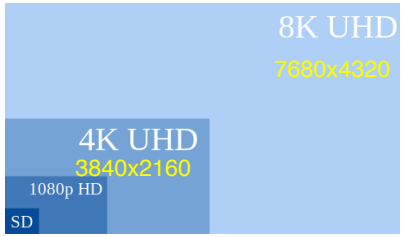
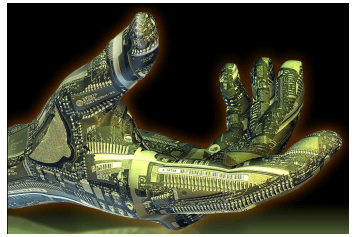
- Evolution of Mobile Communication
- ITU/3GPP Standardization
- **ITU 5G Service Scenarios**
- 5G-New Radio
- 5G System Architecture
- SDN/NFV
- Network Slicing
- Mobile Edge Computing (MEC)
- The Road to the 6G Mobile Communication

ITU 5G Service Scenarios

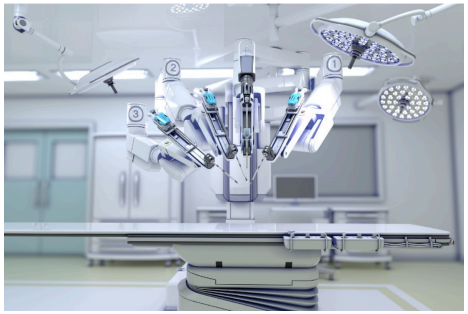
- **Enhanced Mobile Broadband (eMBB)**
- Downlink higher data rate (gigabyte/sec) services
  - Ultra-high definition (UHD) video
  - 3D video
  - Augmented Reality (AR) / Virtual Reality (VR)
- Uplink high data rate service
  - HD video sharing from the users





- **Massive Machine Type Communications (mMTC)**
- Services that use massive number of sensors to report the sensing data to the cloud or a central data center to
  - Smart city
  - Smart homes / buildings
  - Remote sensors

- **Ultra-Reliable and Low Latency Communications (URLLC)**
- Services that are very sensitive to latency and loss of data packets
  - Industry automation
  - Self-driving car
  - Mission-critical application like remote surgery
  - Augmented Reality



增強型行動寬頻 (eMBB)

- 10~20Gbps傳輸峰值
- 10Tbps/平方公里以上流量密度
- 6人/平方米用戶密度

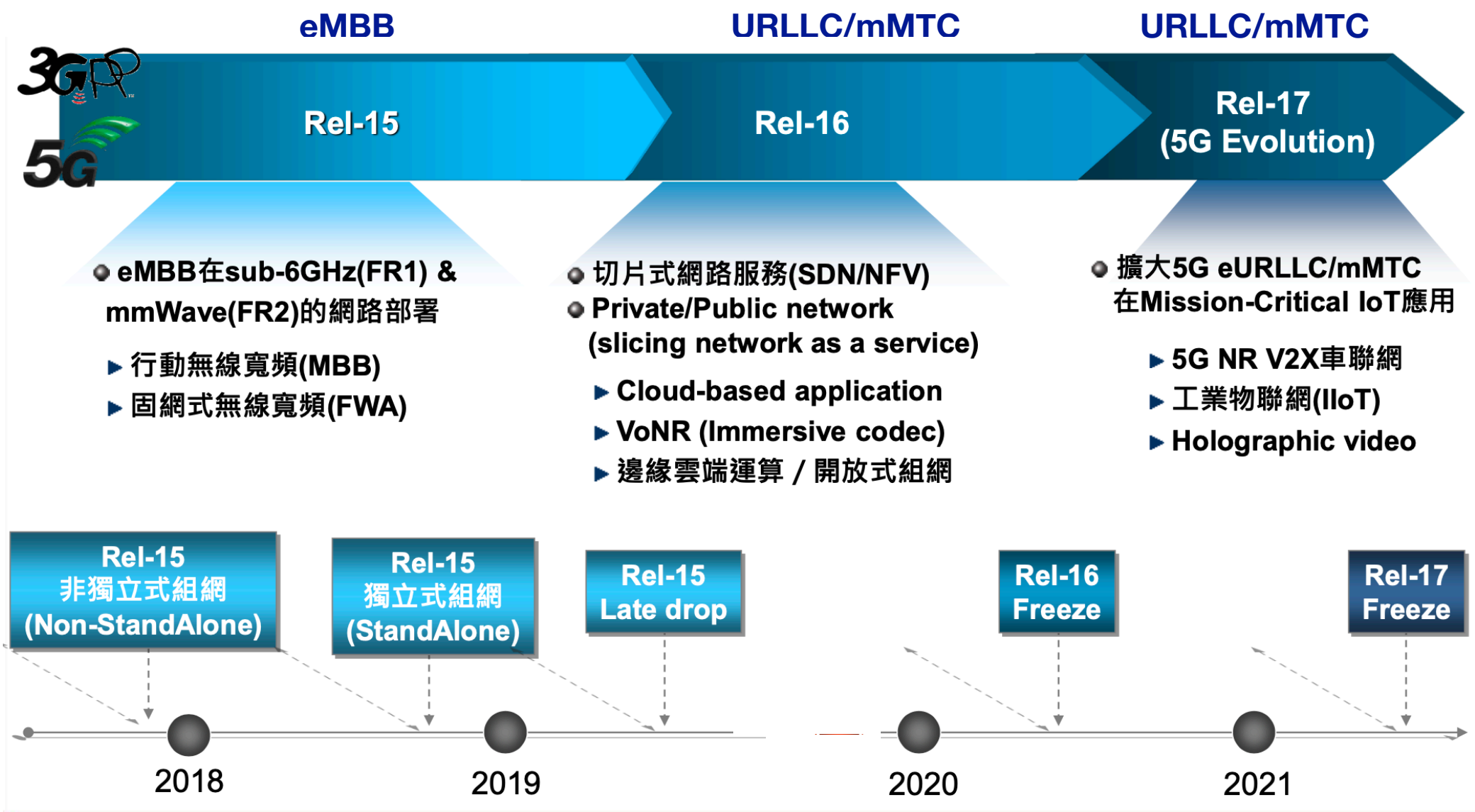
大規模低功耗聯網 (mMTC)

- 低功耗：10Yr battery Life
- 大規模裝置接入：百萬個/平方公里裝置連結數量

高可靠性、低時延聯網 (URLLC)

- 端到端時延：< 10ms
- 網路時延：< 1ms
- 支持500km/h移動性

資料來源：DIGITIMES，2019/11

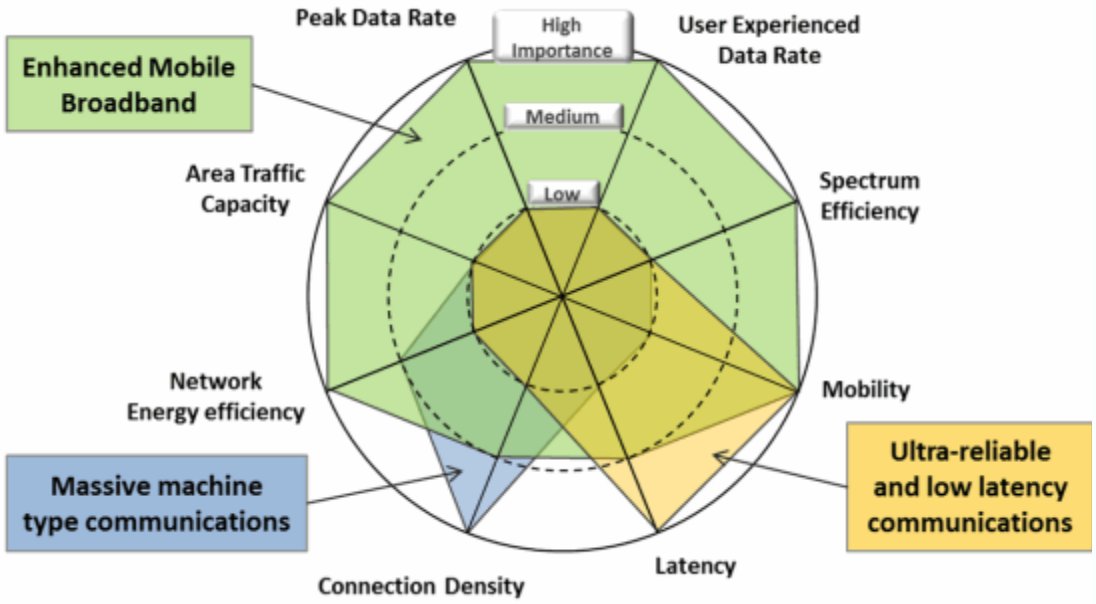


資料來源：DIGITIMES，2019/11

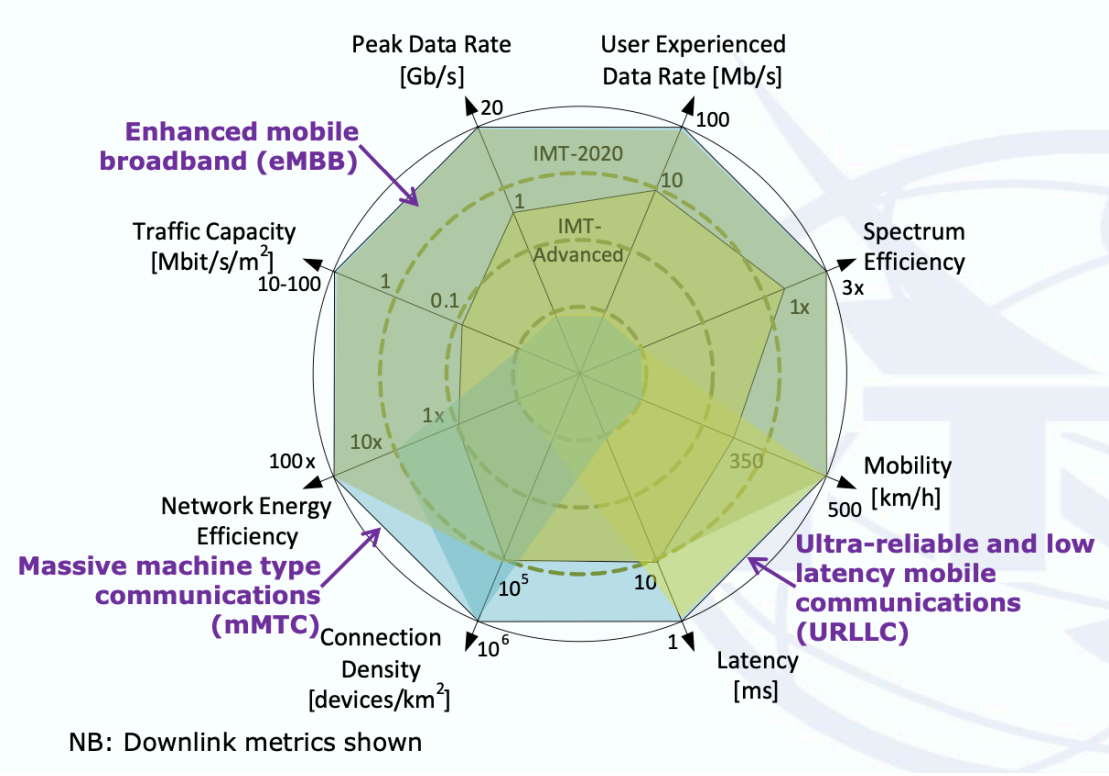
Key Capabilities for 5G

- User experienced data rate [Mb/s]
- Peak data rate [Gb/s]
- Mobility [km/h]
- Latency [ms]
- Connection density [devices/km^2]
- Energy efficiency
- Spectrum efficiency
- Area traffic capacity [Mb/s/m^2]

IMT-2020



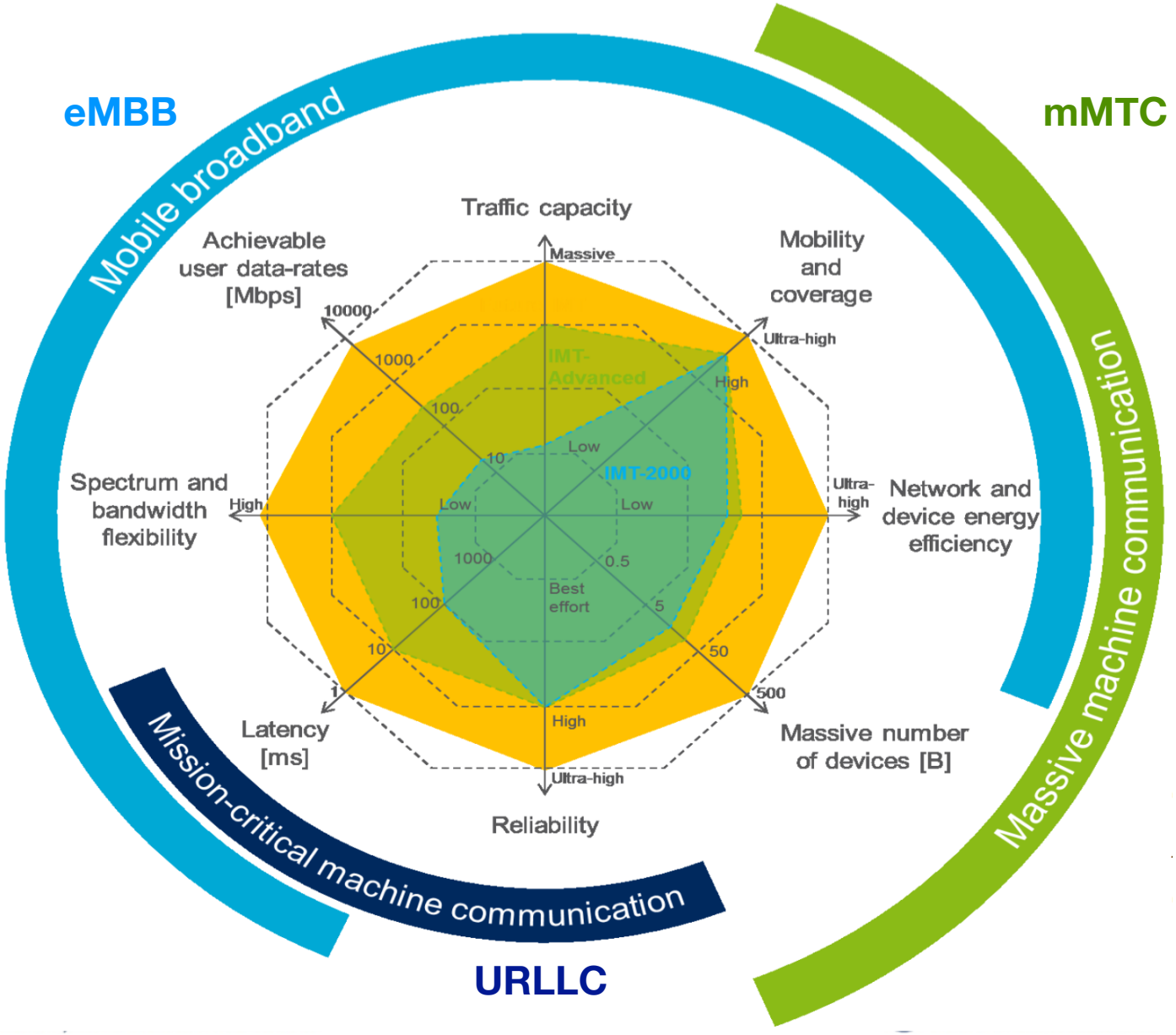
The importance of key capabilities in different usage scenarios



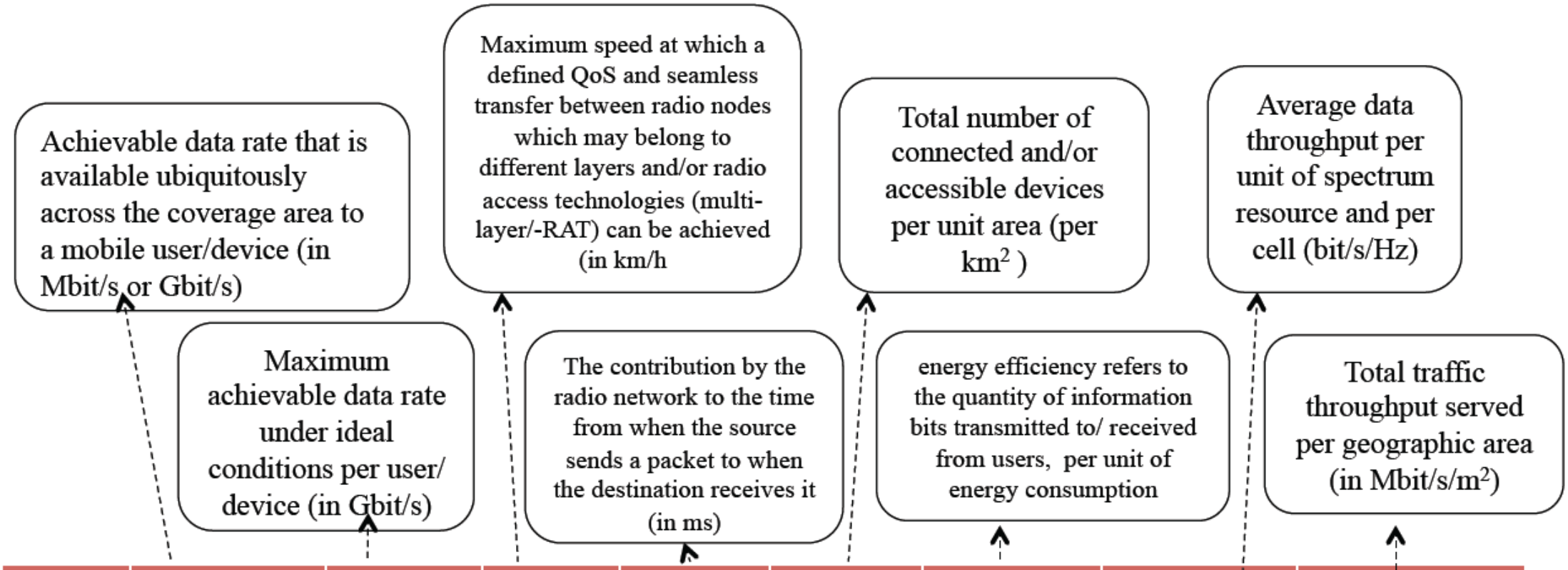
Enhancement of key capability for 5G

IMT-2020 (5G) key capabilities

- Traffic capability
- Mobility and coverage
- Network and device energy efficiency
- Massive number of devices
- Reliability
- Latency
- Spectrum and bandwidth flexibility
- Achievable user data rates



	eMBB	mMTC	URLLC
Data Rate	Very high (e.g. peak rate 10 Gbps)	Not much considered	Not much considered
Latency	Low	Not much considered	Very Low (e.g. 0.5 ms end-to-end)
Mobility	0km/h to 500km/h	Not much considered	Not much considered
Reliability	Not much considered	Not much considered	Very High (e.g. Packet loss rate: as low as 1e-04)
Power Consumption	Not much considered	Very Low	Not much considered
Connection Density	High (e.g. 200-2500 UEs/km^2)	Very High (e.g.1M connections/ km^2)	High (e.g. 10k device/10km^2)



Parameter	User experienced data rate	Peak data rate	Mobility	Latency	Connection density	Energy efficiency	Spectrum efficiency	Area traffic capacity (ultra-dense network)
Value for future IMT	100Mbit/s	20 Gbit/s	500km/h	1ms (radio interface)	10^6 Devices/ km^2	100 times IMT-Advanced (for network)	3 times IMT-Advanced	10Mbits/s/ m^2

1 ms：air latency. **5-10 ms**：E2E latency

應用情境	技術指標	技術目標數值
eMBB	Peak data rate	20 Gbps for downlink 10 Gbps for uplink
	Peak spectral efficiency	30 bps/Hz for downlink 15 bps/Hz for uplink
	C-plane latency	10 ms
	U-plane latency	4 ms for downlink 4 ms for uplink
	Cell/TRxP spectral efficiency	3 times higher than IMT-A
	Area traffic capacity	3 times higher than IMT-A
	User experienced data rate	3 times higher than IMT-A
	5% user spectrum efficiency	3 times higher than IMT-A
uRLLC	U-plane latency	0.5 ms for downlink 0.5 ms for uplink
	Reliability	10^{-5} for 32 bytes with U-plane latency of 1 ms
mMTC	Coverage	Max coupling loss 164 db
	UE battery life	Beyond 10 years
	Connection density	1000000 devices/km^2

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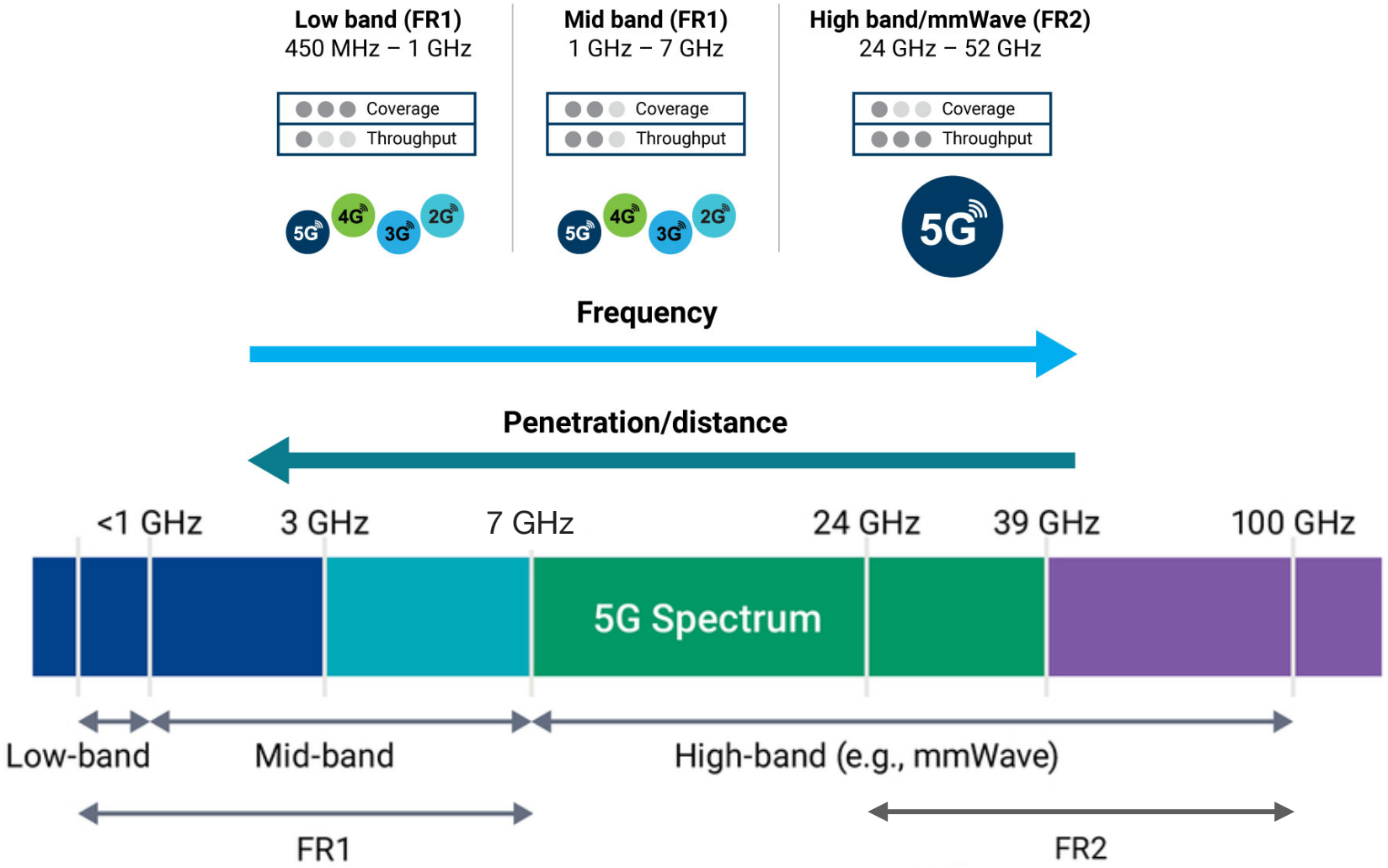
5G-New Radio

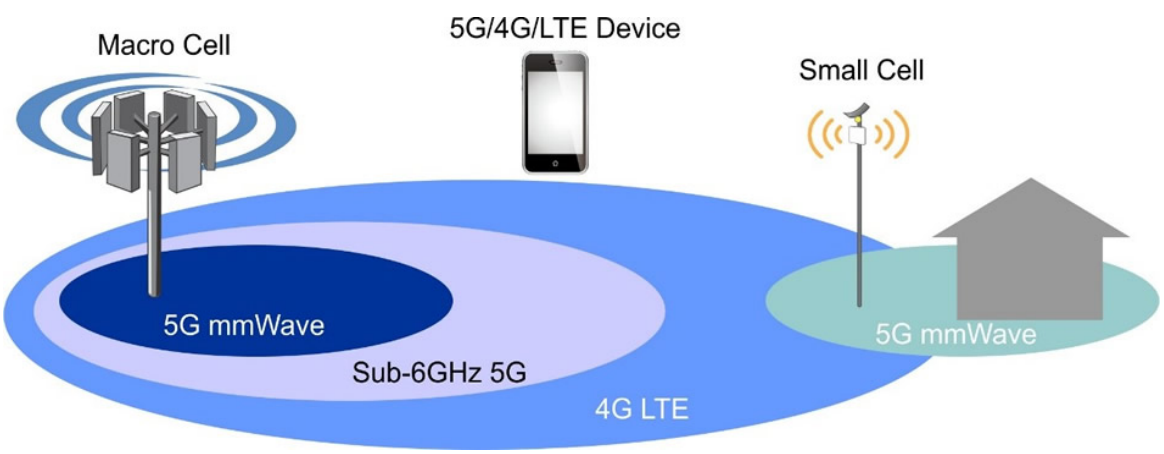

Low band (FR1)
450 MHz – 1 GHz
Coverage
Throughput
5G
4G
3G
2G
Mid band (FR1)
1 GHz – 7 GHz
Coverage
Throughput
5G
4G
3G
2G
High band/mmWave (FR2)
24 GHz – 52 GHz
Coverage
Throughput
5G
Frequency
Penetration/distance
<1 GHz
3 GHz
7 GHz
24 GHz
39 GHz
100 GHz
5G Spectrum
Low-band
Mid-band
High-band (e.g., mmWave)
FR1
FR2

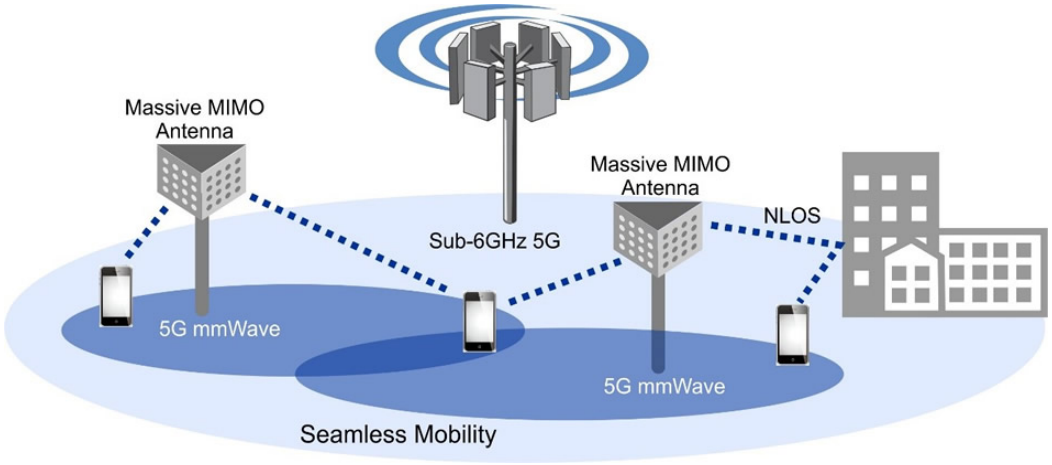
Millimeter Waves (mmWave)

$c = f \times \lambda = 3.00 \times 10^8$ m/s

mmWave : 30 GHz ~ 300 GHz (10 mm ~ 1 mm)

- Have a short wavelength, possible to pack a large no. of antenna elements into a small area
- Help realize **massive MIMO** (Multiple Input Multiple Output) at both the base stations and user devices



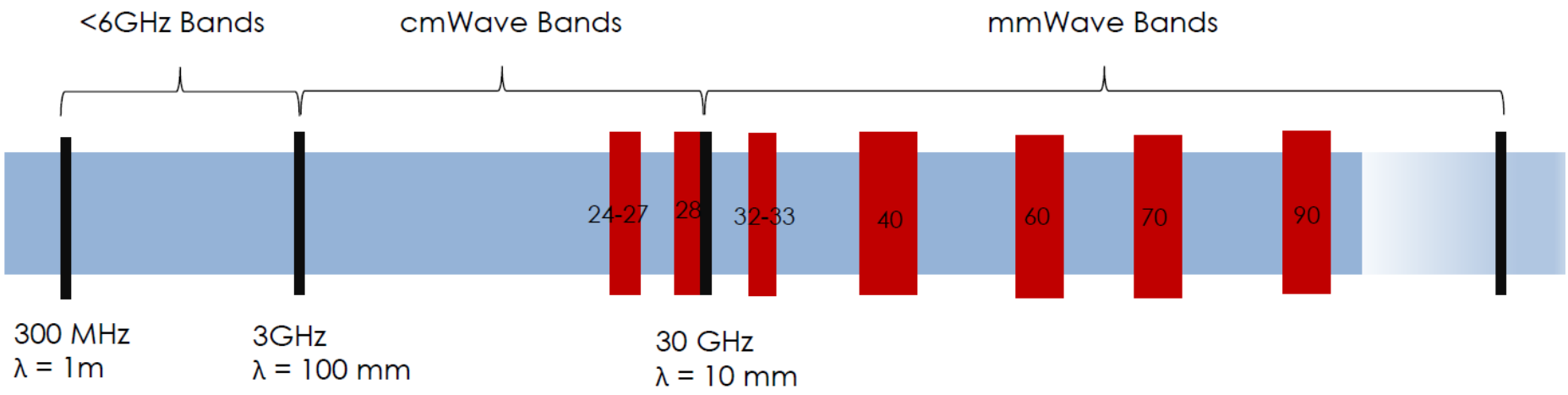


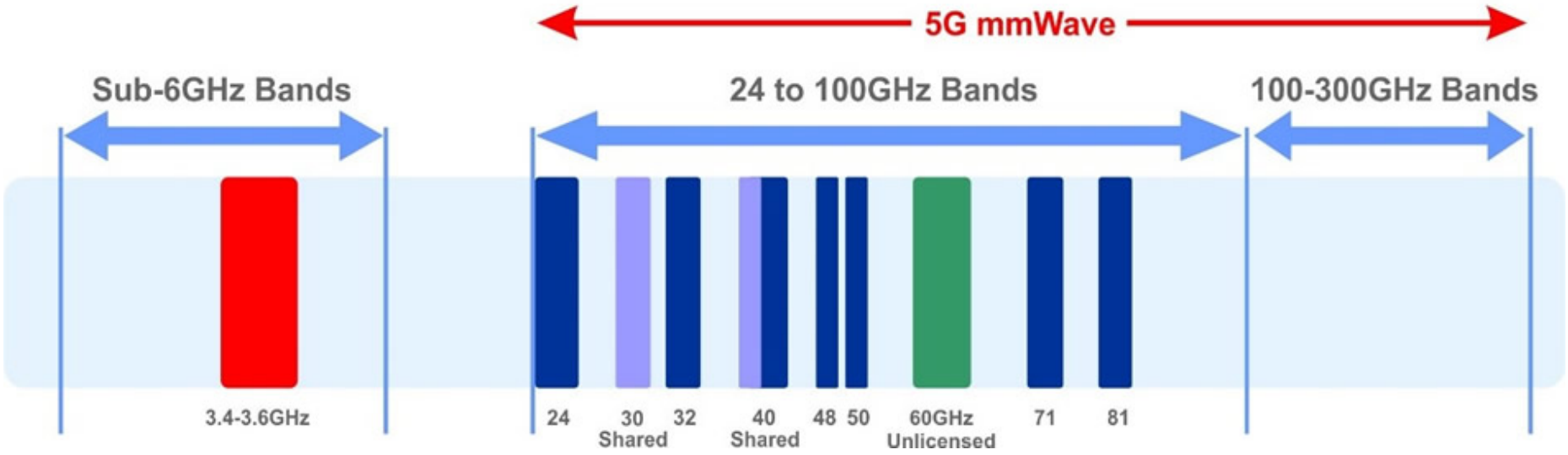
https://www.accton.com/Technology-Brief/the-emergence-of-5g-mmwave/

cmWave : 3 GHz ~ 30 GHz
(100 mm ~ 10 mm)

mmWave : 30 GHz ~ 300 GHz
(10 mm ~ 1 mm)

$c = f \times \lambda = 3.00 \times 10^8$ m/s





https://www.accton.com/Technology-Brief/the-emergence-of-5g-mmwave/

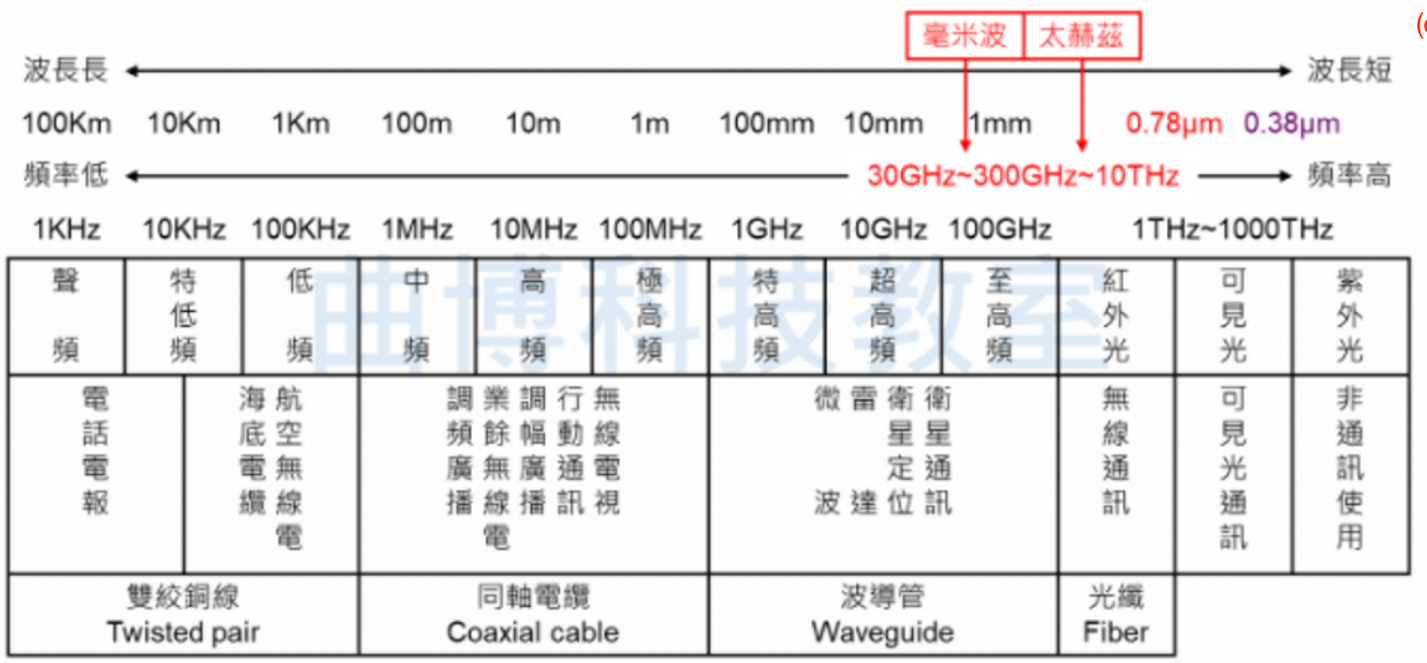
- **Shannon's Theorem**
  - Gives an upper bound to the capacity (***C***) of a link, in bits per second (bps), as a function of the available bandwidth (***B***) and the signal-to-noise ratio (***S/N***, ***SNR***) of the link

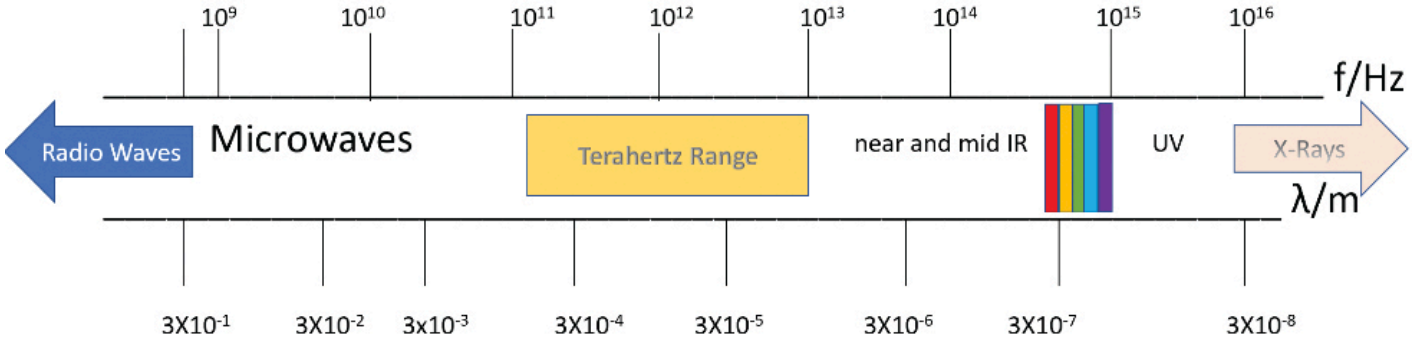
$$C = B * \log_2(1 + S/N)$$

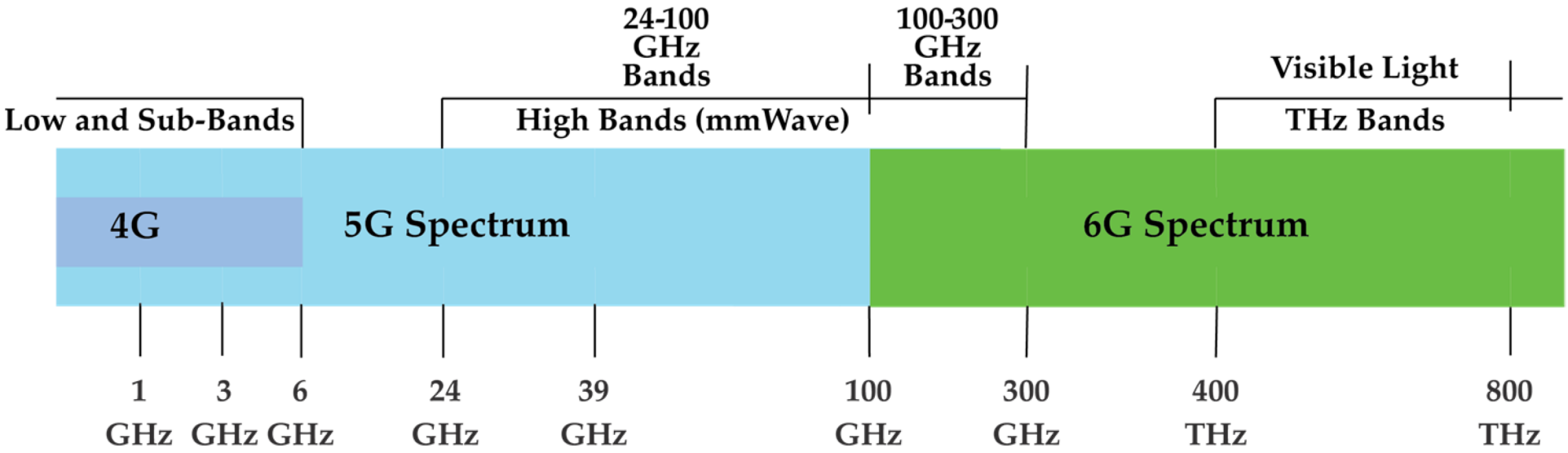
    - *C*: the achievable channel capacity (bps)
    - *B*: the bandwidth of the line (Hz)
    - *S*: the average signal power
    - *N*: the average noise power

Spectrum Bands for 5G & 6G

Terahertz
—spectrum: 0.3~3 THz,
— wavelentg: 1mm~0.1mm
(or 100μm)

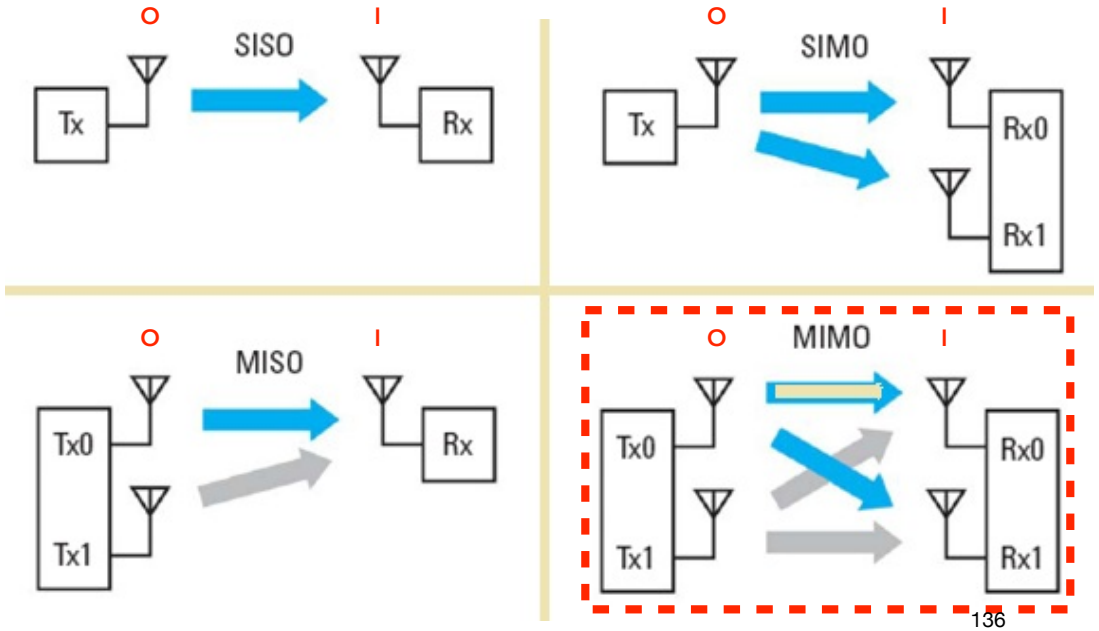


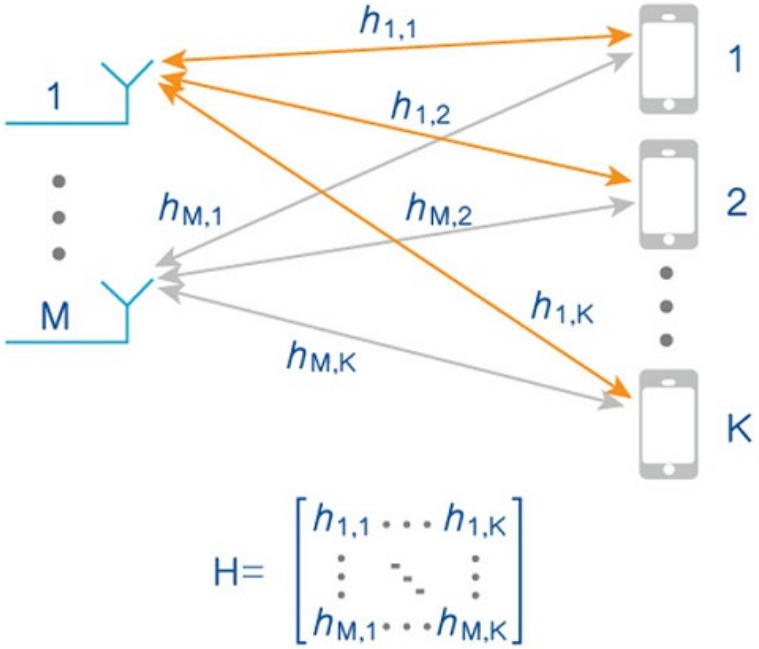



24-100 GHz Bands
100-300 GHz Bands
Visible Light
Low and Sub-Bands
High Bands (mmWave)
THz Bands
4G
5G Spectrum
6G Spectrum
1 GHz
3 GHz
6 GHz
24 GHz
39 GHz
100 GHz
300 GHz
400 THz
800 THz

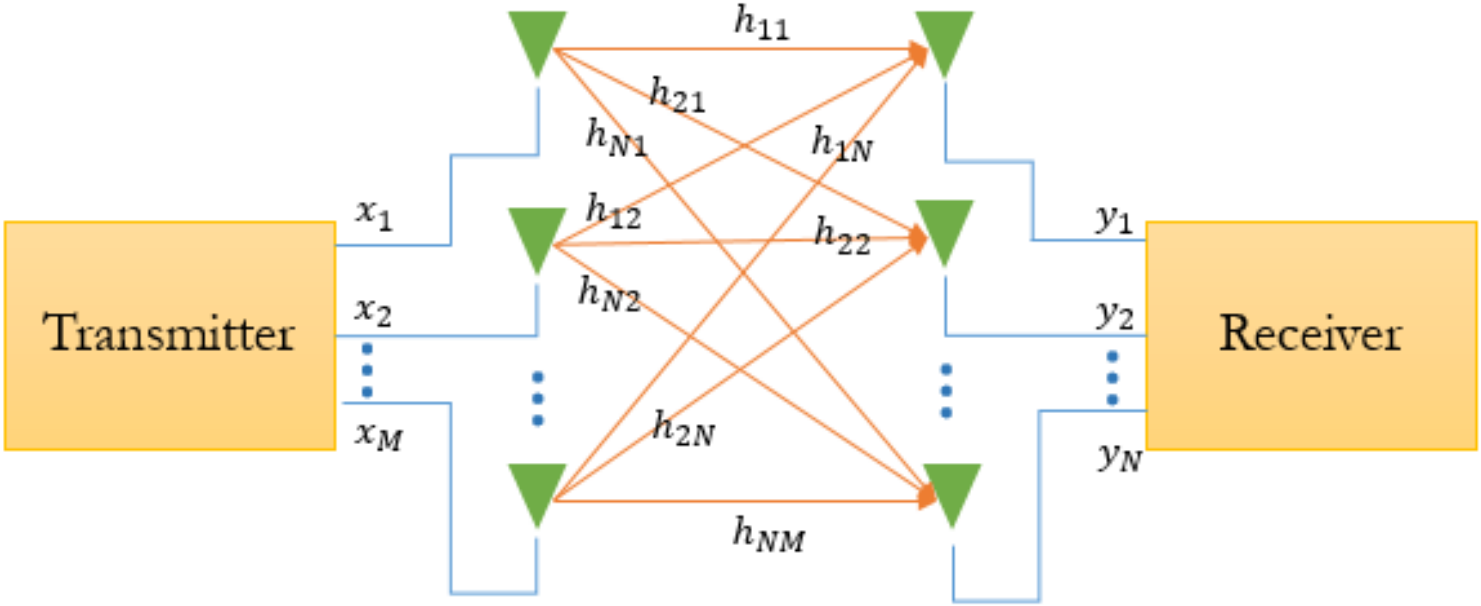
MIMO

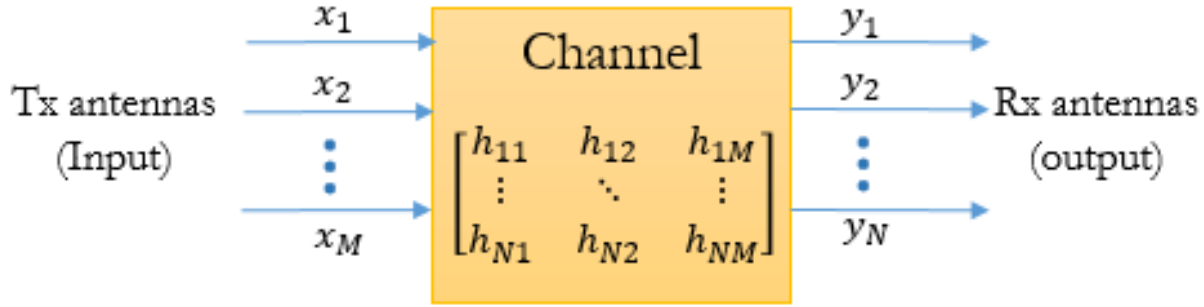
- MIMO terminology refers to the channel
  - Transmitter (T_x) is the channel input (I)
  - Receiver (R_x) is the channel output (O)





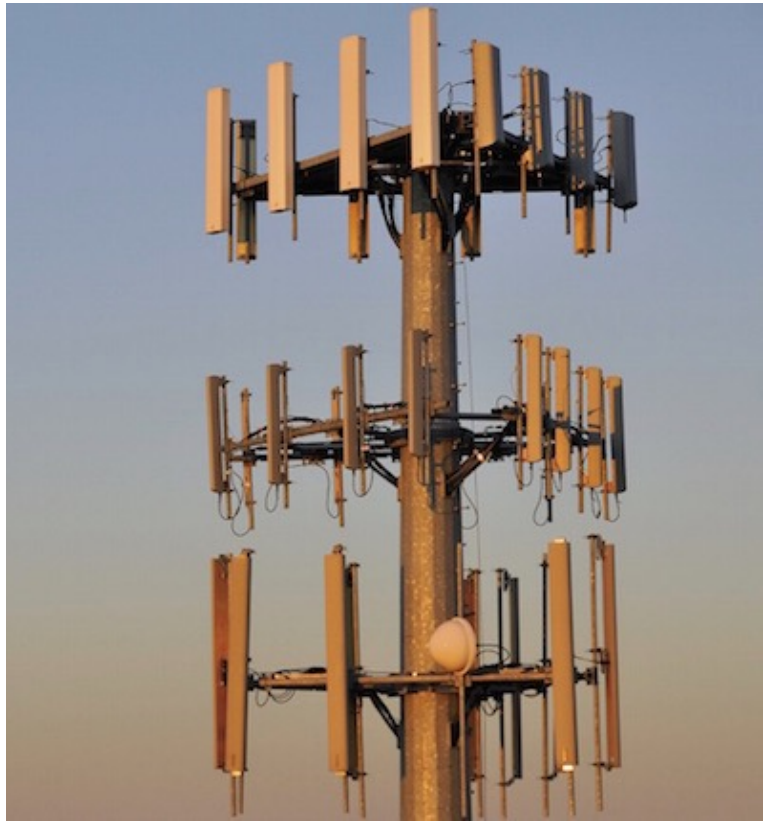
MIMO SYSTEM



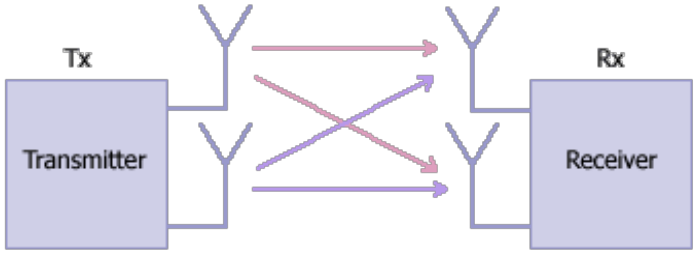


MIMO from channel perspective

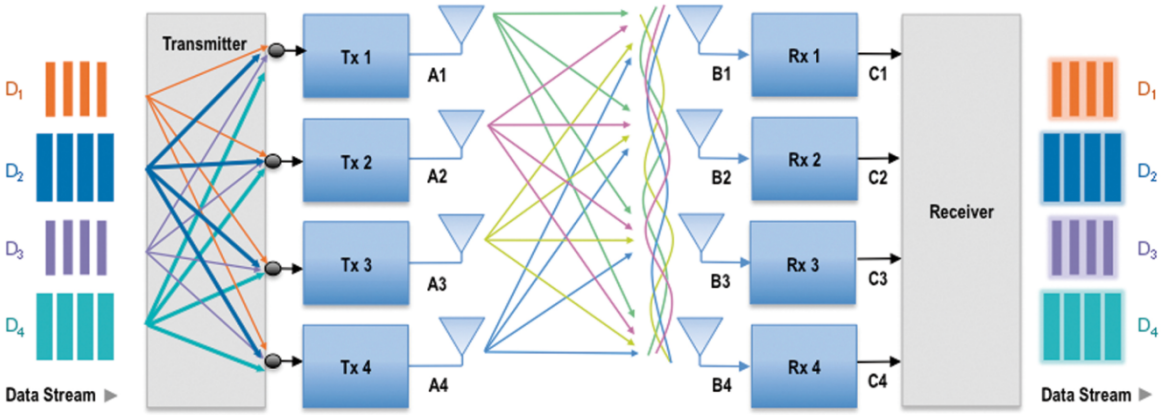
Massive Antenna



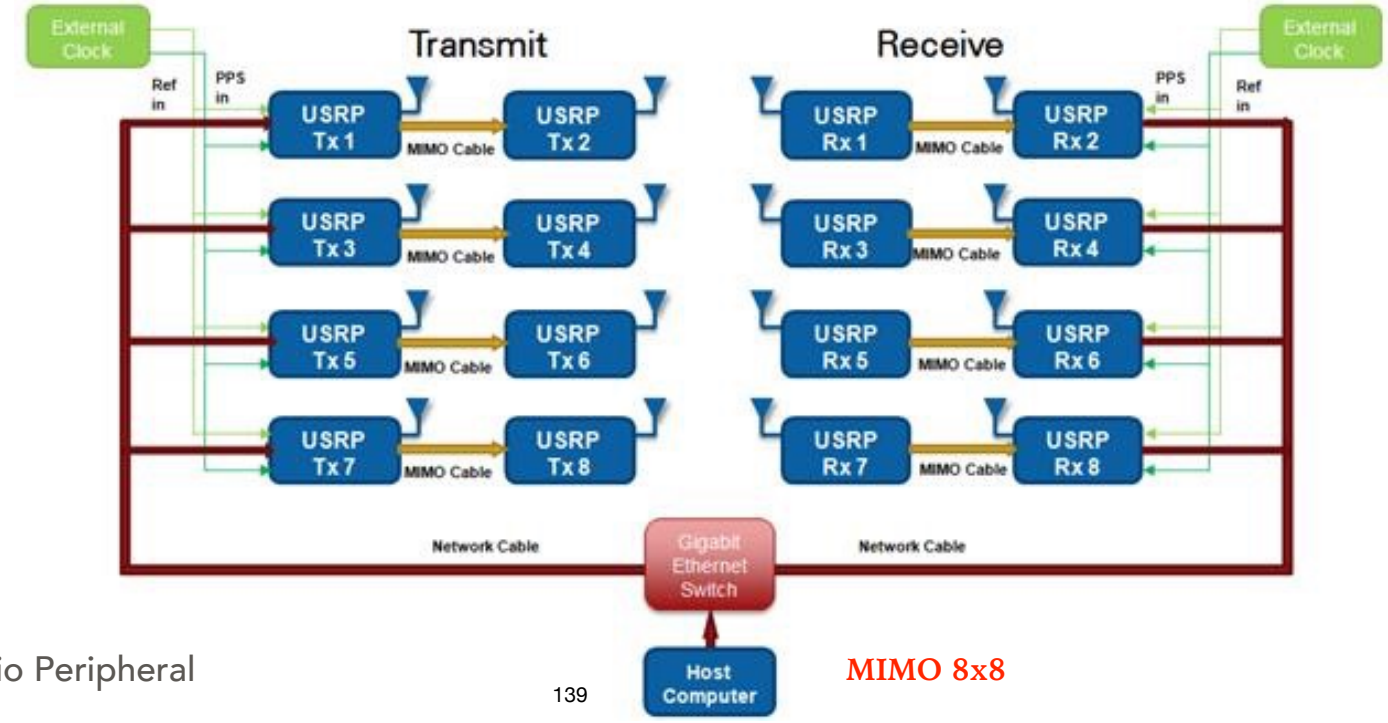
MIMO



MIMO 2x2



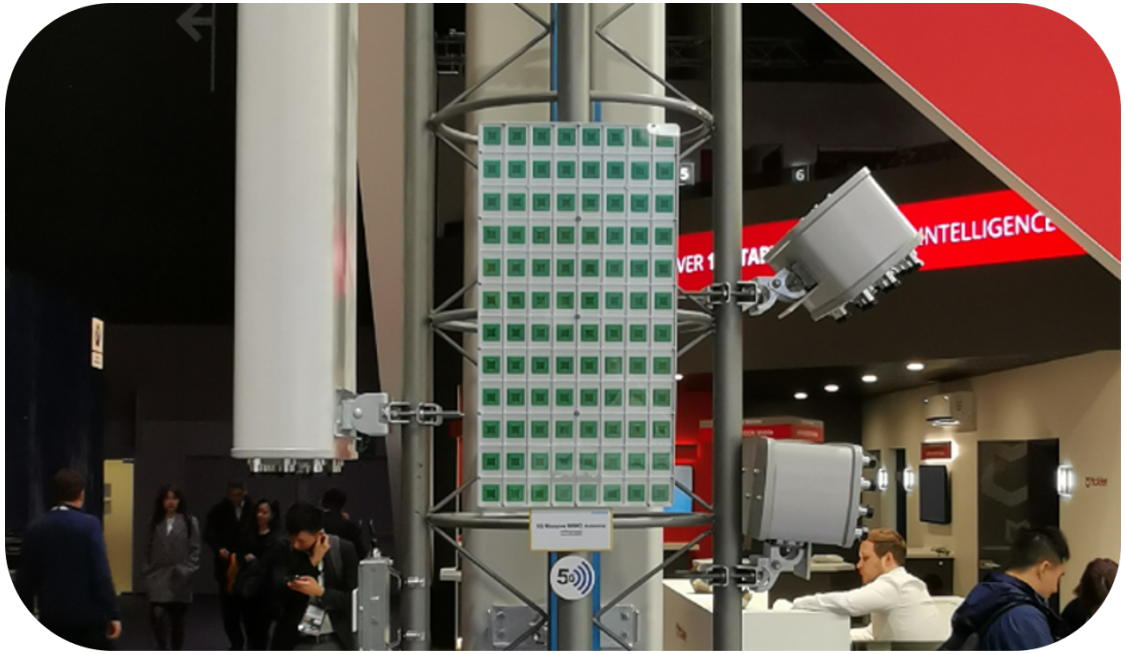
MIMO 4x4



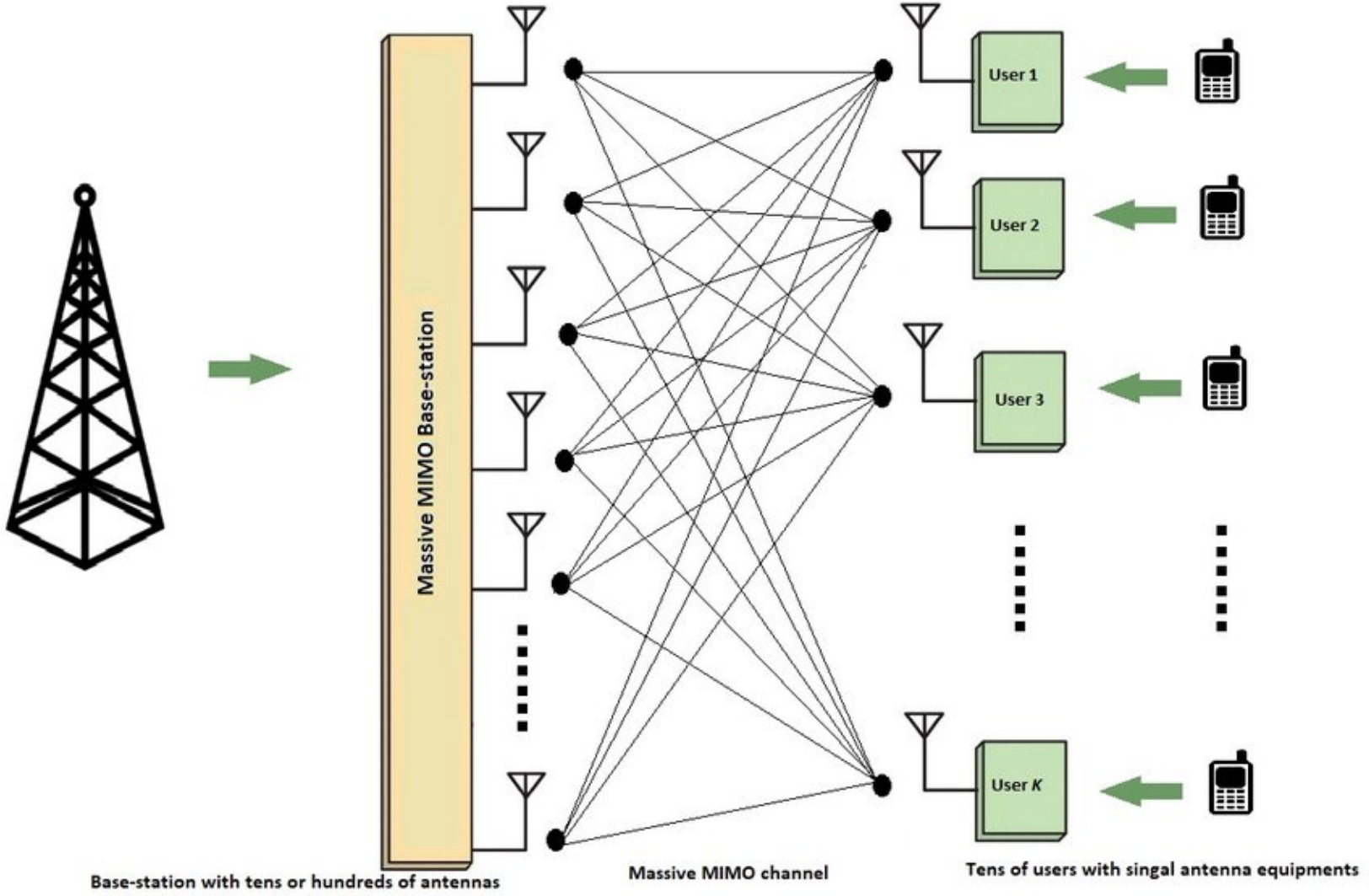
MIMO 8x8

USRP: Universal Software Radio Peripheral

5G Massive MIMO



Massive MiMO Architecture



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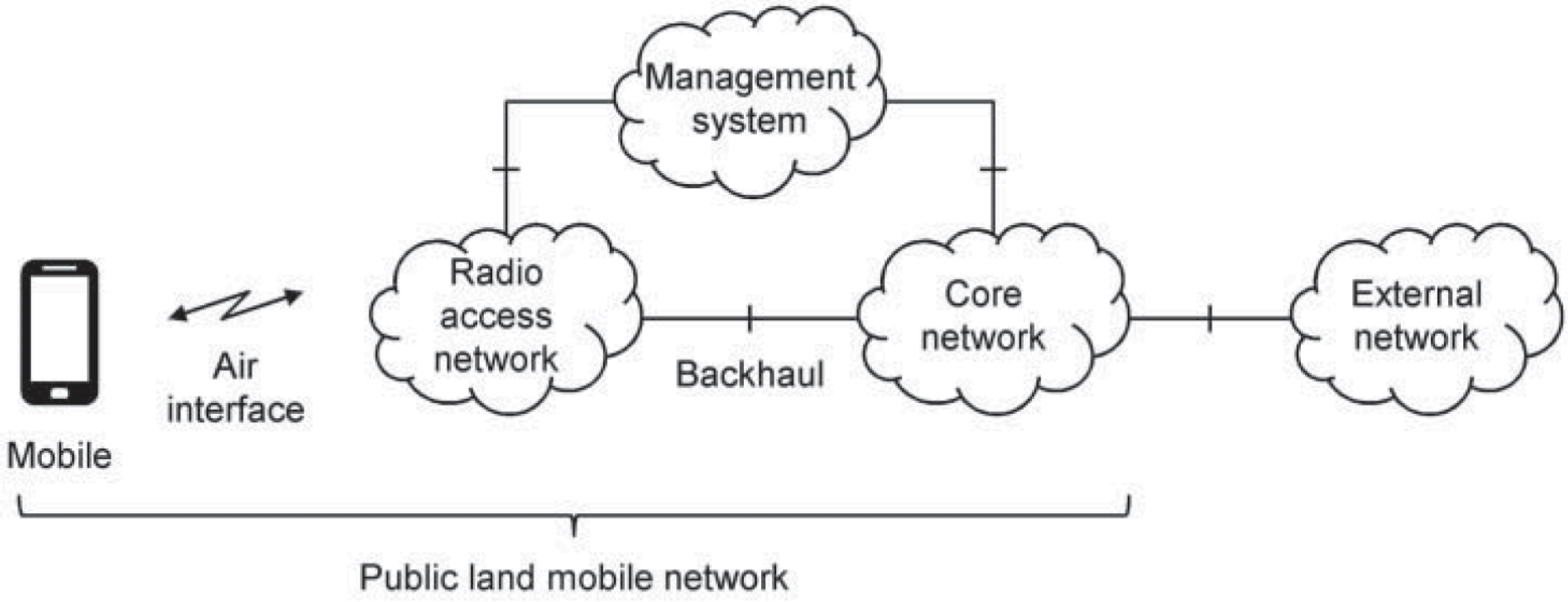
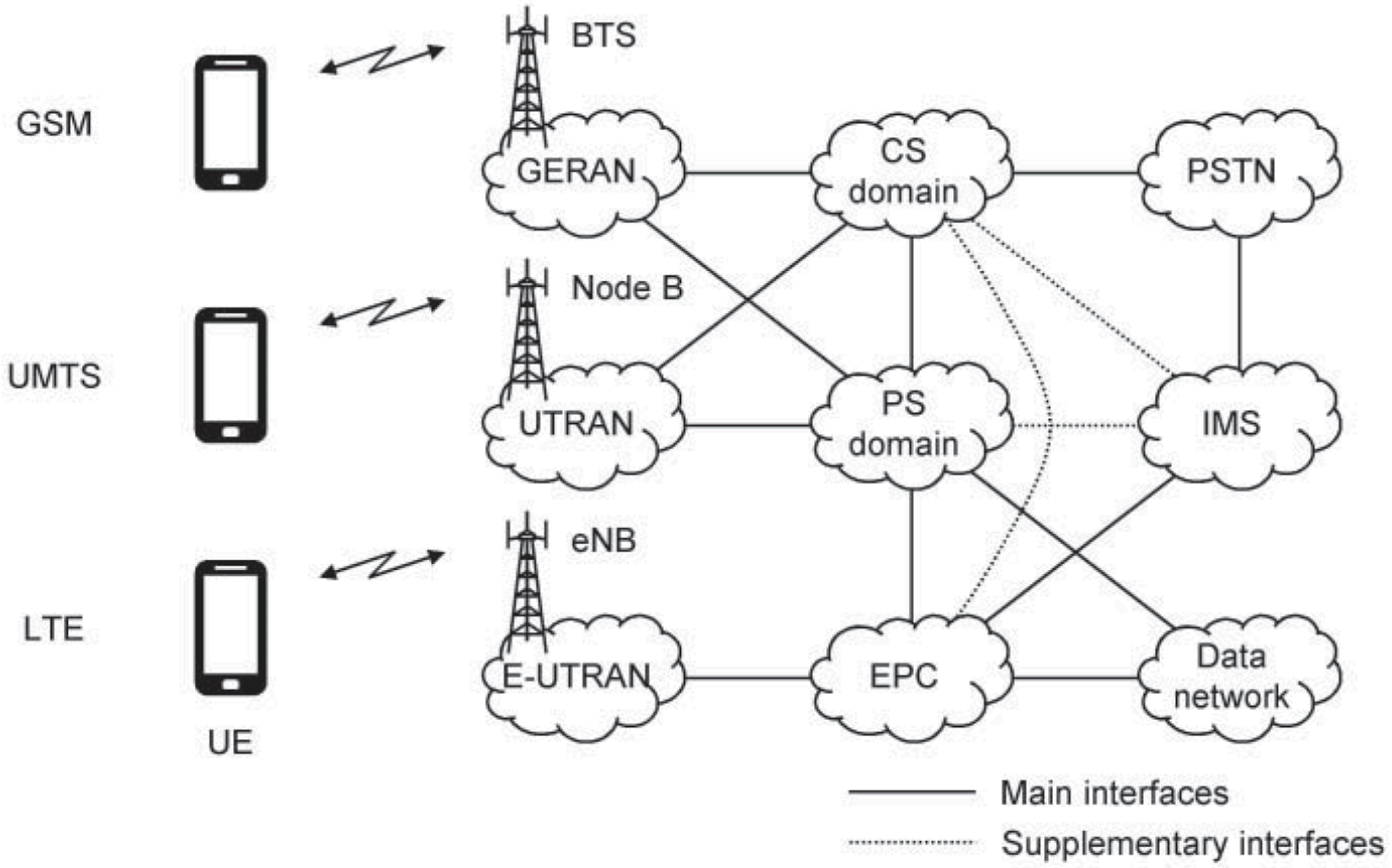
5G System Architecture

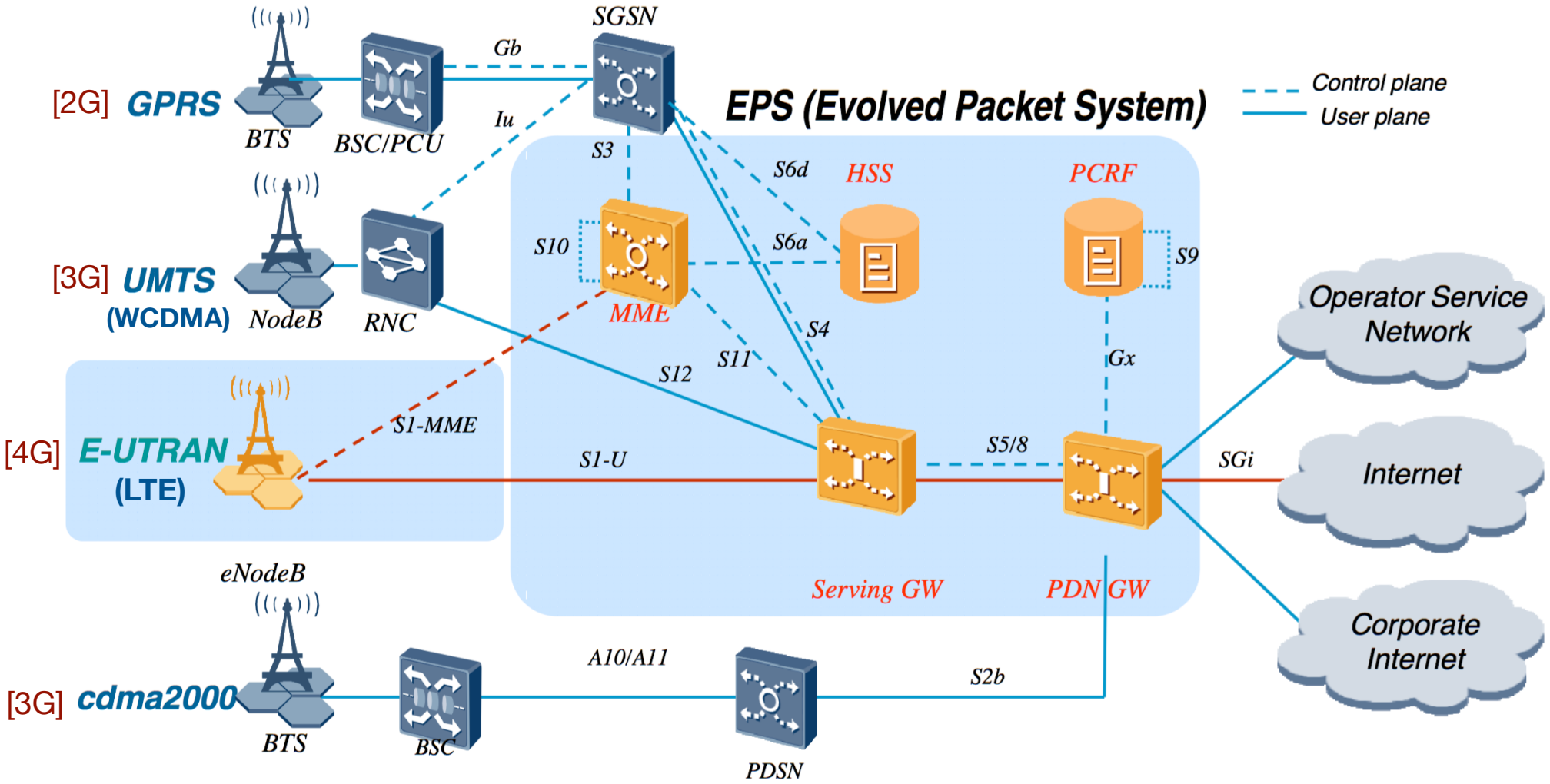


Architecture of a mobile telecommunication system

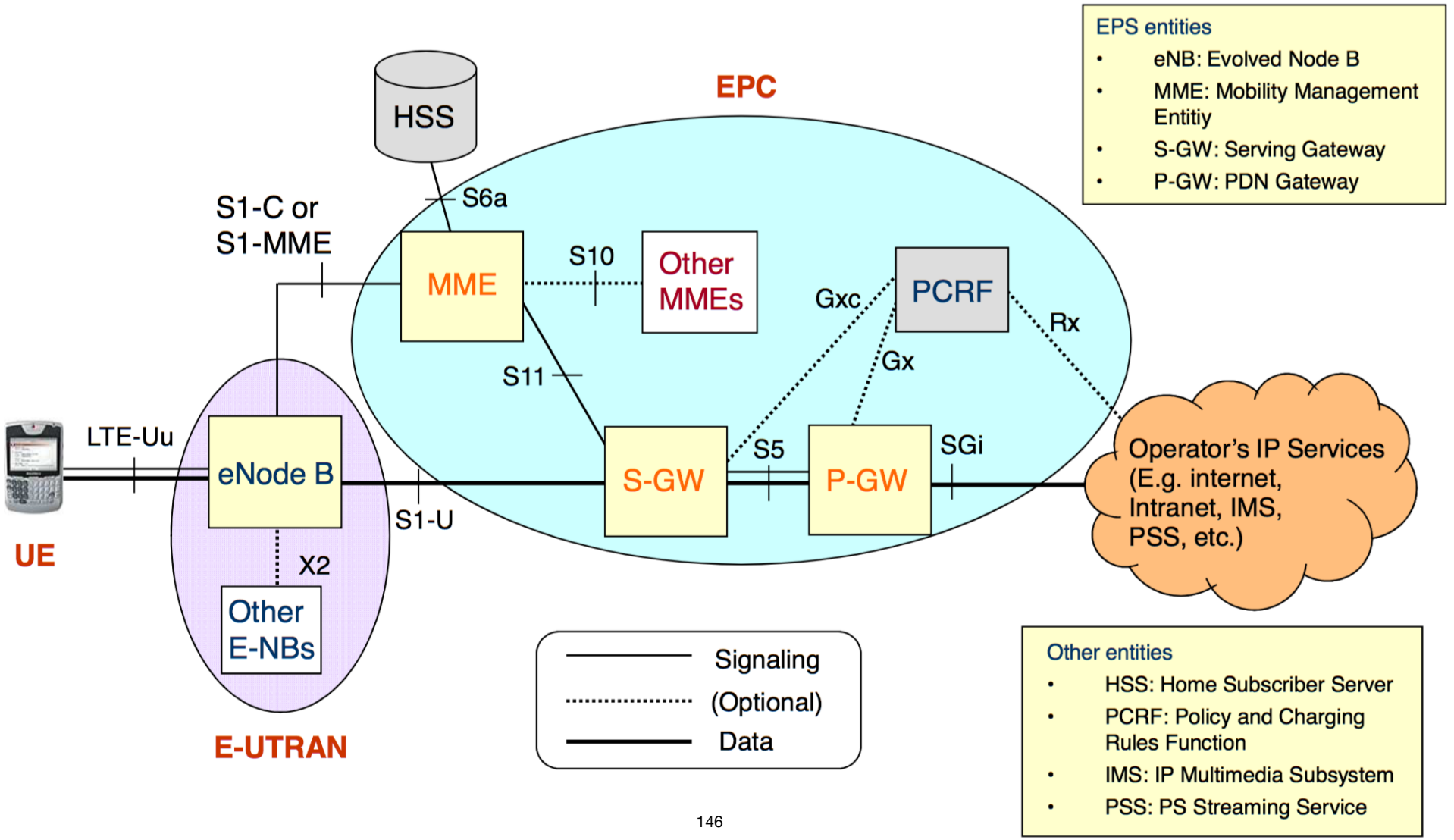


Architecture of GSM, UMTS and LTE

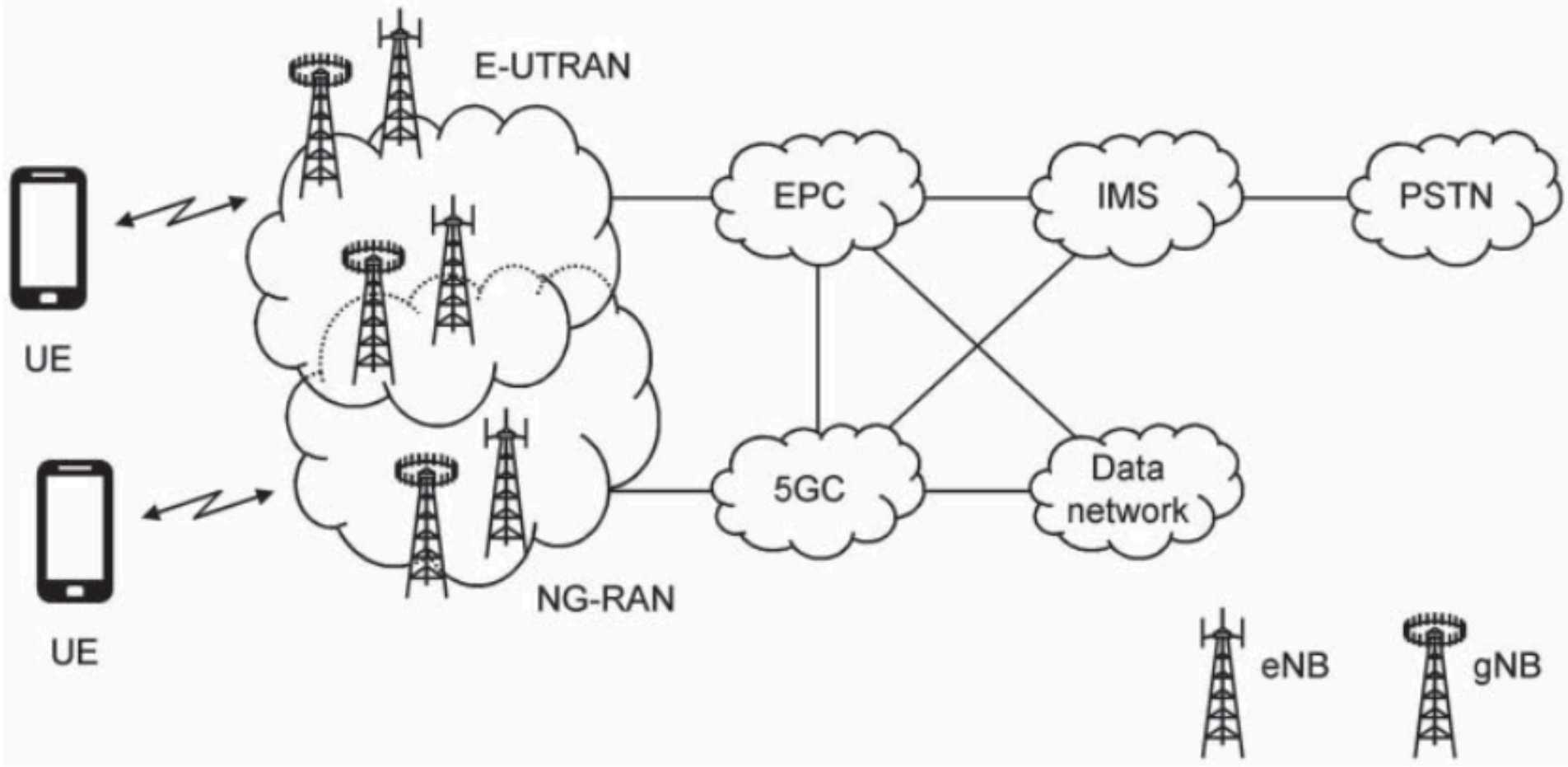
GSM/UMTS/LTE Network Architecture



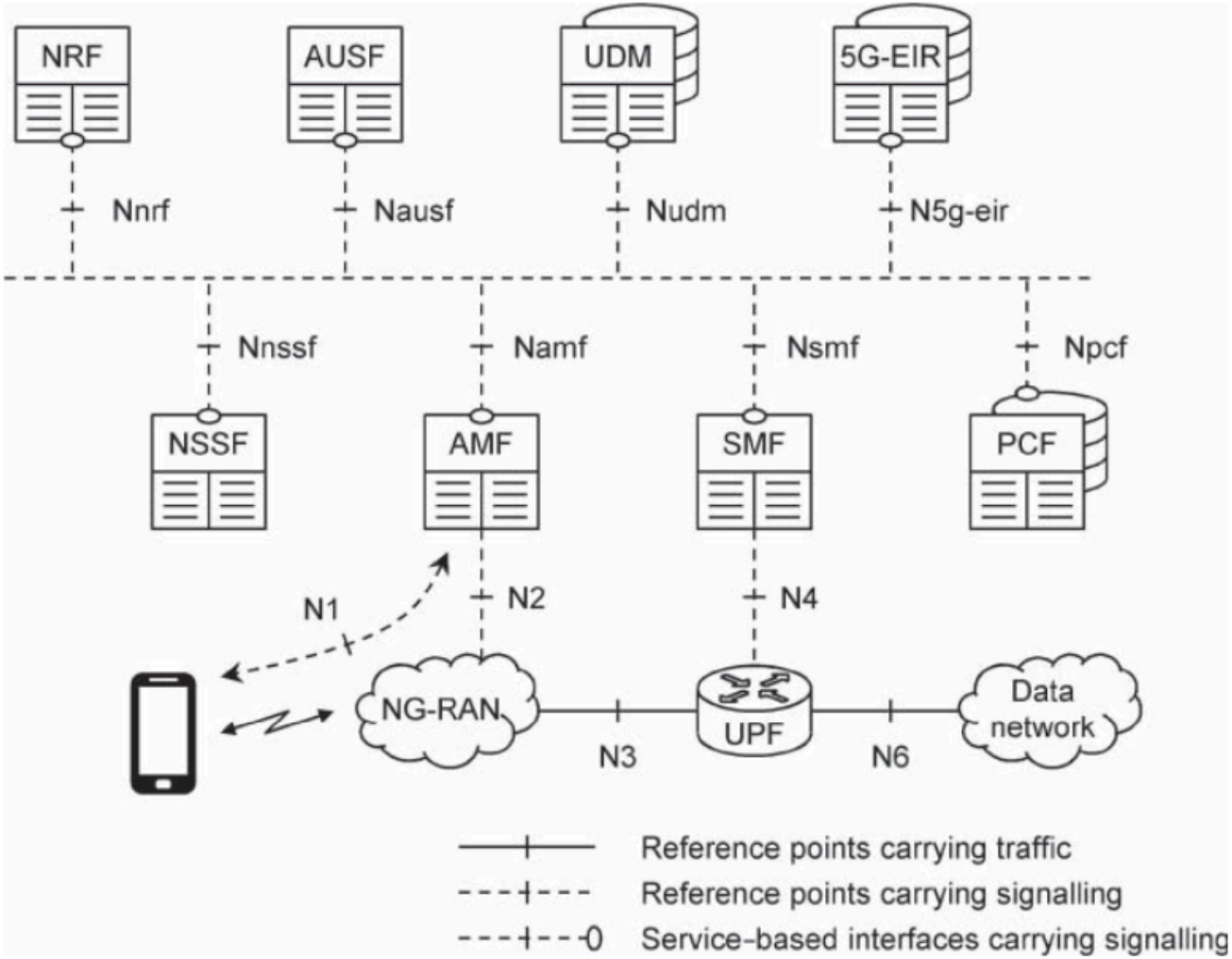
LTE Evolved Packet System (EPS) Architecture



High-level Architecture of 5G

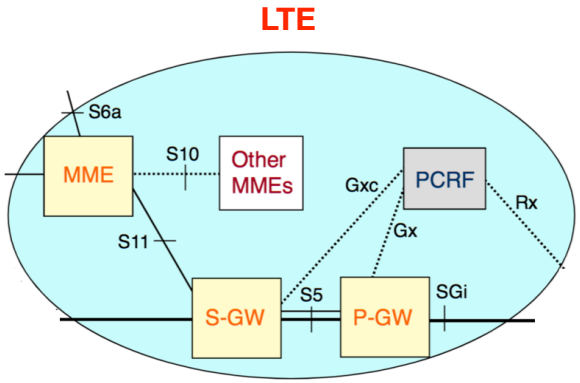


5G Core Network (SBA)

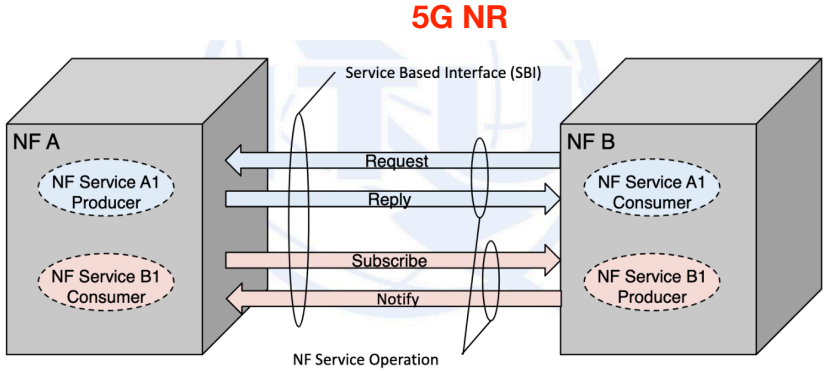


5G Core (5GC) Service-Based Architecture (SBA)

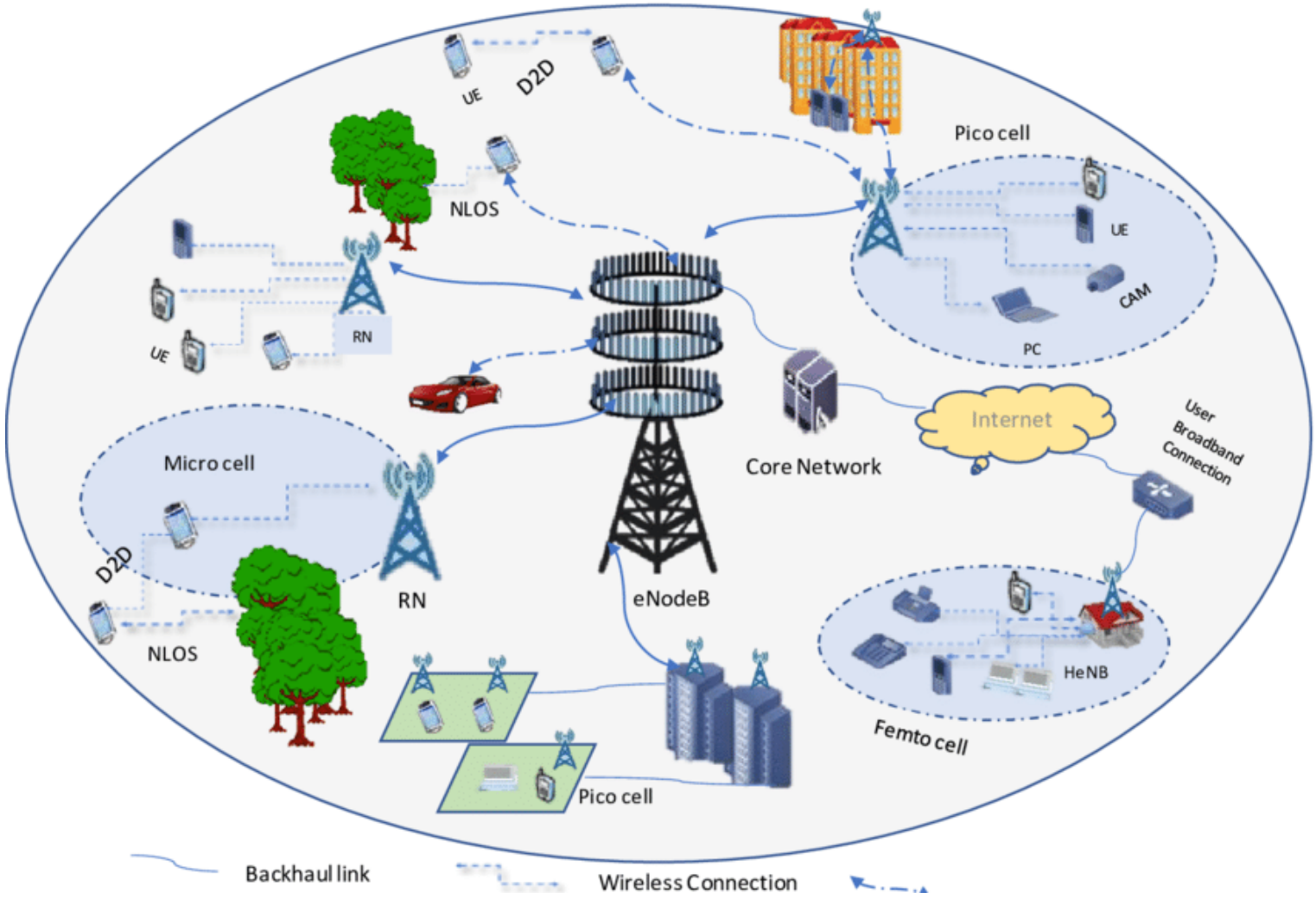
- **EPC architecture**
  - The control plane functions communicate with each other via the direct interfaces (or reference points) with a standardized set of messages

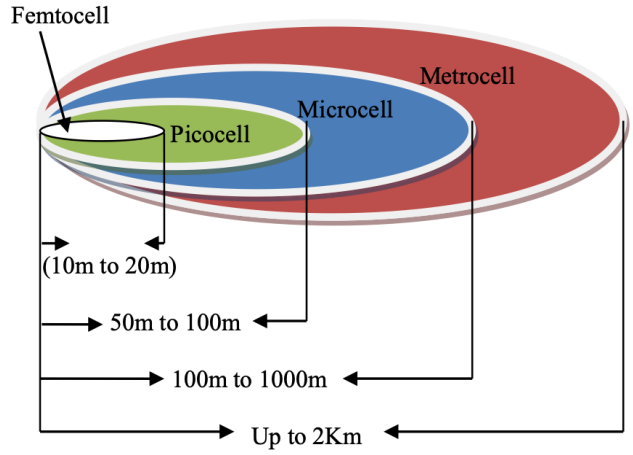


- **SBA architecture**
  - The Network Functions (NF), using a common framework, expose their services for use by other network functions through Service-Based Interfaces (SBI)

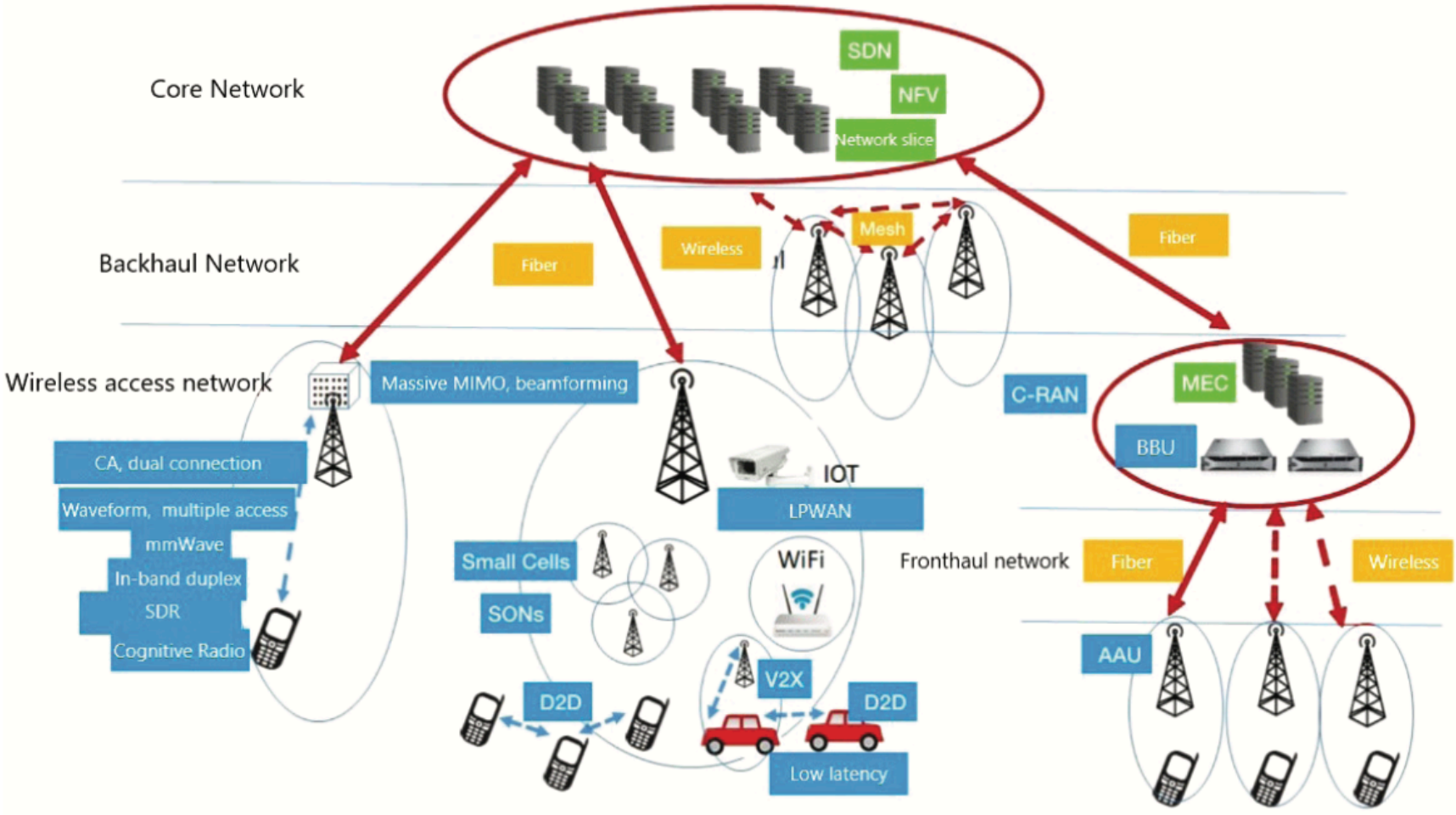


5G Heterogeneous Networks (HetNets)





Overall Architecture of 5G Network (Core Network, Backhaul / Fronthaul Network, RAN)



5G vs. 4G and Earlier

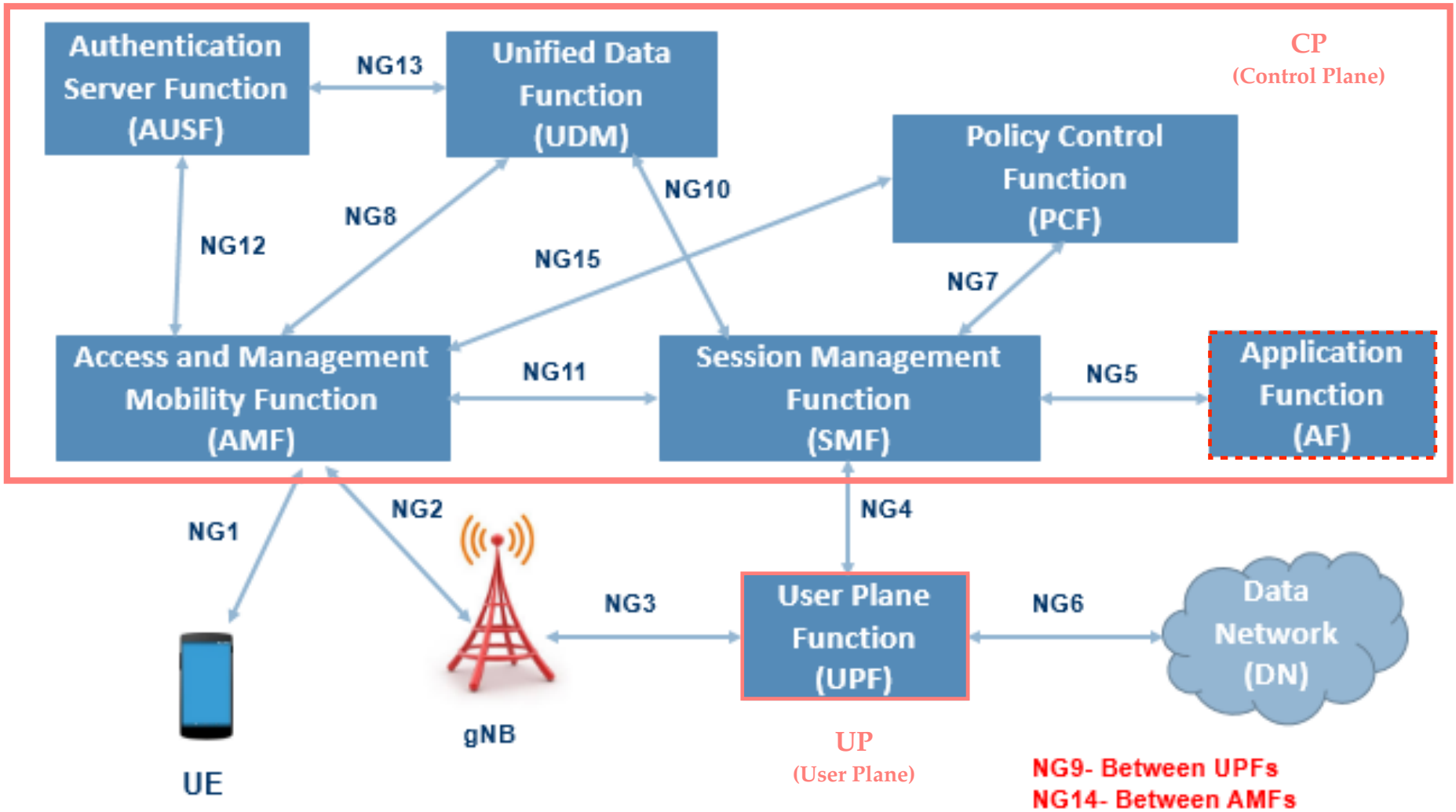
5G	4G and Earlier
New waveforms based on filter banks and other novel technologies	Waveforms based mainly on OFDM and variations
Gbps performance	Up to hundreds Mbps
End-to-end latency of some milliseconds	End-to-end latency of hundreds of milliseconds
Support of massive MIMO	SISO and limited MIMO technologies
Support of mm-wave bands up to hundreds GHz (30-300 GHz)	Operation mainly below 6 GHz bands
Efficient support of massive number of devices in ultradense environments	Support of limited number of devices in dense/congested areas

QoS Requirements: 4G & 5G

Parameters	4G	5G
Air Link User Plane Latency	10 ms	1 ms
Air Link Control Plane Latency	100 ms	50 ms
Simultaneous Connection Density per km^2	10^5	10^6
Mobility	300 km/h	500 km/h
Uplink Cell Spectral Efficiency	1.8 bps/Hz	5 bps/Hz
Downlink Cell Spectral Efficiency	2.6 bps/Hz	10 bps/Hz
Peak Throughput (Downlink) per Connection	100 Mbps to 1 Gbps	10 Gbps to 50 Gbps
Cell Edge Data Rate	1 Mbps	1 Gbps
Cost Efficiency	10 times	100 times
Packet Delay Budget without Quality Assurance	100 to 300 ms	Undetermined
Packet Delay Budget with Guaranteed Quality	50 to 300 ms	1 ms
Packet Loss Ratio for video broadcasting	10^{-8} (4k UHD)	10^{-9} (8k UHD)
Packet Loss Ratio for M2M Services (without quality assurance)	10^{-3}	10^{-4}
Packet Loss Ratio for M2M Services (without guaranteed quality)	10^{-6}	10^{-7}

- These 5G features support for
  - New types and massive number of devices
  - Very high mobile traffic volumes
  - Universal access for users
  - Very high frequency reuse and spectrum reuse in wireless technologies
  - Automated provisioning, configuration and management of a wide range of new network services
  - Ultrareliable / ultralow latency / ultradensification
  - and more

5G Network Architecture

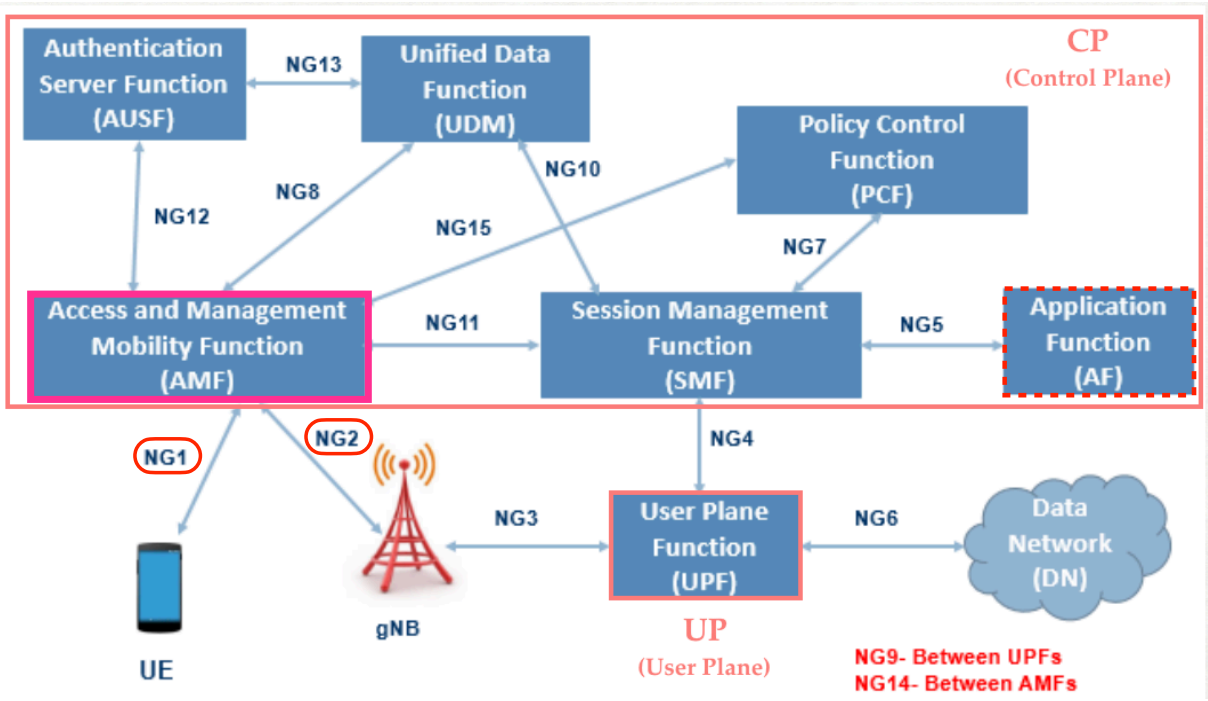


UE：User Equipment
gNB：Next Gen Node Basestation

Source 3GPP TR 23.799

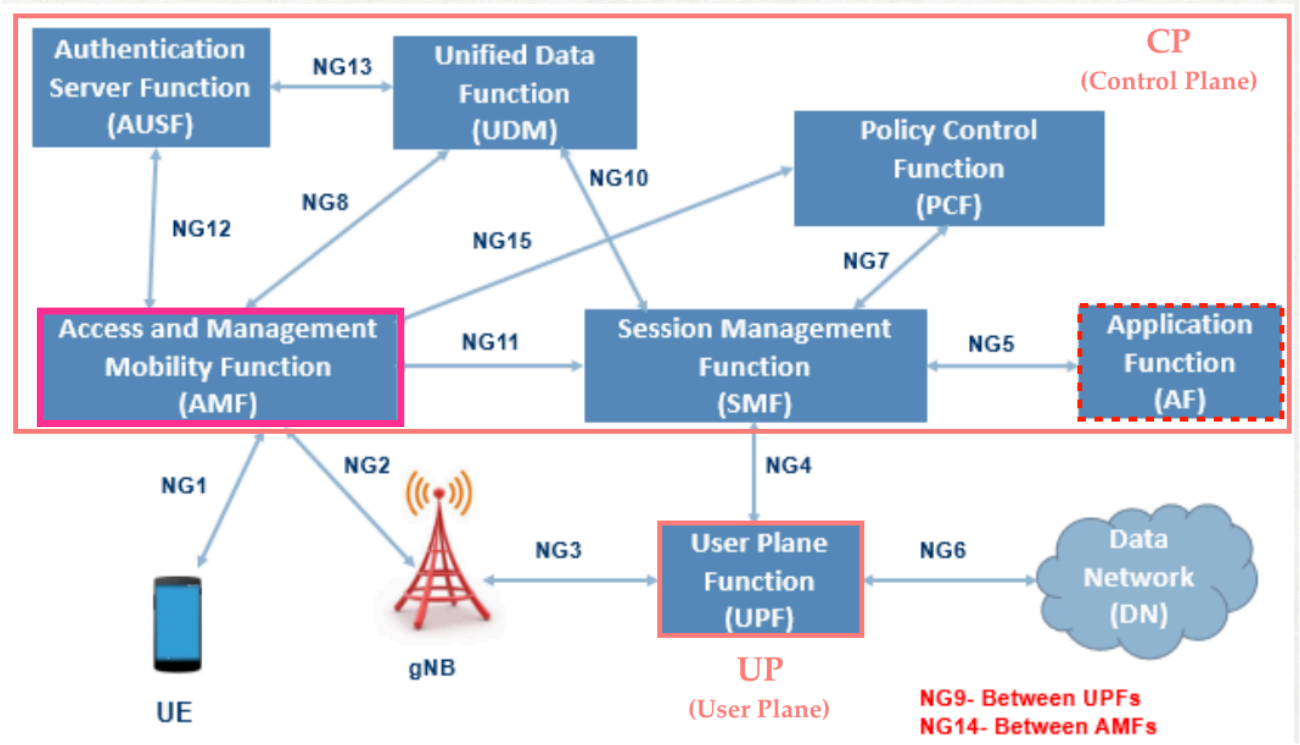
Network Nodes and Functions

- **Access and Mobility Management Function (AMF)**
  - Termination of RAN Control Plane interface (**NG2**)
  - Termination of NAS (**NG1**), NAS ciphering and integrity protection
  - Mobility management

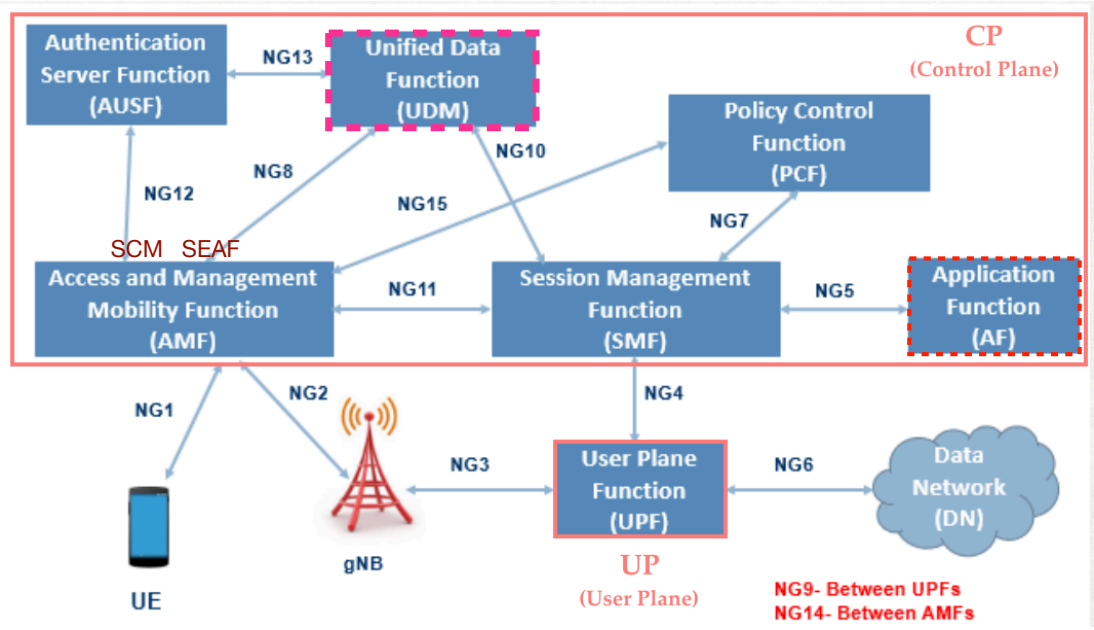


AS：Access Stratum
NAS：Non-Access Stratum

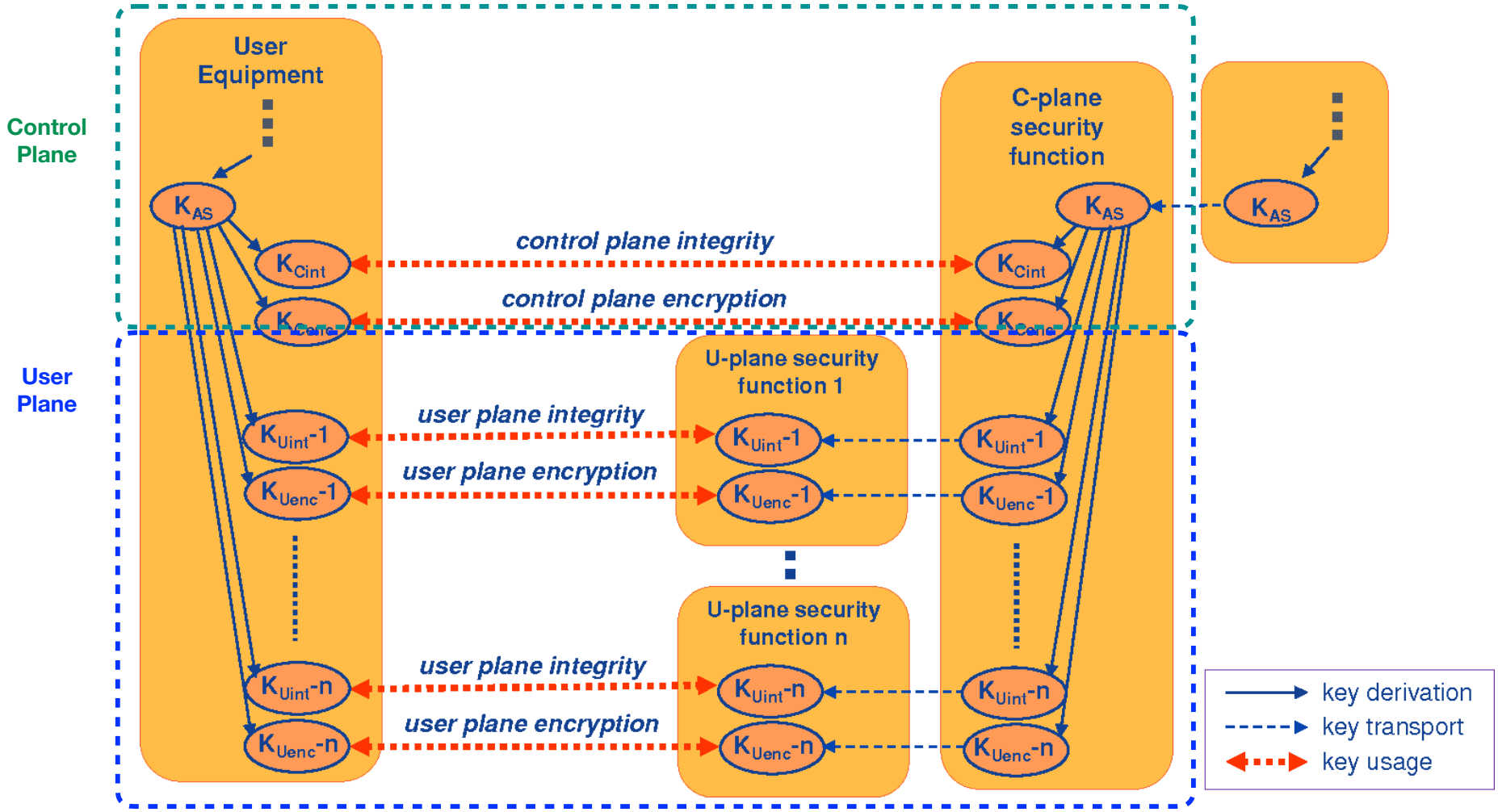
- Lawful intercept for AMF events and interface to Lawful Inetercept System
- Transparent proxy for routing access authentication and SM messages
- Access authentication
- Access authorization

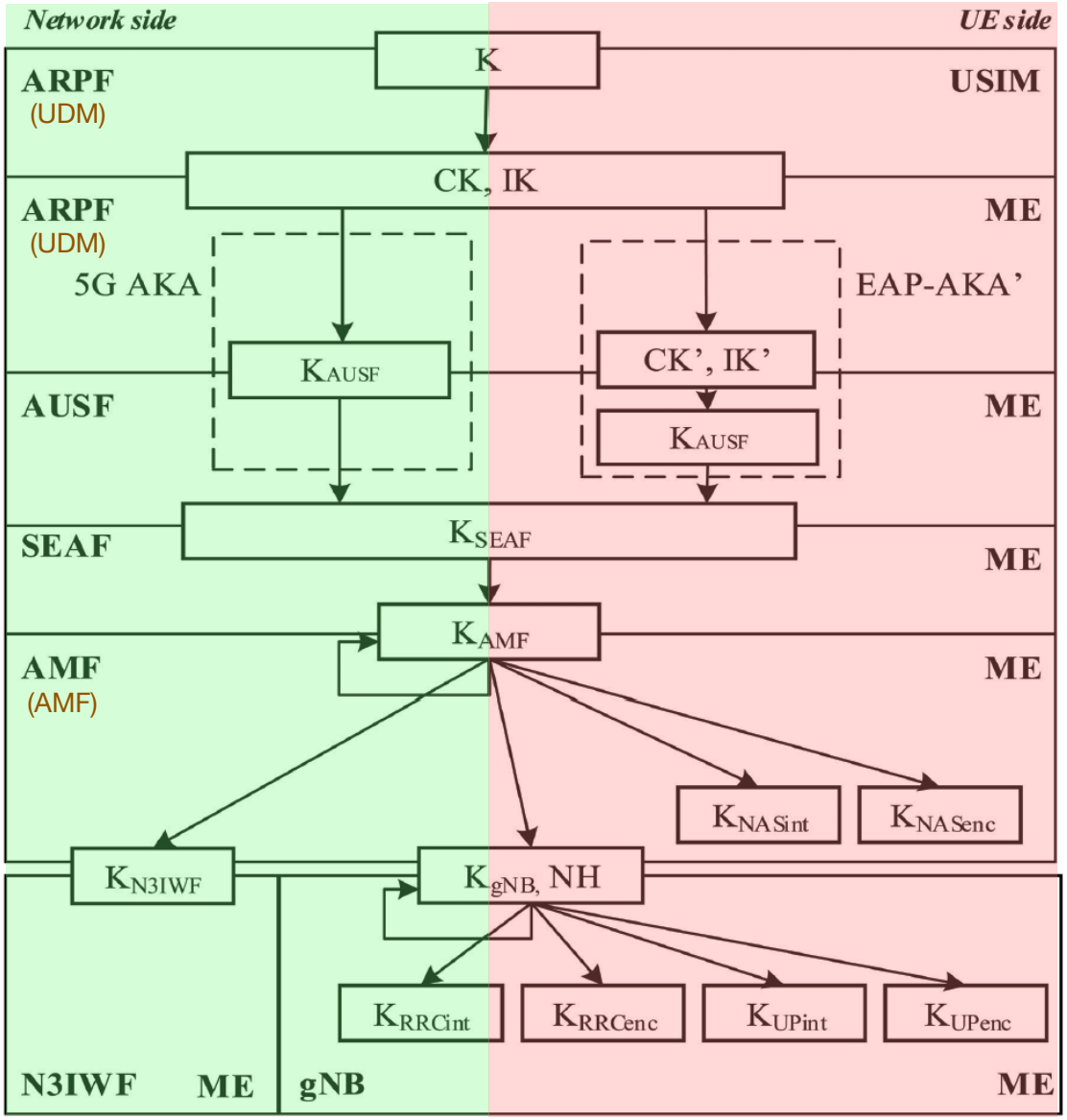


- **Security Anchor Function (SEAF)**
  - Interact with UDM and UE, receives the intermediate key that was established as a result of UE authentication process
  - In case of USIM based authentication, AMF retrieves the security material from UDM
- **Security Context Management (SCM)**
  - Receive a key from SEAF that it uses to derive access-network specific keys

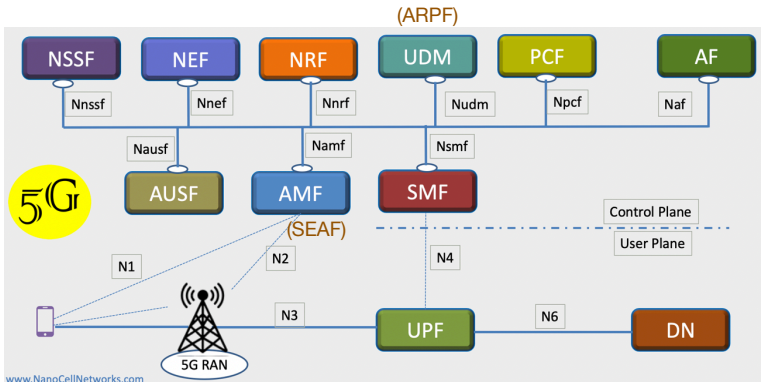


Access Stratum (AS) Security





3GPP 5G key hierarchy



ARPF：Authentication credential Repository and Processing Function

AUSF：Authentication Server Function

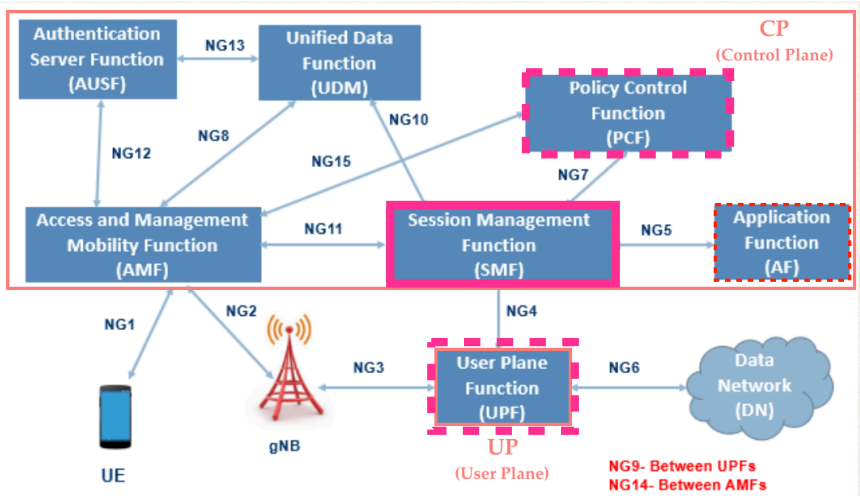
SEAF：SEcurity Anchor Function

AMF：Access and Mobility Management Function

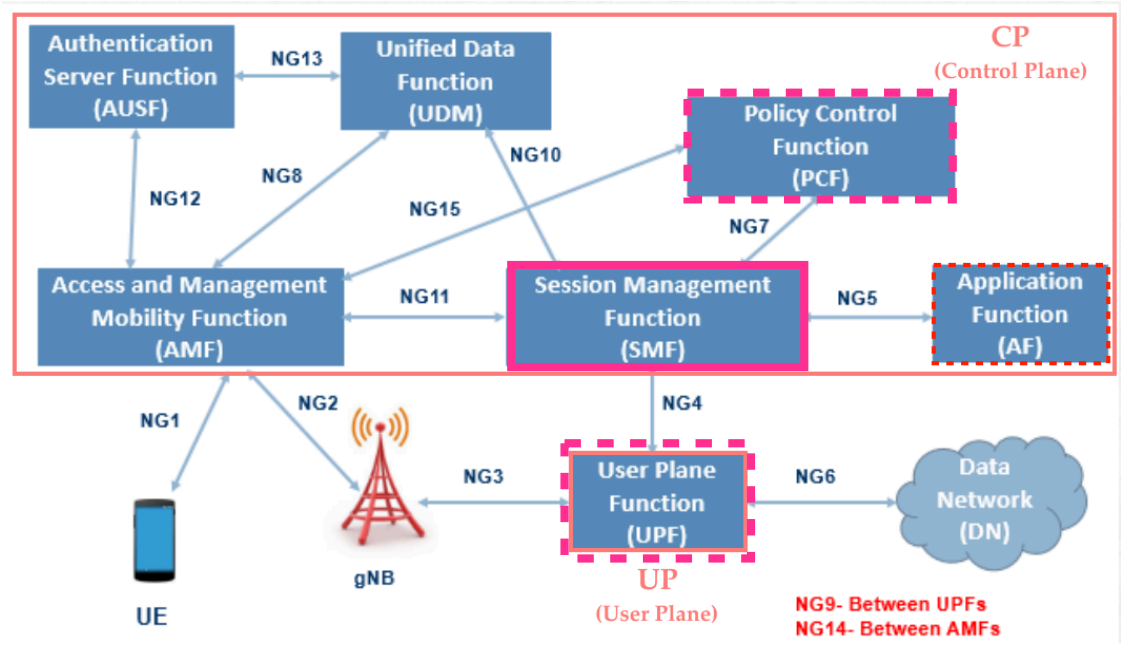
EAP-AKA：Extensible Authentication Protocol Method for 3rd Generation Authentication and Key Agreement

N3IWF：Non-3GPP Inter Working Function

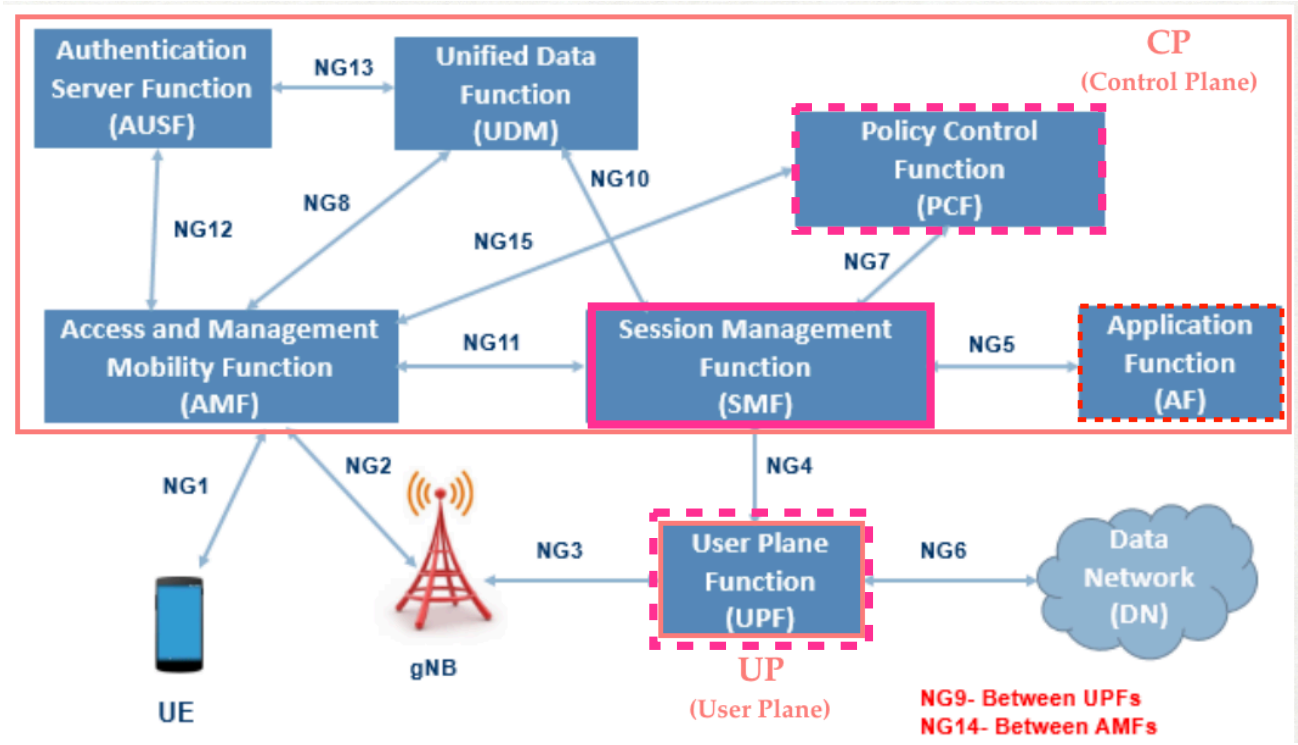
- **Session Management Control Function (SMF)**
  - Session management
  - UE IP address allocation & management (including optional authorization)
  - Selection and control of User Plane function (UPF)
  - Termination of interfaces towards Policy control and Charging functions (PCF)
  - Control part of policy enforcement and QoS



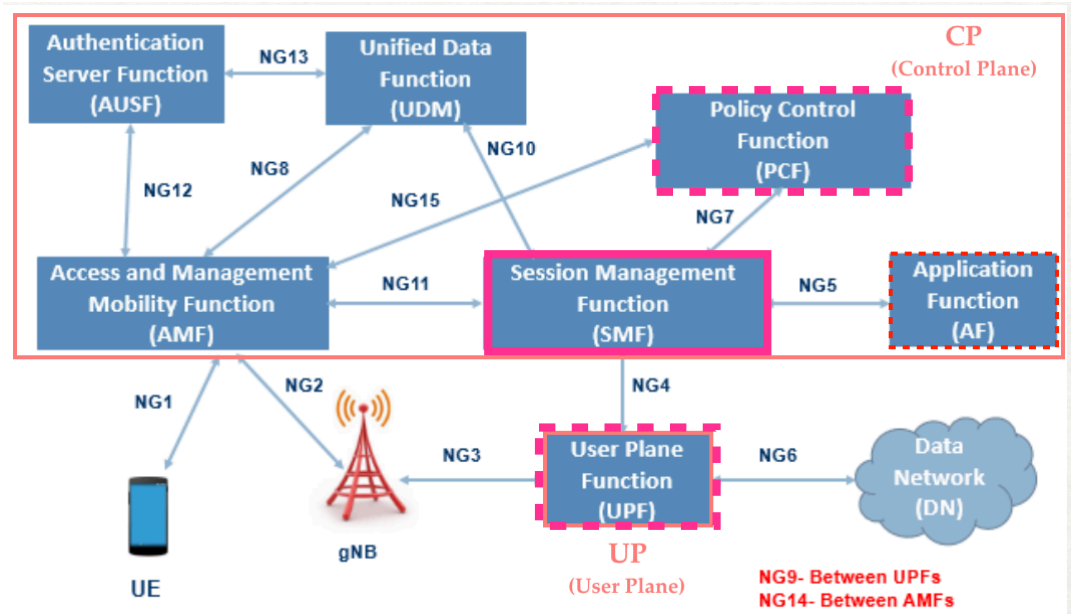
- Lawful intercept for session management events and interface to Lawful Intercept System
- Termination of Session Management parts of NAS messages
- Downlink data notification



- Initiator of Access Node specific Session Management information, sent via AMF over NG2 to Access Node
- Roaming functionality

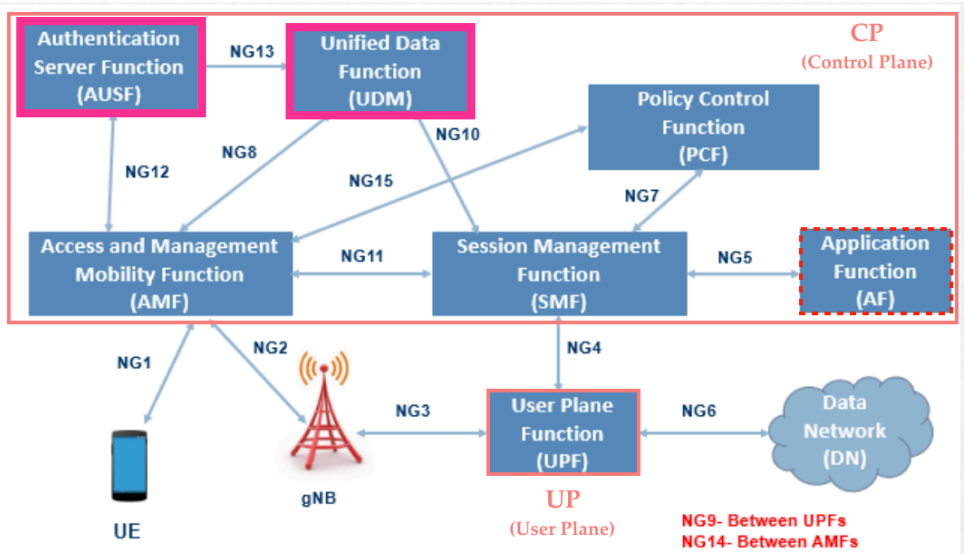


- Handle local enforcement to apply QoS SLAs (VPLMN)
- Charging data collection and charging interface (VPLMN)
- Lawful intercept in VPLMN for Session Management events and interface to Lawful Intercept System

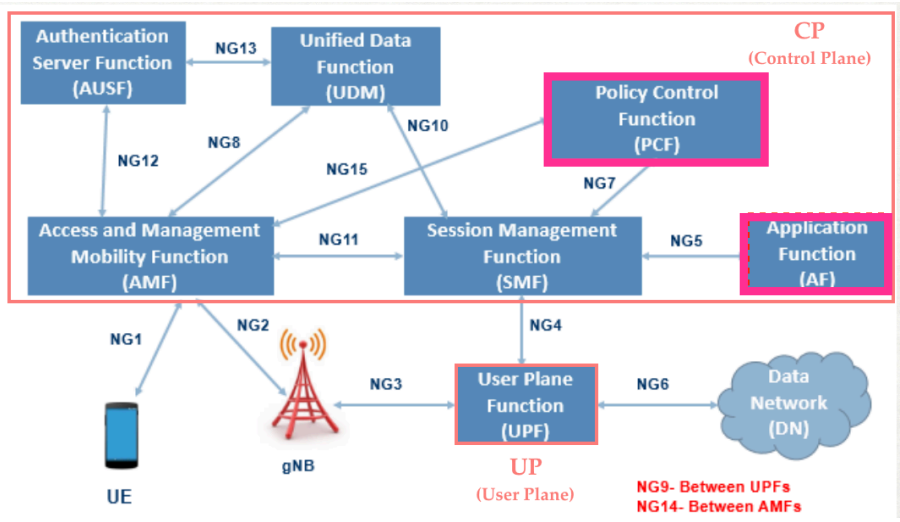


VPLMN (Visited Public Land Mobile Network)：a PLMN upon which the mobile subscriber has roamed when leaving their HPLMN (Home Public Land Mobile Network)

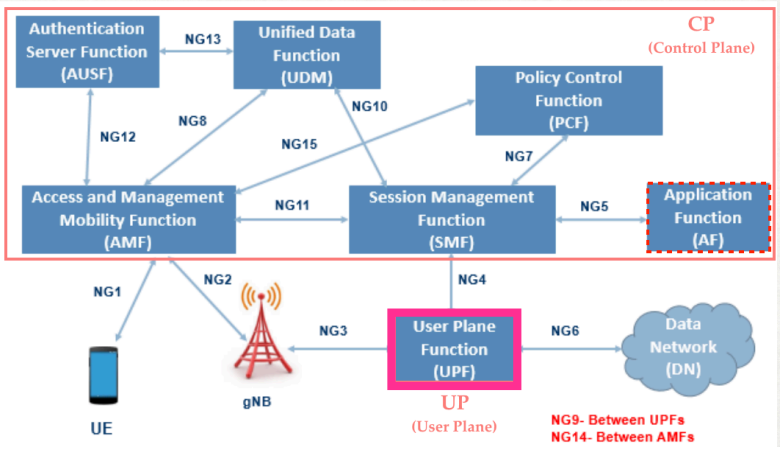
- **Authentication Server Function (AUSF)**
  - Performs authentication processes with UE
- **Unified Data Management (UDM)**
  - Authentication Credential Repository and Processing Function (ARPF); this function stores the long-term security credentials used in authentication for AKA (Authentication and Key Agreement)
  - Storing of subscription information



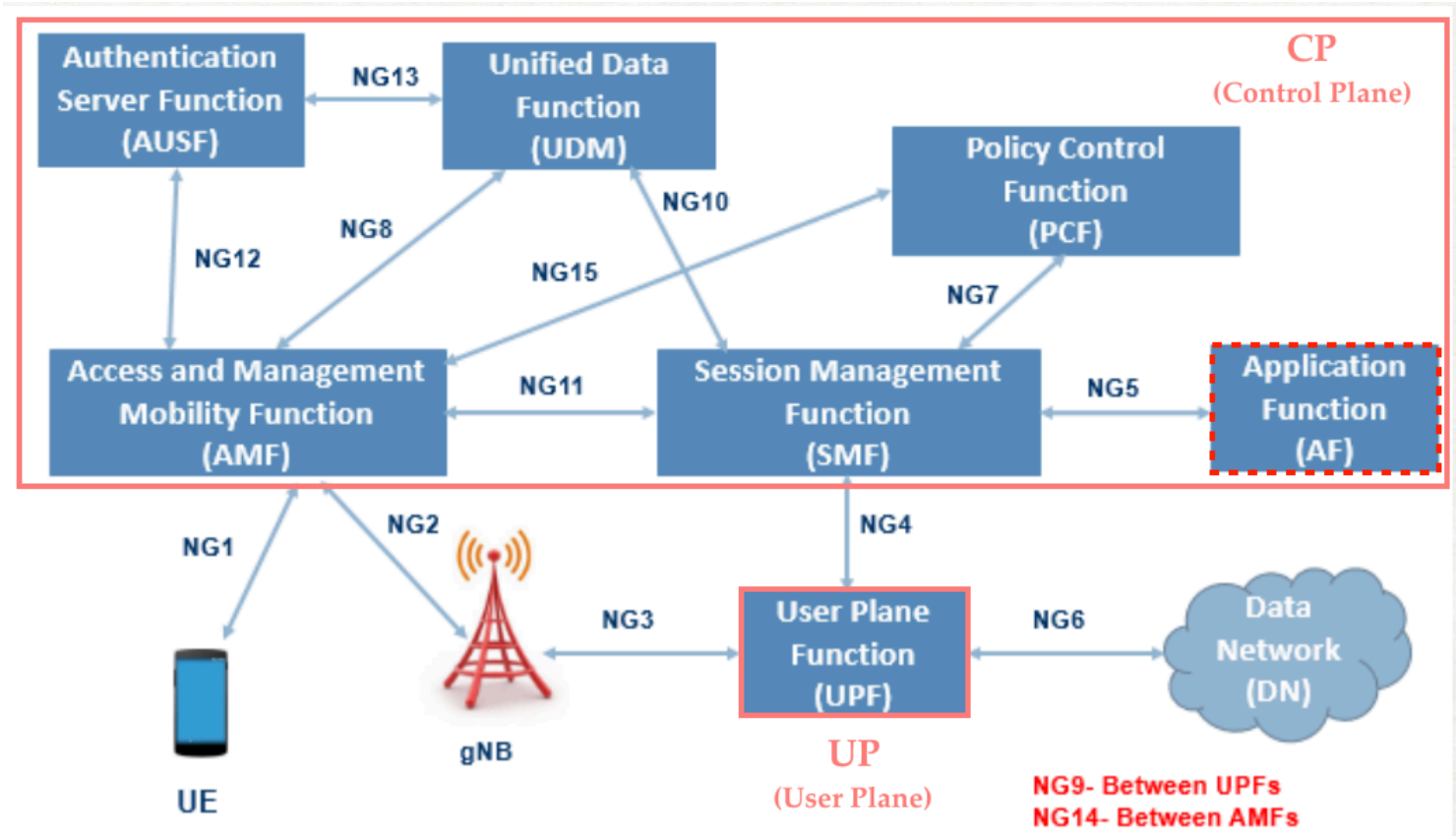
- **Policy Control Function (PCF)**
  - Support of unified policy framework to govern network behavior
  - Policy rules to control plane function(s) that enforce them
- **Application Function (AF)**
  - Request dynamic policies and/or charging control



- **User plane Function (UPF)**
  - QoS handling for User Plane
  - Packet routing & forwarding
  - Packet inspection and policy rule enforcement
  - Lawful intercept (User Plane)
  - Traffic accounting and reporting
  - Anchor point for Intra-/Inter-RAT mobility (when applicable)
  - Support for interaction with external DN for transport of signaling for PDU (Protocol Data Unit) session authorization/authentication by external DN

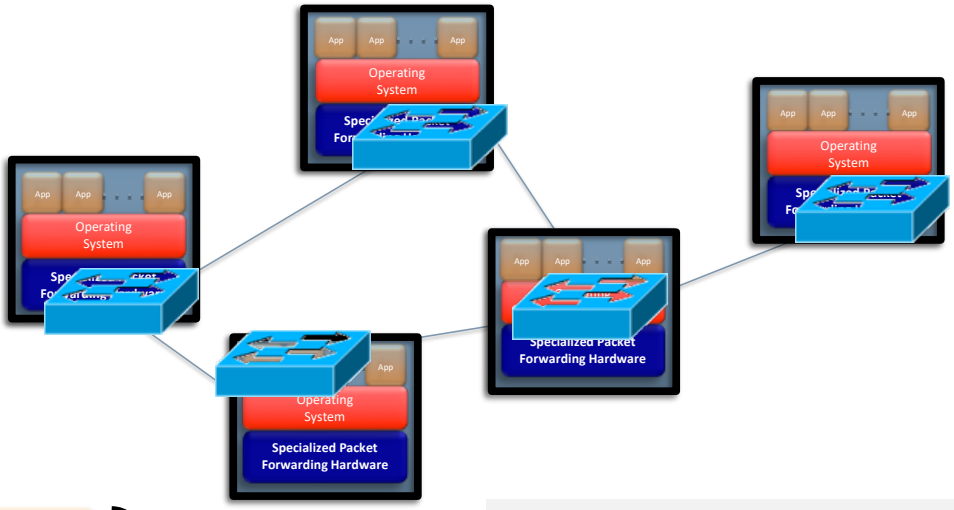


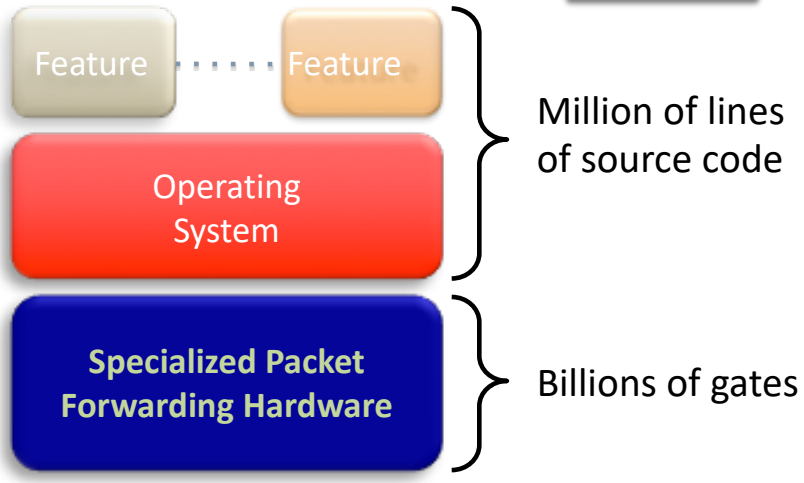
- **Data Network (DN)**
  - Operator services, Internet access or other services



- Evolution of Mobile Communication
- ITU/3GPP Standardization
- ITU 5G Service Scenarios
- 5G-New Radio
- 5G System Architecture
- **SDN/NFV**
- Network Slicing
- Mobile Edge Computing (MEC)
- The Road to the 6G Mobile Communication

Traditional Network





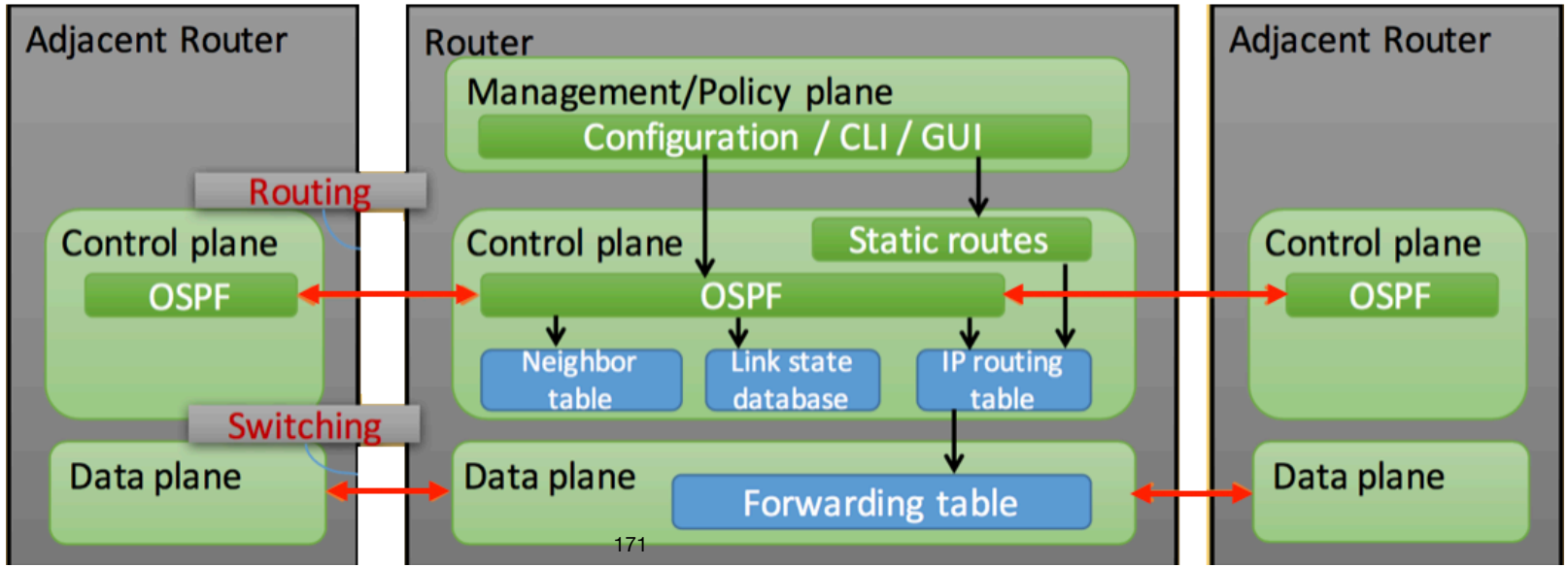
Many complex functions baked into infrastructure

OSPF, BGP, multicast, differentiated services, Traffic Engineering, NAT, firewalls, …

Cannot dynamically change according to network conditions

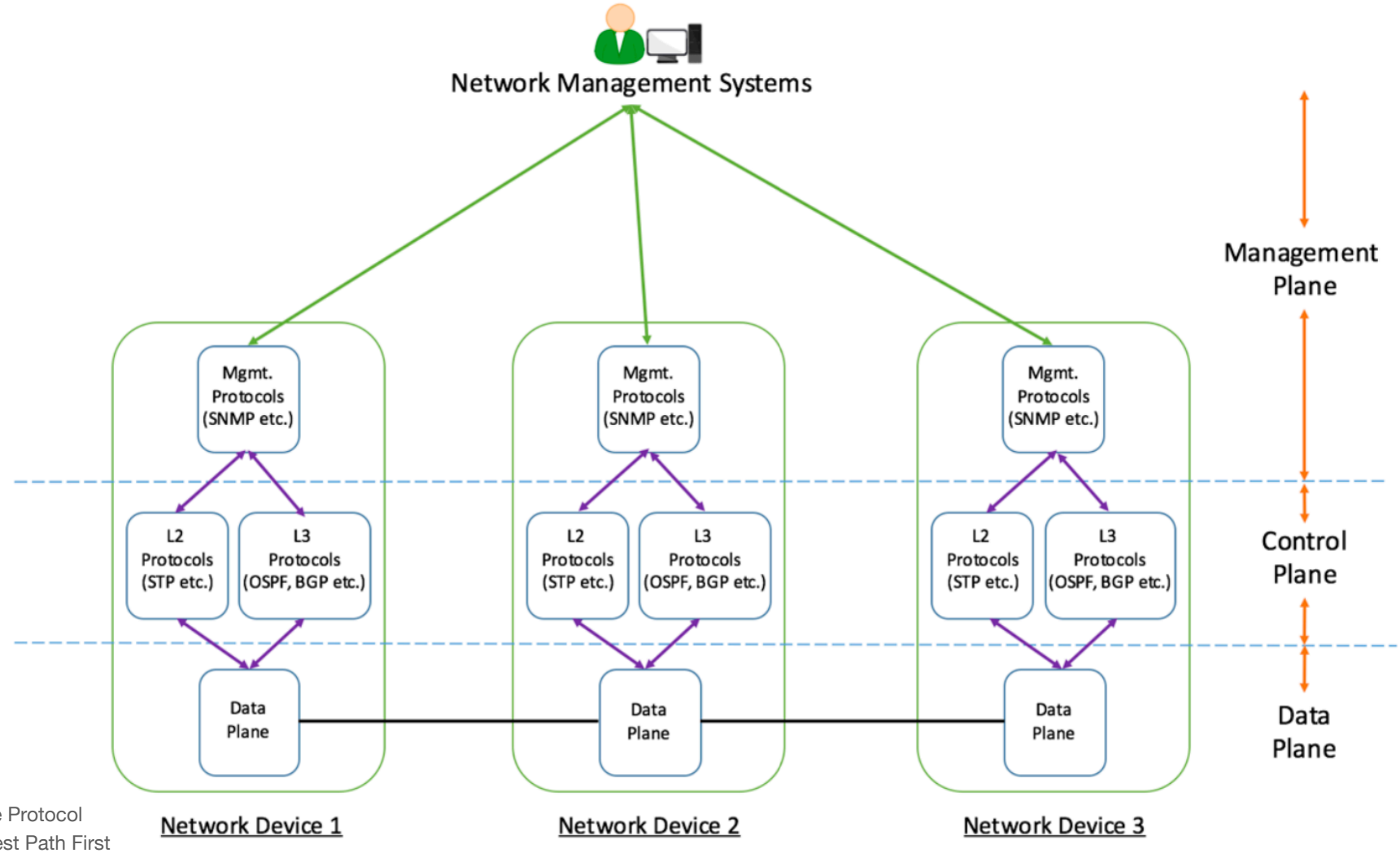
Traditional Network Router

- **Management plane**: collect measurements and configure the equipment
- **Control plane**: track topology changes, compute routes, install forwarding rules, e.g. OSPF (Open Shortest Path First)
- **Data plane**: forward, filter, buffer, mark, rate-limit, and measure packets



RIP：Routing Information Protocol
OSPF：Open Shortest Path First
BGP：Border Gateway Protocol
CLI：Command Line Interface
GUI：Graphical User Interface

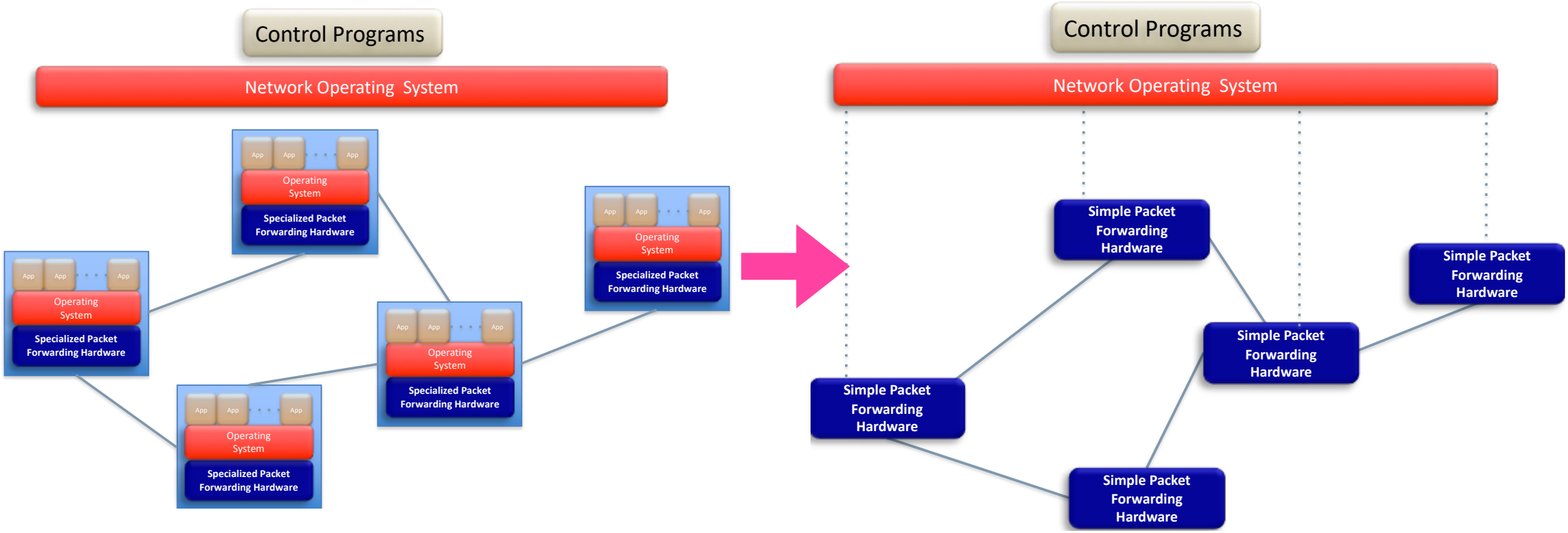
Traditional Network Architecture



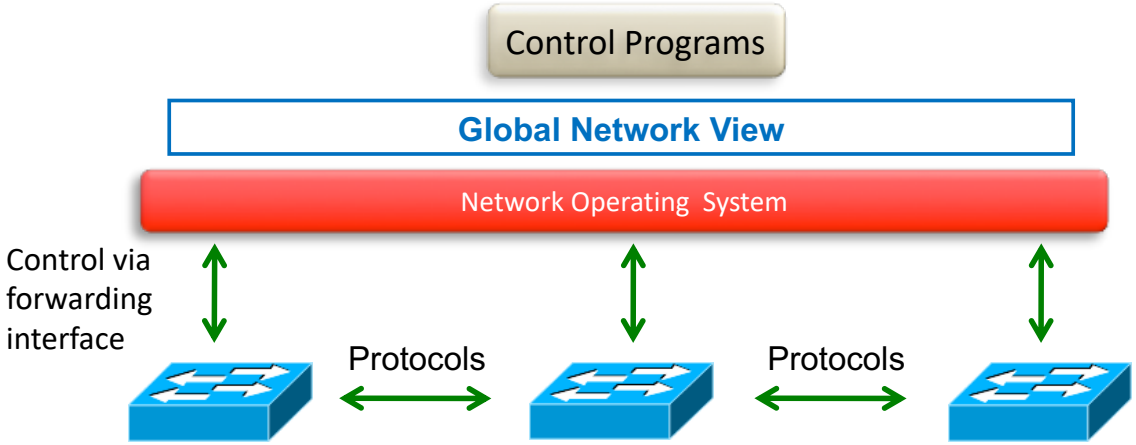
STP：Spanning Tree Protocol
OSPF：Open Shortest Path First
BGP：Border Gateway Protocol

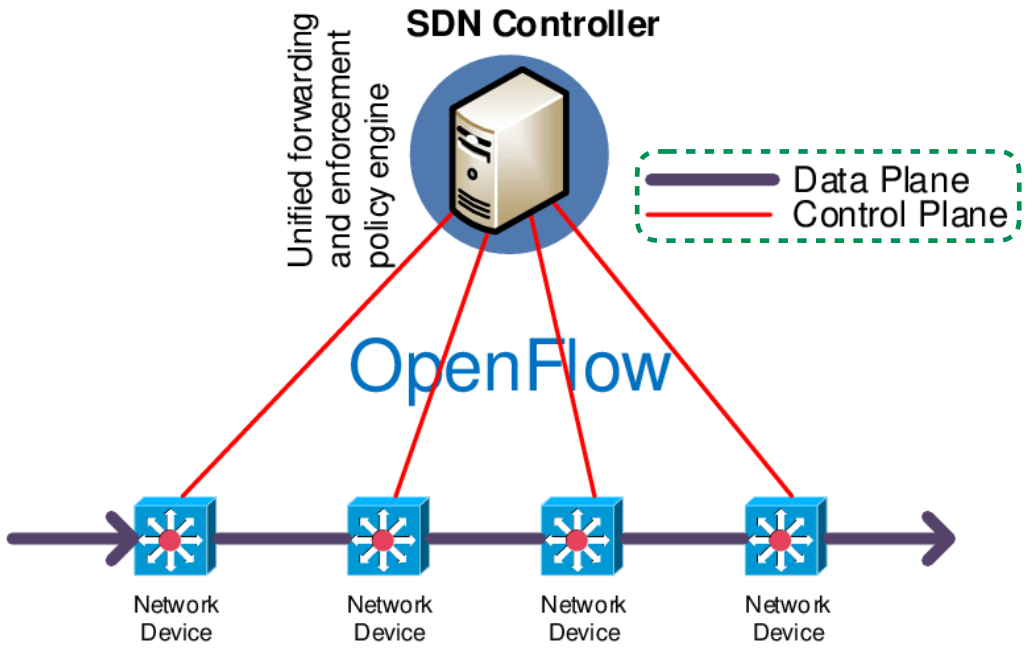
- **Problems**
  - Closed equipment
    - Software bundled with hardware
    - Vendor-specific interfaces
    - Slow protocol standardization
  - Few people can innovate
    - Equipment vendors write the code
    - Long delays to introduce new features
  - Impact performance, security, reliability, cost, etc.

Idea – An OS for Networks

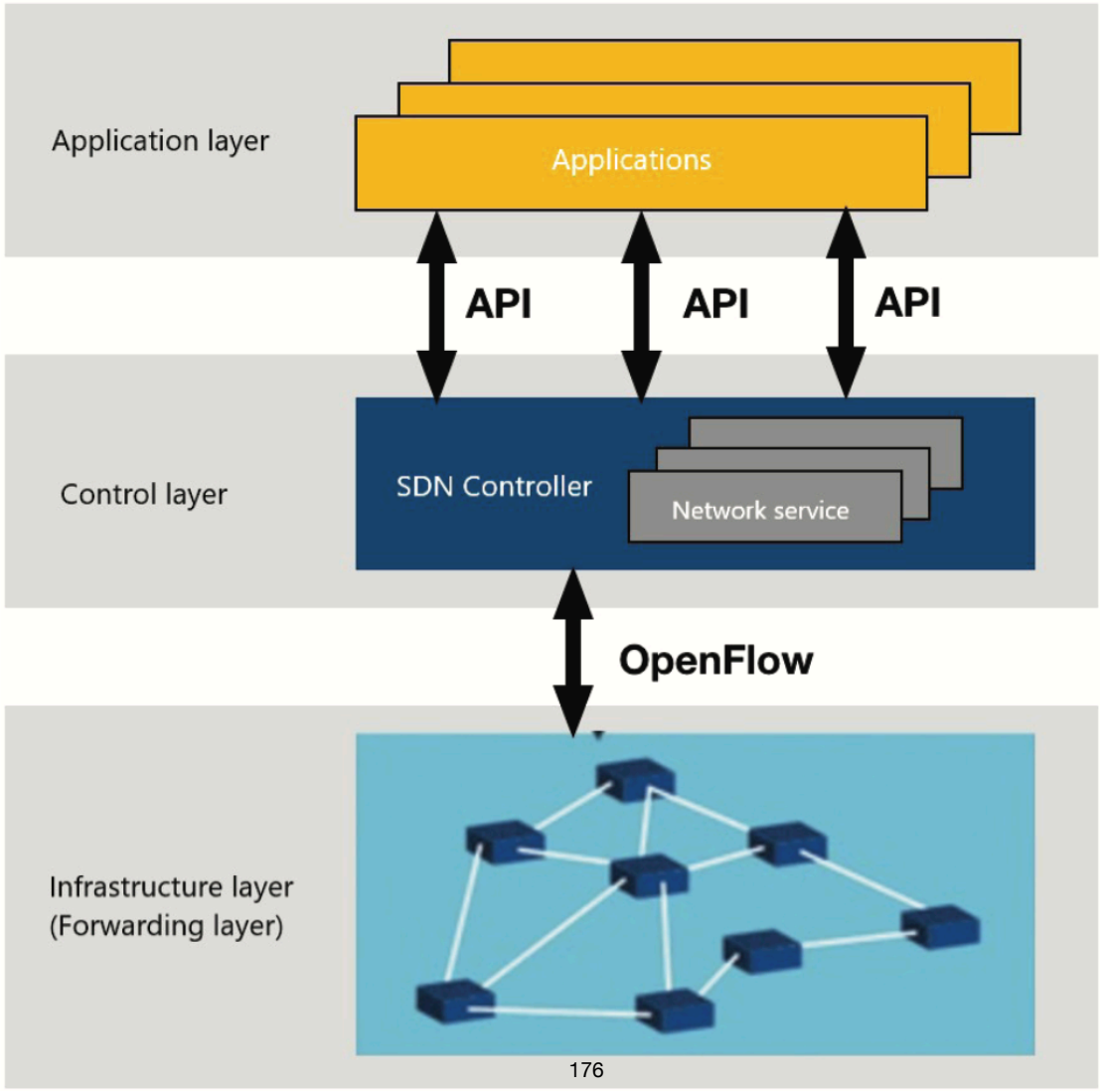


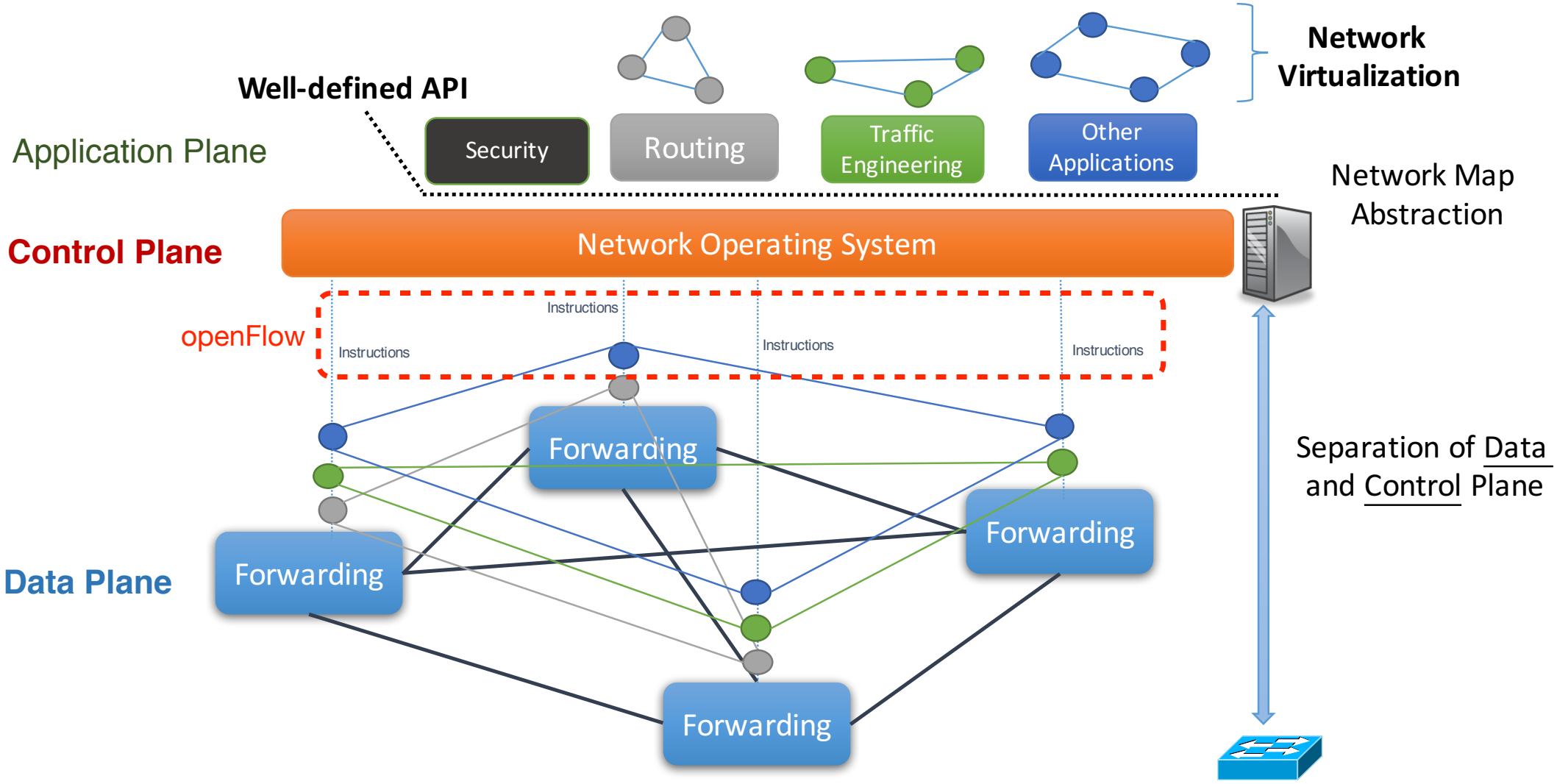
Software-Defined Networking (SDN)

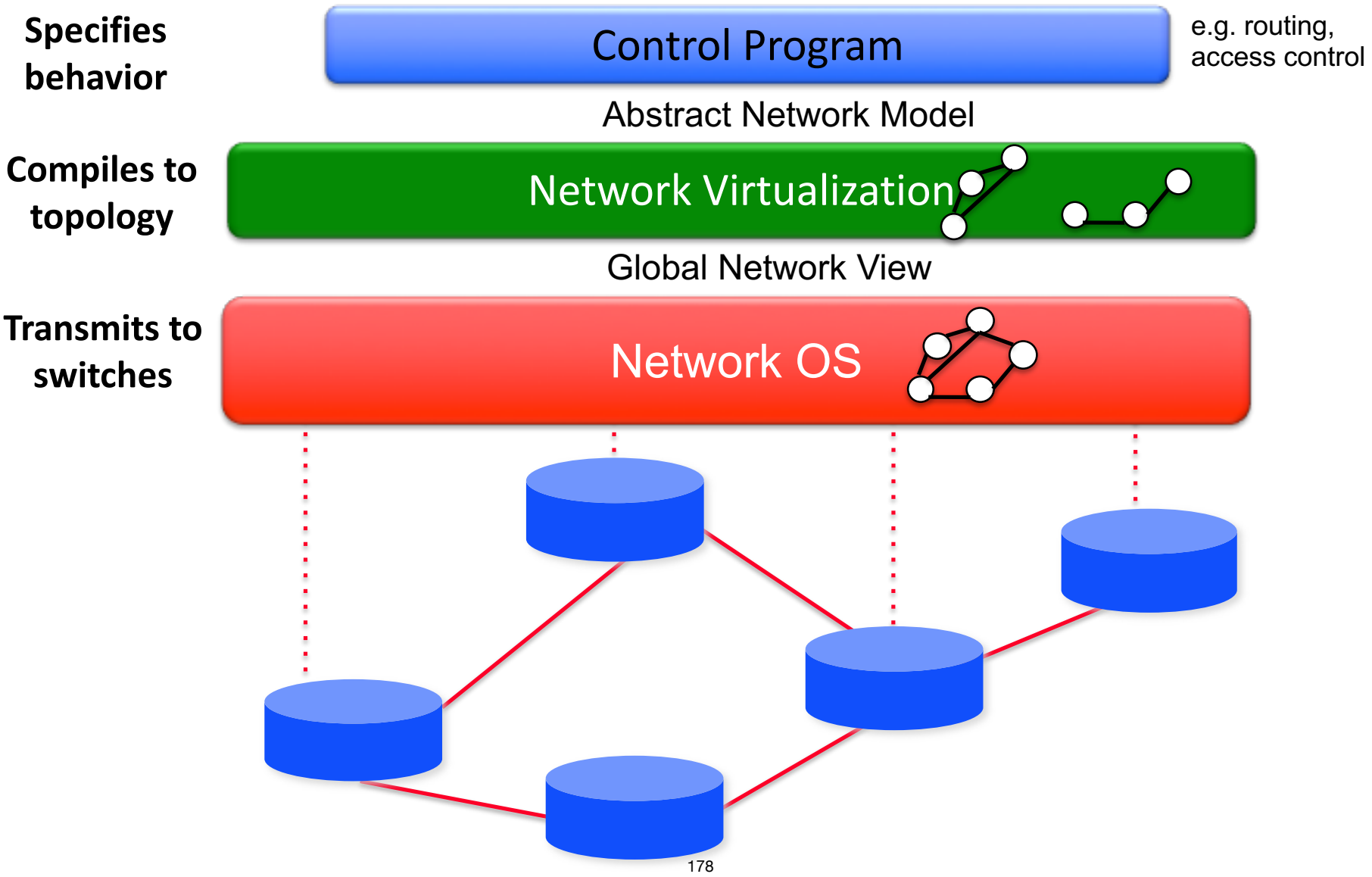


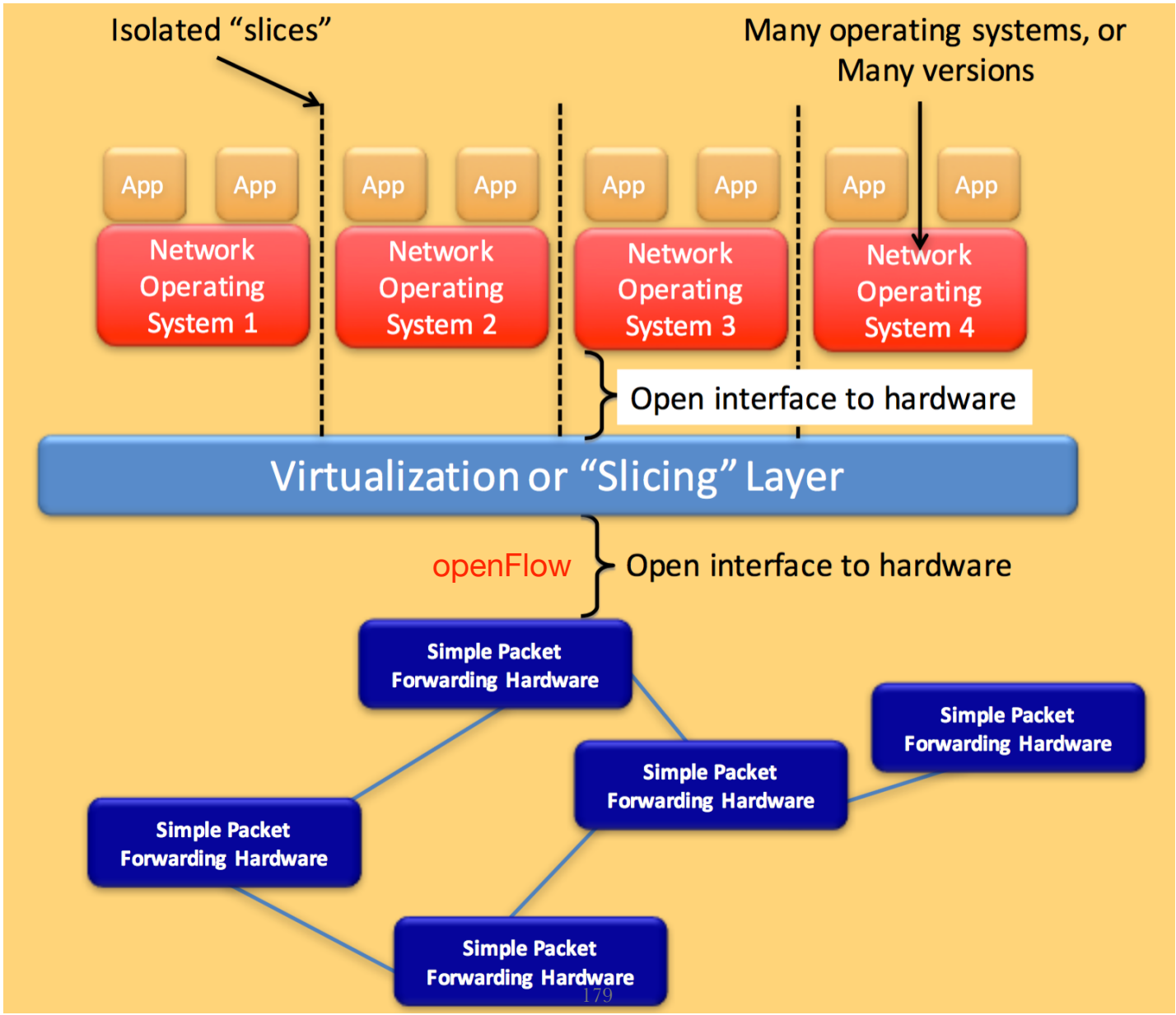


SDN Architecture

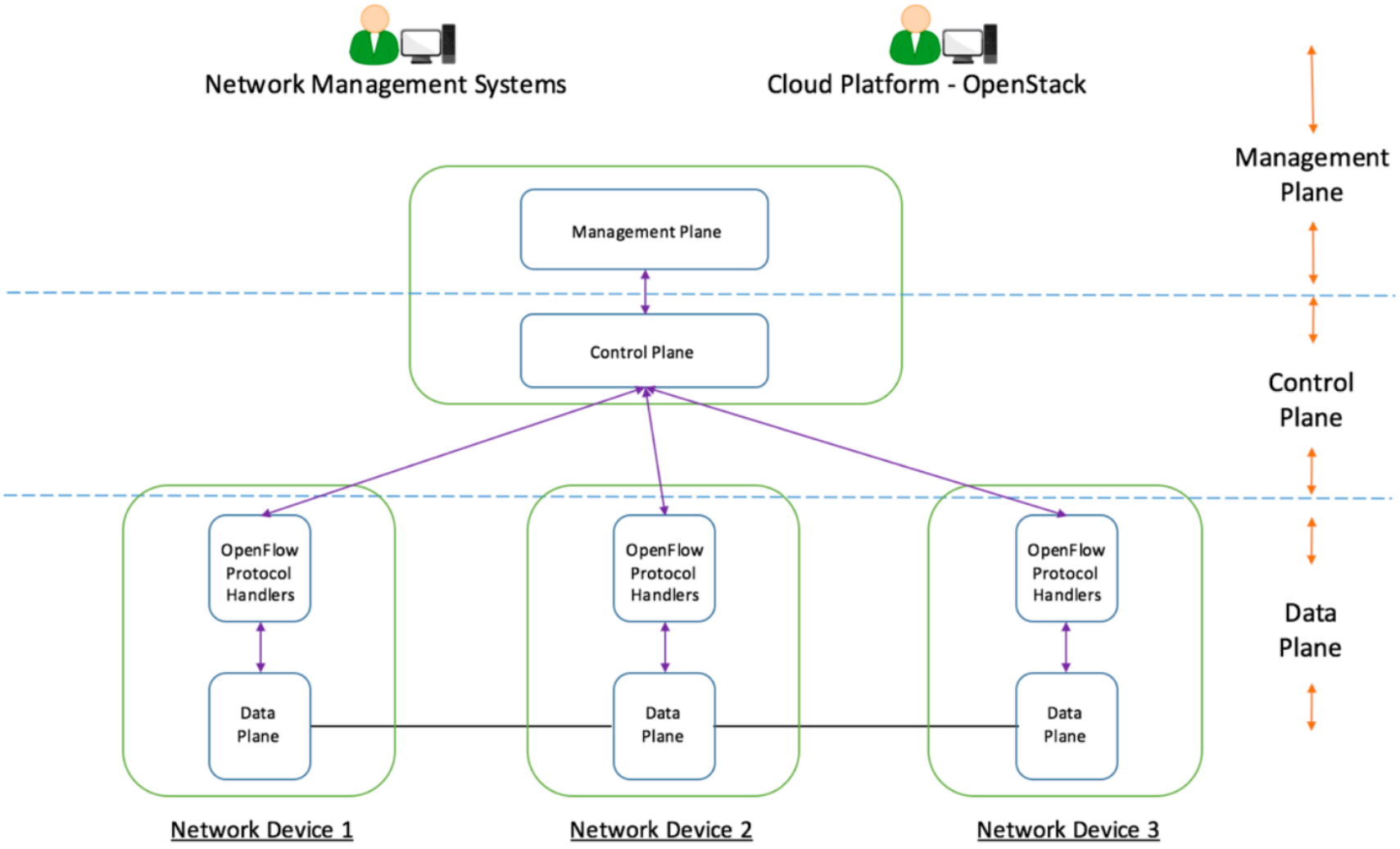



Well-defined API
Application Plane
Security
Routing
Traffic Engineering
Other Applications
Network Virtualization
Network Map Abstraction
Control Plane
Network Operating System
openFlow
Instructions
Instructions
Instructions
Instructions
Forwarding
Forwarding
Forwarding
Forwarding
Data Plane
Separation of Data and Control Plane


Specifies behavior
Control Program
e.g. routing, access control
Abstract Network Model
Compiles to topology
Network Virtualization
Global Network View
Transmits to switches
Network OS

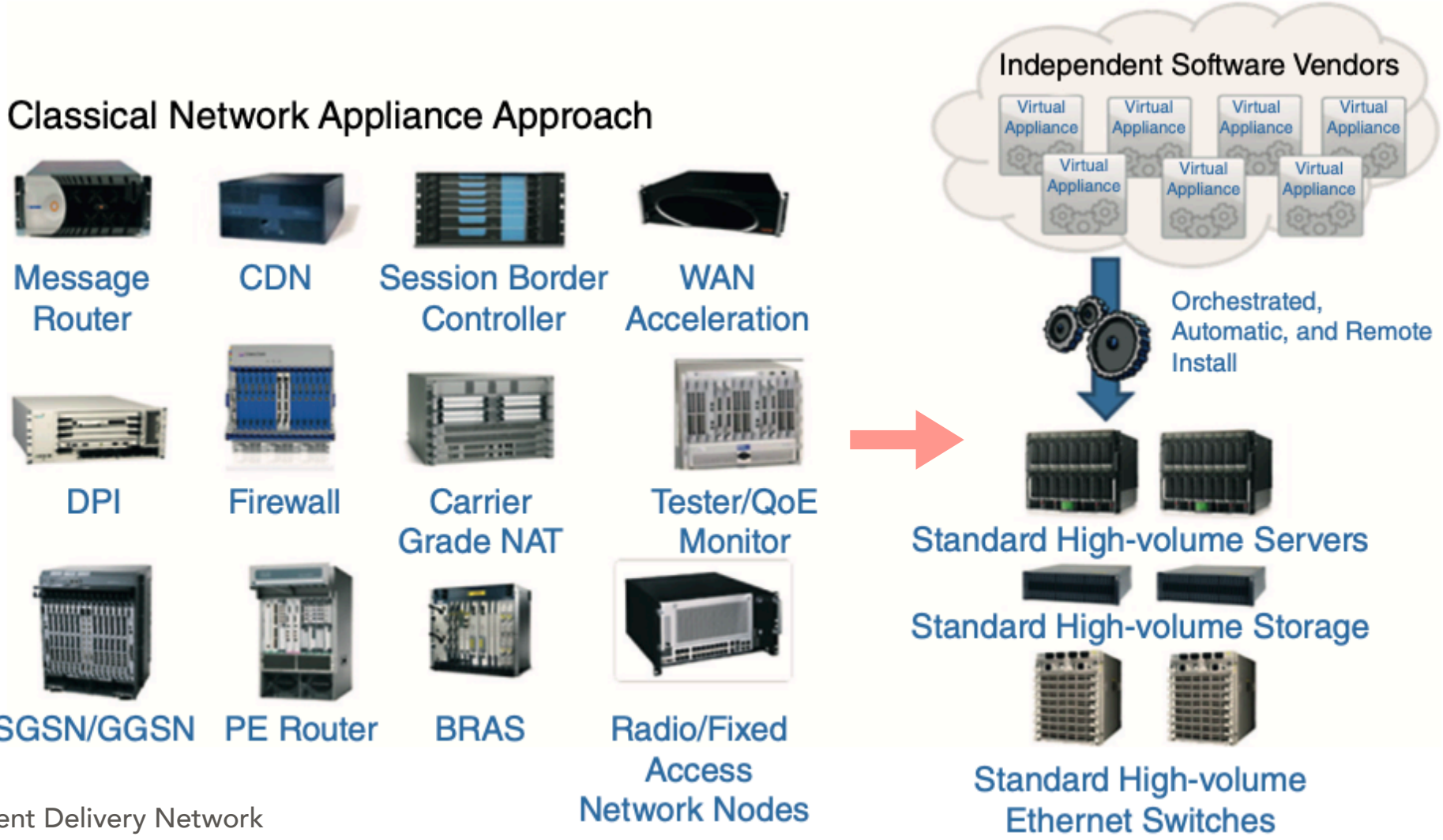

Isolated “slices”
Many operating systems, or
Many versions
App
App
App
App
App
App
App
App
Network Operating System 1
Network Operating System 2
Network Operating System 3
Network Operating System 4
Open interface to hardware
Virtualization or “Slicing” Layer
openFlow
Open interface to hardware
Simple Packet Forwarding Hardware
Simple Packet Forwarding Hardware
Simple Packet Forwarding Hardware
Simple Packet Forwarding Hardware
Simple Packet Forwarding Hardware

Simplified SDN-based Network Architecture

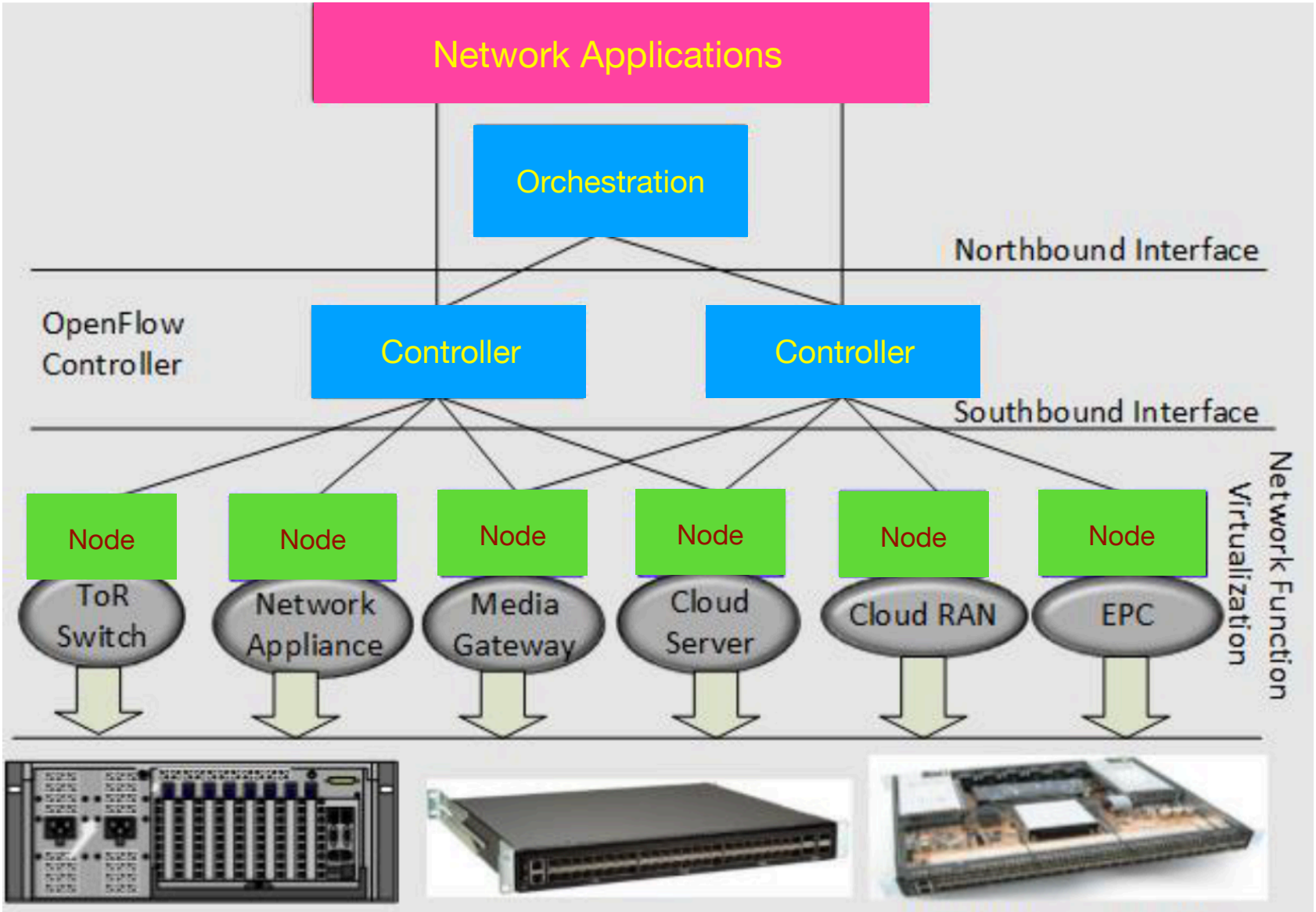


Network Functions Virtualization (NFV)

- Virtualize entire network node functions onto industry standard high volume servers, switches and storage, which could be located in data centers or centralized locations
- Implement network functions in a software that can run on a range of industry standard server hardware, and that can be moved to, or instantiated in, various locations in the network

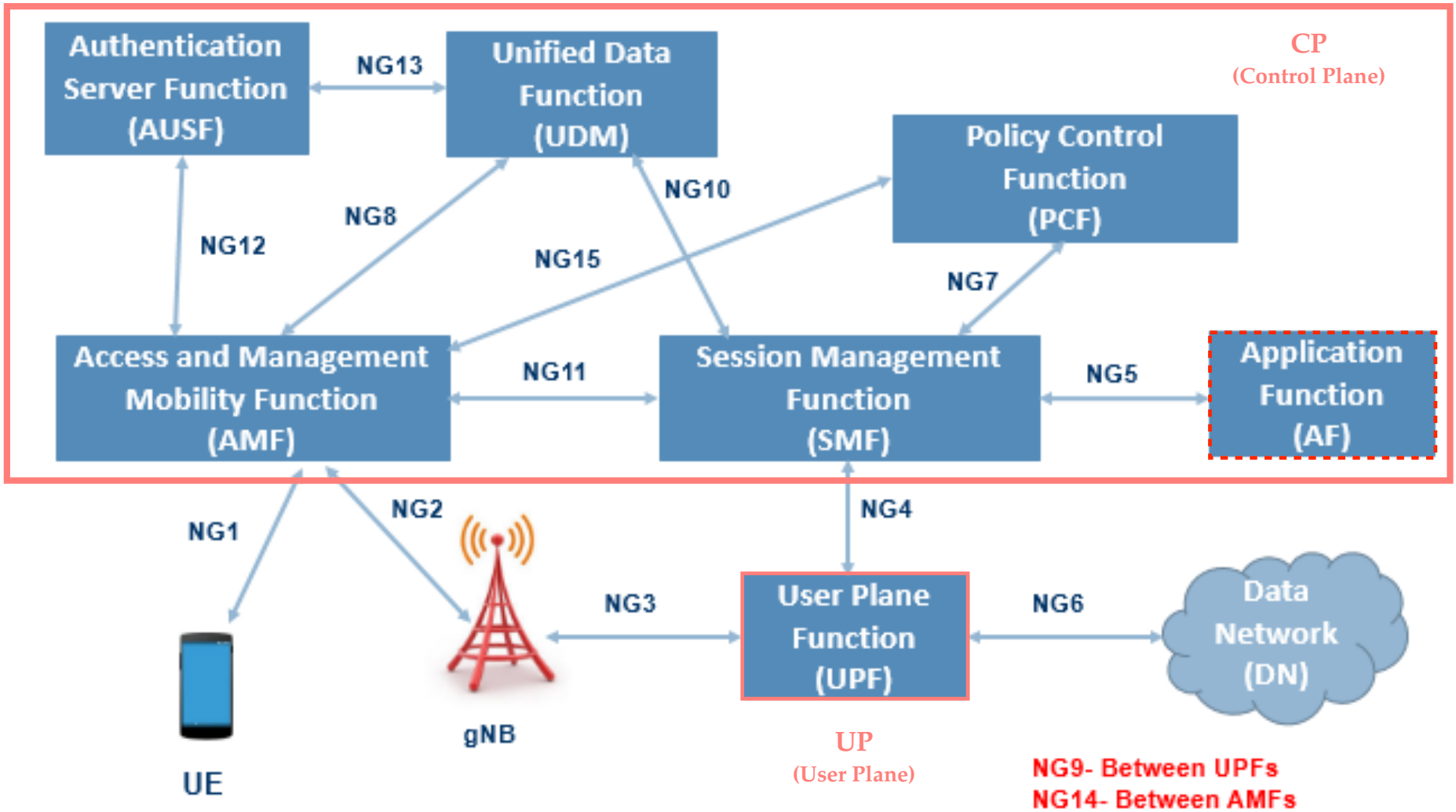


CDN：Content Delivery Network
DPI：Deep Packet Inspection
NAT：Network Address Translation
BRAS：Broadband Remote Access Server



ToR：Top of Rack　EPC：Evolved Packet Core

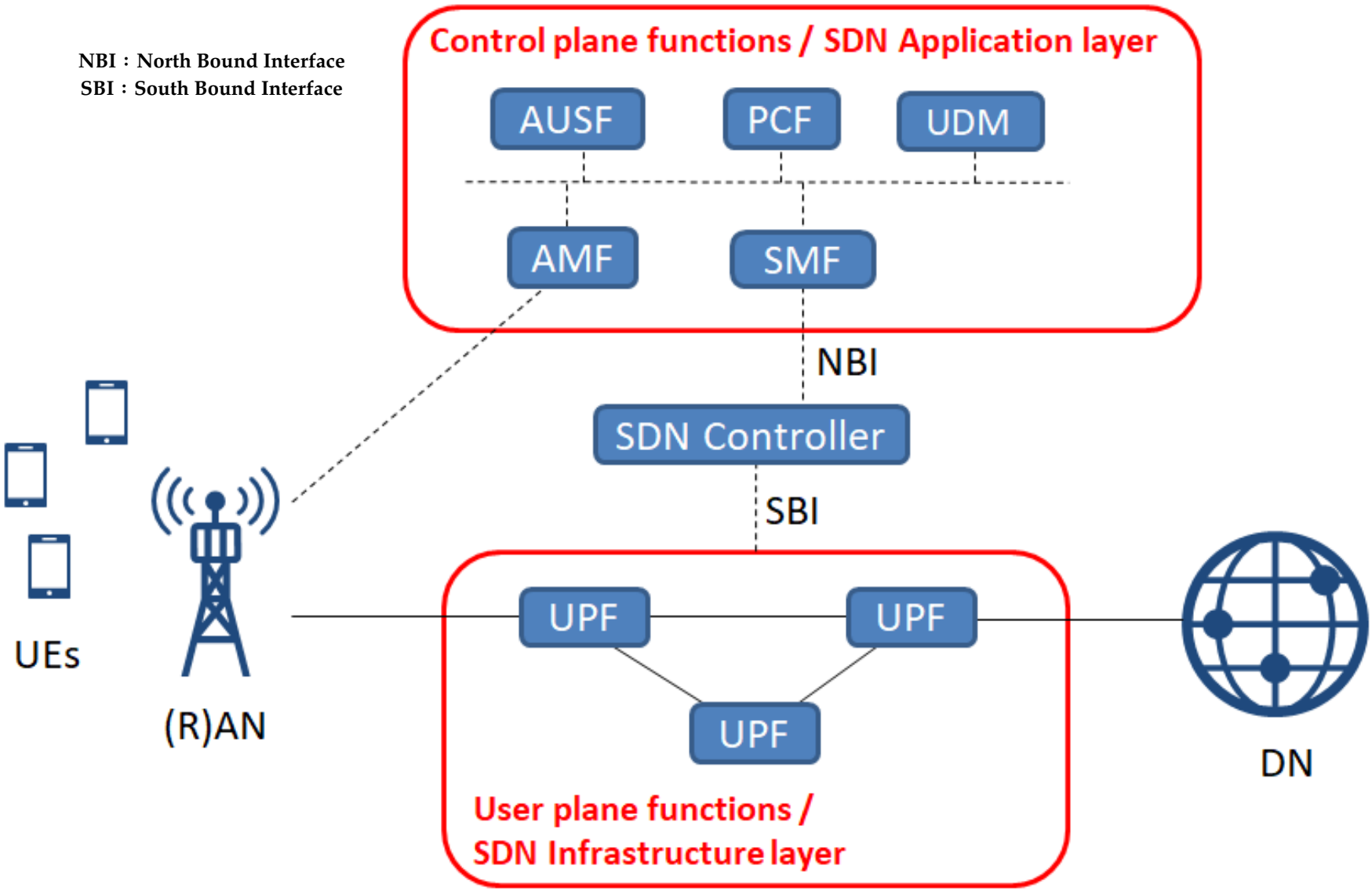
5G Network Architecture



UE：User Equipment
gNB：Next Gen Node Basestation

Source 3GPP TR 23.799

NBI：North Bound Interface
SBI：South Bound Interface



https://itnspotlight.com/control-user-plane-separation-cups-in-mobile-networks/

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Network Slicing

- 5G services requirements: heterogeneity
  - **Enhanced Mobile Broadband**
    - Deal with hugely increased data volumes, overall data capacity and user density
  - **Massive Machine-type Communications for the IoT**
    - Requiring low power consumption and low data rates for very large numbers of connected devices
  - **Ultra-reliable and Low Latency Communications**
    - Cater for safety-critical and mission critical applications

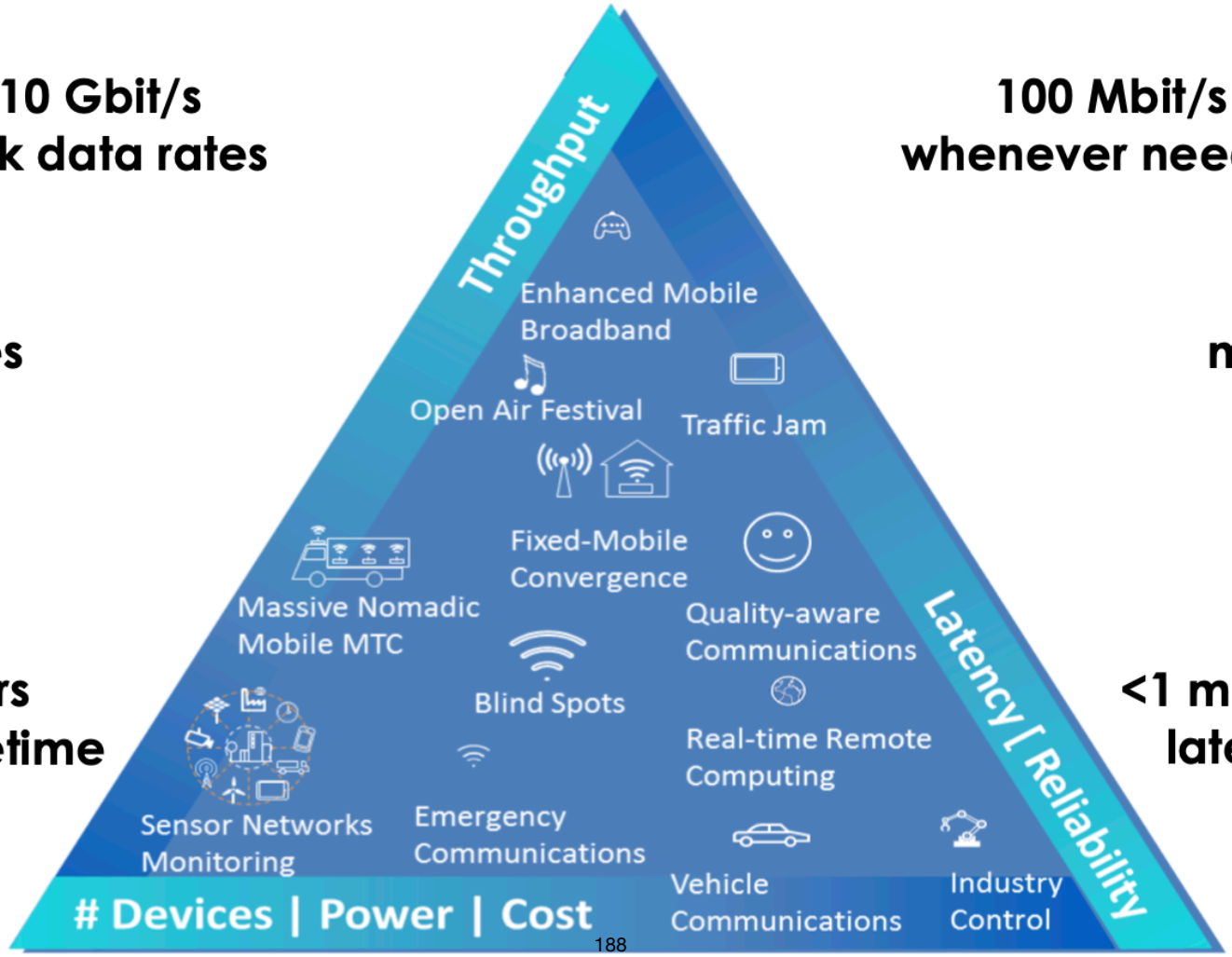
Requirements: Heterogeneity

>10 Gbit/s
peak data rates

10 – 100 x
more devices

M2M
ultra low cost

10 years
battery lifetime



100 Mbit/s
whenever needed

10 000 x
more traffic

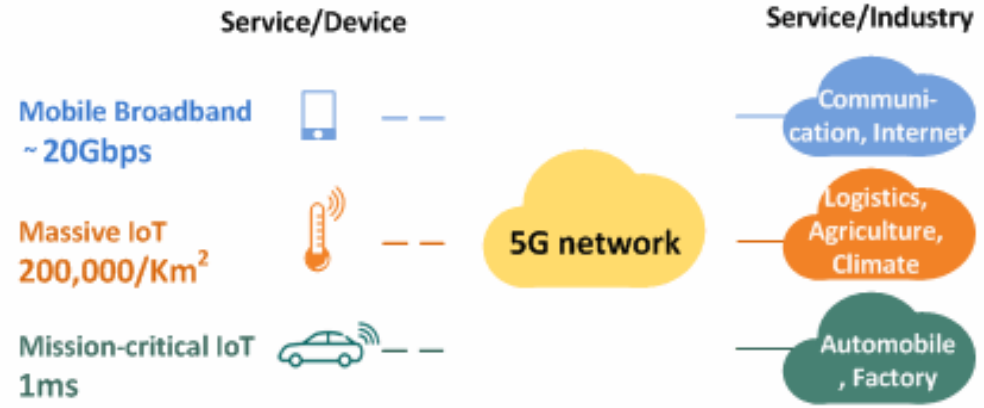
ultra
reliability

<1 ms radio
latency

4G Network: communication service via phones in the communication industry

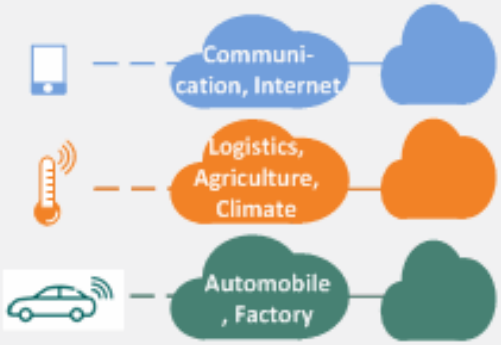
Communication service
(voice, text and Internet)

5G network: all mobile services via all types of devices across all industries

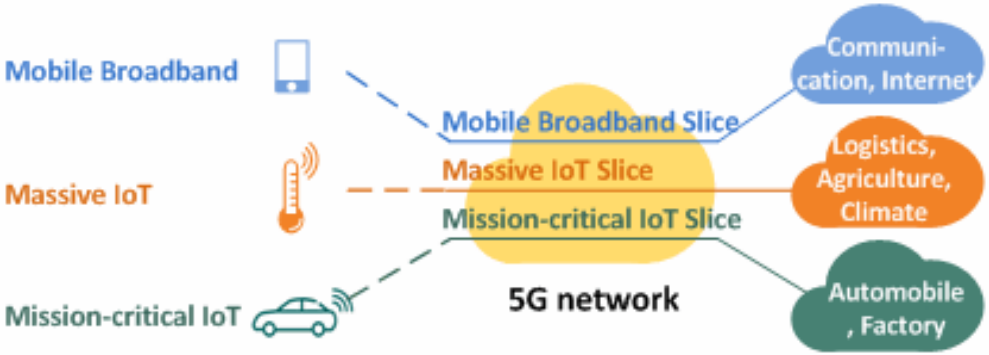


how?

Multiple 5G networks ? X



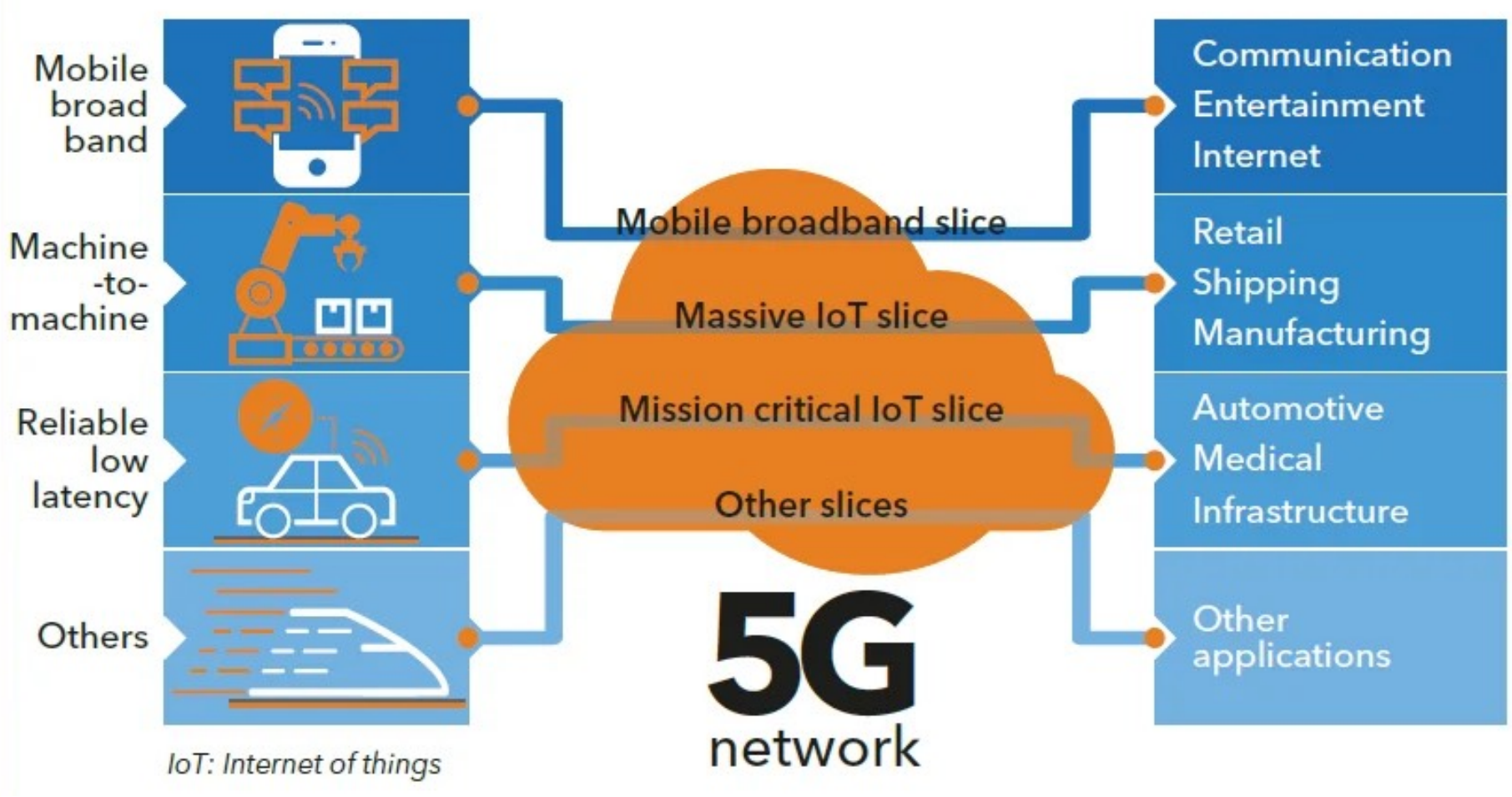
Network Slicing !



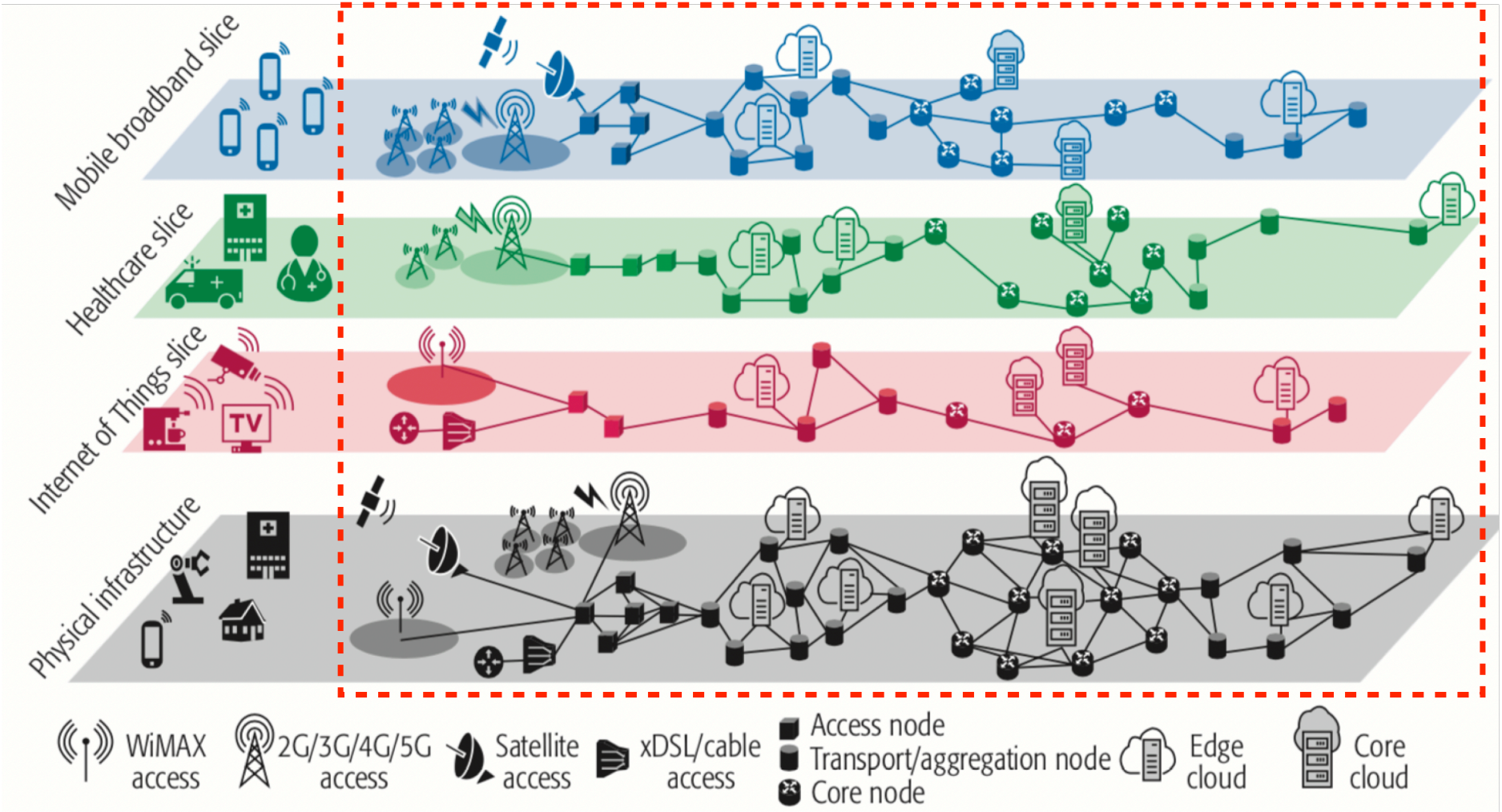
What is Network Slicing?

- **Network slice**
  - A set of infrastructure resources and service functions that has attributes specifically designed to meet the needs of an industry vertical or a service
- **Network slicing**
  - A management mechanism that Network Slice Provider can use to allocate dedicated infrastructure resources and service functions to the users of the network slice

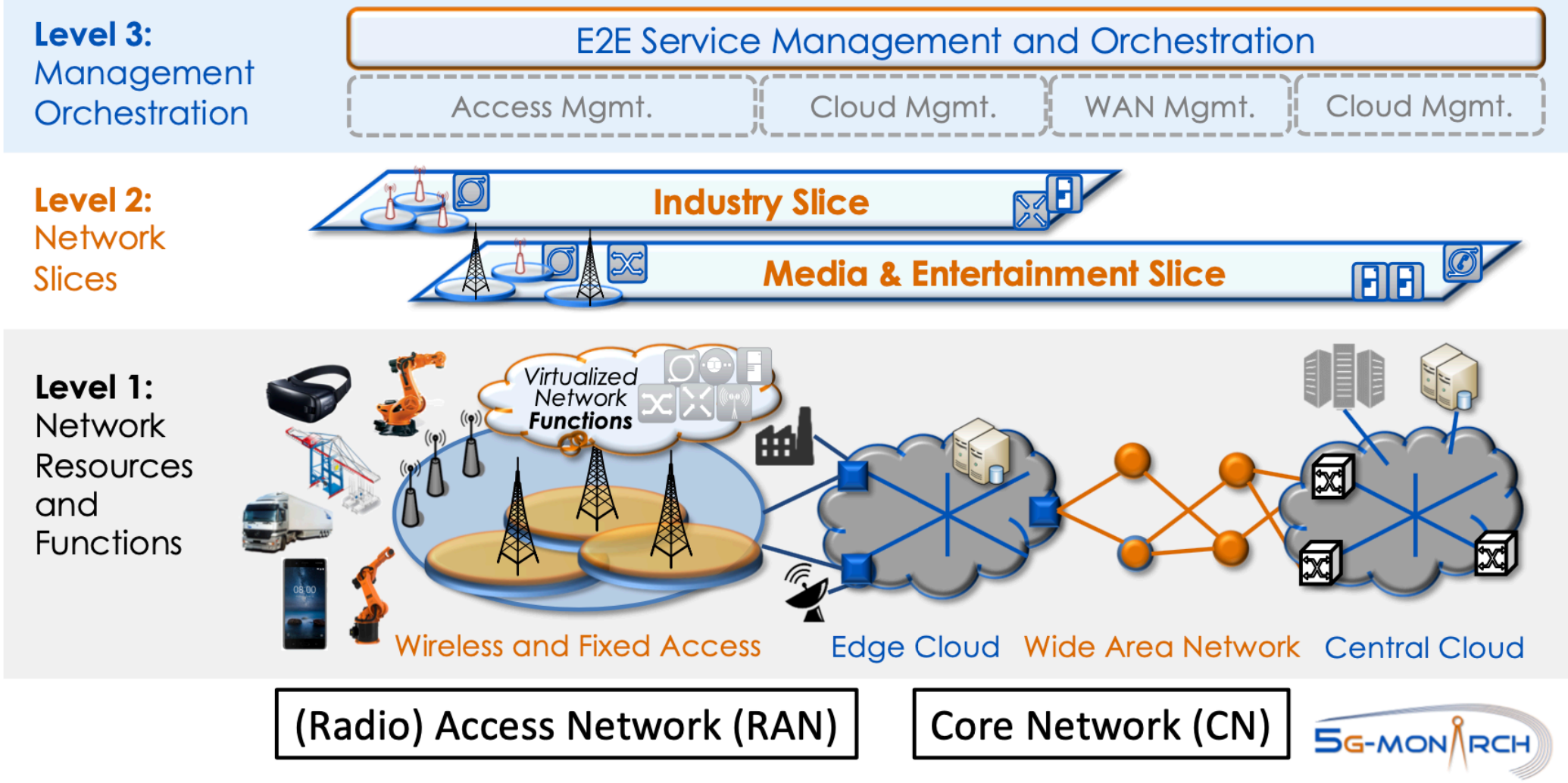
5G Network Slicing



Challenge: In One Network

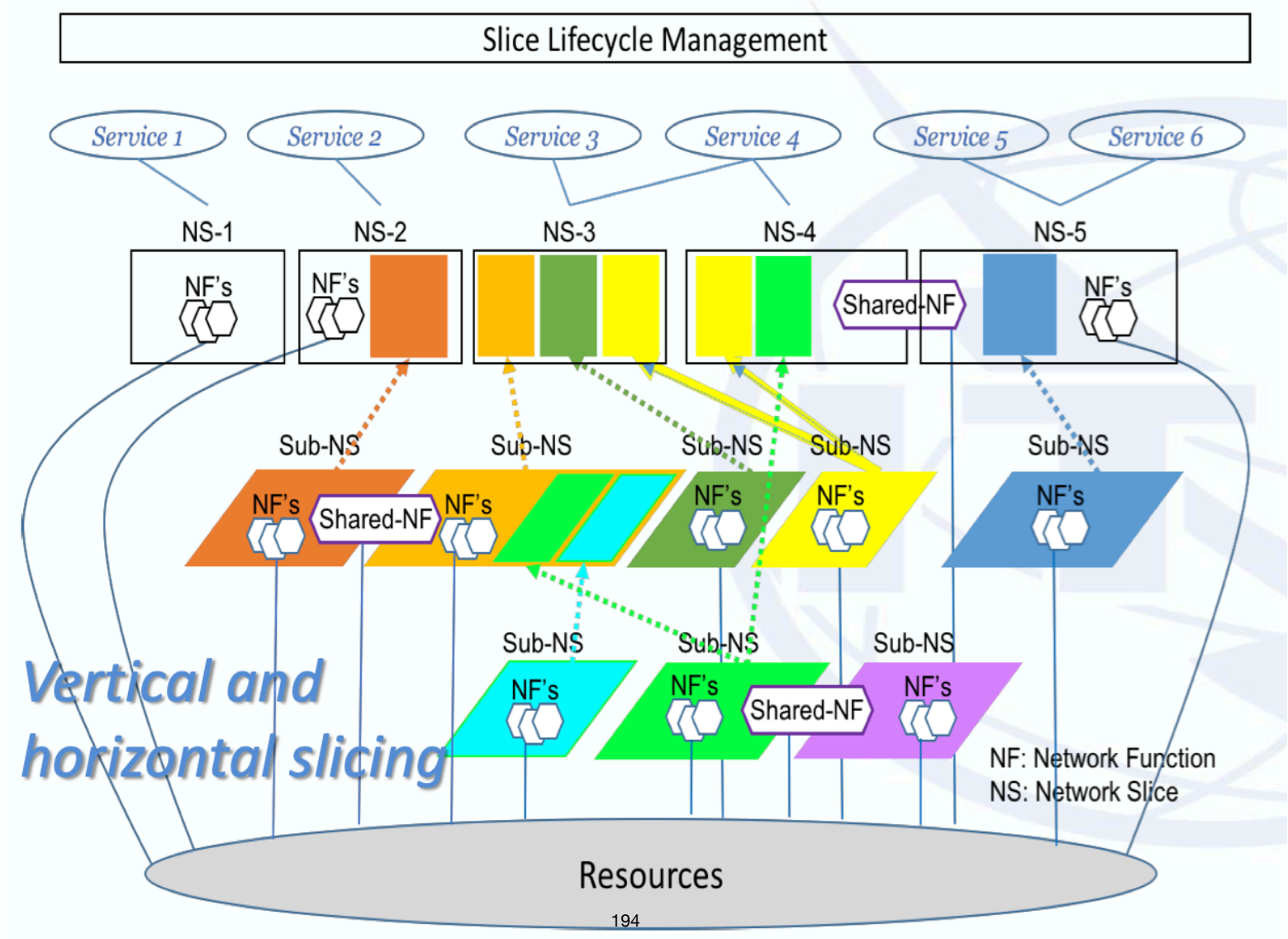


Customization over One Network



From: 5G-MoNArch Project video https://www.youtube.com/watch?v=y6b9FNniPuQ

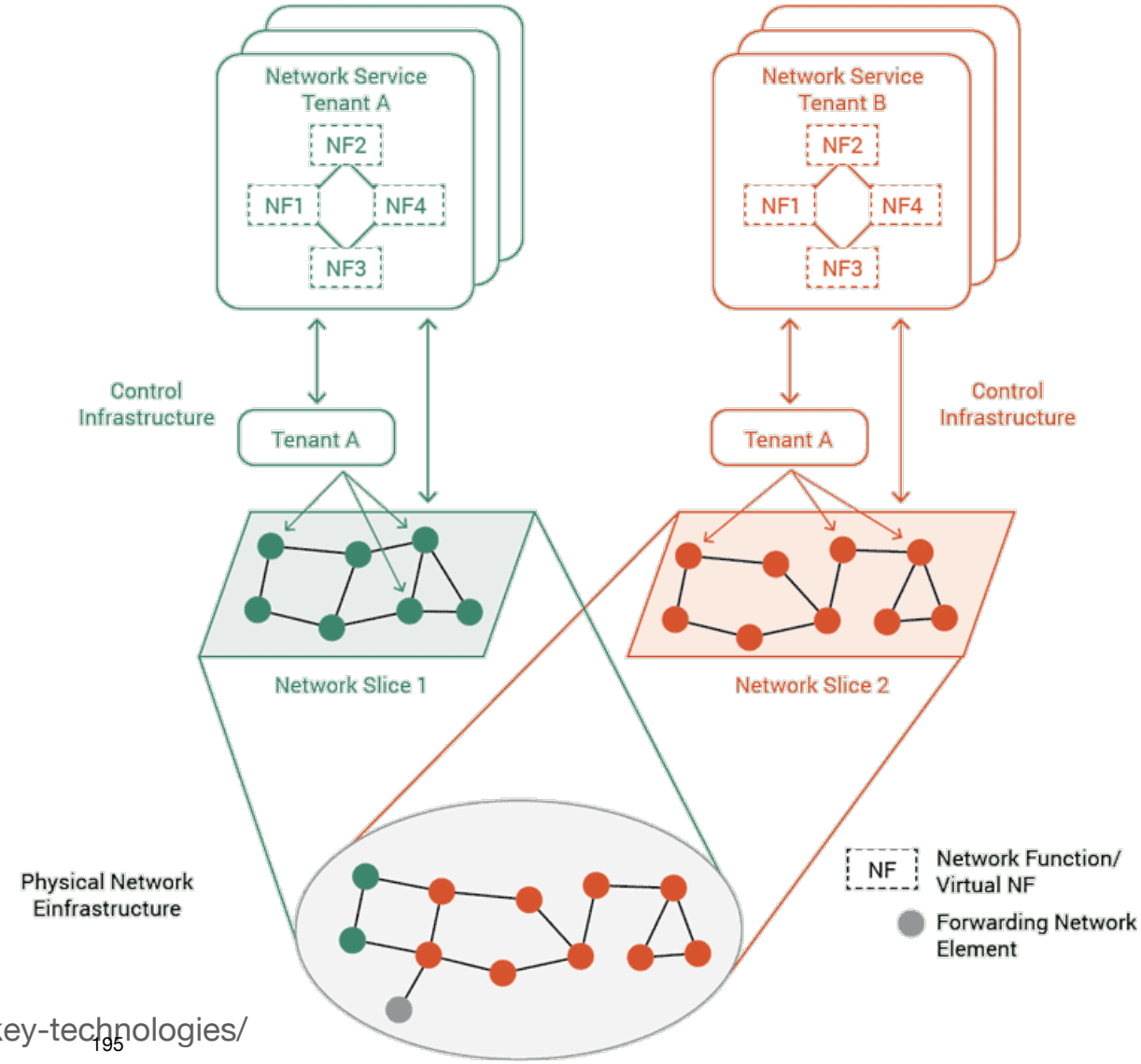
Network Slicing: Customized Support of Applications



Source: ITU

- **Network slices**
  - Self-contained
  - Mutually isolated
  - Manageable & programmable
  - Support for multi-service
  - Support for multi-tenancy

Multi-tenancy in Mobile Carrier Infrastructures



https://www.a10networks.com/blog/5g-key-technologies/

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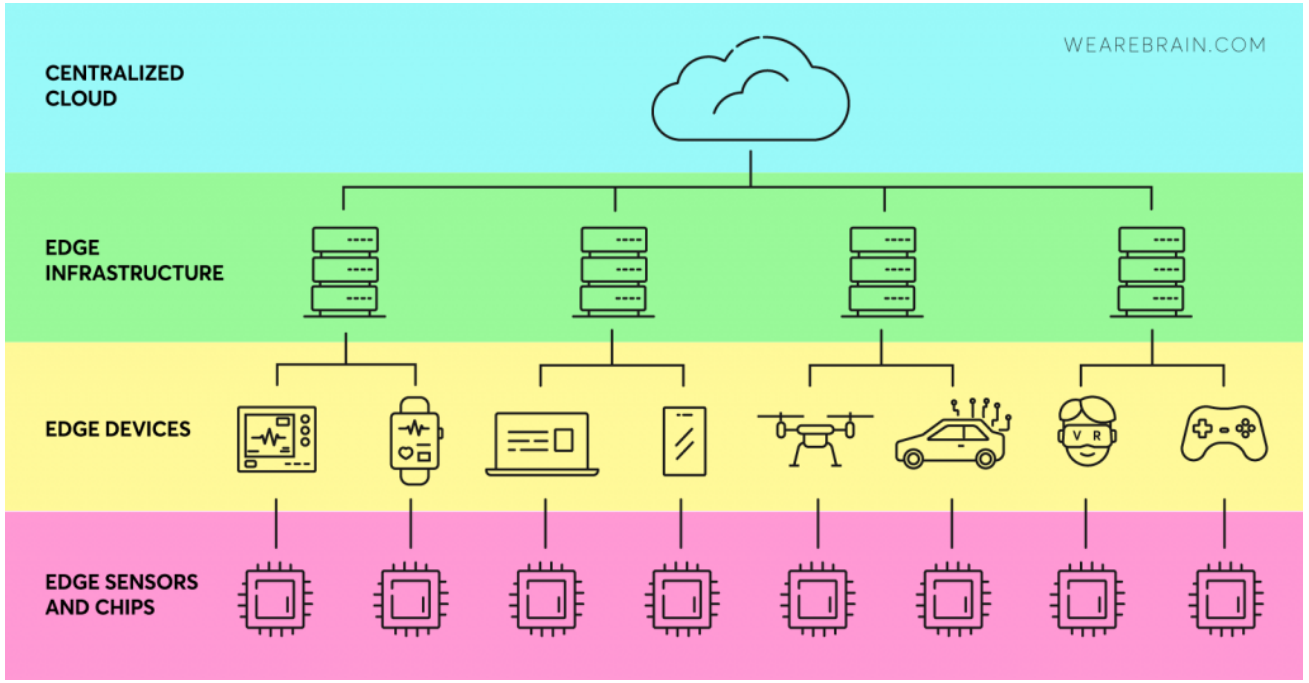
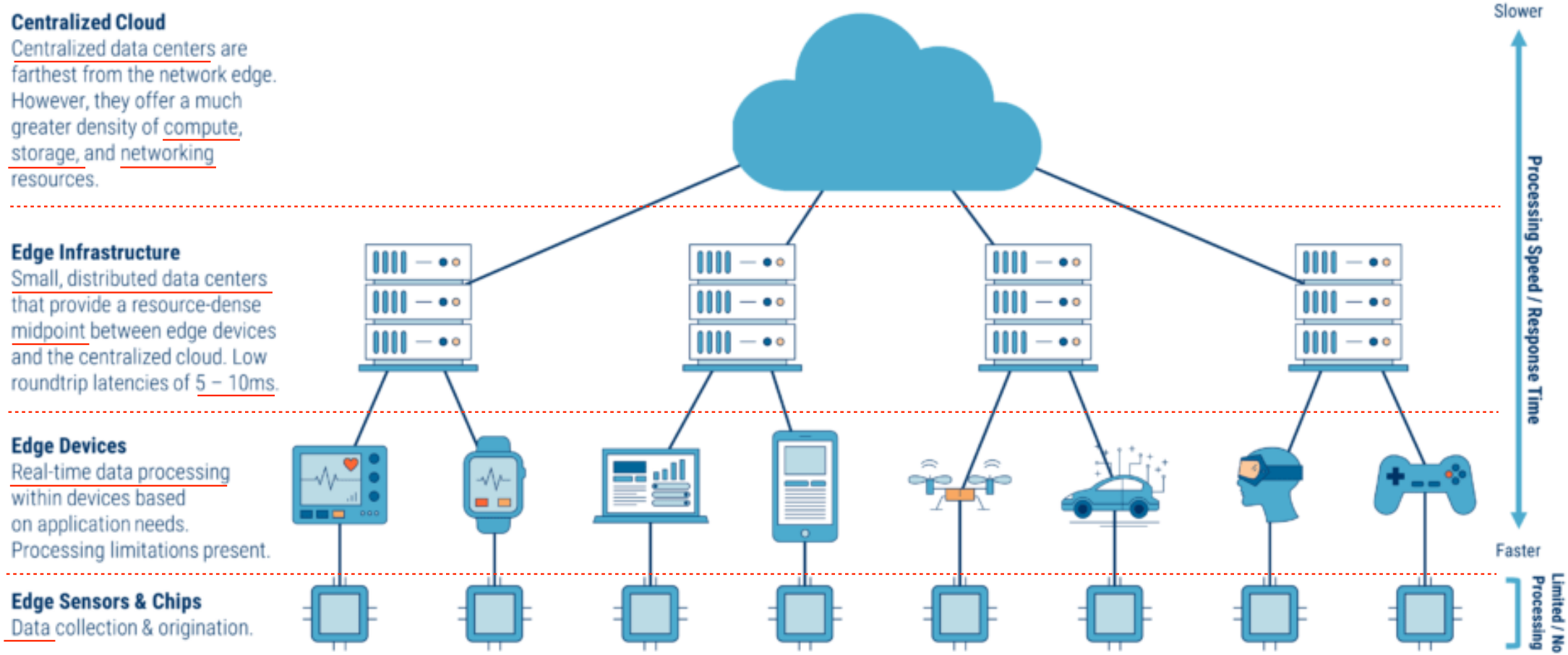
Edge Computing

- Facilitate data processing at or near the source of data generation
- Promise near real-time insights and facilitates localized actions



From Edge Sensors to Centralized Cloud



https://www.cbinsights.com/research/edge-computing-ecosystem/

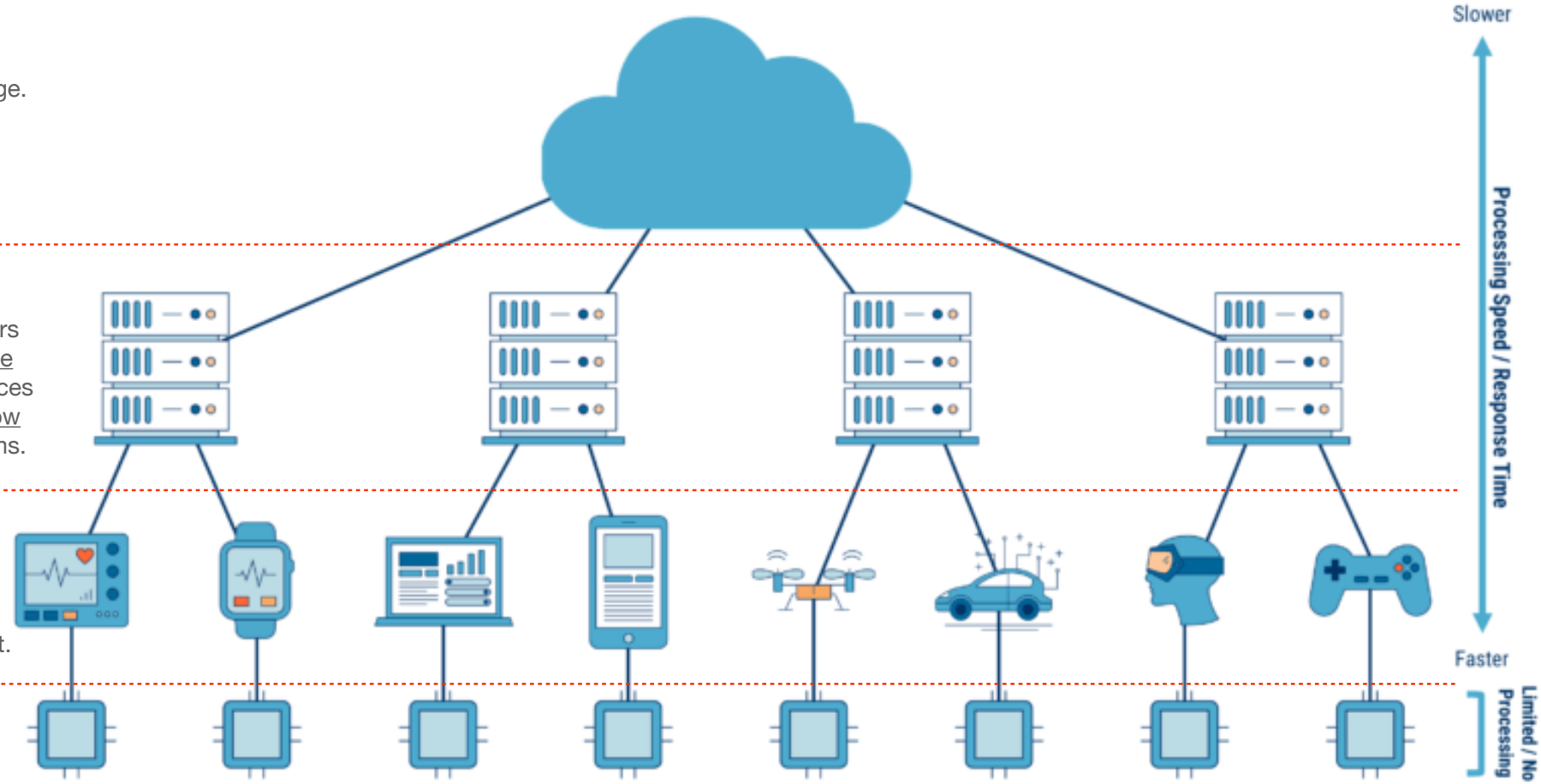
From Edge Sensors to Centralized Cloud

Centralized Cloud
Centralized data centers are farthest from the network edge. However, they offer a much greater density of compute, storage, and networking resources.

Edge Infrastructure
Small, distributed data centers that provide a resource-dense midpoint between edge devices and the centralized cloud. Low roundtrip latencies of 5 - 10ms.

Edge Devices
Real-time data processing within devices based on application needs. Processing limitations present.

Edge Sensors & Chips
Data collection& origination.



https://www.cbinsights.com/research/edge-computing-ecosystem/

Cloud Computing vs Edge Computing

CLOUD COMPUTING	EDGE COMPUTING
LOCATION	
REMOTE - Storage, management and processing occurs on a remote central network server. The data is accessible over the Internet, away from the source.	**NEAR-ACCESS** - Data is processed physically close to or on the actual device, the data source, which is located at the edge of the network.
LATENCY	
HIGH - Frequent and high load data exchange puts strain on the network, resulting in high latency.	**LOW** - Requires little bandwidth as information is initially processed close to the data source.
CAPACITY	
HIGH - Can process large volumes of data and scale accordingly; cost is also determined by processing unit used.	**LOW** - Can only process so much data due to limited availability of resources. This is somewhat compensated by near-access communication with nodes.

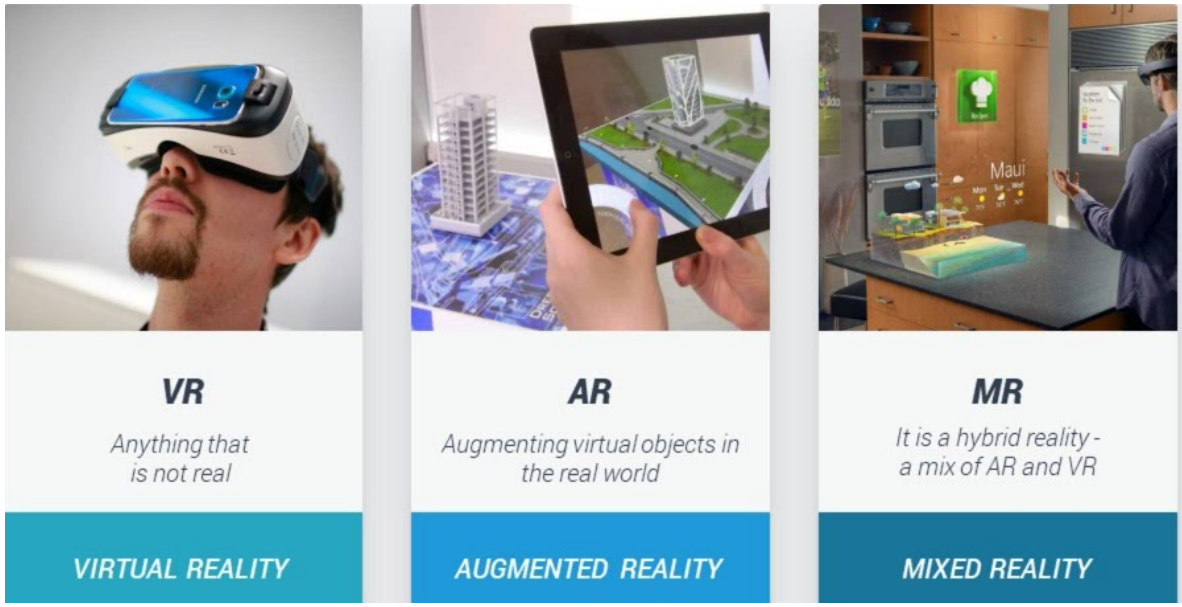
https://smart-it.io/blog/cloud-computing-vs-edge-computing-infographic/

CLOUD COMPUTING	EDGE COMPUTING
DISTRIBUTION	
CENTRALIZED - The cloud is a Centrally Managed System (CMS), which means it is controlled by a single entity.	**DECENTRALIZED** - Computations are performed at the edge of the network, often utilizing distributed nodes.
SECURITY	
HIGH - The virtual server is managed by one entity, which ensures maximum protection	**MEDIUM** - Distributed data means security can be more susceptible to individual threats and unaccounted outside factors.

CLOUD COMPUTING	EDGE COMPUTING
BENEFITS	
• Cost reduction • Scalability • Accessibility • Security	• High speed and responsiveness • Low latency • Real-time results • Edge analytics
USE CASES	
• Inventory • BI and Big Data storage • Deep analysis • Rich data visualization • Dashboards • Reports • Back-end access	• IoT (handheld devices, wearables) devices • IIoT (factory floor robots, digital signage at retail stores) devices • MRIs (Magnetic Resonance Imaging) • Traffic lights • Autonomous vehicles • ATMs - mission critical use cases in general

Edge Computing Applications

- **Immersive experience**
  - AR/VR and mixed reality



- **Automotive & transportation**
  - Connected vehicles

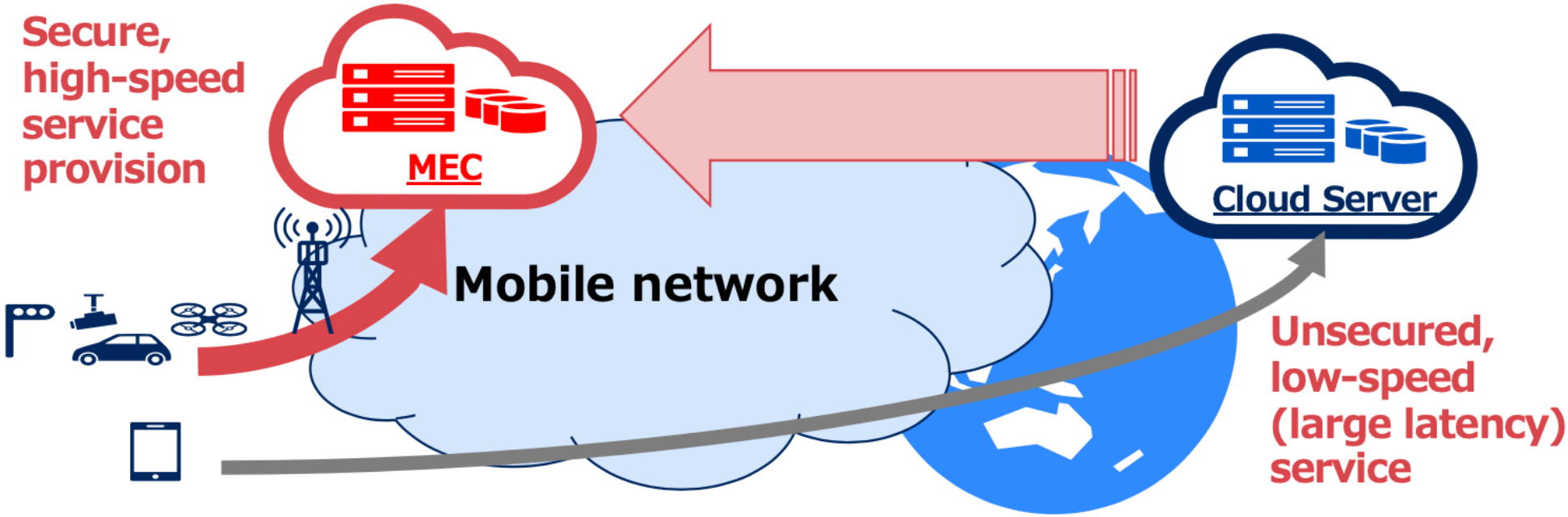
- **Remote operation**
  - Factory, hospital

- **Intelligent automation**
  - Industrial and smart cities

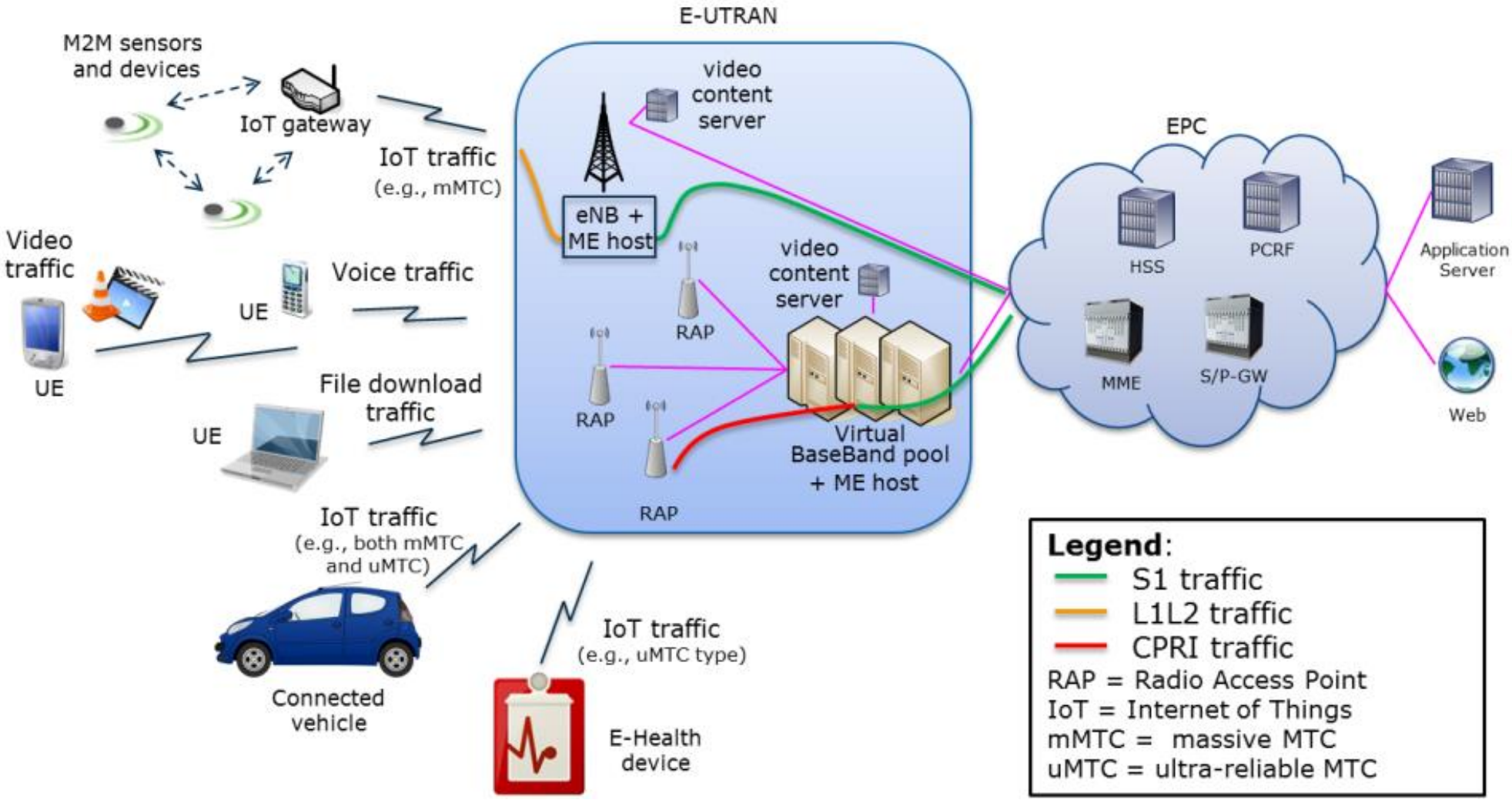
Tactile Internet

Mobile Edge Computing (MEC)

- Increases responsiveness from the edge
- Context related services, more information about the consumer (e.g., radio)

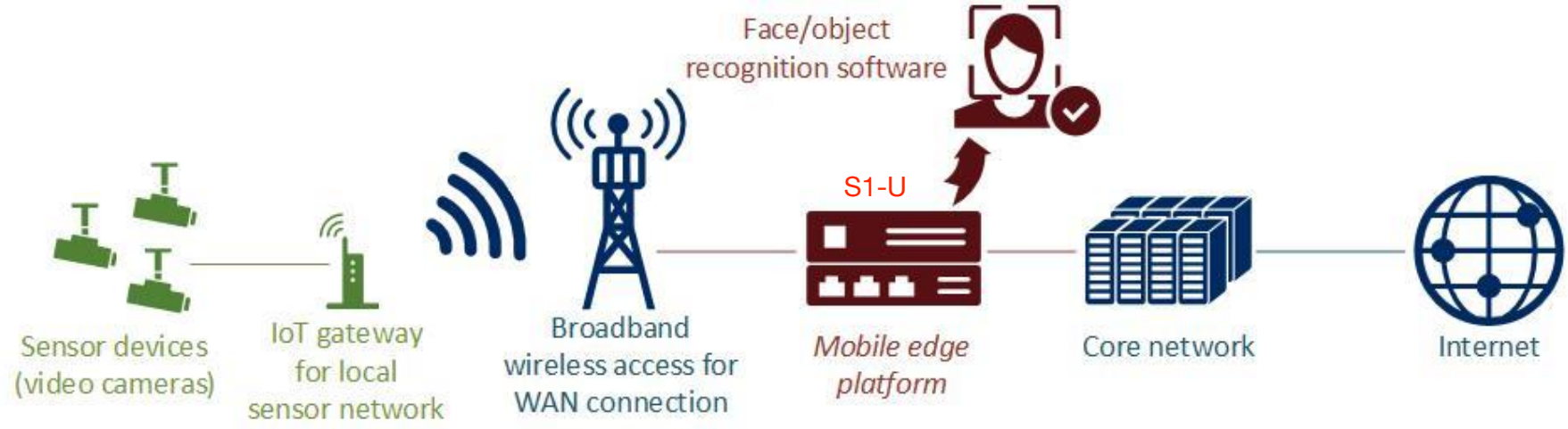


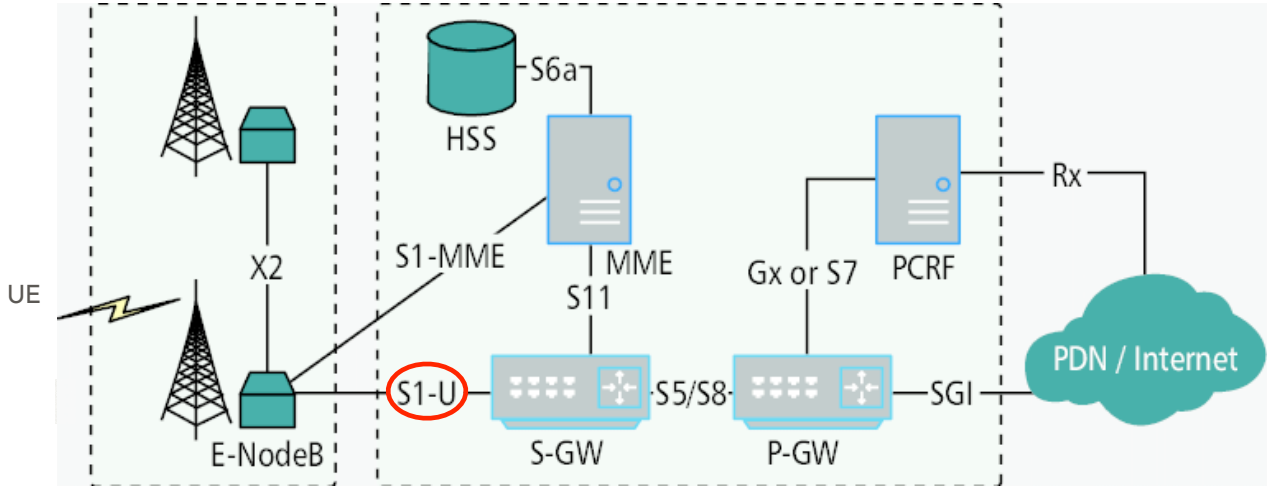
Mobile Edge Computing for 5G Scenarios



https://www.researchgate.net/publication/308767796_Mobile-Edge_Computing_Architecture_The_role_of_MEC_in_the_Internet_of_Things

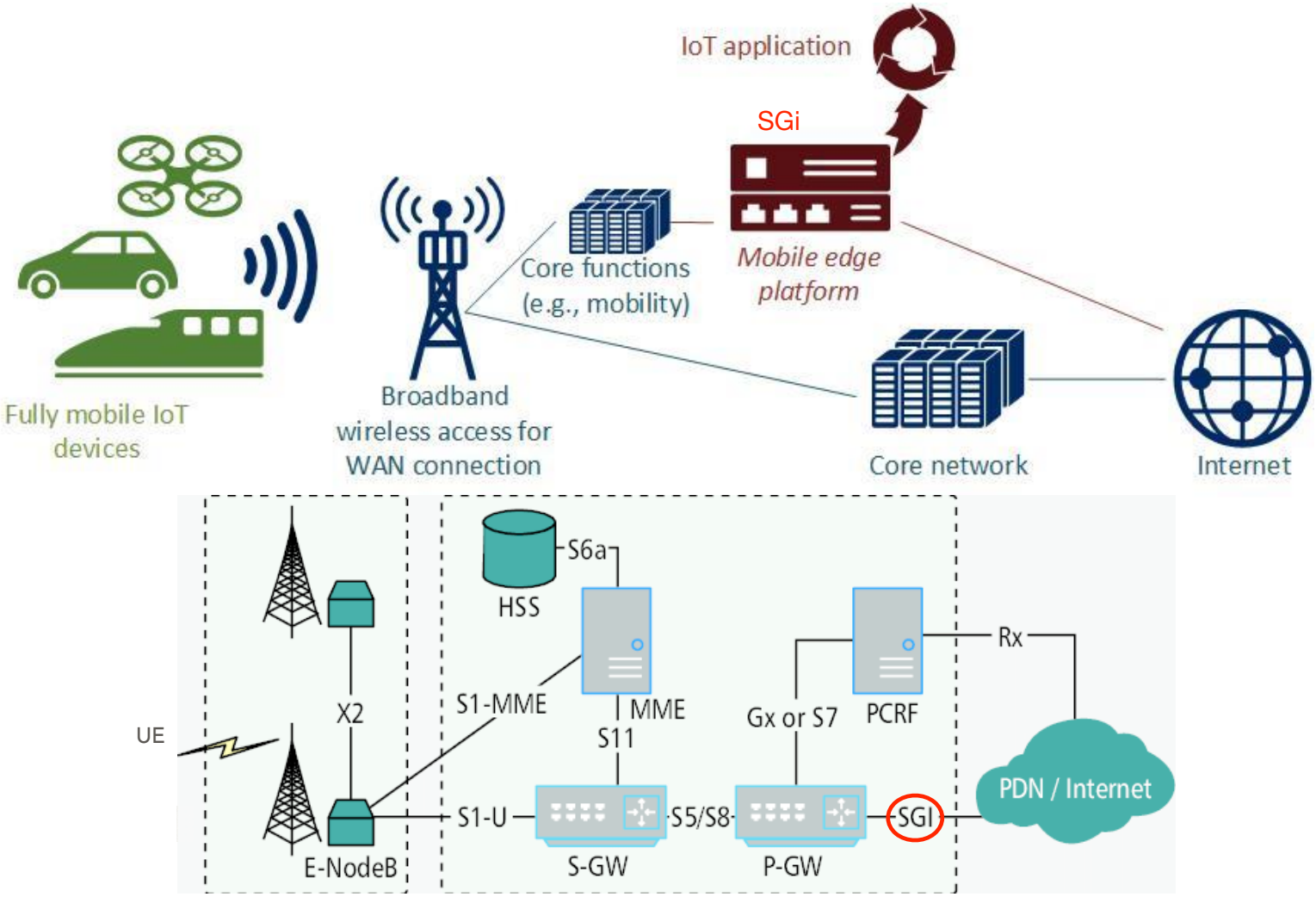
MEC-based Video Surveillance (S1-U Option)





https://www.researchgate.net/publication/308767796_Mobile-Edge_Computing_Architecture_The_role_of_MEC_in_the_Internet_of_Things

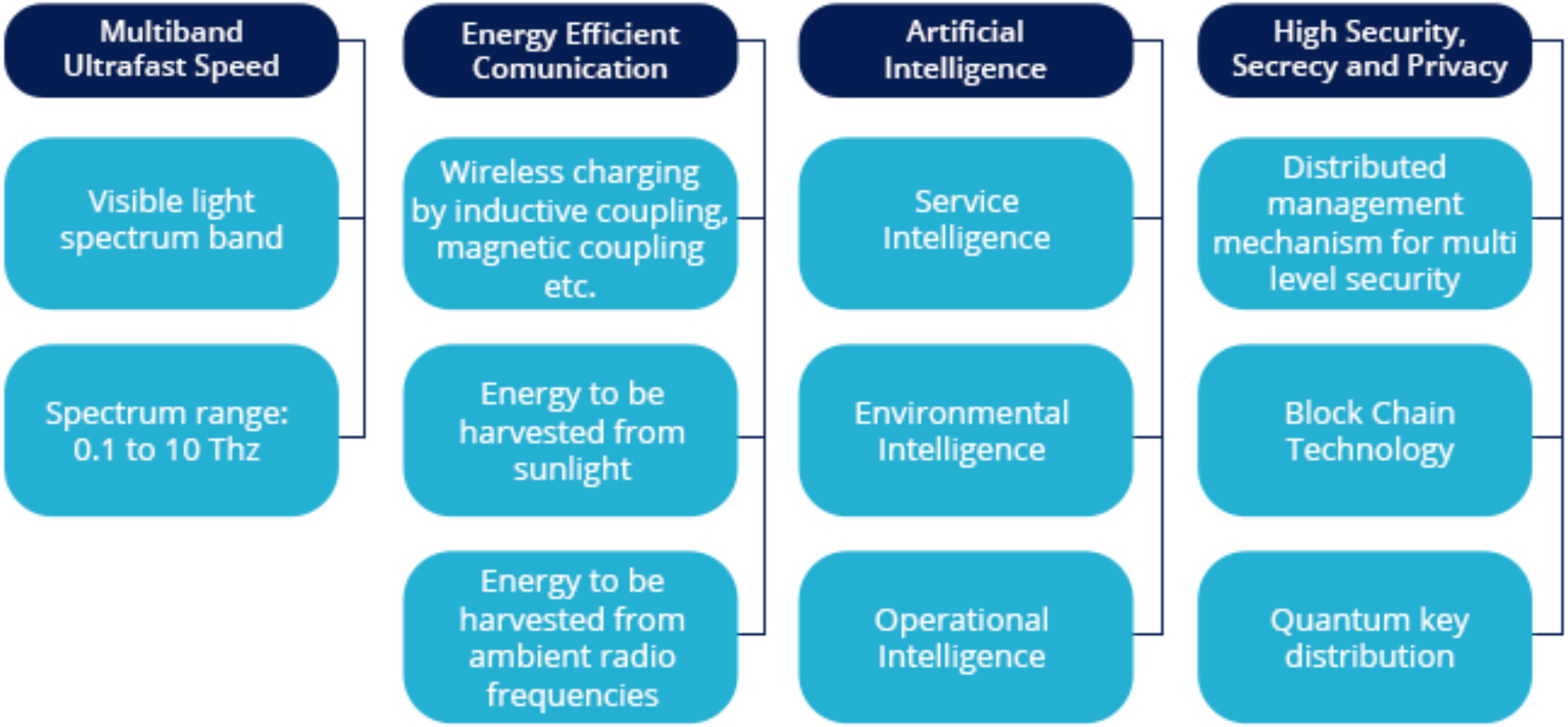
MEC-based Mobile IoT Scenario (SGi Option)

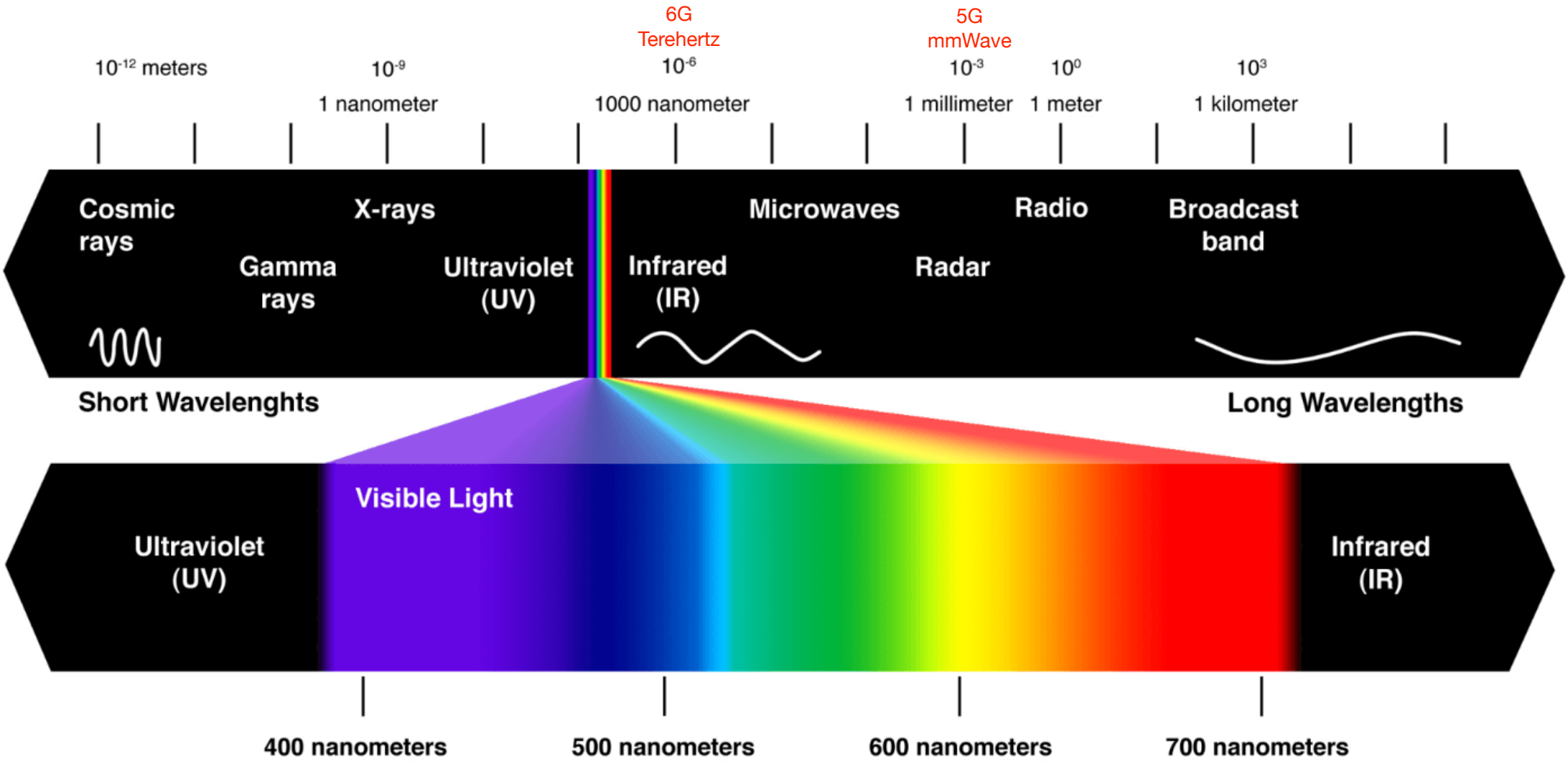


https://www.researchgate.net/publication/308767796_Mobile-Edge_Computing_Architecture_The_role_of_MEC_in_the_Internet_of_Things

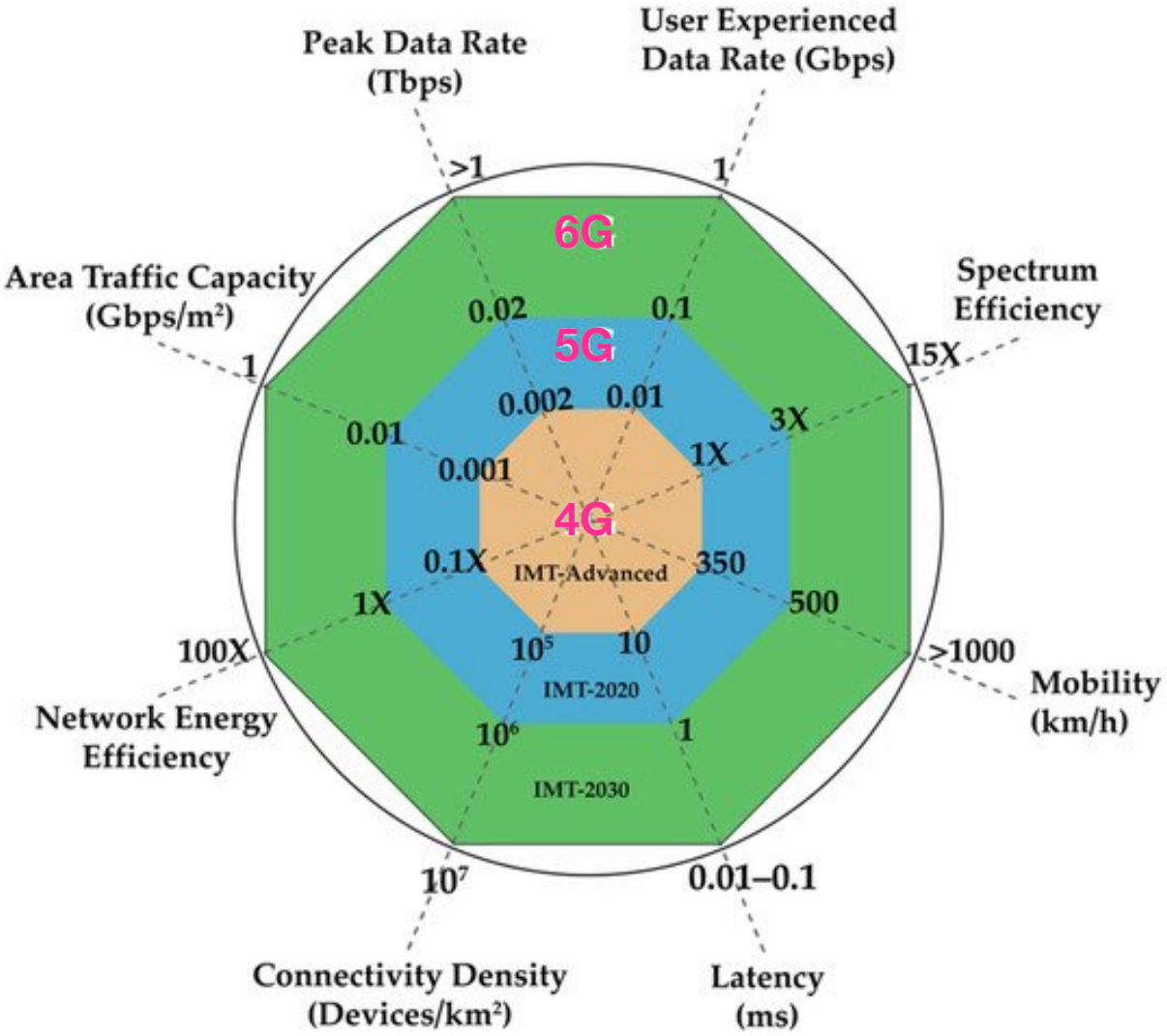
- Evolution of Mobile Communication
- ITU/3GPP Standardization
- ITU 5G Service Scenarios
- 5G-New Radio
- 5G System Architecture
- SDN/NFV
- Network Slicing
- Mobile Edge Computing (MEC)
- **The Road to the 6G Mobile Communication**

Key Features of 6G




6G
Terehertz
5G
mmWave
10^{-12} meters
10^{-9}
1 nanometer
10^{-6}
1000 nanometer
10^{-3}
1 millimeter
10^{0}
1 meter
10^{3}
1 kilometer
Cosmic rays
Gamma rays
X-rays
Ultraviolet (UV)
Infrared (IR)
Microwaves
Radar
Radio
Broadcast band
Short Wavelenghts
Long Wavelengths
Ultraviolet (UV)
Visible Light
Infrared (IR)
400 nanometers
500 nanometers
600 nanometers
700 nanometers

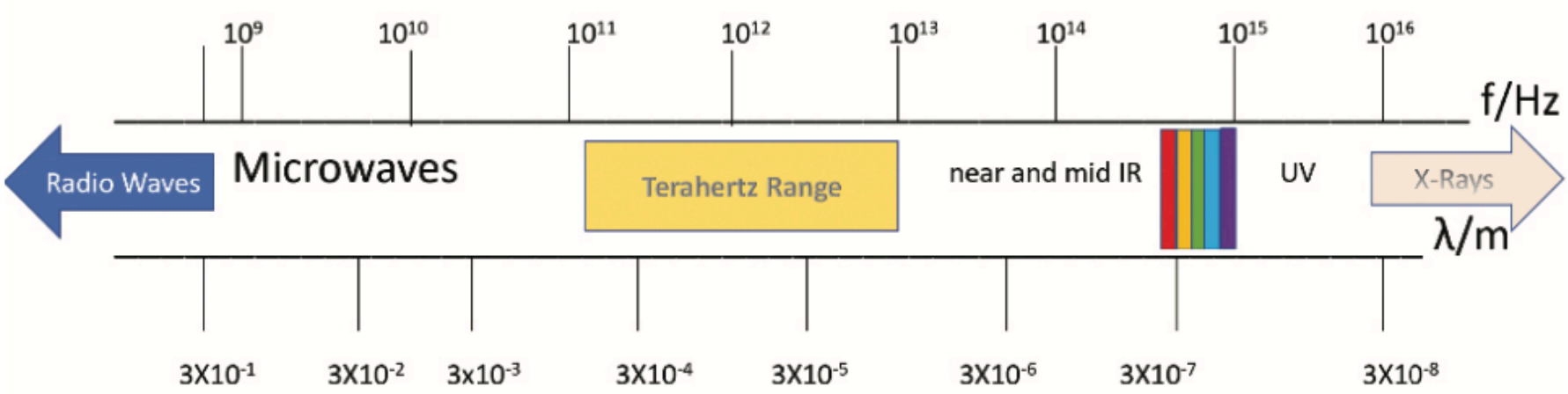
Key Capabilities for 6G

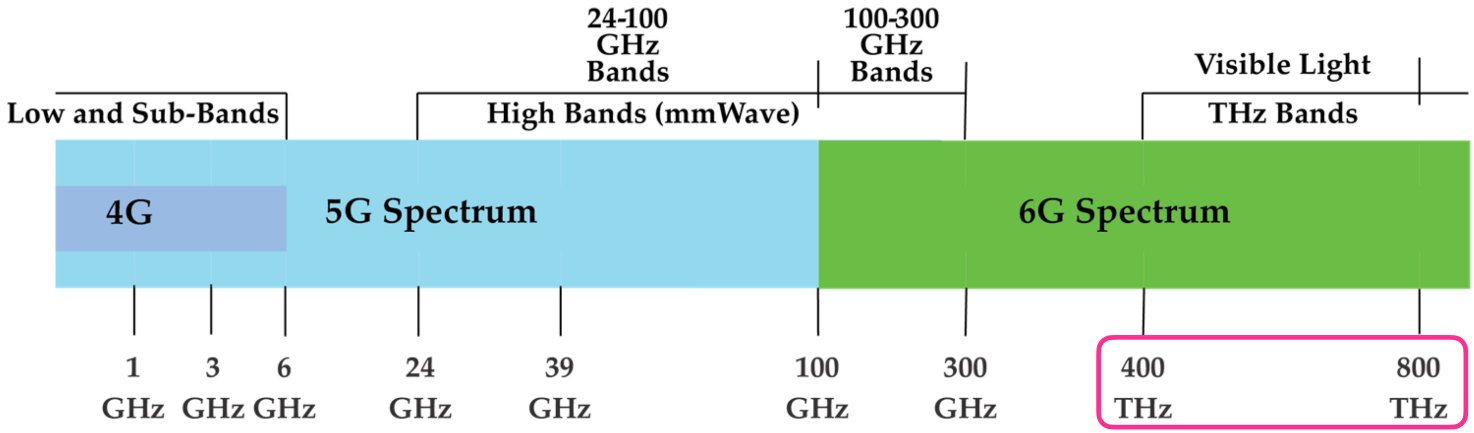


5G vs. 6G KPIs

KPIs	5G	6G
Maximum Bandwidth	1 GHz	100 GHz
Peak Data Rate	20 Gb/s	>= 1 Tb/s
Experienced Data Rate	0.1 Gb/s	1 Gb/s
Spectrum Efficiency	Peak: 30 b/s/Hz Experienced: 0.3 b/s/Hz (3 times that of 4G)	Peak: 60 b/s/Hz Experienced: 3 b/s/Hz (5 to 10 times that of 5G)
Network Energy Efficiency	Not Specified	1 pJ/b
Area Traffic Capacity	10 $Mb/s/m^2$	1 $Gb/s/m^2$
Connection Density	10^6 devices/Km^2	10^7 devices/Km^2
Latency	1 ms	10 to 100 µs
Jitter	Not specified	1 µs
Reliability or FER	1×10^{-5}	1×10^{-9}
Mobility	500 Km/h	>= 1000 Km/h
Uniform User Experience	50 Mb/s, 2D everywhere	10 Gb/s, 3D everywhere
Localization Accuracy	10 cm in 2D	1 cm in 3D

Terahertz Spectrum





Enabling Technologies for B5G/6G

B5G / 6G Technologies	
Edge/Fog Computing	Distributed AI & Big Data
Ultra-dense Small Cell Network	Quantum Communications
Virtualized Network	Visible Light Communications
Energy Harvesting	Optical-Wireless Convergence
Energy Efficiency	3D Network
THz Communications	Full Duplex Communications