教育部「5G行動寬頻人才培育跨校教學聯盟計畫」
5G行動網路協定與核網技術聯盟中心

行動邊緣計算
可推廣教材模組

單元-01：行動邊緣計算與4G/5G 網路架構

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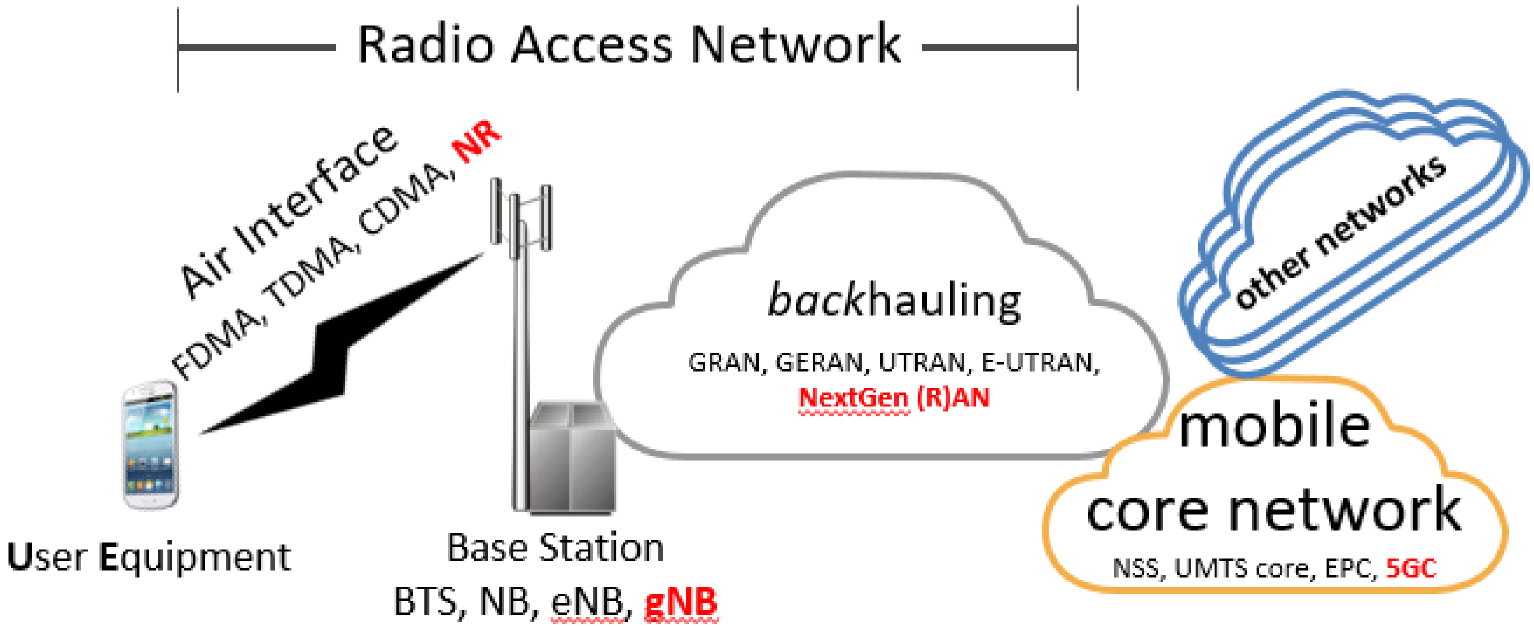
Outline

- System Architecture Evolution
- 4G EPC 核心網路架構
- 4G LTE 通訊與協定
- Self-Organizing Network
- Air Interface
- Radio Access Network (RAN)
- 5G Architecture

System Architecture Evolution

Mobile Core Network



Function of Mobile Core

- Mobile core networks
  - originally circuit switched
  - have migrated to packet switching using IP technologies
  - unlike the connectionless (CL) Internet, the PSTN and mobile networks are connection oriented (CO)
  - mobile cores need to maintain sessions despite mobility
- Like all core networks, the mobile core handles transport of user data, with
  - very high data rates
  - relatively small number of network elements and links
  - relatively stable environment

PSTN and Mobile vs. Internet

- PSTN and mobile core networks are very different from other IP core networks (e.g., Internet)
  - the PSTN assumes dumb terminals and intelligence in the network
  - the Internet assumes smart terminals and dumb pipes in the network (the end-to-end principle)
- The PSTN and mobile core networks have a rich set of functionalities not present in the Internet model

Mobile Core Functionality

- end-to-end transport of voice traffic (at least until 4G)
- connection-oriented data transport (session management)
- maintenance of sessions despite mobility (mobility management)
- user (not necessarily true end-user) management
  - authentication and registration
  - mobility management (tracking where users are)
  - user profile, home location, roaming
  - billing (aka charging)
- session management (call establishment, management and termination)
- lawful interception and metadata collection
- QoS enforcement

Core Network Elements (before 5G)

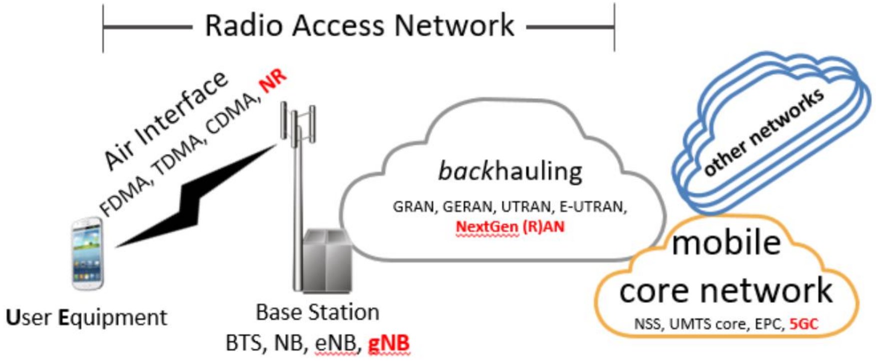
- Home Subscriber Server / Home Location Register
  - database containing user-related and subscriber-related information
  - support mobility management, call/session setup, user authentication
- Serving Gateway (SGSN)
  - transport traffic between UE and network
  - mobility anchor point
- Packet Data Gateway (GGSN)
  - interconnection between mobile core and external packet networks

Core Network Elements (before 5G) (cont'd)

- Policy and Charging Rules Function
  - software component that determines and disseminates policy rules
  - separated rom PCEF enforcement function
- Mobility Management Entity
  - control plane entity handling signallingrelated to mobility and security
  - tracking and paging UEs in idle-mode

Other Networks

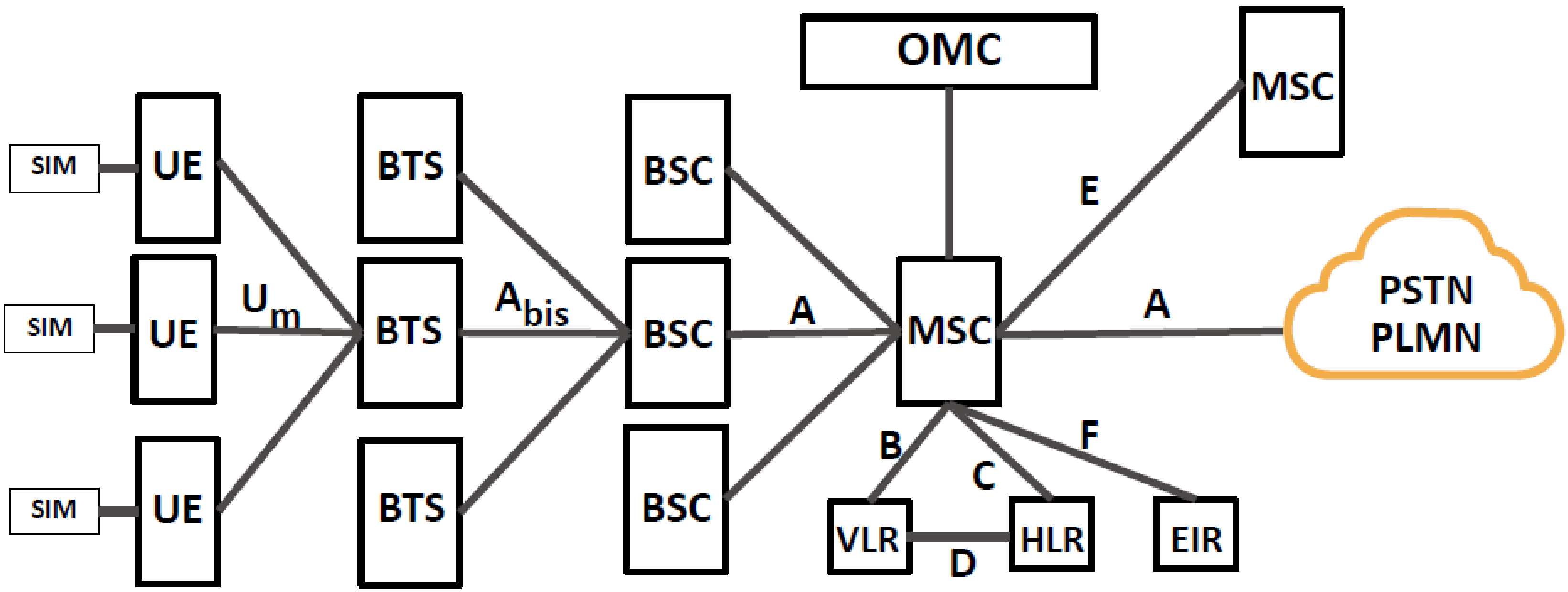
- Public Switched Telephone Network –for voice calls to non-cellular users
- Core networks of other mobile service providers
- Internet
  - local breakout (facilitated by Mobile Edge Computing) is more efficient
  - Content Delivery Networks change the architecture
- Data Centers
- Corporate Networks



Cellular System Architecture

- Telecommunications systems architectures are composed of
  - Network Elements (NEs) or Network Functions (NFs)
    - NEs may be composed of many NFs
    - NFs may be micro-services
  - Interfaces or reference points between NEs or NFs
- Architectures differ in
  - types of NEs/NFs
  - granularity of NEs/NFs
  - flat networks vs. hierarchical/heterogeneous
  - separation of user, control, and management planes
- System (top-down) design starts with architecture and afterwards designs protocols

2G GSM Architecture



Radio Access Network *Core Network*

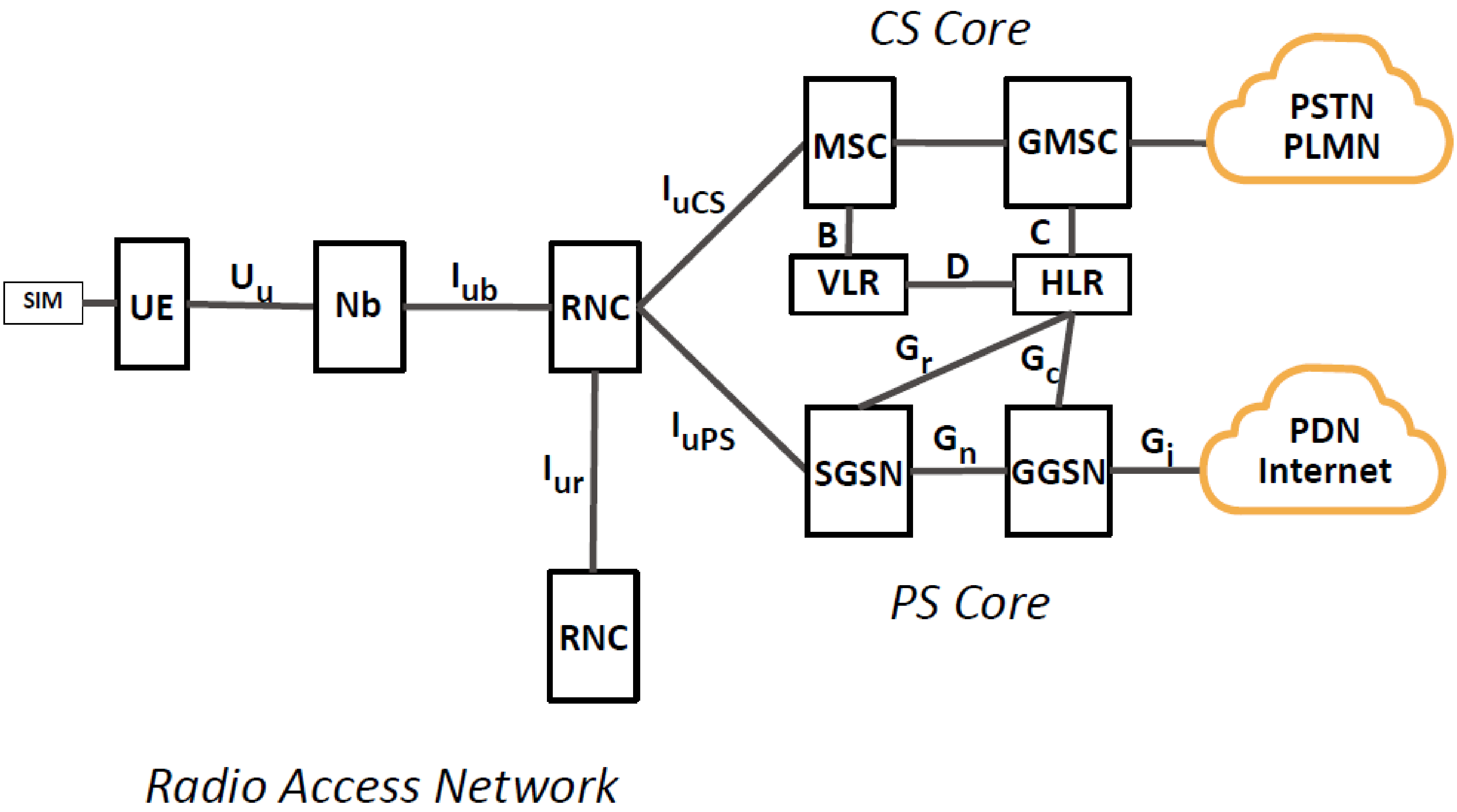
2G GSM Interfaces and NEs (1/2)

- A interface: the standard PSTN voice trunk
- Abis interface: for 2G mobile framed compressed voice
- Um interface: user mobile (air) interface
- BS (Base Station): Base Transceiver Station
- BSC (Base Station Controller): controls a group of BTSs
  - manages radio resources, allocates channels, controls handoff
- MSC (Mobile Switching Centre)
  - acts like a PSTN switch
  - provides interconnection to the PSTN and other mobile networks
  - provides authentication, registration, call location/routing, inter-MSC handoff

2G GSM Interfaces and NEs (2/2)

- HLR (Home Location Register)
  - A database containing all user information including last known location (even if the UE is idle)
- EIR (Equipment Identity Register)
  - lists block phones connects to the MSC over the F interface
- VLR (Visitor Location Register)
  - receives information from the HLR
- OMC (Operations and Maintenance Center)
  - manages the entire system

GPRS architecture



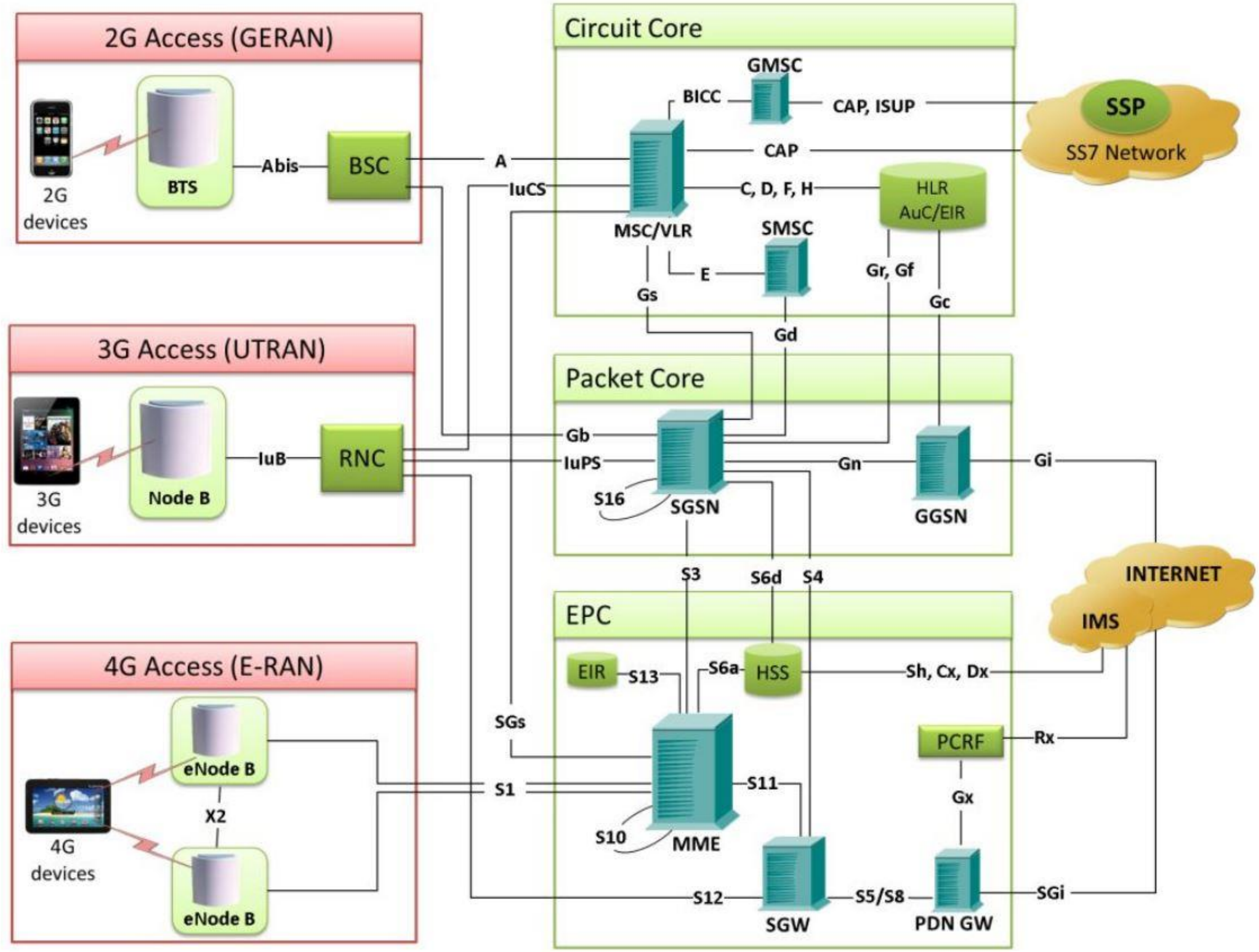
2.5/3G GPRS NEs

- The General Packet Radio Service extends GSM for packet service
- BTS is replaced by NodeB in 3G
- The BSC is replaced by the Radio Network Controller (RNC)
  - is responsible for controlling the NBs
  - performs radio resource and some mobility management functions
  - performs encryption of data sent to and from UE
- The MSC is the same as in the GSM architecture (replaced in R5 by MGW)
  - supplemented by a Gateway MSC to connect to the PSTN
- Serving GPRS Support Node
  - for packet traffic
  - is similar to MSC+VLR for voice
  - performs access control, security functions and tracks UE location
- Gateway GPRS Support Node (GGSN)
  - for packet traffic is similar to the GMSC
  - acts as an IP router to connect to external IP networks
  - handles billing, filtering and firewall functions

2.5/3G GPRS Interfaces

- The Um air interface
  - replaced with the Uu interface
- Iu-CS interface
  - the interface between the RNC and MSC
- Iu-PS interface
  - the interface between the RNC and the SGSN
- Iur interface
  - an optional interface between RNCs for smooth handoff
- Gn interface
  - transports user data and signaling between SGSN and GGSN
  - uses GPRS Tunnelling Protocol to tunnel through IP networks
- Gp interface: interface to foreign networks
- Other G interfaces: for mobility management (HLR, authentication), etc.

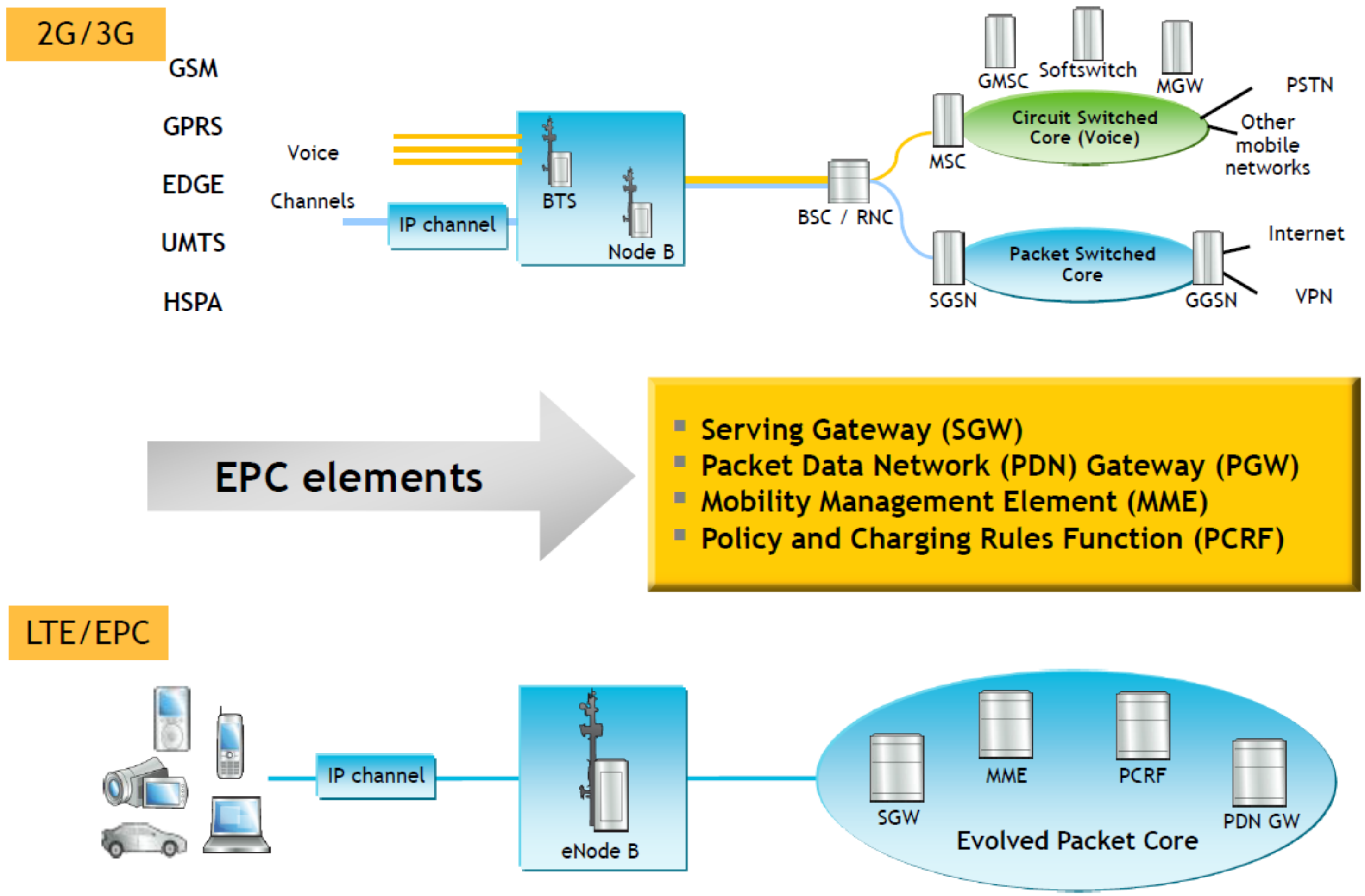
2G, 3G and 4G Network Architecture



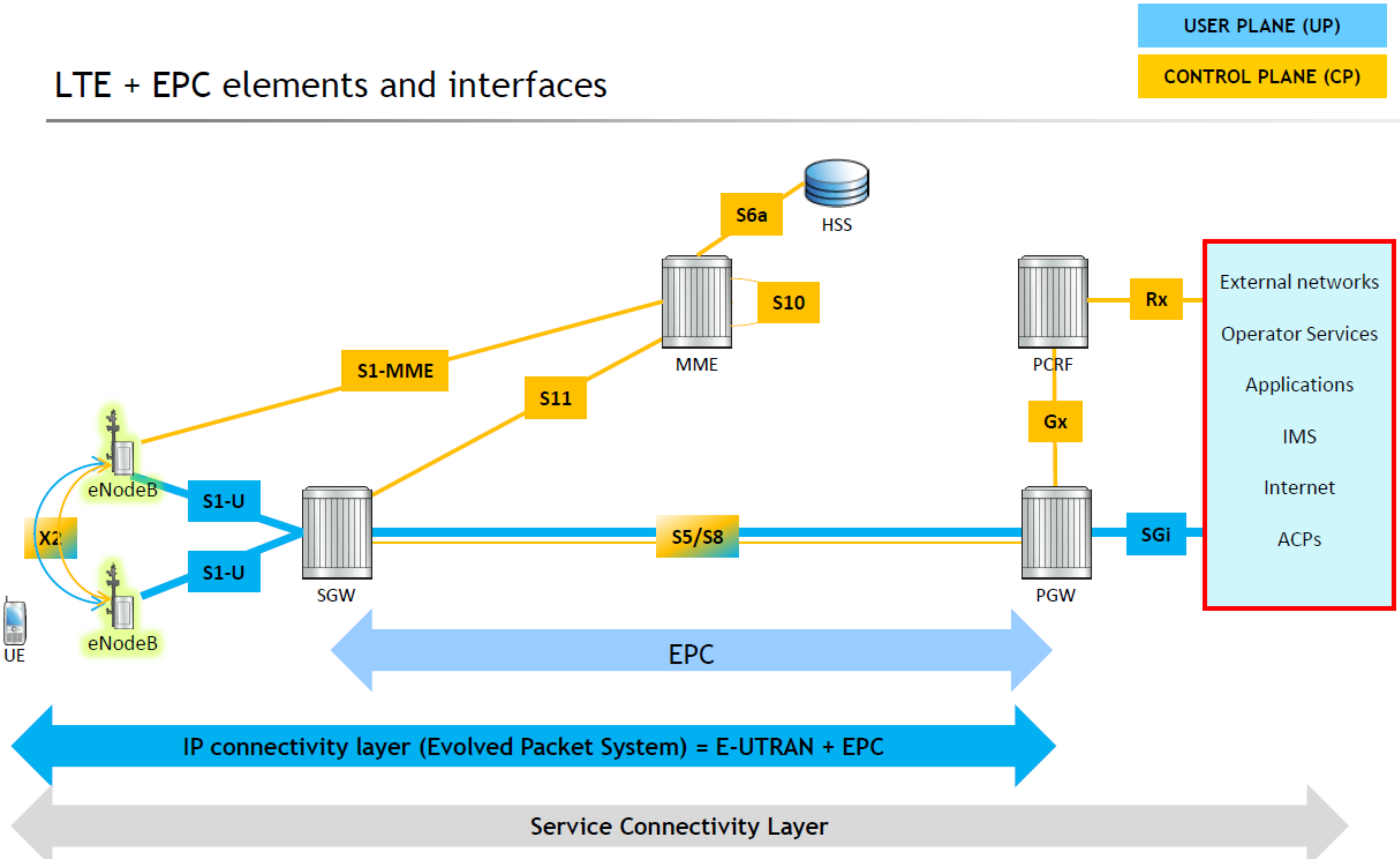
4G: LTE and SAE

- Long Term Evolution (LTE) refers to the Evolved UMTS Radio Access Network (E-UTRAN)
- System Architecture Evolution (SAE) refers to the Evolved Packet Core (EPC)

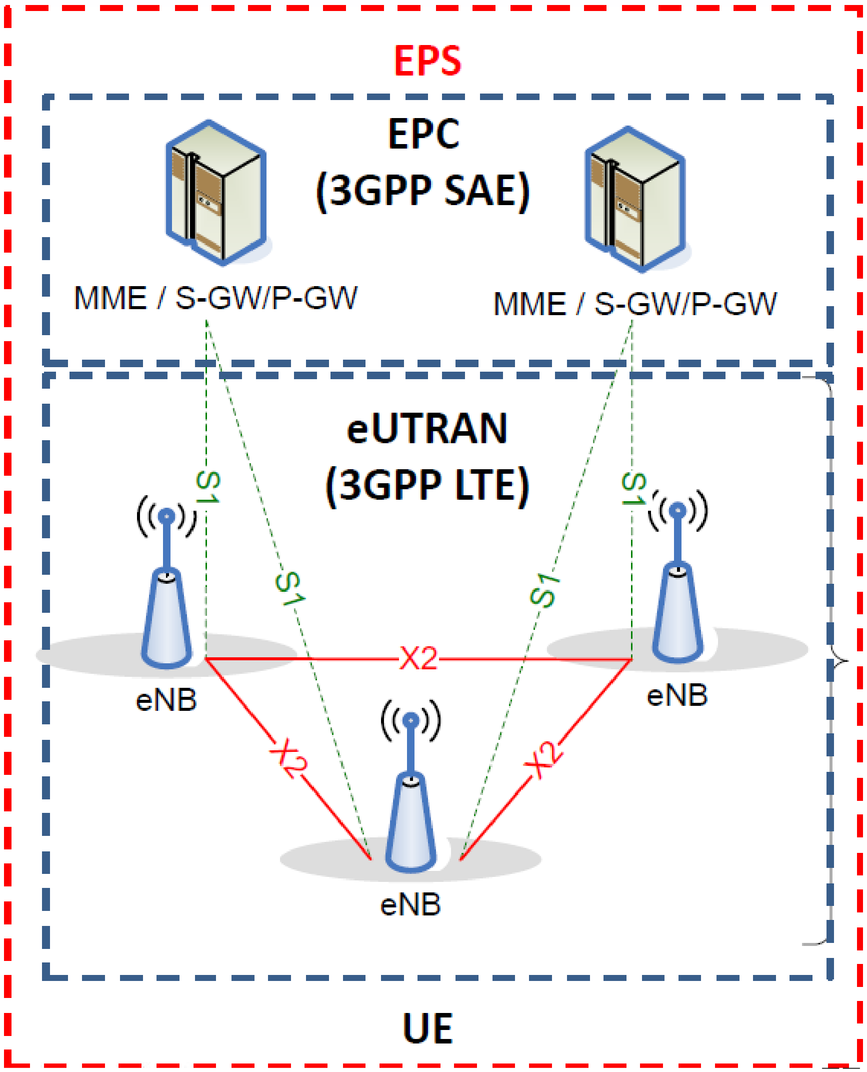
All-IP Core, New Network Elements



LTE + EPC Elements & Interface



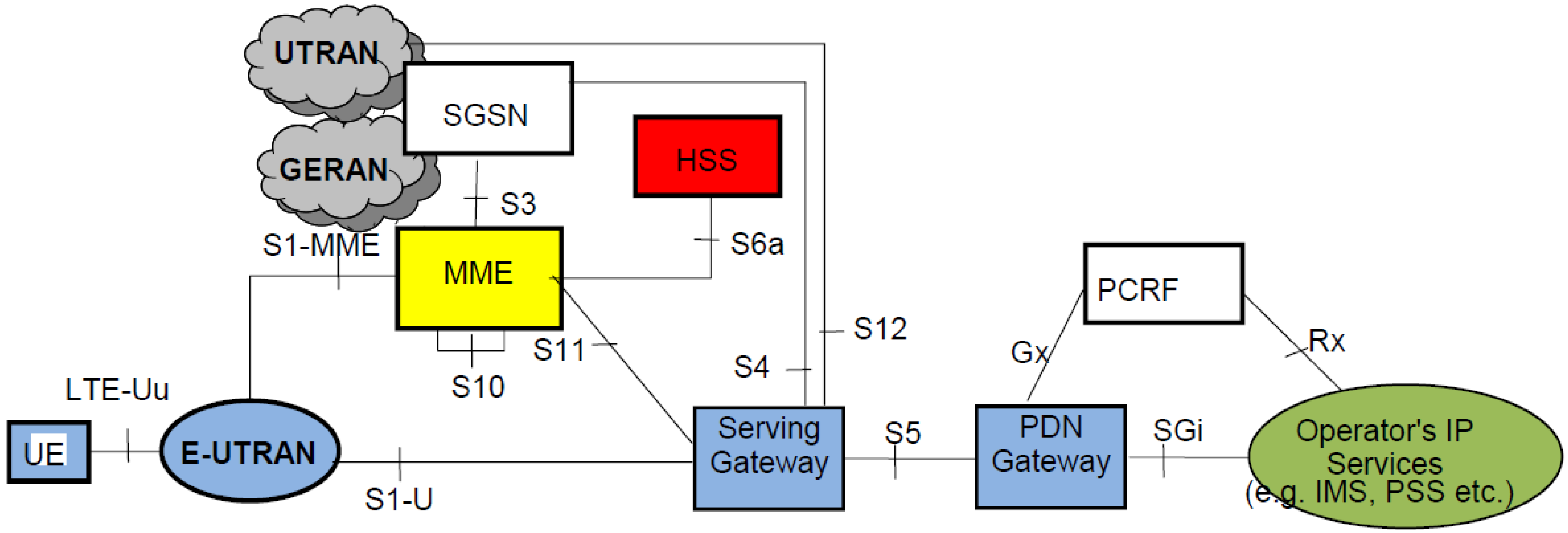
LTE Architecture &Terminologies



EPC: Evolved Packet Core
MME: Mobility Management Entity
S-GW: Serving Gateway
P-GW: Packet Data Network Gateway
eUTRAN: Evolved UTRAN
S1: Interface between EPC and eNB
X2: Inter-eNB interface (logical Interface)
SAE: System Architecture Evolution
LTE: Long Term Evolution
EPS: Evolved Packet System

Ref. 3GPP TS 36.300

Architecture for 3GPP Accesses

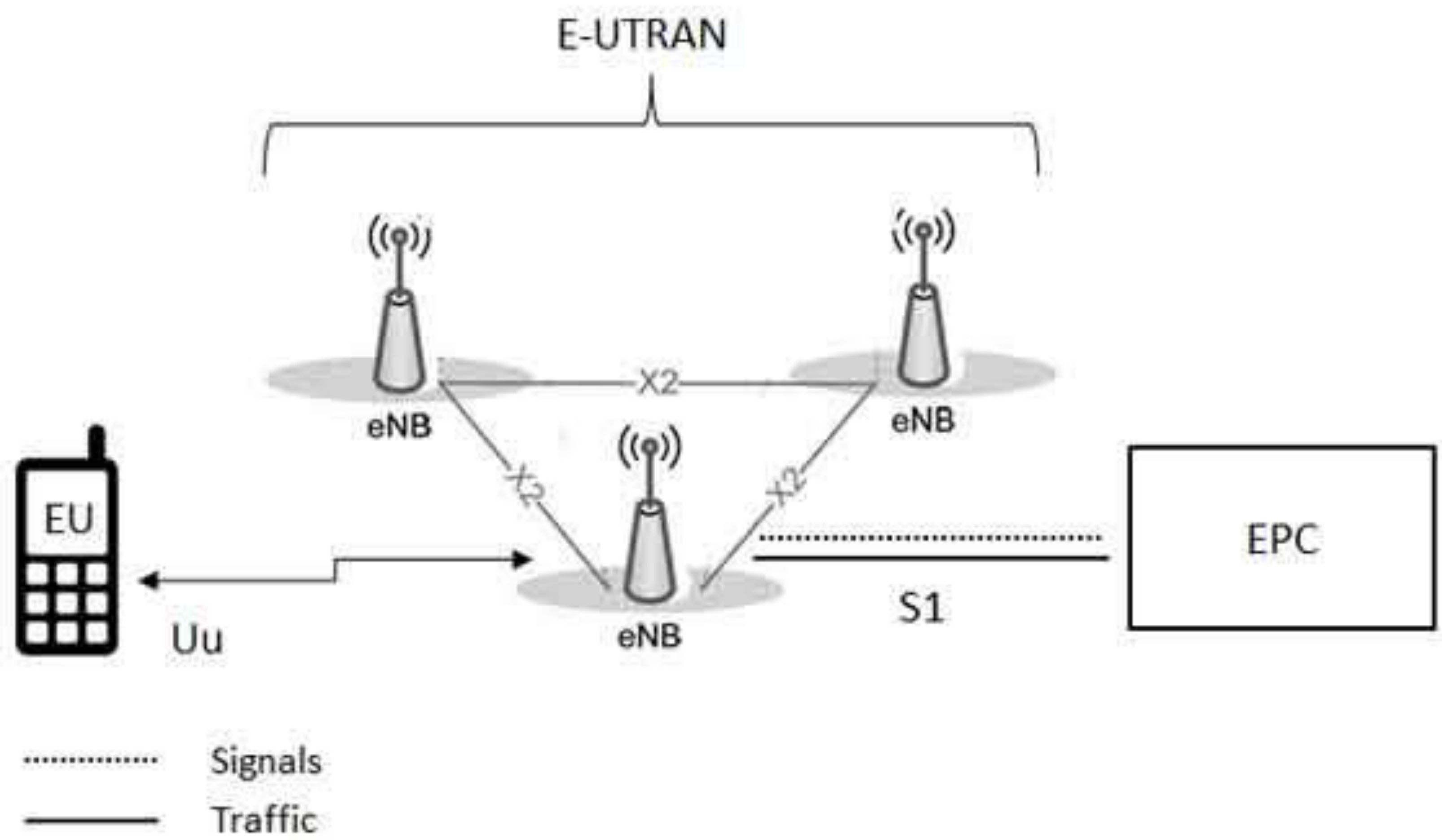


HSS: Home Subscriber Server
PCRF: Policy & Charging Rule Function

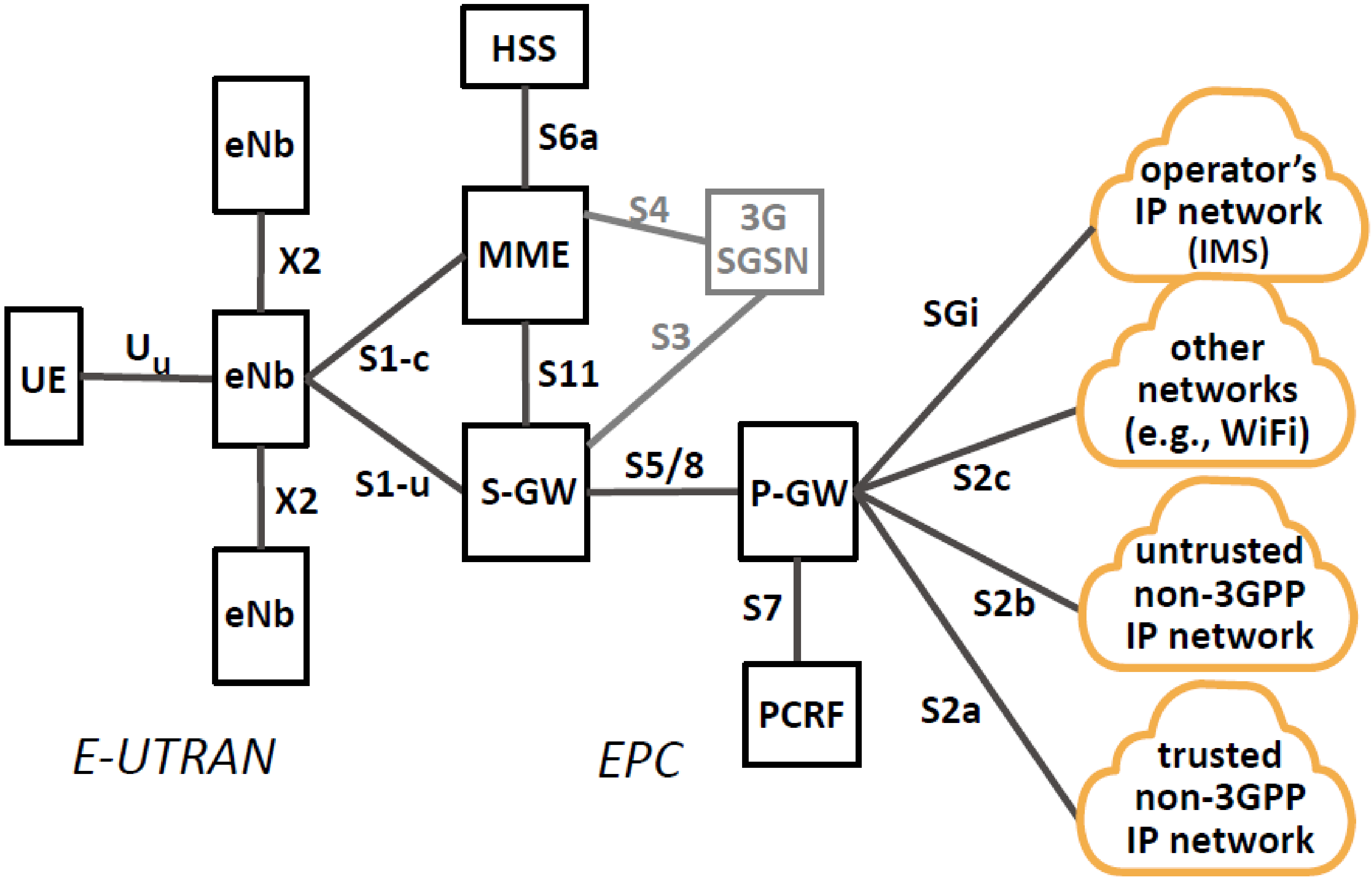
Ref. 3GPP TS 23.401

4G EPC 核心網路架構

Interface Uu, X2 and S1



4G LTE Architecture



4G LTE NEs and Interfaces

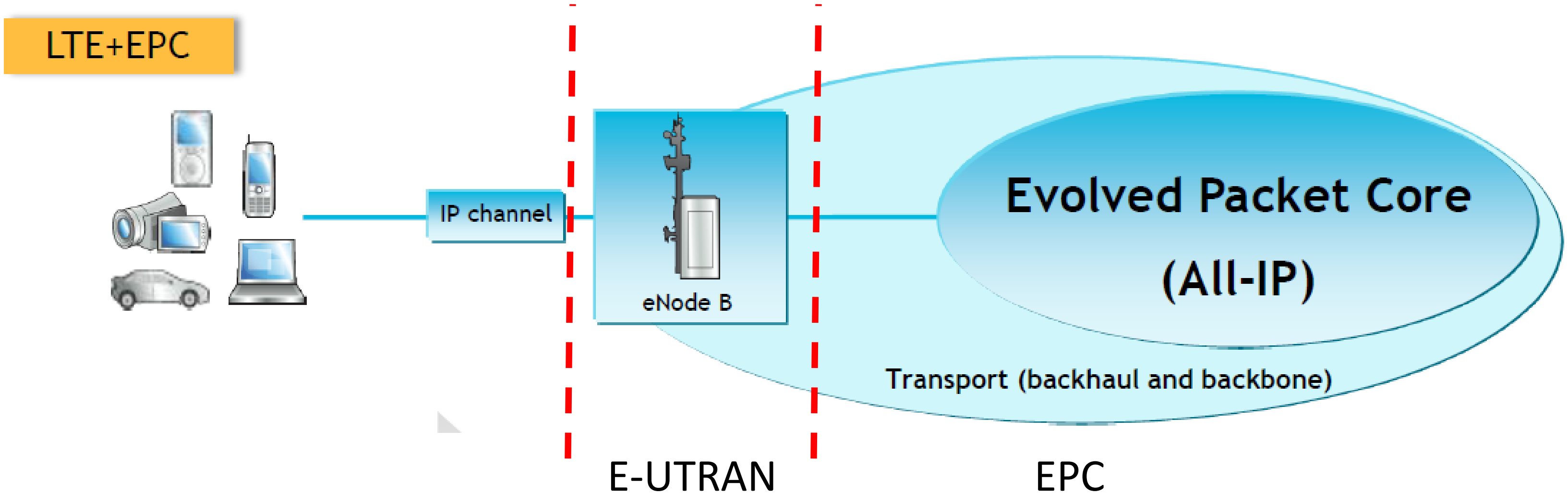
- Long Term Evolution was developed as 3GPP System Architecture Evolution
  - Evolved UMTS Terrestrial Radio Access Network (E-UTRAN)
  - Evolved Packet Core
- The air interface is still called Uu
- The main backhaul from eNodeB to core is called the S1interface(s)
- There are other S interfaces, such as S2 for non-3GPP access
- eNodeBs are interconnected (for handoff and other reasons) by X2 interfaces

EPC Architecture

- The BS is a single NE called the evolved Node B (replacing the NB and RNC)
- The EPC has more user/control separation
- The EPC is a single flat IP network, consisting of
  - Serving GateWay (S-GW) connecting to the E-UTRAN
  - Mobility Management Entity (most of the gateway signaling)
  - Packet Data Network GateWay (P-GW) to connect to other PDNs
  - Home Subscriber Server (HSS) database (instead of HLR)
  - R11 introduced the Traffic Detection Function (Deep Packet Inspection)

Evolved Packet Core (EPC)

- All-IP mobile core network
- From 3GPP Release:
  - (Radio access): LTE → E-UTRAN (eNodeB)
  - (Core network): SAE → EPC
- Evolved Packet System = E-UTRAN + EPC



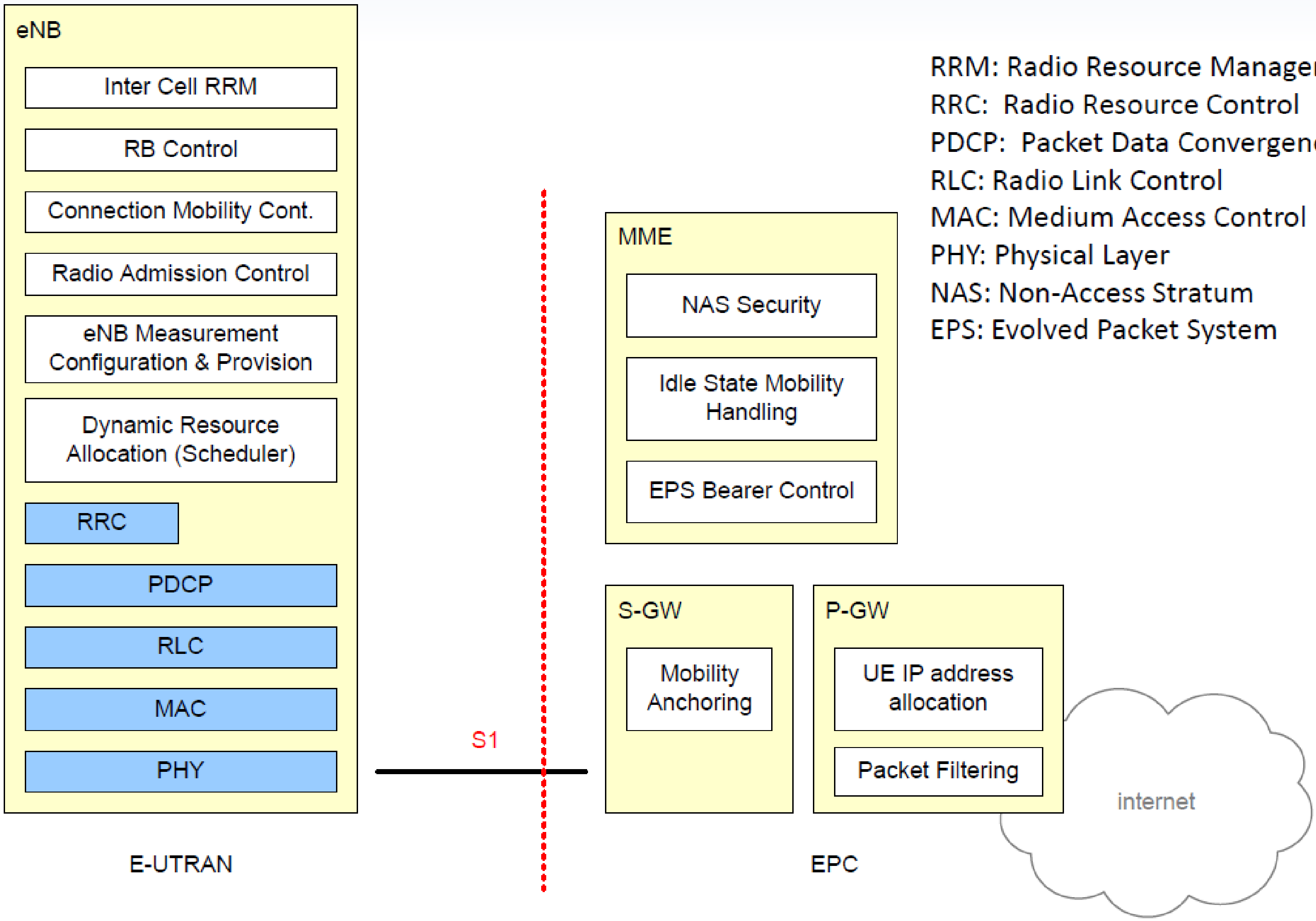
Evolved Packet Core (EPC)

- New, all-IP mobile core network introduced with LTE
  - End-to-end IP (All-IP)
  - Clear delineation of control plane and data plane
  - Simplified architecture: flat-IP architecture with a single core
- A multi-access core network based on the Internet Protocol (IP)
- EPC enables operators to deploy and operate one common packet core network for
  - 3GPP radio access (LTE, 3G, and 2G)
  - non-3GPP radio access (HRPD, WLAN, and WiMAX)
  - fixed access (Ethernet, DSL, cable, and fiber).

Basic EPC Elements

- Mobility Management Entity (MME)
  - Control-plane element, responsible for high volume mobility management and connection management (up to thousands of eNodeBs)
- Serving Gateway
  - Serving a large number of eNodeBs, focus on scalability and security
- Packet Data Network (PDN) Gateway
  - IP management ("IP anchor"), connection to external data networks
  - focus on highly scalable data connectivity and QoS enforcement
- Policy and Charging Rules Function (PCRF)
  - Network-wide control of flows: detection, gating, QoS and flow-based charging, authorizes network-wide use of QoS resources (manages millions of service data flows)

Function Split between E-UTRAN and EPC

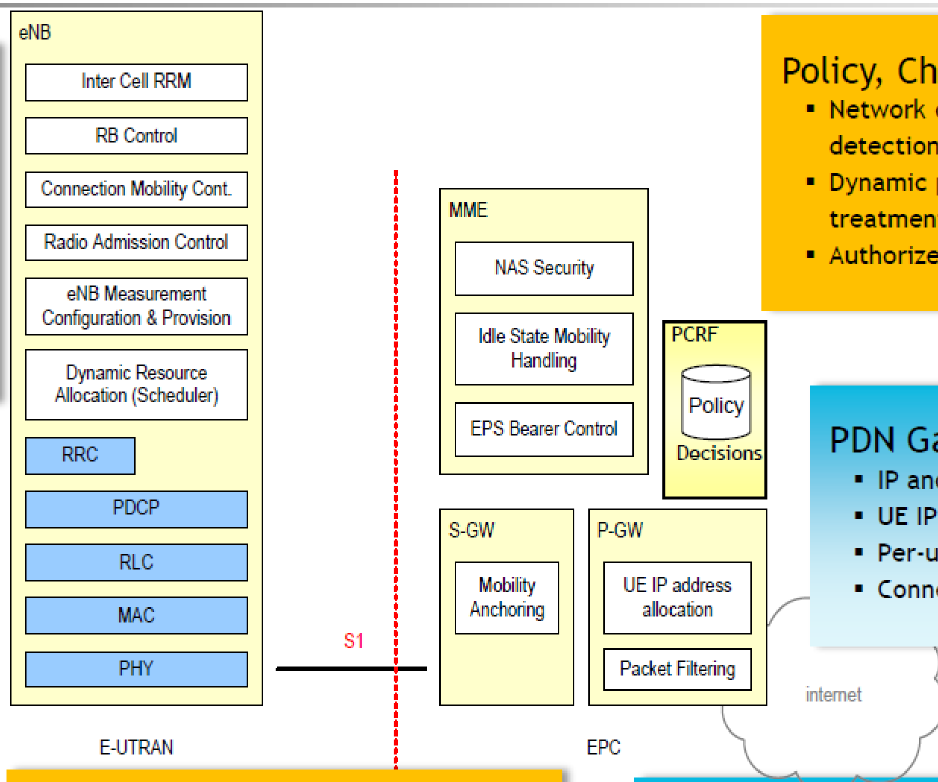


RRM: Radio Resource Management
RRC: Radio Resource Control
PDCP: Packet Data Convergence Protocol
RLC: Radio Link Control
MAC: Medium Access Control
PHY: Physical Layer
NAS: Non-Access Stratum
EPS: Evolved Packet System

Ref. 3GPP TS 36.300

Overview of EPC components and functionality

eNodeB:
all radio access functions
- Radio admission control
- Scheduling of UL and DL data
- Scheduling and transmission of paging and system broadcast
- IP header compression (PDCP)
- Outer-ARQ (RLC)



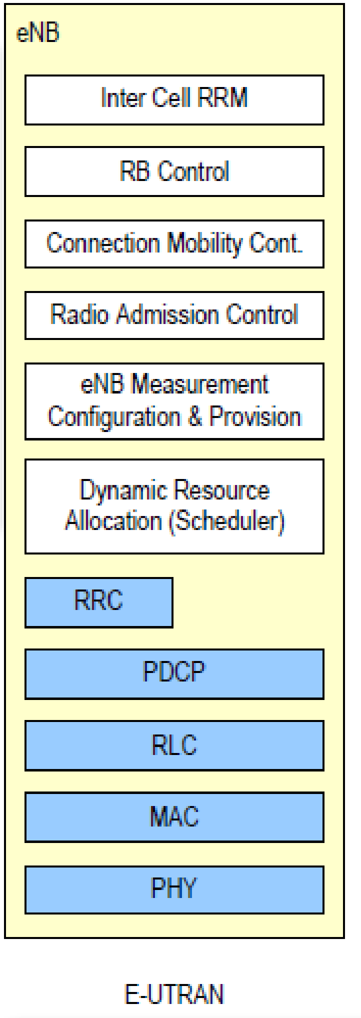
Policy, Charging & Rules Function
- Network control of Service Data Flow (SDF) detection, gating, QoS & flow based charging
- Dynamic policy decision on service data flow treatment in the PCEF (xGW)
- Authorizes QoS resources

PDN Gateway
- IP anchor point for bearers
- UE IP address allocation
- Per-user based packet filtering
- Connectivity to packet data network

Mobility Management Entity
- Authentication
- Tracking area list management
- Idle mode UE reachability
- S-GW/PDN-GW selection
- Inter core network node signaling for mobility between 2G/3G and LTE
- Bearer management functions

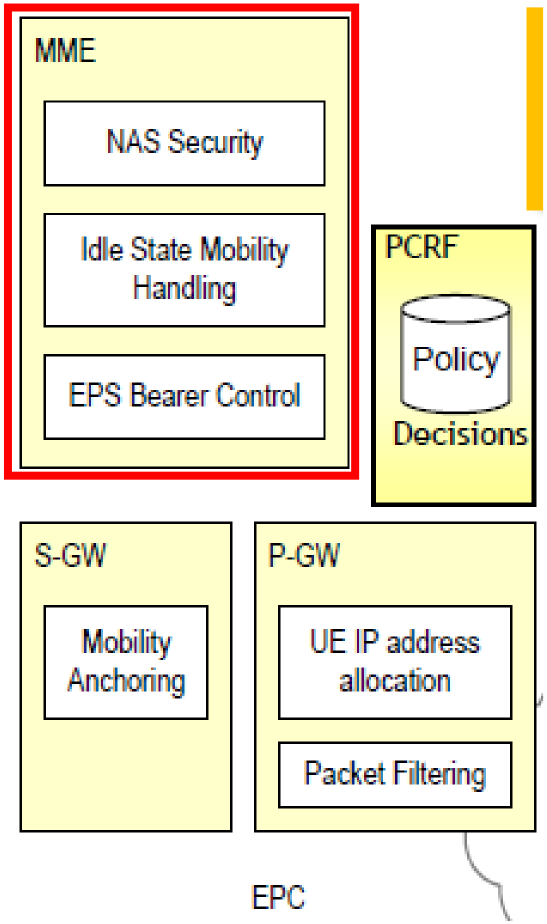
Serving Gateway
- Local mobility anchor for inter-eNB handovers
- Mobility anchoring for inter-3GPP handovers
- Idle mode DL packet buffering
- Lawful interception
- Packet routing and forwarding

Functions at eNodeB



- All radio access functions
  - Radio admission control
  - Scheduling of UL and DL data
  - Scheduling and transmission of paging and system broadcast
  - IP header compression (PDCP)
  - Outer-ARQ (RLC)

Functions of Mobility Management Entity (MME)



- Authentication
- Tracking area list management
- Idle mode UE reachability
- S-GW/PDN-GW selection
- Inter core network node signaling for mobility between 2G/3G and LTE
- Bearer management functions

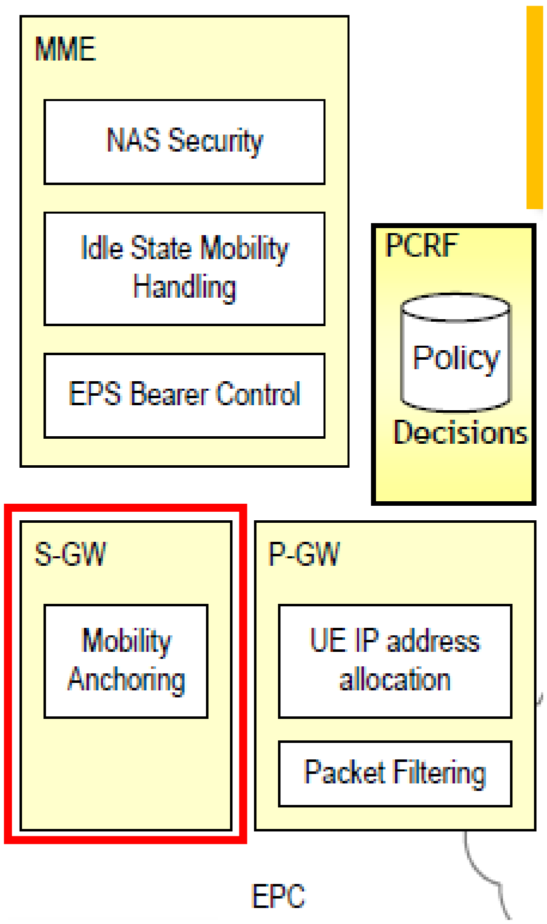
MME Functionality

- NAS signaling;
- NAS signaling security;
- Inter CN node signaling for mobility between 3GPP access networks;
- Idle mode UE Reachability(including control and execution of paging retransmission);
- Tracking Area list management (for UE in idle and active mode);
- PDN GW and Serving GW selection;
- MME selection for handovers with MME change;
- SGSN selection for handovers to 2G or 3G 3GPP access networks;
- Roaming;
- Authentication;
- Bearer management functions including dedicated bearer establishment;
- Support for ETWS message transmission.

*One user can only be served by **ONE** MME.*

Ref. 3GPP TS 23.401

Functions of Serving Gateway (S-GW)



- Local mobility anchor for inter-eNB handovers
- Mobility anchoring for inter-3GPP handovers
- Idle mode DL packet buffering
- Lawful interception
- Packet routing and forwarding

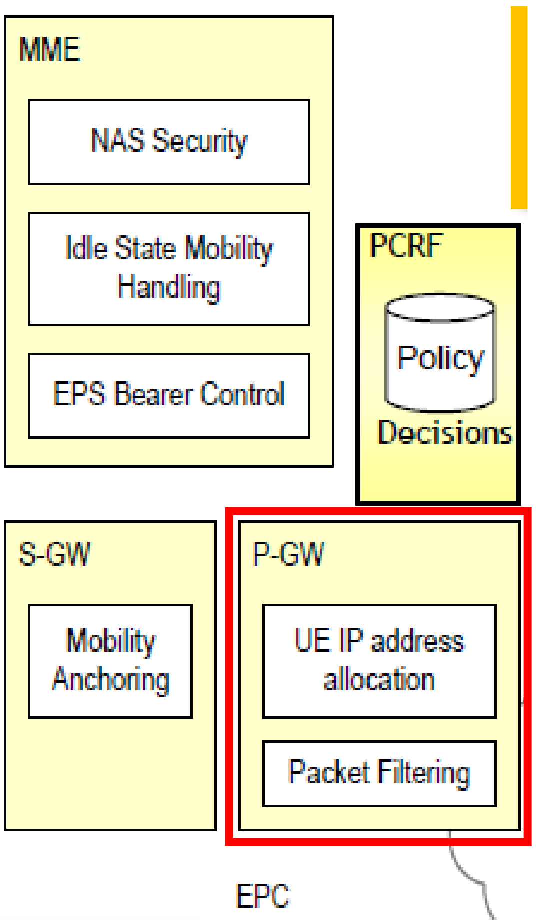
S-GW Functionality

- The local Mobility Anchor point for inter-eNB handover;
- Mobility anchoring for inter-3GPP mobility;
- E-UTRAN idle mode downlink packet buffering and initiation of network triggered service request procedure;
- Lawful Interception;
- Packet routing and forwarding;
- Transport level packet marking in the uplink and the downlink;
- Accounting on user and QCI granularity for inter-operator charging;
- UL and DL charging per UE, PDN, and QCI.

*One user can only be served by **ONE** S-GW but more than one P-GW.*

Ref. 3GPP TS 23.401

Functions of Packet Data Network (PDN) Gateway (P-GW)



- IP anchor point for bearers
- UE IP address allocation
- Per-user based packet filtering
- Connectivity to packet data network

P-GW Functionality

- Per-user based packet filtering
- Lawful Interception
- UE IP address allocation
- Transport level packet marking in the downlink
- UL and DL service level charging, gating and rate enforcement
- DL rate enforcement based on APN-AMBR (APN-Aggregate Maximum Bit Rate)

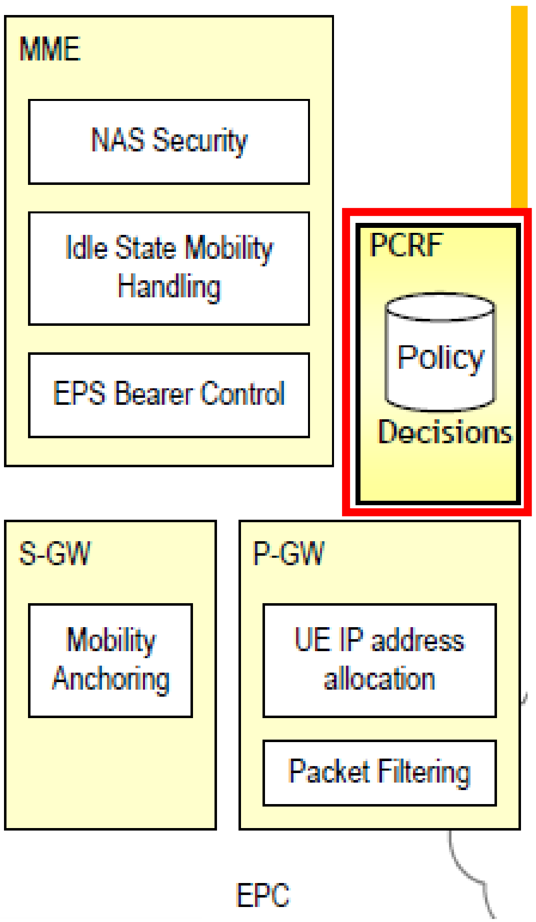
*One user can only be served by **ONE**S-GW but more than one P-GW.*

Ref. 3GPP TS 23.401

Functions of
Home Subscriber Server (HSS)

- Basically, the HSS (for Home Subscriber Server) is a database.
- HSS contains user-related and subscriber-related information.
- HSS also provides support functions in mobility management, call and session setup, user authentication and access authorization.
- It is based on the pre-3GPP Release 4 - Home Location Register (HLR) and Authentication Centre (AuC).

Functions of Policy, Charging & Rules Function (PCRF)



- Network control of Service Data Flow (SDF)
  - detection, gating, QoS & flow based charging
- Dynamic policy decision on service data flow treatment in the PCEF (xGW)
- Authorizes QoS resources

4G LTE 通訊與協定

LTE

- LTE
  - A standard for mobile data communications technology
  - An evolution of the GSM/UMTS standards
- However, LTE wireless interface
  - Incompatible with 2G and 3G networks
  - Must be operated on a separate wireless spectrum

History of LTE

- LTE was first proposed by NTT DoCoMo of Japan in 2004, and studies on the new standard officially commenced in 2005.
- The LTE standard was finalized in December 2008.
- The first publicly available LTE service was launched by TeliaSonera in Oslo and Stockholm on December 14, 2009 as a data connection with a USB modem.
- Samsung Galaxy Indulge: the world's first LTE smartphone starting (February 10, 2011).

History of LTE (Cont'd)

- Initially, CDMA operators planned to upgrade to rival standards called UMB and WiMAX.
- But all the major CDMA operators have announced that they intend to migrate to LTE after all.
  - Verizon, Sprint and MetroPCS in the United States
  - Bell and Telus in Canada
  - KDDI in Japan
  - SK Telecom in South Korea
  - China Telecom/China Unicom in China

LTE-Advanced (LTE-A)

- The evolution of LTE is LTE Advanced
  - was standardized in March 2011.
- Services of LTE Advanced commenced in 2013.

Features of LTE

- Increase of capacity and speed of wireless data networks using new DSP and modulation techniques.
- Redesign and simplification of the network architecture to an IP-based system
- Reduced transfer latency compared to the 3G architecture

Major Requirements for LTE

- **Higher peak data rates**: 100 Mbps (downlink) and 50 Mbps (uplink)
- **Improved spectrum efficiency**: 2-4 times better compared to 3GPP release 6
- **Improved latency**:
  - Radio access network latency (user plane UE – RNC – UE) below 10 ms
  - Significantly reduced control plane latency
- Support of **scalable bandwidth**: 1.4, 3, 5, 10, 15, 20 MHz
- Support of **paired and unpaired spectrum** (FDD and TDD mode)
- Support for **interworking with legacy networks**

Evolution of UMTS FDD and TDD

Evolution of UMTS FDD and TDD
driven by data rate and latency requirements

FDD evolution	WCDMA	HSDPA/ HSUPA	HSPA+	LTE and HSPA+	LTE-advanced
TDD evolution	TD-SCDMA	TD-HSDPA	TD-HSUPA	TD-LTE and TD-HSPA+	
3GPP release	3GPP Release 99/4	3GPP Release 5/6	3GPP Release 7	3GPP Release 8	3GPP Study Item initiated
App. year of network rollout	2003/4	2005/6 (HSDPA) 2007/8 (HSUPA)	2008/2009	2010	
Downlink data rate	384 kbps (typ.)	14 Mbps (peak)	28 Mbps (peak)	LTE: 150 Mbps* (peak) HSPA+: 42 Mbps (peak)	100 Mbps high mobility 1 Gbps low mobility
Uplink data rate	128 kbps (typ.)	5.7 Mbps (peak)	11 Mbps (peak)	LTE: 75 Mbps (peak) HSPA+: 11 Mbps (peak)	
Round Trip Time	~ 150 ms	< 100 ms	< 50 ms	LTE: ~10 ms	

*based on 2x2 MIMO and 20 MHz operation

LTE key parameters

Frequency Range	**UMTS FDD bands and UMTS TDD bands**					
Channel bandwidth, 1 Resource Block=180 kHz	**1.4 MHz**	**3 MHz**	**5 MHz**	**10 MHz**	**15 MHz**	**20 MHz**
	6 Resource Blocks	15 Resource Blocks	25 Resource Blocks	50 Resource Blocks	75 Resource Blocks	100 Resource Blocks
Modulation Schemes	**Downlink:** QPSK, 16QAM, 64QAM **Uplink:** QPSK, 16QAM, 64QAM (optional for handset)					
Multiple Access	**Downlink:** OFDMA (Orthogonal Frequency Division Multiple Access) **Uplink:** SC-FDMA (Single Carrier Frequency Division Multiple Access)					
MIMO technology	**Downlink:** Wide choice of MIMO configuration options for transmit diversity, spatial multiplexing, and cyclic delay diversity (max. 4 antennas at base station and handset) **Uplink:** Multi user collaborative MIMO					
Peak Data Rate	**Downlink:** 150 Mbps (UE category 4, 2x2 MIMO, 20 MHz) 300 Mbps (UE category 5, 4x4 MIMO, 20 MHz) **Uplink:** 75 Mbps (20 MHz)					

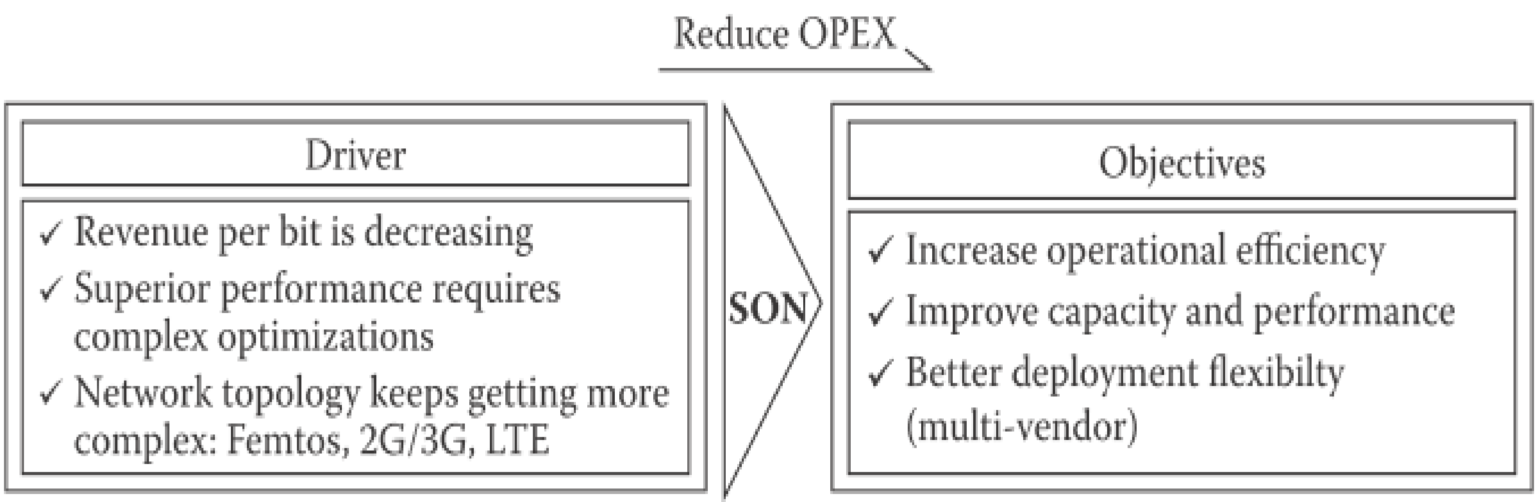
Self-Organizing Network

Introduction to Self-Organizing Network

- The Self-Organizing Network (SON) is a concept originated from the Next-Generation Mobile Networks (NGMN) alliance.
- The SON network can automatically ① extend, ② change, ③ configure, and ④ optimize its ① topology, ② coverage, ③ capacity, ④ cell size, and ⑤ channel allocation, based on changes in ① location, ② traffic pattern, ③ interference, and ④ the environment.
- The SON aims at reducing the cost of installation and management by simplifying operational tasks through automated mechanisms such as self-configuration and self-optimization.

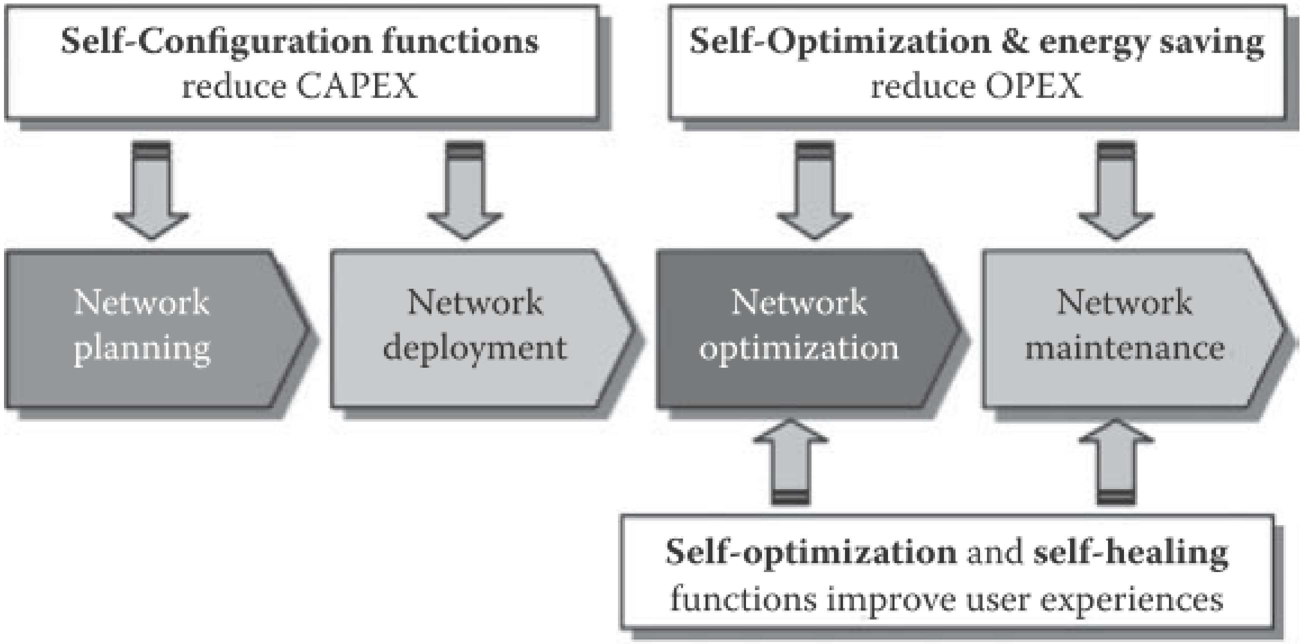
Main Drivers for SON

- From an operator's perspective, the main drivers for SON in LTE are to reduce OPEX (Operating Expense).



Main Objectives of SON (1/2)

- The main objective of the SON is to reduce CAPEX (Capital Expense) as well as OPEX.



Main Objectives of SON (2/2)

- The SON is designed to automatically configure and optimize the LTE network by
  - *Self-configuration*, which involves plug-and-play behavior when installing network elements to reduce costs and simplify procedures.
  - *Self-optimization*, which means automatic optimization based on network monitoring and measurement data.
  - *Self-healing*, which means that the system detects problems itself and mitigates or solves these problems to avoid unnecessary user intervention and to reduce maintenance costs.

Operational Benefits by SON

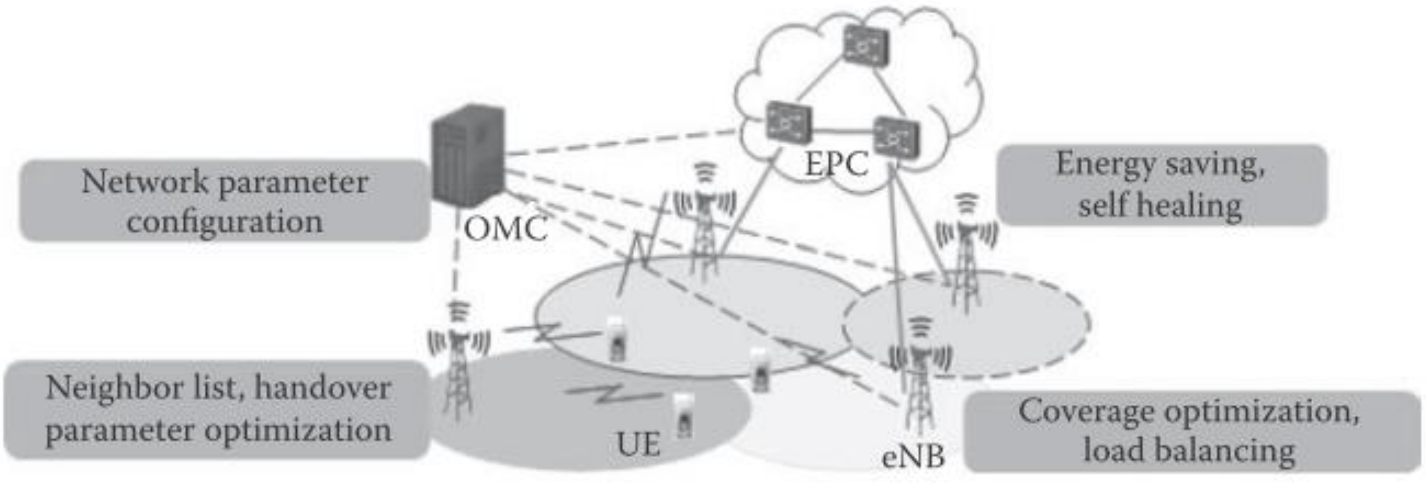
- Self-Configuration
  - Flexibility in logistics (eNB not site specific)
  - Reduced site / parameter planning
- Self-Optimization
- Self-Healing

Operational Benefits by SON

Self-Configuration	– Flexibility in logistics (eNB not site specific) – Reduced site / parameter planning – Simplified installation; less prone to errors – No / minimum drive tests – Faster rollout
Self-Optimization	– Increased network quality and performance – Parameter optimization Reduced maintenance, site visits
Self-Healing	– Error self-detection and mitigation – Speed up maintenance – Reduce outage time

SON Functions

- Initial SON functions can be described as following figure.
  - OMC = Operations and Maintenance Centre, which is the central location to operate and maintain the network.



3GPP Specified SON Functions (1/2)

- A number of SON functions are supported in 3GPP Release-8 and will expand in scope with subsequent releases.

	Rel-8	*Rel-9*
Self-Configuration	– Automated configuration of PCI – ANR – Self-configuration of eNBs – Automatic Software Management	– Automated configuration of PCI – ANR – Self-configuration of eNBs Automatic Software Management – Inter-RAT ANR – Automatic Radio Configuration Function

Details will be shown later

PCI = Physical Cell ID

ANR = Automatic Neighbor Relations

RAT = Radio Access Technology

	Rel-9	*Rel-10*
Self-Healing	Cell outage compensation/ mitigation	Self-healing

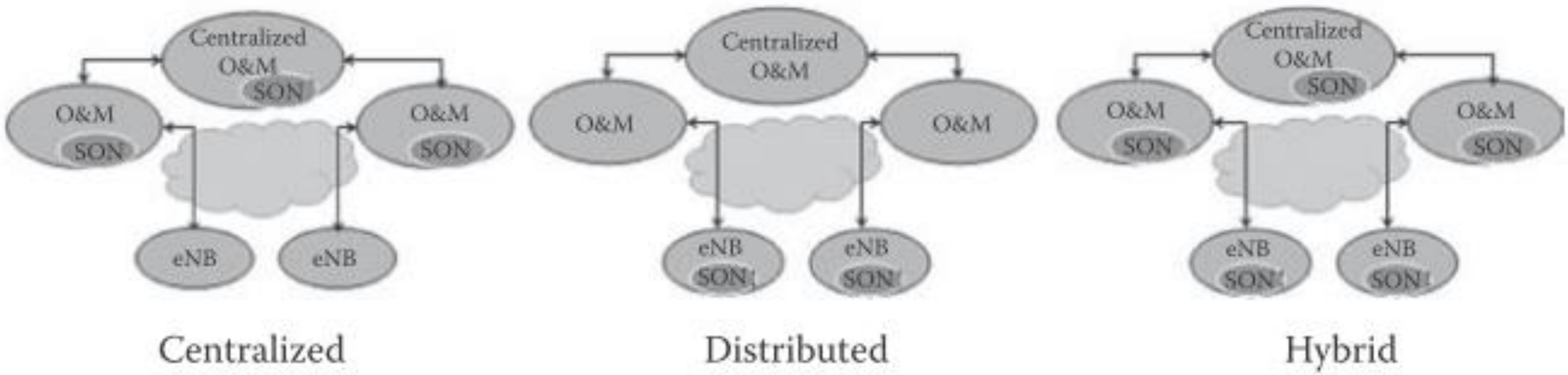
3GPP Specified SON Functions (2/2)

	Rel-9	*Rel-10*
Self-Optimization	– Coverage and capacity optimization – Mobility load balancing – Mobility robustness optimization – Avoidance of drive tests – SON evaluation scenario – RACH optimization RACH = Random Access Channel	– Coverage and capacity optimization (spillover, new features like relays) – Mobility load balancing – Mobility robustness optimization (spillover, new features like relays) – Avoidance of drive tests – SON evaluation scenario – RACH optimization – Interference reduction – Intercell interference coordination – Energy savings – Control and resource optimization of relays

Details will be shown later

SON Structure Category (1/2)

- Based on the location of the functions:
  - Centralized SON, executed in operation and maintenance (OA&M) system
  - Distributed SON, executed in eNBs
  - Hybrid SON, executed in both OA&M system and eNBs

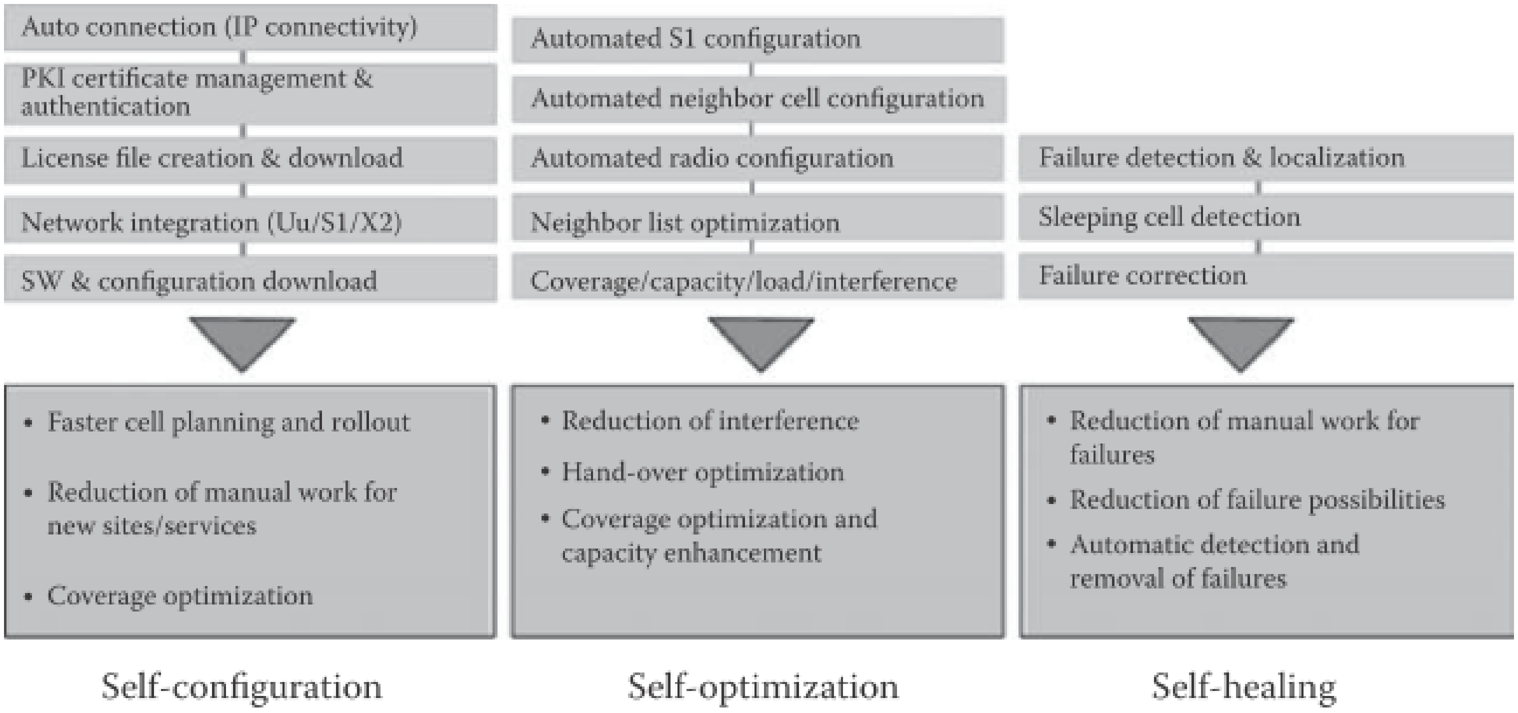


SON Structure Category (2/2)

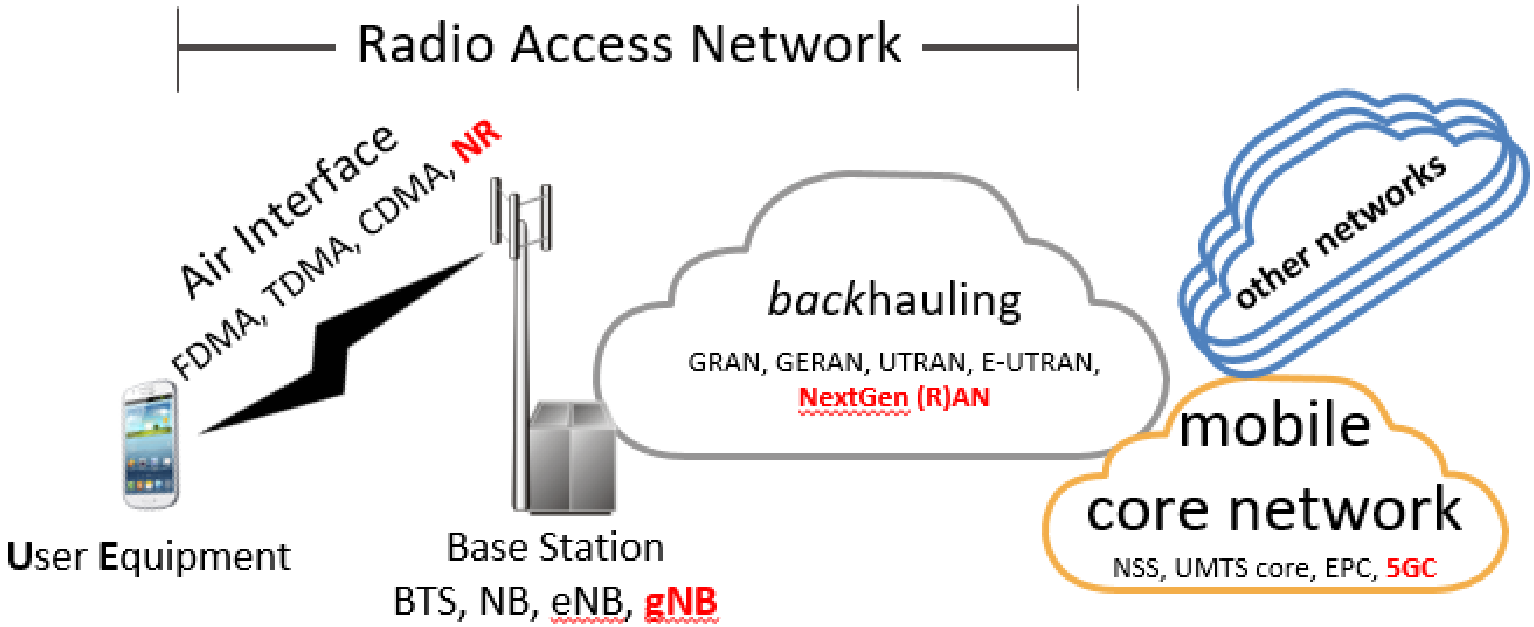
Centralized	Distributed	Hybrid
• The SON system is centrally executed at the network management level; all data has to be forwarded on a central level • Multiple cells involved • All data flow is into and out of the network management level; longer update • Simpler multivendor solution • Stable and easy to implement and upgrade • Addresses multiple cells	• The SON system is distributed in each node; however, cells communicate with each other • Scalable; fast and flexible updates • Short-term statistics • Lower backhaul impact • Low latency, high availability • Addresses only one cell	• The SON is executed partly at the network operations level and partly at the cell level • Advantages and disadvantages of previous solutions • Low latency, high availability • Requires additional interface definition • More complex handing

SON Capabilities

- The main SON functionalities consisting of self-configuration, self-optimization and self-healing are referred to as SON capabilities.



Air Interface



Cells

Area to be covered is tessellated with cells, each served by a BS ideally circular/hexagonal, but precise pattern determined by planning.

- Macrocell < 35 km, typically 5-10 km (terrain dependent), about 25w
- Small cells
  - microcell < 2 km about 5w (often used to supplement coverage)
  - picocell< 200 m < 1w (inside buildings, underground parking, etc.)
  - femtocell ≈ 10 m 100 mW(home, small businesses)

Cells (cont'd)

- Each cell may use multiple frequencies to support multiple users in same cell but adjacent cells do not usually use the same frequencies
- Cell boundaries may be dynamic
  - cell breathing is a load balancing mechanism where overloaded cells reduce transmit power (changing service area), thus offloading subscribers neighboring cells
- Cells may overlap
  - in CO-MIMO BSs jointly transmit/receive data to/from users
  - in CoMP BSs coordinate with each other to reduce interference at edges

Handoff (Handover)

- True mobility is implemented by handoff (handover)
  - which is when an active call or data session is transferred from one cell to another
  - when user moves out of serving cell's coverage area or when serving cell is overloaded
- Hard handoff (break before make)
  - the existing session breaks before new connection is established
  - if performed quickly enough the discontinuity made not be noticed

Handoff (Handover) (cont'd)

- Soft(smooth) handoff (make before break)
  - two sessions exist during handoff
  - no discontinuity, but more costly (consumes double resources)
- To enable handoff (exact details depend on the protocol)
  - UE continually monitors signal strength of serving BS and neighboring BSs
  - UE sends these measurements to network
  - the network knows channel availability in each cell
  - the network decides if/when/how to perform handoff

Spectral efficiency

- Given a spectral bandwidth the obtainable data rate
  - depends on the *spectral efficiency* specified in bits/sec per Hz (b/s/Hz)
- Achievable spectral efficiency for a given BW depends on *path loss* and *noise*
  - Shannon's capacity law states $C = BW \log_2(SNR + 1)$
- Noise sources (ITU-R P.372-13)
  - thermal noise (including that of the receiver front end)
  - atmospheric noise (about 40 lightning flashes per second worldwide)
  - cosmic background noise
  - man-made noise

Spectral efficiency (cont’d)

Spectral efficiency has improved from cellular generation to generation

- GSM channel spacing is 200 kHz and digital rate 16 kBit/sec
  - spectral efficiency is 0.08 b/s/Hz
- 3G HSDPA can provide about 14 Mbps in 5 MHz bandwidth
  - spectral efficiency is 2.8 b/s/Hz
- LTE R8 DL max channel bandwidth is 20 MHz and max bit rate is 300 Mbps
  - channel efficiency is 15 b/s/Hz
- 5G NR may achieve > 50 b/s/Hz

Synchronization

- BSs of neighboring cells use different frequencies
  - how are these frequency generated?
- Any error in frequency will lead to spectral overlap and hence interference
  - leaving *guard* frequencies would lead to inefficient use of spectrum
- Some modulation/duplexing/multiple access techniques
  - additionally need accurate phase (time) in particular to enable smooth handoff

Synchronization (cont'd)

Two synchronization methods are commonly used:

- deriving frequency/time from **G**lobal **N**avigation **S**atellite **S**ystem (e.g., GPS)
- deriving frequency/phase from the backhaul network
  - frequency from physical layer - SDH or SyncE
  - time from time distribution protocols, e.g., IEEE 1588v2 and NTP

Duplexing

- **F**requency **D**omain **D**uplexing
  - (D)AMPS 824-849 MHz uplink (UE→BS), 869-894 MHz downlink (BS→UE)
  - 2G GSM, e.g., 1710.2-1784.8 uplink, 1805.2-1879.8 DL
  - 3G UMTS and 4G LTE FDD, e.g., 1920-1980 UL 2110-2170 DL
- **T**ime **D**omain **D**uplexing, used in:
  - 802.16 WiMAX
  - 3G TD-SCDMA
  - 4G LTE TDD (2.3 GHz and 2.5 GHz bands)

Duplexing (cont'd)

- TDD allocates UL and DL time slots in the same frequency band
- TDD has advantages
  - easy to adapt to asymmetric data rates
  - efficient for burst data
  - can attain higher spectral efficiency than FDD (less guard waste)
  - channel reciprocity
  - facilitates beamforming
  - suffers from the need for highly accurate time synchronization

Multiple Access

- The challenge of **M**ultiple **A**ccess in a single cell is that the sources to be MUXed are (at least initially) uncoordinated
- Different multiple access methods have been used in cellular standards
  - **F**requency **D**omain **MA**(AMPS)
  - **O**rthogonal **FDMA** (LTE BS→UE DL, UL uses similar SC-FDMA to improve PAR)
  - **T**ime **D**omain **MA**(D-AMPS)
  - Combined FDMA and TDMA (GSM)
  - Code Domain **MA** (2G IS-95, 3G EV-DO)

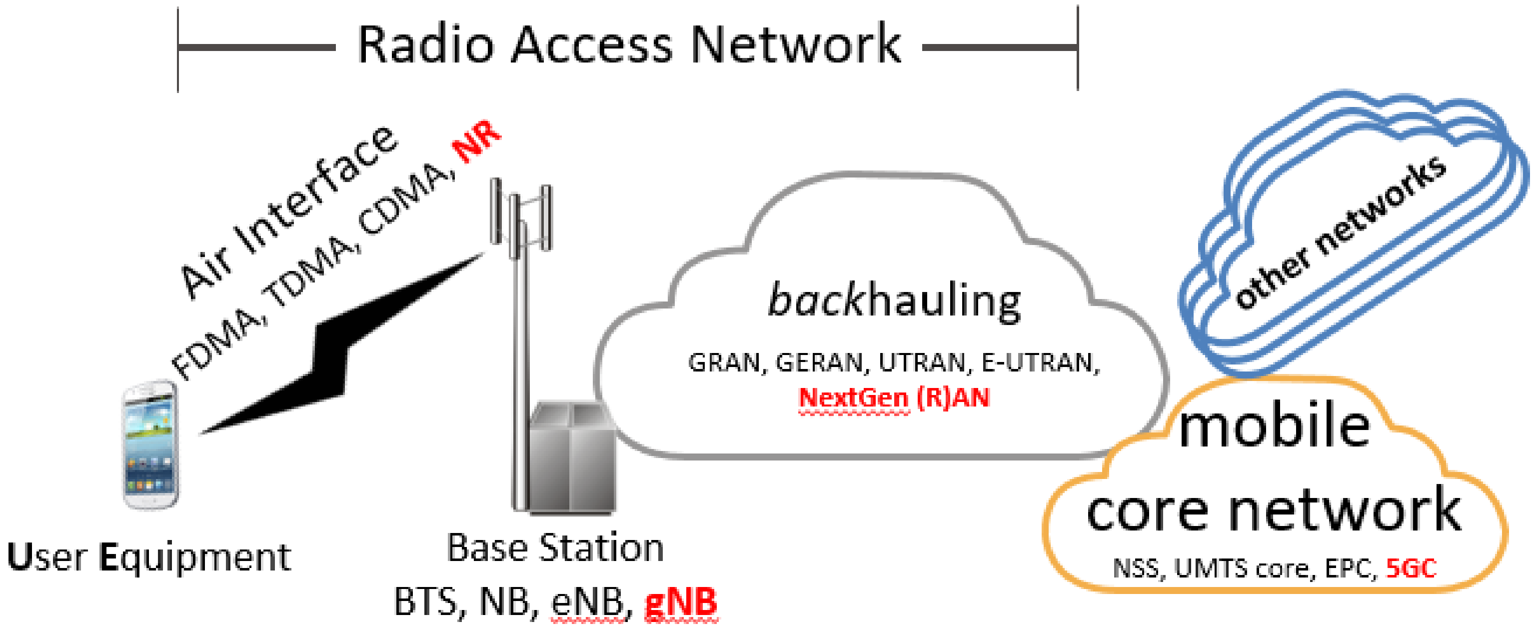
Multiple Access (cont'd)

- In FDMA, users are allocated frequencies in the frequency band
- OFDMA optimizes spectral efficiency by allowing minimal channel spacing
- In TDMA, users are allocated time slots in a periodic frame
- In GSM, there are 125 different UL/DL frequency pairs
  - each supporting 8 time slots
- In CDMA, users are allocated (nearly) orthogonal spreading codes
- Resource allocation is performed by the RAN

Modulation

- Modulation techniques applied to cellular traffic
  - 1G AMPS used analog **F**requency **M**odulation (30 kHz channel BW)
  - 2G GSM and GPRS (8 kbps) use **G**aussian **M**inimum **S**hift **K**eying (PSK variant)
  - 2.75G EDGE data (384kbps) uses 8PSK and evolved to (1.5 Mbps) 16/32-QAM
  - IS-136 CDMA (8 kbps) uses DQPSK, IS-95 cdmaONE (8 kbps) QPSK/OQPSK
  - 3G UMTS WCDMA (2Mbps) BPSK,QPSK
  - 3G CDMA2000 EV-DO (2 Mbps) uses BPSK, QPSK, 16-QAM
  - 3.5G HSPA DL (14Mbps) BPSK, QPSK, 16-QAM
  - 3.75G HSPA+ DL (168Mbps) dual carrier, 2*2 MIMO, up to 64-QAM
  - 4G LTE DL (100 Mbps) OFDM + PSK/QAM up to 64-QAM
  - 4.5G LTE-A (300 Mbps) improves LTE using up to 256-QAM (+ MIMO)
  - 5G **N**ew **R**adio is also based on LTE's OFDMA, but with improvements

Radio Access Network

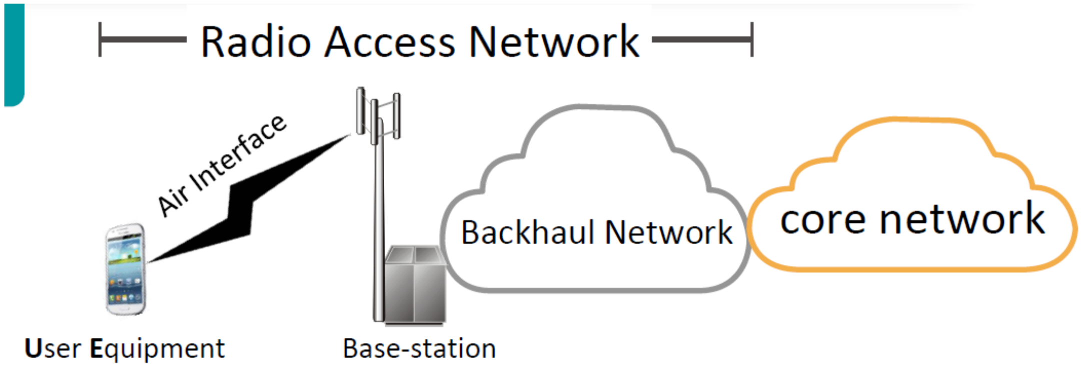


Backhaul

- Connecting base-stations directly to a core network and modern cellular networks are indeed approaching ideal logically if not physically.
- The simplistic approach suffers from drawbacks due to the large number of base-stations.
  - base-stations would require many physical ports (expense)
  - physical ports would need to support high rates
  - many fiber runs would be needed to interconnect
  - base-stations would need to be routers
  - base-stations would need to support redundancy for other base-stations
  - core network would extend to edge with security implications

Backhauling

- Base-station connectivity is supported by a backhaul network that connects the base-stations to the core network
- The air interface and the backhaul network together form the Radio Access Network (RAN)
- The backhaul segment (aka transport segment) is the part of the RAN between the base-station and the core network (aka backbone network)



Backhaul Topologies

- Star (for small backhaul networks)
- Daisy chain (e.g., GSM Abis chaining)
- Tree (implemented actively or using PON)
- Rings

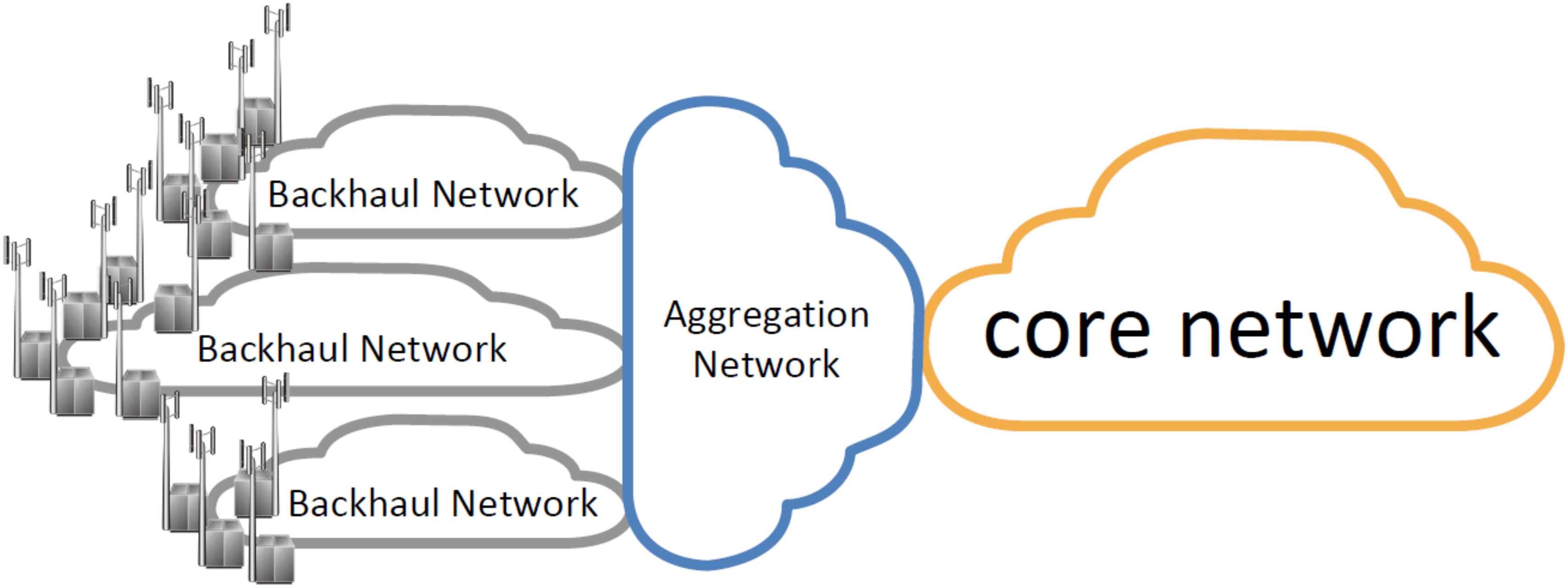
Backhaul Protocols

- Backhaul networks rely on various transport technologies
  - PDH and/or SONET/SDH and/or ATM (2G and 3G)
  - Point-to-point microwave
  - Carrier Ethernet networks
  - IP (IPv4 and IPv6)
  - MPLS
  - DSL
  - Satellite

Aggregation Segment

- Backhaul networks are designed for
  - relatively low data rates from base-stations
  - very high scale
  - constrained cost (CAPEX and OPEX)
- Often backhaul network protocols are not fully standardized
  - necessitating vendor-homogenous backhaul networks
- To support the conflicting requirements, aggregation networks are often employed

Aggregation Network



Fronthaul

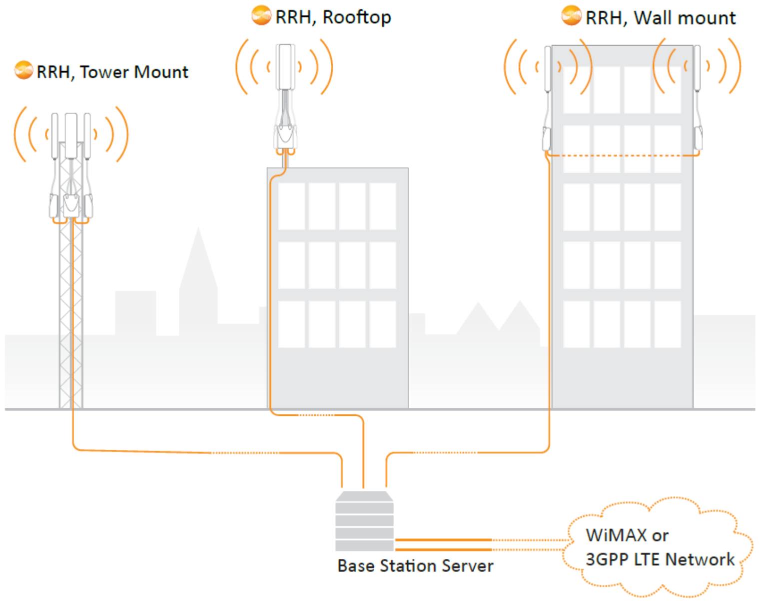
- Fronthaul was initially a solution to transport RF between the antenna at the top of a tower and the BS processing at the bottom of the tower
- When transporting analog RF in coax, there is signal loss and noise to eliminate
  - perform the A/D conversion close to the antenna
  - transport a digital bit-stream down the tower

Fronthaul Protocols

- Common Public Radio Interface (CPRI)
  - specified by forum consisting of (Nortel), Ericsson, Huawei, NEC, Nokia
  - uses complex (I/Q) sampling
  - carried over dark fiber or OTN
- Open Base Station Architecture Initiative (OBSAI)
  - specified by forum consisting of Hyundai, LG, Nokia, Samsung, etc.
  - uses real (Nyquist) sampling

Fronthául Architecture (before 5G)

- Fronthaul decomposes the BS into
  - Remote Radio Head (RRH) at antenna (general 3 per installation per sector)
  - Baseband Unit (BBU) remotely located which are connected by optical fiber



CRAN, CRAN, and vRAN (before 5G)

- Fronthaul decomposes the BS into RRHs and a BBU, but we needn't locate the BBU at the foot of the tower
- It may make sense to have one BBU serve several base-stations using fronthaul links, that now need to be much longer
- Baseband processing places strict limits on the round-trip delay and thus on the fronthauling distance (e.g., 20 km for LTE)
- This architecture called Centralized RAN, is used for improving the scaling of the mobile network

C-RAN, and vRAN (before 5G)

BBU Hotelling or Cloud RAN (C-RAN)

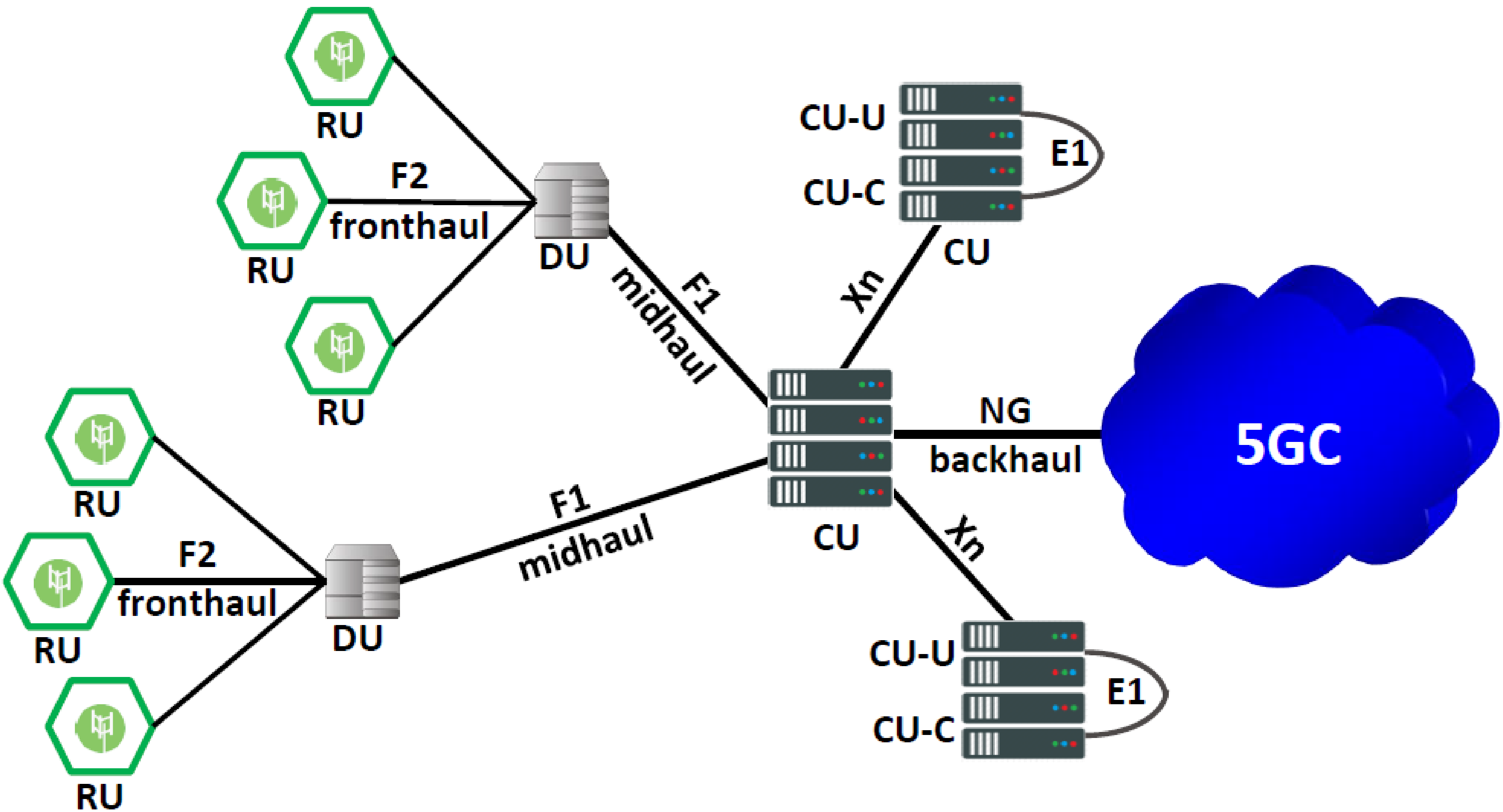
- Using load-balancing/resilience techniques developed for cloud computing may allow a central site to serve hundreds of RRHs.

Virtualized RAN

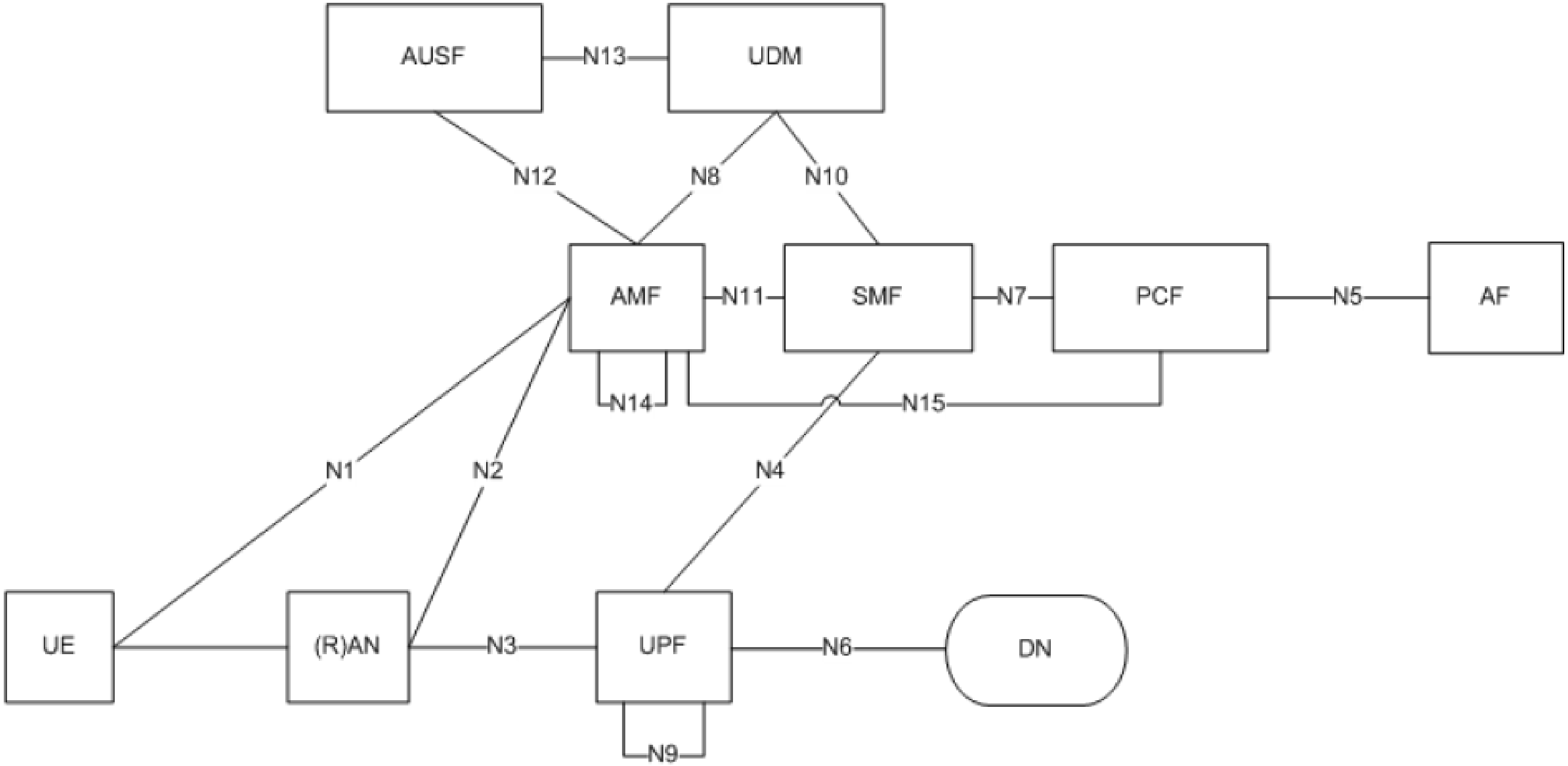
- If we already use cloud techniques, we may implement at least some of the BBU functionality in software (e.g., packet processing, control functionality) running as virtual machines inside a Data Center.

5G Architecture

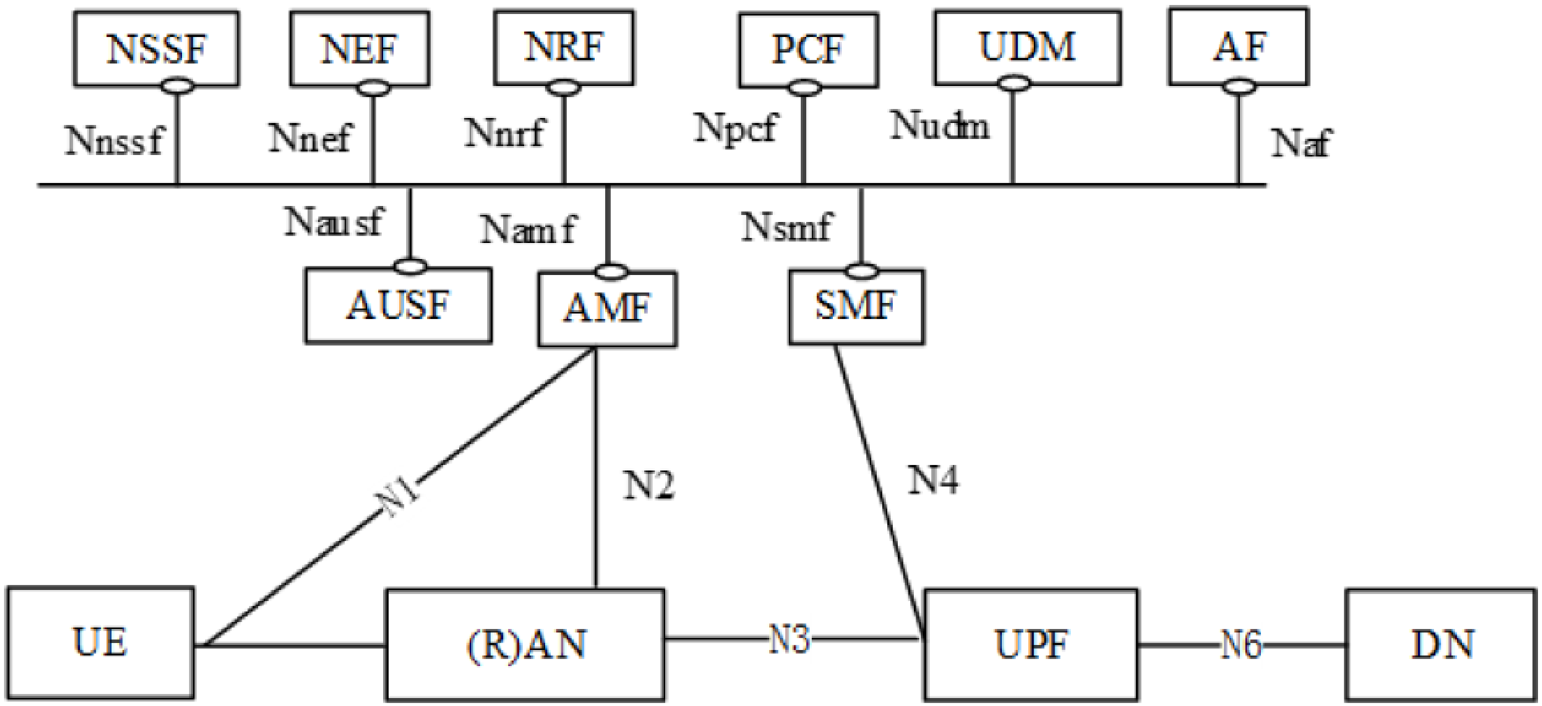
5G Architecture: RAN



5G Core (simplified) without SBA

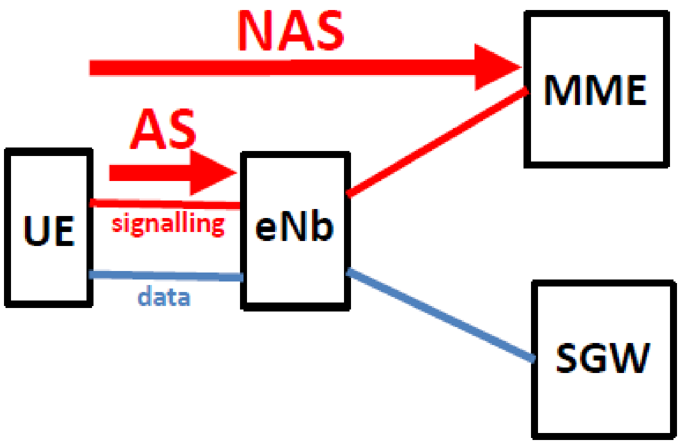


5G Core (simplified) with SBA



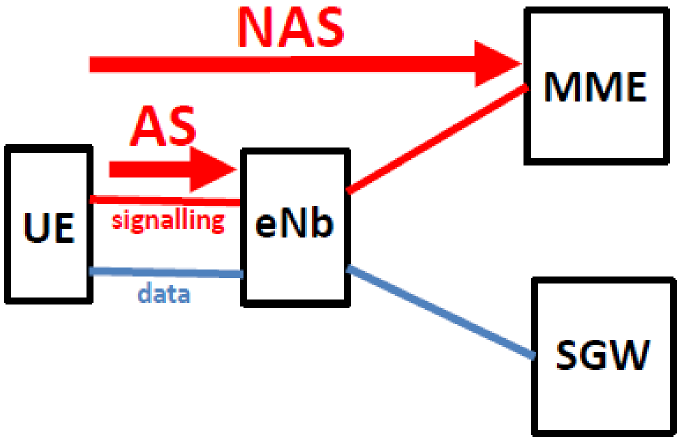
Access Stratum and Non-Access Stratum

- In all networks, we differentiate between user (Data, forwarding) plane and the control (and/or management) plane.
- In mobile networks, the control plane is further split into strata
  - Access Stratum (AS)
  - Non-Access Stratum (NAS)



Strata: AS and NAS

- Access Stratum (AS)
  - the signaling between the UE and the base station (NB, eNB, gNB)
  - deals with all the aspects of the air interface
- Non-Access Stratum (NAS)
  - between the UE and the core (in 4G with the MME)
  - handles establishing sessions and maintaining continuity as UE moves



Bearers

- In the physical layer, we talked about channels
- In higher layers, we talk about bearers
- A bearer is a transparent connection between UE and DN

Types:

- Data (user plane) bearers
- Signaling (control plane) bearers, which can be AS or NAS bearers

Bearers (cont'd)

On the air interface, there are 3 types of signaling bearers:

- Signaling Radio Bearer 0 (SRB0)
  - AS messages over **C**ommon **C**ontrol logical **CH**annel
- Signaling Radio Bearer 1 (SRB1)
  - NAS messages over **D**edicated **C**ontrol logical **CH**annel
- Signaling Radio Bearer 2 (SRB2)
  - high priority AS messages over DCCH logical channel

Access Stratum and Radio Resource Control

- The Access Stratum (AS) only controls the air interface and thus only the connection between the UE and one base station
- The highest layer of the AS is called Radio Resource Control (RRC)

RRC Messages

- RRC messages include:
  - system information broadcast (MIB, SIBs)
  - information for idle UEs (cell selection parameters, neighboring cell info)
  - emergency broadcast messages (Earthquake and Tsunami Warning System)
  - paging
  - connection establishment/modification/release
  - UE state (idle/connected) handling
  - handoff management (including security handling)
  - radio configuration (ARQ configuration, HARQ configuration, etc.)
  - assignment/release of user RBs
  - QoS control
  - recovery from radio link failure
  - measurement configuration and reporting

NAS Messages

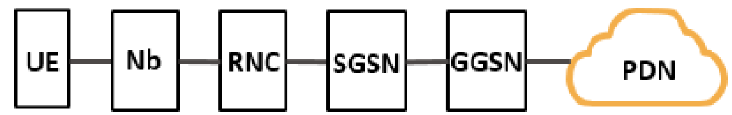
- The Non-Access Stratum controls the connection between the UE and the core independent of the serving base station
- NAS messages include:
  - identity management
    - identity request and response
    - authentication request and response
  - session management
    - session (PDN connection) request and response
    - session detach request and response
  - mobility management messages
    - tracking area update
    - mobility attach request and response
    - mobility detach request and response

Core Network (3G to 4G-CUPS)

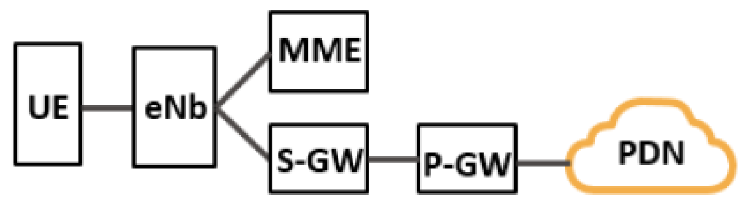
- 3G
  - Nb+RNC connect to the SGSN and GGSN
  - SGSN and GGSN handle both data and control
- 4G
  - Nb+RNC were unified into the eNB
  - eNB connects to S-GW and P-GW
  - Mobility management was separated
- 4G CUPS (R14)
  - separated UPFs and CPFs
  - S-GW-C and S-GW-U; P-GW-C, P-GW-U.

Core Network (3G to 4G-CUPS)

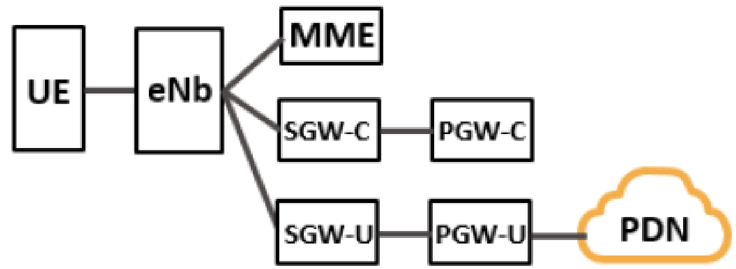
3G



4G

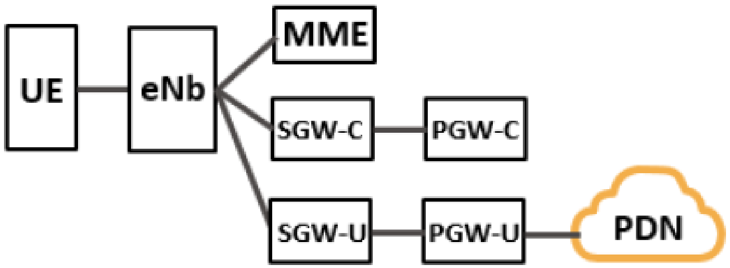


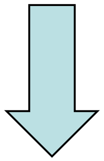
4G CUPS



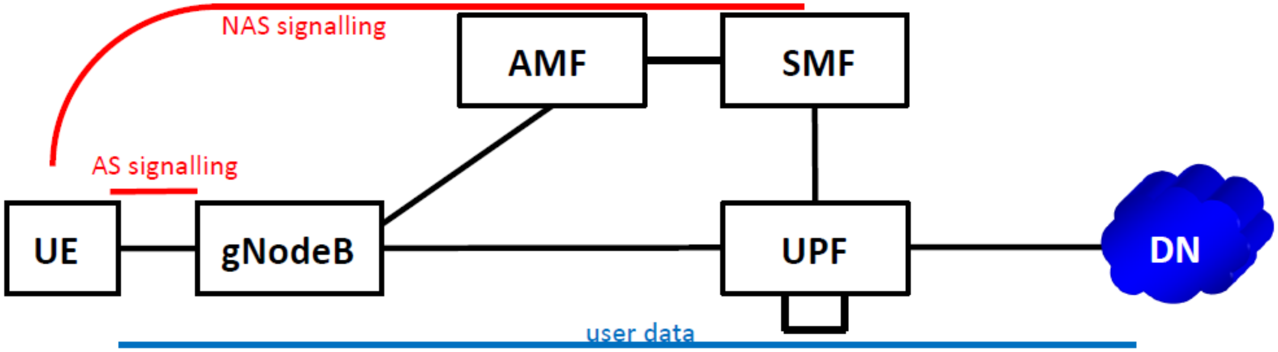
Core Network (4G-CUPS to 5G)

4G CUPS

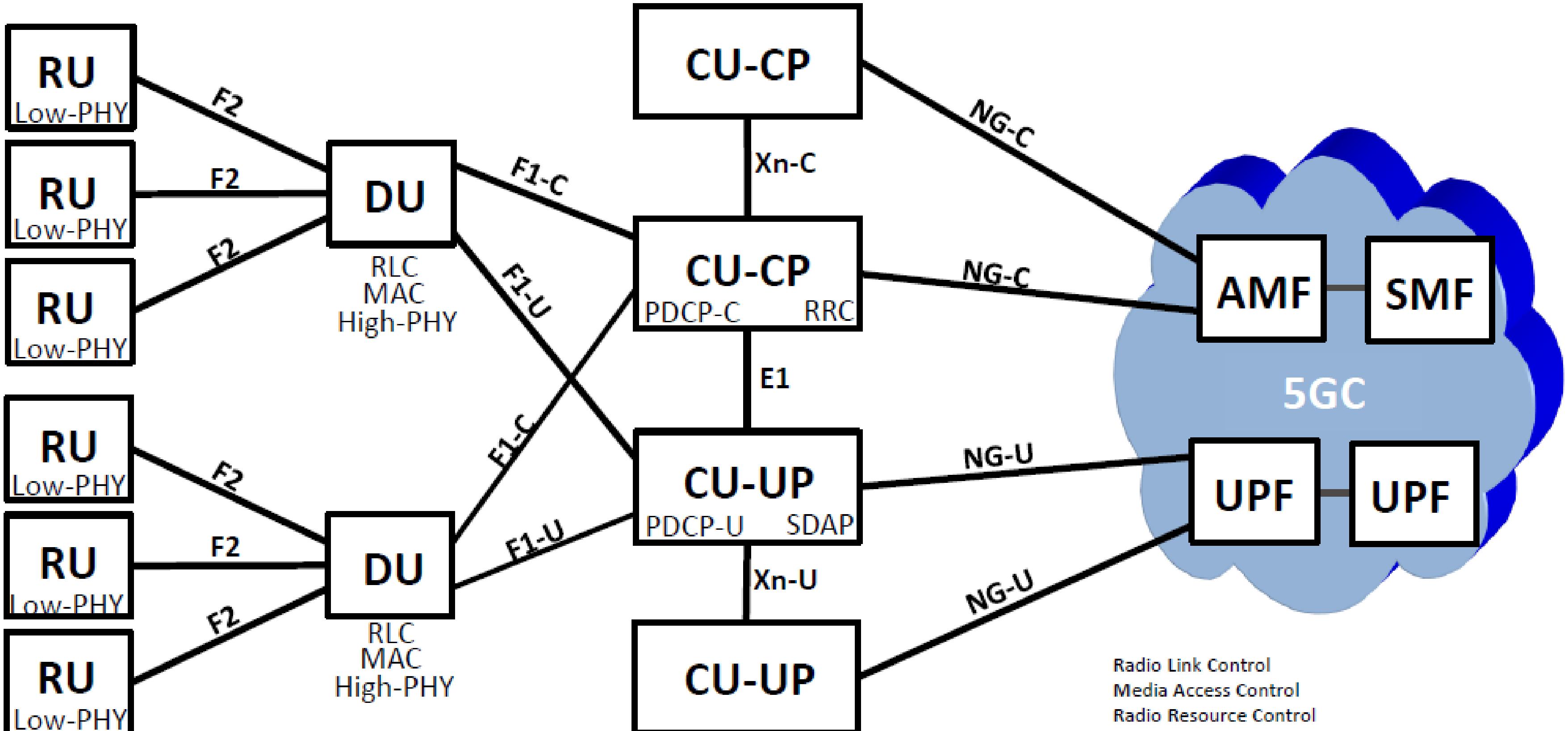




5G



5G RAN Architecture with CUPS



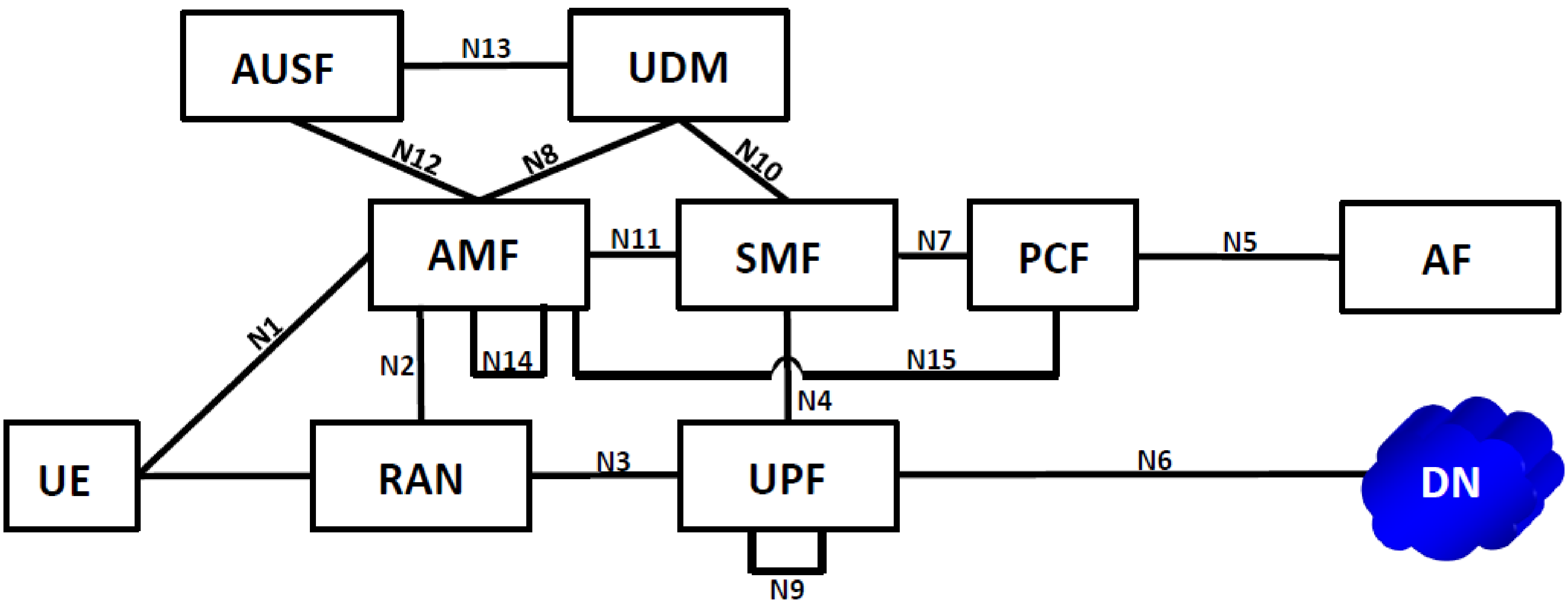
Radio Link Control
Media Access Control
Radio Resource Control
Packet Data Convergence Protocol
Service Data Adaptation Protocol

5G Core (simplified)

AUthentication Server Function
Access & Mobility Management Function

Unified Data Management
Session Management Function
Policy Control Function
User Plane Function

Application Function
Data Network



User Plane Function (UPF)

- The 5GC's User Plane Function performs all the user plane functions handled in 4G by S-GW, P-GW, and TDF
  - anchor for mobility
  - connection to external data networks (e.g., Internet)
  - optionally Firewall and Network Address Translation (NAT) functions
  - packet queuing
  - packet routing and forwarding
  - packet inspection, classification, QoS handling
  - policy enforcement
  - packet marking
  - lawful intercept
  - traffic usage statistics collection and reporting
  - IPv4 ARP and IPv6 neighbor solicitation

Decouple of AMF and SMF

The 4G MME has 2 distinguishable functions

1. access/mobility management
   - contacting the HSS, handling UE authorization and key distribution
   - allocating Temporary Mobile Subscriber Identity
   - managing handoff
   - lawful interception
2. session management
   - creating/updating/removing data sessions
   - allocating IP addresses
   - managing context for the UPF

A single RRC message often performs access and session attaches.
Access/mobility and session management can be separated into micro-services to increase flexibility and scalability

Access and Mobility Function (AMF)

The AMF performs the access and mobility functions that were handled by the 4G MME, S-GW-C and P-GW-C

- NAS signaling for access and mobility management
- UE authentication
- allocation of Globally Unique Temporary Identity and Temporary Mobile Subscriber Identity
- UE security context management
- registration management
- connection management
- reachability management
- mobility management
- apply mobility related policies from PCF (e.g., mobility restrictions)

Session Management Function (SMF)

The SMF performs the session management functions that were handled by the 4G MME, SGW-C, and PGW-C

- NAS signaling for session management
- managing the PDU sessions
- allocates IP addresses to UEs (DHCP server)
- selection and control of UPF
- sends QoS and policy information to RAN via the AMF
- downlink data notification
- supports MEC by selecting a UPF close to the edge
- applies policy and charging for services
- control plane for lawful interception