An introduction to 5G
architecture and use cases

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Summer School in Future Energy Information Networks
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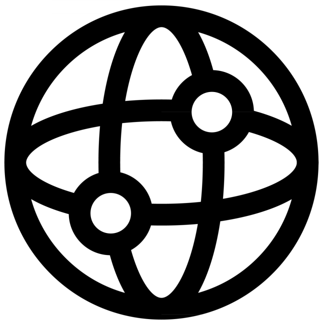
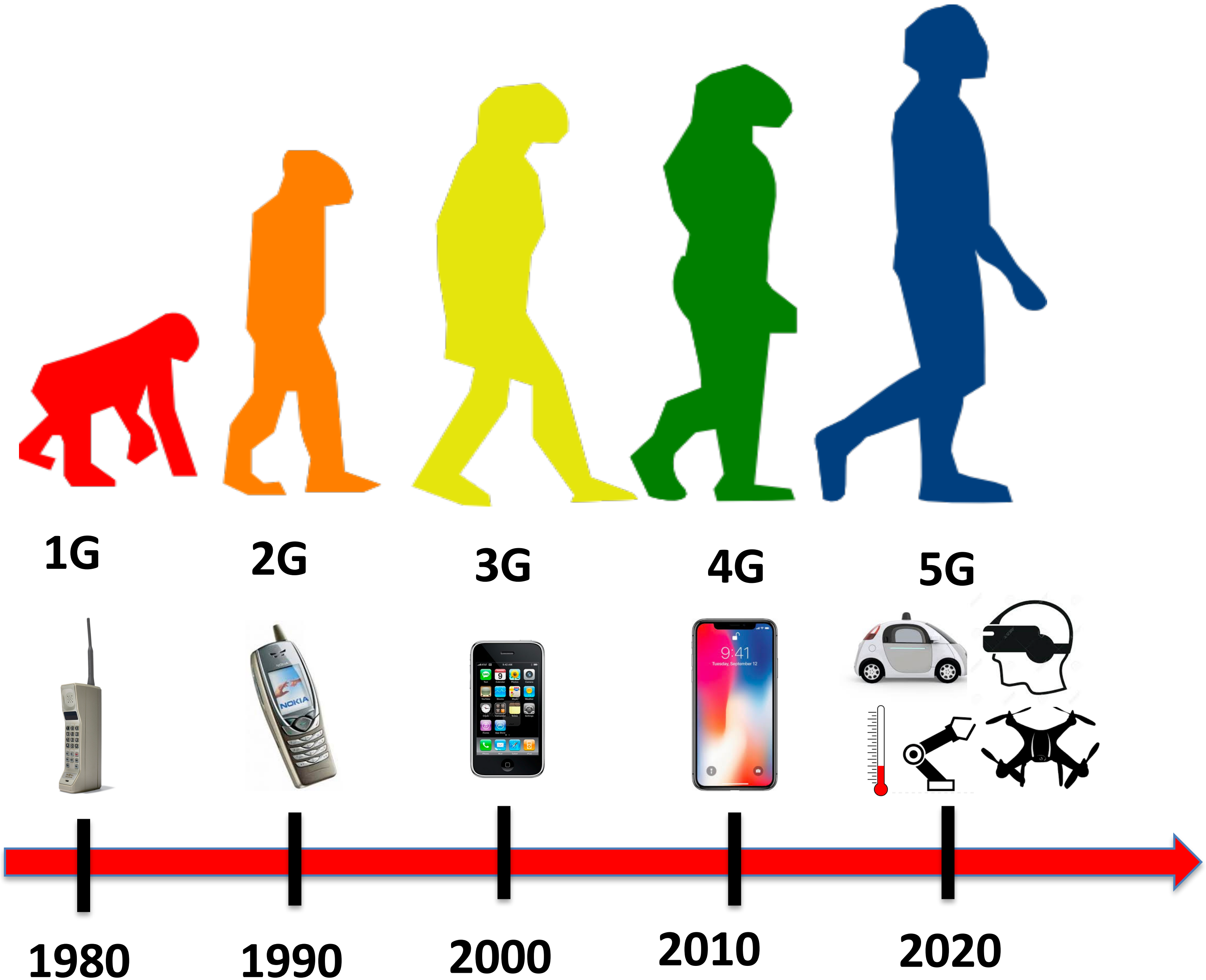
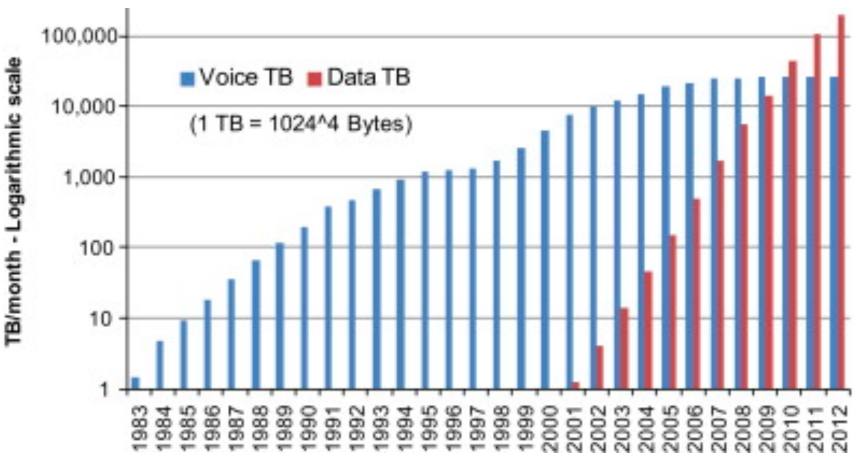
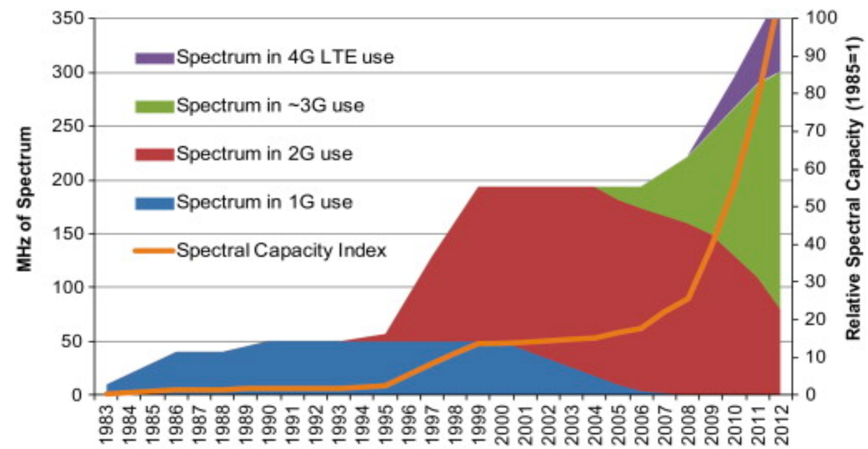




*img-src: ClipartPanda.com

The focus has so far been on supporting voice, data and better spectral efficiency

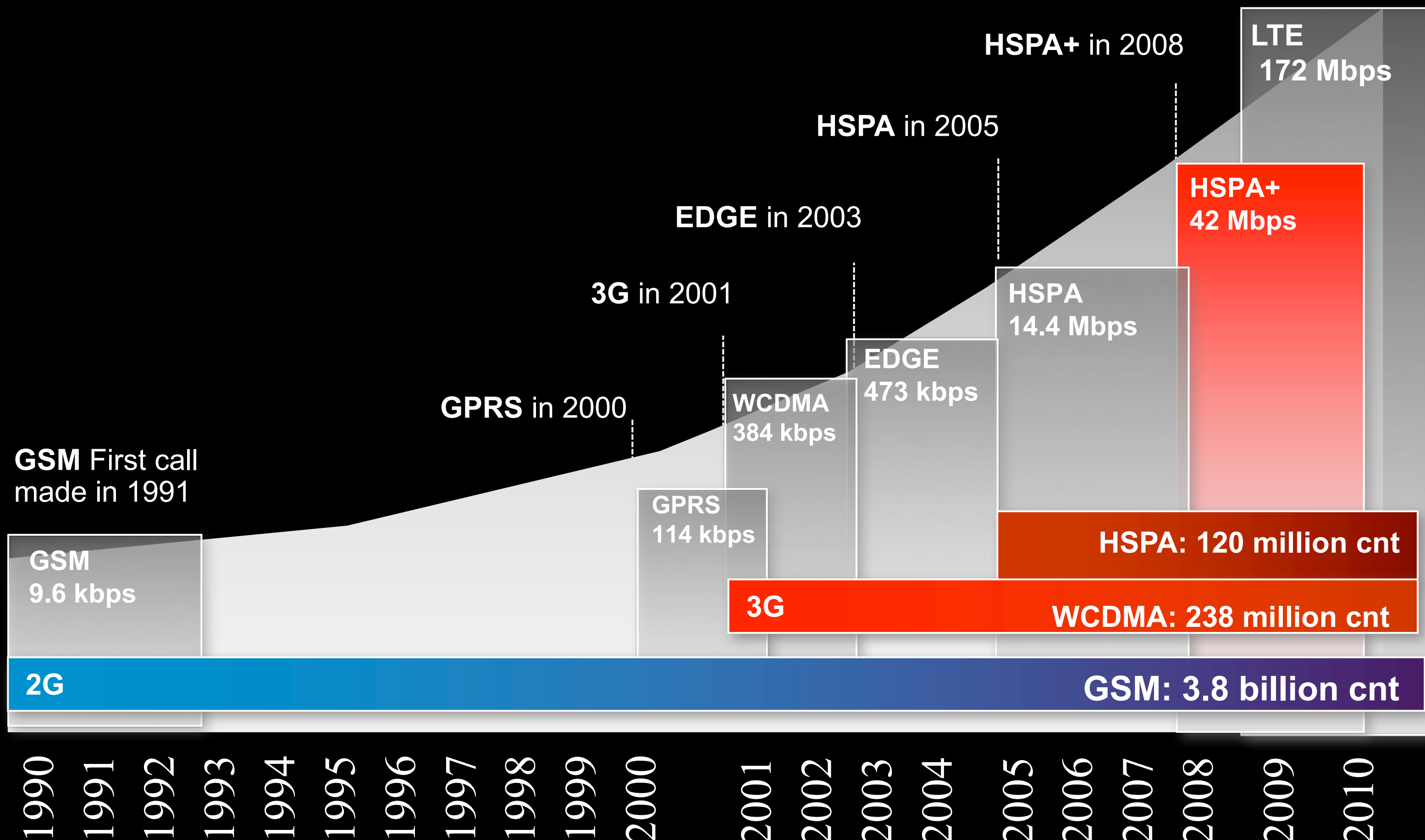




Generation	Spectral efficiency (bps/Hz)
1G	0.064
2G	0.17-0.45
3G	0.51 – 4.22
4G	7.3 - 30

Src:Clarke RN. Expanding mobile wireless capacity: The challenges presented by technology and economics. Telecommunications Policy. 2014 Sep 1;38(8-9):693-708.

The GSM Family - Delivering on Promises

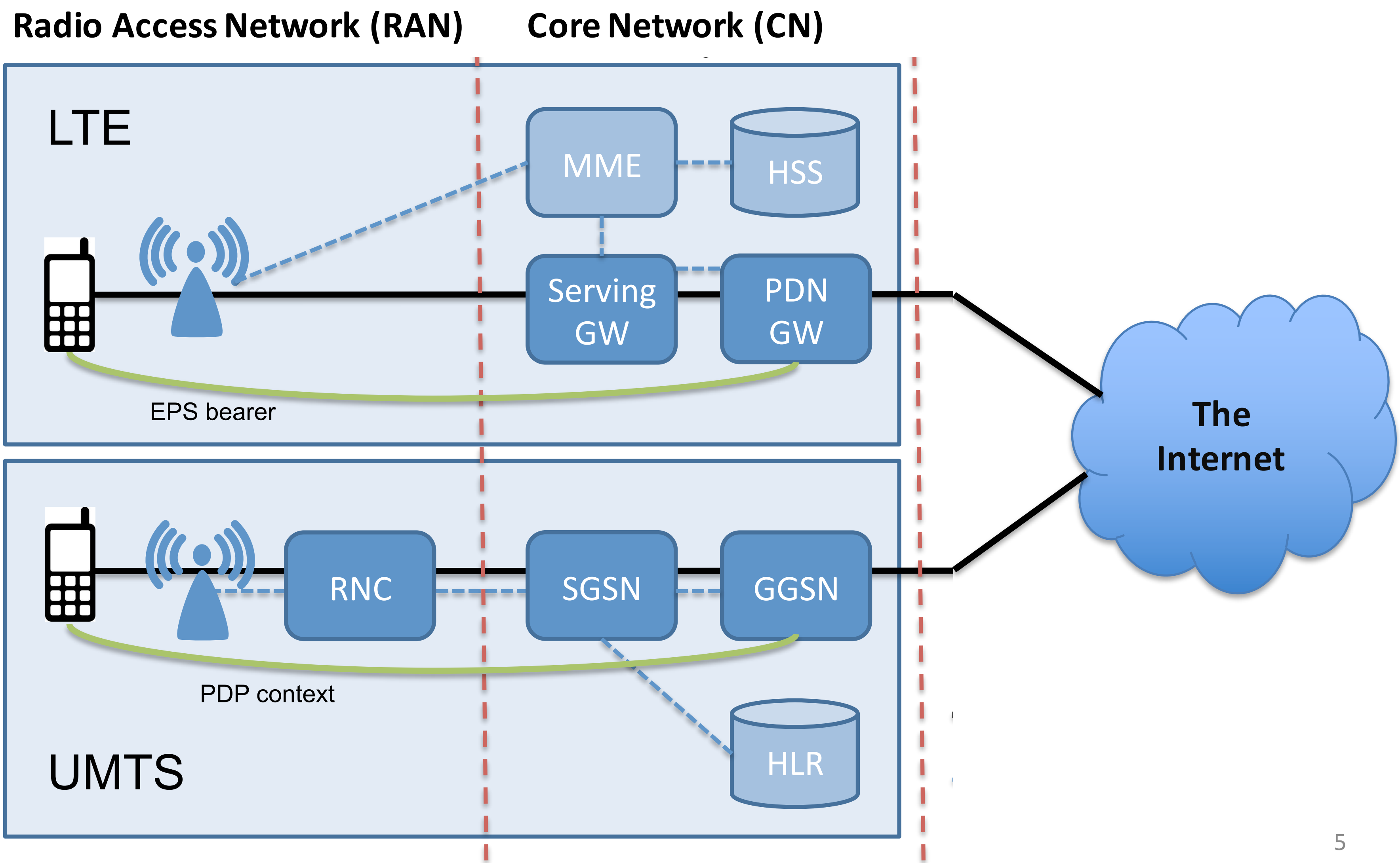


Source: Wireless Intelligence, June, 2009

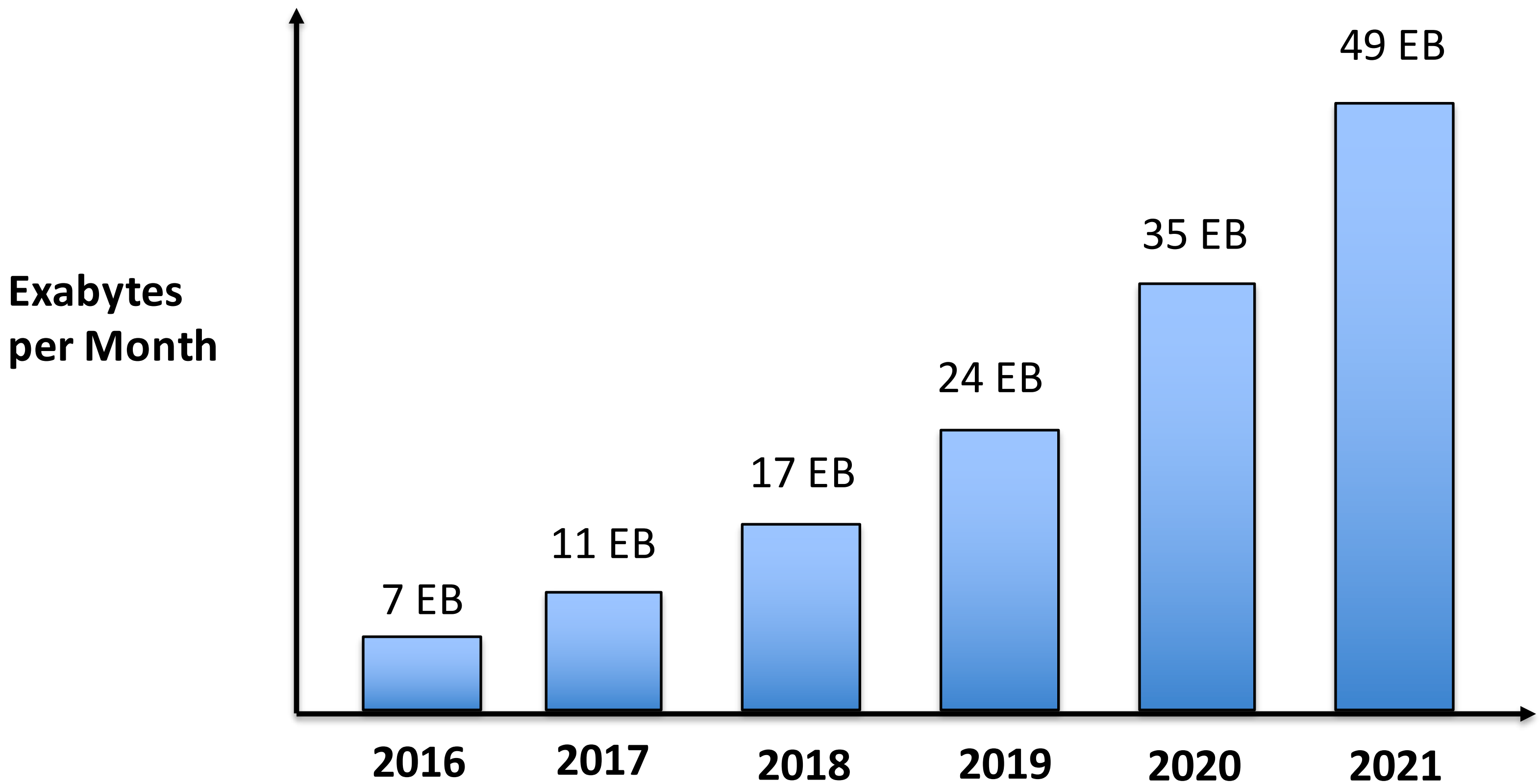
NEARLY TWO DECADES OF PROVEN TECHNOLOGY AND EXPERIENCE

© GSM Association 2009

However, no substantial architectural innovations since 2G



Mobile traffic is expected to grow to 49 exabytes per month by 2021

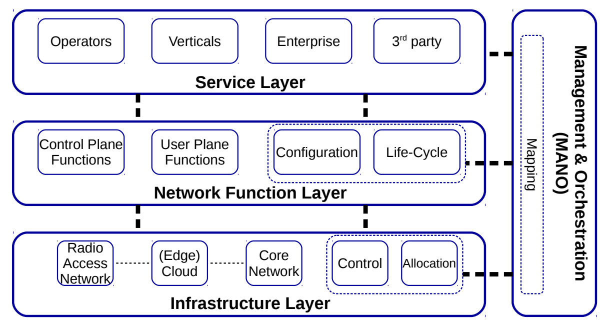


The number of connected devices is projected to grow by 50% from 8 to 12 billions

*src: Cisco VNI

Outline

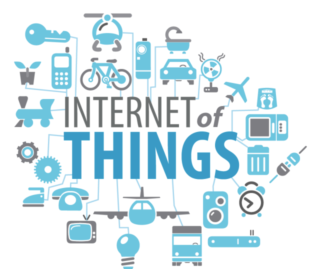
5G vision

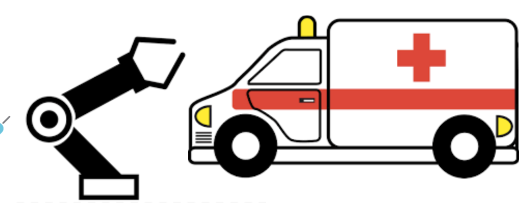


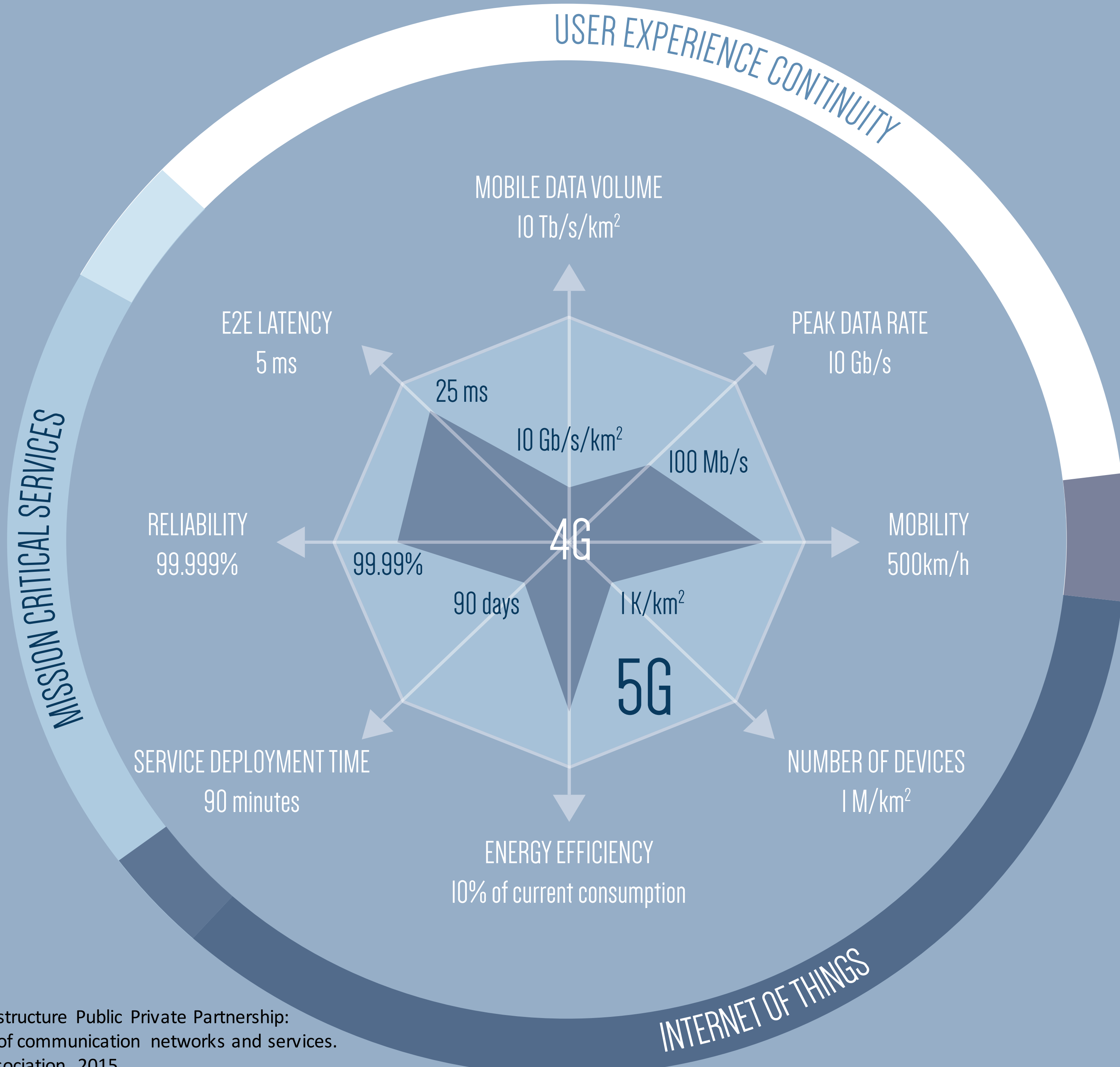
5G realization

Challenging use cases:

The smart grid as an example



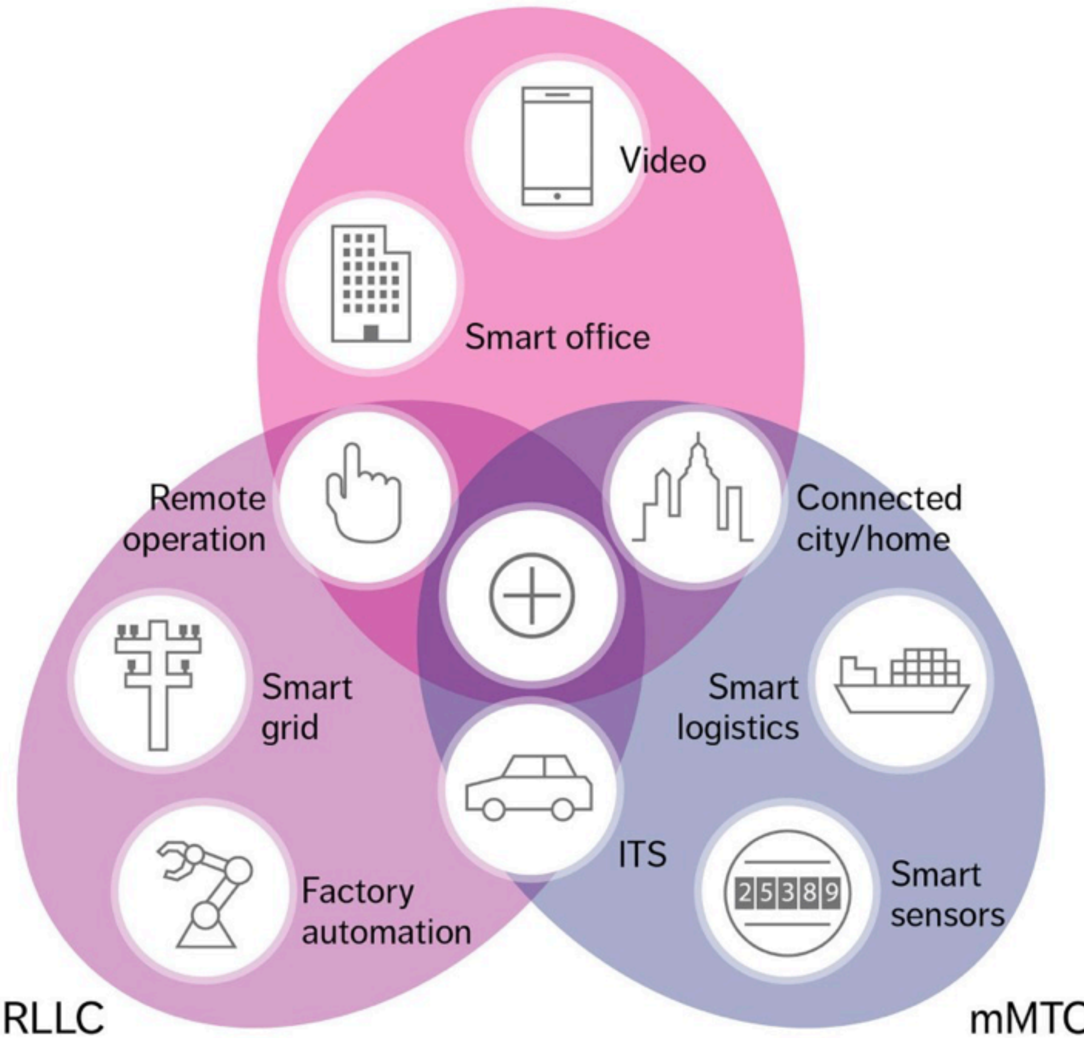




Source: The 5G Infrastructure Public Private Partnership: the next generation of communication networks and services. 5G Infrastructure Association, 2015

5G aims to cater for services with diverse requirements

Enhanced Mobile Broadband eMBB



Ultra Reliable Low Latency Communication

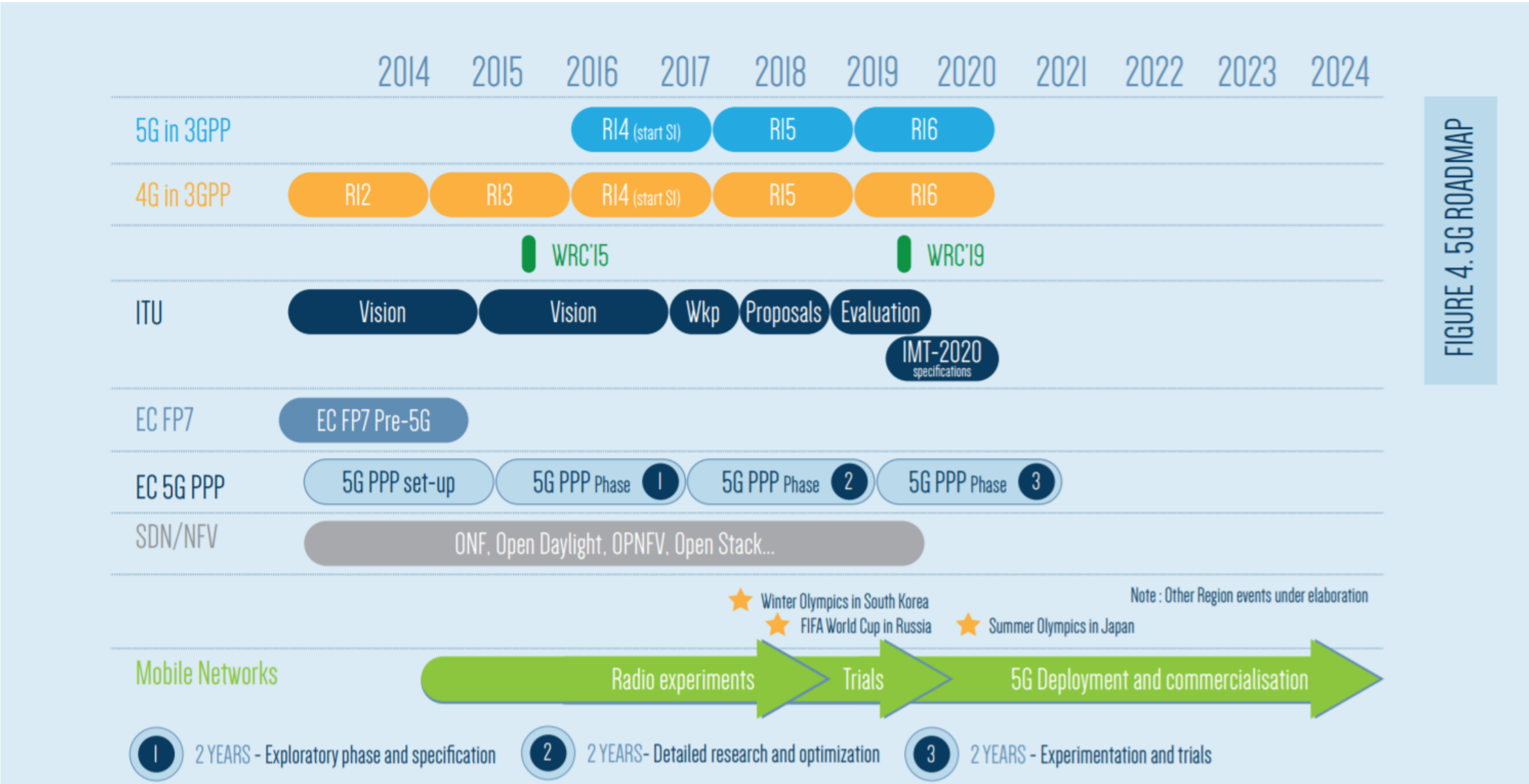
Massive Machine Type Communication

Source: Teyeb et. al. “Evolving LTE to fit the 5G future”. Ericsson Technology Review, 2017.

Use case category	User Experienced Data Rate	E2E Latency	Mobility
Broadband access in dense areas	DL: 300 Mbps UL: 50 Mbps	10 ms	On demand, 0-100 km/h
Indoor ultra-high broadband access	DL: 1 Gbps, UL: 500 Mbps	10 ms	Pedestrian
Broadband access in a crowd	DL: 25 Mbps UL: 50 Mbps	10 ms	Pedestrian
50+ Mbps everywhere	DL: 50 Mbps UL: 25 Mbps	10 ms	0-120 km/h
Ultra-low cost broadband access for low ARPU areas	DL: 10 Mbps UL: 10 Mbps	50 ms	on demand: 0-50 km/h
Mobile broadband in vehicles (cars, trains)	DL: 50 Mbps UL: 25 Mbps	10 ms	On demand, up to 500 km/h
Airplanes connectivity	DL: 15 Mbps per user UL: 7.5 Mbps per user	10 ms	Up to 1000 km/h
Massive low-cost/long-range/low-power MTC	Low (typically 1-100 kbps)	Seconds to hours	on demand: 0-500 km/h
Broadband MTC	See the requirements for the Broadband access in dense areas and 50+Mbps everywhere categories		
Ultra-low latency	DL: 50 Mbps UL: 25 Mbps	<1 ms	Pedestrian
Resilience and traffic surge	DL: 0.1-1 Mbps UL: 0.1-1 Mbps	Regular communication: not critical	0-120 km/h
Ultra-high reliability & Ultra-low latency	DL: From 50 kbps to 10 Mbps; UL: From a few bps to 10 Mbps	1 ms	on demand: 0-500 km/h
Ultra-high availability & reliability	DL: 10 Mbps UL: 10 Mbps	10 ms	On demand, 0-500 km/h
Broadcast like services	DL: Up to 200 Mbps UL: Modest (e.g. 500 kbps)	<100 ms	on demand: 0-500 km/h

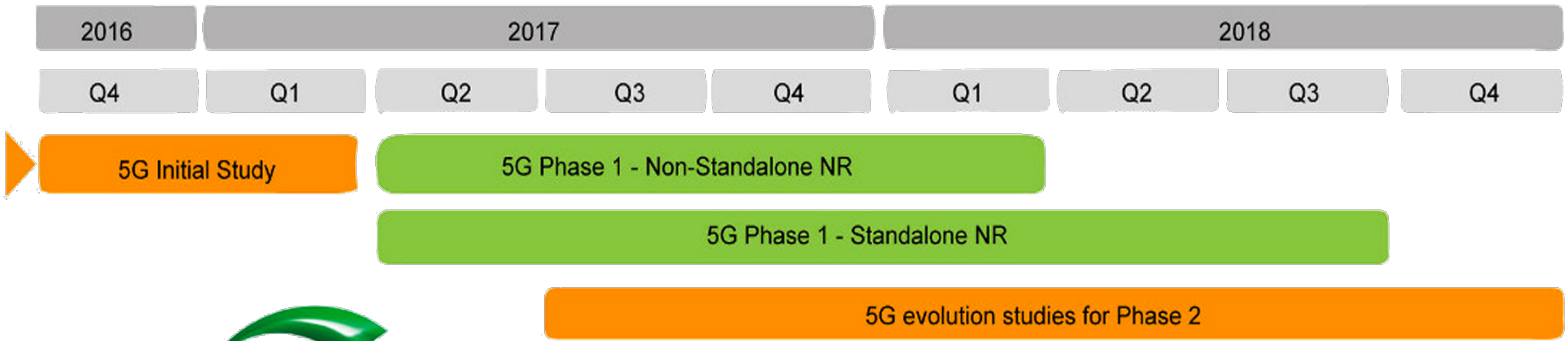
Source: 5G White Paper. NGMN Alliance, 2015

5G timeline (I)



Source: https://5g-ppp.eu/wp-content/uploads/2015/02/5G-Vision-Brochure-v1.pdf

5G timeline (II)



Non-Standalone

Uses LTE core and LTE radio anchor with a 5G small cell
Mobile BroadBand capacity boost

Standalone

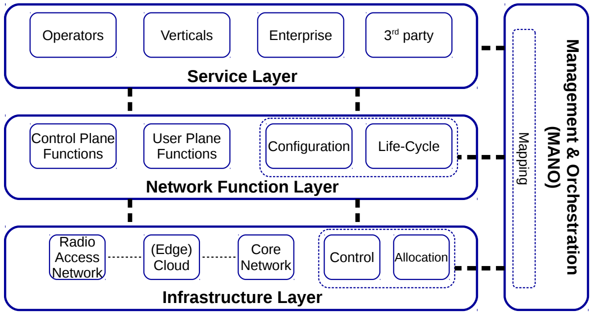
Uses 5G core and 5G radio anchor
5G overlay
Expansion of the wireless ecosystem

"5G product supports either 'NG NR' or 'access via a 5G CN' or both."
Erik Guttman, 3GPP SA Chairman

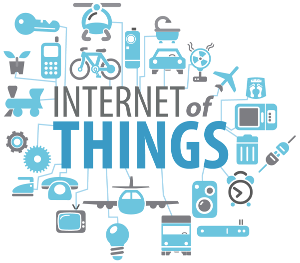
Source: 3GPP

Outline

5G vision



5G realization



Challenging use cases:

The smart grid as an example

Key enabling technologies

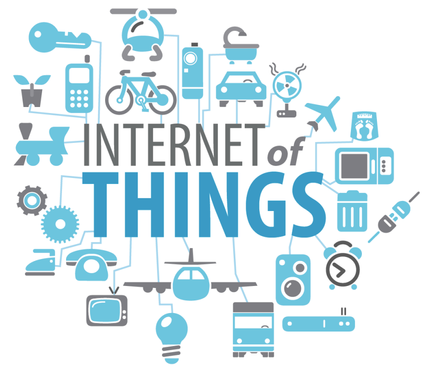
SDN

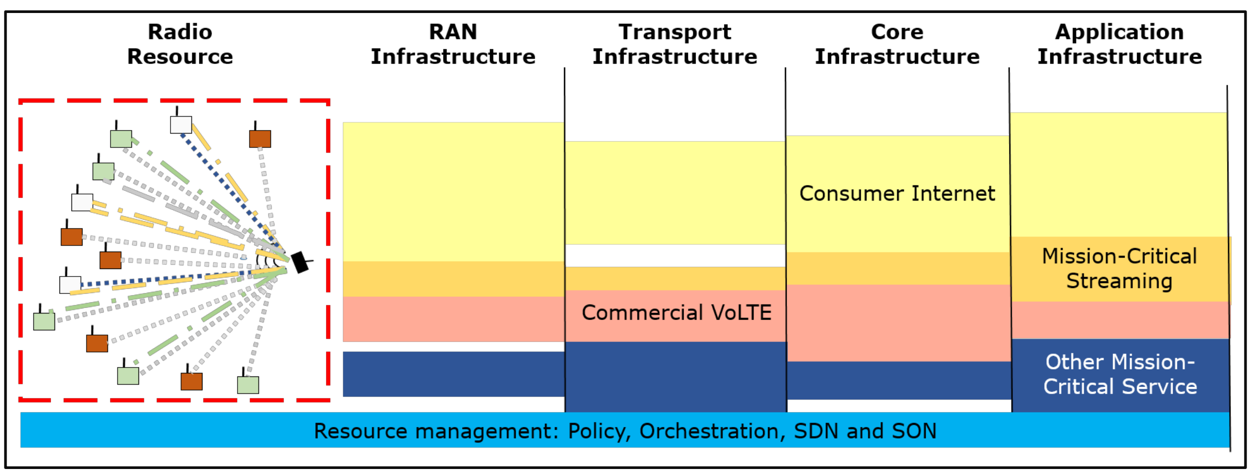
+

NFV

Innovative radio technologies
mmWave, flexible frames, …

NB-IoT, eMTC





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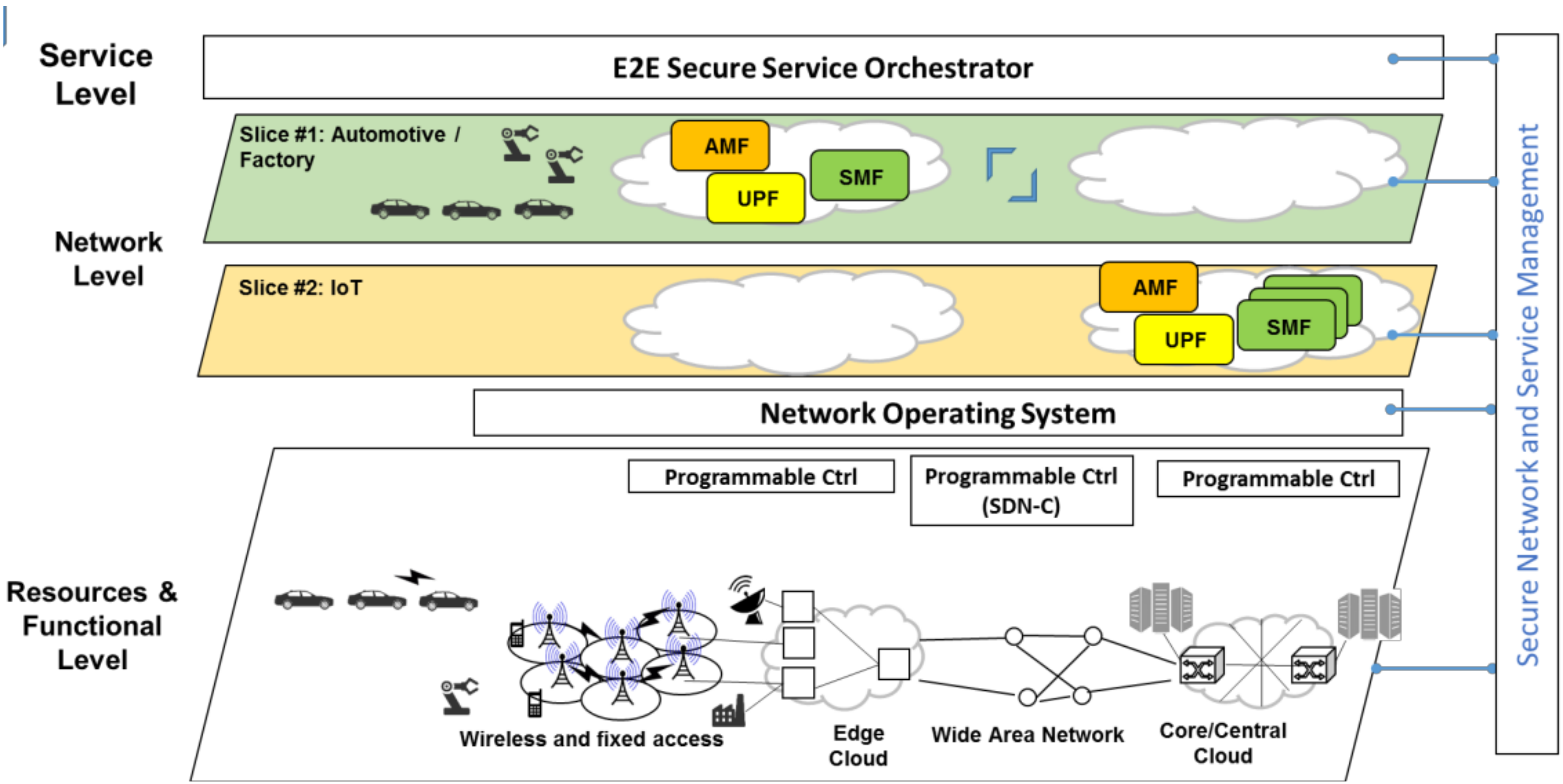
Network Slicing

* source: Heavy Reading: Service-Oriented 5G Core Networks

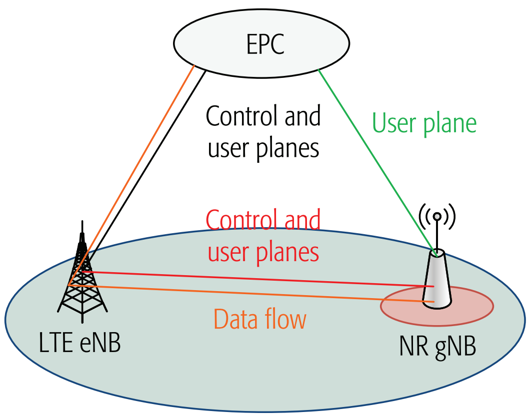
5G overall architecture



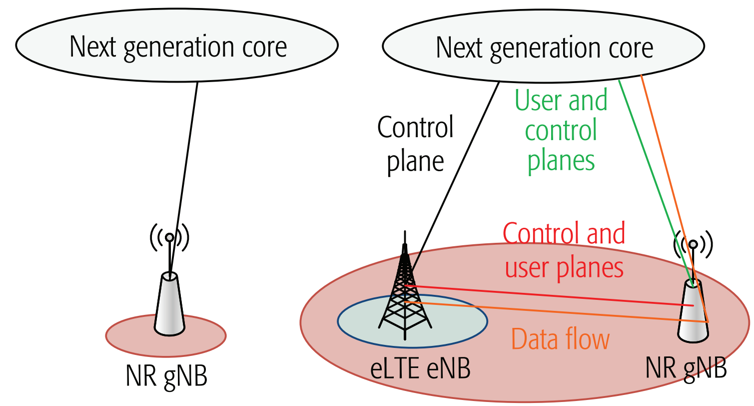
Source: 5G PPP Architecture Working Group - White Paper, Dec, 2017

5G will have several deployment scenarios

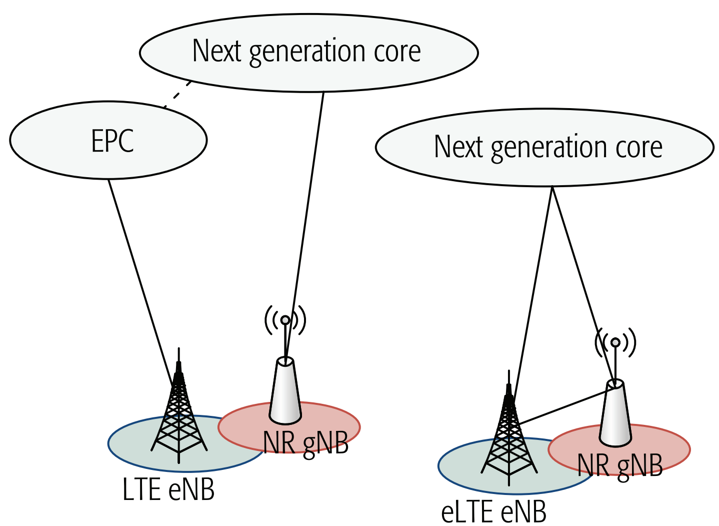
Non-Standalone (NSA)



Standalone (SA)

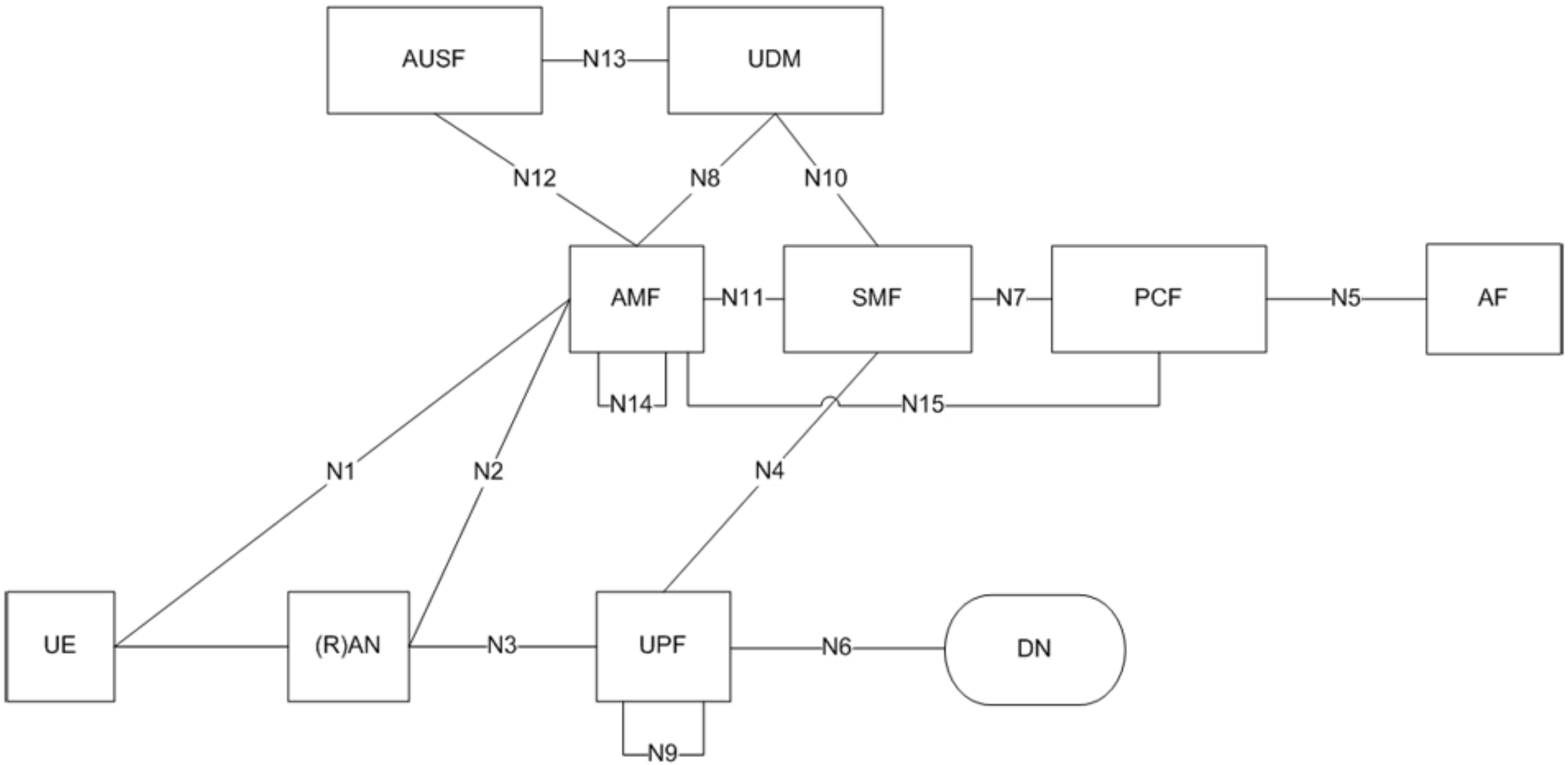


Standalone (SA) + co-existence with legacy LTE



Lien, Shao-Yu, et al. "5G new radio: Waveform, frame structure, multiple access, and initial access." IEEE communications magazine 55.6 (2017): 64-71.

The core network will witness the most radical innovation since 2G

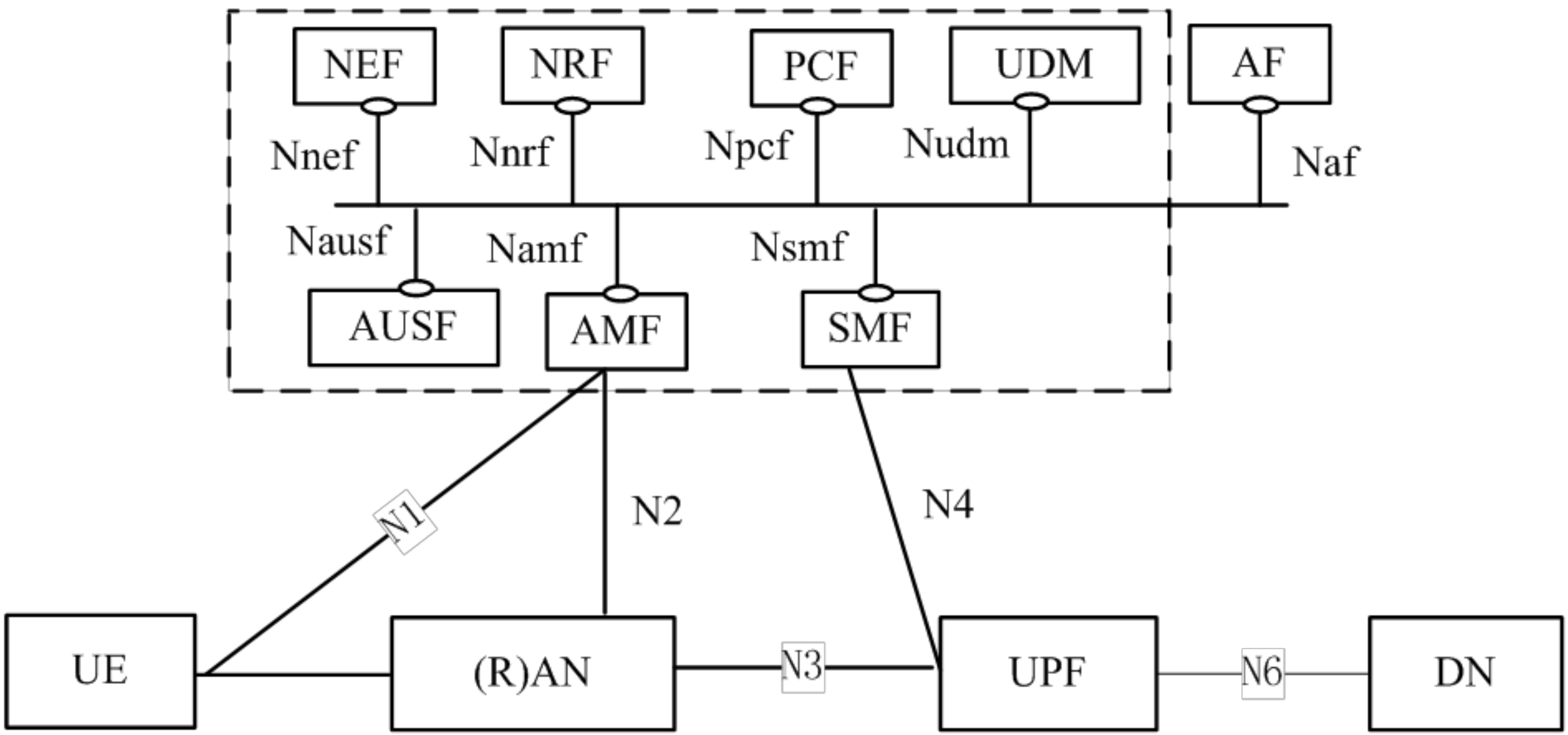


Legend: UE = User Equipment; UPF = User Plane Function; DN = Data Network; AMF = Access and Mobility Management Function; SMF = Session Management Function; PCF = Policy Control Function; UDM = Unified Data Management; AUSF = Authentication Server Function; AF = Application Function

Point-to-Point reference architecture

Source: 3GPP TR 23.501, January 2017, Figure 4.2.3-2

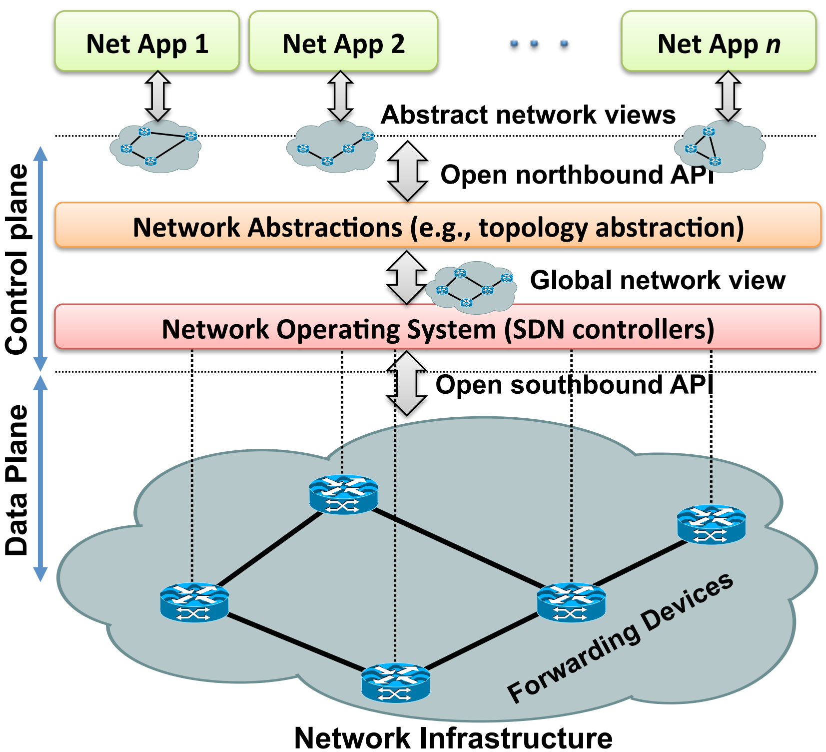
The core network will witness the most radical innovation since 2G

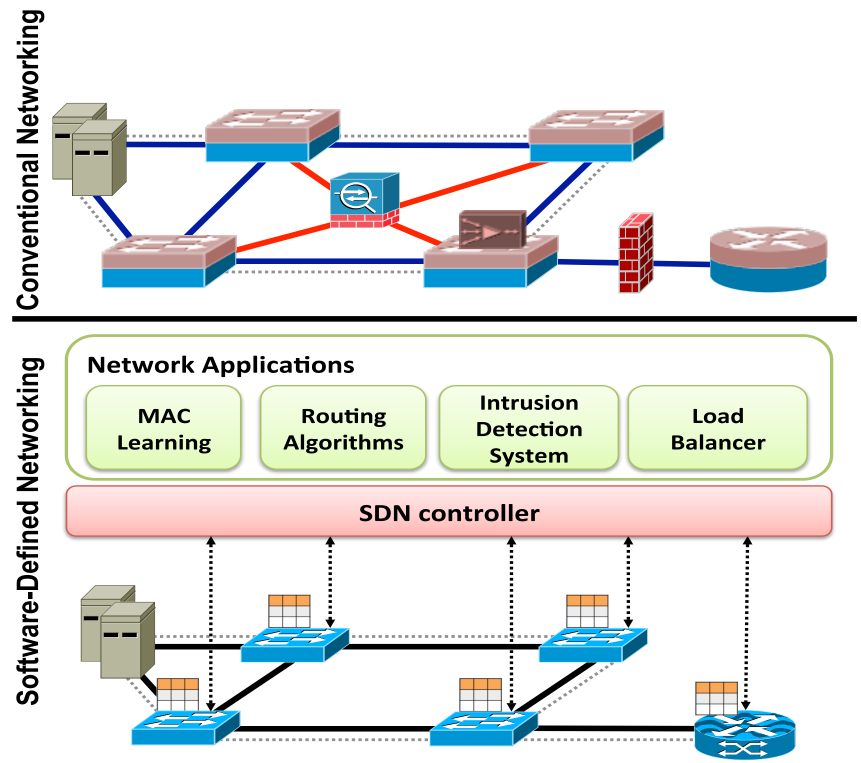


Service-Based architecture

Source: 3GPP TR 23.501, January 2017, Figure 4.2.3-1

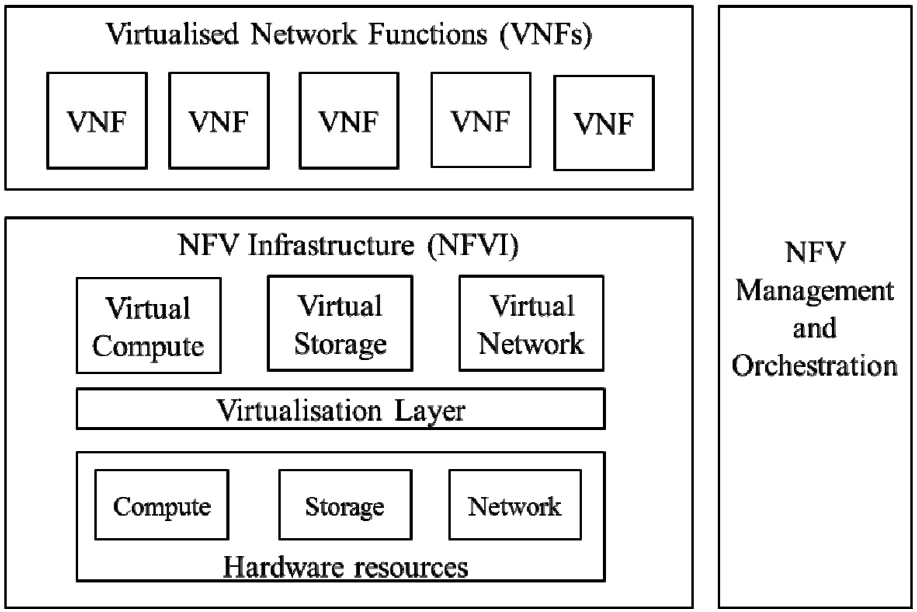
SDN separates the control and data planes and allows for network programmability

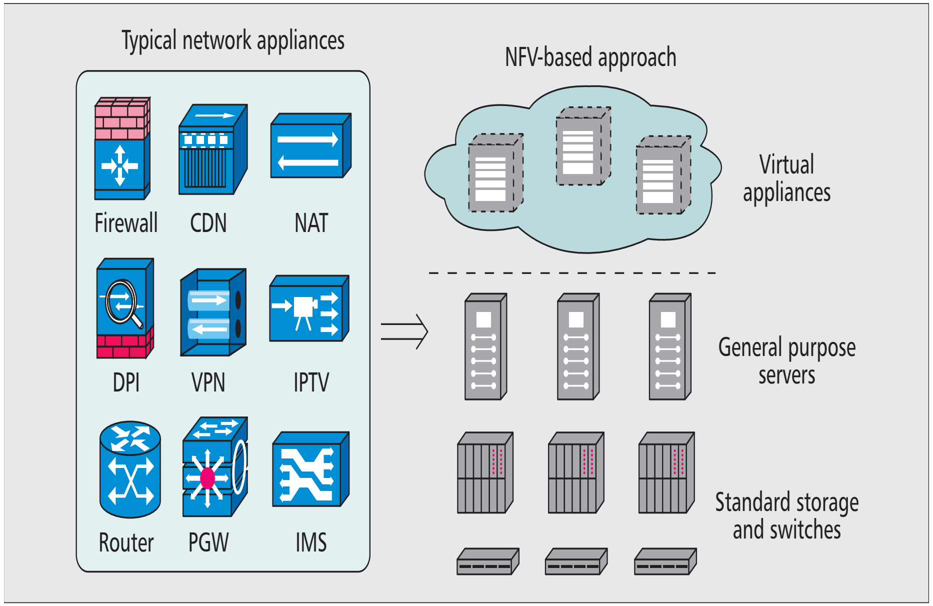




Source: Kreutz, Diego, et al. "Software-defined networking: A comprehensive survey." Proceedings of the IEEE 103.1 (2015): 14-76.

NFV decouples software implementation of network functions from hardware



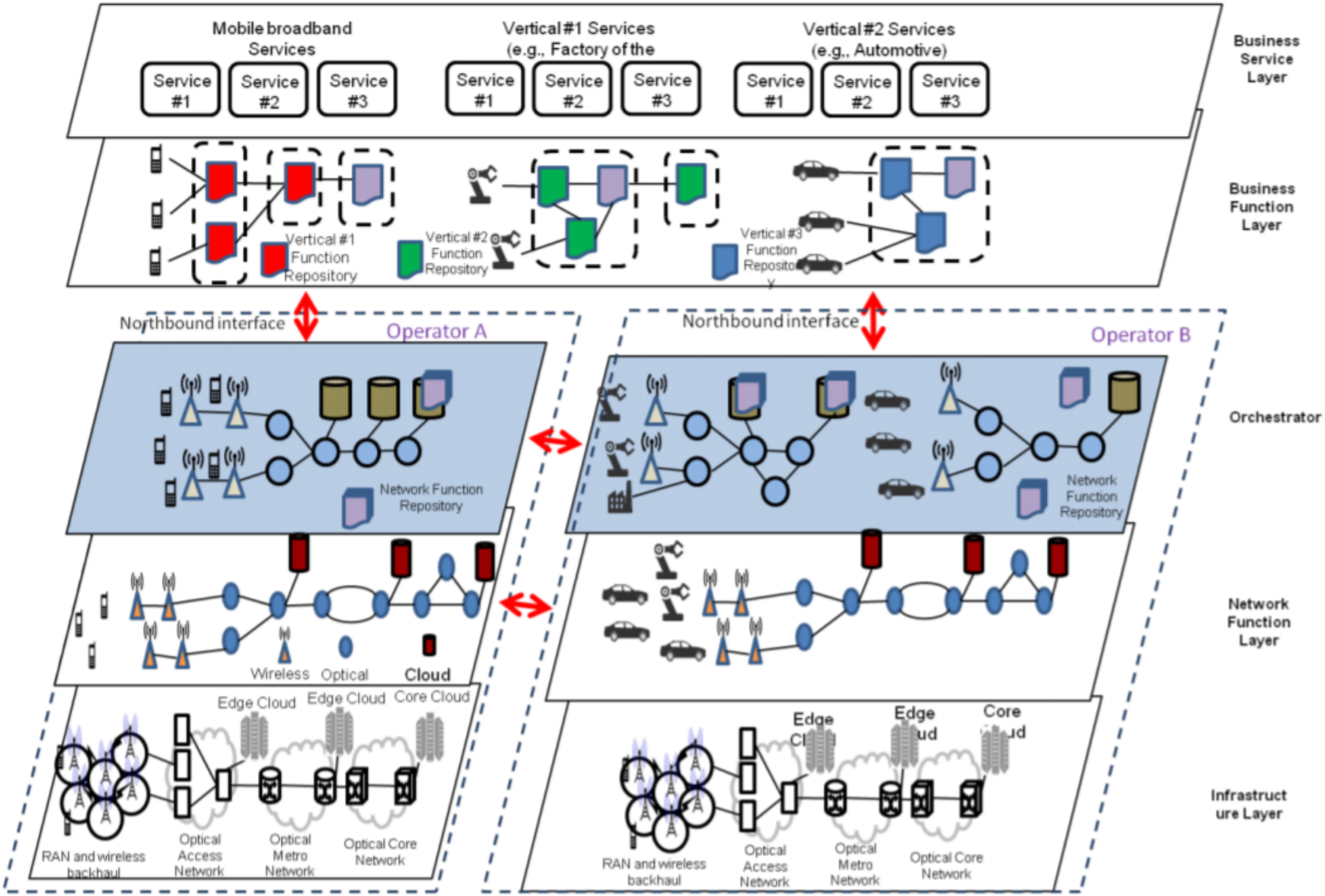


ETSI NFV reference architecture

Source: https://www.etsi.org/technologies-clusters/technologies/nfv
Han, Bo, et al. "Network function virtualization: Challenges and opportunities for innovations." IEEE Communications Magazine 53.2 (2015): 90-97.

NFV has several open challenges

- Performance
  - A carrier grade performance is expected
- Management
  - Heterogenous physical resources
- Reliability and stability
  - Efficient monitoring and control
- Security
  - Third party VNFs



Source: 5G PPP Architecture Working Group - White Paper, Dec, 2017

5G Radio must support a wide range of frequencies and spectrum types

5G

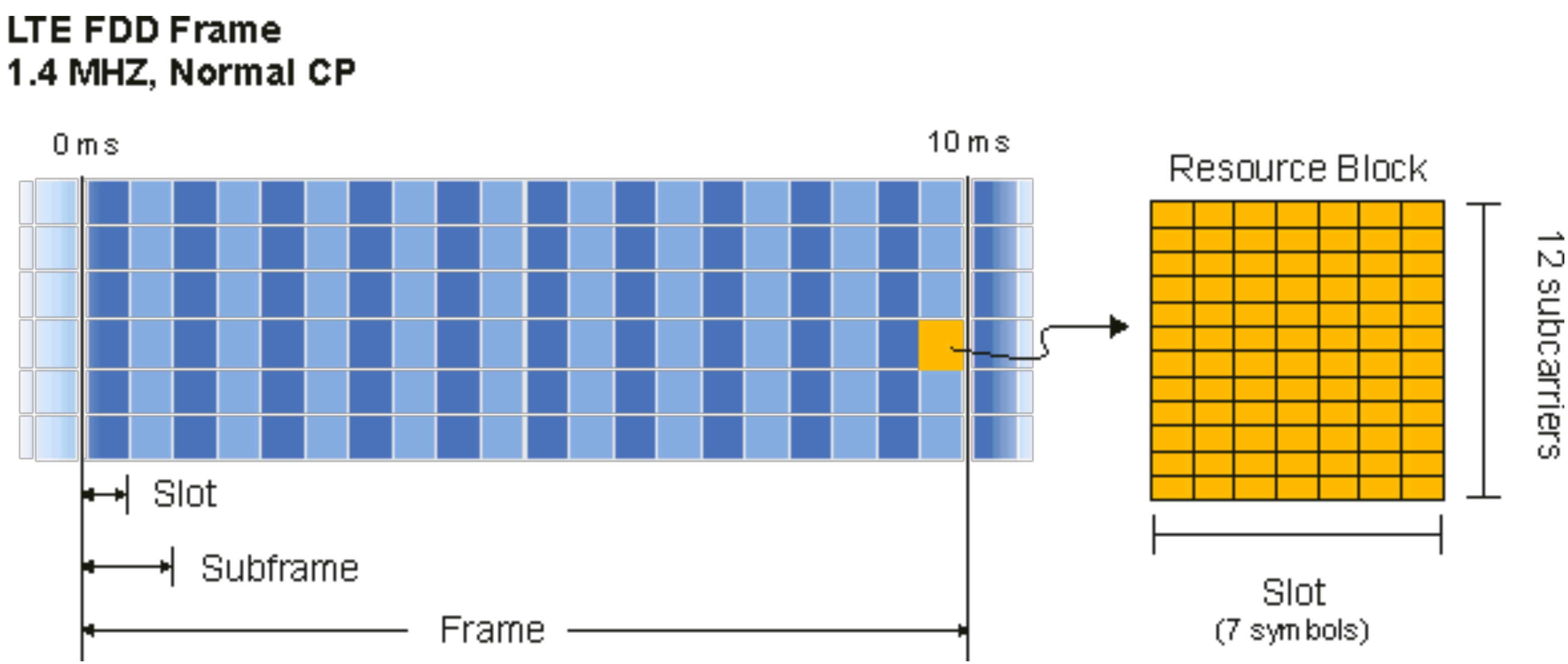
Low bands below 1 GHz: longer range for e.g. mobile broadband and massive IoT

Mid bands 1 GHz to 6 GHz: wider bandwidths for e.g. eMBB and mission-critical

High bands above 24 GHz (mmWave): extreme bandwidths

Licensed Spectrum	Shared Spectrum	Unlicensed Spectrum
Exclusive use	New shared spectrum paradigms	Shared use

LTE supports carrier bandwidth up to 20 MHz with fixed OFDM numerology

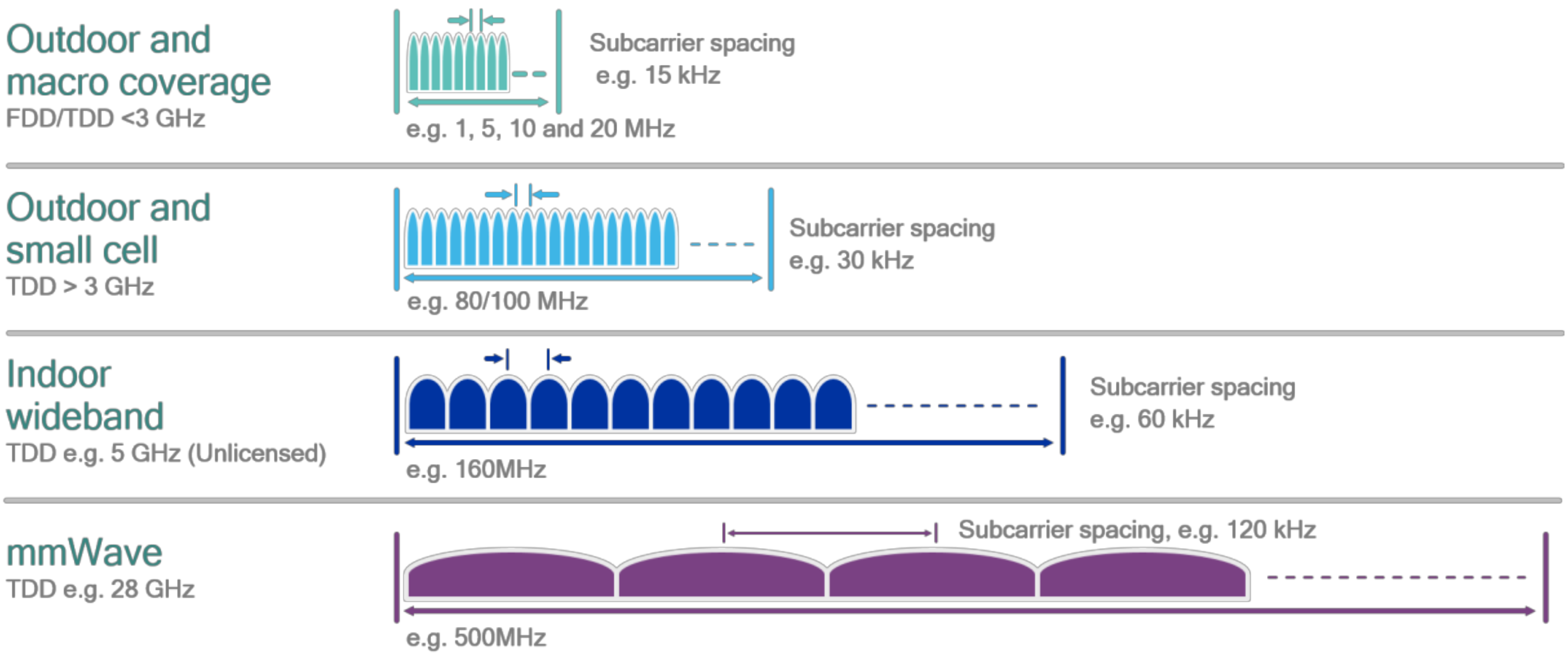


OFDM sub-carriers are spaced by 15 kHz

Resource block is fixed to 180 kHz in frequency and 1 slot long in time

http://rfmw.em.keysight.com/wireless/helpfiles/89600b/webhelp/subsystems/lte/content/lte_overview.htm

In 5G-NR OFDM sub-carrier spacing will scale with the channel bandwidth



$$\Delta f = 2^{\mu} \cdot 15\ kHz$$

Qualcomm. Making 5G NR a reality. December 2016

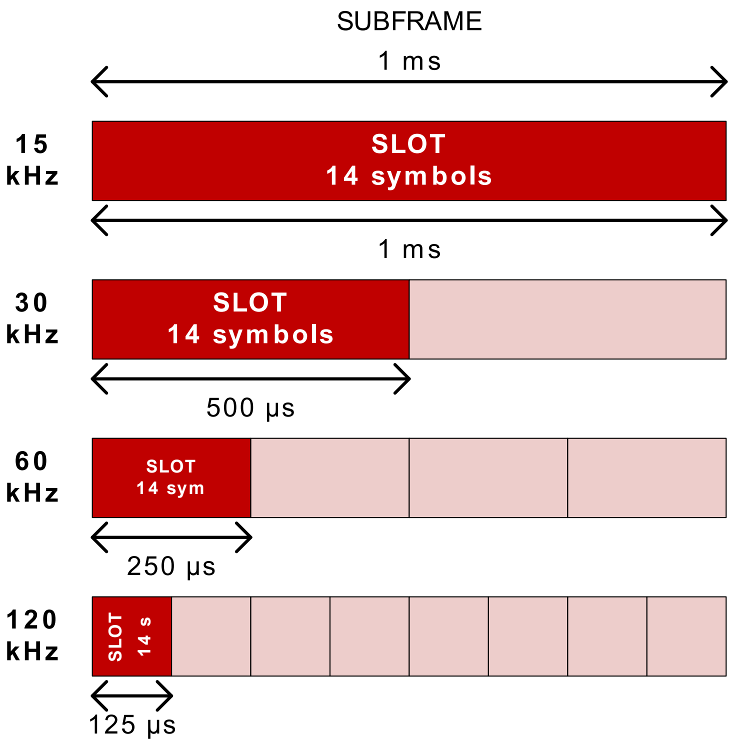
μ	Δf = $2^{\mu} \cdot 15$ kHz	Cyclic Prefix
0	15 kHz	Normal
1	30 kHz	Normal
2	60 kHz	Normal, Extended
3	120 kHz	Normal
4	240 kHz	Normal
5	480 kHz	Normal

Data < 6 GHz (μ = 0–2)

Data > 6 GHz (μ = 2–3)

Specified but not supported in Rel- 15 (μ = 5)

Variable length slot duration helps in supporting URLLC use cases



Keysight. Understanding the 5G NR Physical Layer. Nov 2017

Mobile-IoT must be scalable, energy efficient and ubiquitous

Long battery life

Low device cost

Low deployment cost

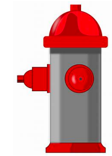
Extended coverage

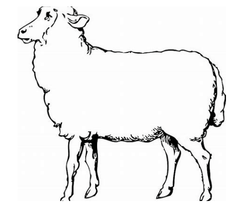
Support for many devices

User security, control & service API

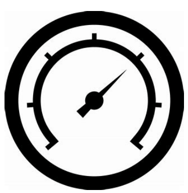
IoT applications, however, have diverse requirements

Shorter to medium battery life
Medium coverage
Some mobility
Latency in order of seconds

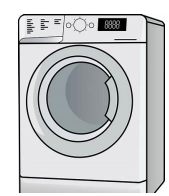




Battery life 5-10 years
Ubiquitous outdoor coverage
Some mobility
Medium to high reliability
Latency < 10 seconds



Battery life 10-15 years
Outdoor and deep indoors (+20dB)
Stationary
Medium to high reliability
Latency 10 to 60 seconds

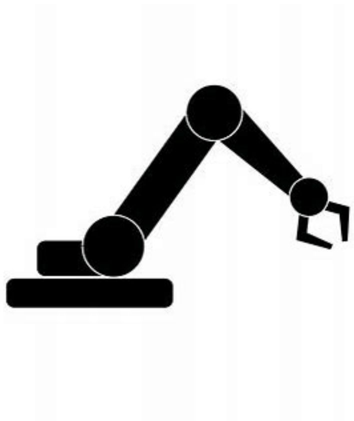


Mains powered
Outdoor and indoors
Stationary
low to high reliability
Latency < 30 seconds

GSMA white Paper. 3GPP Low Power wide Area Technologies

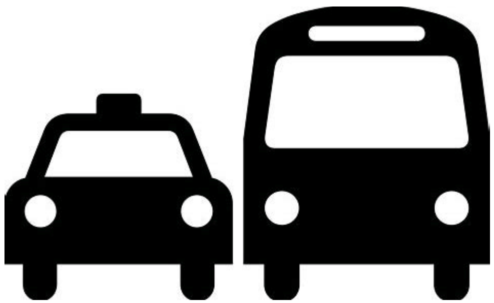
Future IoT applications will have stricter reliability and latency requirements

Factory automation



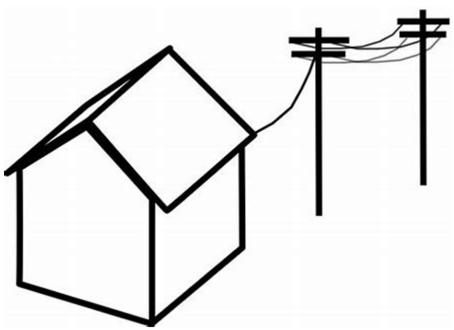
Latency: 0.25 to 10ms
PLR: 10E-9

Intelligent transportation systems



Latency: 10 to 100ms
PLR: 10E-3 to 10E-5

Smart grids



Latency: 3 to 20ms
PLR: 10E-6

PLR: Packet Loss Rate

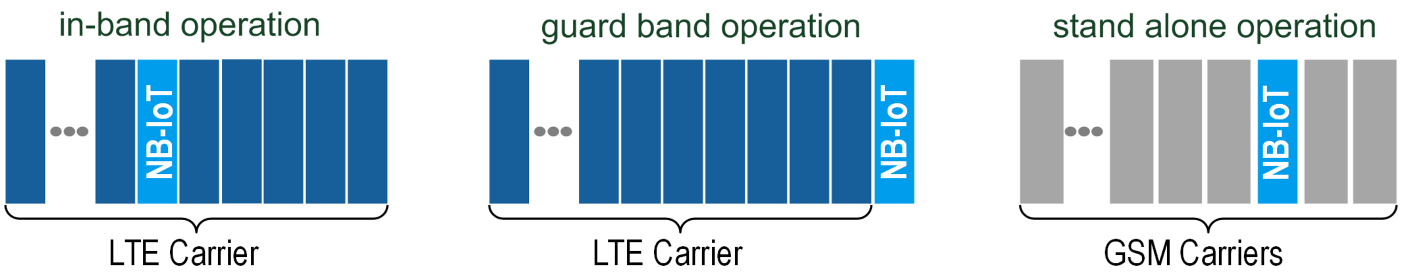
Schulz, Philipp, et al. "Latency critical IoT applications in 5G: Perspective on the design of radio interface and network architecture." IEEE Communications Magazine 55.2 (2017): 70-78.

3GPP Release 13 standardized two solutions for current and future IoT

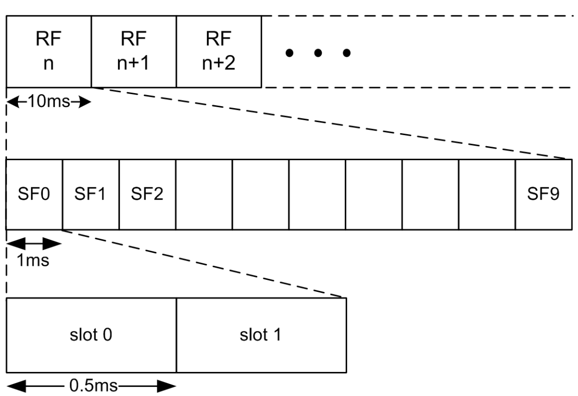
	NB-IoT LTE Cat. NB	eMTC LTE Cat. M1
Deployment	In-Band LTE, guard-band LTE and standalone	In-Band LTE
Bandwidth	180 KHz	1.08 MHz
Peak data rate	~150 kbps	1 Mbps
Latency	1.6s-10 s	10-15 ms
Max UE tx power	23 or 20 dBm	23 or 20 dBm
Power Saving	PSM, eDRX	PSM, eDRX
Duplex	Half	Full/Half
Complexity relative to LTE	10%	20-25%

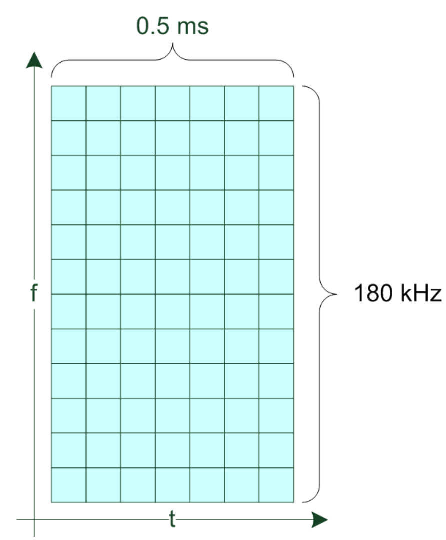
NOKIA. LTE-M – Optimizing LTE for the Internet of Things, 2015

eMTC coexists with LTE, while NB-IoT can coexist with LTE or be deployed alone



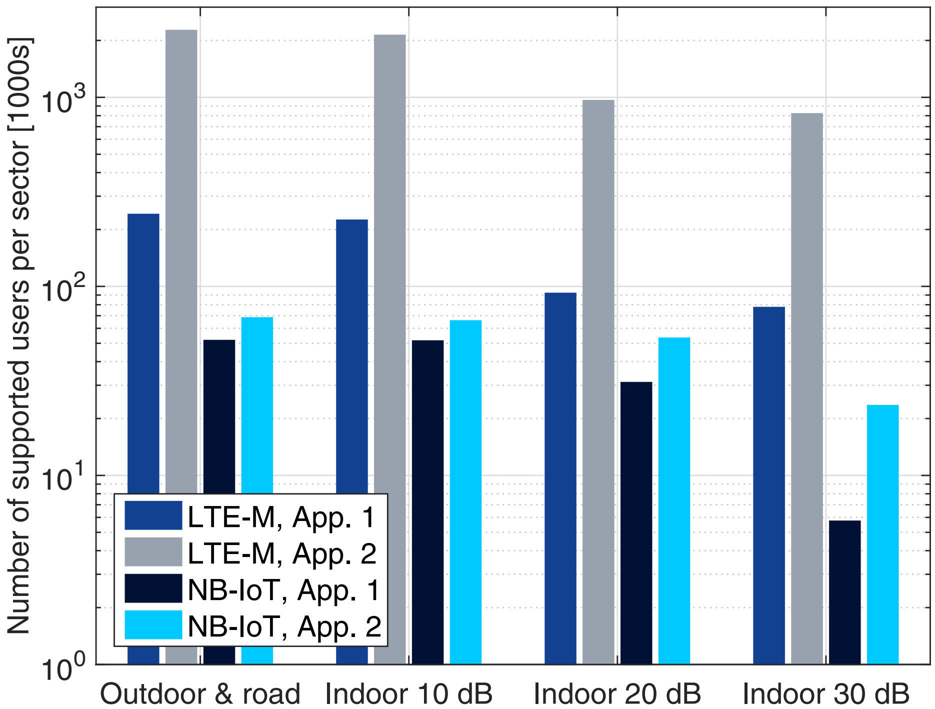
Frame structure similar to LTE but the max system bandwidth is much lower 180 KHz as opposed to 20 MHz

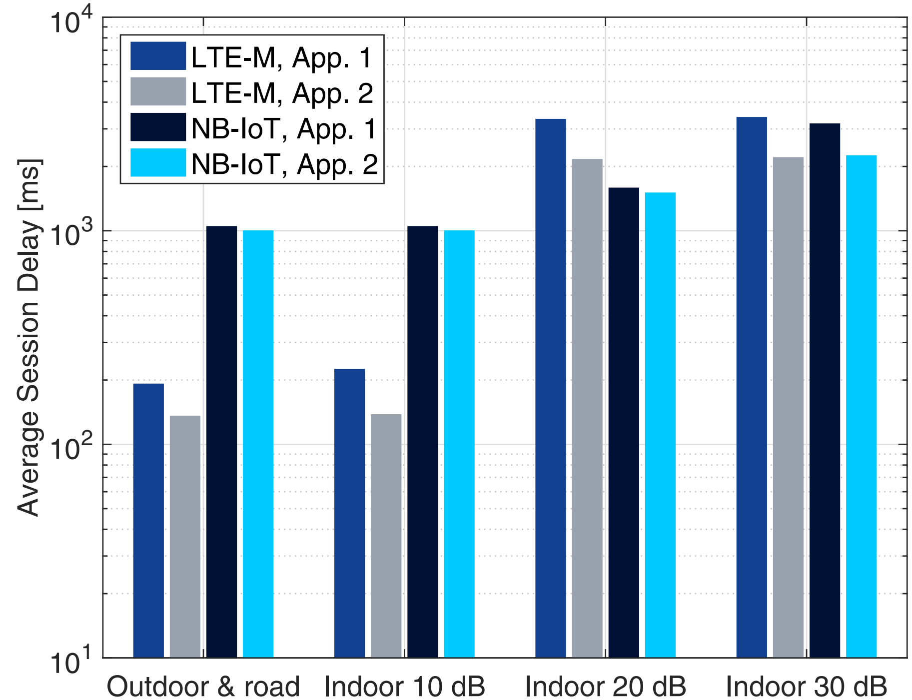




www.rohde-schwarz.com/appnote/ 1MA266

Each NB-IoT/eMTC carrier can support 10000x devices per cell

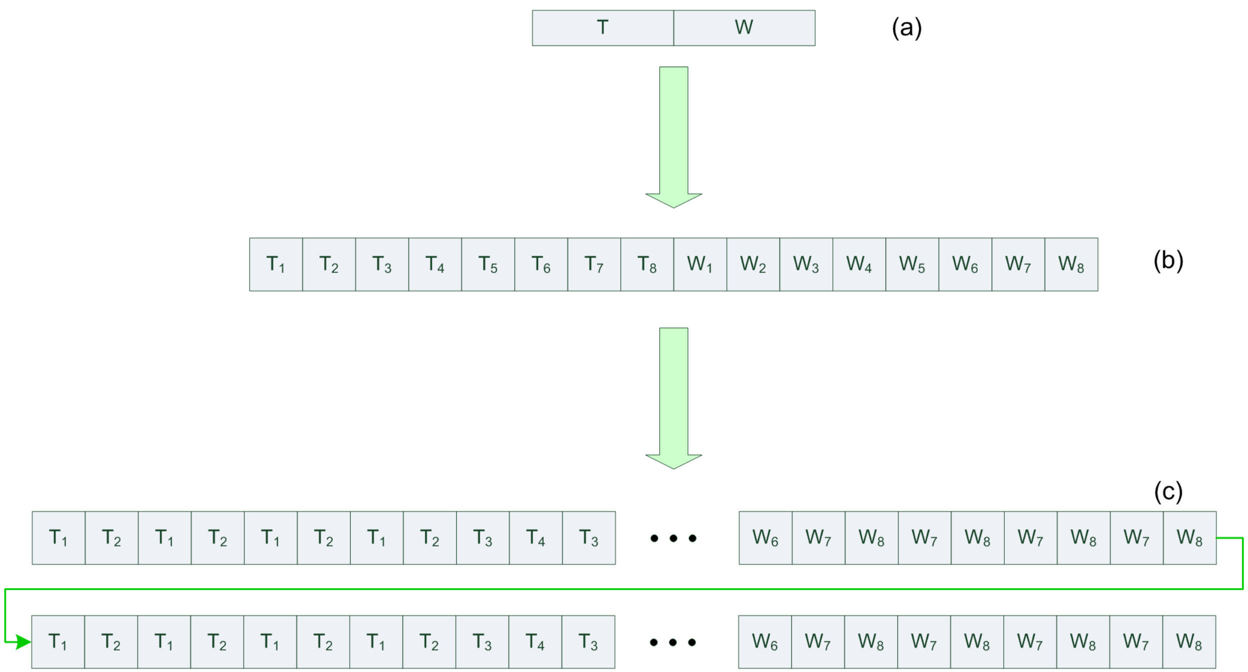




- App.1 models a secure information exchange and uses 4 payloads
- App.2 models a mobile autonomous reporting with a tx payload of 128 or 256 bytes uplink and 29 bytes ack downlink

Lauridsen, Mads, et al. "Coverage and capacity analysis of LTE-M and NB-IoT in a rural area." Vehicular Technology Conference (VTC-Fall), 2016 IEEE 84th. IEEE, 2016.

NB-IoT enhances coverage by using transmission repetitions

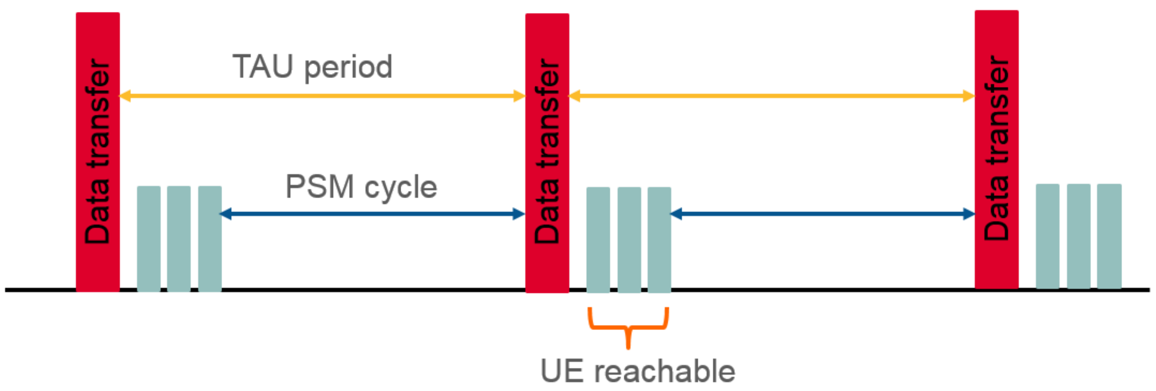


- 2x repetitions translates into 3dB coverage gain
- 2x repetitions results in 0.5x speed and 2x latency

www.rohde-schwarz.com/appnote/ 1MA266

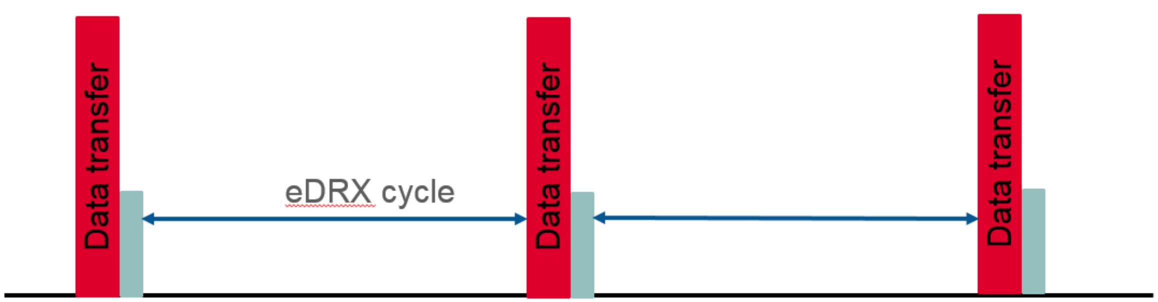
Cellular IoT has two mechanism to help devices conserving battery power

Power Saving Mode (PSM)



- UE initiated mechanism
- Akin to power off but the UE remain registered

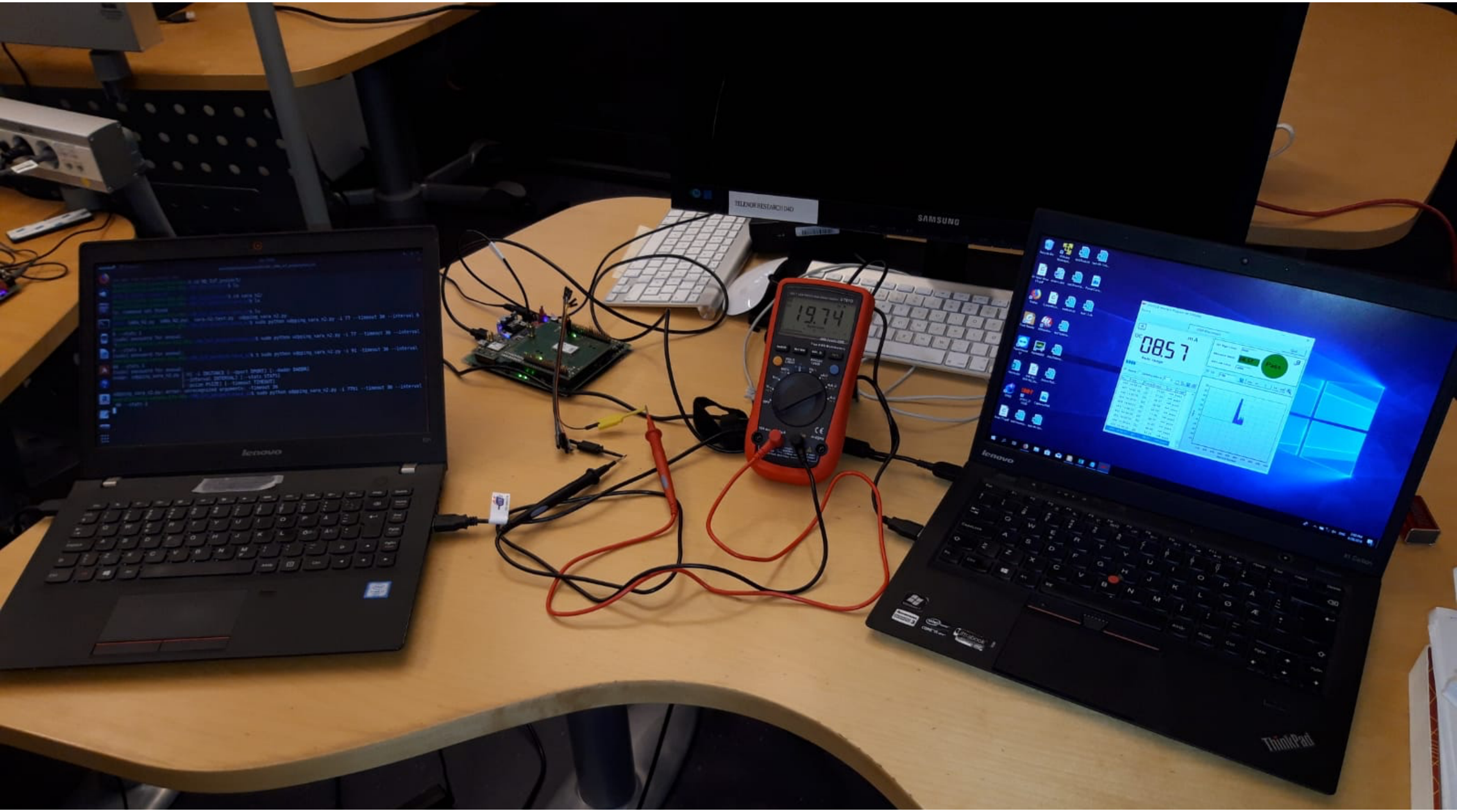
Extended Discontinuous Reception (eDRX)



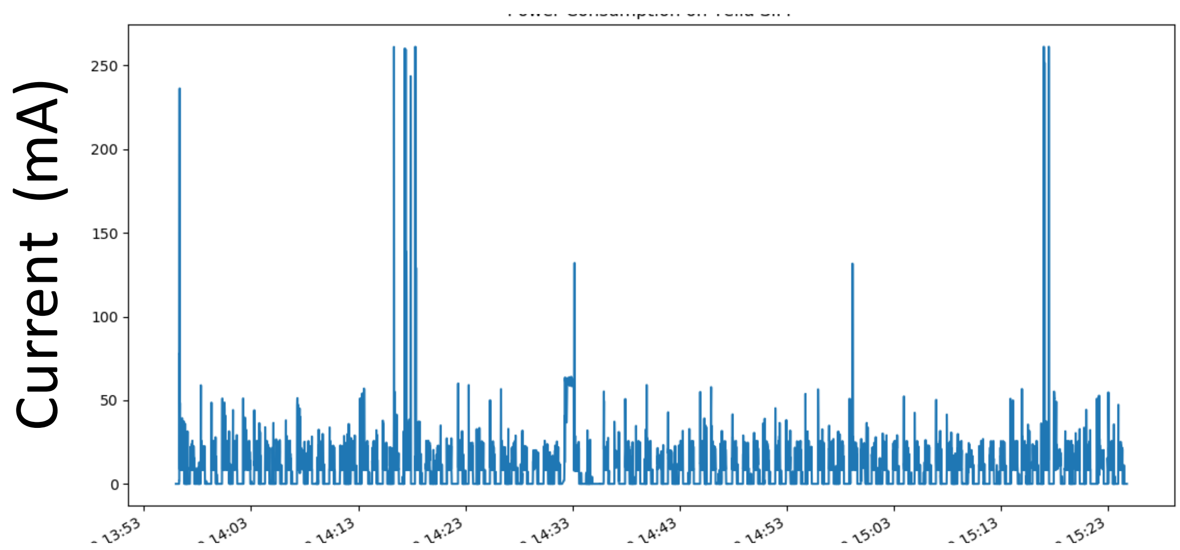
- Negotiated upon attachment
- The UE shuts off its receiver during eDRX
- Up to 3 hours

GSMA. NB-IoT DEPLOYMENT GUIDE to Basic Feature set Requirements April 2018

Early measurements of pilot NB-IoT commercial deployments



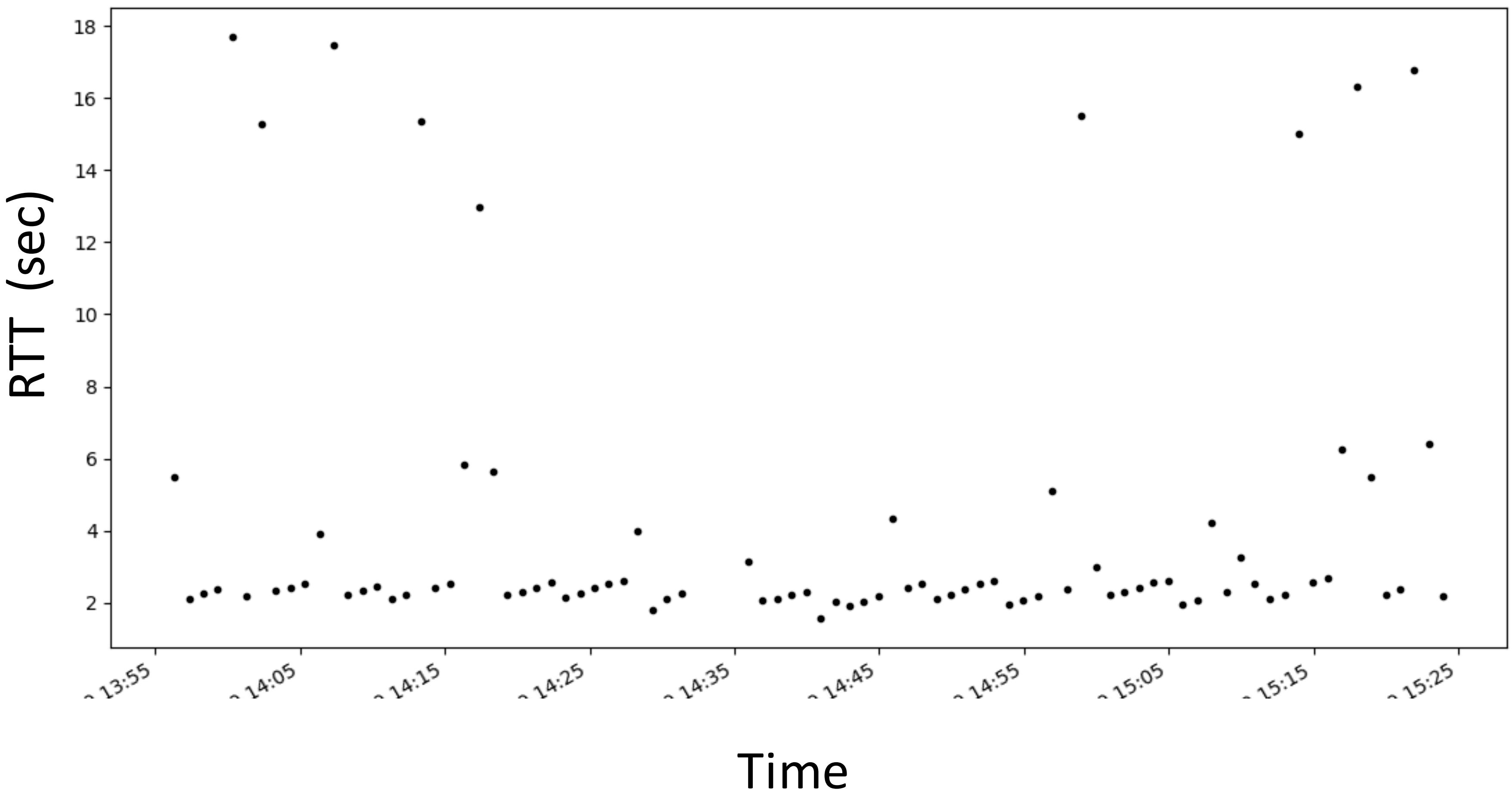
Measurements show that deployments meet expectations to a large extent



Assuming that we are using a CR2032 battery with 235 mAh capacity and 128 bytes payload and 6 activity periods per day

Total Load during transmission (mA)	Life time (years)
300 mA	~17
Up to 1500 mA	~10

Initial measurements indicate that delays may go well beyond the 10s limit

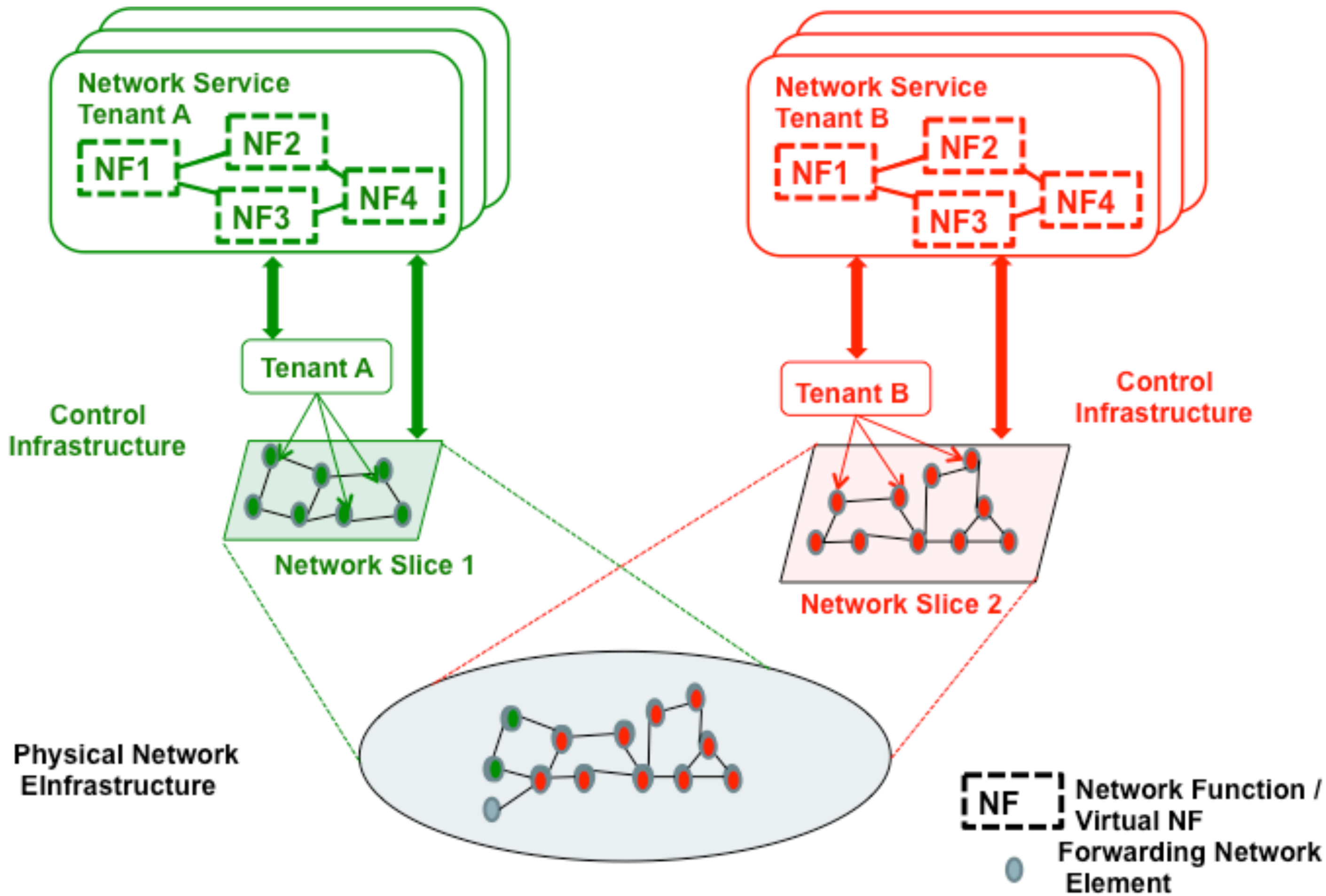


NB-IoT faces a number of challenges including complexity and methods for KPI evaluation

- Large parameter space
  - PSM, eDRX
  - Repetitions
  - Carrier bandwidth

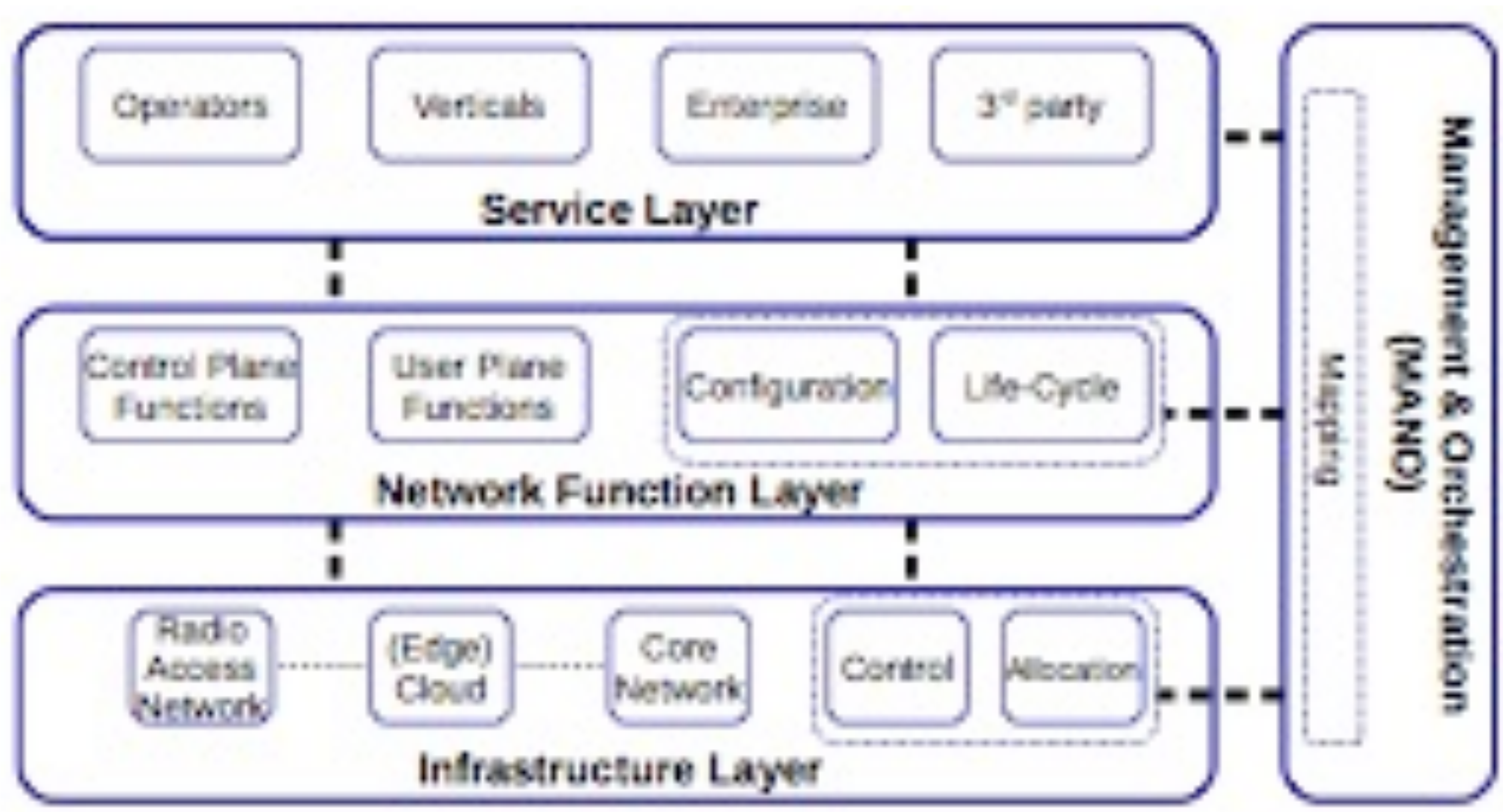
- Diverse use cases with different SLA requirements
  - Low traffic volumes
  - New metrics are needed for describing reliability

Key to the realization of 5G vision is the slicing the network on a per service basis



Source: 5G PPP Architecture Working Group - White Paper, Dec, 2017

A generic framework for 5G networks

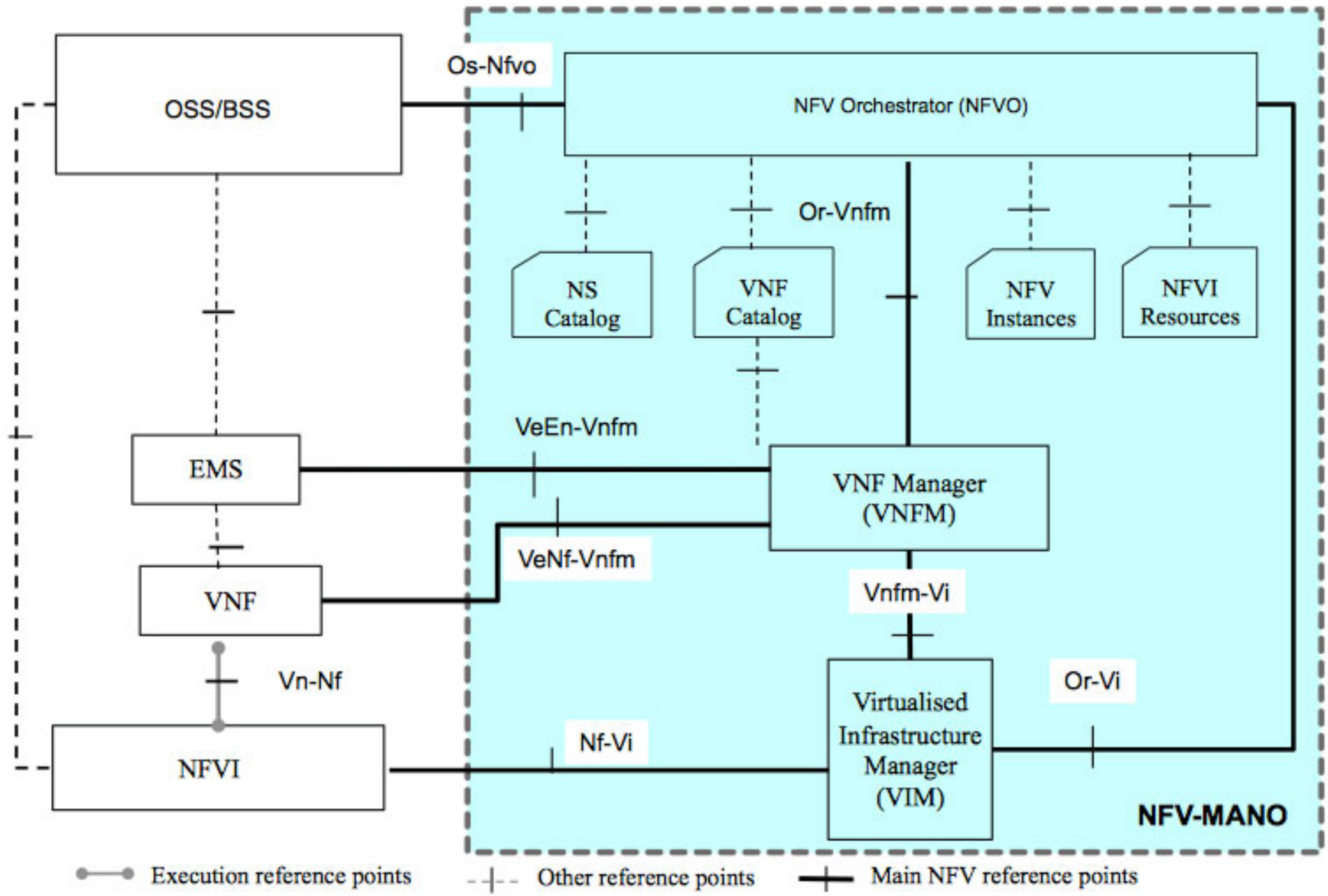


Management and Orchestration Entity (MANO) - I

- It comprises three parts:
  - NFV Orchestrator
  - VNF Manager
  - Virtualized Infrastructure Manager

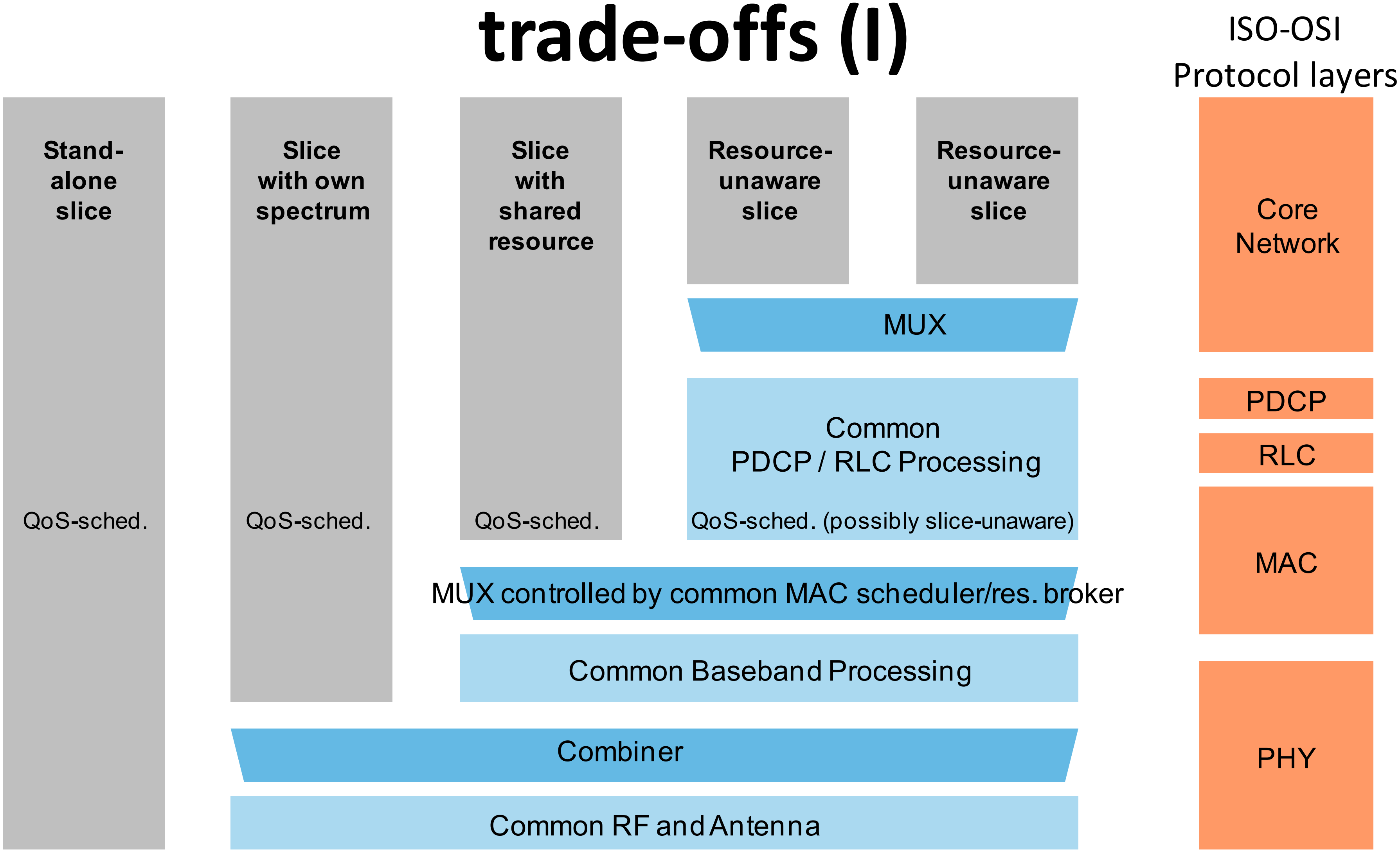
- Translates uses cases and models into services and slices:
  - VNF instantiation
  - VNF chaining
  - Service life cycle management

Management and Orchestration Entity (MANO) - II



ETSI GS NFV-MAN 001 V1.1.1 Network Functions Virtualisation (NFV); Management and Orchestration

Realizing E2E slicing involves several trade-offs (I)

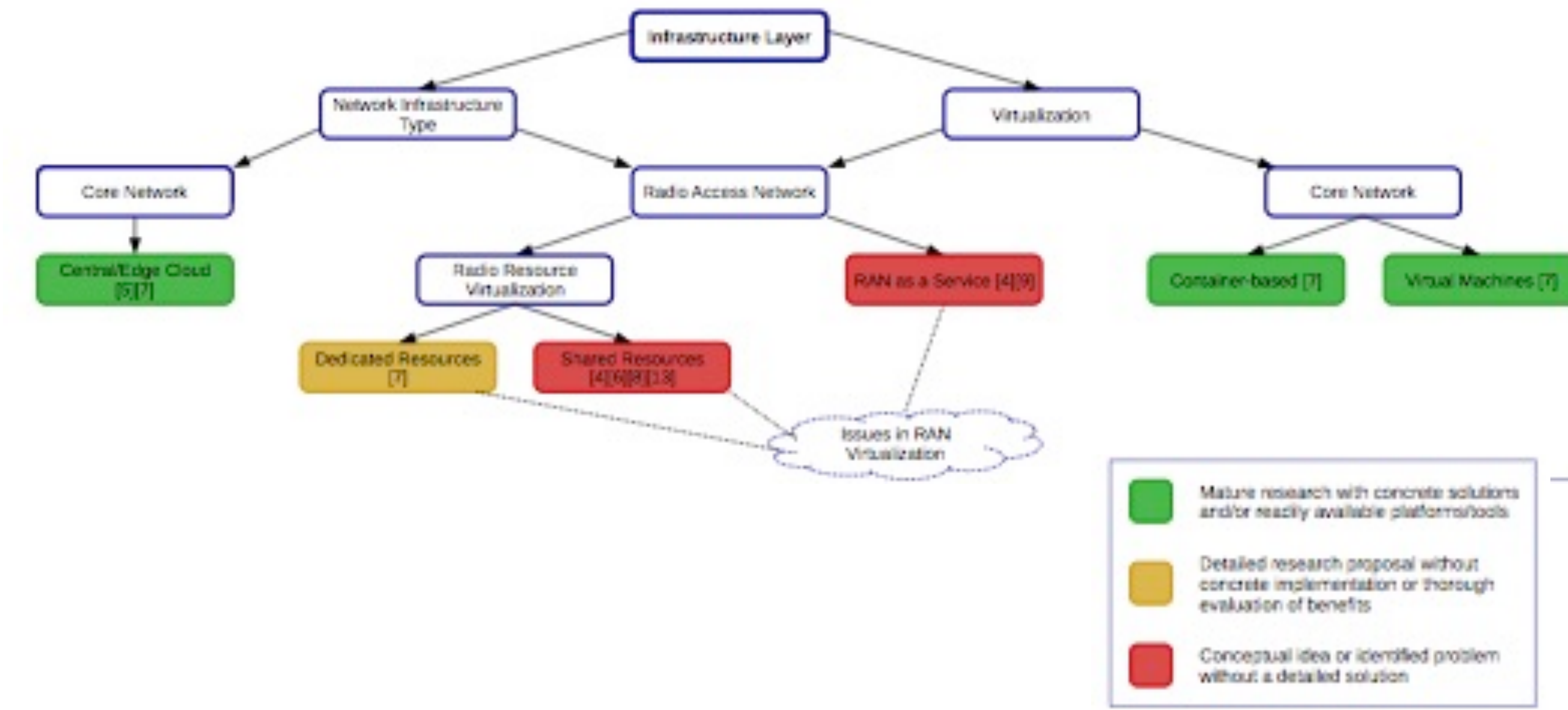


Source: 5G PPP Architecture Working Group - White Paper, Dec, 2017

Realizing E2E slicing involves several trade-offs (II)

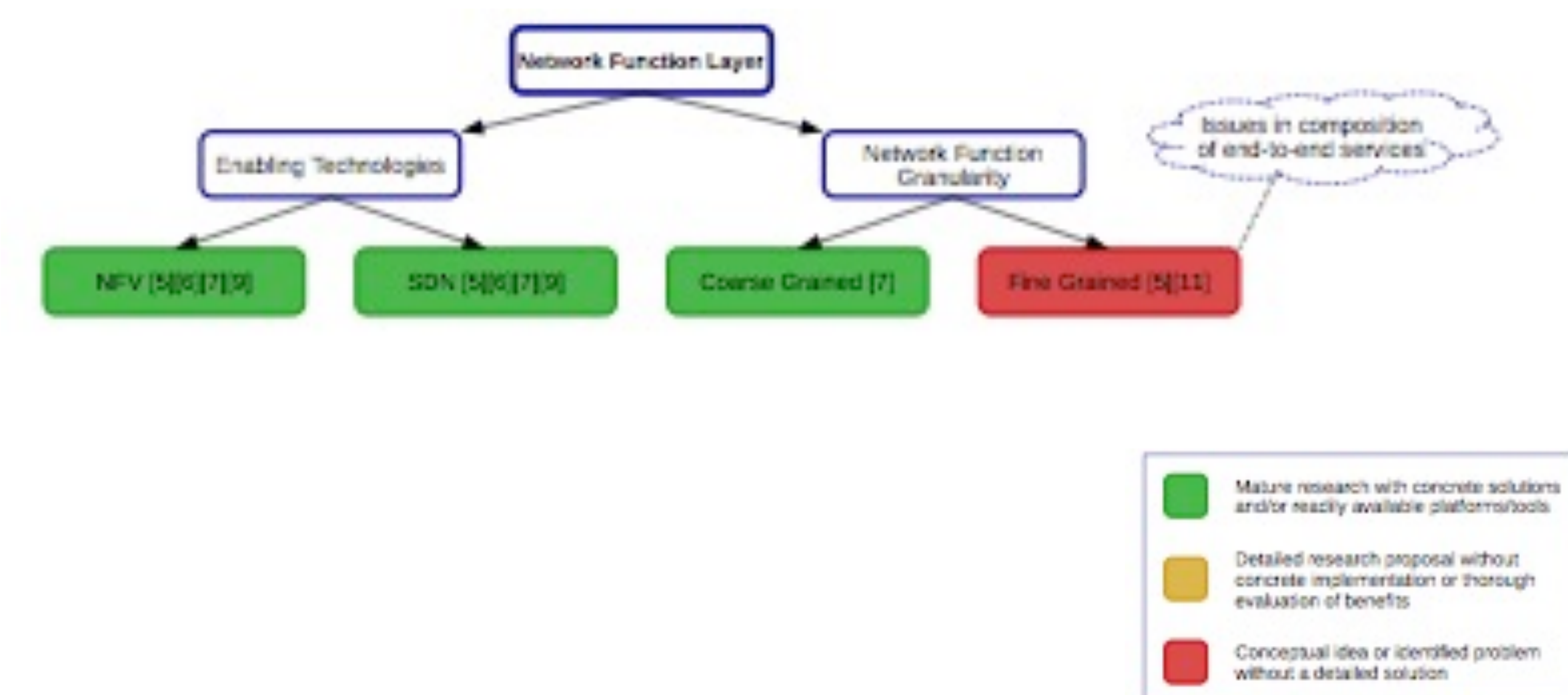
- How to virtualize radio resources?
  - Dedicated vs shared
- What is the proper network function granularity?
  - monolithic vs composable?
- How to describe services?
  - Human readable vs non-human readable

There is no agreement on how to virtualize the RAN



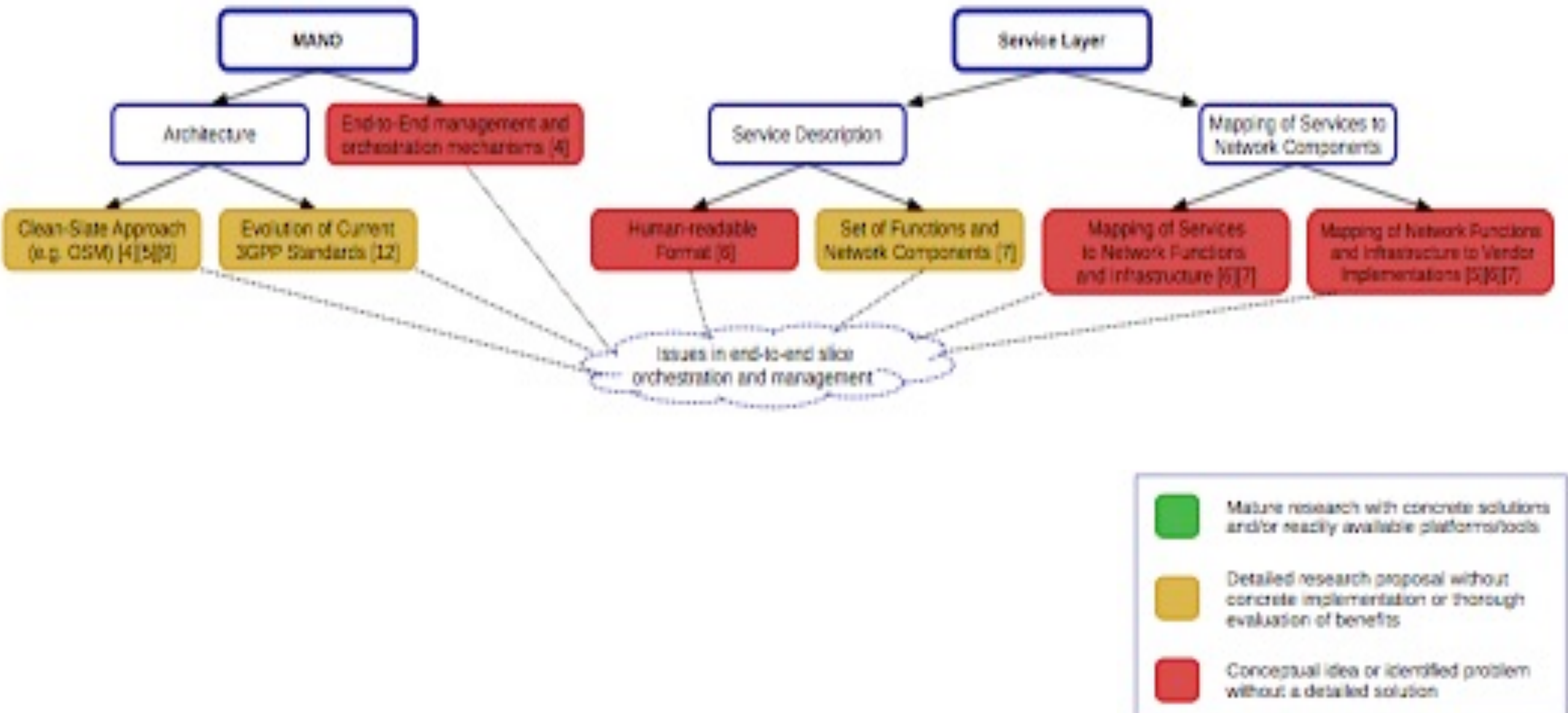
Foukas, X., Patounas, G., Elmokashfi, A., & Marina, M. K. (2017). Network slicing in 5G: Survey and challenges. IEEE Communications Magazine, 55(5), 94-100.

Fine grained function allow for flexible service composition at the expense of increased complexity



Foukas, X., Patounas, G., Elmokashfi, A., & Marina, M. K. (2017). Network slicing in 5G: Survey and challenges. IEEE Communications Magazine, 55(5), 94-100.

The MANO entity is still in the conceptual phase



Foukas, X., Patounas, G., Elmokashfi, A., & Marina, M. K. (2017). Network slicing in 5G: Survey and challenges. IEEE Communications Magazine, 55(5), 94-100.

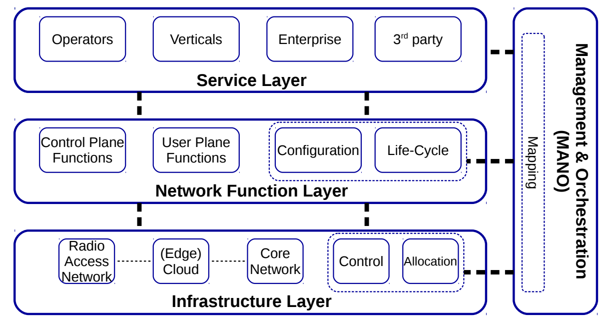
A number of issues must be resolved before implementing E2E slicing fully

- Dynamic and fine-grained spectrum sharing based RAN virtualization
  - Multi-RAT virtualization
  - RAN as a service
- Frameworks and standards for defining granular network functions
- Adaptive and dynamic management and orchestration plane
  - Integrating measurements and control
  - Anticipatory and predictive analytics

Outline

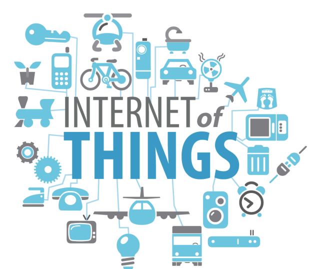
5G vision

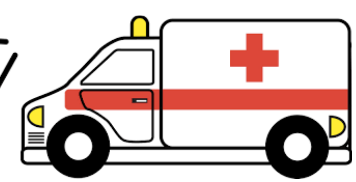
5G realization



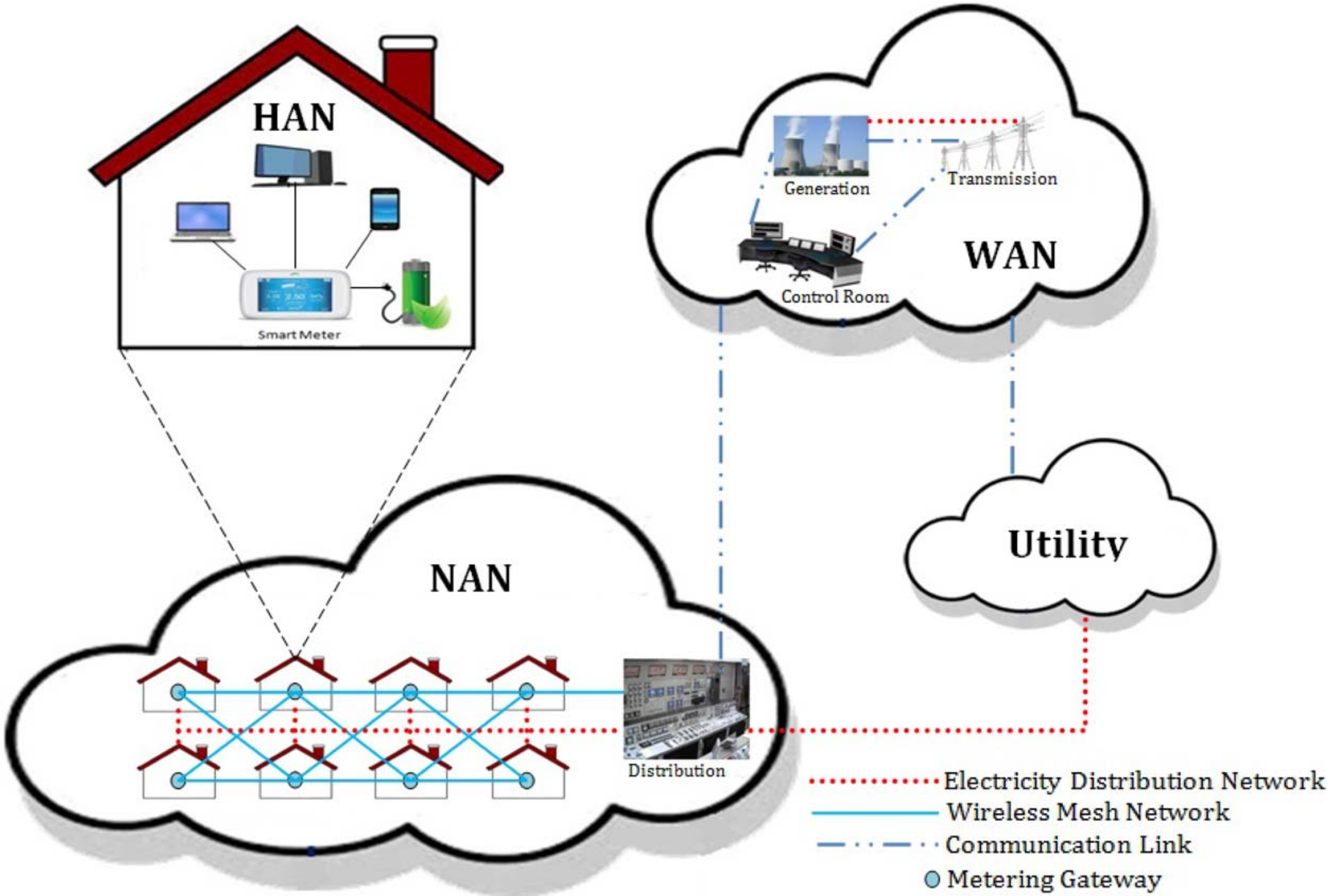
Challenging use cases:

The smart grid as an example



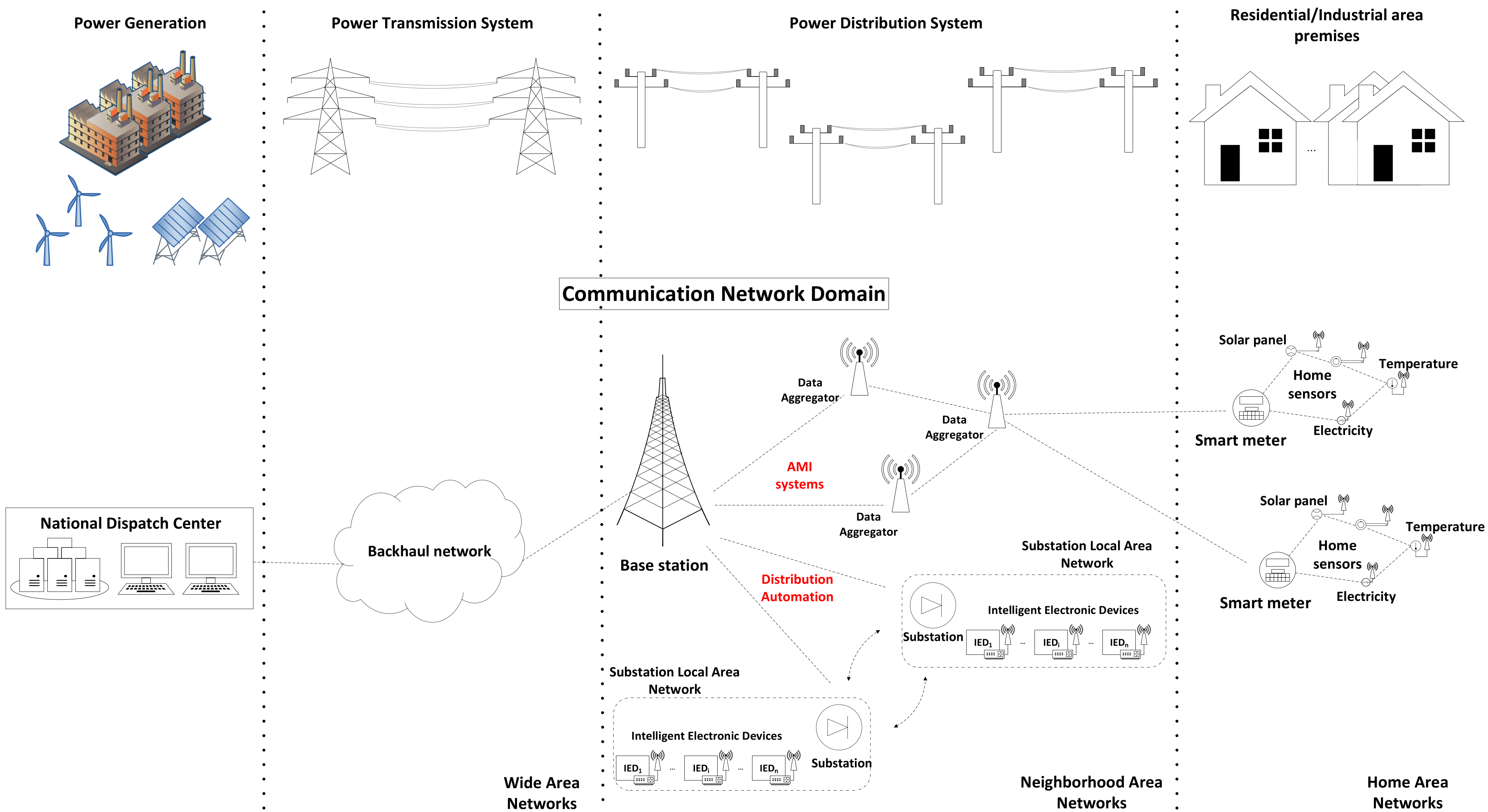


Unlike the traditional power grid, the smart grid is dependent on distributed control



Khan, Athar Ali, Mubashir Husain Rehmani, and Martin Reisslein. "Cognitive radio for smart grids: Survey of architectures, spectrum sensing mechanisms, and networking protocols." IEEE Communications Surveys & Tutorials 18.1 (2016): 860-898.

Distribution automation within NANs is arguably the focal point of the smart grid



Kalalas, Charalampos, Linus Thrybom, and Jesus Alonso-Zarate. "Cellular communications for smart grid neighborhood area networks: A survey." *IEEE Access* 4 (2016): 1469-1493.

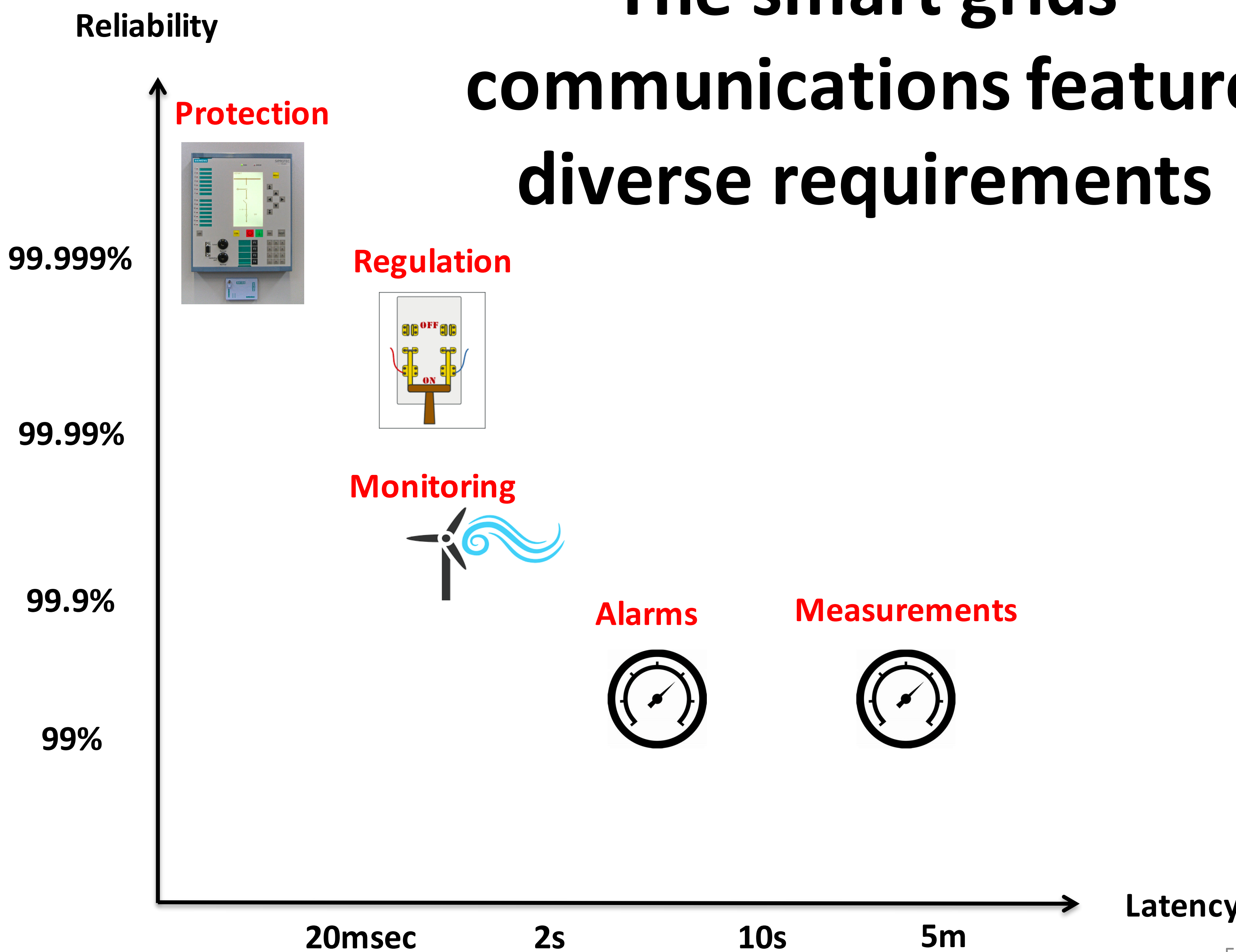
Distribution automation functionalities require reliable interactions between IEDs

- Distributed control and protection
  - Time critical control messaging
  - Fault identification

- Wide-area monitoring system
  - Combine data from Phasor Measurement units

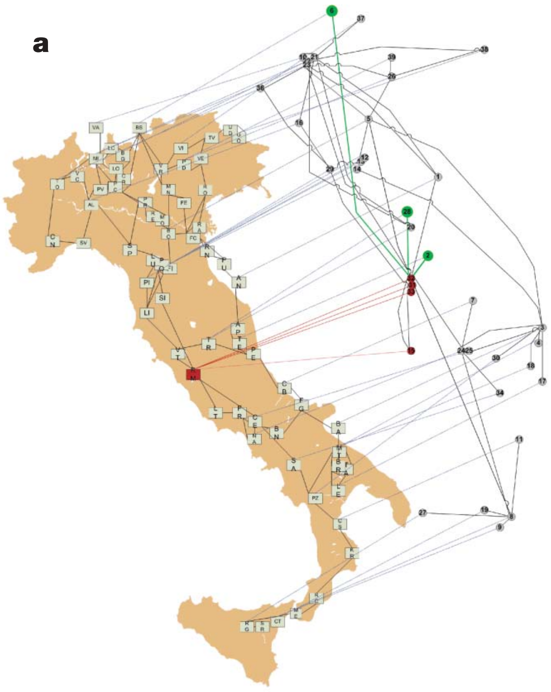
- Real time monitoring of distribution equipment for example capacitor banks, re-closers and switches

The smart grids communications feature diverse requirements



Kuzlu, Murat, Manisa Pipattanasomporn, and Saifur Rahman. "Communication network requirements for major smart grid applications in HAN, NAN and WAN." Computer Networks 67 (2014): 74-88.

A meta-requirement is that the inter-dependence should not increase chances of cascades



Buldyrev, Sergey V., et al. "Catastrophic cascade of failures in interdependent networks." Nature 464.7291 (2010): 1025.

NB-IoT is already being considered for connecting smart meters

Portugal

Belgium

https://www.u-blox.com/en/press-releases/portugal-presents-first-nb-iot-smart-meter
https://www.mobileeurope.co.uk/press-wire/proximus-launches-nb-iot-to-connect-1-3m-smart-meters

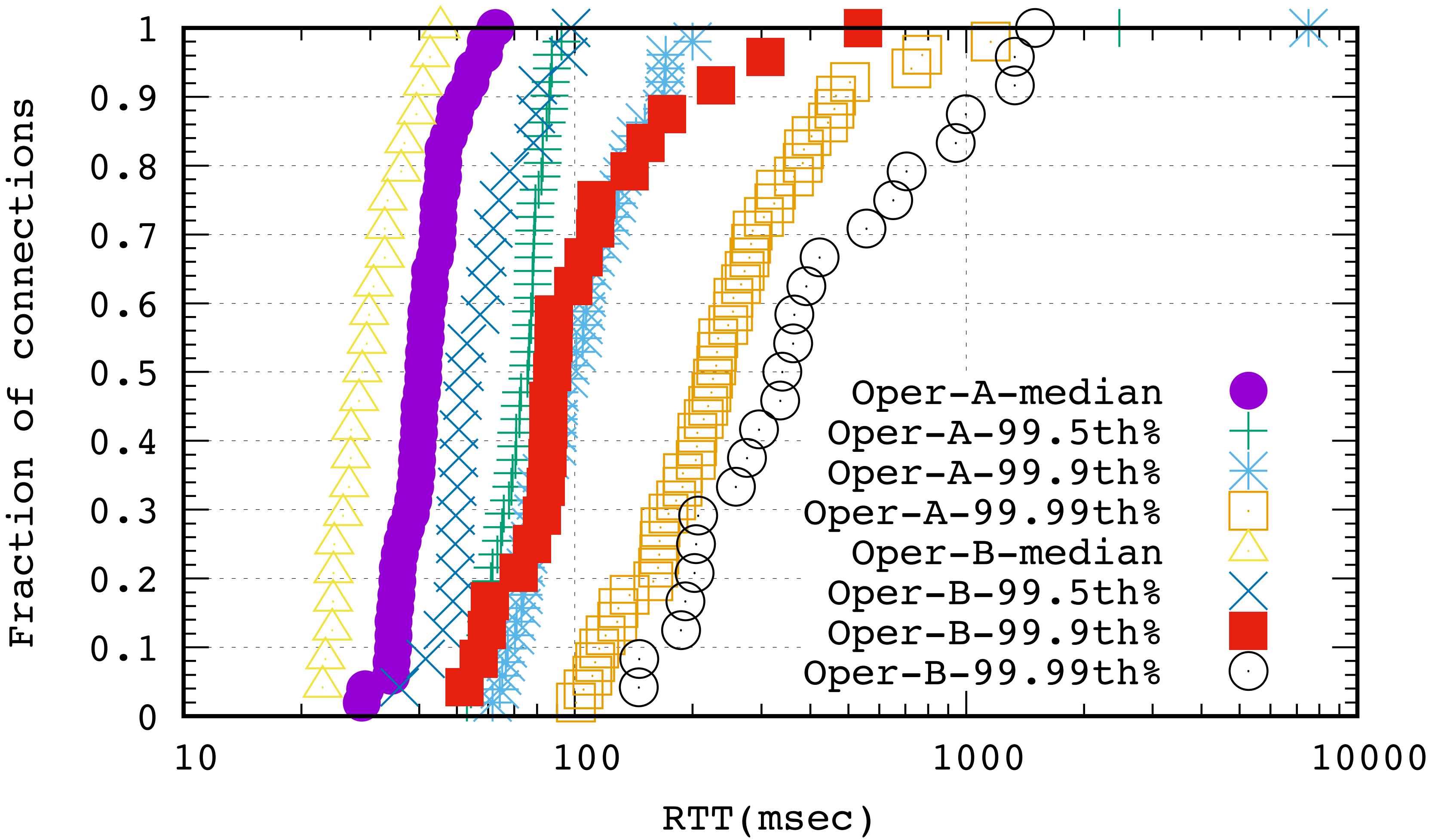
Measurement nodes spread across Norway

About 100 active stationary measurement nodes

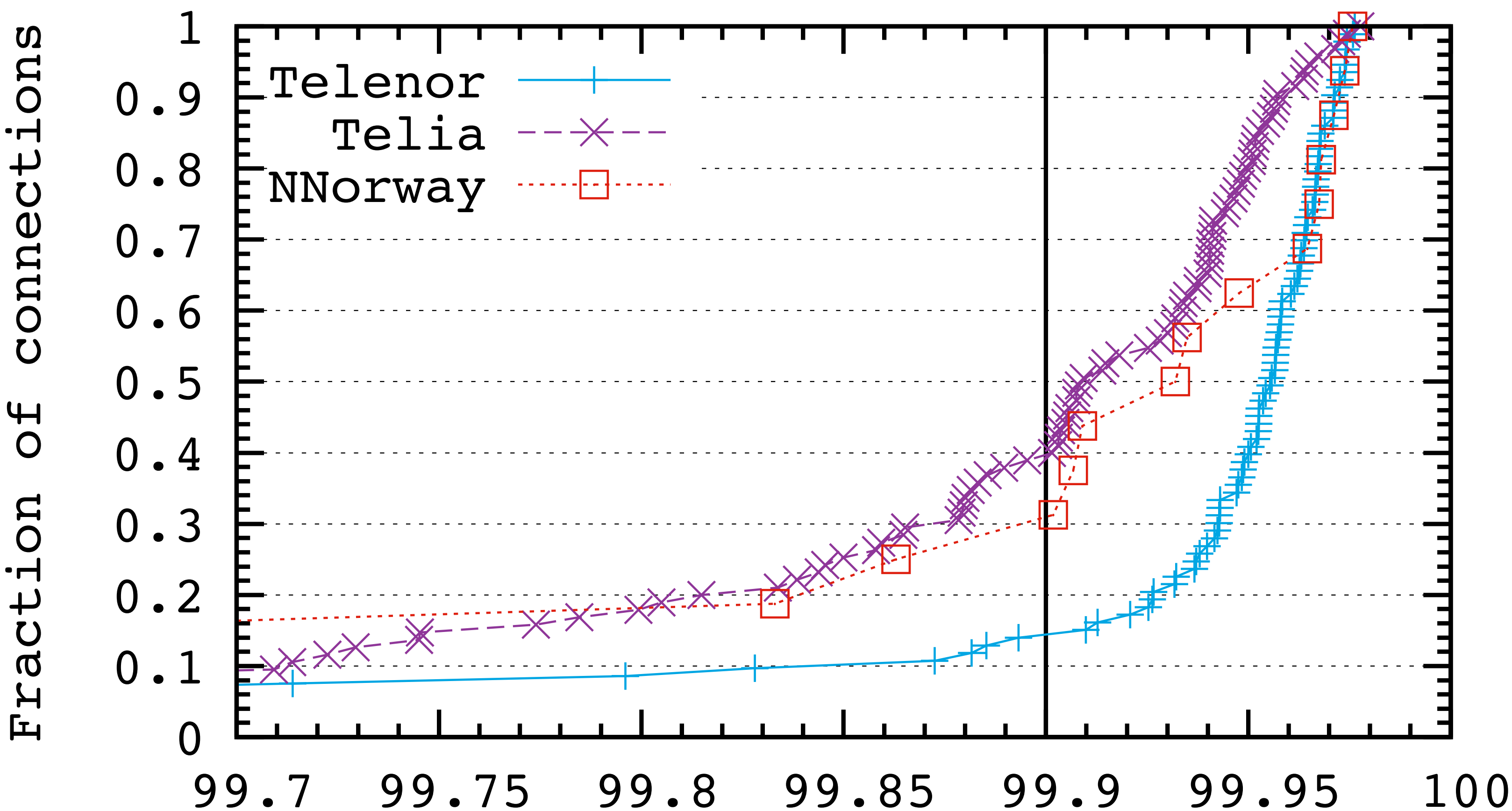
Multi-homed to all major Norwegian MBB operators

Operational since July 2013

LTE networks do not ensure a consistent low delay < 50ms even when stationary

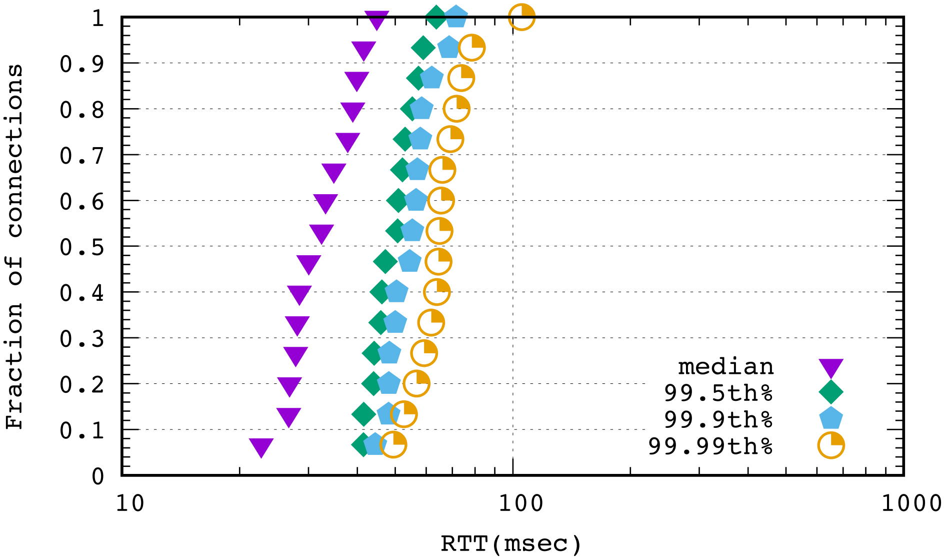


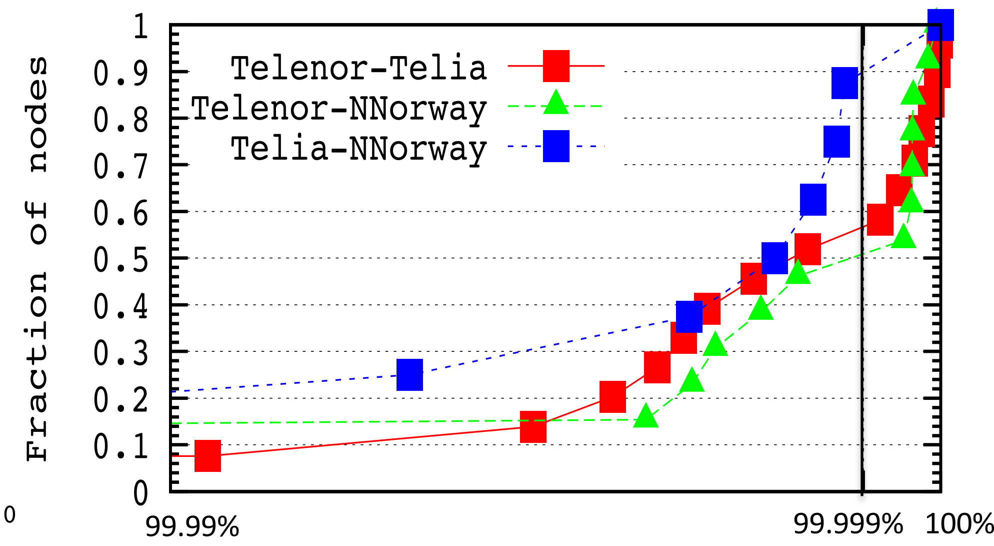
Although LTE networks offer high availability, they do not meet the smart grid requirements



Elmokashfi, Ahmed, Dong Zhou, and Džiugas Baltrūnas. "Adding the next nine: An investigation of mobile broadband networks availability." In MobiCom. ACM, 2017.

Multihoming can help providing consistent delays and availability

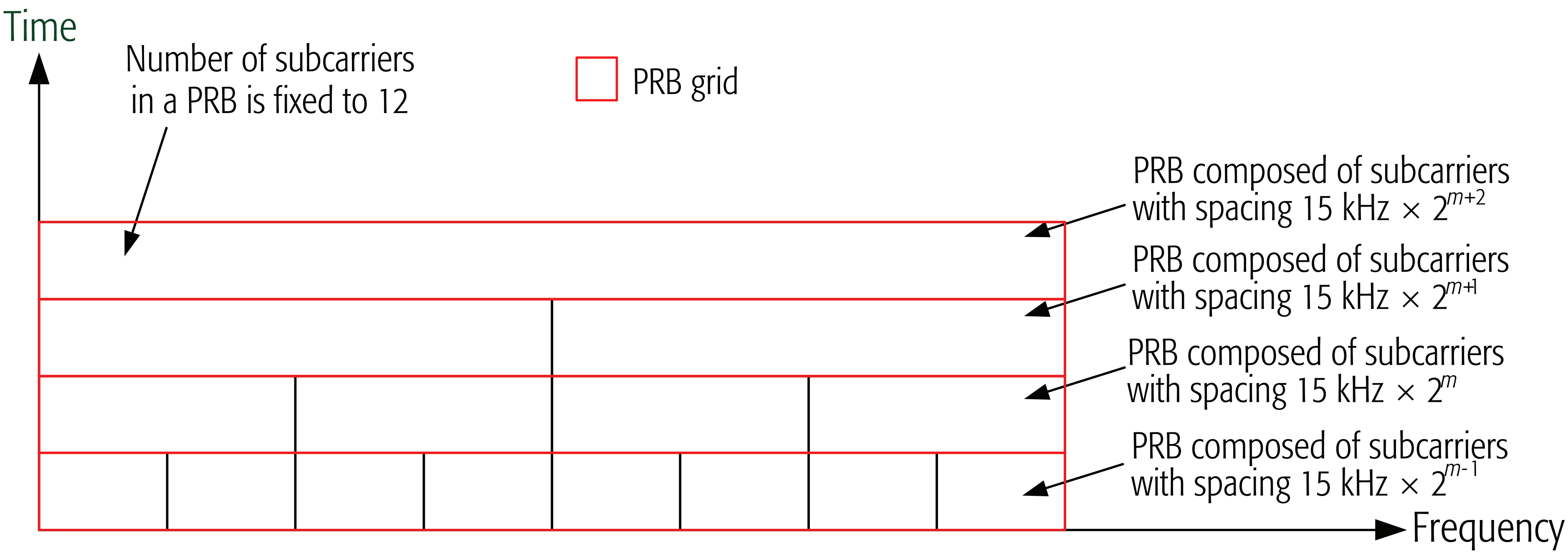




Delays still need to reduced by an order of magnitude

Elmokashfi, Ahmed, Dong Zhou, and Džiugas Baltrūnas. "Adding the next nine: An investigation of mobile broadband networks availability." In MobiCom. ACM, 2017.

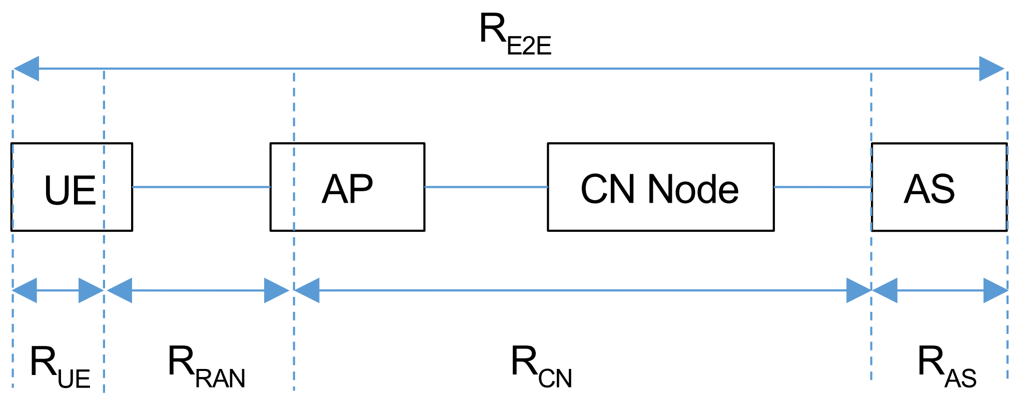
5G NR scalable numerology can significantly reduce the air interface delay

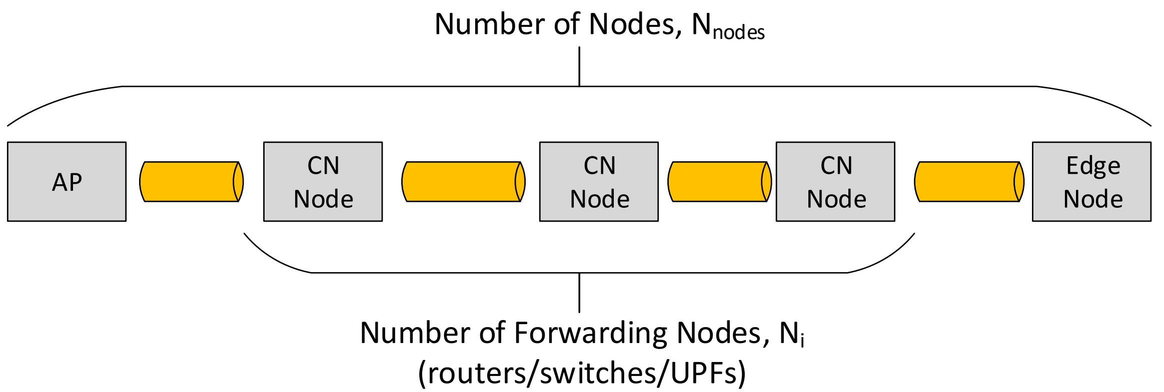


0.5msec sub-frame results in approximately 4msec uplink delay

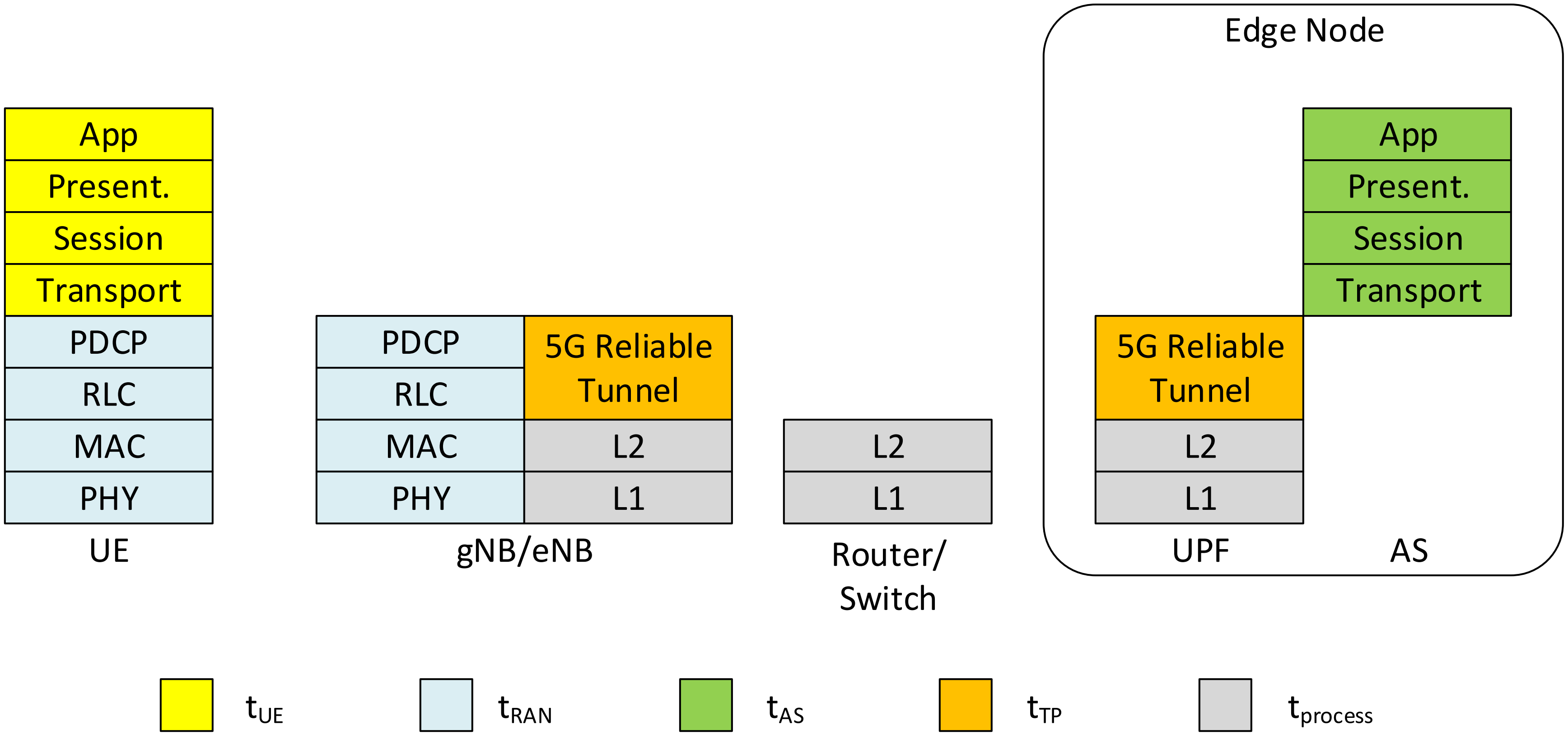
Lien, Shao-Yu, et al. "5G new radio: Waveform, frame structure, multiple access, and initial access." IEEE communications magazine 55.6 (2017): 64-71.

Supporting extreme requirements necessitates an end-to-end consideration



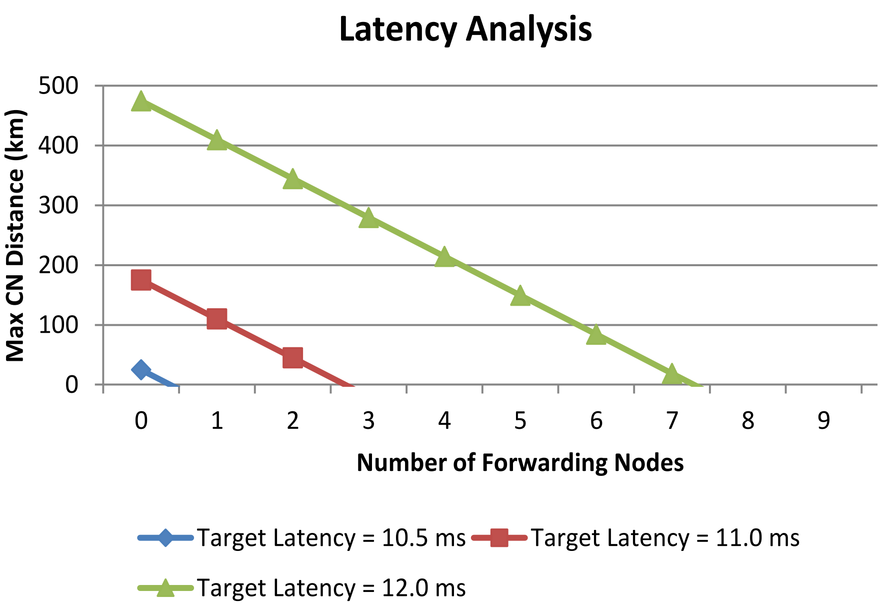


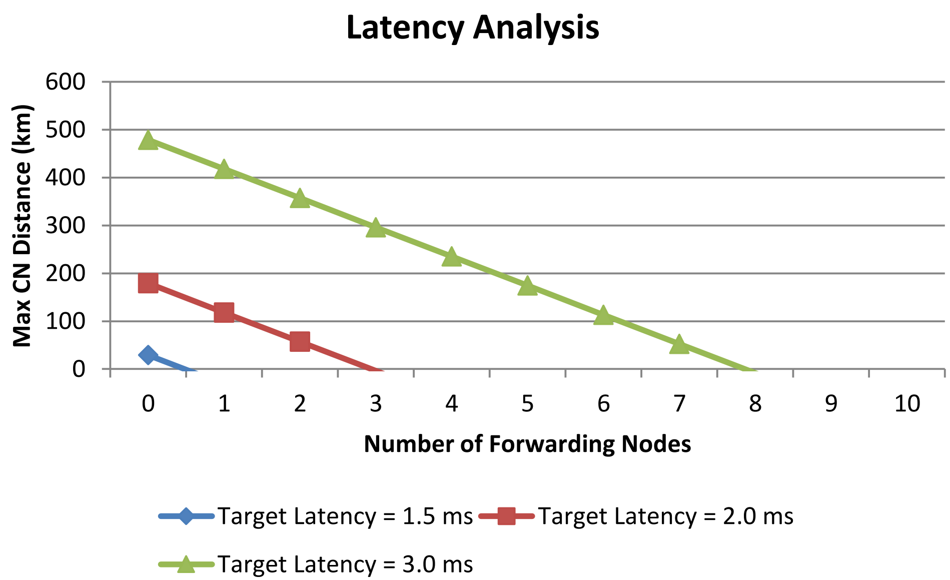
Supporting extreme requirements necessitates an end-to-end consideration



NGMN 5G Extreme Requirements: End-to-End Considerations, Aug 2018

Service placement is central to reliably reducing delay





RAN latency 10msec

RAN latency 1msec

NGMN 5G Extreme Requirements: End-to-End Considerations, Aug 2018

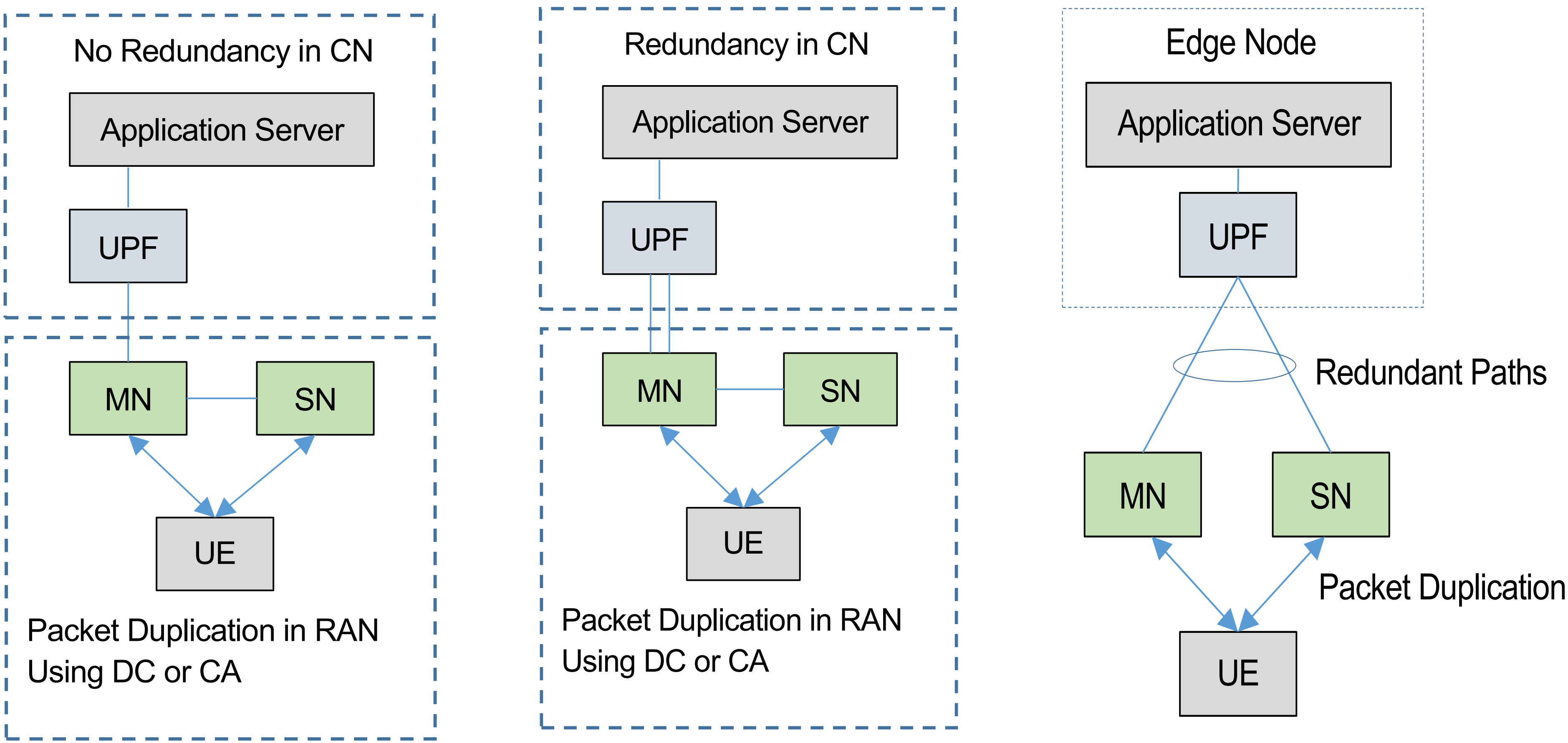
Multi-homing can help relaxing reliability requirements on individual paths

Single path reliability	Path Redundancy	Overall Reliability
90.000%	6	99.999900%
99.000%	3	99.999900%
99.900%	2	99.999900%
99.990%	2	99.999999%
99.999%	2	100.000000%

- Inherent tradeoff between resource efficiency and added reliability
- Informed selective duplication can boost reliability and constrain resource usage
  - Duplications during handover
  - Duplications upon interference/congestion detection

NGMN 5G Extreme Requirements: End-to-End Considerations, Aug 2018

There is a need to evaluate different approaches to redundancy



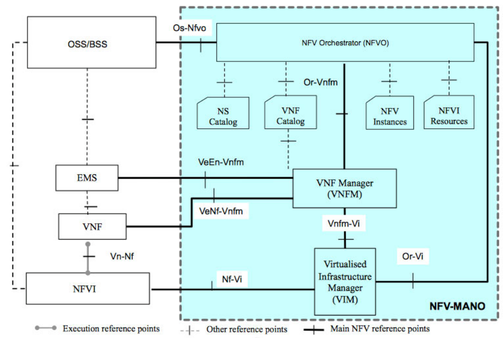
NGMN 5G Extreme Requirements: End-to-End Considerations, Aug 2018

5G vision is very ambitious. The main blocks are being worked out, but key challenges remain

There is a need for building adaptive, carrier grade, infrastructure agnostic VNFs

SDN
+
NFV

To fully realize dynamic slicing, the MANO must go beyond the basic instantiation of VNFs



Supporting extreme requirements mandates taking an E2E approach to improving reliability