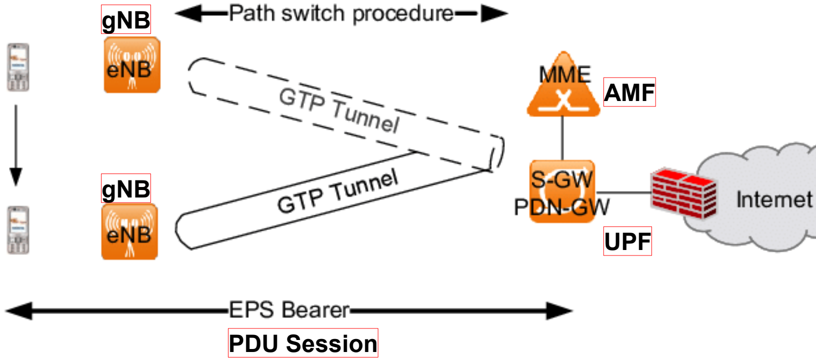
Mobility

Mobility in 5G

Support seamless and reliable end users/equipment continuous mobility (vs ‘nomadicity’) is paramount and a distinguishing characteristic of cellular networks (PLMN: *Public Land Mobile Networks*)

- Being always wirelessly best connected!

https://www.researchgate.net/figure/Handover-procedure-in-3GPP-R8-networks_fig1_224264314



Keep track of UEs’ location (to which gNB are they connected)

- Required to deliver MT (*Mobile Terminated*) messages and calls

Guarantee services continuity when moving around

- Handover mechanisms, with active sessions (*Connected Mode*)

Mobility scenarios: 5G manages mobility in both "connected" and "idle" modes

- **Connected Mode**: The device performs <u>handovers</u> to maintain its active connection
- **Idle Mode**: The device performs <u>cell selection and reselection</u> to find the best available network connection when it is not actively transmitting data (Paging may have to come into action)

Supported by the tunnelling mechanism provided by GTP (tunnel switching) with no IP change (not always!)

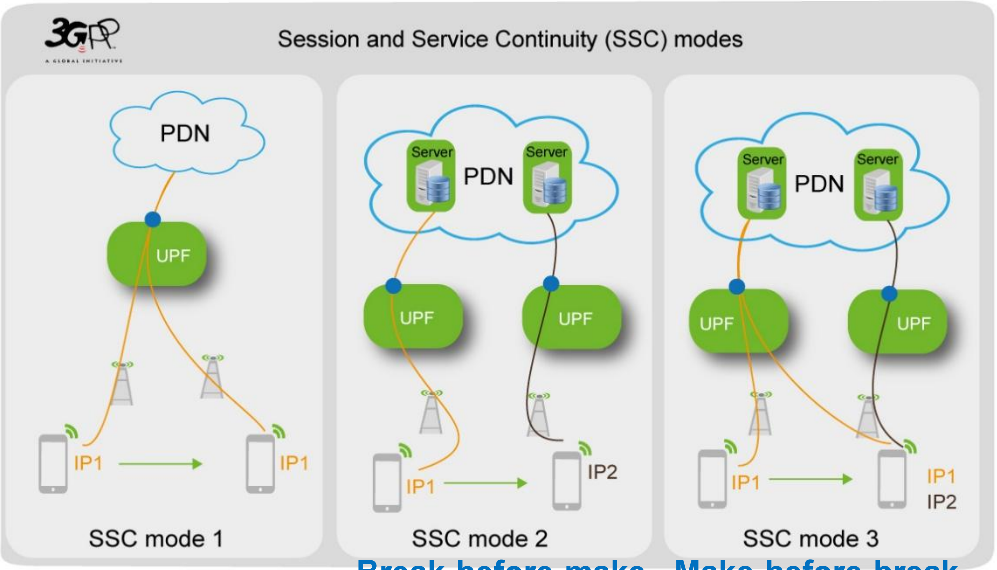
Session and Service Continuity (SSM)

5G provides three SSC modes (it is a PDU Session characteristic):

- Mode 1 for a stable connection and IP address (keeping the same UPF as PSA – *PDU Session Anchor Point*)
- Mode 2 for releasing the PDU session and IP address; a new session is established to a new PSA; IP changes
- Mode 3 for seamless, uninterrupted connectivity that allows the IP anchor to move; new PDU session is established, before releasing the existing one

These modes are designed to meet the varied requirements of different applications and services, from long-lasting, stable connections to those needing high mobility and low latency

Mode	Description	Use Case
SSC Mode 1	The network maintains a stable connection, and the IP address is preserved during mobility	Applications that require a stable, uninterrupted connection, such as online banking or streaming, where maintaining the same IP address is crucial
SSC Mode 2	The network is allowed to release the connectivity service and the PDU session	Services that are not time-sensitive and can tolerate a temporary interruption, like some IoT applications
SSC Mode 3	The network ensures no loss of connectivity by establishing a new connection before terminating the old one, even though the user plane path may change	Applications needing uninterrupted connectivity while moving, such as those that require a low-latency connection but can tolerate a brief user plane change, like in-vehicle communications or gaming

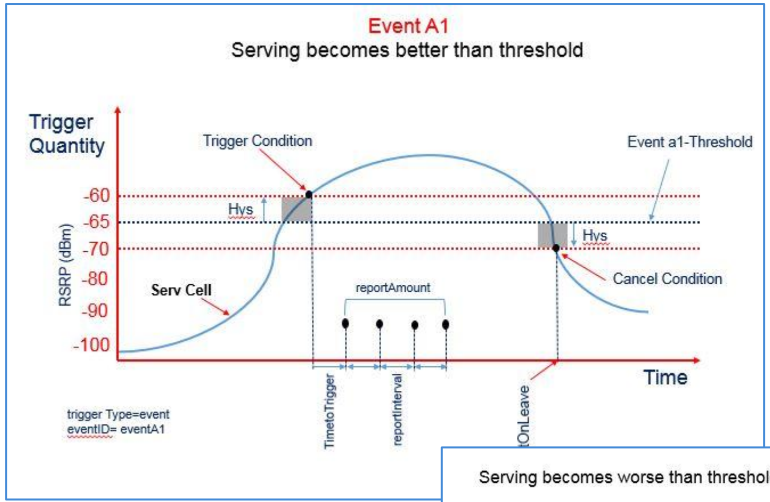


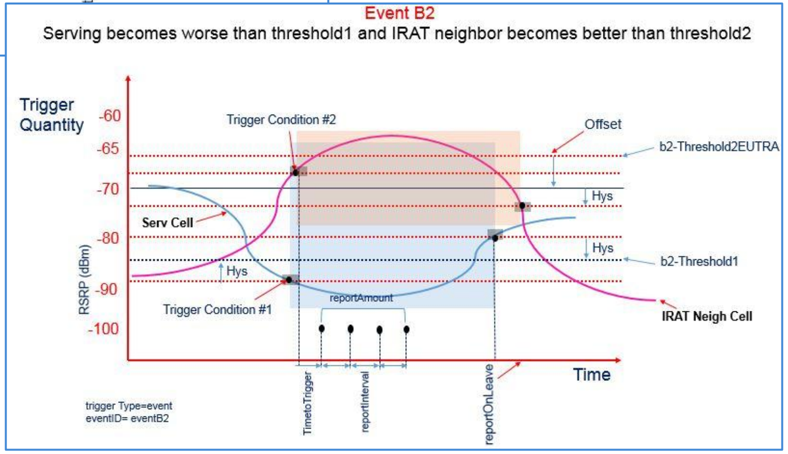
Break-before-make **Make-before-break**

SSC Mode 1 is the most common and supported by default
Edge computing requires SSM Modes 2 or 3

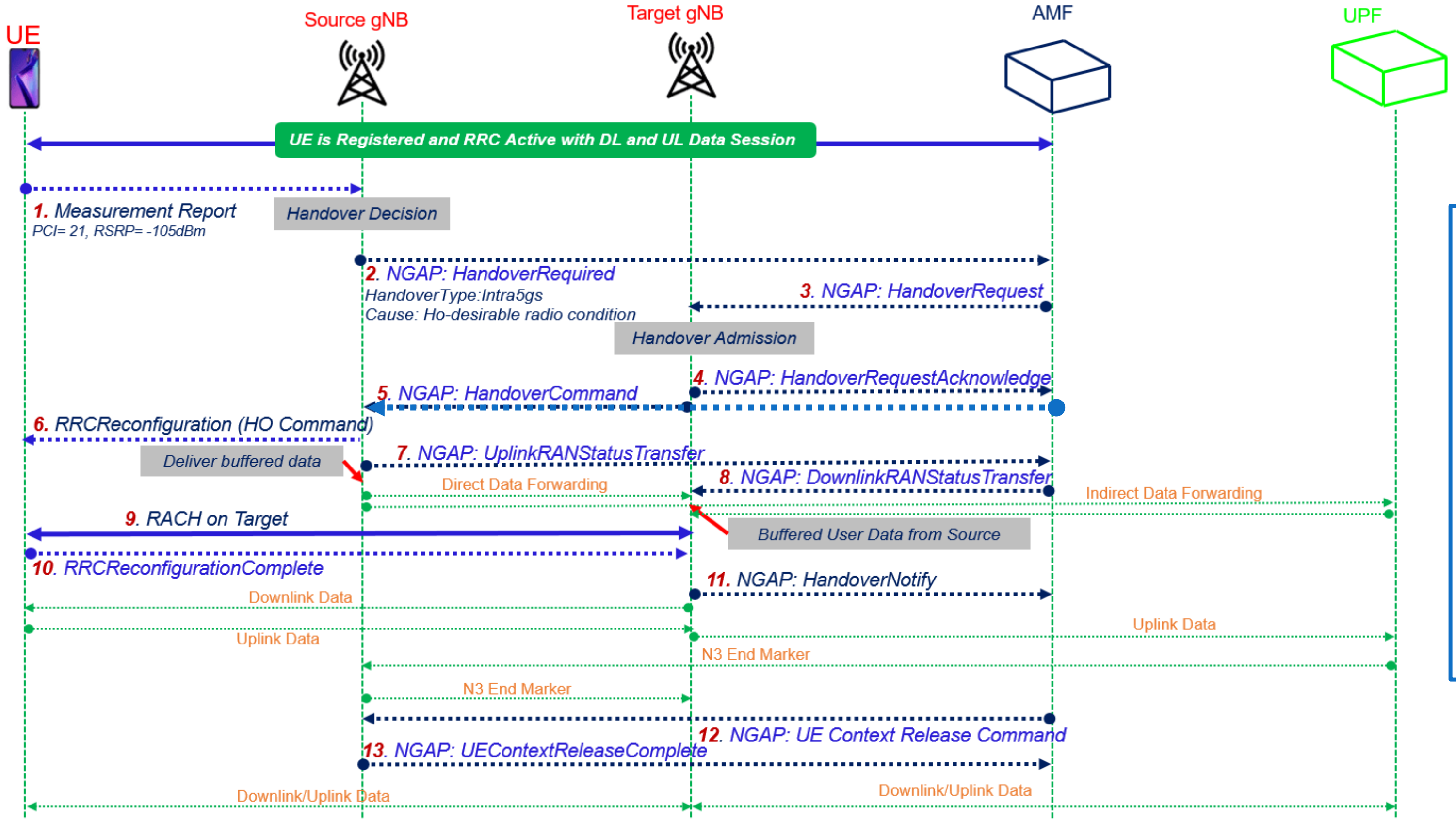
5G UE Reports

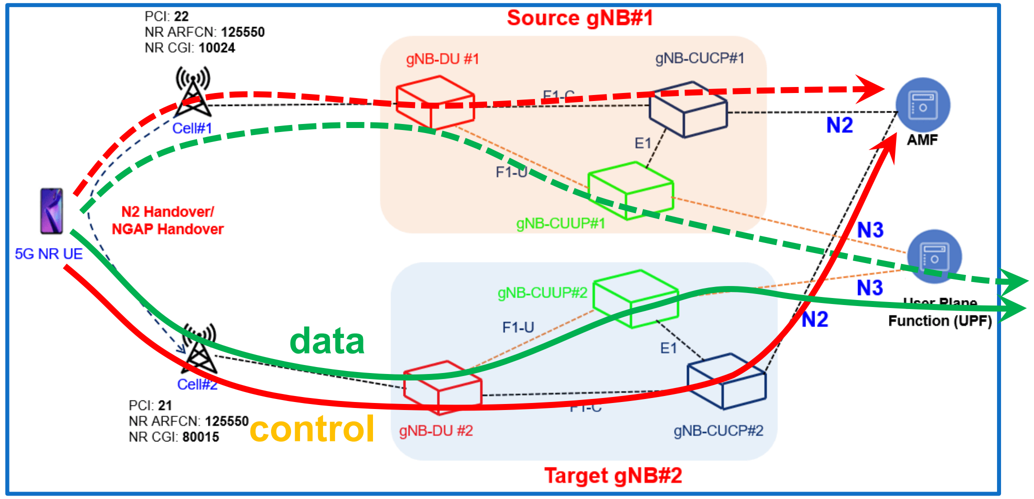
- Mobility (handover) decision is taken by base stations (in all generations!), based on measurement reports from the mobile device (UE)
- There are multiple measurement items: RSRP, RSRQ, SINR
- There are multiple reporting types (periodic, event triggered)
- Measurements include the signal quality of the serving cell and neighbor cells
- 3GPP specification 38.331 specified following events defined for 5G NR
  - Event A1 (Serving becomes better than threshold)
  - Event A2 (Serving becomes worse than threshold)
  - Event A3 (Neighbor becomes offset better than SpCell)
  - Event A4 (Neighbor becomes better than threshold)
  - Event A5 (SpCell becomes worse than threshold1 and neighbor becomes better than threshold2)
  - Event A6 (Neighbour becomes offset better than SCell)
  - Event B1 (Inter RAT neighbour becomes better than threshold)
  - Event B2 (PCell becomes worse than threshold1 and inter RAT neighbor becomes better than threshold2)





Inter gNB mobility in 5G



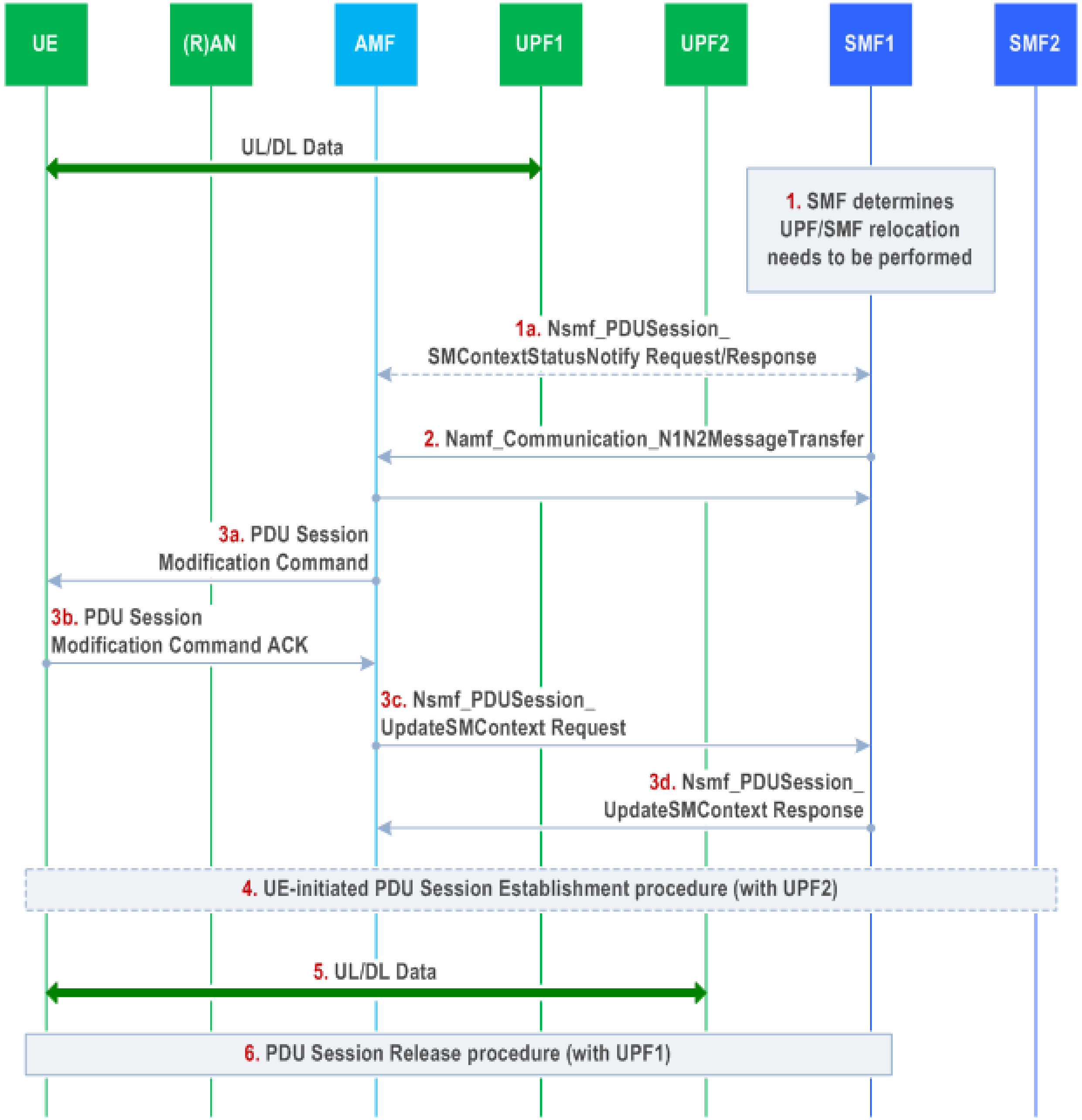


N2-based Handover (slower, relies on AMF); **SSC Mode 1**

1. **Handover Required (Source gNB → AMF)**: Triggered when the UE needs to move
2. **Handover Request (AMF → Target gNB)**: The AMF forwards the request to the new gNB
3. **Handover Request Acknowledge (Target gNB → AMF)**: The new gNB reserves resources
4. **Handover Command (AMF → Source gNB)**: The AMF sends the command to the old gNB
5. **Handover Notify (Target gNB → AMF)**: The new gNB confirms the handover completion

Same PSA (UPF) → No IP change

SSC mode 3 scenario



A new PDU Session is established to a new UPF

The UE/Apps move to the new PDU Session

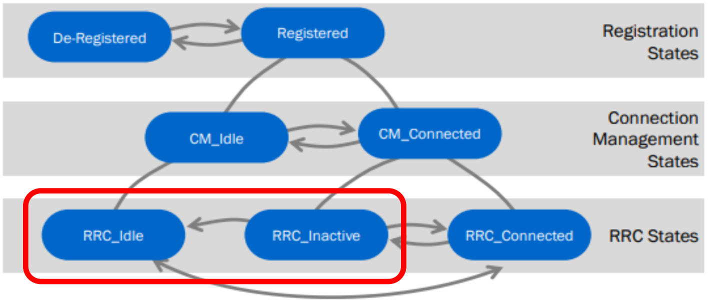
The old PDU Session is released

PSA change (UPF) → IP change!

- DNN changed

Paging

5G Paging



Paging is used to wake UEs from both RRC idle and inactive states

Mobile terminals going dormant (*RRC Idle* or *Inactive* state) in order to save energy

- Very relevant for battery powered devices as some IoT (e.g. RedCap)

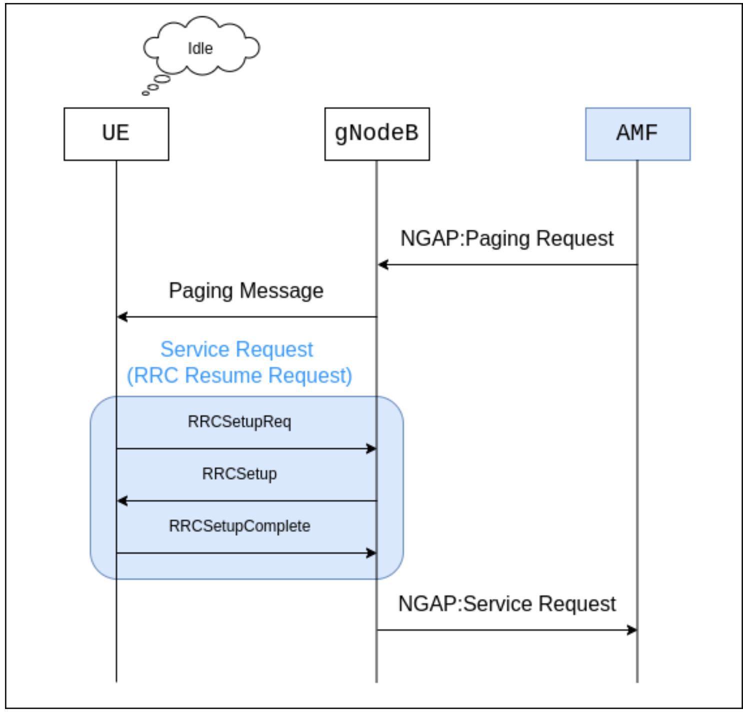
Mechanism used in mobile networks to notify a device (like a smartphone or IoT device) that the network wants to communicate with it, even if the device is in a low-power or idle state

Purpose: alert a device about incoming data (like a call, message, or app notification) when it's not actively connected to the network

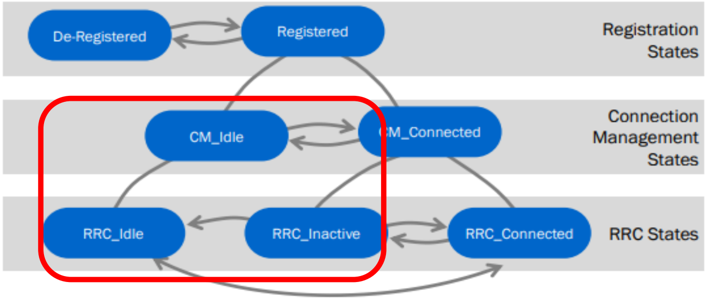
How it works: The network sends a paging message to the device's last known location (called a *Tracking Area* in 5G); if the device is still there, it responds and re-establishes a connection

Use in IoT: For massive IoT deployments, 5G uses extended paging cycles to allow devices to sleep for more time

Paging Message: NGAP message (Class 2 Procedure)



5G Paging



Core network paging (UE in CM-IDLE state)

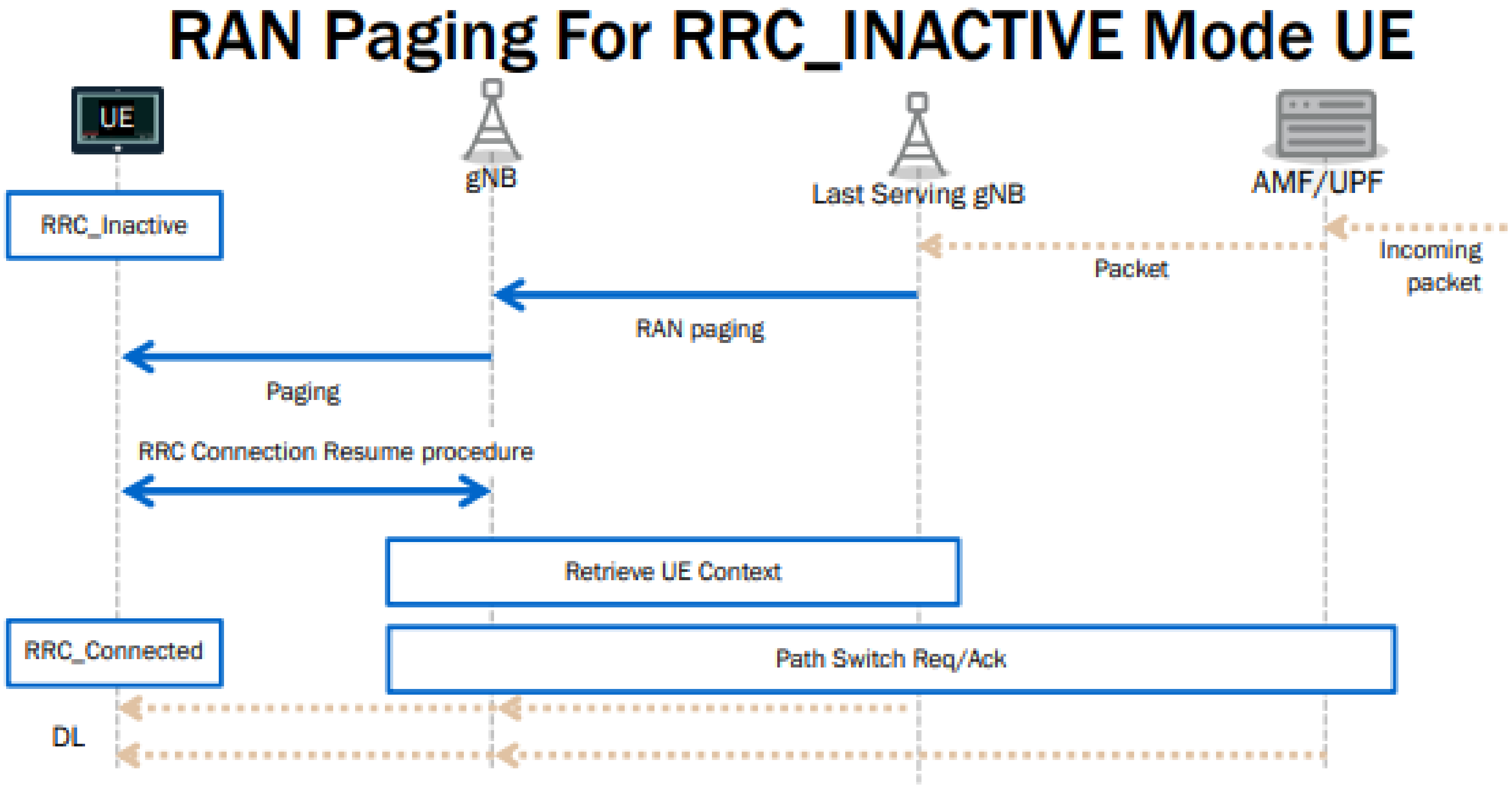
1. **Data arrival**
   - The UPF receives a downlink packet for a UE that is in the CM-IDLE state
2. **Buffering and notification**
   - The UPF buffers the packet and informs the SMF that data is pending
3. **AMF paging request**
   - The SMF requests the AMF to page the UE
   - The AMF determines the UE's location and sends a paging request to the gNB in the corresponding Tracking Area
4. **Paging occasion**
   - The gNB calculates the specific time and channel (*Paging Occasion*) for the UE to listen and sends the Paging message
5. **UE response**
   - The UE monitors for paging messages at its scheduled PO
   - When it receives the paging message, it sends an RRC resume request back to the gNB
6. **Connection establishment**
   - The gNB establishes a connection with the UE, fetches its context from the last serving gNB, and the UE enters the RRC_CONNECTED state
7. **Data forwarding**
   - The gNB updates the AMF to change the downlink path, allowing the data to be forwarded from the UPF to the UE.

RAN-based paging (UE in RRC_INACTIVE state)

1. **Data arrival**
   - A UPF receives a downlink packet for a UE in RRC_INACTIVE state
2. **RAN paging**
   - The last serving gNB initiates a RAN-based paging procedure within the area of the UE's last known location, called the RNA (*Registration Area*)
3. **Paging broadcast**
   - The gNB sends a RAN paging message to other gNBs in the RNA, which then broadcast an RRC Paging message to the UE
4. **UE response**
   - The UE receives the paging message and sends an RRC resume request to the gNB
5. **Connection and context**
   - The gNB resumes the UE's context and establishes a connection, moving the UE to RRC_CONNECTED state.

Paging Occasion (PO): A specific, pre-calculated time window when the UE wakes up to listen for the paging message, based on its identifier. This allows the UE to conserve battery by sleeping most of the time

5G Paging

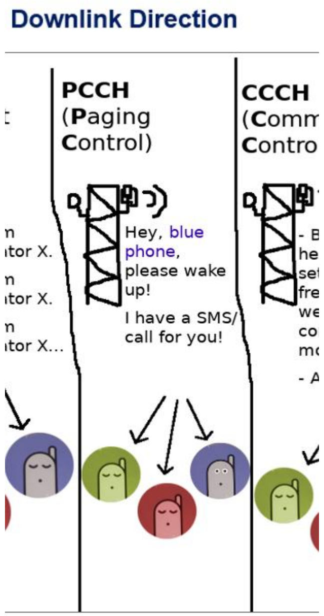


Logical channel

- **Paging Control Channel** (PCCH): Page the UEs whose location at cell level is not known to the network

Transport channel

- **Paging Channel** (PCH): This channel is used for transmission of paging information from the PCCH logical channel. The PCH supports discontinuous reception (DRX) to allow the device to save battery power by waking up to receive the PCH only at predefined time instants.



Roaming

Roaming

5G (NR) roaming refers to **a terminal (UE) that moves from its *Home Public Land Mobile Network* (HPLMN) to a *Visited PLMN* (VPLMN)** and continues accessing 5G services through the VPLMN

Ensures subscribers can **seamlessly access calls, messaging, and mobile data across different networks or countries** (restrictions may apply)

Normally roaming is a paid service

Requires agreements between MNOs

National vs International Roaming

- **National**: When a mobile user's device connects to a different network within the same country, typically to access service where their home network has no coverage or is unavailable (e.g. failure)
- **International**: the UE moves to another country where its HPLMN is not available

Roaming procedure

1. UE Registration in the Visited PLMN (VPLMN)

- When the UE powers on in a roaming area, it scans for available PLMNs and selects the VPLMN based on roaming agreements (information stored in the UICC)
- Then, the UE sends a registration request to the V-AMF (*Access and Mobility Function* in VPLMN), which checks the PLMN ID (MCC+MNC) and detects that the UE is roaming

2. Authentication and Security Procedures

- Since the UE is unfamiliar with the VPLMN, authentication must happen through the HPLMN
- V-AMF contacts the AUSF in the HPLMN through **SEPP** (*Security Edge Protection Proxy*), which ensures secure inter-PLMN signaling
- The AUSF verifies the UE's credentials, and if successful, V-AMF will proceed with security procedures

3. SMF Selection

- Once authentication is complete, the UE needs a PDU session to access the data
- The UE sends a PDU session establishment request to V-AMF, and it selects available SMFs based on the requested DNN and routing approach
  - In 5G roaming, there are two ways of routing user data: *Home-Routed* (HR) and *Local Breakout* (LBO)
- They determine how a UE's traffic is forwarded when it connects to a visited network (VPLMN)

Roaming: SEPP

SEPP: ***Security Edge Protection Proxy***

- 5G core network function acting as a secure gateway at the edge of a 5G *Public Land Mobile Network* (PLMN) to protect signaling messages exchanged with other mobile network operators, especially during 5G roaming
- Provides end-to-end confidentiality and integrity for these control plane messages, ensuring secure communication between networks by implementing features like message filtering, topology hiding, and protection against *denial-of-service* (DoS) attacks

Data path: *Home Routed* vs *Local Breakout* scenarios

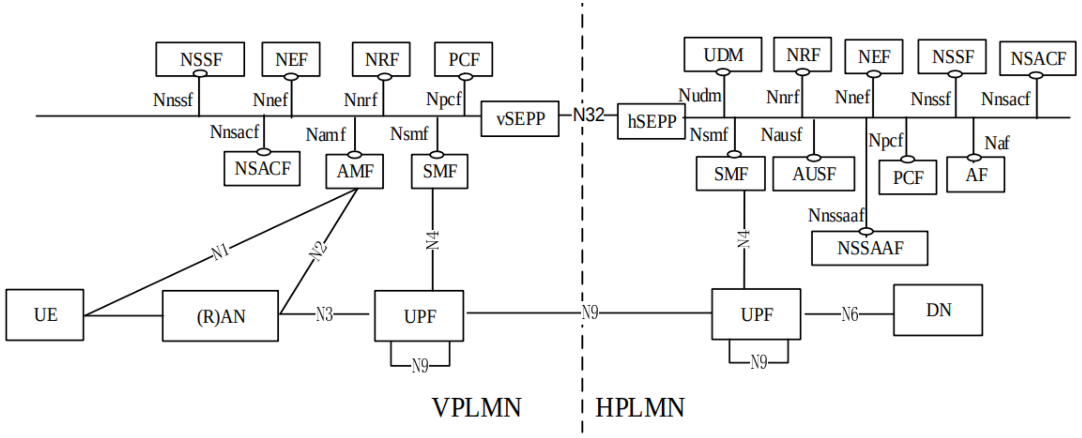


Figure 4.2.4-3: Roaming 5G System architecture - home routed scenario in service-based interface representation

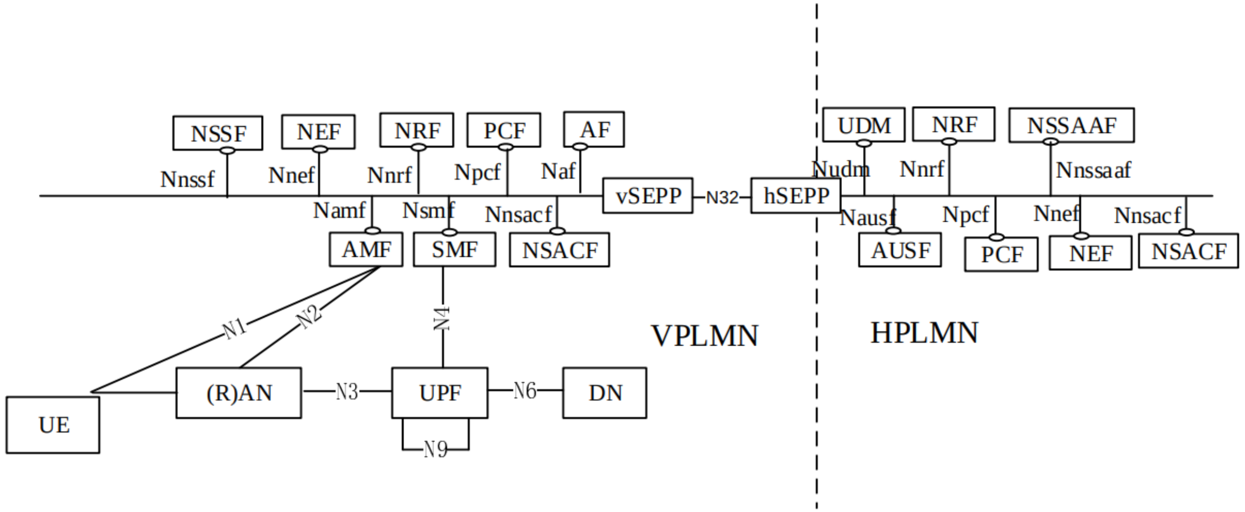


Figure 4.2.4-1: Roaming 5G System architecture- local breakout scenario in service-based interface representation

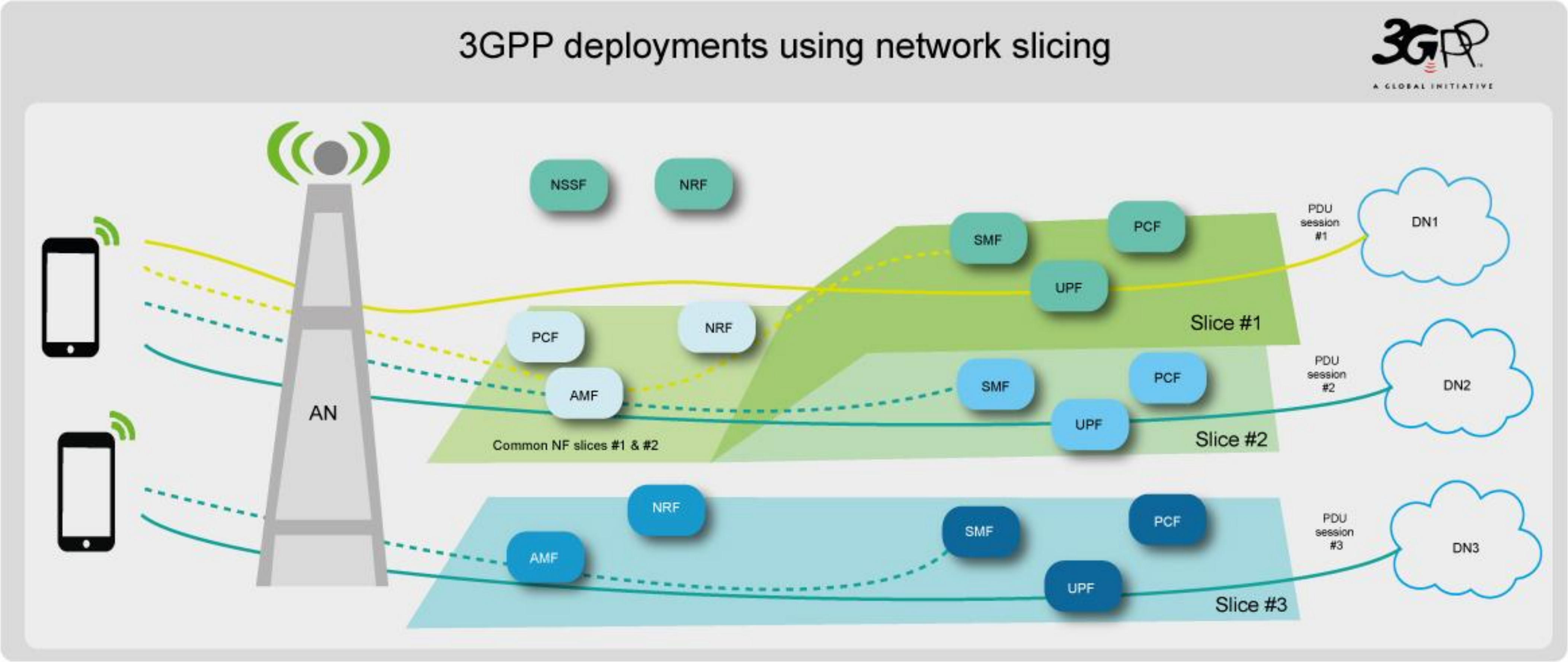
Services are accessed via the home network

Services are accessed locally

Slicing

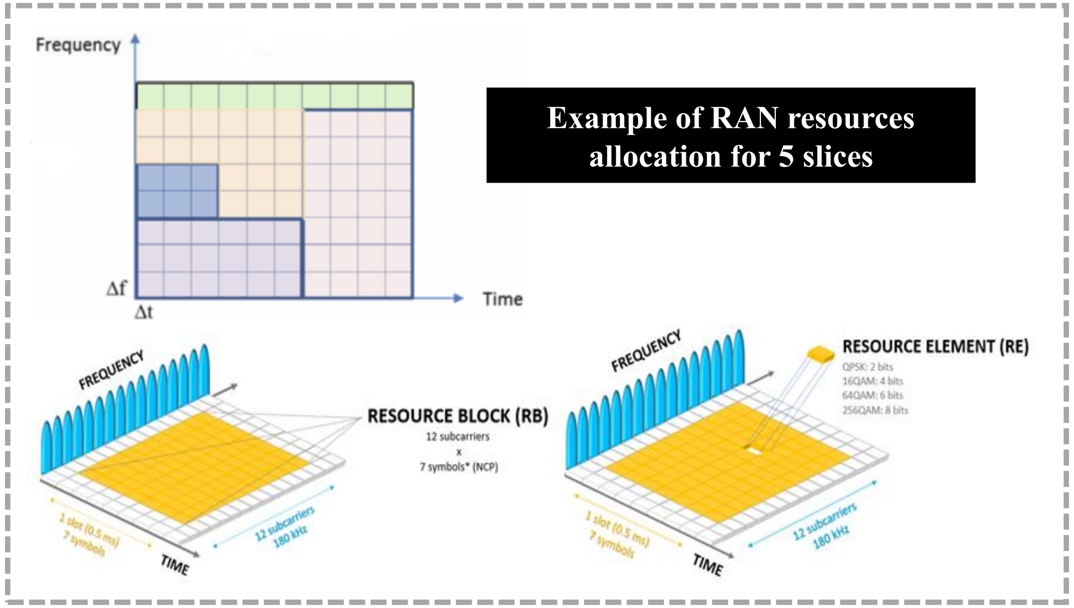
5G Slicing

Network Slice definition (TR 23.799): ***complete logical network (providing Telecommunication Services and Network Capabilities) including AN and CN***

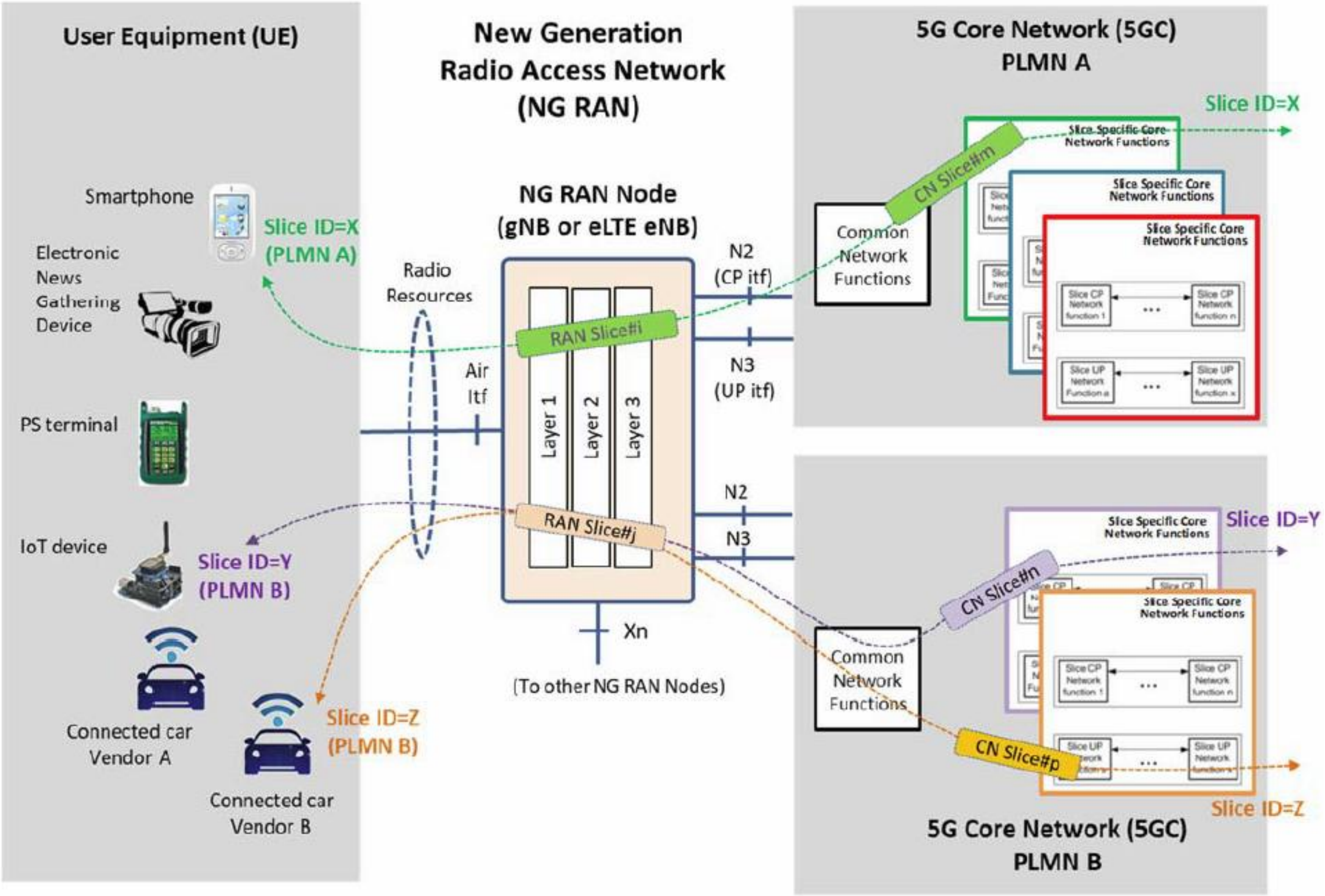


5G Slicing

- Slicing enables the creation of distinct logical networks
  - Of the same type (different businesses)
  - Providing differentiated behaviour (different services)
- 5G supports end-to-end slicing (radio and core)
  - Resources isolation between services
  - Customized functions and/or capacities, according to SLA
- Each terminal (UE) may connect simultaneously to max 8 slices (no limit for the number of slices in the core)
- Takes benefit of NVF for easy slices creation and management (LCM – *Lyfe Cycle Management*)



MORAN



5G Americas, *NetWork Slicing for 5G networks & services*, Nov/16
On 5G Radio Access Network Slicing: Radio Interface Protocol Features and Configuration, R. Ferrús

5G Slicing: S-NSSAI

Network Slice (S-NSSAI)

- Network slicing in 5G allows one physical network to be split into multiple virtual network slices, each optimized for particular service types or customers
- Each slice is identified by S-NSSAI (*Single Network Slice Selection Assistance Information*), which is included in the PDU session request alongside the DNN
- A PDU Session is always associated with a specific slice (S-NSSAI) and DNN combination

Identified by SST/SD:

- SST (*Slice/Service Type*): Specifies the type of service the slice is optimized for
- SD (*Slice Differentiator*): An optional field used to further distinguish slices with the same SST

3GPP Standardised Slice/Service Type (SST) Values

SST	3GPP Release	Slice/Service Type	Characteristics
1	Rel-15	eMBB (Enhanced Mobile Broadband)	Slice suitable for the handling of 5G enhanced Mobile Broadband.
2	Rel-15	URLLC (Ultra Reliable and Low Latency Communications)	Slice suitable for the handling of ultra- reliable low latency communications.
3	Rel-15	MIoT (Massive Internet of Things)	Slice suitable for the handling of massive IoT.
4	Rel-16	V2X (Vehicle to Everything)	Slice suitable for the handling of V2X services.
5	Rel-17	HMTC (High-Performance Machine-Type Communications)	Slice suitable for the handling of High-Performance Machine-Type Communications.
6	Rel-18	HDLLC (High Data rate and Low Latency Communications)	Slice suitable for the handling of High Data rate and Low Latency Communications.
7	Rel-19	GBRSS (Guaranteed Bit Rate Streaming Service)	Slice suitable for the handling of Guaranteed Bit Rate Streaming Service.

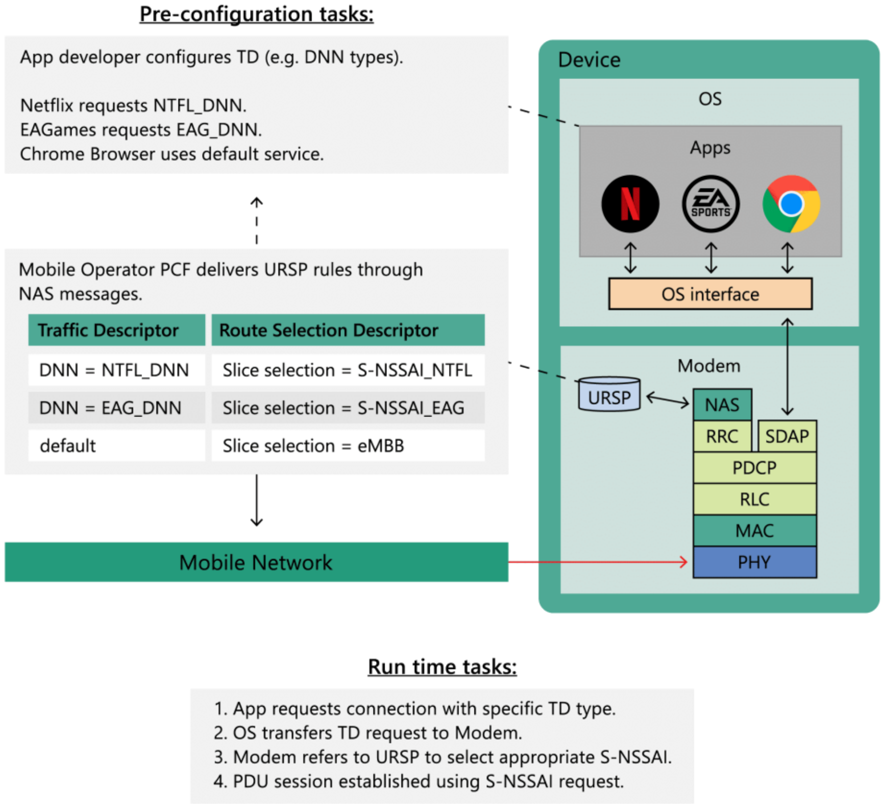
Based on: ***3GPP TS 23.501 V19.4.0 (2025-06)***

URSP (*UE Route Selection Policy*)

Influences how a 5G UE selects the DNN (*Data Network Name*) when establishing new PDU sessions or routing application traffic
Allows devices to automatically use specific network slices based on application or traffic type

Mechanism of URSP for DNN Selection

- **Rule-Based Selection:**
  URSP supplies (via PCF or ANDSF) the UE with a set of operator-defined rules, each including match criteria such as application ID, FQDN, or traffic descriptors. The rules can specify one or more DNNs as part of a Route Selection Descriptor.
- **Application-Level Routing:**
  When an app or a system process requests a network connection, the UE matches the app's characteristics against its URSP rules. If a rule matches, the DNN(s) specified in the rule take precedence over the DNN requested by the app or upper layers.
- **Dynamic PDU Session Routing:**
  The UE may select an existing PDU session (if it matches the DNN and S-NSSAI in the policy) or trigger establishment of a new PDU session with the policy-indicated DNN, ensuring traffic for high-priority or specific use cases (like enterprise, IMS, or edge compute) is routed to the correct data network.
- **Policy-Controlled Flexibility:**
  If no URSP rule matches, or if the rule doesn't specify a DNN, the UE defaults to the DNN originally requested by the application or the default DNN configured for the slice.
- **DNN Replacement:**
  URSP can enforce DNN replacement for specific traffic types, ensuring apps transparently connect to operator-preferred or optimized networks without explicit user action.



https://www.redeweb.com/en/Articles/device-tests-for-fragmentation-or-slicing-of-the-5g-network/

Network sharing

Network sharing

When two or more MNO share parts of their infra-structure, as a way of:

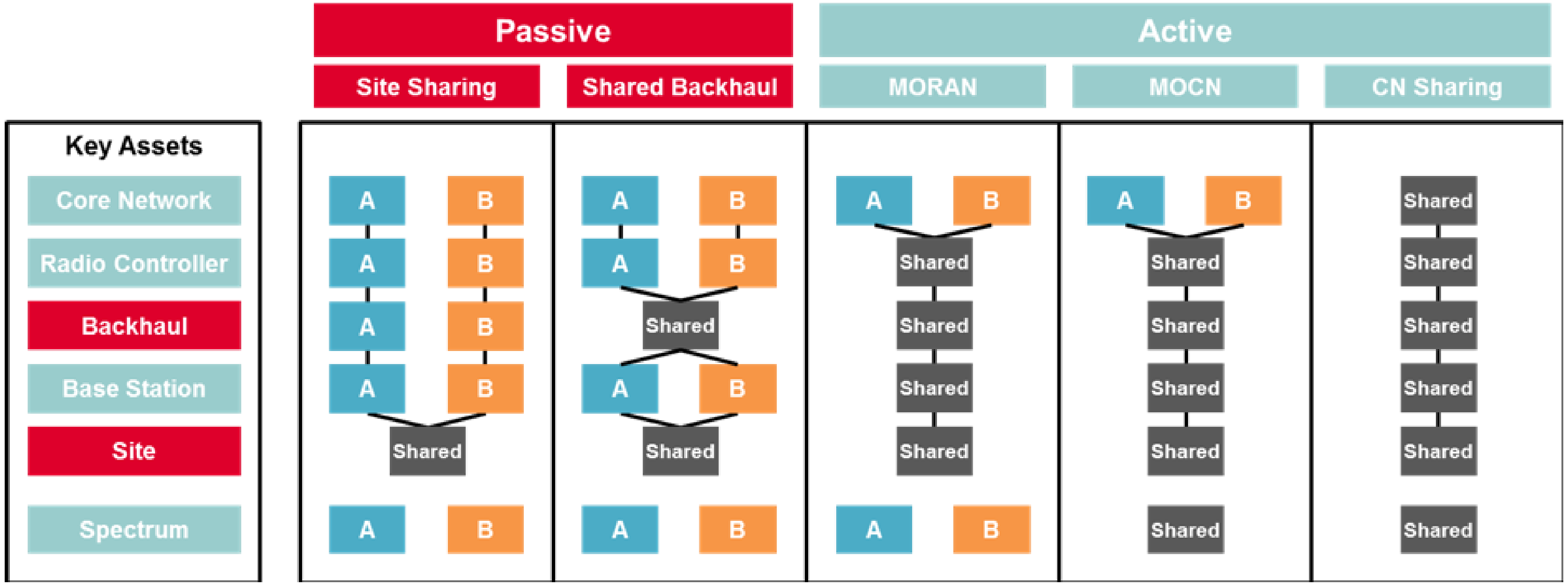
- Reduce costs (CapEx and OpEx)
- Accelerate network deployment
- Densify the network or expand coverage
- Difficulties in acquiring sites for access network
- other

Most common shared resources:

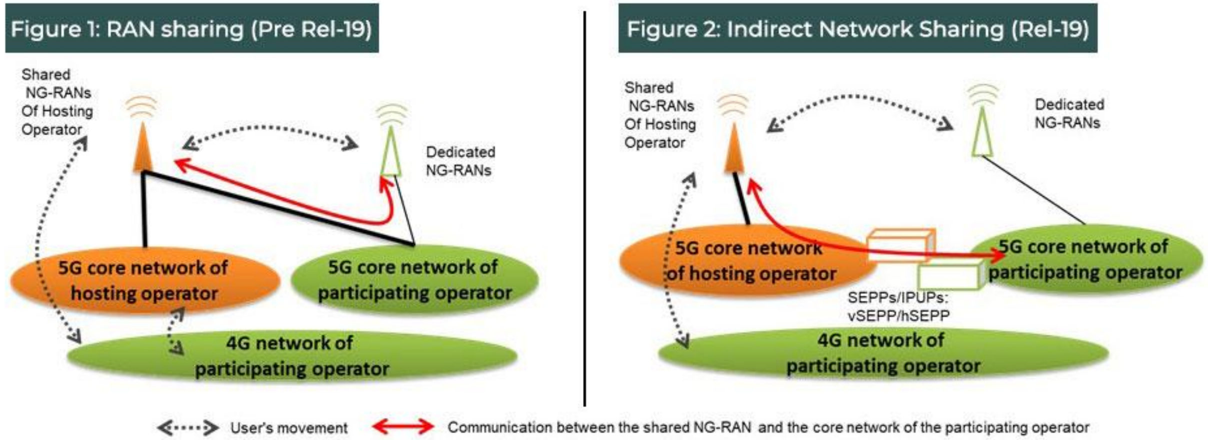
- **Sites and towers**: The physical locations and towers are shared, which is also known as "passive sharing"
- **Base stations**: Operators can share the active equipment like the baseband and radio, or "active sharing"
- **Spectrum**: In some cases, operators can share spectrum licenses

Passive/Active sharing

https://www.gsma.com/solutions-and-impact/technologies/networks/gsma_resources/infrastructure-sharing-an-overview/



Indirect network sharing has recently emerged



Most common:

- Site sharing (space, energy supply, AC, …)
- **MORAN (*Multi Operator RAN*)**
- **MOCN (*Multi Operator Core Network*)**

MOCN (*Multi-Operator Core Network*)

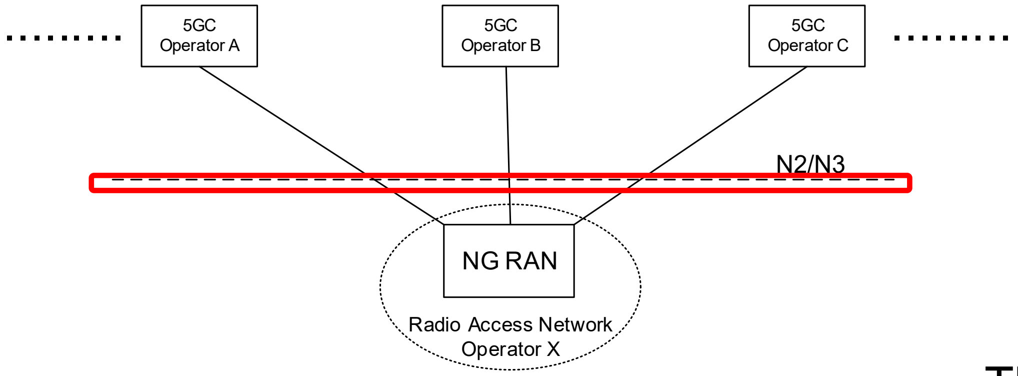
- **Sharing**: Multiple operators share the physical RAN equipment and the same frequency spectrum
- **Spectrum**: The radio frequencies are shared and pooled by the operators
- **Core Network**: Each operator has its own independent core network

MORAN (*Multi-Operator RAN*)

- **Sharing**: Multiple operators share the physical RAN equipment, including base stations, towers, and antennas
- **Spectrum**: Each operator maintains its own, independent frequency spectrum
- **Core Network**: Each operator has its own independent core network

Network sharing

5G Multi-Operator Core Network ('Legacy')

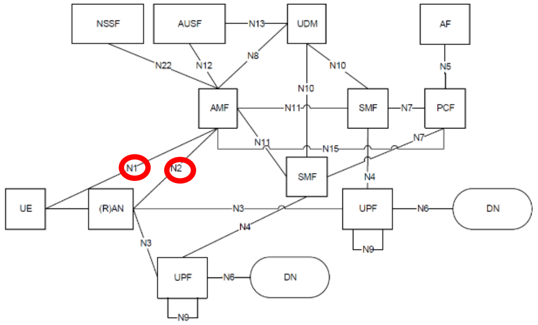


Only the RAN is shared amongst several operators owning their own CN

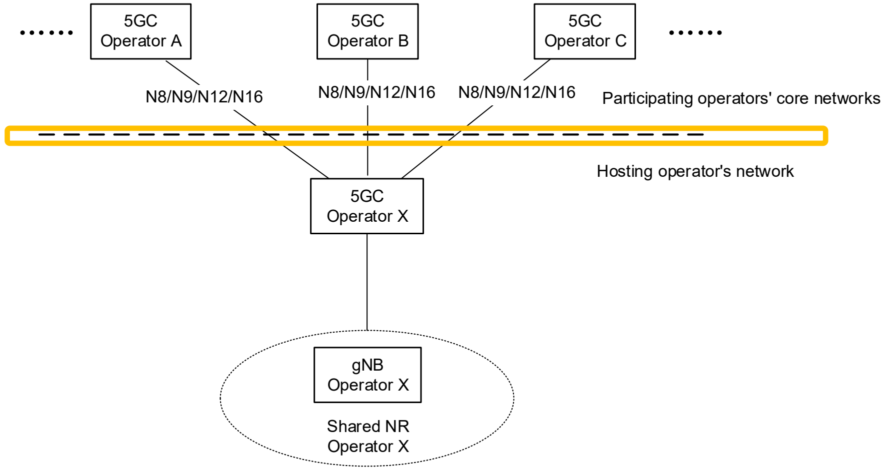
Each shared gNB (CU) must have connections to each CN

N2: (R)AN and the AMF

N3: (R)AN and the UPF



Indirect network sharing (Rel-20)



The communication between the shared NG-RAN and the participating parties' core network happens via a number of inter-network interfaces that are independent of the actual number of base stations at the shared NG-RAN

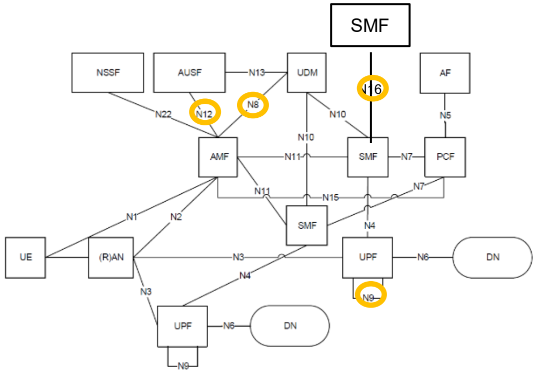
- 'Donor' provides: RAN, AMF, SMF, UPF
- Others have: AUSF, PCF, NSSF, UDM, UDR, …

N8: UDM and the AMF

N9: two UPFs

N12: AMF and AUSF

N16: two SMFs (roaming, visited/home)



Private 5G
Non-Public Networks (NPN)

Non Public (NPN)*/Private 5G Networks* definition

"Intended for the sole use of a private entity such as an enterprise, may be deployed in a variety of configurations, utilizing both virtual and physical elements.

3GPP, TS 23.501

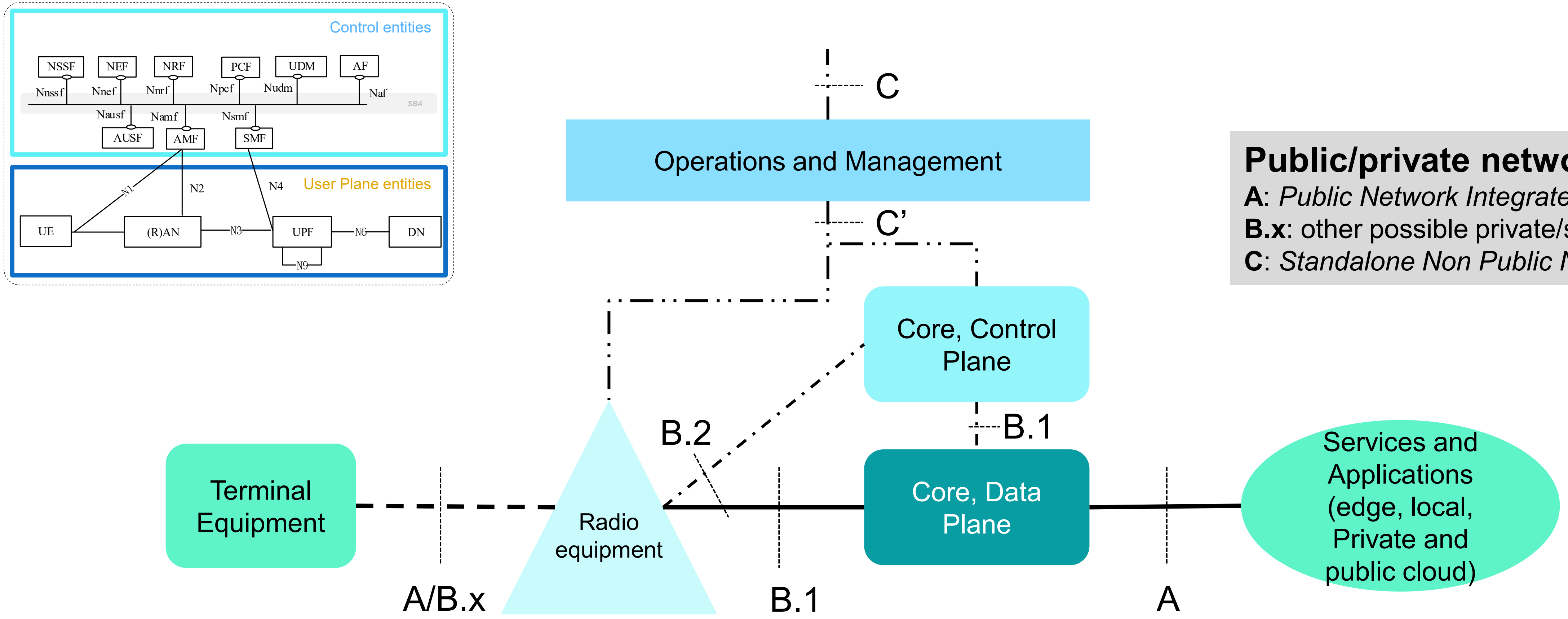
- Specifically, they may be deployed as:
  - **completely standalone** networks (***Standalone NPN***)
  - be **hosted by a Public** Land Mobile Network (PLMN) or
  - offered **as a slice** of a PLMN (***Public Network Integrated NPN*/PNI-NPN**)"

New business opportunities, fostered by the new industrial application scenarios made possible by 5G (e.g. based on URLLC and mMTC)

Why private 5G networks

- Designed and operated aligned with specific requirements:
  - Specific functionalities
  - Specific geographic reach/presence at key locations
  - Appropriate redundancy levels (e.g. radio coverage, backhaul network, powering)
  - Performance level suited to specific requirements (e.g. higher priority to low latency services)
  - Integration of pre-existing services and/or vertical-specific solutions
  - Data privacy and sovereignty
  - Complete control over security aspects
  - Control over growth and functional evolution

Separation interfaces between public/private components



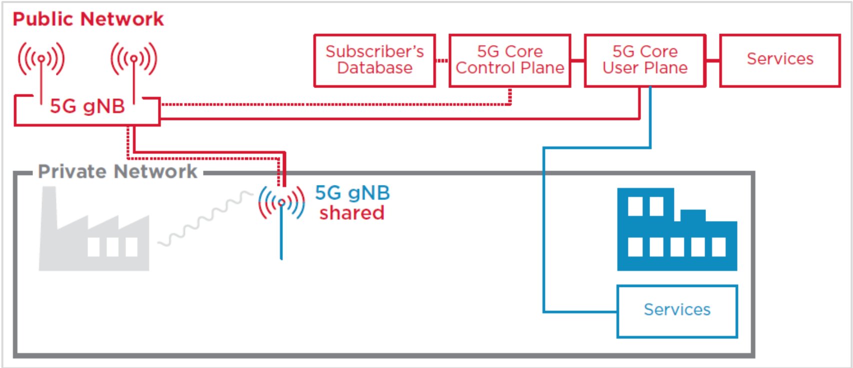
Public/private network scenarios:

A: *Public Network Integrated NPN* (PNI-NPN)

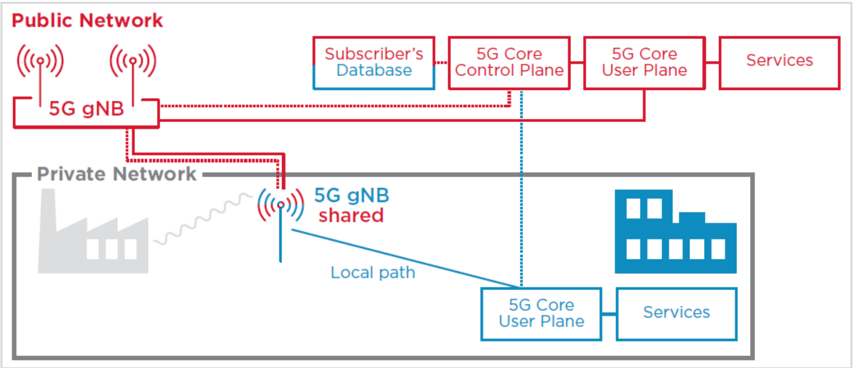
B.x: other possible private/shared split points

C: *Standalone Non Public Network* (SNPN)

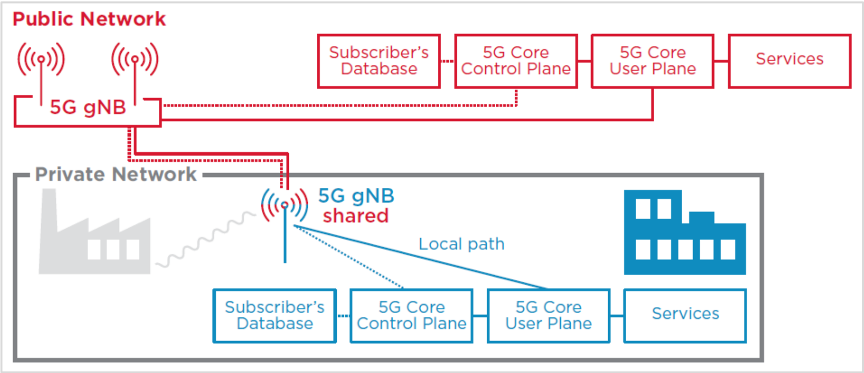
NPN evolution path (a scenario)



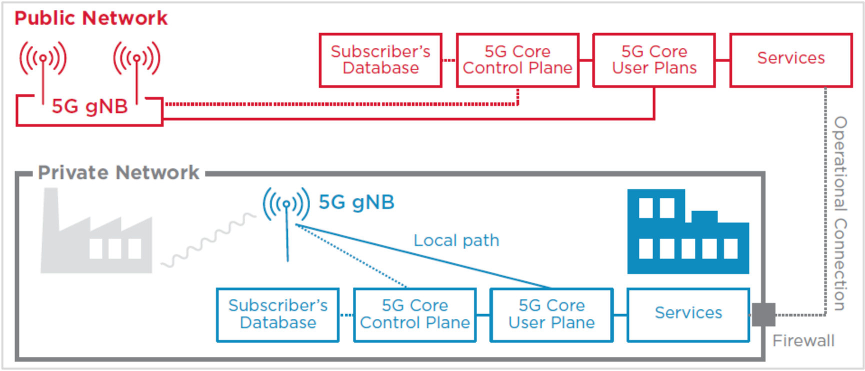
A: **Shared operator RAN (PNI-NPN)**



B.1: Shared RAN; local data



B.2: Shared RAN; dedicated control and data



C: **Autonomous network (SNPN)**

SNPN vs PNI-NPN

***Standalone NPN* (SNPN)**	***Public Network Integrated NPN* (PNI-NPN)**
• Complete control over topology, resources, functionalities, redundancies, and their evolution • Total sovereignty over information • Improved performance, preferably in some areas (e.g., reduced latency or higher upstream bandwidth) • Functional flexibility • Specific coverage or micro-coverages are possible	• Faster deployment and lower costs • Off-site operation, also with lower costs • Broad geographic coverage and easy to change • Roaming

SNPN is the most suitable solution for scenarios where strict control, security and isolation are needed over the control planes and the 5G data and/or the necessary 5G connectivity must have features that cannot be achieved with a non-public network supported by PLMN (PNI-NPN)

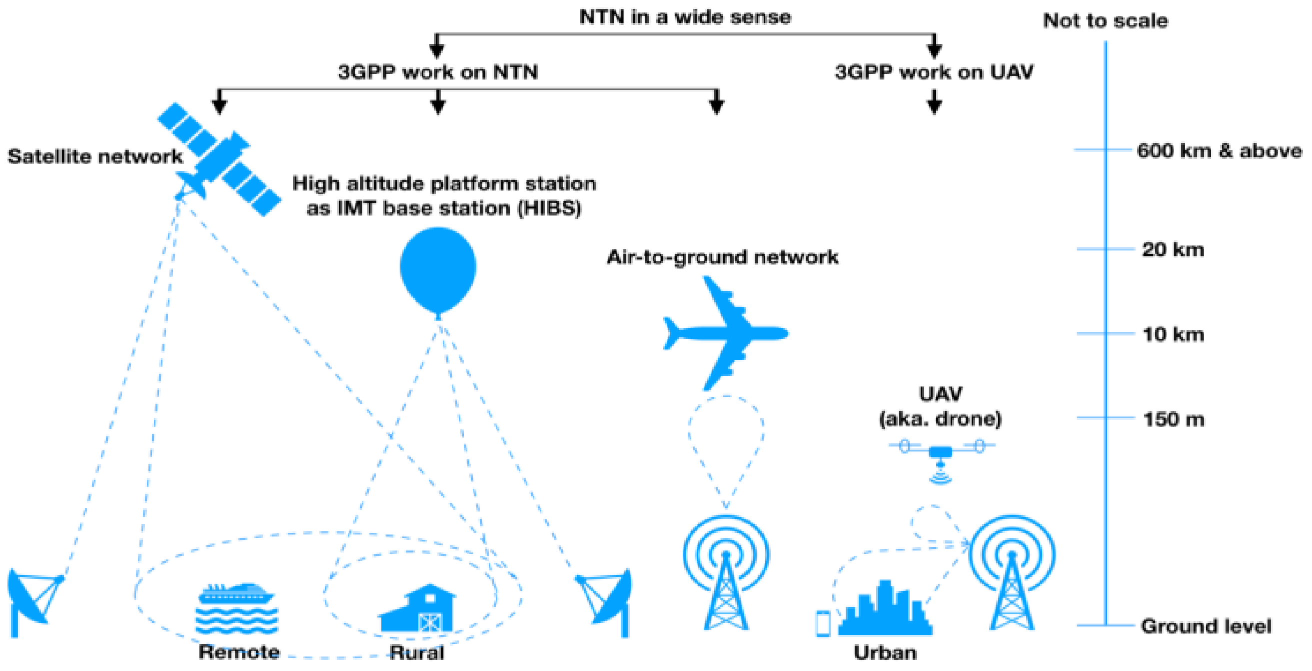
Being supported by public infrastructures (MNOs), PNI-NPNs are suitable and an alternative to SNPN, for example, in an early stage of implementation, reducing investment (requiring only OpEx, no CapEx), with the advantage of global presence and connectivity

***Non Terrestrial Networks* (NTN)**

5G NTN (*Non-Terrestrial Networks*)

5G NTN refers to using satellites, and other airborne platforms, to extend 5G mobile coverage beyond traditional ground-based cellular towers

- **Satellites**: In various orbits, including Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Orbit (GEO)
- **High-Altitude Platform Stations** (HAPS): Such as drones, balloons, and aircraft operating at altitudes between 17km to 22km



5G NTN (*Non-Terrestrial Networks*)

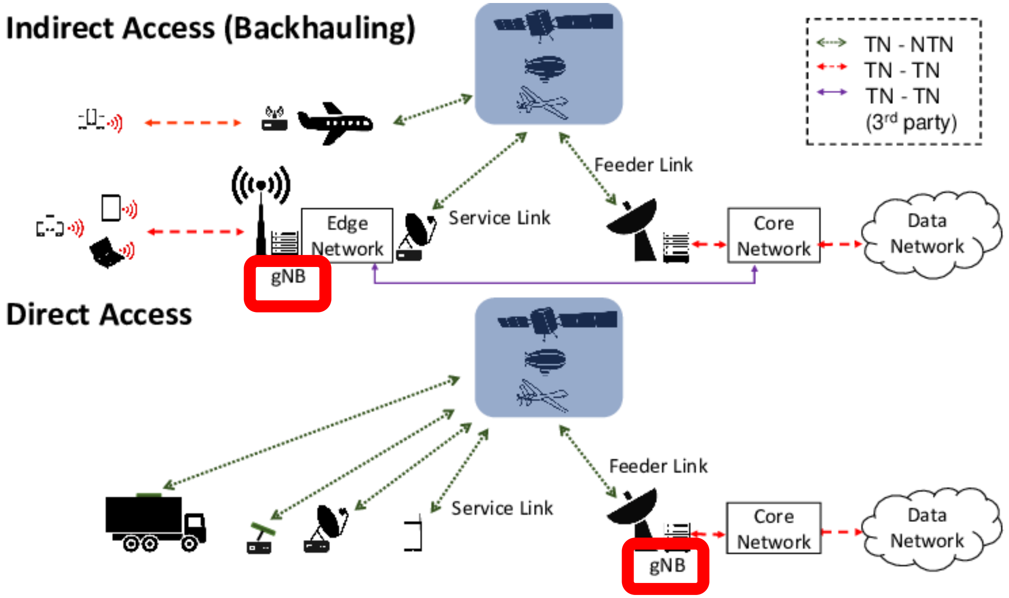
Advantages:

- Coverage expansion
- Enhanced network resilience and reliability
  - Public Protection and Disaster Recovery (PPDR)
- New applications and use cases
  - Global IoT and asset tracking
  - Maritime and aviation connectivity
- Cost-effectiveness in specific scenarios

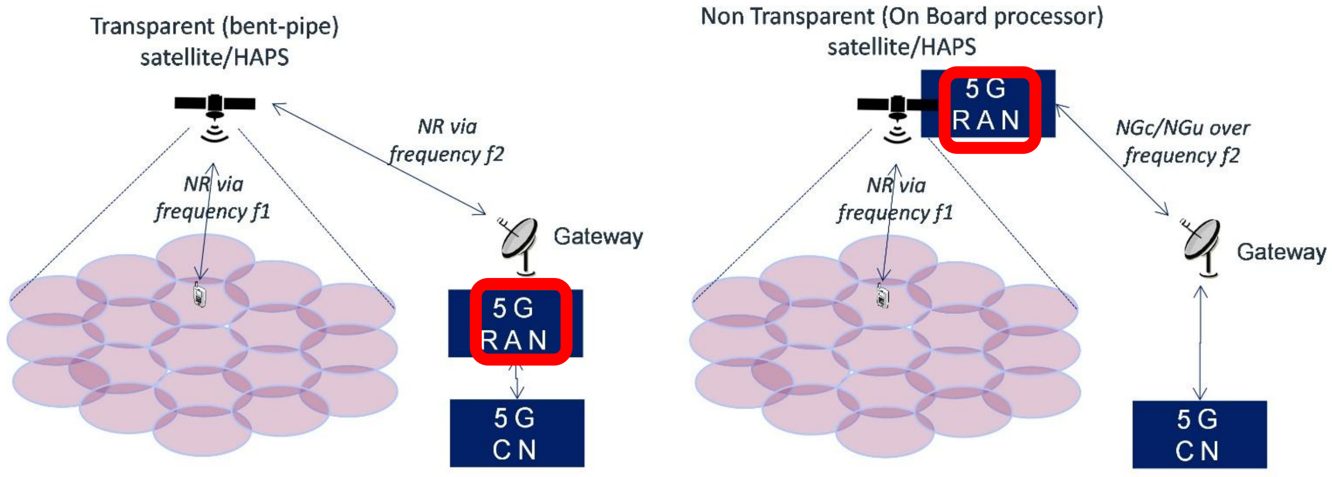
Challenges:

- Signal propagation delay (Latency)
- Large and rapid Doppler shifts
- Handover management between satellites
- Signal attenuation and interference
- Network Synchronization
- Cost and Infrastructure

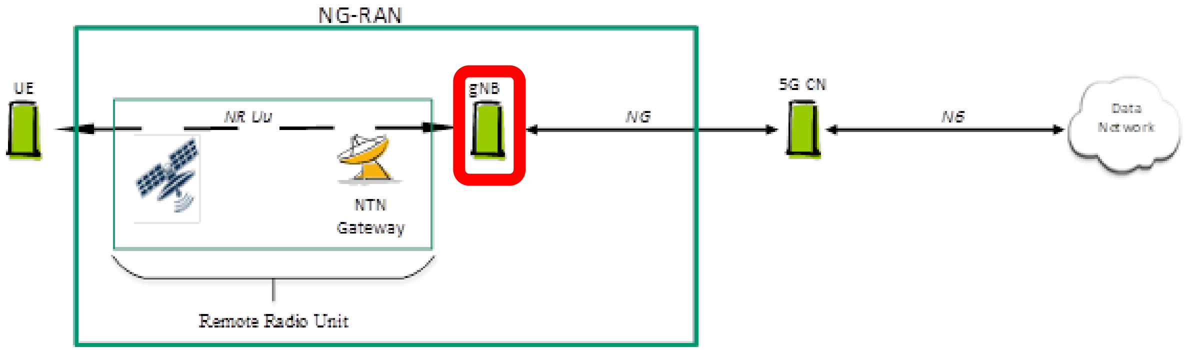
Scenarios: Direct vs Indirect access

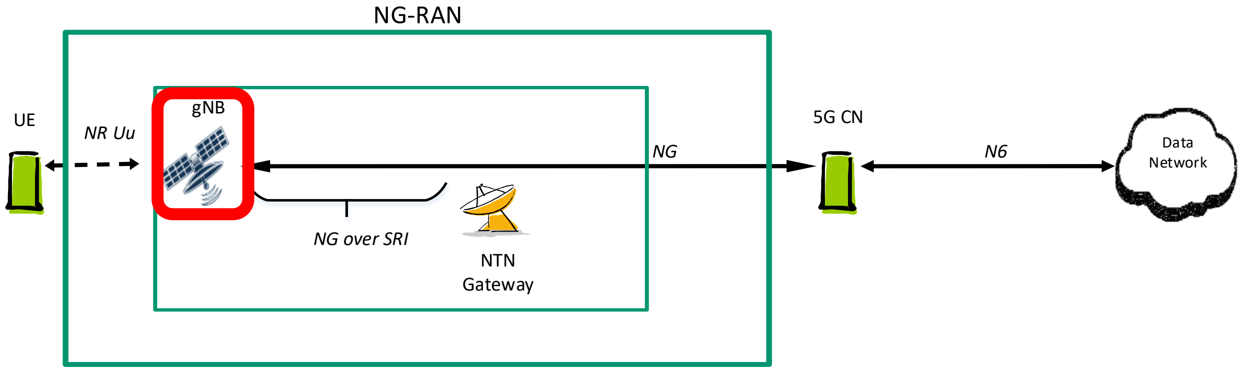


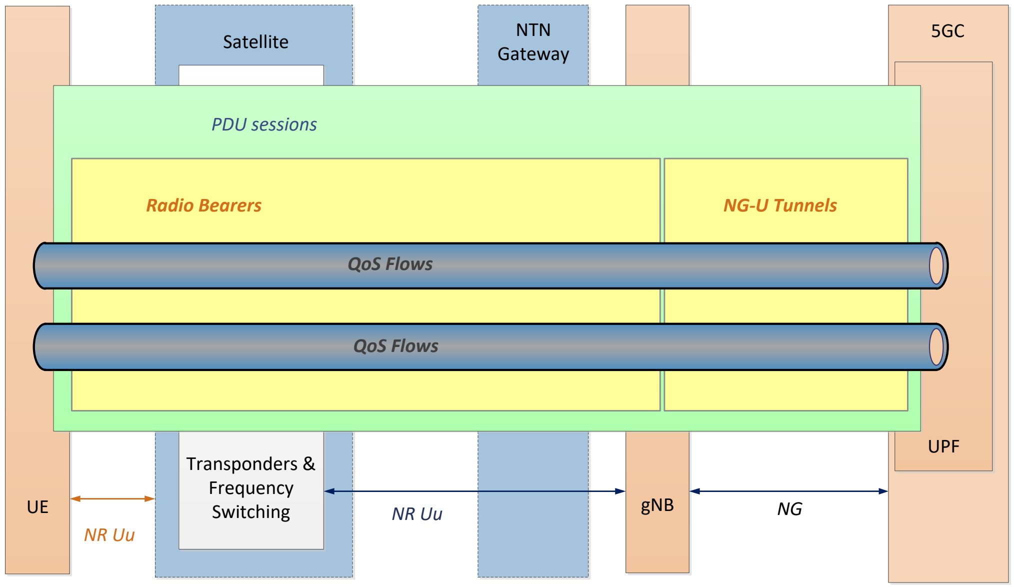
Scenarios: Transparent vs regenerative

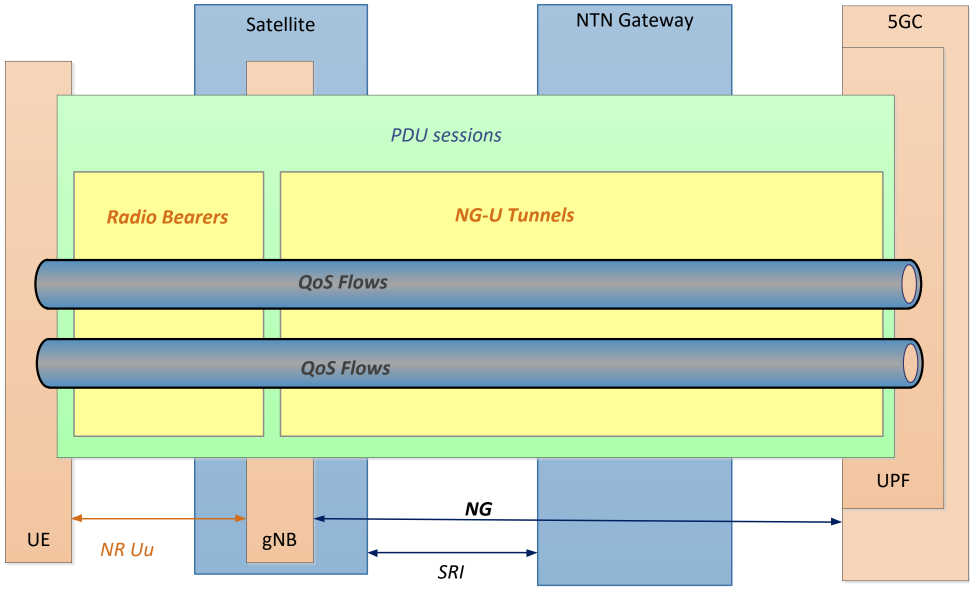


NTN Transparent vs Regenarative: QoS Flows



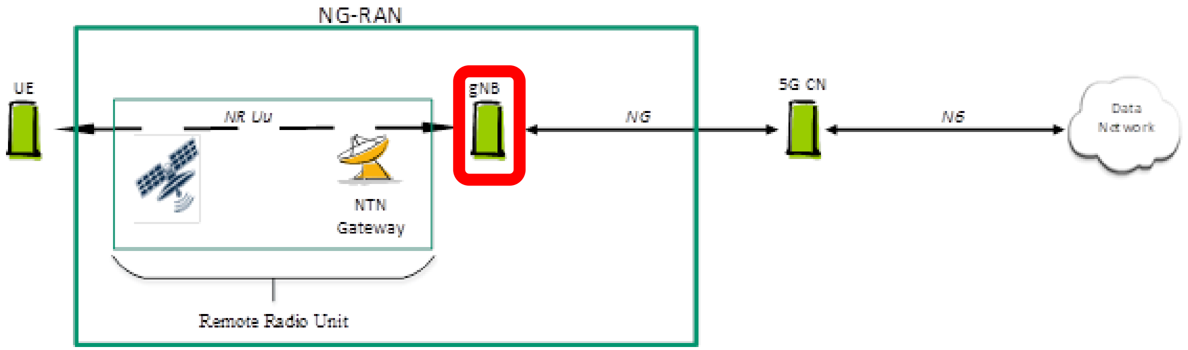


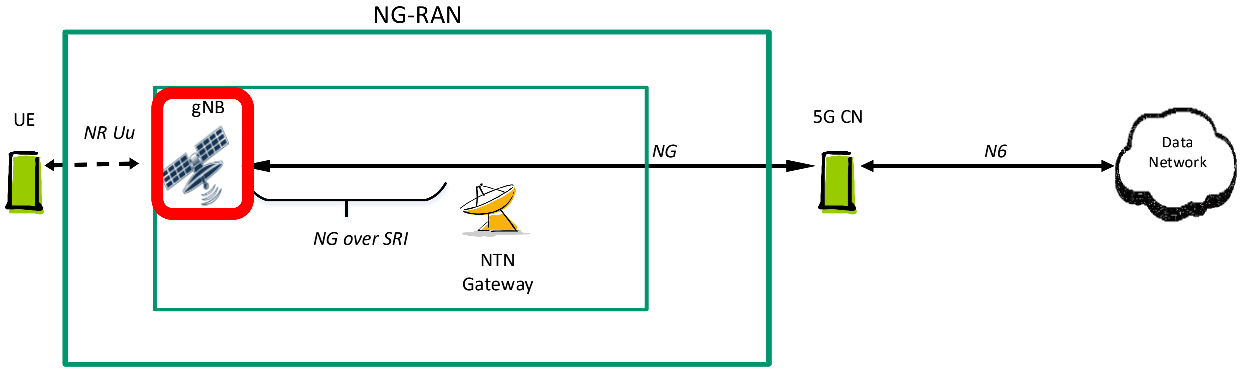


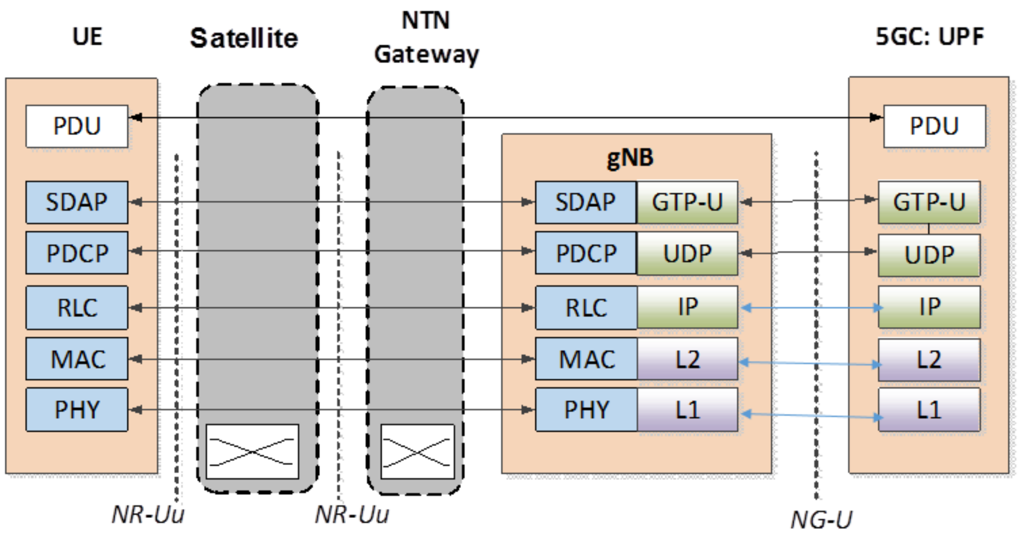


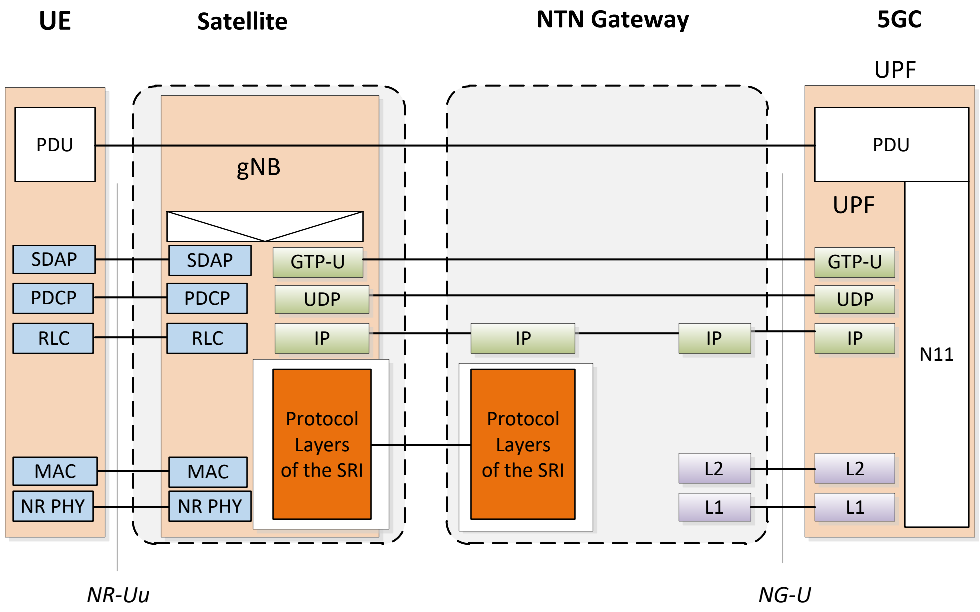
NTN Transparent vs Regenarative: User Planes

3GPP TS 38.821









NTN Transparent vs Regenarative: Control Planes

3GPP TS 38.821