Mobile Communications

The 5th Generation of Cellular Networks

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References

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- Erik Dahlman, Stefan Parkvall, Johan Skold, “5G NR: The Next Generation Wireless Access Technology”, Elsevier, 2018
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- 3GPP TS 38.211 V2.0.0 (2017-12) Technical Specification Group Radio Access Network; NR; Physical channels and modulation (Release 15)
- 3GPP TS 23.501 V2.0.1 (2017-12) Technical Specification Group Services and System Aspects; System Architecture for the 5G System; Stage 2 (Release 15)
- 3GPP site, information related to 5G

Motivation and Capacity Enablers

Motivation for 5G

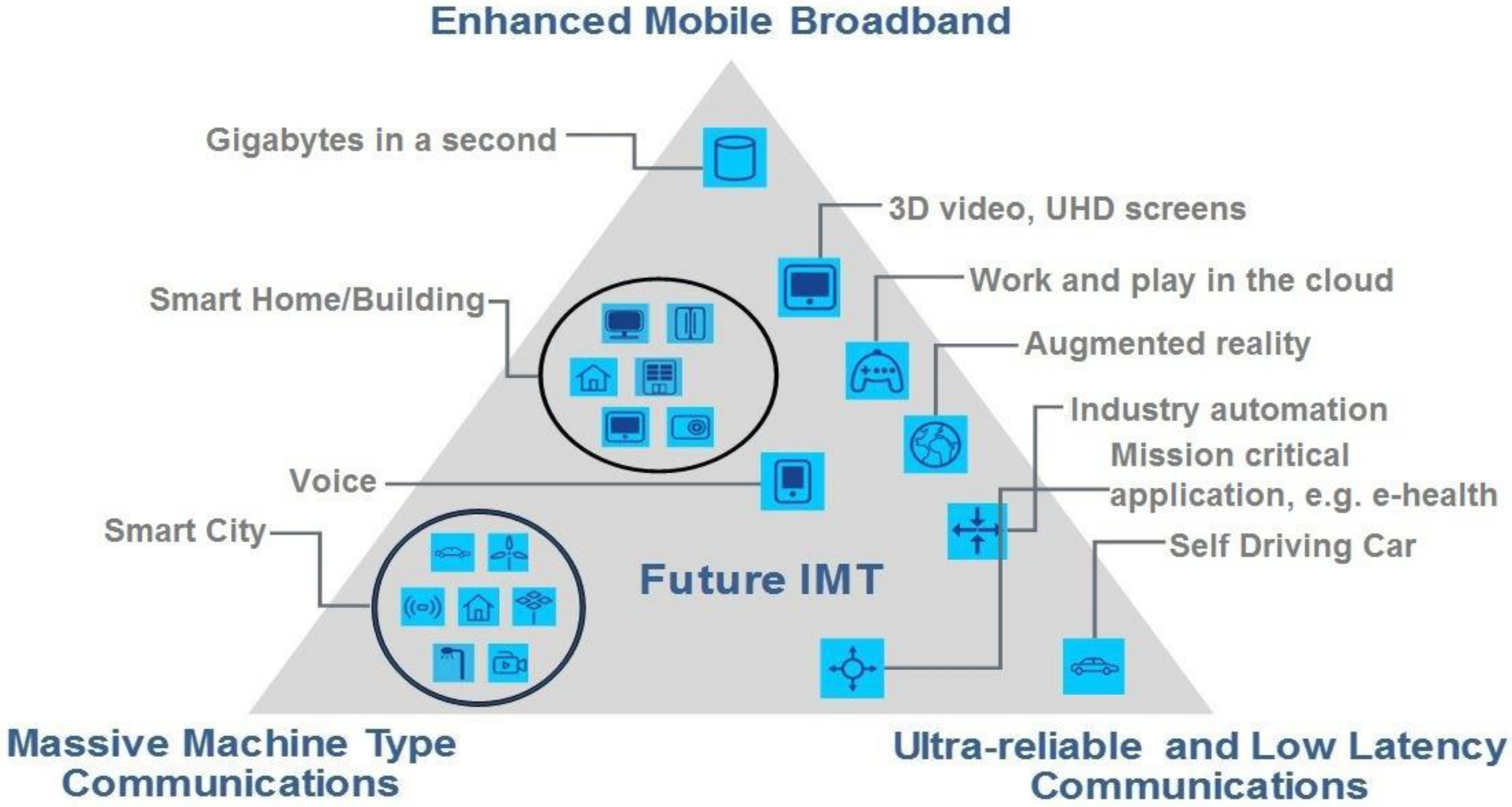
- Capacity demands posed mainly by video
  - 4K video demands a data rate of ~15 Mbit/s
  - Number of video views and viewing times are increasing
- But 5G (IMT 2020) is not limited to mobile broadband

5G Supported Categories

5G supports 3 broad categories

- » eMBB: Enhanced Mobile Broadband
  - – high user data rates
  - – wide-area coverage: seamless coverage, high mobility
  - – hotspot coverage: high user density, high traffic capacity
- » URLLC: Ultra-Reliable and Low Latency Communications
  - – stringent requirements for: reliability, latency, availability
  - – Examples: remote medical surgery, wireless control of industrial manufacturing
- » mMTC: Massive Machine Type Communications
  - – large number of devices, low volume of non-delay-sensitive data
  - – Devices required to: be low cost, have long battery life

IMT 2020 Use Case Categories



Minimum Performance Requirements

KPI	Key Use Case	Values
Peak Data Rate	eMBB	DL: 20 Gbps, UL: 10 Gbps
Peak Spectral Efficiency	eMBB	DL: 30 bps/Hz, UL: 15 bps/Hz
User Experienced Data Rate	eMBB	DL: 100 Mbps, UL: 50 Mbps (Dense Urban)
5% User Spectral Efficiency	eMBB	DL: 0.3 bps/Hz, UL: 0.21 bps/Hz (Indoor Hotspot); DL: 0.225 bps/Hz, UL: 0.15 bps/Hz (Dense Urban); DL: 0.12 bps/Hz, UL: 0.045 bps/Hz (Rural)
Average Spectral Efficiency	eMBB	DL: 9 bps/Hz/TRxP, UL: 6.75 bps/Hz/TRxP (Indoor Hotspot); DL: 7.8 bps/Hz/TRxP, UL: 5.4 bps/Hz/TRxP (Dense Urban); DL: 3.3 bps/Hz/TRxP, UL: 1.6 bps/Hz/TRxP (Rural)
Area Traffic Capacity	eMBB	DL: 10 Mbps/m^2 (Indoor Hotspot)
User Plane Latency	eMBB, URLLC	4 ms for eMBB and 1 ms for URLLC
Control Plane Latency	eMBB, URLLC	20 ms for eMBB and URLLC
Connection Density	mMTC	1,000,000 devices/km^2
Energy Efficiency	eMBB	Capability to support high sleep ratio and long sleep duration to enable low energy consumption when there is no data
Reliability	URLLC	$1–10^{-5}$ success probability of transmitting a layer 2 protocol data unit of 32 bytes within 1 ms in channel quality of coverage edge
Mobility	eMBB	Up to 500 km/h
Mobility Interruption Time	eMBB, URLLC	0 ms
Bandwidth	eMBB	At least 100 MHz; Up to 1 GHz for operation in higher frequency bands (e.g., above 6 GHz)

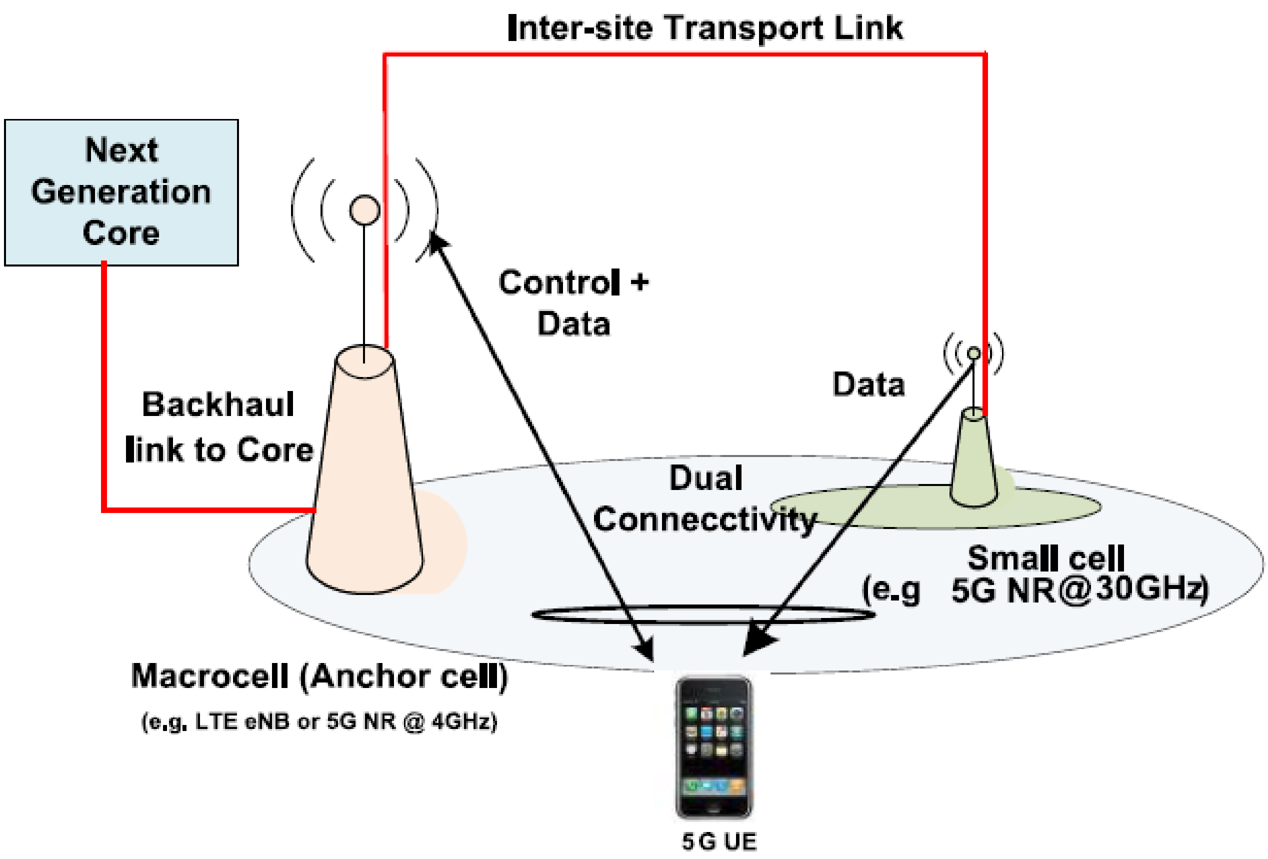
Performance Indicators

- High peak data rate determines
  - maximum bandwidth
  - spatial degrees of freedom
  - modulation and coding
- User experienced data rate (5 percentile of CDF) determines
  - cell sizes
  - interference mitigation techniques to overcome low SINR at cell edge
- High area capacity demands
  - network densification via small cells
- Low latency requirement demands
  - Low transmit time intervals
- High energy efficiency requires
  - low power consumption when there is no data to transmit

Capacity Enablers

- Increased bandwidth
  - Current mobile systems deployed in congested bands smaller than 6 GHz
  - Plenty of spectrum available in 28-300 GHz bands
- Massive MIMO antenna arrays at the base station
  - Arrays from 256 to 1024 antenna elements
  - Providing array and spatial multiplexing gains
  - Enabling multiuser
- Network densification
  - Traffic offloading to small cells (indoor hotspots, dense urban micro cells)
  - Interference mitigation techniques
- Flexible radio and network management schemes

Dual connectivity principle



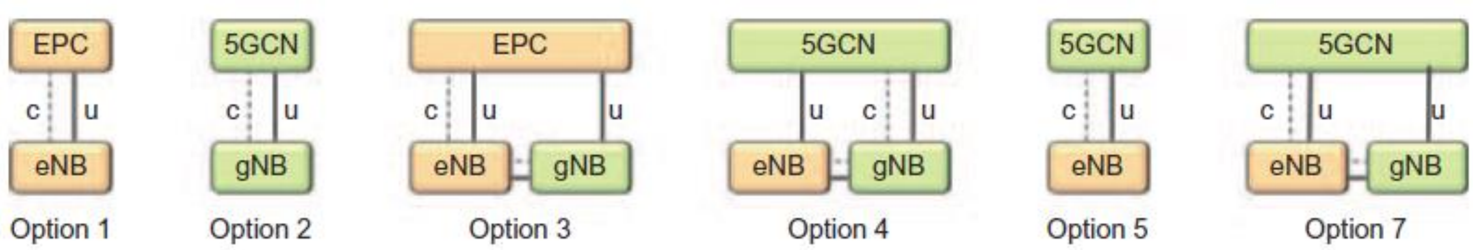
Radio Access Network

Radio Access Network (RAN)

- RAN is responsible for radio-related functions
  - » Scheduling, radio-resource handling, retransmission protocol
  - » modulation, coding, multi-antenna schemes

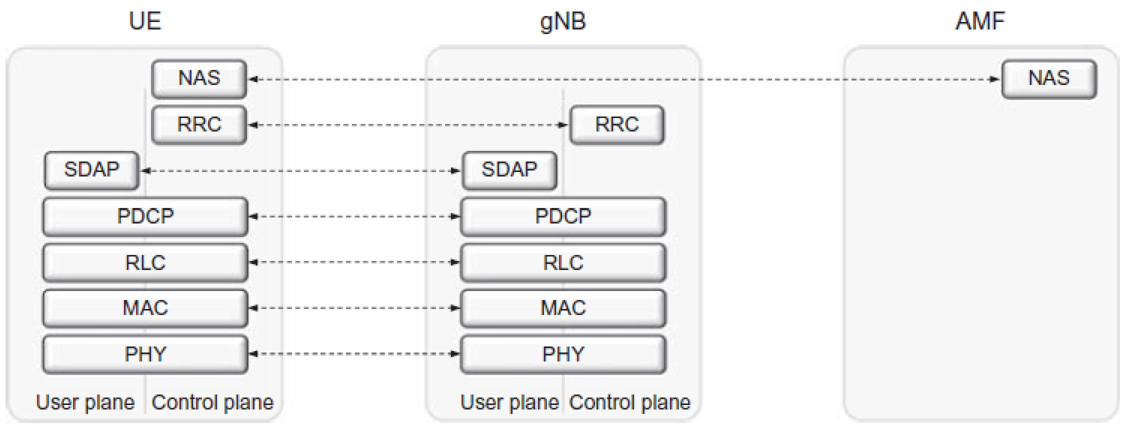
- NG-RAN may connect to 5GCN (5G core network) or EPC (LTE)

- NG-RAN has 2 types of nodes connected to the core network
  - » gNB: serving New Radio (NR) devices
  - » eNB: serving LTE devices



Radio Access Network - Protocol Architecture

- User-plane and Control-plane protocol stack
  - » Service Data Adaptation Protocol (SDAP, for QoS)
  - » Packet-Data Convergence Protocol (PDCP)
  - » Radio Link Control (RLC)
  - » Radio Resouce Control (RRC)



- AMF is not part of the RAN

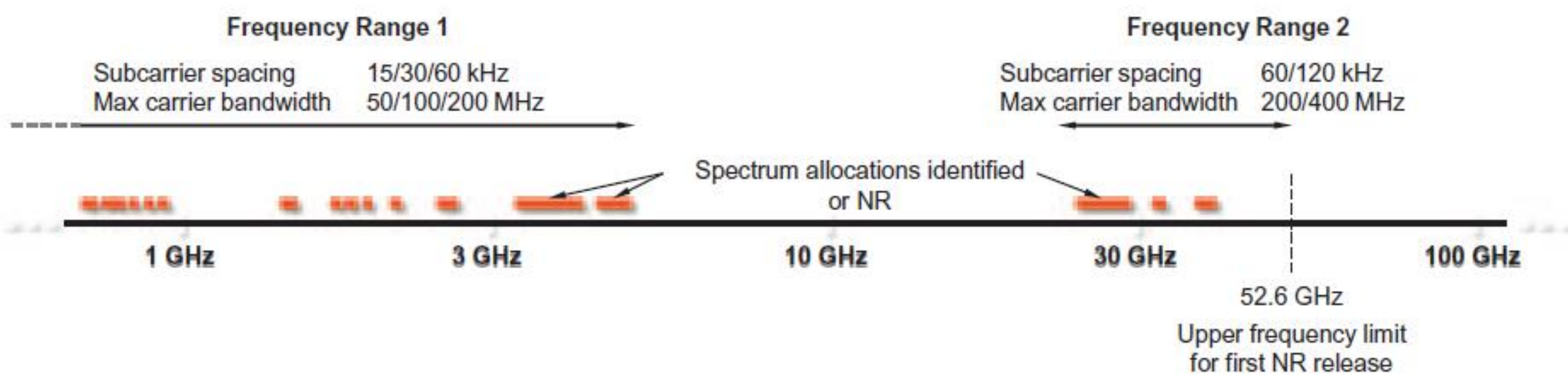
5G Spectra

- 2 frequency ranges defined
  - » Frequency Range 1 (FR1): 0.45 – 6 GHz
  - » Frequency Range 2 (FR2): 24.25 – 52.6

Faixas de frequências, número de lotes

Faixas	Número de lotes
700 MHz	6 lotes de 2 x 5 MHz
900 MHz	1 lote de 2 x 5 MHz
900 MHz	4 lotes de 2 x 1 MHz
1800 MHz	3 lotes de 2 x 5 MHz
2,1 GHz	1 lote de 2 x 5 MHz
2,6 GHz	2 lotes de 2 x 5 MHz
2,6 GHz	1 lote de 25 MHz
3,6 GHz (com restrições até 2025)	6 lotes de 10 MHz
3,6 GHz (com restrições até 2025)	4 lotes de 10 MHz
3,6 GHz	30 lotes de 10 MHz

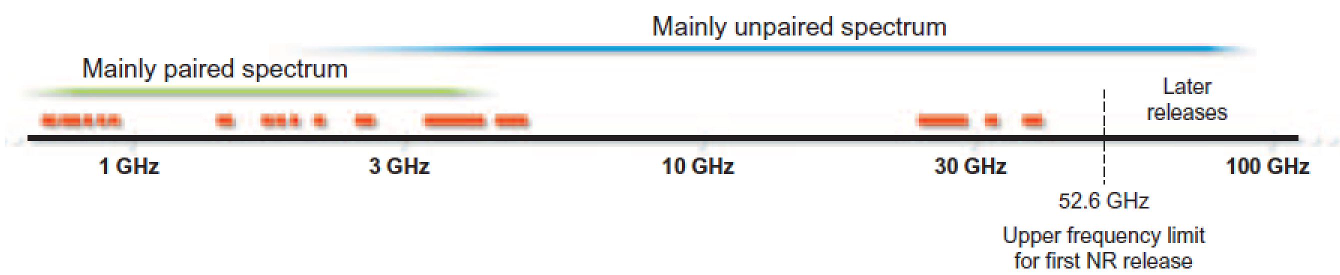
Auction in Portugal



Duplex Schemes

- Lower frequencies
  - » Allocations are often paired → Frequency Division Duplex (FDD)

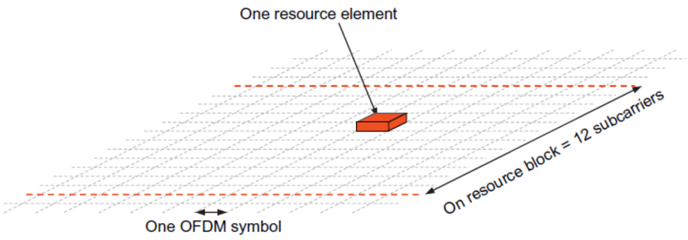
- Higher frequencies
  - » Unpaired spectrum allocations are increasingly used



New Radio for 5G - Numerologies

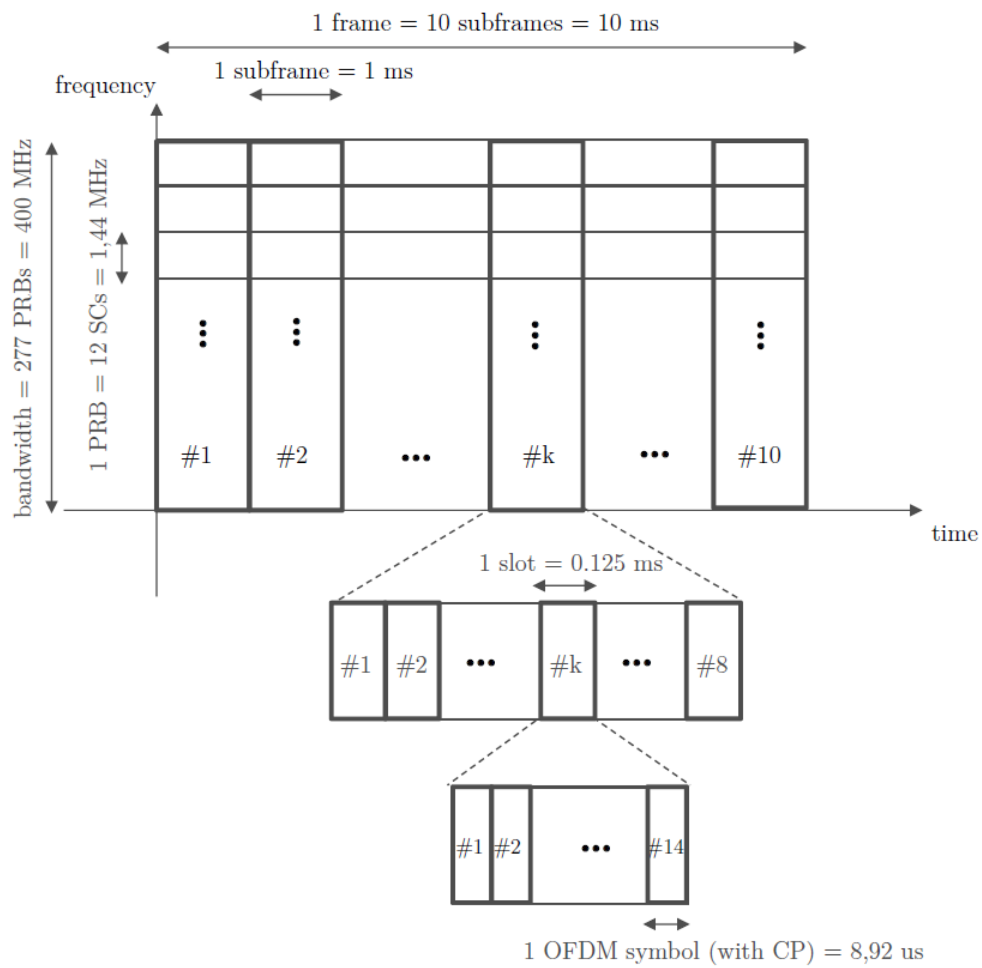
- 5G defines flexible OFDMA resource blocks by means the numerologies μ
- Objective of numerologies:
  - » address tradeoff between delay and throughput for different types of traffic
- URLLC traffic demands low latency
  - » Short symbol duration → High numerology number
- eMBB traffic demands high throughput
  - » Large slot duration → Low numerology number

	$\mu = 0$	$\mu = 1$	$\mu = 2$	$\mu = 3$	$\mu = 4$
SCS [kHz]	15	30	60	120	240
OFDM symbol length [us]	66.67	33.33	16.67	8.33	4.17
Cyclyc prefix [us]	~4.8	~2.4	~1.2	~0.6	~0.3
Number of subframes in frame	10	10	10	10	10
Number of slots in subframe	1	2	4	8	16
Slot length [us]	1000	500	250	125	62.5
Number of OFDM symbols in slot	14	14	14	14	14
Number of subcarriers in a PRB	12	12	12	12	12
PRB width [MHz]	0.18	0.36	0.72	1.44	2.88

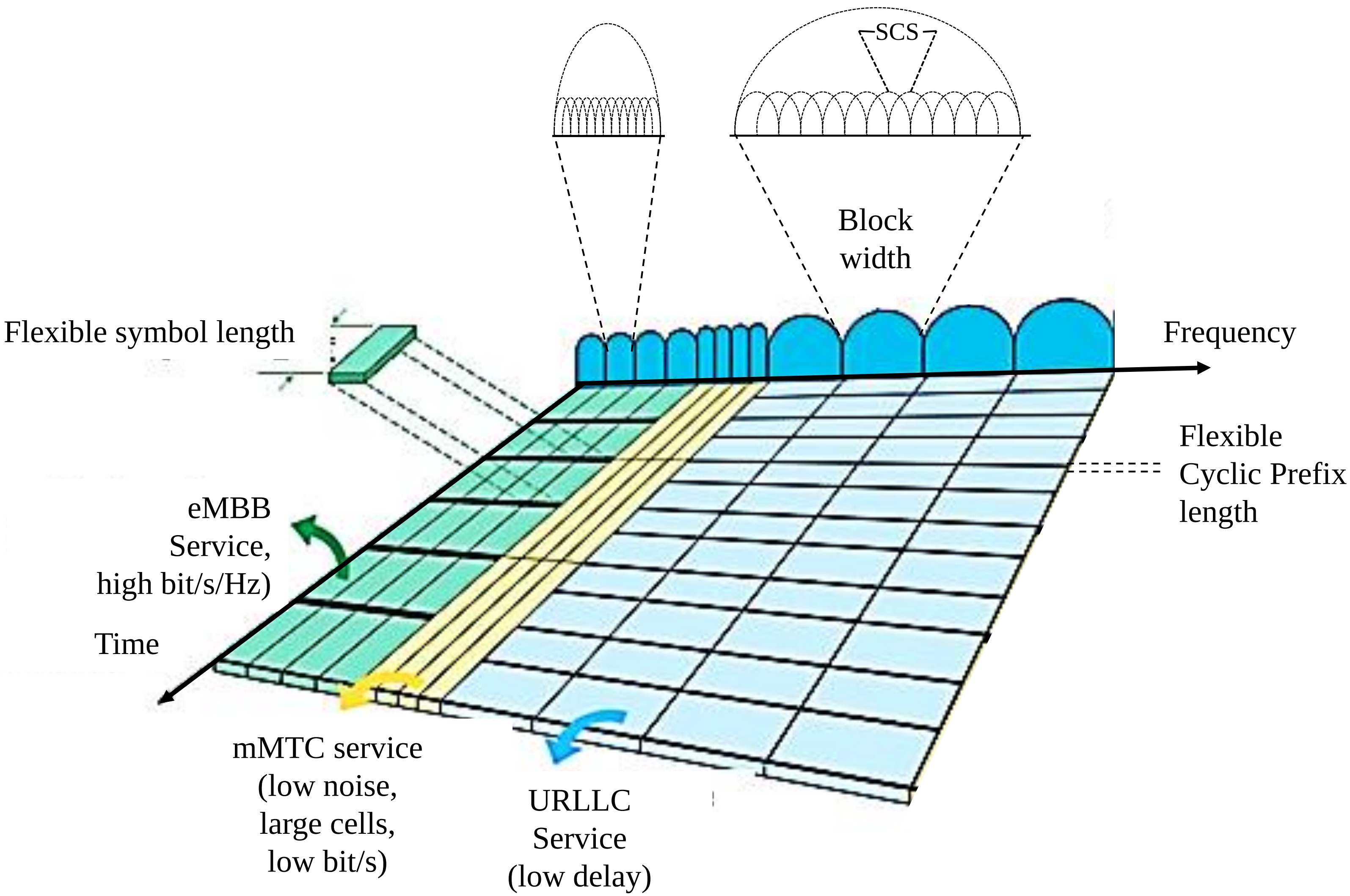


New Radio Time-Domain Frame Structure

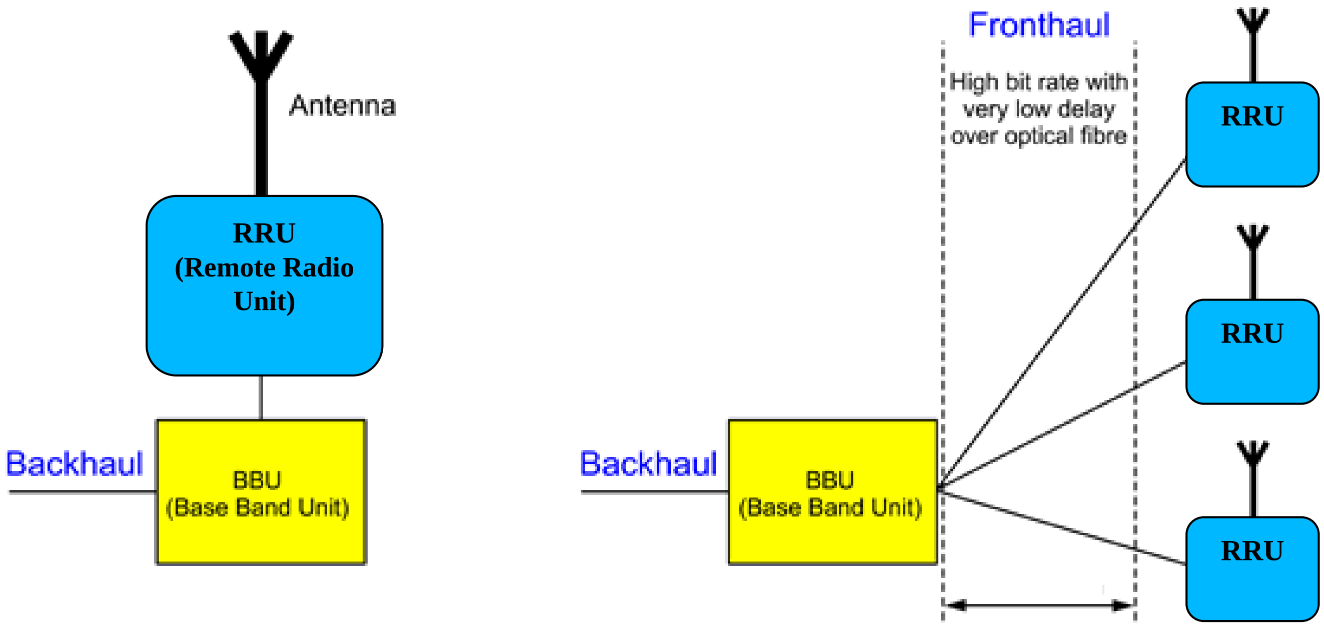
- Example: μ = 3, total bandwidth = 400 MHz



New Radio for 5G - Numerologies



Cloud RAN Architecture



Traditional Compact Base Station with self-contained baseband processing

C-RAN Architecture with Centralised Baseband Processing with distributed **Remote Radio Units**

Cloud RAN Architecture

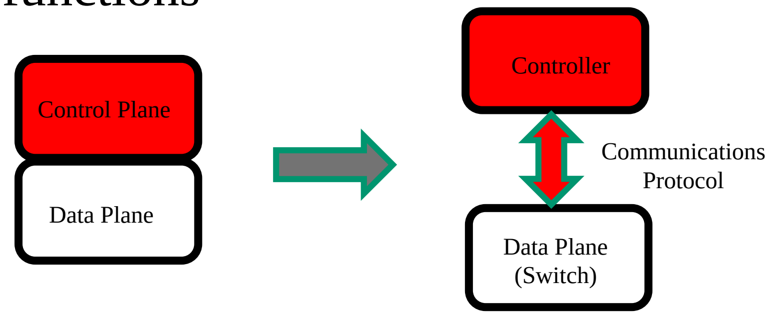
- Cloud RAN (C-RAN) architecture
  - » Split of base station functions
  - » Remote Radio Unit (RRU) located at the base station site
  - » Baseband Unit (BBU), centralized, located in data center
  - » Digital I/Q samples are transported between RRU and BBU

- Benefits of C-RAN
  - » Inter-site scheduling and cooperative techniques
  - » NFV can be applied also the radio protocol stack

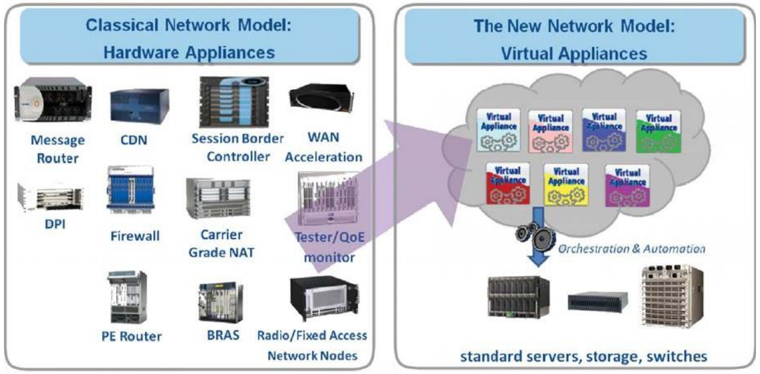
Software-enabled 5G Core Network

SDN and NFV - Principles

- Software-Defined Networking (SDN)
  - » Logical separation of the control and data functions



- Network Functions Virtualisation (NFV)
  - » Abstracting software from the hardware platform



Software Defined Networking (SDN) Enabled 5G Core Network

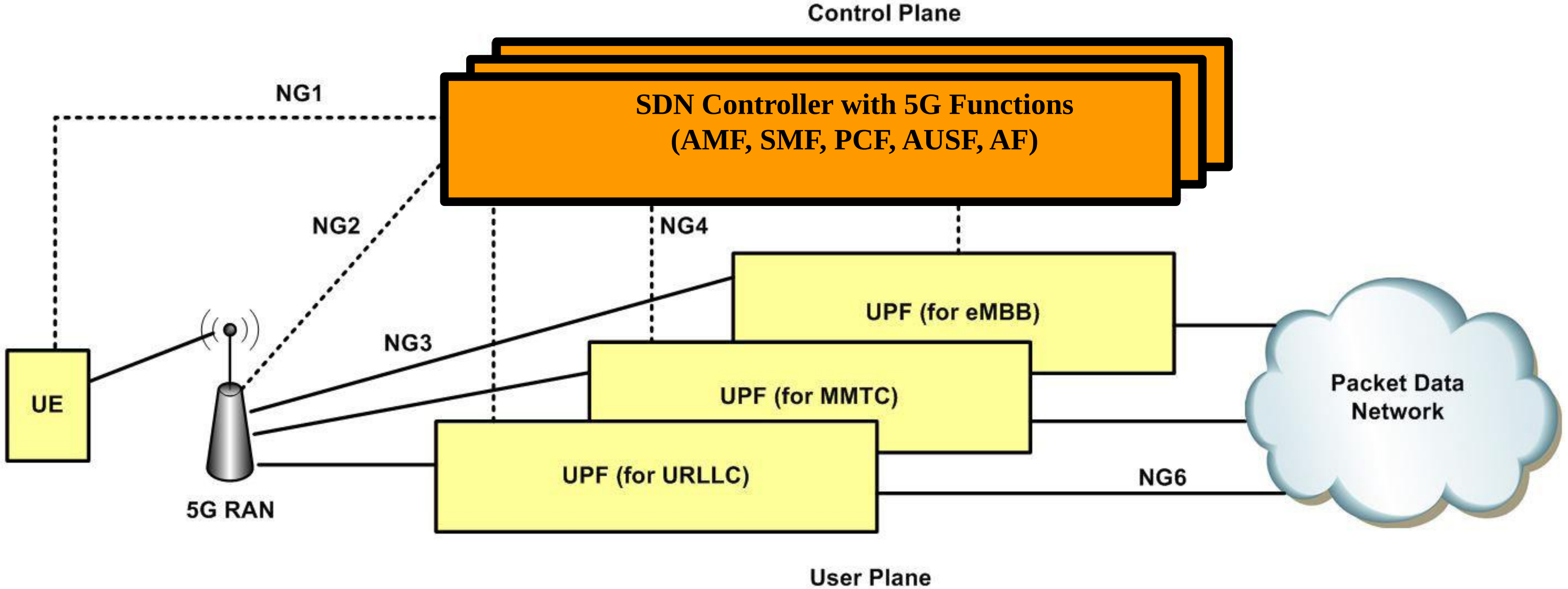
- Motivation of Software Defined Networking (SDN) → programmability of networks

- Decoupling of control plane and user plane
  - Scalable, distributed, stateless forwarding plane
  - Flow tables define how packets are forwarded
  - Flow tables are populated by a centralised control plane entity

- SDN concept applied to 4G Evolved Packet Core (EPC) implies
  - Redefinition of 4G MME, SGW, PGW
    because control functions exist also in these entities

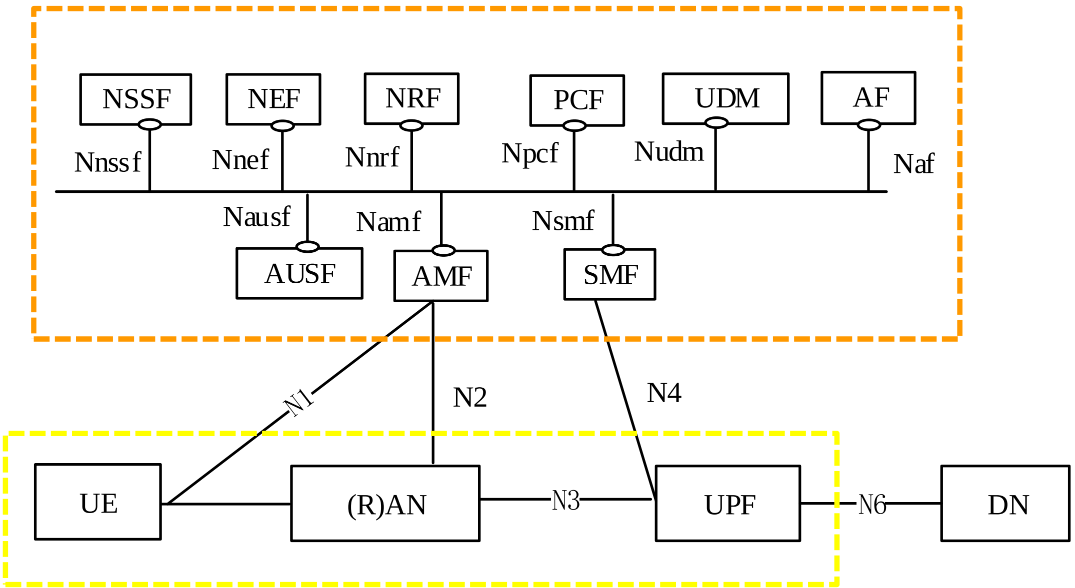
- Separation between control plane and user plane functions leads to Functional Entities:
  - Access and Mobility Management Function (AMF)
  - Session Management Function (SMF)
  - Policy Control Function (PCF)
  - Authentication Server Function (AUSF)
  - Application Functions (AF)
  - User Plane Function (UPF)

Software Defined Networking (SDN) Enabled 5G Core Network



*5G Network Functions **

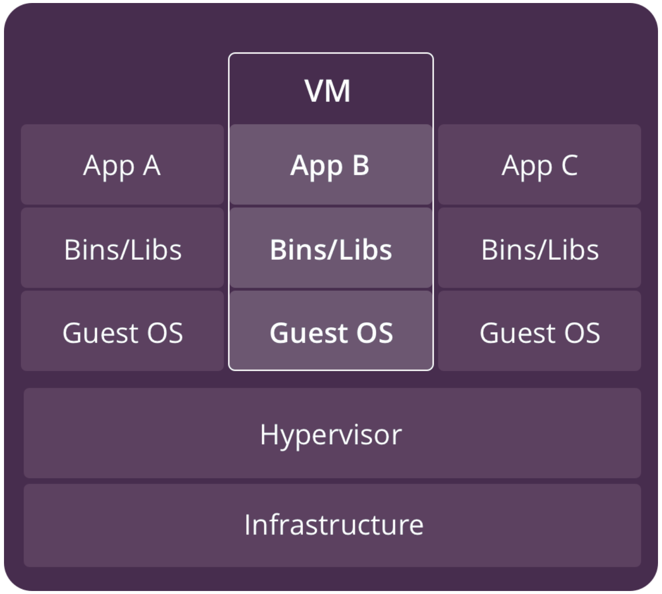
- Authentication Server Function (AUSF)
- Access and Mobility Management Function (AMF)
- Data Network (DN), e.g. operator services, Internet access or 3rd party services
- Unstructured Data Storage Function (UDSF)
- Network Exposure Function (NEF)
- NF Repository Function (NRF)
- Network Slice Selection Function (NSSF)
- Policy Control Function (PCF)
- Session Management Function (SMF)
- Unified Data Management (UDM)
- Unified Data Repository (UDR)
- User Plane Function (UPF)
- Application Function (AF)
- User Equipment (UE)
- (Radio) Access Network ((R)AN)
- 5G-Equipment Identity Register (5G-EIR)
- Security Edge Protection Proxy (SEPP)

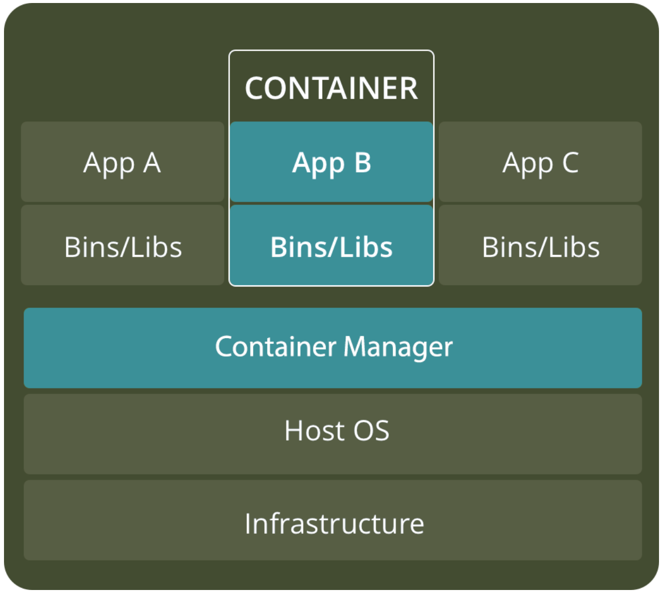


* see standard 3GPP TS 23.501 for details

NFV Infrastructure (NFVI) - Virtual Machines vs Containers

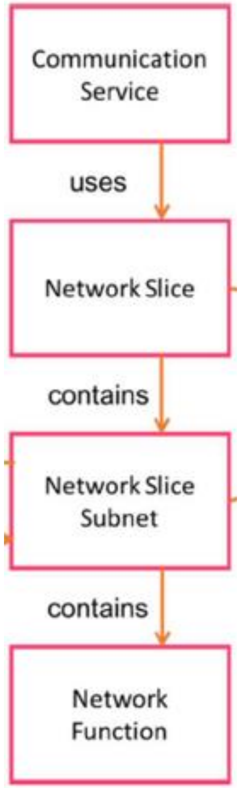
- With Virtual Machines, the hardware is virtualized to run multiple (guest) OS instances
- Containers provide a way to virtualize an OS so that multiple applications can run on a single OS instance





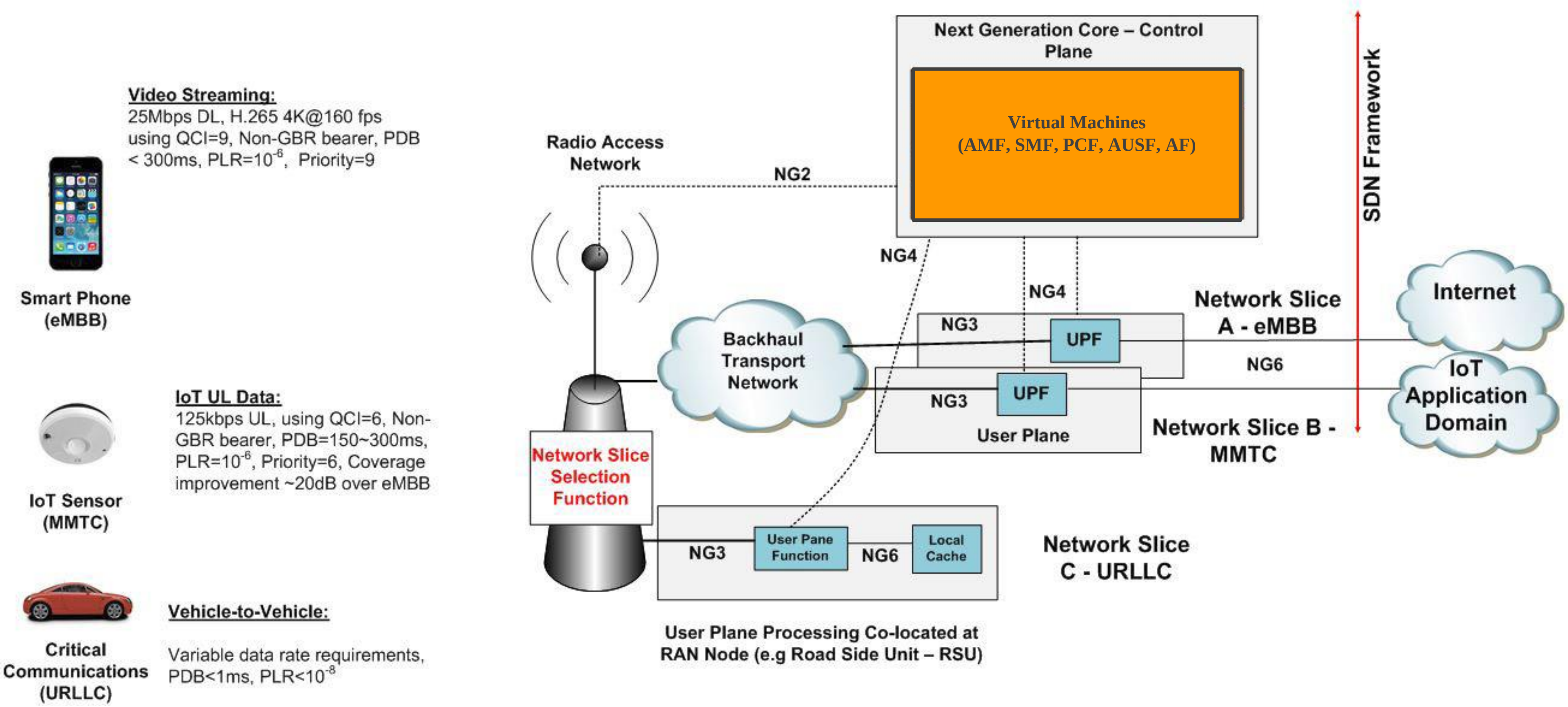
Network Slicing

Network Slice - Definitions

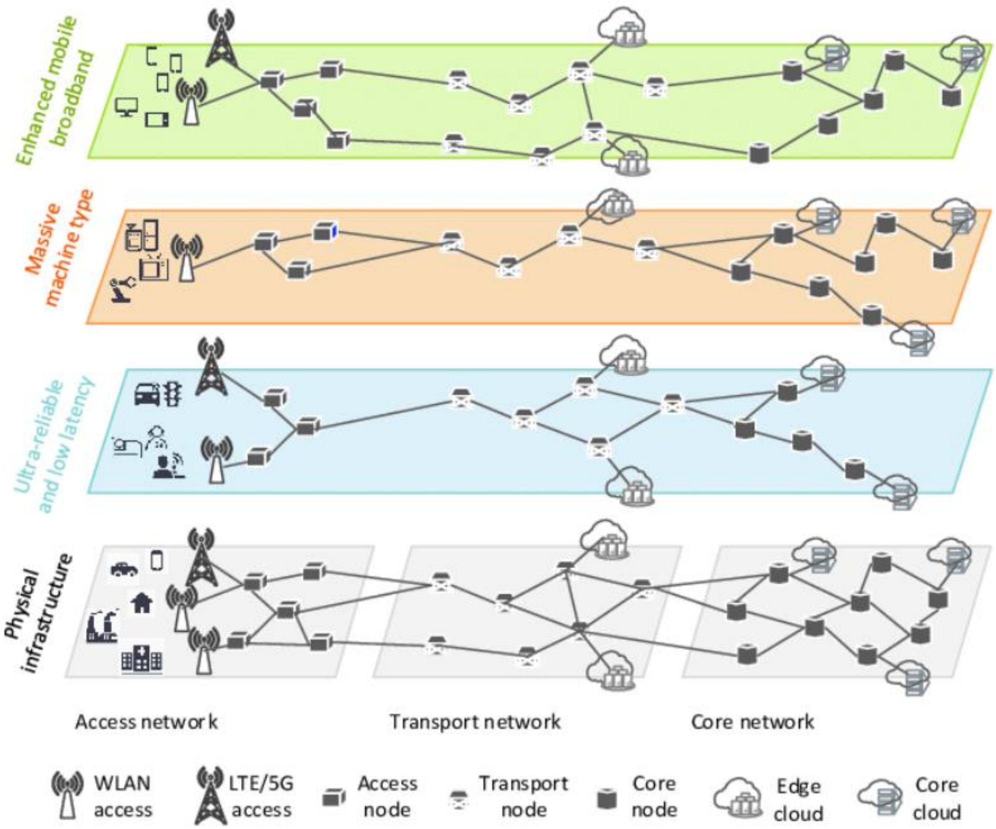


- Network Function (NF)
  - » 3GPP adopted or defined processing function in a network
- NF service
  - » functionality exposed by a NF through a service-based interface
  - » consumed by other authorized NFs
- Network Slice
  - » logical network that provides
    specific network capabilities and characteristics
  - » end-to-end concept, covering all network segments
  - » defined for given Service Level Agreements and KPIs
  - » composition of configured network functions and the underlying cloud infrastructure
- Network Slice instance
  - » a set of NF instances and associated resources (e.g., compute, storage, networking)

SDN/NFV Supporting 5G Slicing

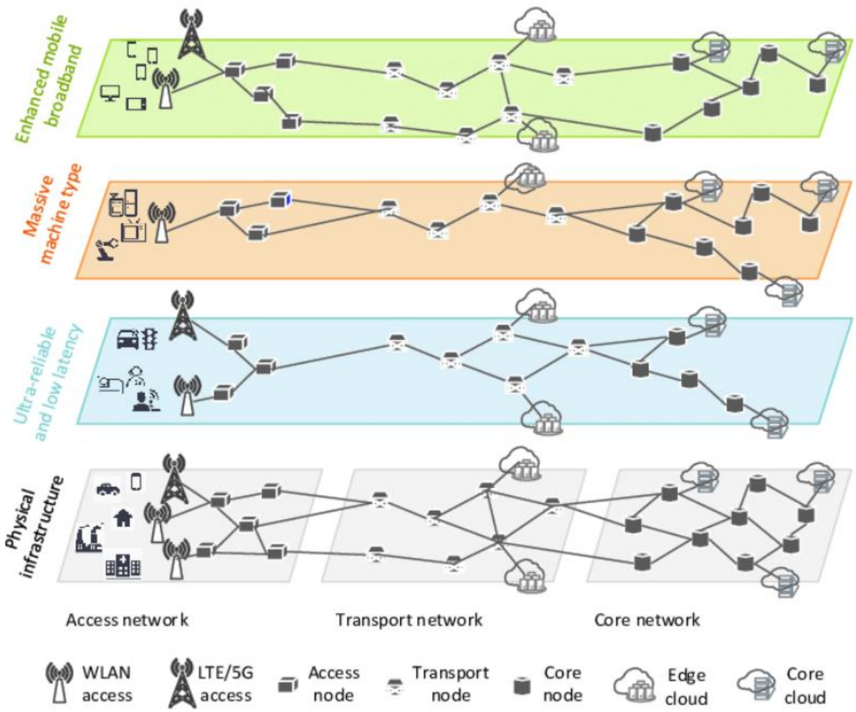


Network Slices - Examples



Network Slice - Properties

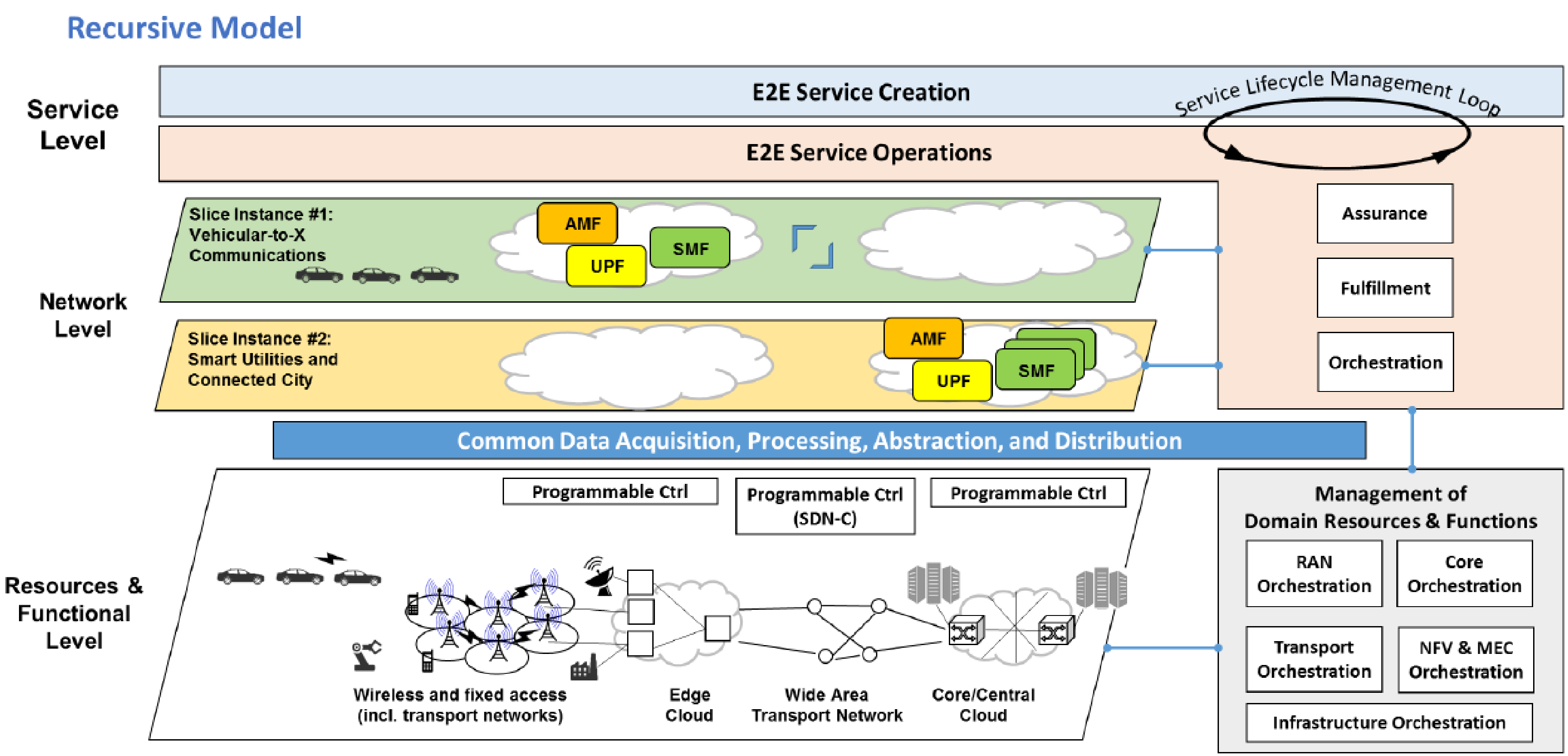
- Network Slices are
  - » Self-contained
  - » Mutually isolated
  - » Created on demand
  - » Manageable & Programmable



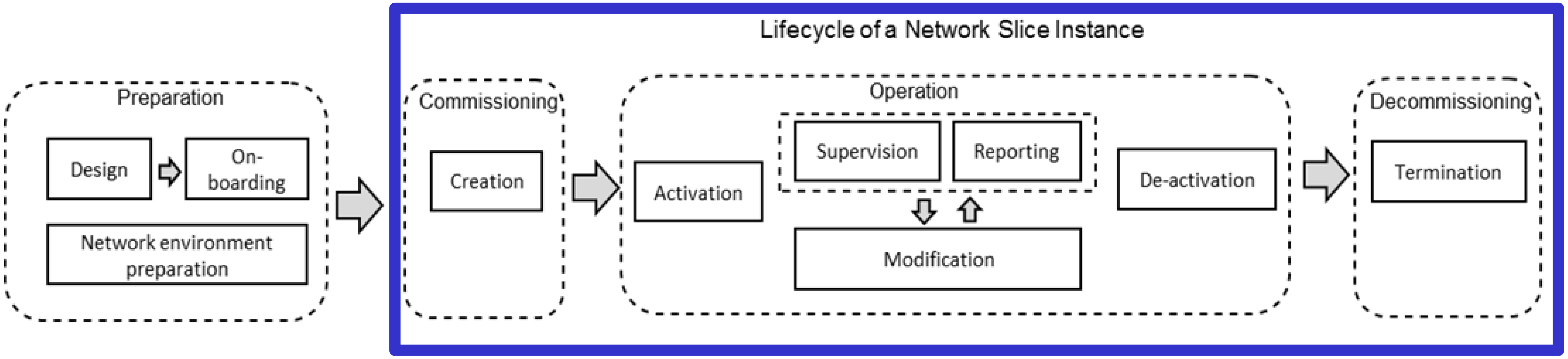
- Network Slices provide
  - » Support for multi-service
  - » Support for multi-tenancy

- Network Slices run on common underlying infrastructure

5G Overall Architecture



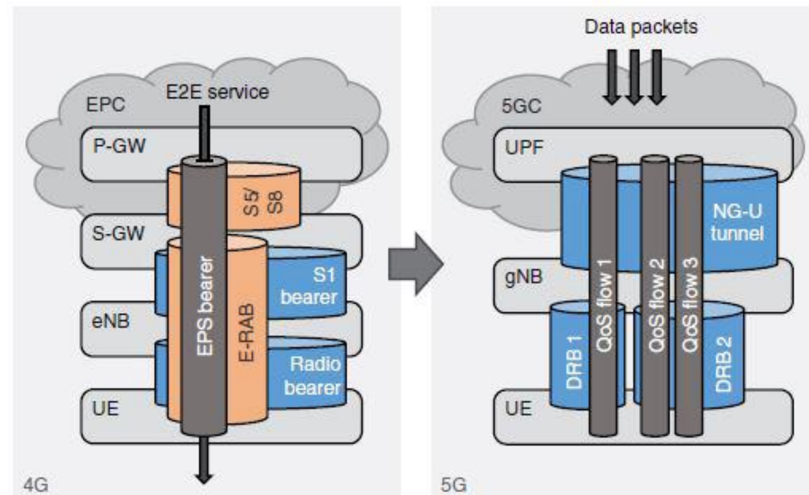
Network Slice Instance (NSI) lifecycle



5G QoS Model

4G and 5G QoS Models - Concepts and differences

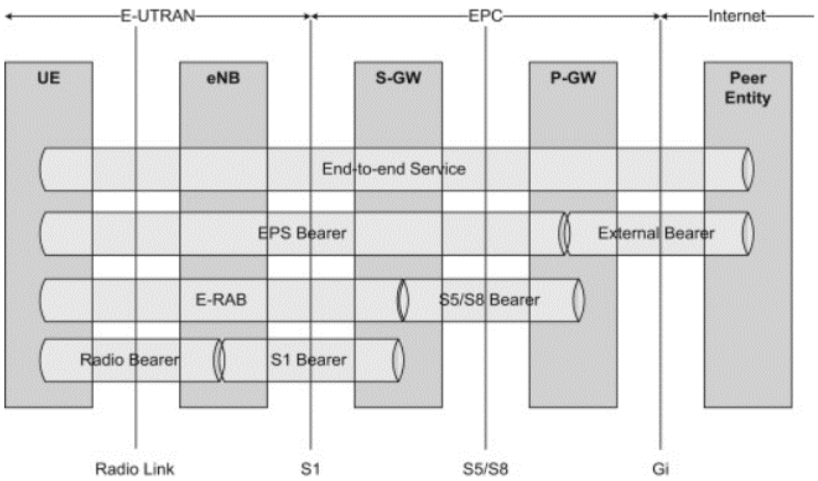
- 4G / LTE
  - » Evolved Packet System (EPS)
  - » Evolved Packet Core (EPC)
  - » QoS is bearer-oriented – EPS bearer
  - » PDN connection / EPS session



- 5G
  - » 5G System (5GS)
  - » 5G Core (5GC)
  - » QoS is flow-oriented – 5G QoS Flow
  - » PDU session

4G / LTE QoS Model - EPS Bearer

- An EPS bearer is formed by concatenating
  - » a Radio bearer (between UE and eNodeB),
  - » an S1 bearer (between eNodeB and S-GW) and
  - » an S5/S8 bearer (between S-GW and P-GW)



- There is a one-to-one mapping between EPS bearers and Radio bearers

5G QoS Model - Basic Concepts

- PDU Session

  is an association between a UE and a Data Network (DN)

- The 5G QoS model is based on QoS Flows

- The QoS Flow

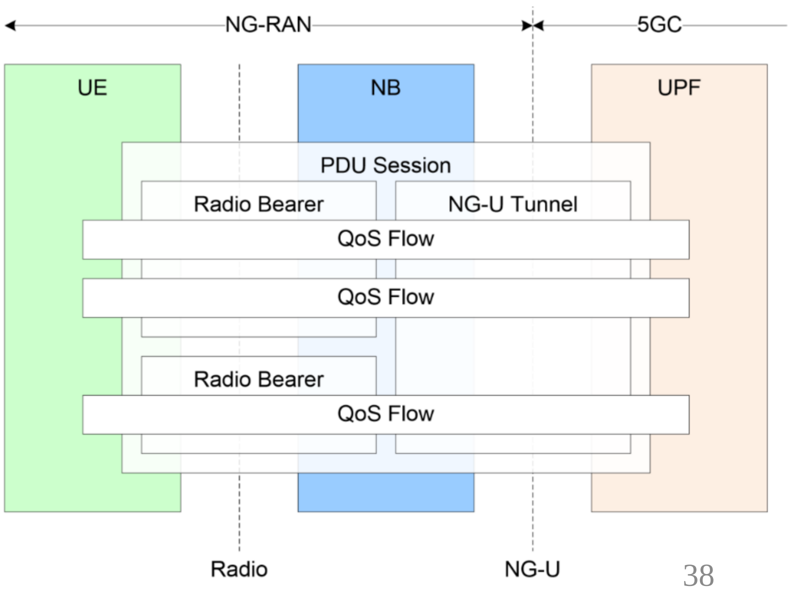
  is the finest granularity of QoS differentiation in a PDU Session

- The model supports GBR QoS Flows and Non-GBR QoS Flows

- The bearer concept is kept on the Radio Access Network (RAN)

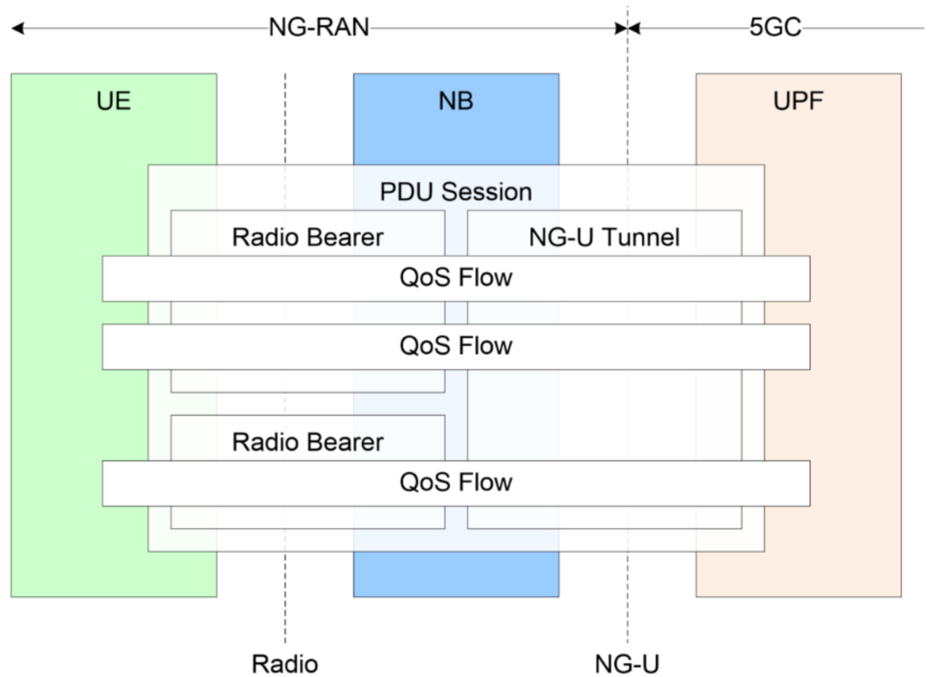
5G QoS Flows and Data Radio Bearers

- A PDU session may contain multiple QoS Flows
- The flows of the same PDU session are mapped to the same GTP-U tunnel
- A QoS Flow is mapped to one Data Radio Bearer (DRB)
- Data Radio Bearers (DRBs) may transport multiple QoS Flows
- QoS Flows belonging to different PDU sessions are
  - Mapped to different sets of DRBs and
  - Carried on different GTP-U tunnels



5G QoS Flows and Data Radio Bearers - Example

- One PDU Session
- One GTP-U tunnel



- Three QoS Flows (UE – UPF)
- Two Data Radio Bearers (DRBs)

- Two Flows mapped to one DRB
- One Flow mapped to the other DRB

5G QoS Parameters

5G QoS Parameters	
All QoS Flows	5G QoS Identifier (5QI)
	Allocation and Retention Priority (ARP)
Non-GBR QoS Flows	Per Session Aggregate Maximum Bit Rate (Session-AMBR)
	Per UE Aggregate Maximum Bit Rate (UE-AMBR)
GBR QoS Flows	Guaranteed Flow Bit Rate (GFBR)
	Maximum Flow Bit Rate (MFBR)
	Maximum Packet Loss Ratio, UL, DL, optional

5G QoS Characteristics

- 5G QoS characteristics describe the **packet forwarding treatment** that a QoS Flow receives between the UE and the UPF in terms of performance metrics

5G QoS Characteristics
Resource Type (GBR, Delay critical GBR or Non-GBR)
Priority Level
Packet Delay Budget
Packet Error Ratio
Averaging window (for GBR and Delay-critical GBR resource type)
Maximum Data Burst Volume (for Delay-critical GBR resource type)

- Standardized 5G QoS characteristics are indicated by the 5QI value

5G QoS Parameters and QoS characteristics

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Packet Error Ratio
Averaging window (for GBR and Delay-critical GBR resource type)
Maximum Data Burst Volume (for Delay-critical GBR resource type)

Mapping standardized 5QI to QoS characteristics - Guaranteed Bit Rate (GBR)

5QI Value	Resource Type	Default Priority Level	Packet Delay Budget	Packet Error Ratio	Default Maximum Data Burst Volume	Default Averaging Window	Example Services
1	GBR	20	100 ms	10^{-2}	N/A	2000 ms	Conversational Voice
2		40	150 ms	10^{-3}	N/A	2000 ms	Conversational Video (Live Streaming)
3		30	50 ms	10^{-3}	N/A	2000 ms	Real Time Gaming, V2X messages (see TS 23.287). Electricity distribution – medium voltage, Process automation monitoring
4		50	300 ms	10^{-6}	N/A	2000 ms	Non-Conversational Video (Buffered Streaming)
65		7	75 ms	10^{-2}	N/A	2000 ms	Mission Critical user plane Push To Talk voice (e.g., MCPTT)
66		20	100 ms	10^{-2}	N/A	2000 ms	Non-Mission-Critical user plane Push To Talk voice
67		15	100 ms	10^{-3}	N/A	2000 ms	Mission Critical Video user plane
71		56	150 ms	10^{-6}	N/A	2000 ms	"Live" Uplink Streaming (e.g. TS 26.238)
72		56	300 ms	10^{-4}	N/A	2000 ms	"Live" Uplink Streaming (e.g. TS 26.238)
73		56	300 ms	10^{-8}	N/A	2000 ms	"Live" Uplink Streaming (e.g. TS 26.238)
74		56	500 ms	10^{-8}	N/A	2000 ms	"Live" Uplink Streaming (e.g. TS 26.238)
76		56	500 ms	10^{-4}	N/A	2000 ms	"Live" Uplink Streaming (e.g. TS 26.238)

Mapping standardized 5QI to QoS characteristics - Non-Guaranteed Bit Rate (Non-GBR)

5QI Value	Resource Type	Default Priority Level	Packet Delay Budget	Packet Error Ratio	Default Maximum Data Burst Volume	Default Averaging Window	Example Services
5	Non-GBR	10	100 ms	10^{-6}	N/A	N/A	IMS Signalling
6		60	300 ms	10^{-6}	N/A	N/A	Video (Buffered Streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		70	100 ms	10^{-3}	N/A	N/A	Voice, Video (Live Streaming) Interactive Gaming
8		80	300 ms	10^{-6}	N/A	N/A	Video (Buffered Streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
9		90					
69		5	60 ms	10^{-6}	N/A	N/A	Mission Critical delay sensitive signalling (e.g., MC-PTT signalling)
70		55	200 ms	10^{-6}	N/A	N/A	Mission Critical Data (e.g. example services are the same as 5QI 6/8/9)
79		65	50 ms	10^{-2}	N/A	N/A	V2X messages (see TS 23.287)
80		68	10 ms	10^{-6}	N/A	N/A	Low Latency eMBB applications Augmented Reality

Mapping standardized 5QI to QoS characteristics - Delay Critical GBR

5QI Value	Resource Type	Default Priority Level	Packet Delay Budget	Packet Error Ratio	Default Maximum Data Burst Volume	Default Averaging Window	Example Services
82	Delay Critical GBR	19	10 ms	10^{-4}	255 bytes	2000 ms	Discrete Automation (see TS 22.261)
83		22	10 ms	10^{-4}	1354 bytes	2000 ms	Discrete Automation (see TS 22.261); V2X messages (UE - RSU Platooning, Advanced Driving: Cooperative Lane Change with low LoA. (see TS 22.186, TS 23.287)
84		24	30 ms	10^{-5}	1354 bytes	2000 ms	Intelligent transport systems (see TS 22.261)
85		21	5 ms	10^{-5}	255 bytes	2000 ms	Electricity Distribution- high voltage (see TS 22.261). V2X messages (Remote Driving, see TS 22.186, TS 23.287)
86		18	5 ms	10^{-4}	1354 bytes	2000 ms	V2X messages (Advanced Driving: Collision Avoidance, Platooning with high LoA, see TS 22.186, TS 23.287)