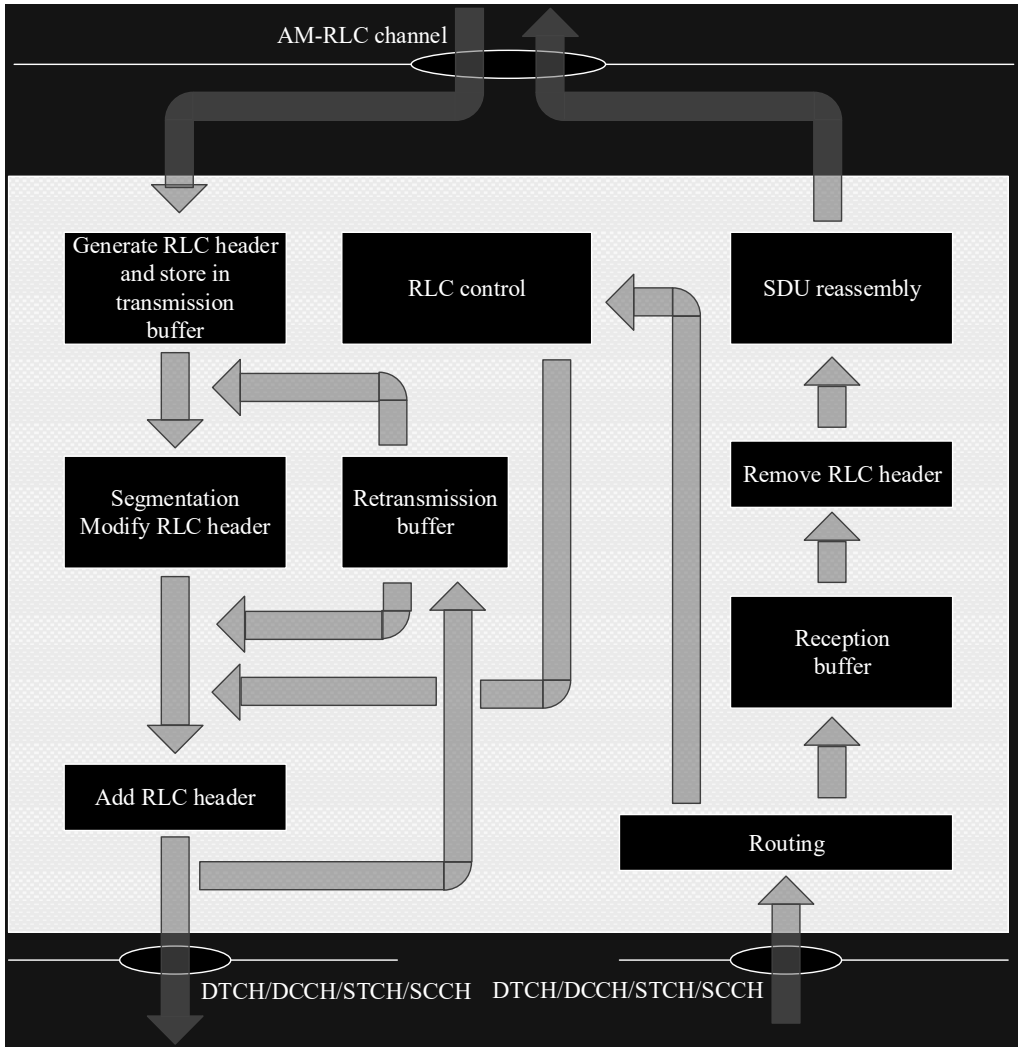


RLC TM/UM/AM

- TM: forward RRC payload as-is
- UM: data buffering/forwarding without retransmissions
- AM: data buffering/forwarding with retransmissions





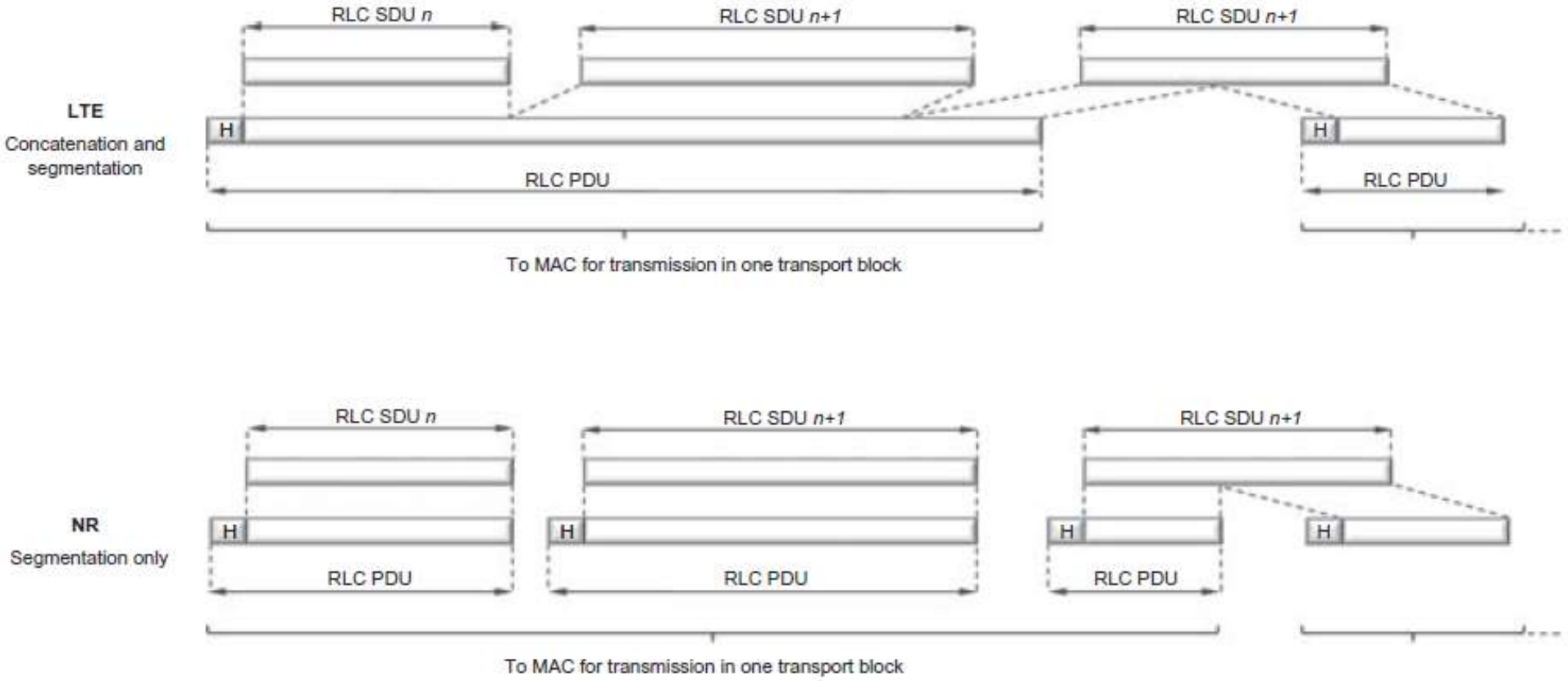


RLC TM/UM/AM

- The main services and functions depend on the transmission mode and include:
  - Transfer of upper layer PDUs;
  - Sequence numbering independent of the one in PDCP (UM and AM);
  - Error Correction through ARQ (AM only);
  - Segmentation (AM and UM) and re-segmentation (AM only) of RLC SDUs;
  - Reassembly of SDU (AM and UM);
  - Duplicate Detection (AM only);
  - RLC SDU discard (AM and UM);
  - RLC re-establishment;
  - Protocol error detection (AM only)

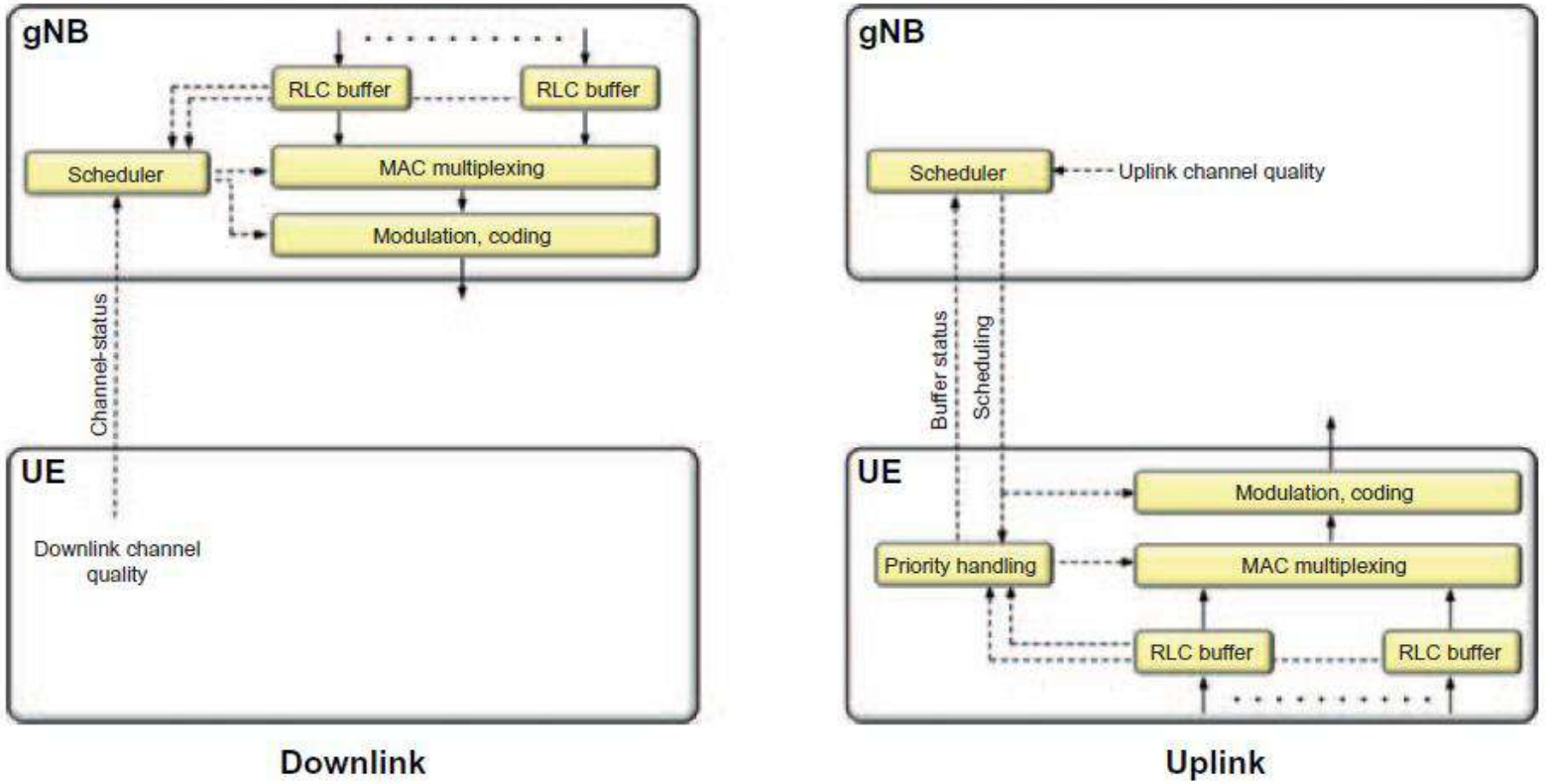
RLC SEGMENTATION 4G VS 5G

➔ **NOTE: NO CONCATENATION AND NO REORDERING TO REDUCE LATENCY FOR u**RLLC** AND x**MBB



MAC

- Multiplexing of UEs onto radio resources with QoS- and channel-awareness, retransmissions
- "Brain" for many advanced features (CA, BWP, Beamforming, …)
- In simple use-cases, Relatively similar to LTE



MAC - MEDIUM ACCESS CONTROL

- The main services and functions of the MAC sublayer include:
  - Mapping between logical channels and transport channels;
  - Multiplexing/demultiplexing of MAC SDUs belonging to one or different logical channels into/from transport blocks (TB) delivered to/from the physical layer on transport channels;
  - Scheduling information reporting;
  - Error correction through HARQ (one HARQ entity per carrier in case of CA);
  - Priority handling between UEs by means of dynamic scheduling;
  - Priority handling between logical channels of one UE by means of logical channel prioritisation;
  - Padding

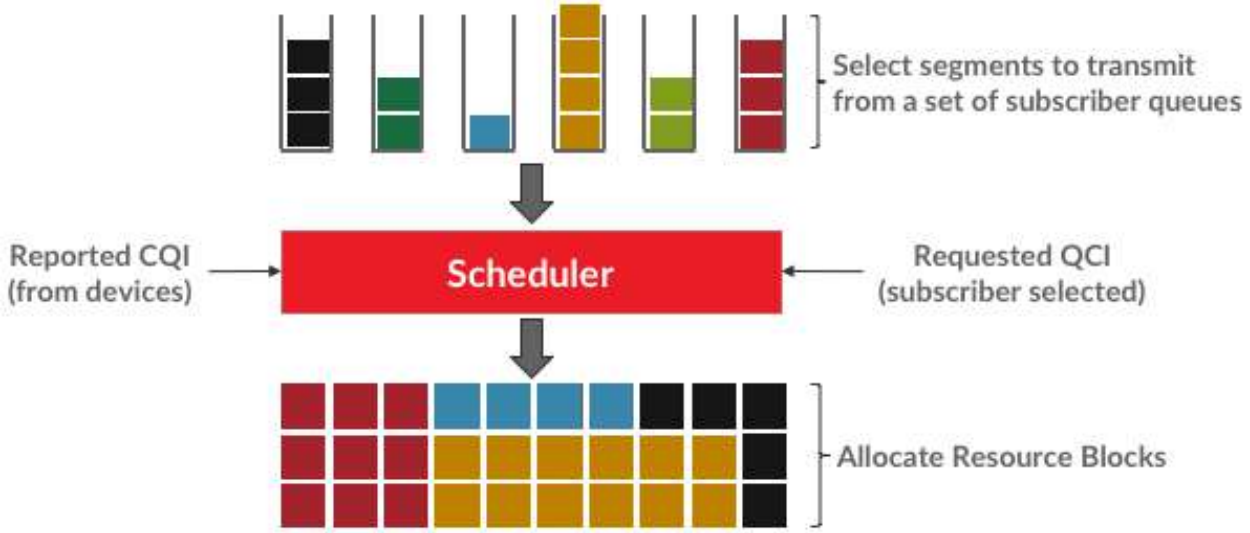
RRC - RADIO RESOURCE CONTROL

- RRC: Handling RAN-related Control, transmitted using signaling radio bearers via CCCH or DCCH
- Broadcast of System Information related to AS and NAS;
- Paging initiated by 5GC or NG-RAN;
- Establishment, maintenance and release of an RRC connection between the UE and NG-RAN including:
  - Addition, modification and release of carrier aggregation;
  - Addition, modification and release of Dual Connectivity in NR or between E-UTRA and NR.
- Security functions including key management;
- Establishment, configuration, maintenance and release of Signalling Radio Bearers (SRBs) and Data Radio Bearers (DRBs);
- Mobility functions including:
  - Handover and context transfer;
  - UE cell selection and reselection and control of cell selection and reselection;
  - Inter-RAT mobility.
- QoS management functions;
- UE measurement reporting and control of the reporting;
- Detection of and recovery from radio link failure;
- NAS message transfer to/from NAS from/to UE.

PROCEDURES – MAC SCHEDULER

MAC SCHEDULING: SCHEDULING OPERATION

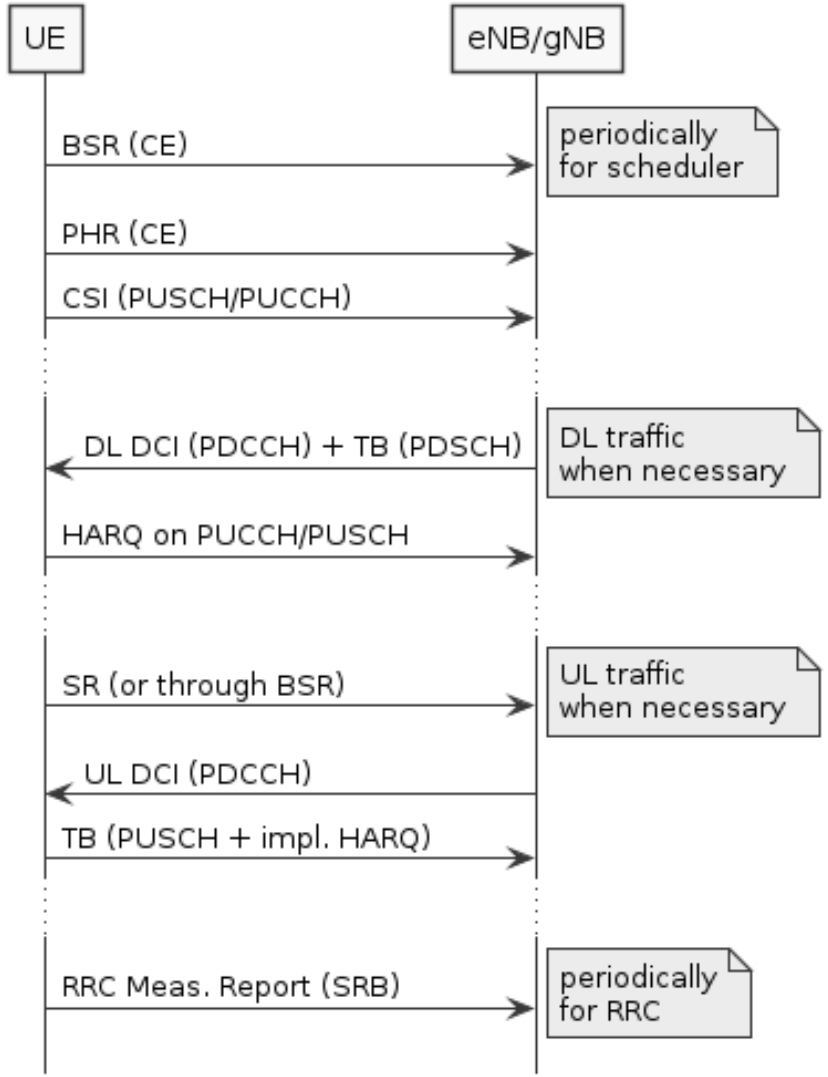
- **MAC ACTS AS A MASTER WITH RESPECT TO**
  - RLC: DETERMINE WITCH PACKETS TO SERVE
  - PHY: DETERMINE HOW THE PACKET MUST BE SENT
- SCHEDULER DECIDES IN EVERY TTI (SIMPLIFIED): **WHICH UES GET WHICH RBS AT WHAT MCS?**
- USES INFORMATION:
  - CHANNEL QUALITY/RADIO CONDITIONS
  - BUFFER STATUS AND QOS REQUIREMENTS
- ADDS MAC CONTROL ELEMENTS (CE) AS COMMANDS FOR UE
- UES IDENTIFY RESOURCES VIA PDCCH
- UES SUPPORT OPERATION WITH BSR AND PHR
- TTI/RBS ARE DEPENDENT ON NUMEROLOGY



https://5g.systemsapproach.org/primer.html

MAC BASIC OPERATION (4G/5G)

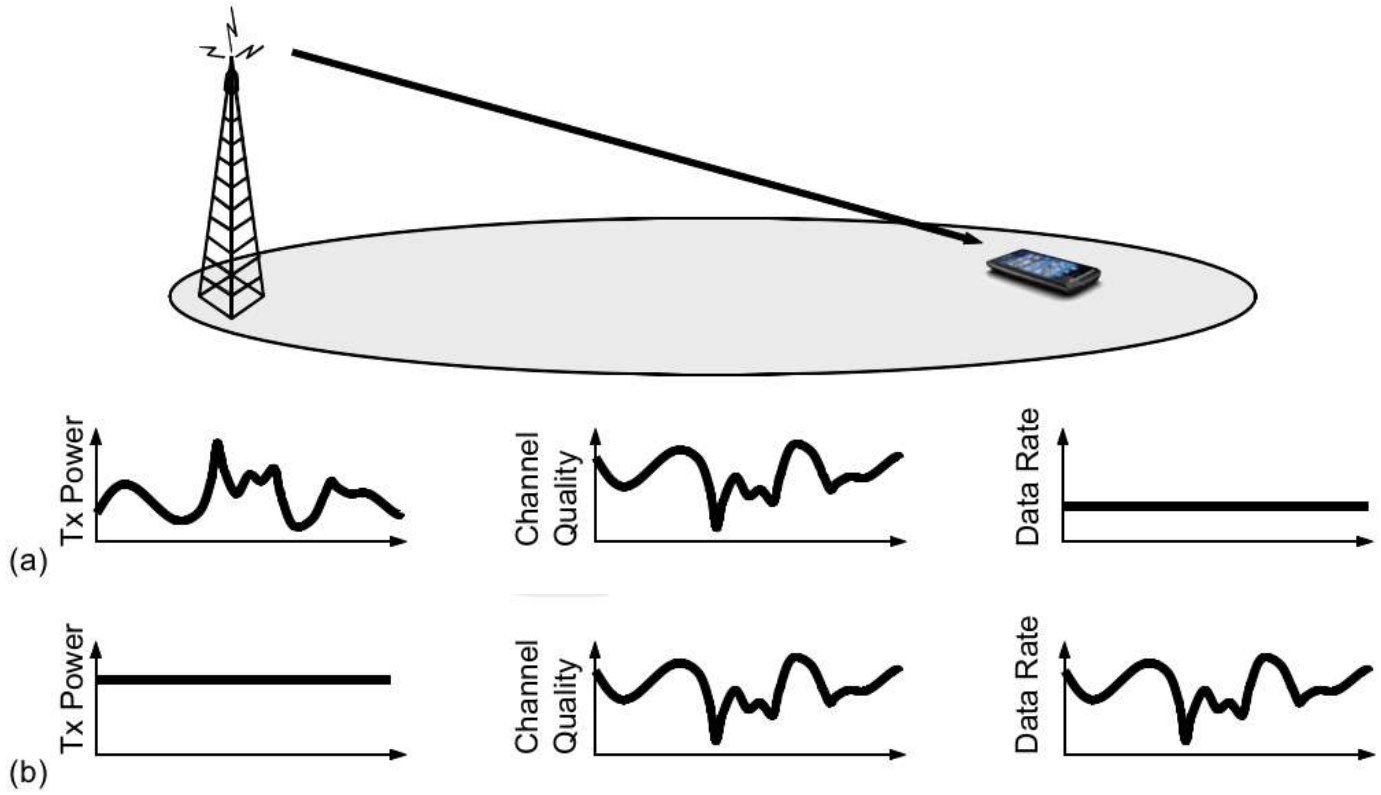
- (MAC) CE = Control Element
- BSR = Buffer Status Report
- PHR = Power HeadRoom
- SR = Scheduling Request
- CSI = Channel State Information
  - CQI = Channel Quality Information
- DCI = Downlink Control Information
- HARQ = Hybrid Automatic Repeat Request
- TB = Transport Block
- DRB/SRB = Data/Signaling Radio Bearer



BASELINE PROCEDURE

- DATA TRANSMISSION
  - DCIS (UL=GRANT, DL)
  - DL: RLC BUFFER, CQI, RANK, CSI, TA, TPC, …
  - UL: SR, BSR, PHR,
- PUT IMAGE SIMILAR TO ATTACH, I.E. HOW BASIC PROCESSING IS DONE TO HAVE DATA TRANSMISSION, WHAT IS HAPPENING

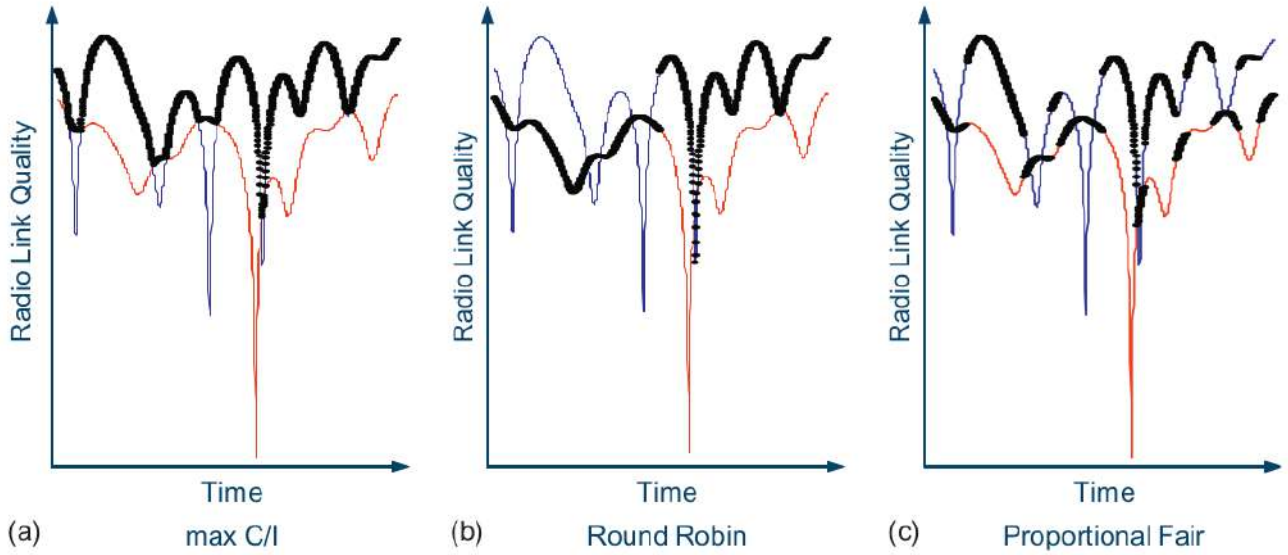
MAC SCHEDULING: LINK ADAPTATION



- CHANNEL QUALITY OF CHANNEL CHANGES
- "HYSTORICALLY", ADAPT TX POWER TO MAINTAIN CONSTANT DATA RATE (→ CIRCUIT-SWITCHED NETWORKS, E.G 2G, EARLY 3G)
- FOR PACKET-SWITCHED NETWORKS, RATE CHANGES ARE OK → DYNAMIC RATE CONTROL
  - COMPENSATE CHANNEL QUALITY VARIATIONS
  - USE ADVANTAGEOUS CHANNEL QUALITY
  - FULLY USE TX POWER AMPLIFIER
- ALSO CALLED ADAPTIVE CODING AND MODULATION

Dahlman, Parkvall, Sköld: 4G LTE/LTE-Advanced for Mobile Broadband, Elsevier, 2011

MAC SCHEDULING: CHANNEL-AWARE SCHEDULING



Dahlman, Parkvall, Sköld: 4G LTE/LTE-Advanced for Mobile Broadband, Elsevier, 2011

More on (DL) scheduling:
https://www.doi.org/10.1109/SURV.2012.060912.00100

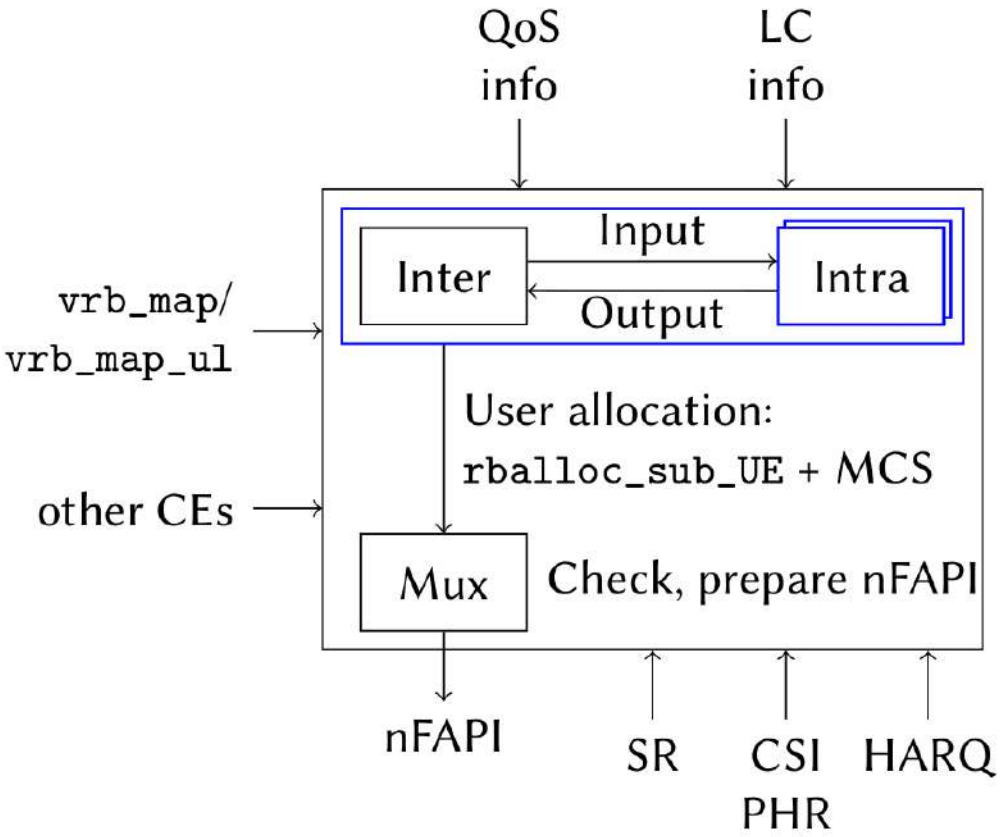
- TWO UES EXPERIENCE SMALL-SCALE/LARGE-SCALE FADING
- MAX C/I OR MAXIMUM THROUGHPUT: SCHEDULE UE WITH BEST RATE

$$k = \arg\max_i R_i$$

- ROUND-ROBIN: SCHEDULE UES IN "ROTATING" FASHION
- PROPORTIONAL FAIR: COMPROMISE OF MT/RR TO SCHEDULE UES OPPORTUNISTICALLY, I.E. WHEN THEY HAVE GOOD CSI RELATIVE TO THROUGHPUT HISTORY

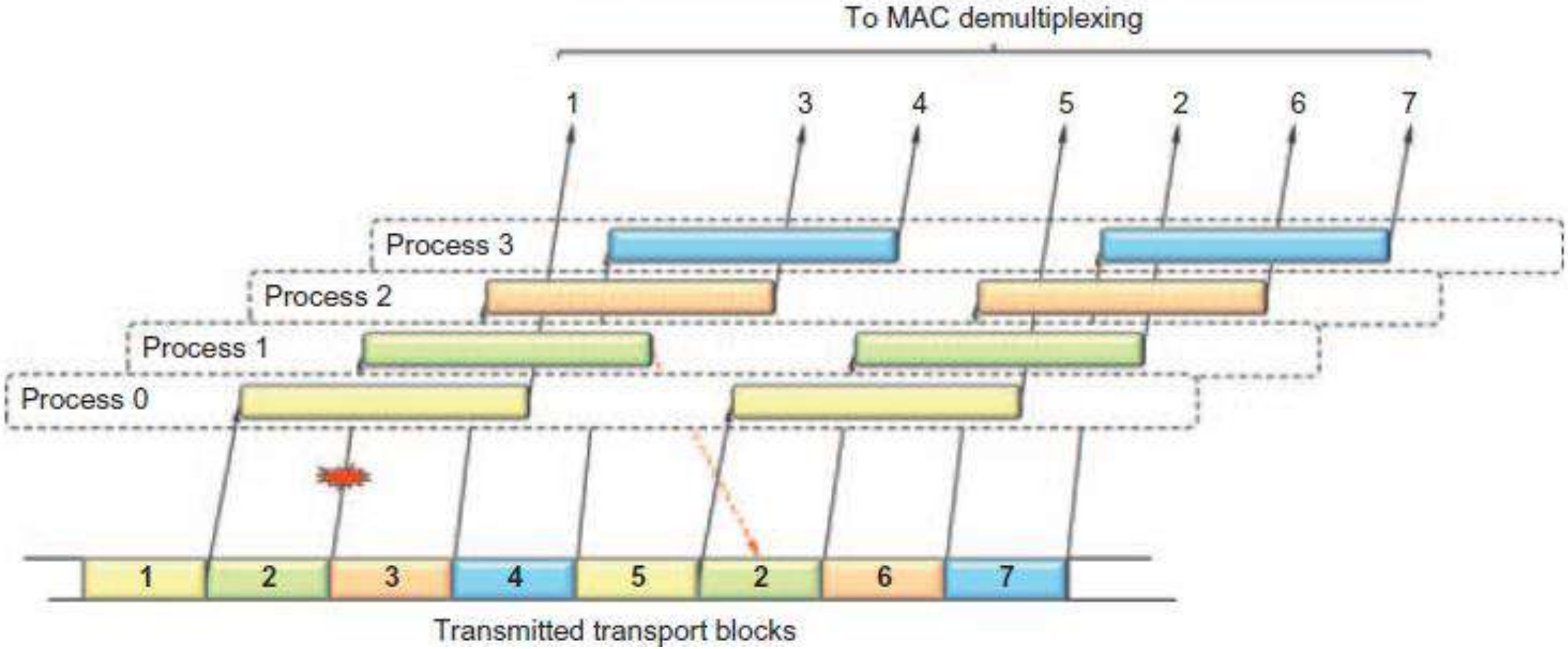
$$k = \arg\max_i \frac{R_i}{\overline{R_i}}$$

EXAMPLE OF MAC SCHEDULING DESIGN IN OAI



- INFORMATION THAT THE SCHEDULER MIGHT USE:
  - QOS INFO, LC INFO: INFORMATION ON LCS AND POSSIBLE QOS
  - VRB_MAP: RBS ALREADY USED
  - OTHER CES: CONTROL ELEMENTS (MAC CONTROL INFORMATION) THAT NEED TO BE TRANSMITTED TO THE UE
  - SR: SCHEDULING REQUEST OF A UE TO BE SCHEDULED IN UL
  - CSI: CHANNEL STATE INFORMATION IN DL AS SEEN BY UE (FOR LINK ADAPTATION)
  - PHR: POWER HEADROOM INDICATES THE FREE TRANSMIT POWER OF THE UE FOR UL
  - HARQ: FOR HANDLING RETRANSMISSIONS IN CASE OF TRANSMISSION FAILURES

RETRANSMISSIONS VIA HARQ



HARQ

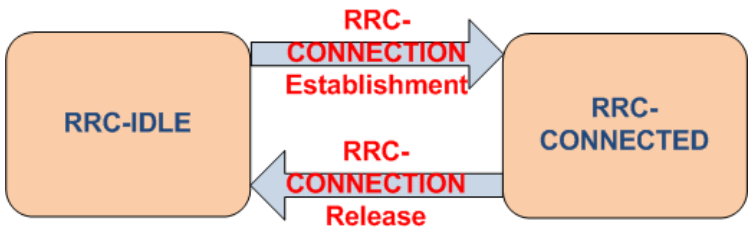
- NR uses Hybrid Automatic Repeat-Request with Incremental redundancy
- When data received erroneously, gNB can schedule retransmission (MAC)
  - Retransmissions are *soft-combined* with old data (PHY)
  - Soft-combining: same data bits, different coded bits
- Up to 16 Stop-And-Wait Processes
- Both DL & UL: Asynchronous (in LTE: UL Synchronous)
- Can be seen as *implicit rate adaptation*

- Q: Why do we need MAC HARQ and RLC ARQ? PDCP sequencing? TCP ACK?...

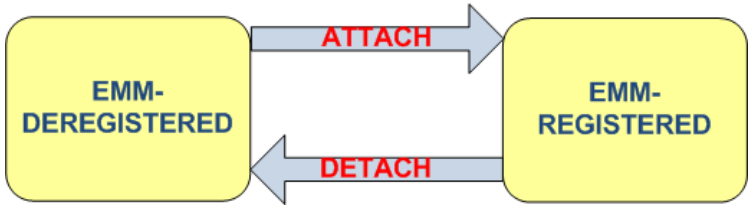
PROCEDURES – RRC

RRC STATES IN 4G/LTE

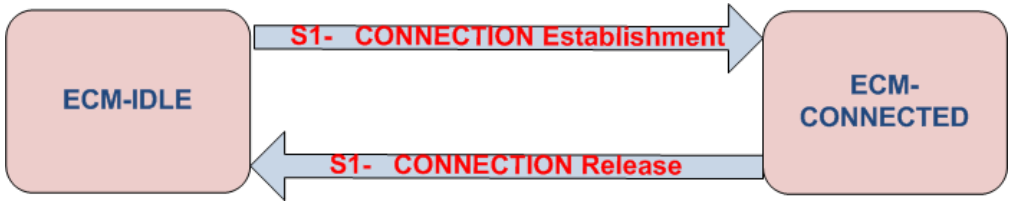
RADIO

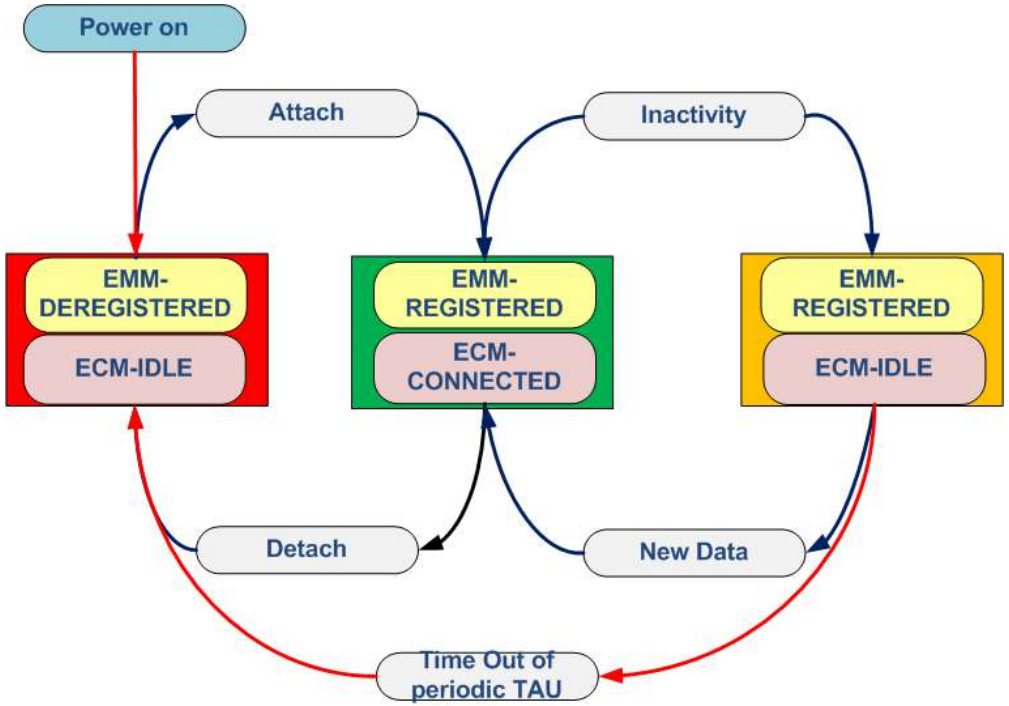


NAS

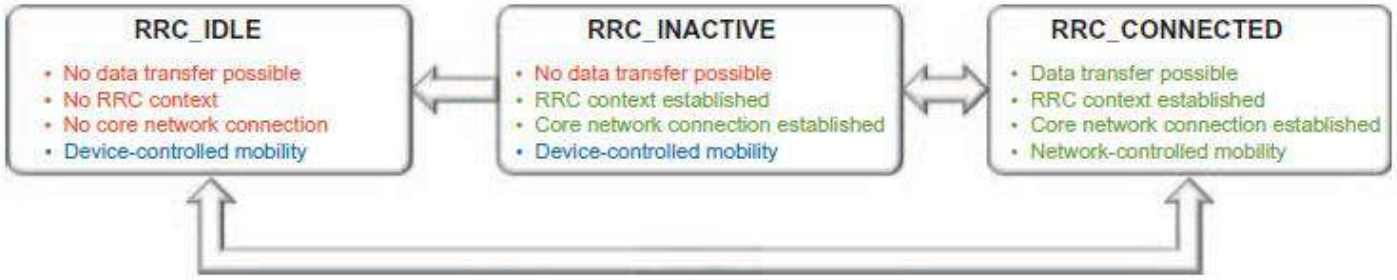


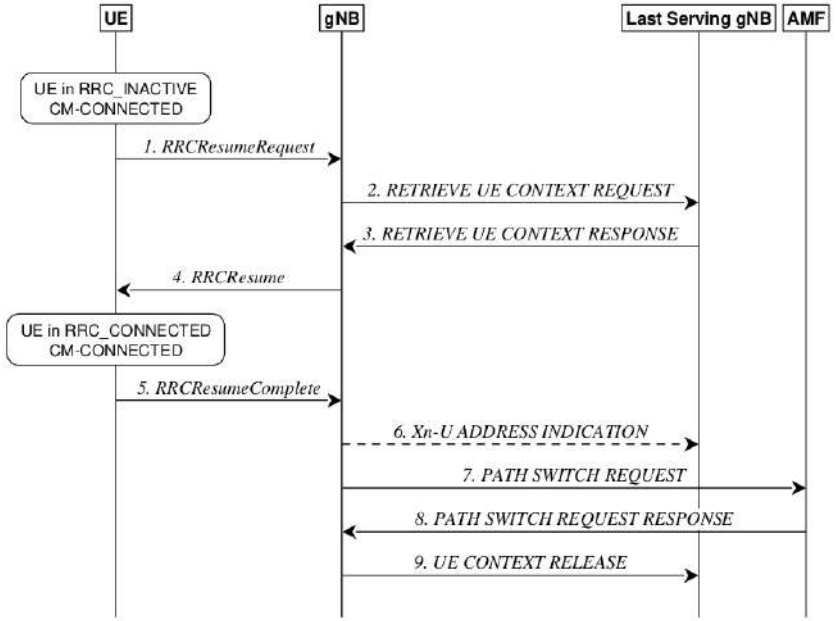
PDU Session





RRC STATES IN 5G/NR



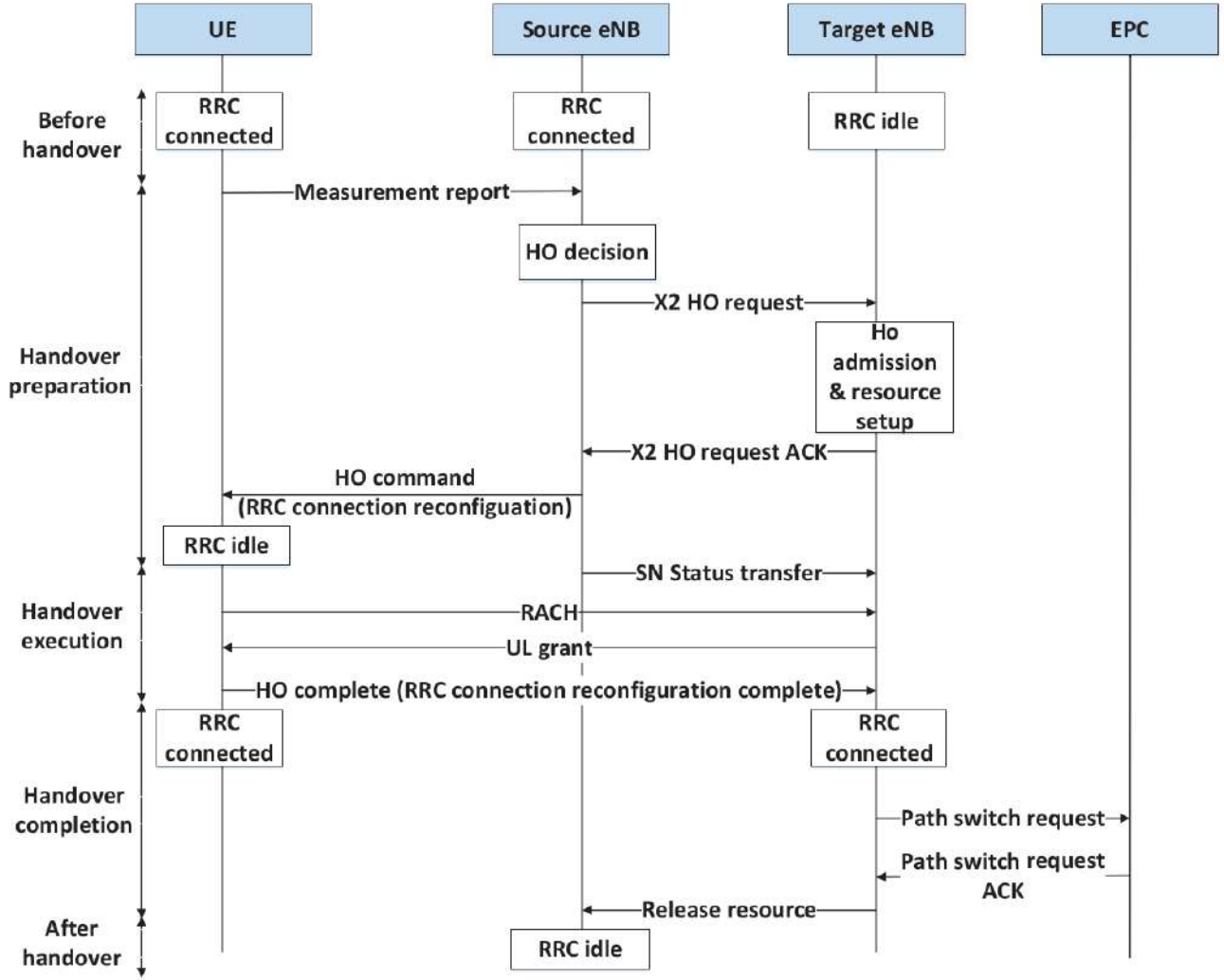


- Introduction of new state for low-latency and low-overhead: RRC_INACTIVE
- In RRC_IDLE and RRC_INACTIVE, mobility device-controlled
  - RAN Areas for RAN tracking: out of RAN area → RRC RAN Notification Area Update
  - Tracking Areas for CN tracking: out of CN area → NAS Registration Update
- Paging to find UEs: Periodical PDSCH transmissions with PI-RNTI

RRC MOBILITY IN 4G AND 5G

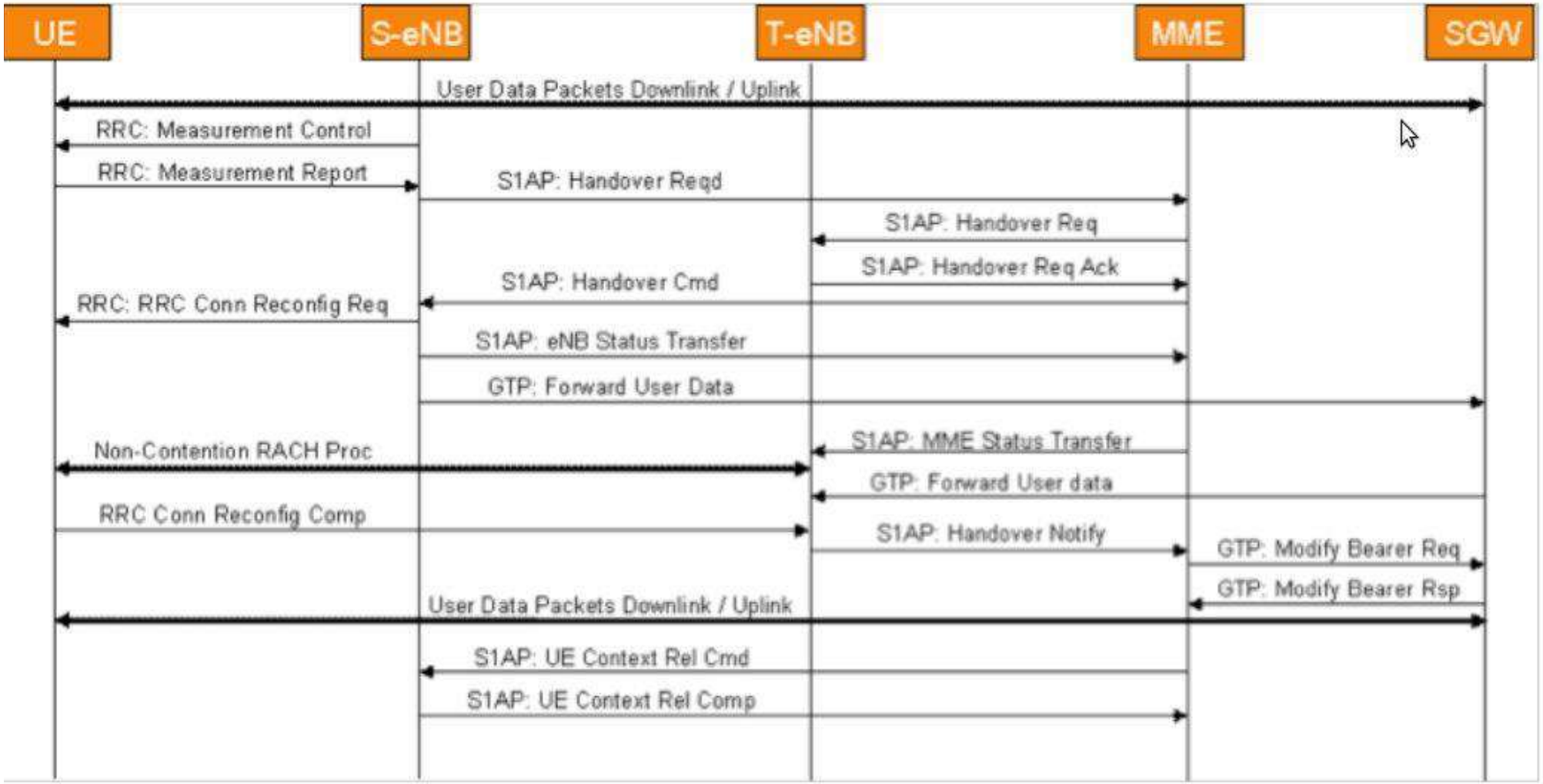
- 4G IS SIMPLER THAN 5G
- 4G X2 HANDOVER (UE-INITIATED OR NETWORK-INITIATED)
- 4G S1 HANDOVER (INTRA-MME AND INTER-MME)
- 5G SA XN HANDOVER
- 5G SA INTRA-CU/INTER-DU HANDOVER
- 5G NSA HANDOVERS
- …

RRC: MOBILITY IN 4G (X2 HANDOVER)



Instructive: http://www.3glteinfo.com/intra-lte-handover-using-x2-interface/

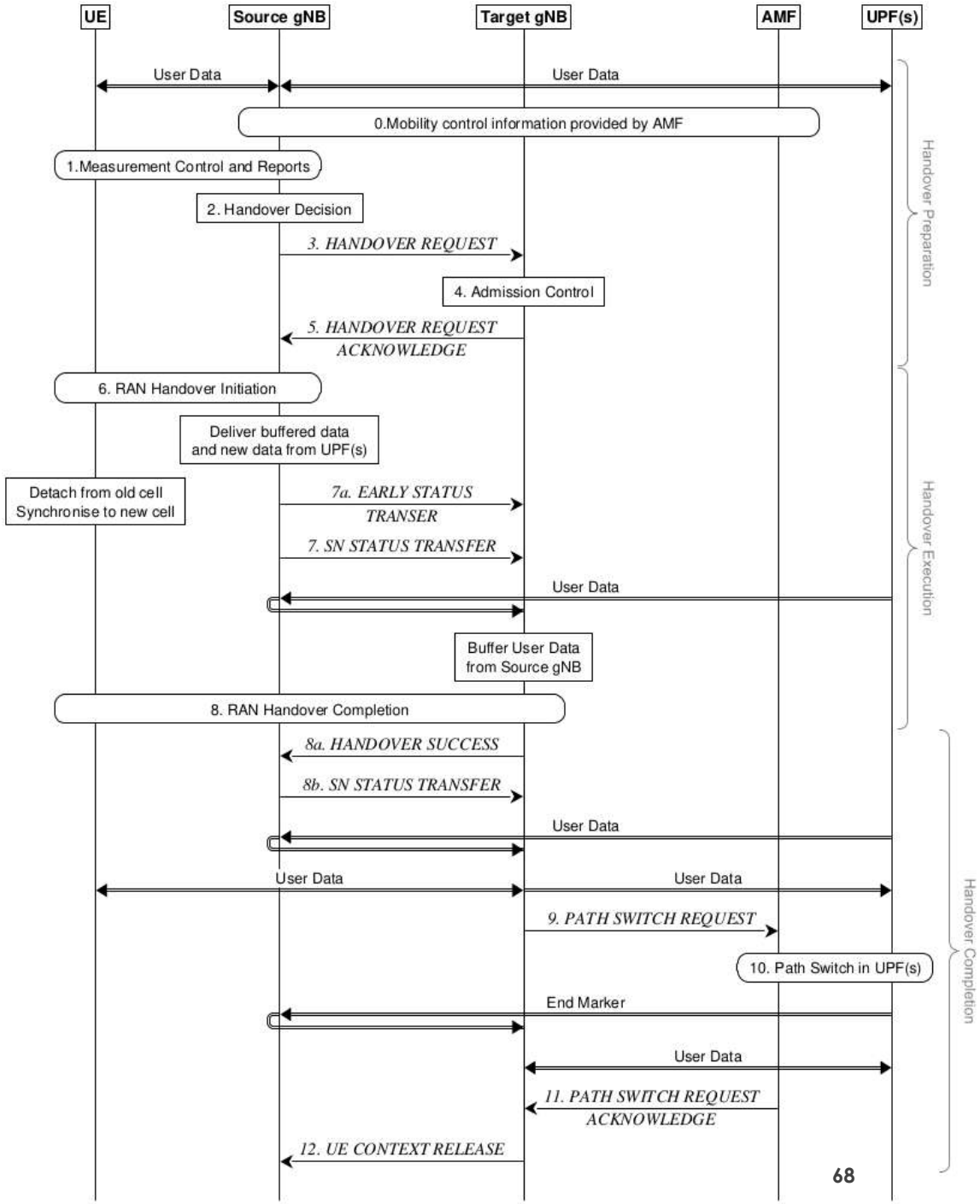
RRC: MOBILITY IN 4G (S1 INTRA-MME HANDOVER)



Source: http://www.3glteinfo.com/intra-lte-handover-using-s1-interface/

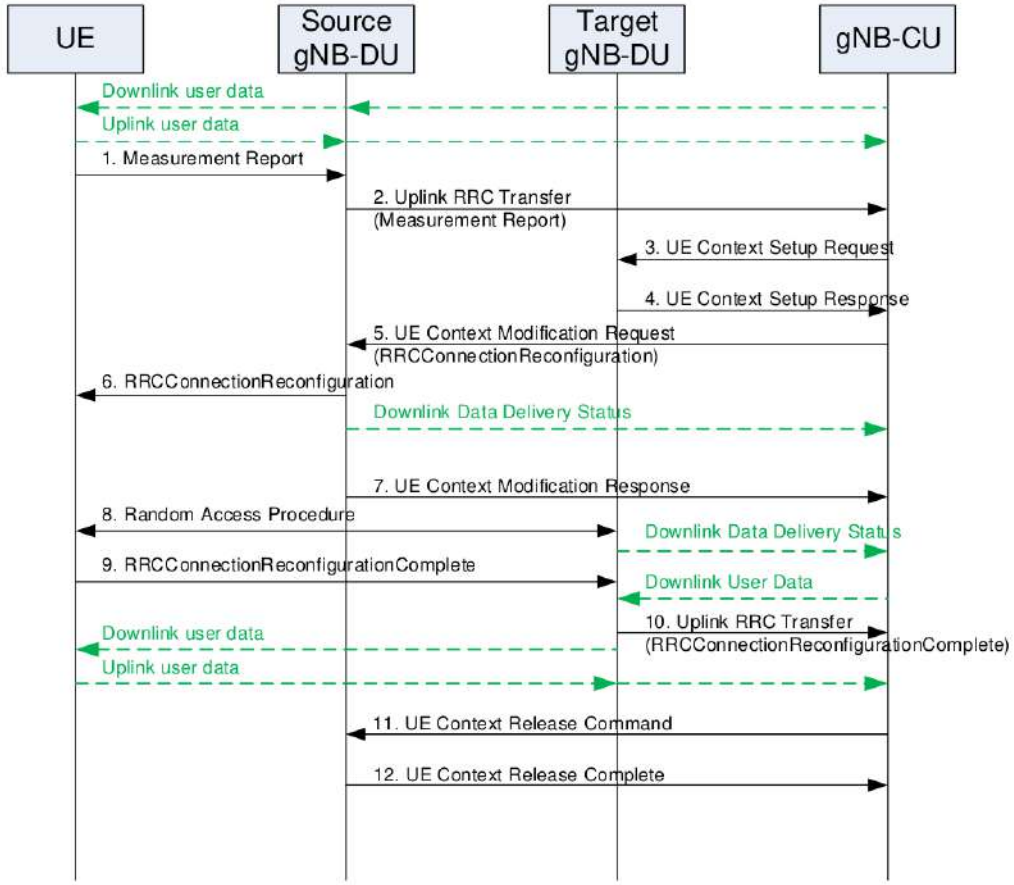
RRC: MOBILITY IN 5G

- BASIC 5G MOBILITY: FROM TS 38.300
- 5G SA XN HANDOVER



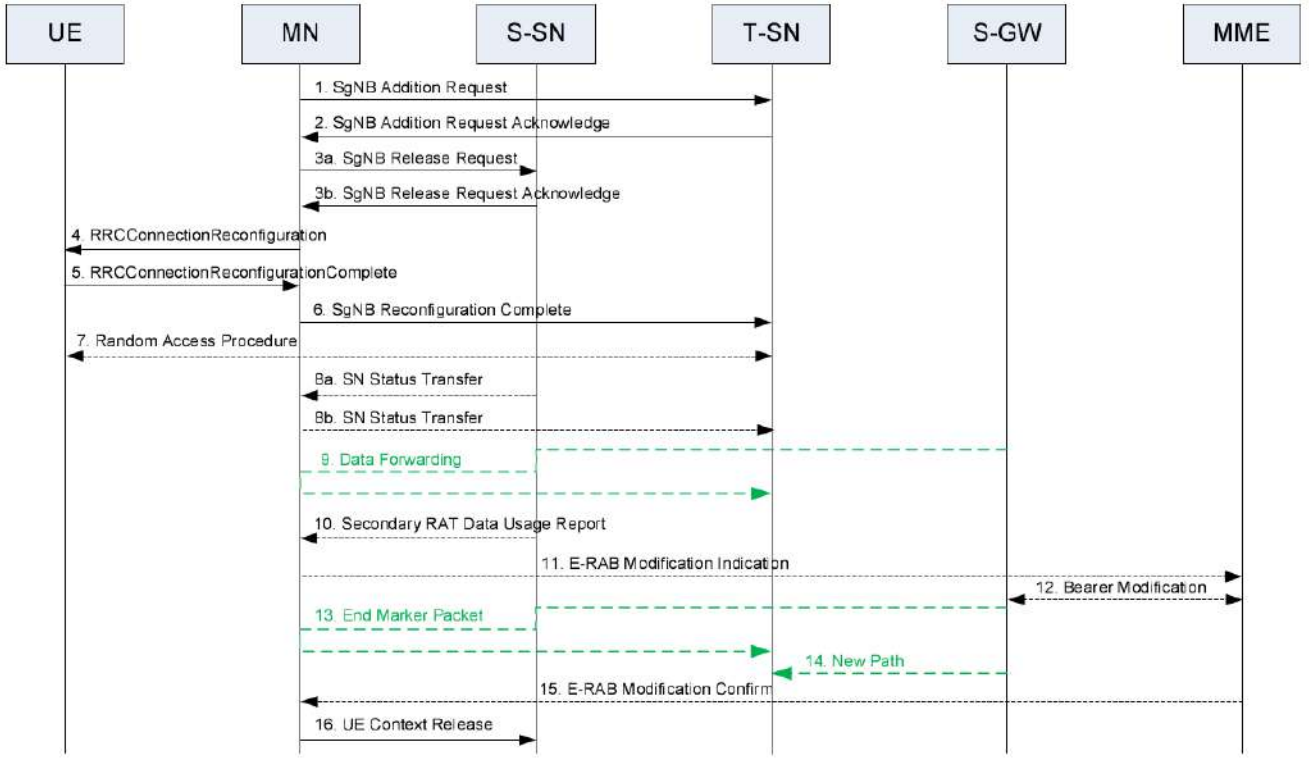
RRC: MOBILITY IN SA WITH CU-DU SPLIT

- SA INTRA-CU/INTER-DU HANDOVER
- ONLY WHEN DISAGGREGATED GNB WITH F1 SPLIT



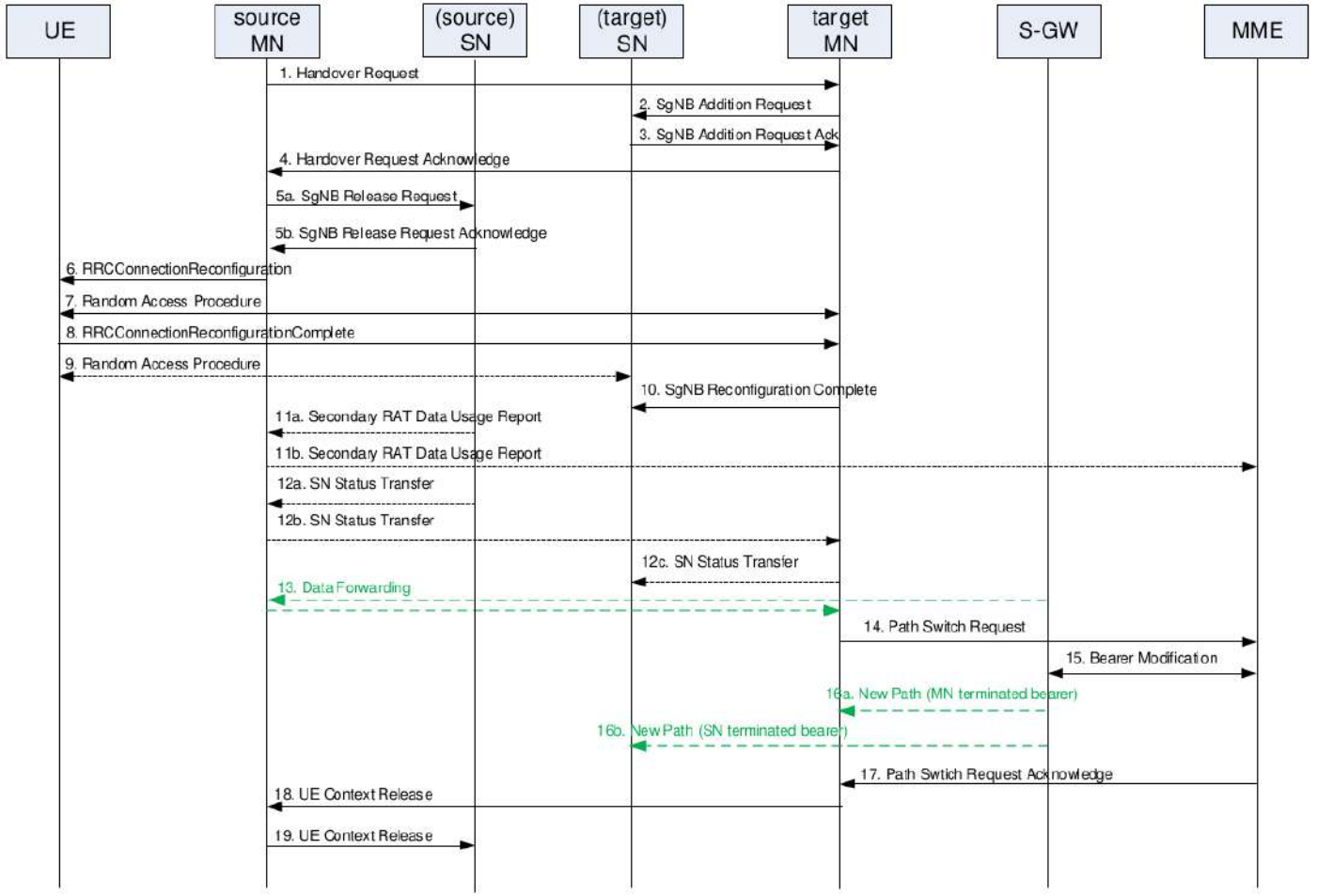
RRC: SECONDARY NODE MOBILITY IN 5G NSA

- 5G NSA/MULTI-CONNECTIVITY SECONDARY NODE MOBILITY
- CAN BE MN OR SN-INITIATED



RRC: MOBILITY IN NSA

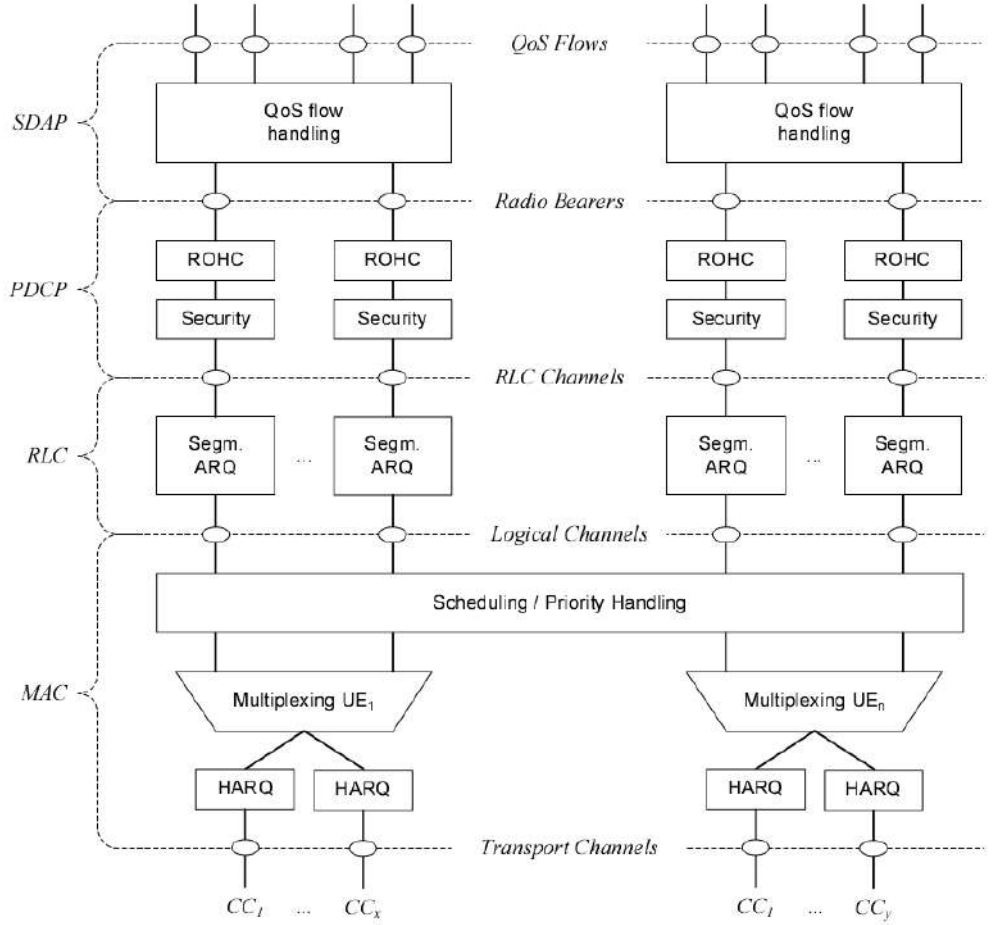
- 5G NSA/MULTI-CONNECTIVITY MASTER NODE MOBILITY (WITH SECONDARY MOBILITY)
- OVER XN

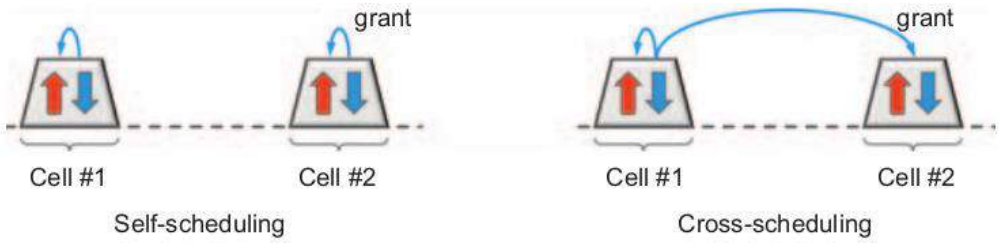


ADVANCED 4G/5G FEATURES

CARRIER AGGREGATION

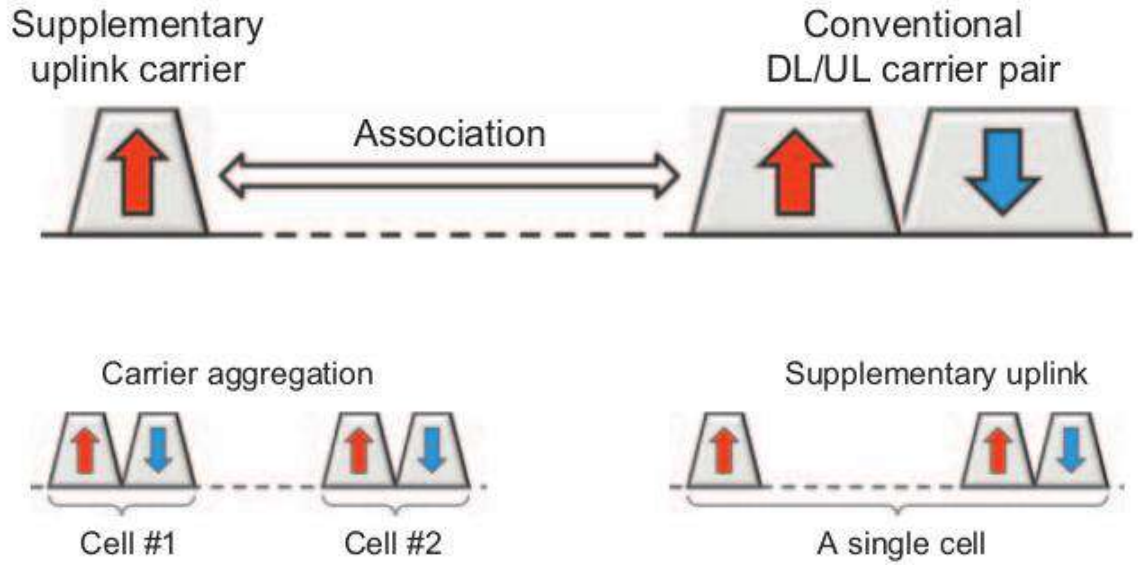
- CARRIER AGGREGATION: USE MULTIPLE CARRIERS
  - INCREASE BANDWIDTH (AND DATA RATE)
  - AGGREGATED MULTIPLE NON-CONTIGUOUS FREQUENCIES
- 5G: UP TO 16 CARRIERS OF UP TO 400 MHZ → 6,4 GHZ (IN THEORY)
- 4G: UP TO 5 CARRIERS OF UP TO 20 MHZ → 100 MHZ
- ONLY VISIBLE UP TO MAC
- LIKE MULTIPLE CELLS, (DE-)ACTIVATED WITH CES, SCHEDULING GRANTS ON EITHER CARRIER





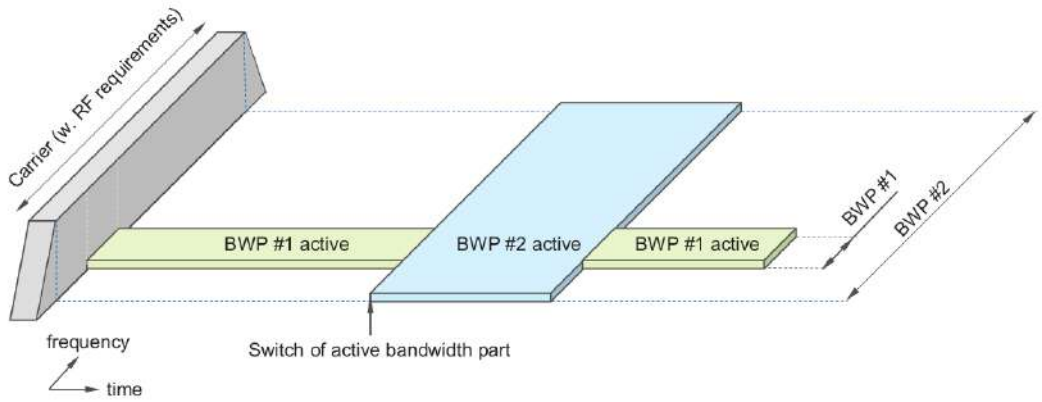
SECONDARY UPLINK (5G)

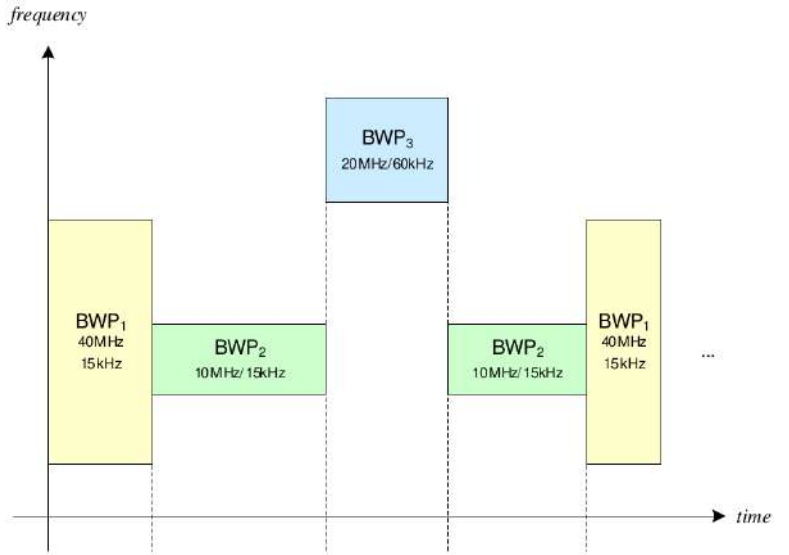
- SUL: CONVENTIONAL DL/UL PAIR(S) HAVE ASSOCIATED UL
- EXTEND UL COVERAGE
  - PAIR 3,5 GHZ CARRIER WITH 800 MHZ SUL
- SUL RATE TYPICALLY LOW → NO TRANSMISSION ON BOTH SUL AND NON-SUL
- APPEARS LIKE SINGLE CELL (UNLIKE CA)

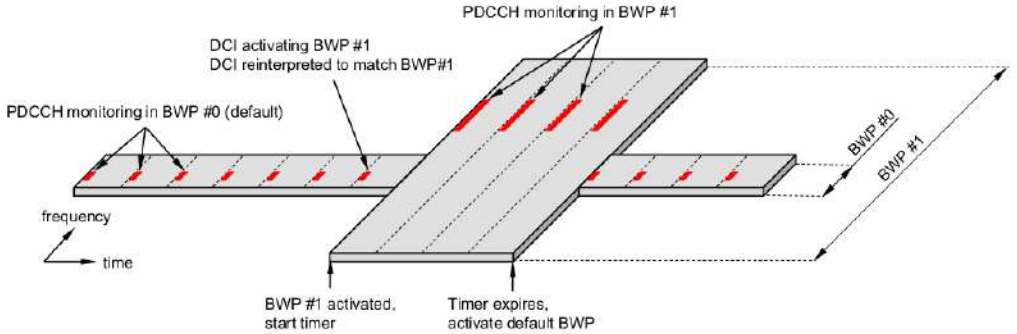


BANDWIDTH PARTS (5G)

- BWP: CHUNK OF SPECTRUM (NUMEROLOGY + RBS)
  - FOR HANDLING DEVICE CAPABILITIES
  - LOWER ENERGY CONSUMPTION
  - MULTI-SERVICE
- RRC:
  - PBCH GIVES CORESET → INITIAL BWP
  - UP TO 4 BWPS IN UL & DL, ONLY ONE ACTIVE
  - CONFIGURATION, SEMI-STATIC SWITCHING
- MAC:
  - DYNAMIC ALLOCATION AND SWITCHING THROUGH DCI

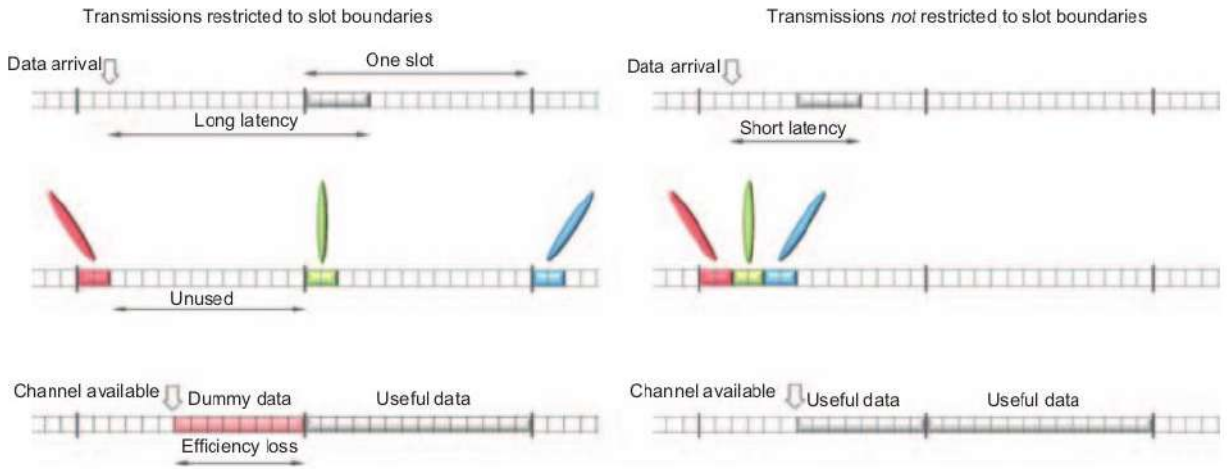






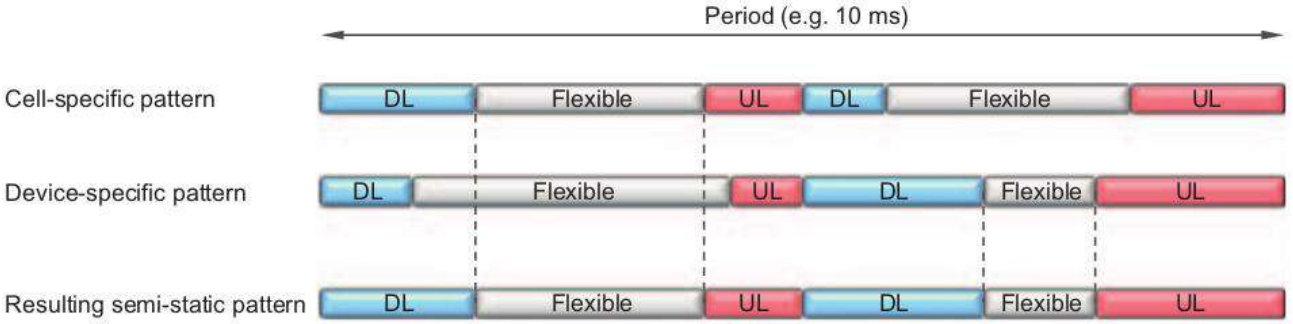
LOW-LATENCY AND MINISLOTS (5G)

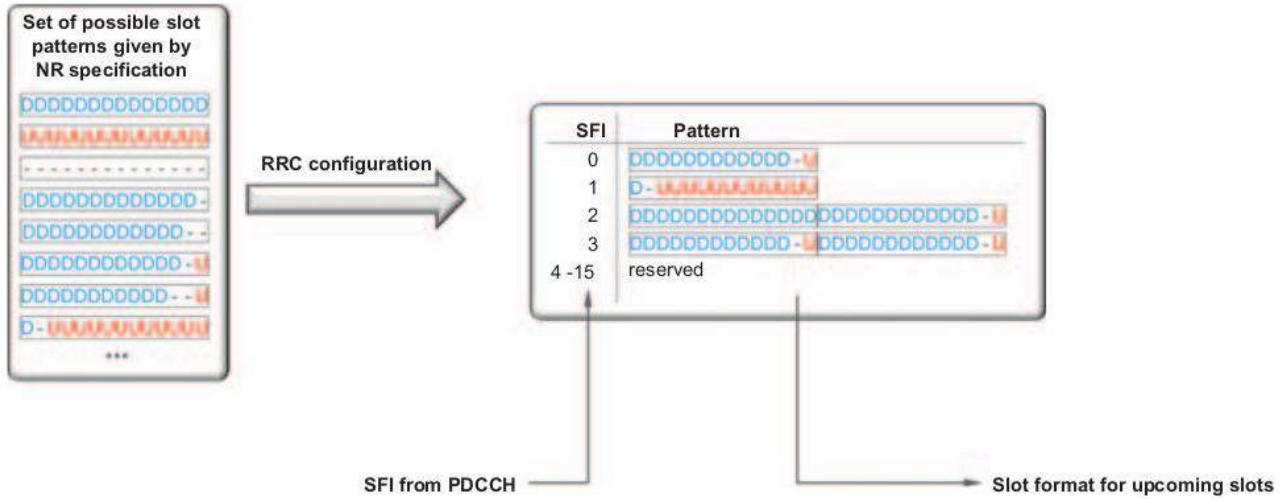
- "FRONT-LOADED" REFERENCE SIGNALS WITHOUT TIME-DOMAIN INTERLEAVING ACROSS SYMBOLS
- TIGHTER DEVICE/NETWORK PROCESSING TIMES (DOWN TO ONE SLOT FOR HARQ AND UL GRANT)
- DESIGN DECISIONS IN VARIOUS LAYERS
- CONTENTION-FREE OR GRANT-FREE UPLINK ACCESS (ONLY IN 5G)
- MINISLOT SCHEDULING: SCHEDULED DATA
  - DOES NOT HAVE TO START AT SLOT BOUNDARIE
  - CAN BE SHORTER THAN A SYMBOL
- NUMEROLOGIES WITH SHORT SLOT TIMES



TDD PATTERNS/DYNAMIC TDD (5G)

- In LTE: fixed/standardized TDD patterns
- In NR: TDD pattern signaled via RRC and Dynamic TDD
  - Dynamic: via RRC and Slot-format switched by MAC, or always Flexible and UE follows grants only
  - meet spatio-temporal traffic variability in short time-scale
- Sending Slot-format indicator can switch flexible to UL or DL symbols, adjusting flexible symbols in the cell-specific pattern

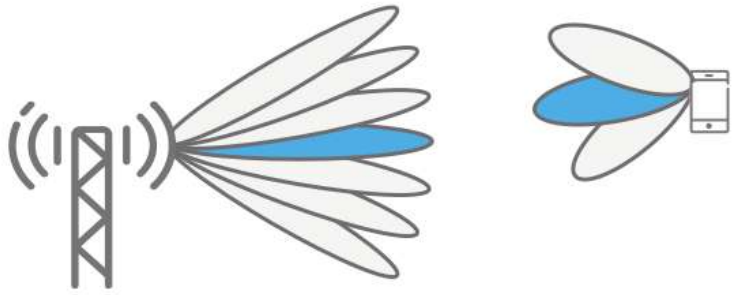




http://www.sharetechnote.com/html/5G/5G_FrameStructure.html#Slot_Format

BEAM-CENTRIC DESIGN (5G)

- Support many antenna elements for beam-forming and massive MIMO
- Beam-forming: steer beam for coverage extension (High Freq.)
- Massive MIMO: Interference avoidance for spatial separation (Low Freq.)
  - Spatial multiplexing → concurrent directional/beam transmission
- All NR channels/signals designed for beamforming
  - Beam Switching in MAC with specific signaling
  - Supports Analog Beamforming (beam shaped after DAC)
  - Supports Digital Beamforming (beam shaped before DAC using pre-coding)



FREQUENCY RANGE 2/MMWAVE (5G)

- NR: operation at sub-6 GHz and mmWave
- Only certain numerologies
- Counter with beam-forming and joint operation of lower and higher spectra
  - Provide coverage to all users with low Frequency
  - Provide service with high data rate to many(!) users with low frequency

5GC SPECS

- 5G System:
  - TS23.501 - System Architecture for the 5G System
  - TS23.502 - Procedures for 5G System
  - TS29.500 - 5G System, Technical Realization of Service Based Architecture
  - TS29.501 - 5G System, Principles and Guidelines for Services Definition
  - TS 33.501: "Security Architecture and Procedures for 5G System".

- 5GC components
  - AMF: - TS29.518 - Access and Mobility Management Services
  - NRF: TS29.510 - Network Function Repository Services
  - SMF: TS29.502 - Session Management Services, TS29.508 - Session Management Event Exposure Service
  - UDM: TS29.503 - Unified Data Management Services
  - AUSF: TS29.509 - Authentication Server Services, PCF: TS29.507 - Access and Mobility Policy Control Service, TS29.512 - Session Management Policy Control Service, TS29.571 - Common Data Types for Service Based Interfaces

- Others:
  - TS 24.501: Non-Access-Stratum (NAS) protocol for 5G System (5GS)
  - TS 38.413: NG-RAN; NG Application Protocol (NGAP)