5G: An Evolution Towards a Revolution

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Roadmap

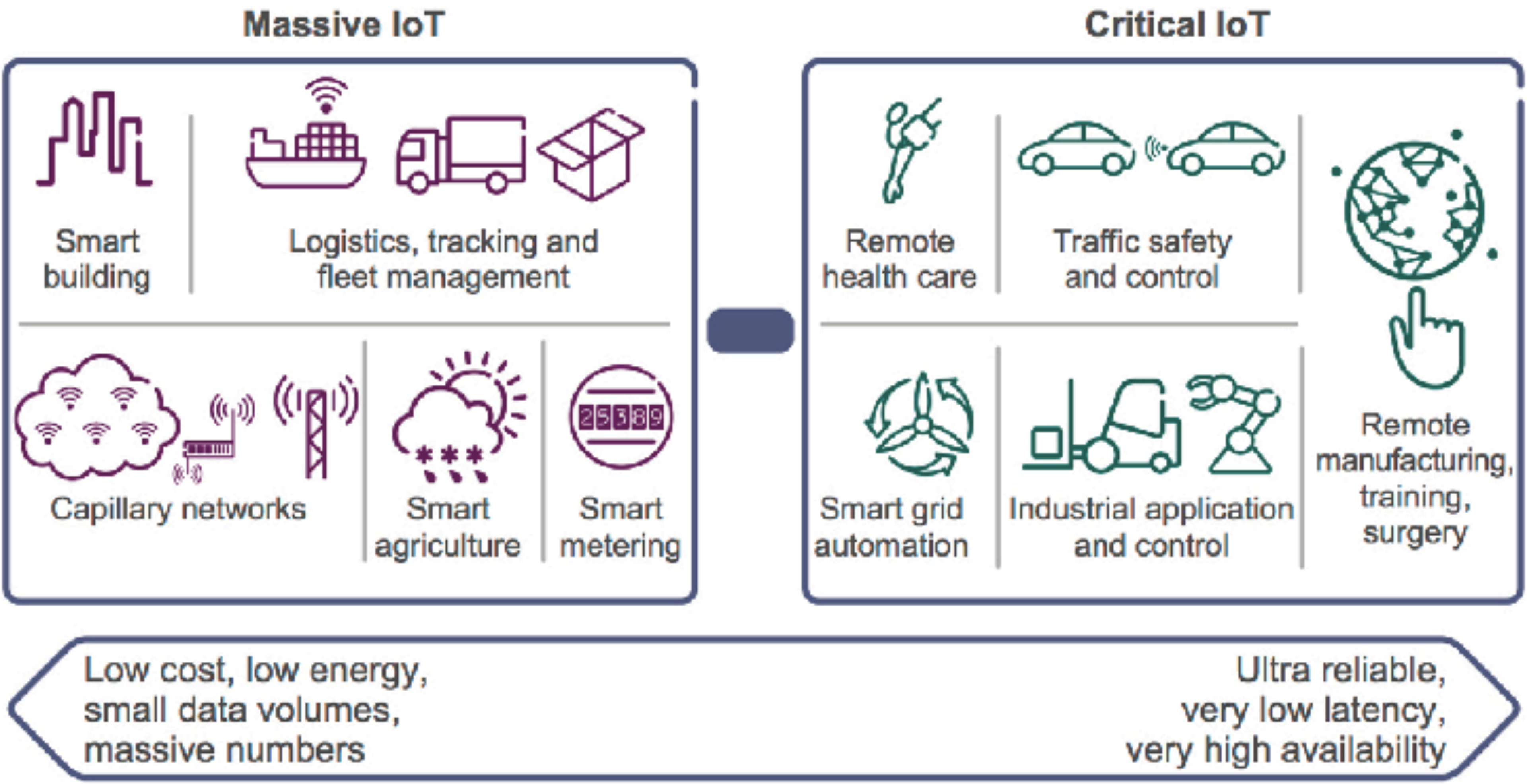
- Drivers of 5G
  - Single network caters to diverse use cases, which is revolutionary
- Building Blocks: Evolution at Multiple Layers
  - Radio
  - Access
  - Network
  - Computing
- Case Studies
  - SDN in wireless access
  - Mobile augmented reality through edge computing
  - LTE in the Sky: UAVs for on-demand LTE connectivity

Diverse 5G Services

e network requirements fo

Source: Ericcson

IoT Proliferation



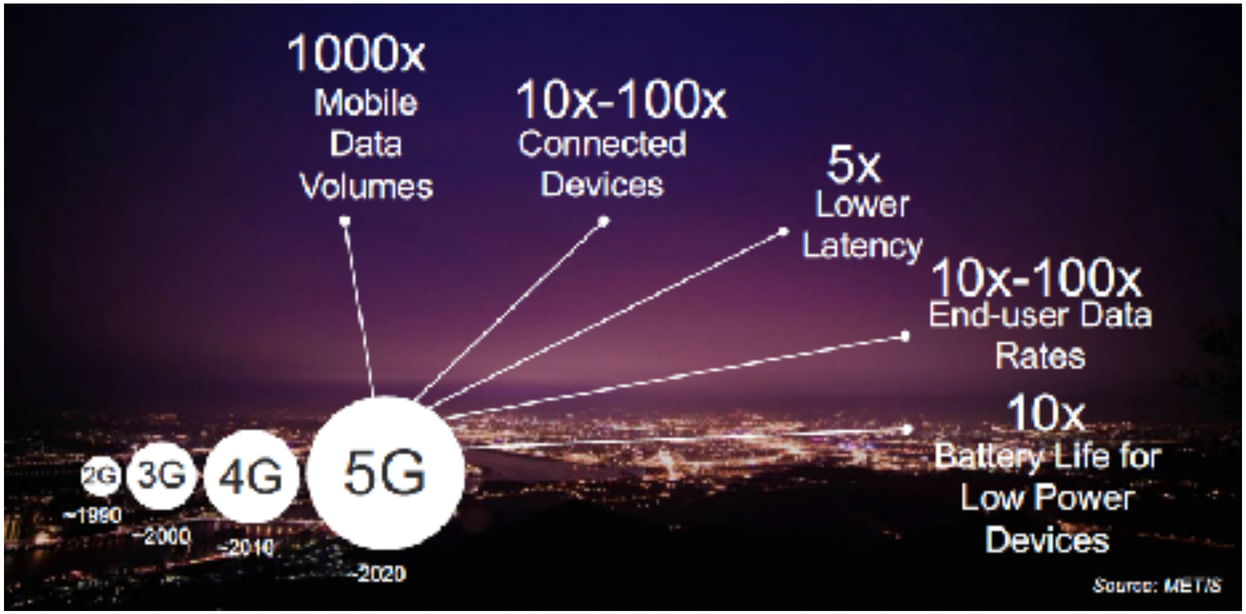
Source: Ericsson W.P. on IoT

New Opportunities

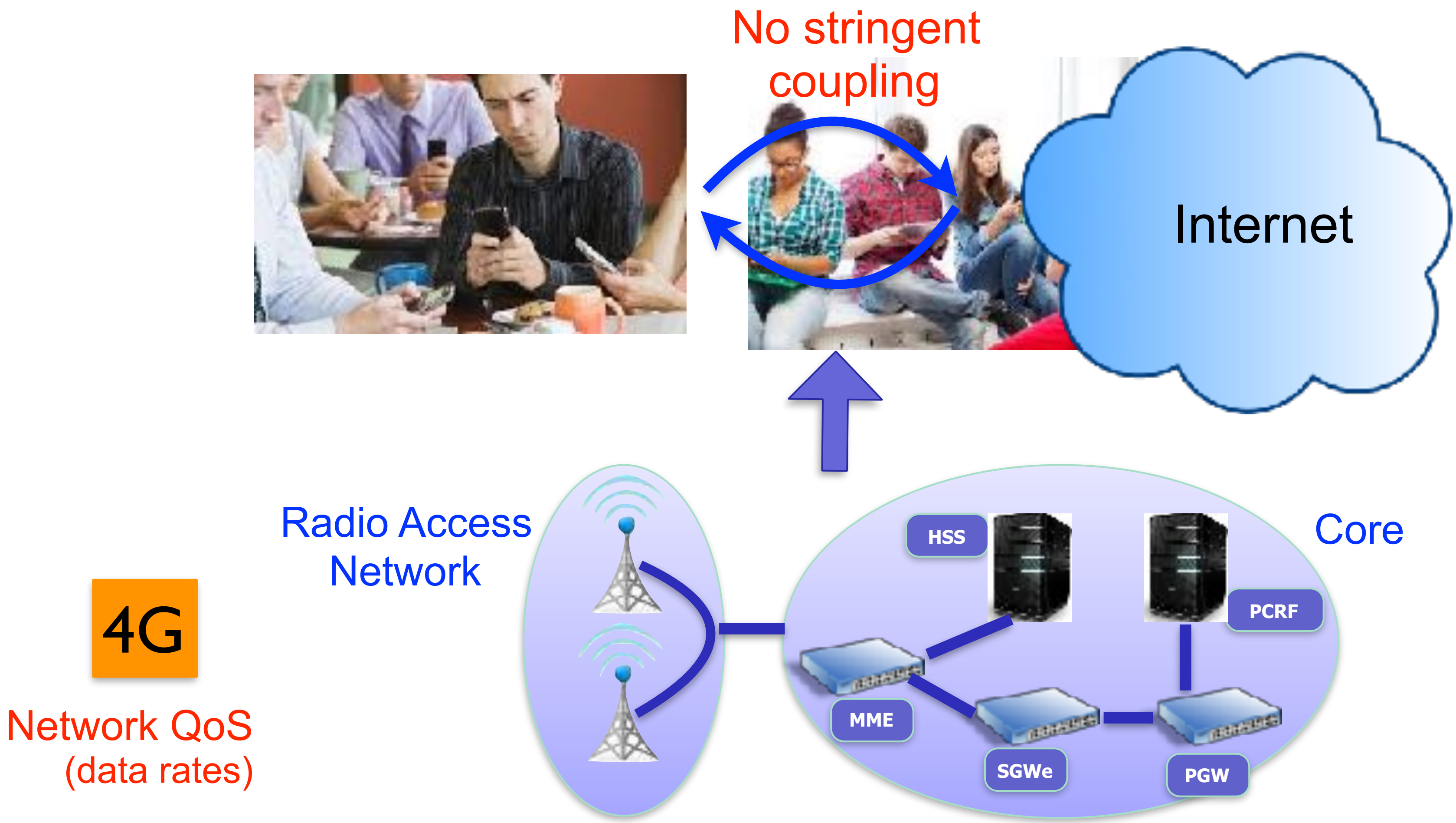
Source: Qualcomm

Optimization across Multiple Dimensions

- Services drive multi-dimensional network requirements for 5G



4G: Today …



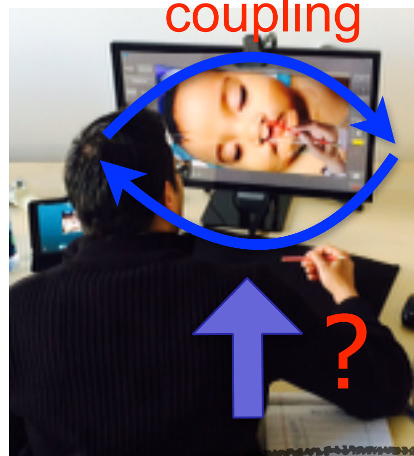
- Consumers/creators of content (audio, video, data)
- Today’s 4G (LTE, WiFi) networks focus on data rates

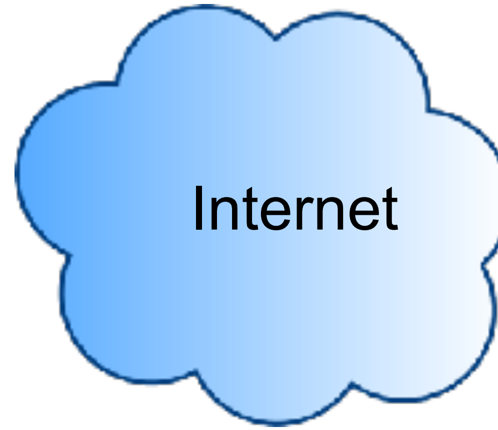
5G: Heading Towards …

User Recreation

Remote Surgery

Real-time coupling

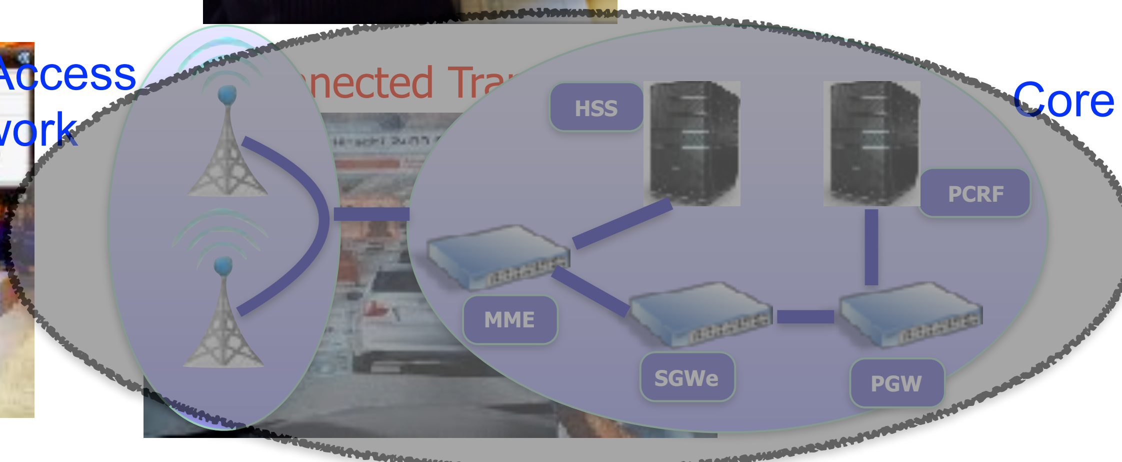




Industrial Automation

User QoE
(data rates, latency, energy scalability, reliability)

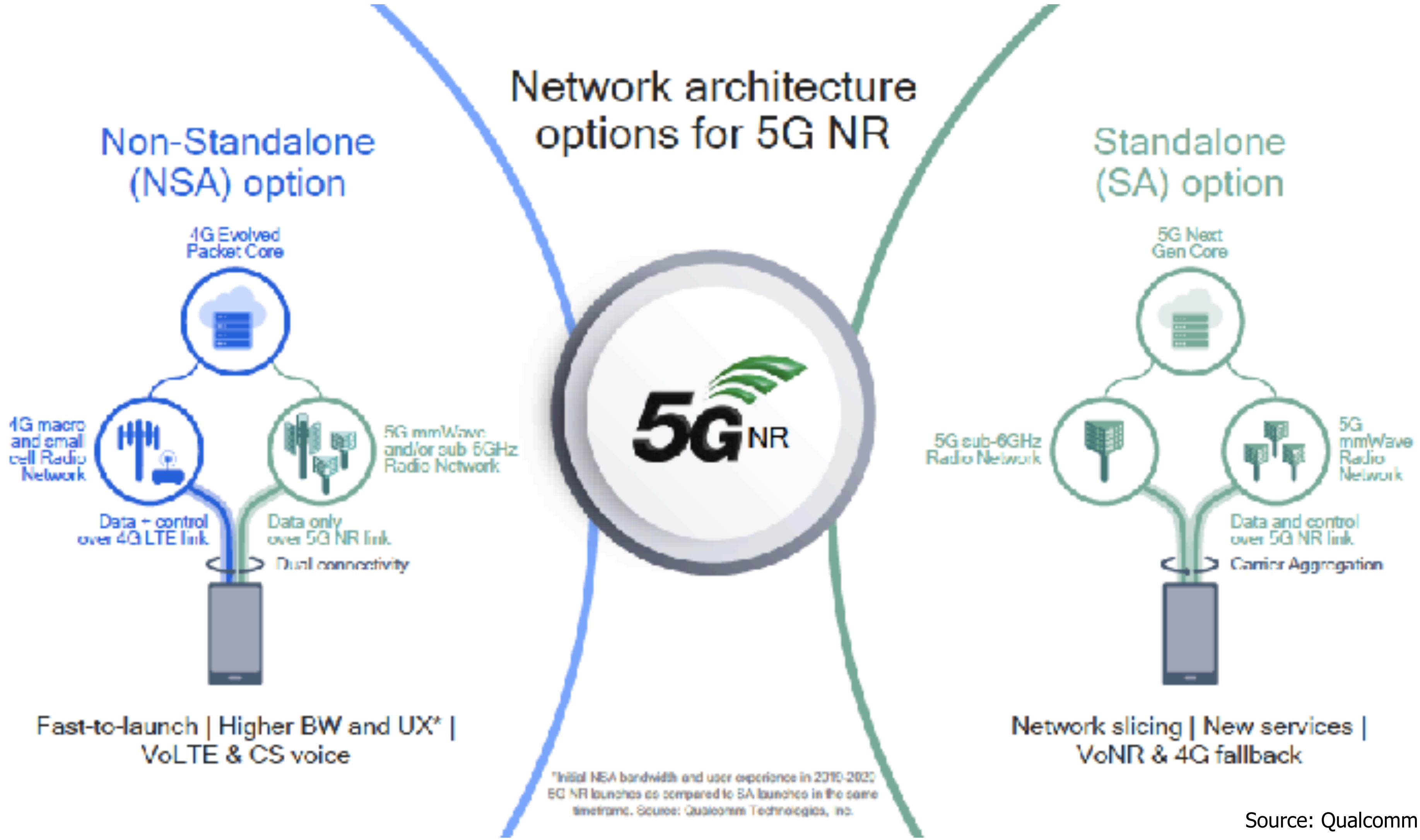
Radio Access Network



- Internet of Users/Things: Disruptive in multiple domains

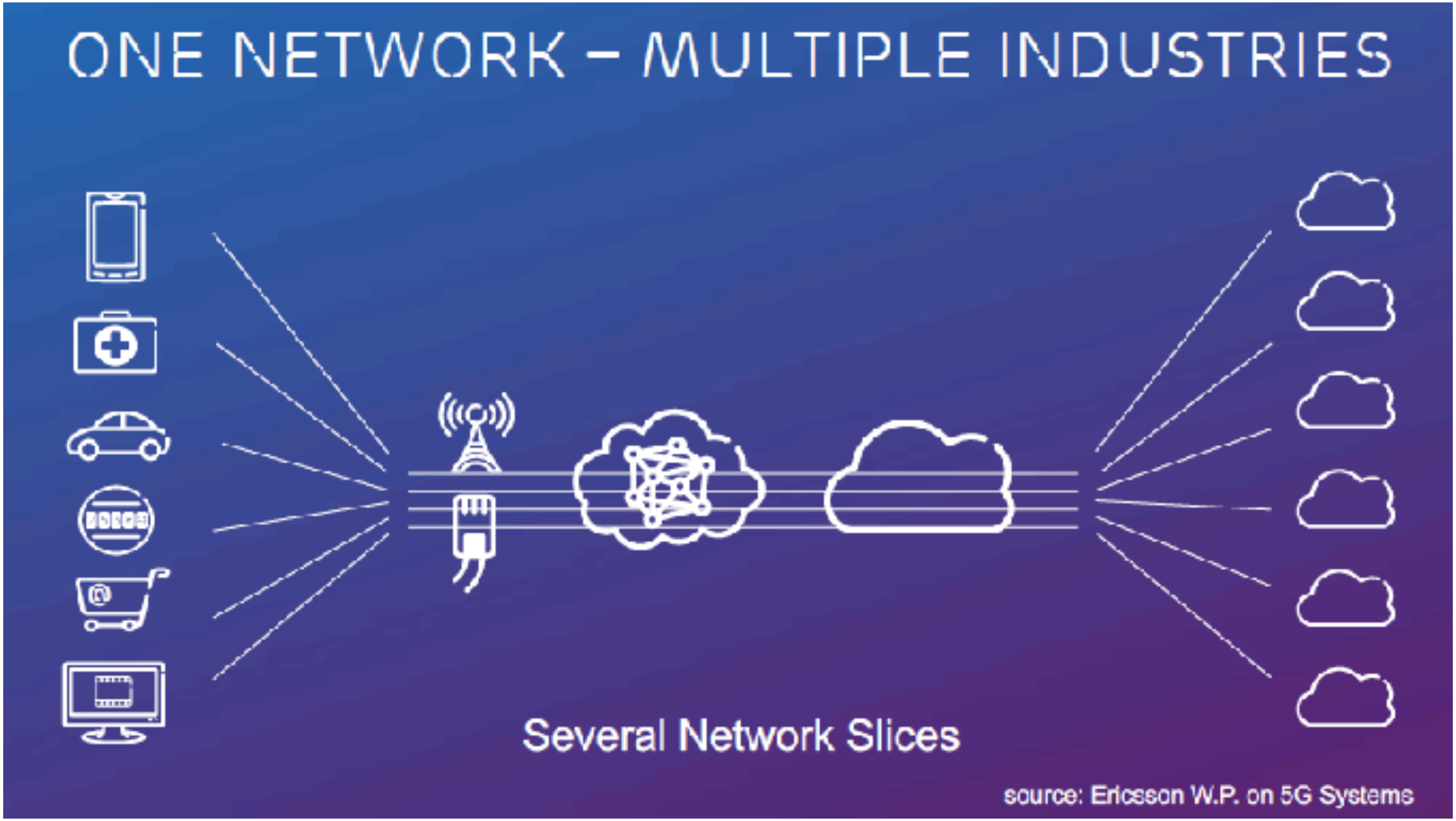
How should a single wireless network evolve to deliver these revolutionary user experiences and services?

5G Architecture Evolution



Source: Qualcomm

5G Vision



- Wireless network (RAN + core) plays a critical role in this vision

Evolution at Multiple Layers

Radio	New Radio (NR), flexible OFDM numerology, mmWave, massive MIMO, advanced coding
Access	IoT-optimized access, hybrid/dynamic spectrum access
Network	Cloud-RAN deployments, SDN, network slicing
Computing	NFV for scalable core design, mobile edge computing

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- Case Studies
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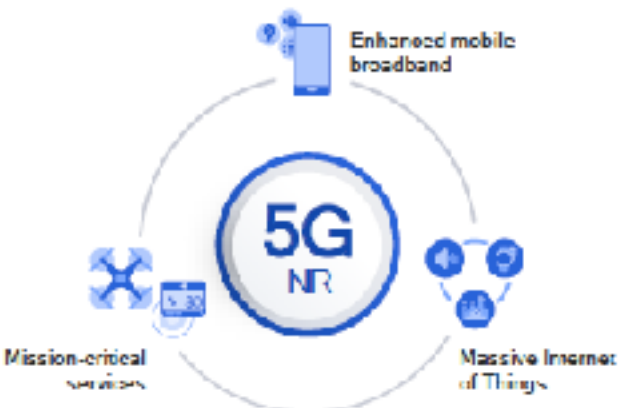
(I) Radio (New Radio, NR)

Scalable OFDM interface, Advanced channel coding, Massive MIMO, mmWave

A Unified 5G Interface



Diverse services

Scalability to address an extreme variation of requirements

Diverse spectrum

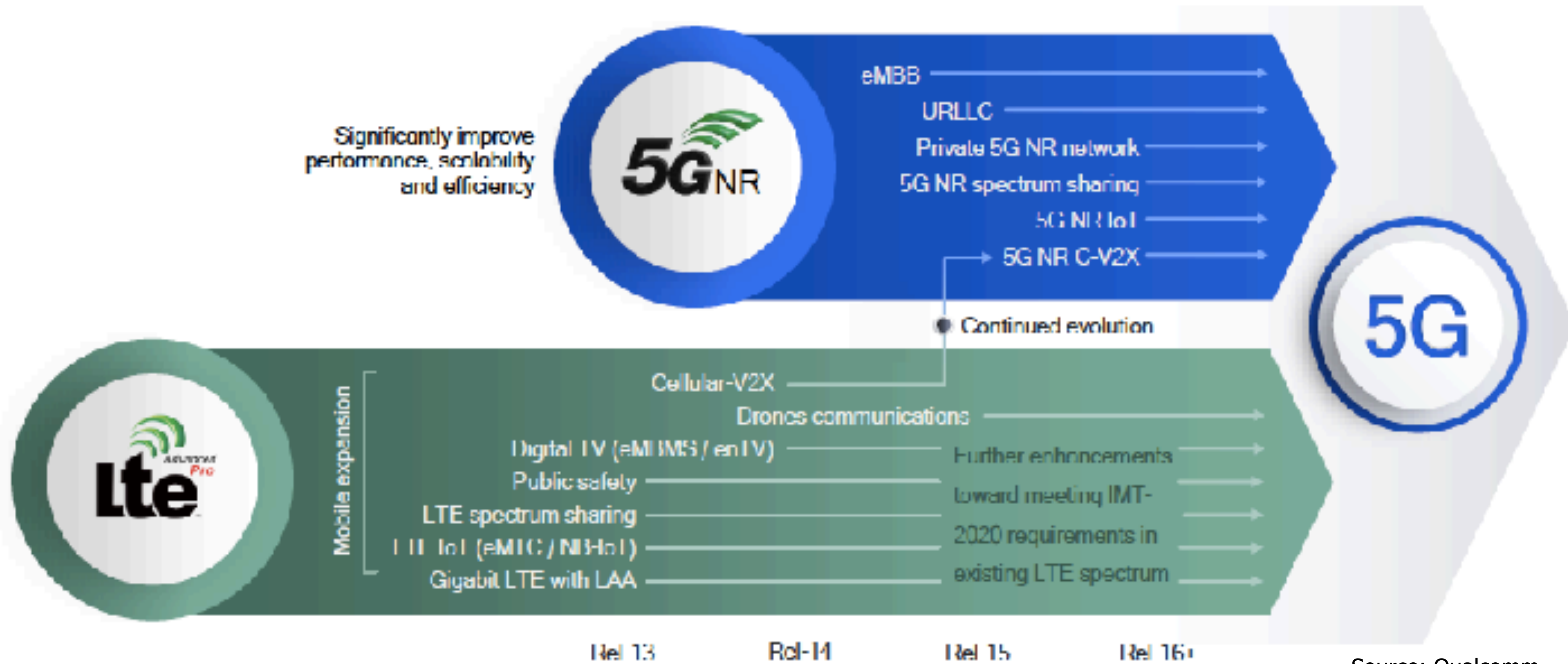
Getting the most out of a wide array of spectrum bands/types

Diverse deployments

From macro to indoor hotspots, with support for diverse topologies

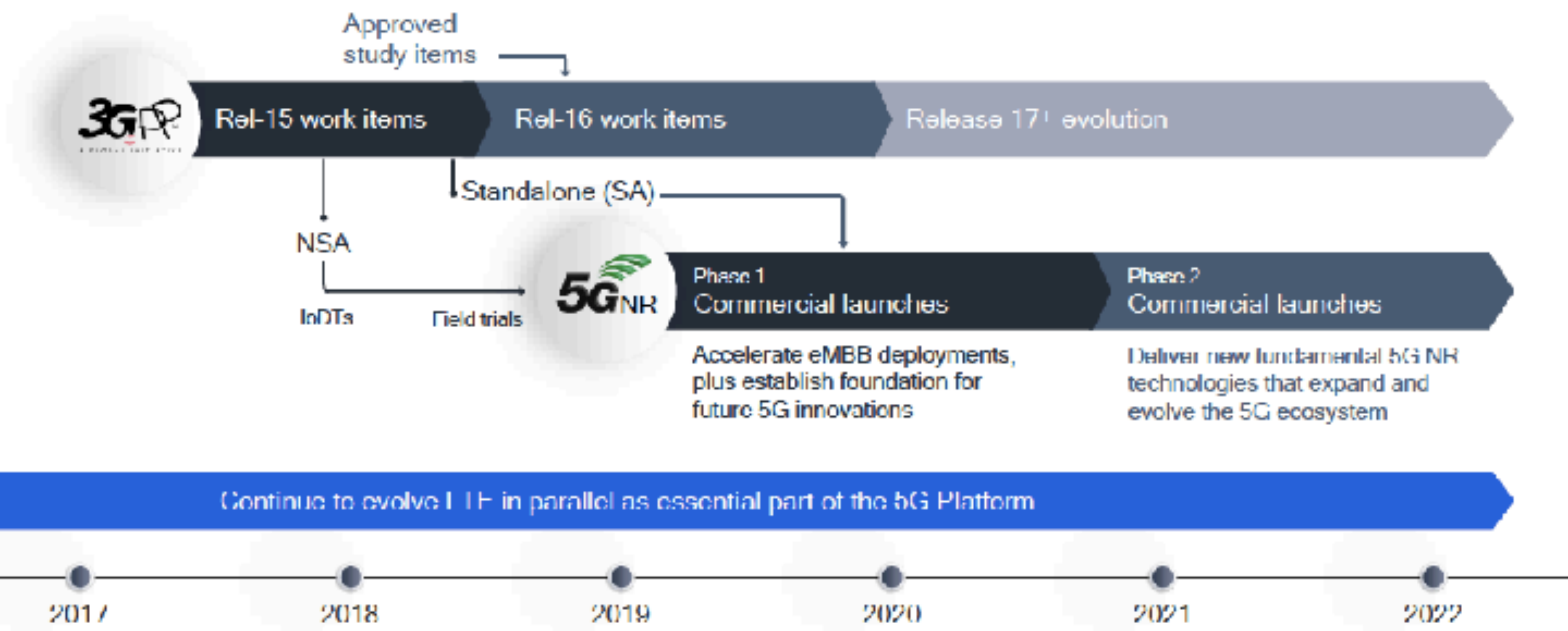
Source: Qualcomm

Seamless Convergence to 5G



Source: Qualcomm

Standardization Status

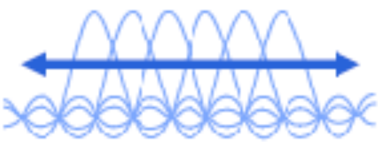


Source: Qualcomm

- LTE and 5G NR will evolve in parallel

Key Components of NR

Scalable OFDM-based air interface



Scalable OFDM numerology

Efficiently address diverse spectrum, deployments/services

Advanced channel coding

Multi-Edge LDPC and CRC-Aided Polar

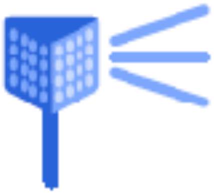
Efficiently support large data blocks and a reliable control channel

Massive MIMO

Reciprocity-based MU-MIMO

Efficiently utilize a large number of antennas to increase coverage/capacity

Mobile mmWave

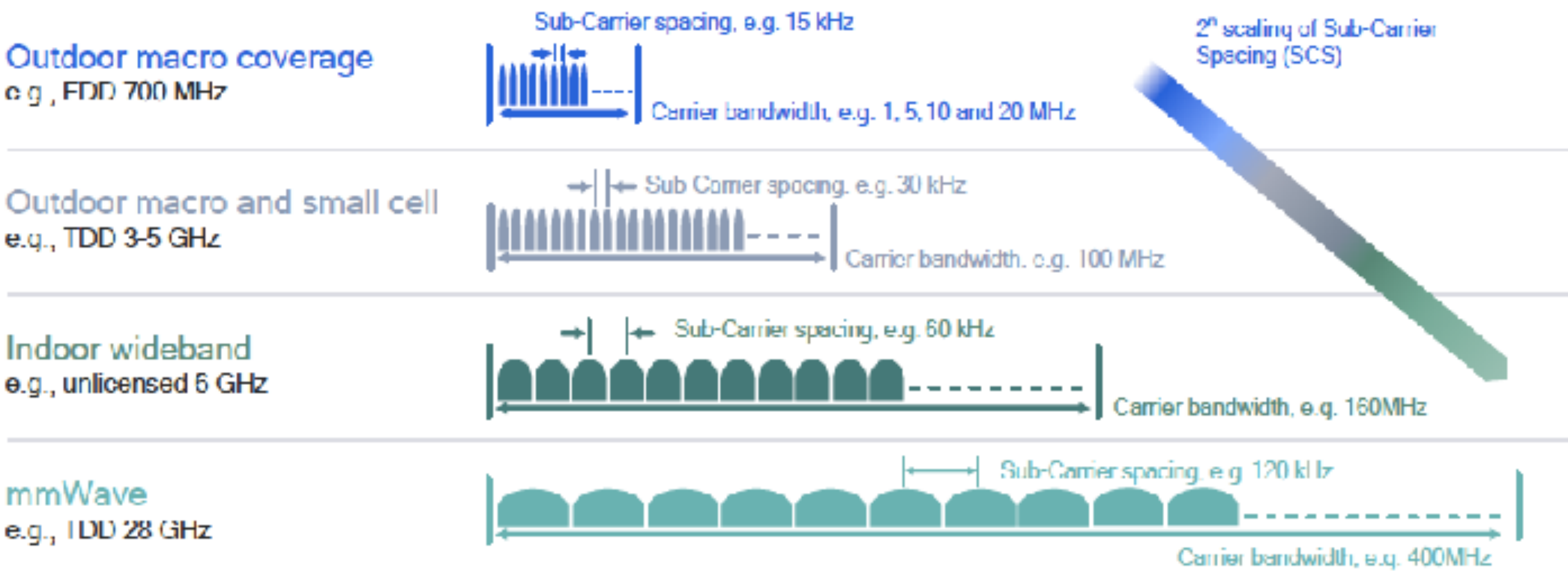


Beamforming and beam-tracking

Enables wide mmWave bandwidths for extreme capacity and throughput

Source: Qualcomm

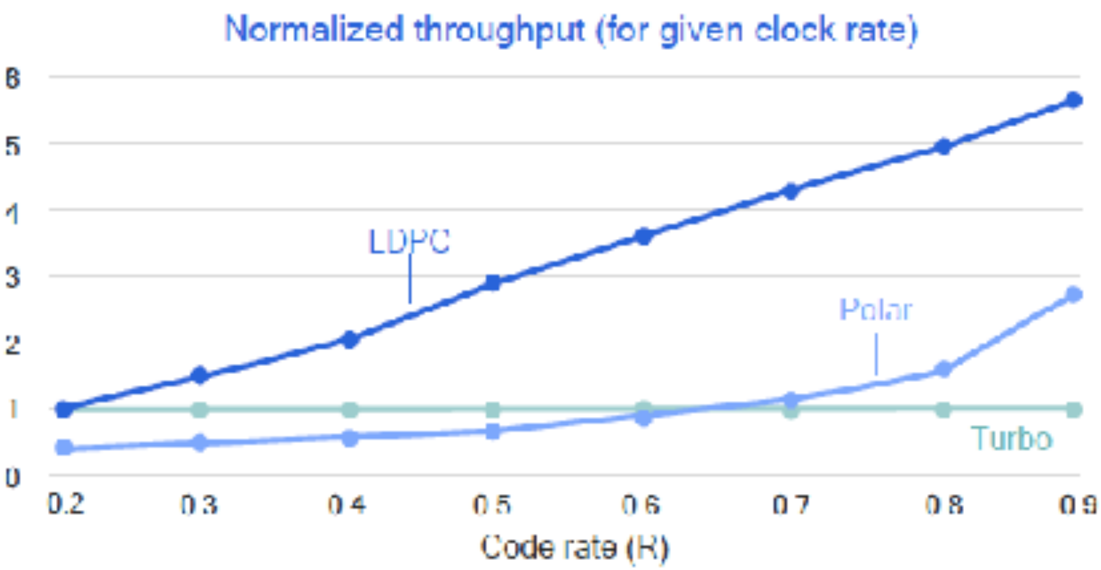
Scalable OFDM Numerology



Source: Qualcomm

- Scaling reduces FFT processing complexity for wider bandwidths while reusing hardware
- Serves diverse 5G deployment scenarios

Advanced Multi-edge LDPC Coding



Source: Qualcomm

High efficiency

Significant gains over LTE Turbo–particularly for large block sizes suitable for MBB

Low complexity

Easily parallelizable decoder scales to achieve high throughput at low complexity

Low latency

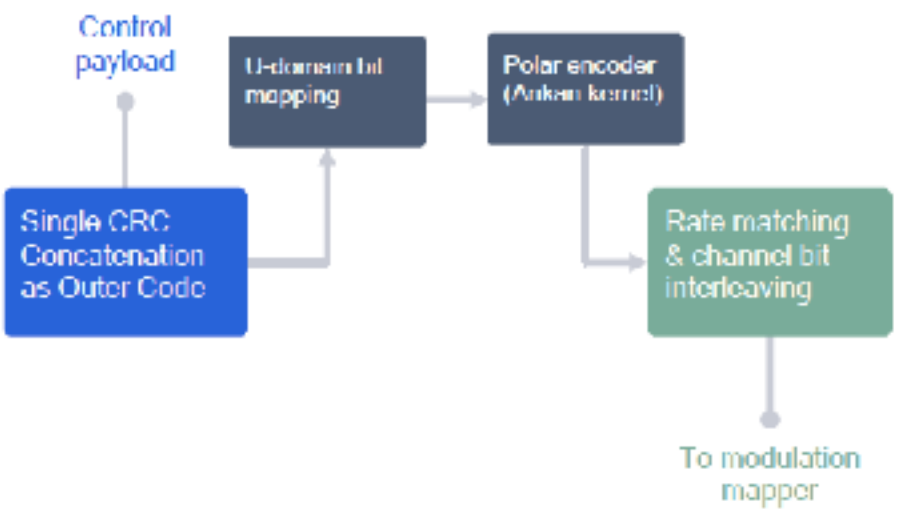
Efficient encoding/decoding enables shorter transmission time at high throughput

- High efficiency at low complexity and latency
- Useful as 5G targets high throughput transmissions
- Selected for 5G NR eMBB data channel in Rel-15

CRC-aided Polar Codes

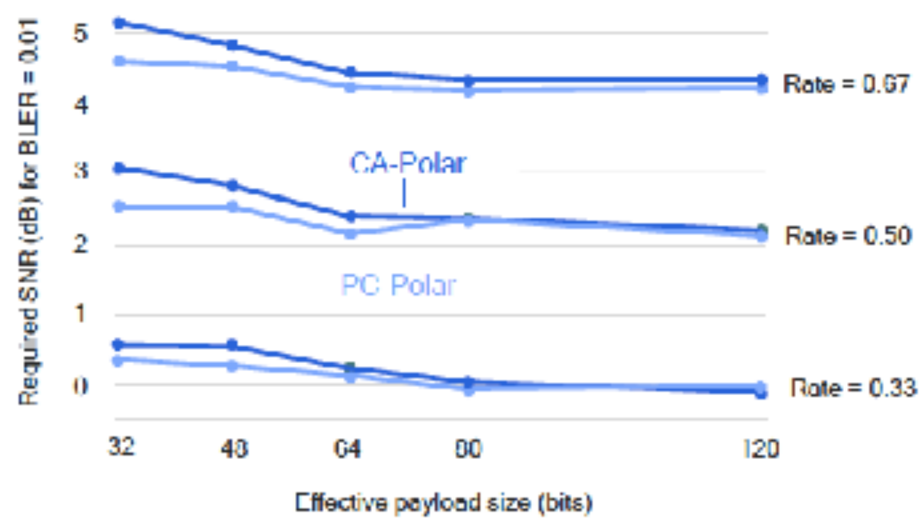
5G NR CRC-Aided (CA-Polar) design

Efficient construction based on single Cyclic Redundancy Check (CRC) for joint detection and decoding



Link-level gains of 5G NR CA-Polar design

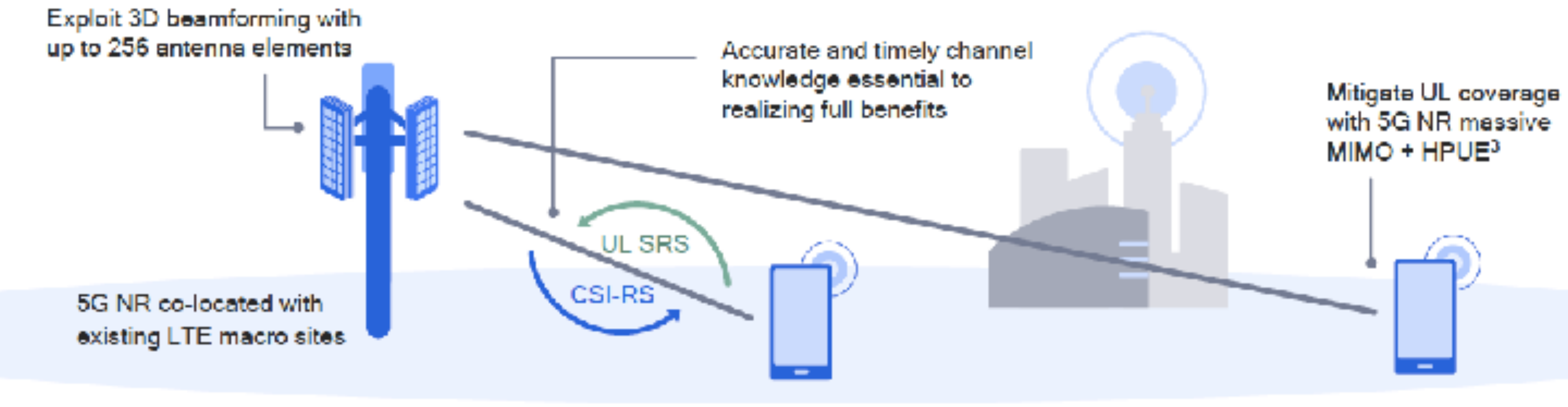
Versus PC-Polar[1] (lower is better)



Source: Qualcomm

- Adopted for many 5G NR control use cases

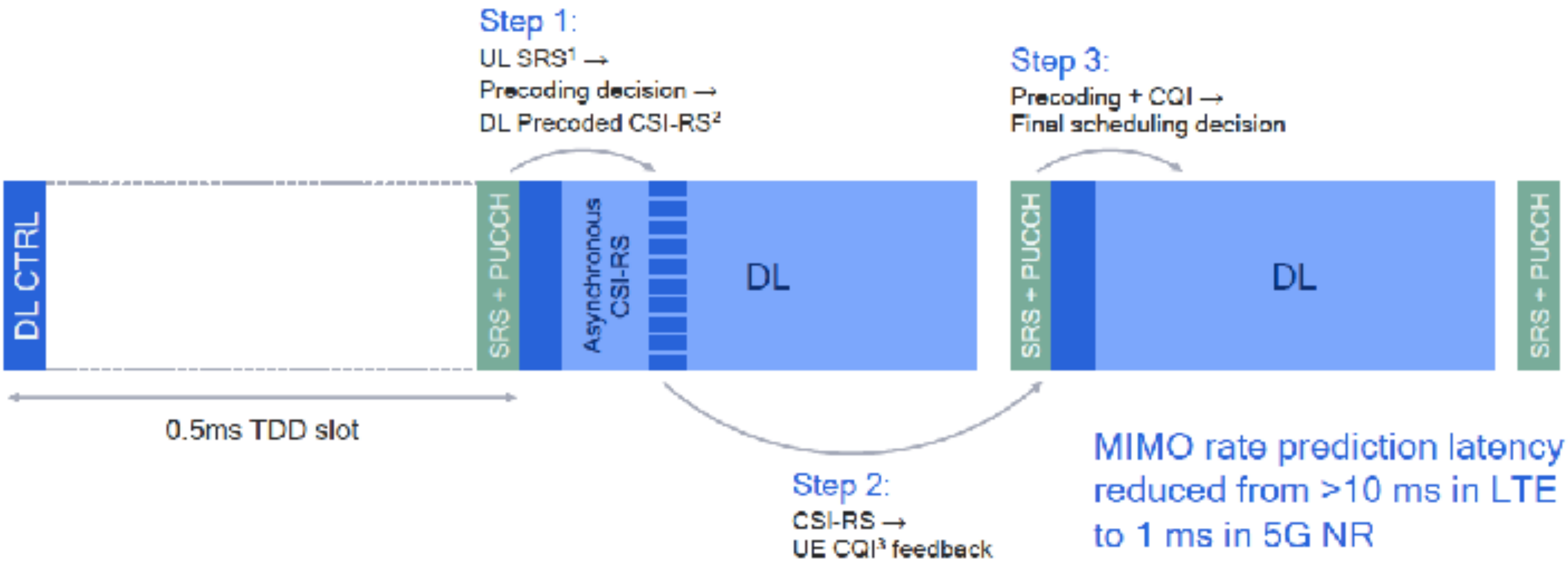
Massive MIMO



Source: Qualcomm

- Key enabler for using higher frequency, e.g. 4 GHz with existing LTE cell sites
- Optimized design for TDD reciprocity using UL SRS
- High spatial resolution codebook for up to 256 antennas

Massive MIMO



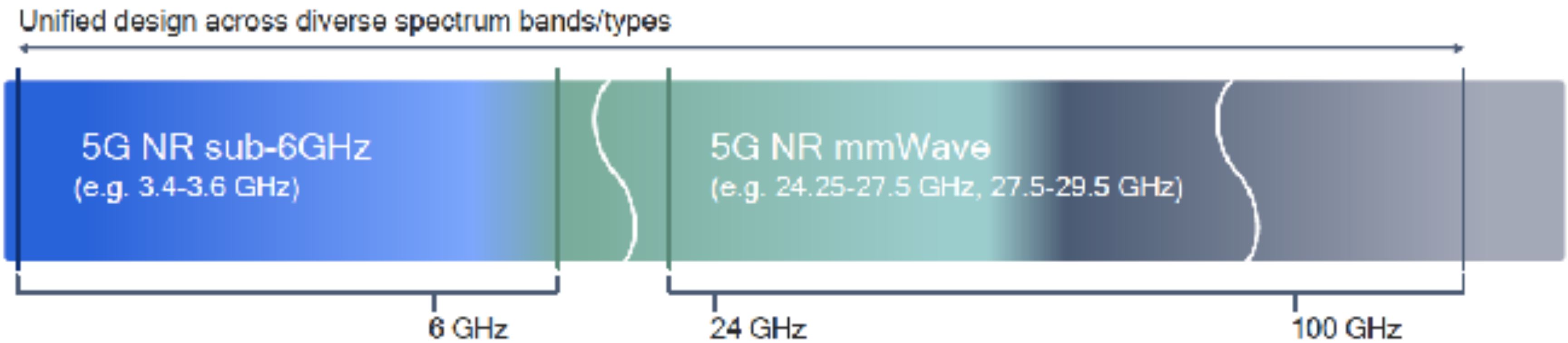
Source: Qualcomm

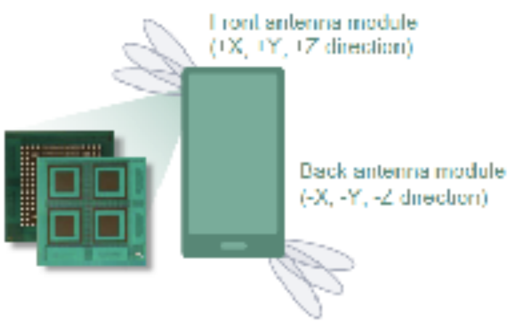
- NR slot structure and enhanced reference signals enable fast and accurate feedback

Massive MIMO

Source: Qualcomm

mmWave





Coverage

Innovations to overcome significant path loss in bands above 24 GHz

Robustness

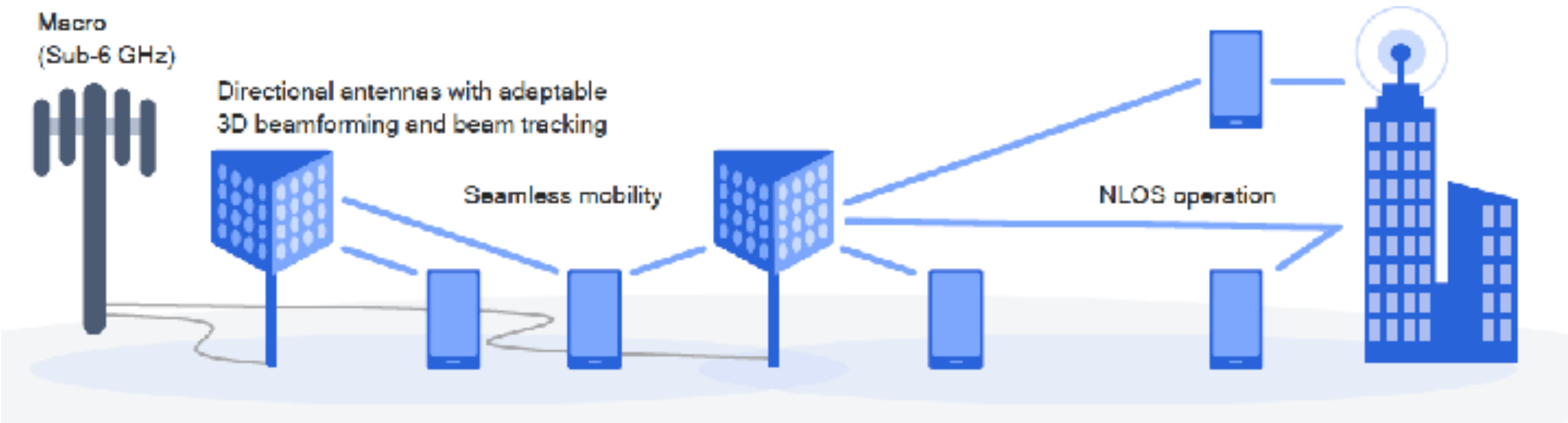
Innovations to overcome mmWave blockage from hand, body, walls, foliage, etc.

Device size/power

Innovations to fit mmWave design in smartphone form factor and thermal constraints

Source: Qualcomm

mmWave

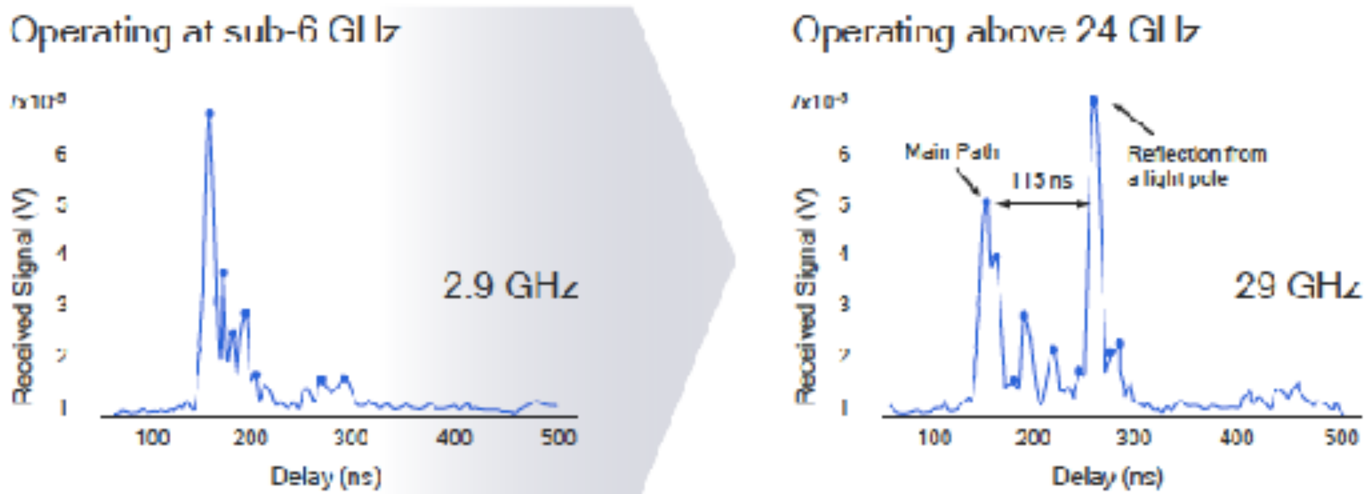


Source: Qualcomm

- Spatial reuse for dense deployment
- Fast beam steering/switching within a cell and switching across cells
- Integration with sub-6 GHz

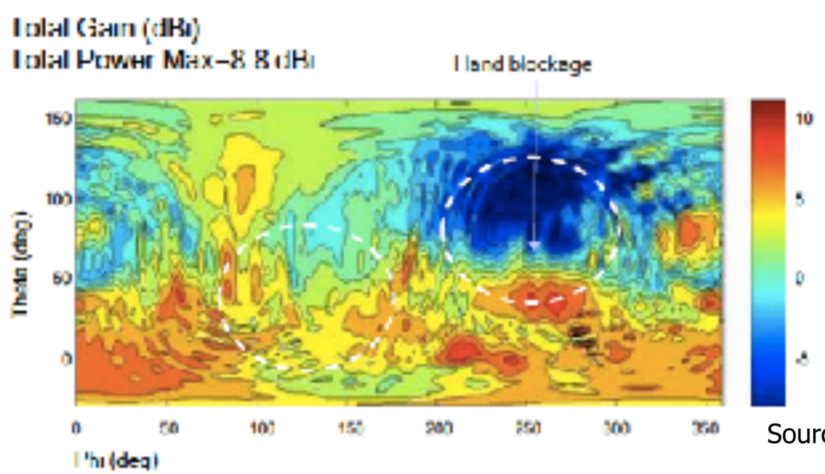
mmWave

- Path diversity to handle LOS blockage



Source: Qualcomm

- UE antenna diversity to handle hand blockage



Source: Qualcomm

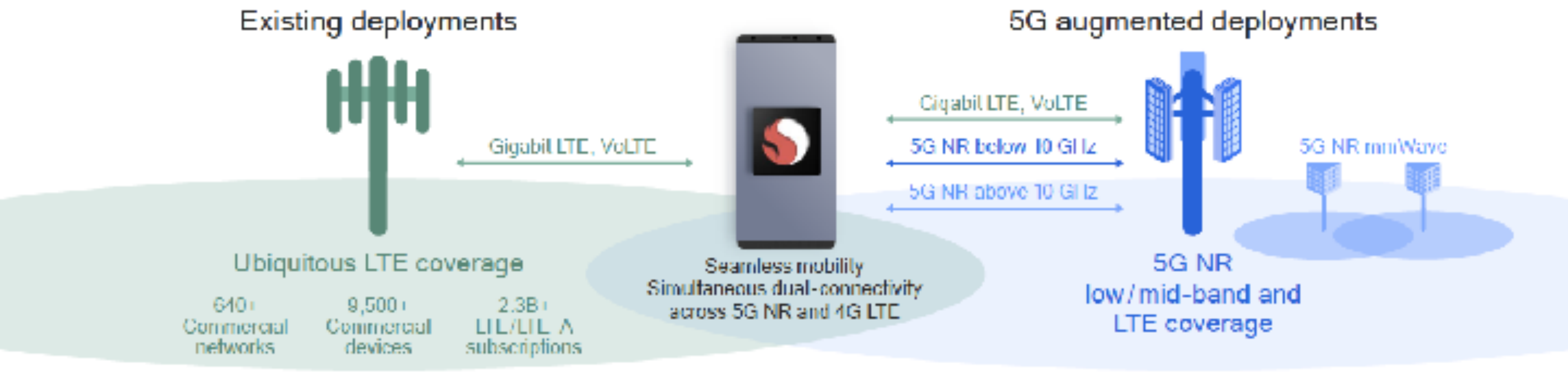
New Radio (NR) Recap

- Rel-15 has set the stage for various NR ingredients
  - Scalable OFDM numerology, advanced channel coding, massive MIMO, mmWave
- Rel-16+ will build on these features and introduce new features for NR evolution
- Targets beyond enhanced mobile broadband (eMBB)
  - Cellular-V2X, wireless industrial ethernet, etc.

(II) Access

Dual connectivity, Flexible frame structure,
Spectrum sharing

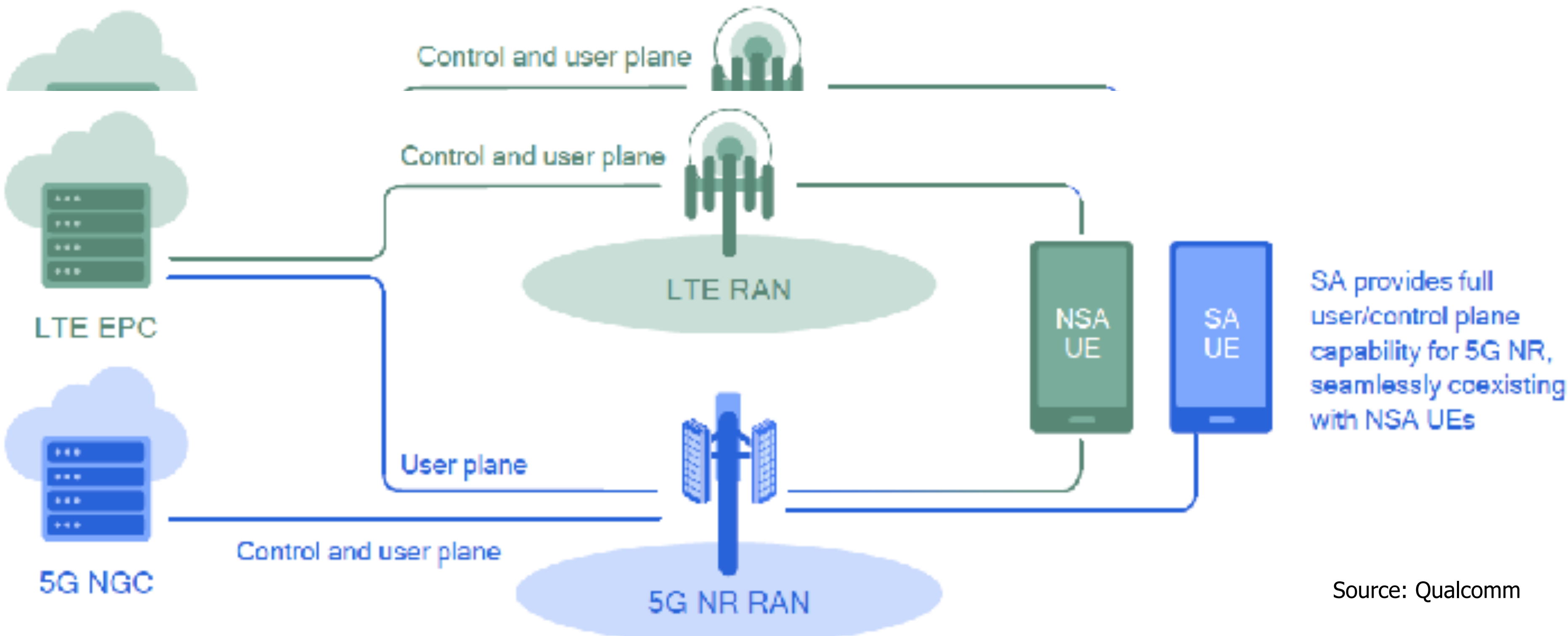
Dual Connectivity



Source: Qualcomm

- Leverage LTE investments and provide path to 5G convergence
- Evolve from non-standalone (4G LTE + 5G NR) to standalone (5G NR)
- Dual connectivity for LTE + NR in NSA

Dual Connectivity for NSA

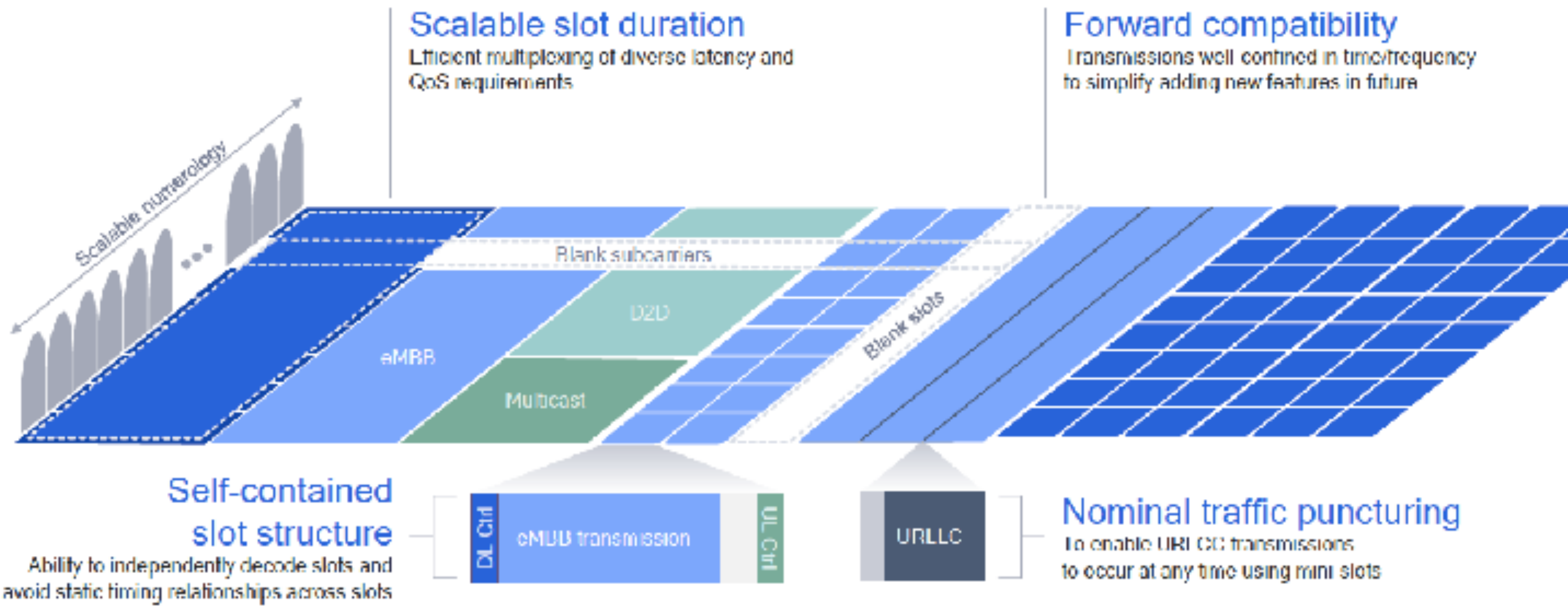


Source: Qualcomm

- Control and coverage from LTE, data from LTE + NR
- Reuse core network (EPC) from LTE
  - NSA stepping stone to SA 5G NR

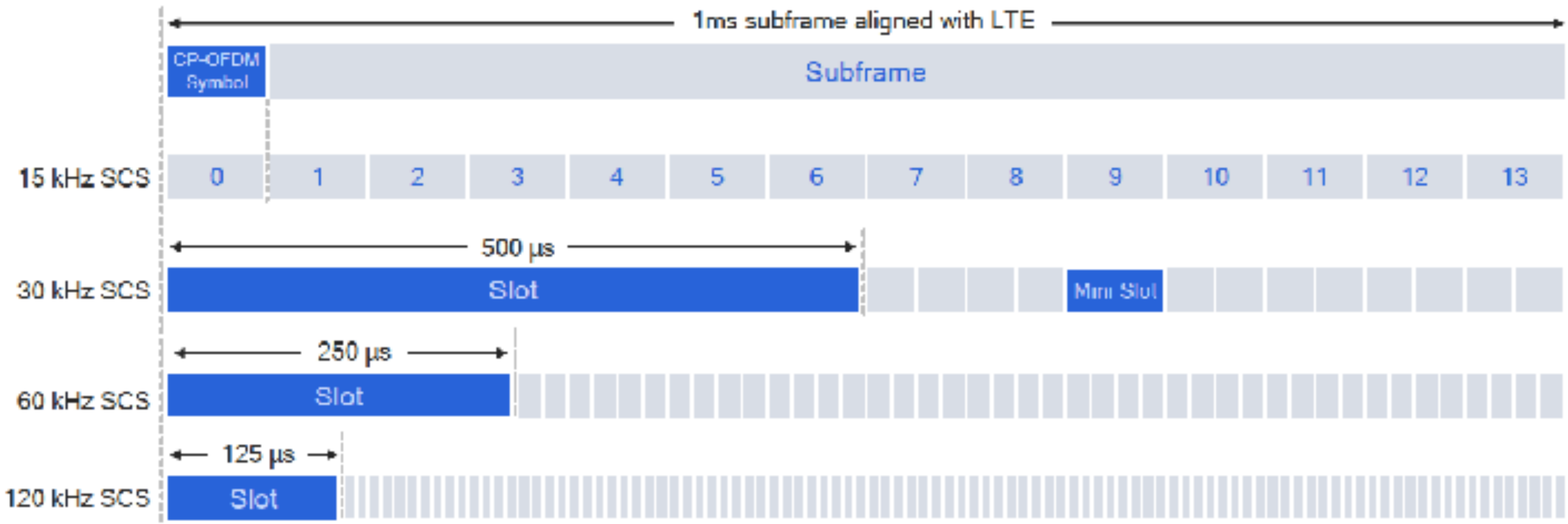
Flexible Frame Structure

- Enables heterogeneous access modes



Source: Qualcomm

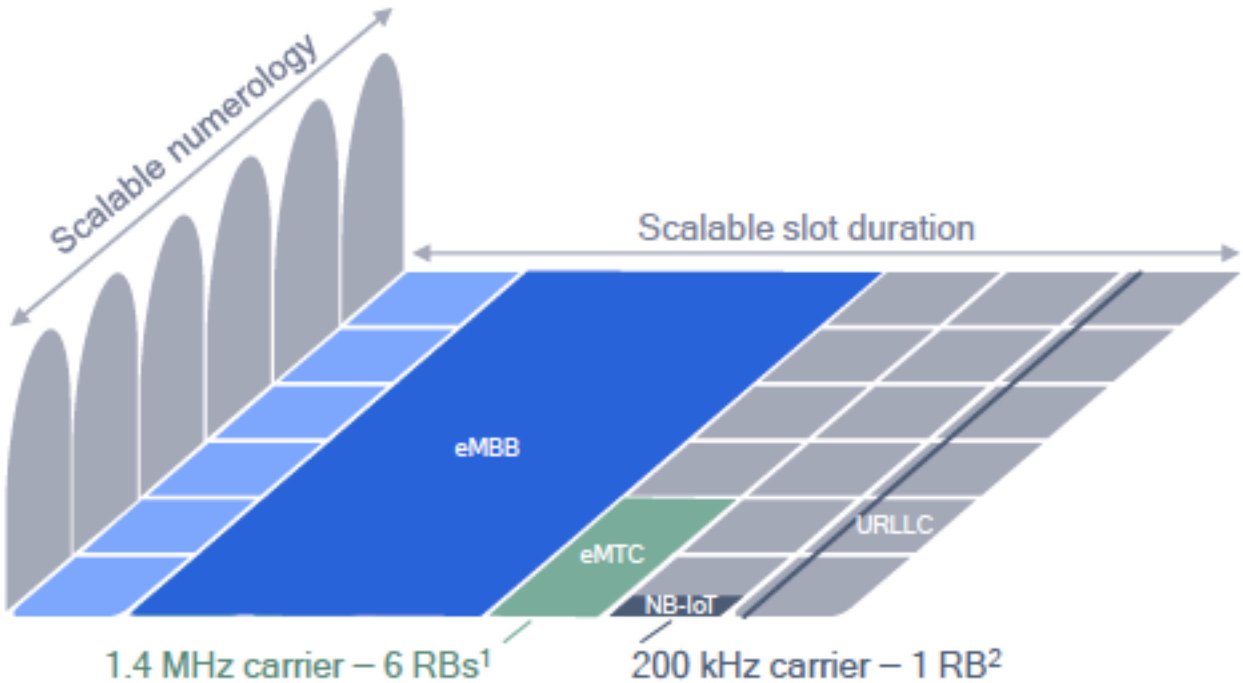
Scalable Slot Duration



Source: Qualcomm

- Diverse latency and QoS
- Mini-slots (2, 4 or 7 symbols) for shorter transmissions
- Slot aggregation for data-heavy transmissions

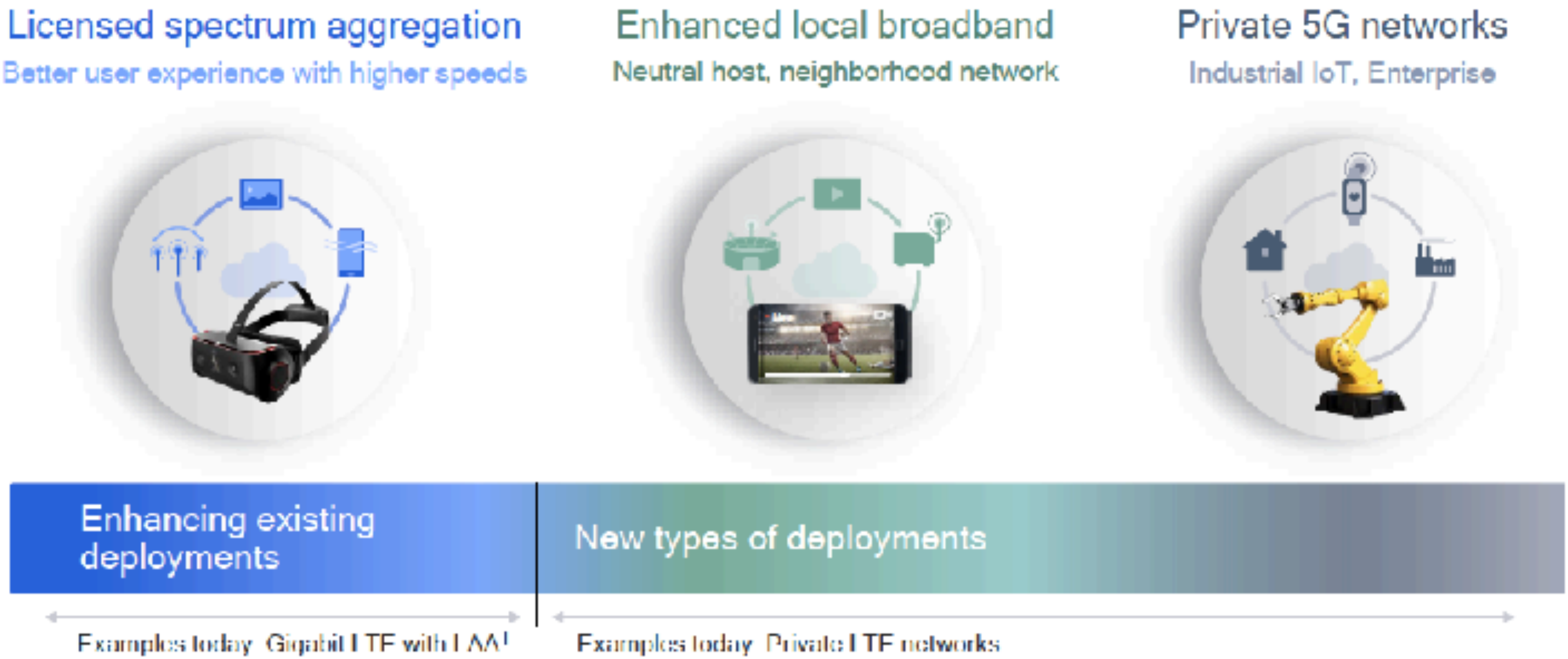
Suited for 5G NR IoT Evolution



Source: Qualcomm

- Rel 16: In-band eMTC/NB-IoT support
- 15 KHz sub-carrier spacing

Shared Spectrum Access



Source: Qualcomm

- Lack of sufficient licensed spectrum
- Critical for wide range of deployments and new business models

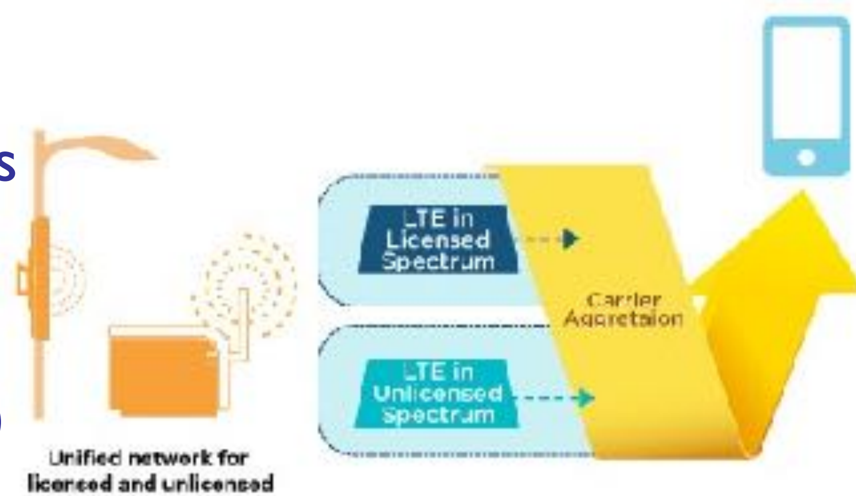
Spectrum Sharing Models

Source: Qualcomm

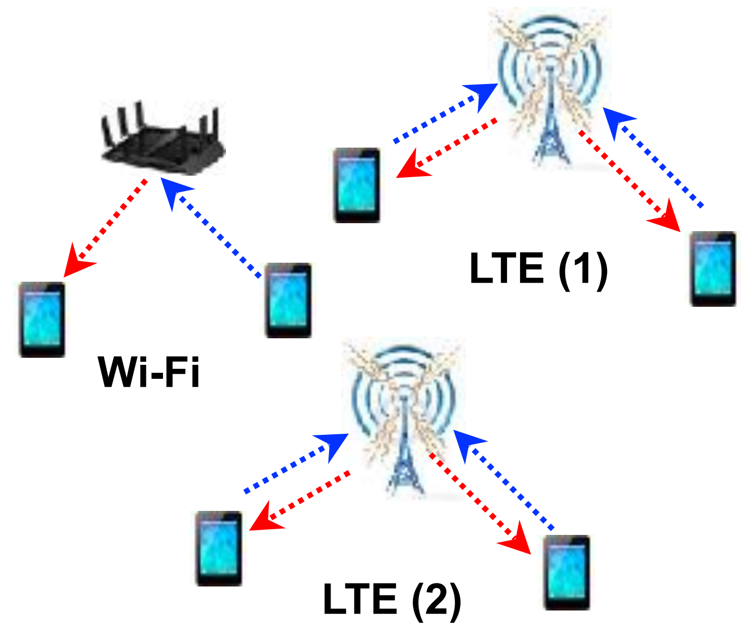
- License-assisted access
  - Supplement licensed with unlicensed channels
  - LTE/NR on unlicensed carrier, aggregated with LTE or NR on licensed (anchor) carrier
- Standalone access
  - LTE/NR on unlicensed carrier (also serves as anchor)

Convergence in Access?

- Started with LTE using WiFi bands as unlicensed carriers
- Other bands (e.g. CBRS 3.5 GHz) for shared and standalone
  - Shared (using spectrum server), unlicensed (e.g. MulteFire)
- Co-existence challenges
  - Co-existence with WiFi and other LTE operators
  - Asynchronous access in traditional synchronous network

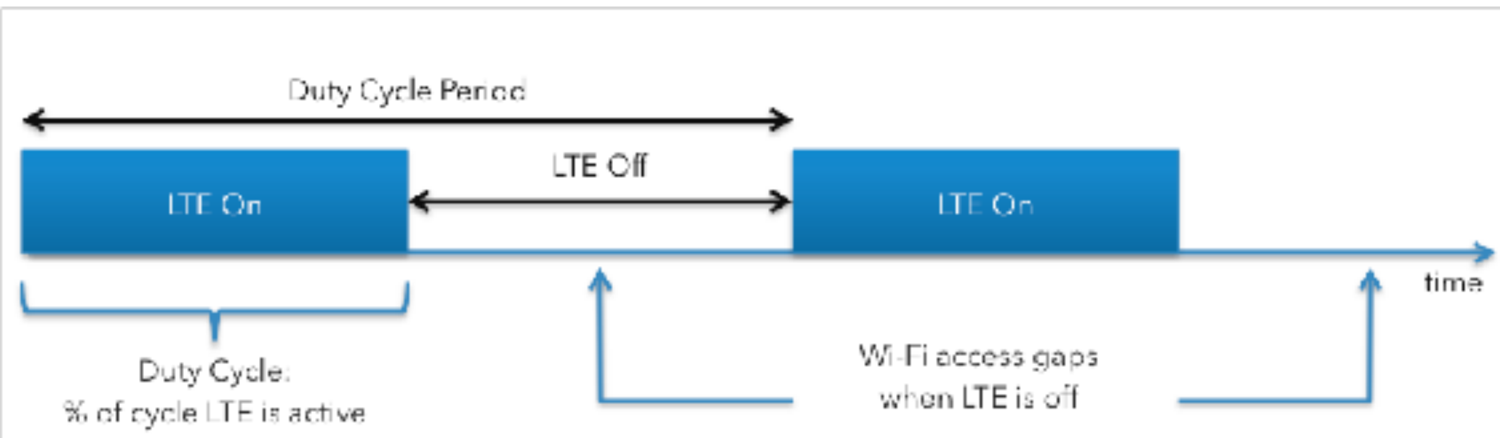


Source: Qualcomm



LTE-WiFi Co-existence

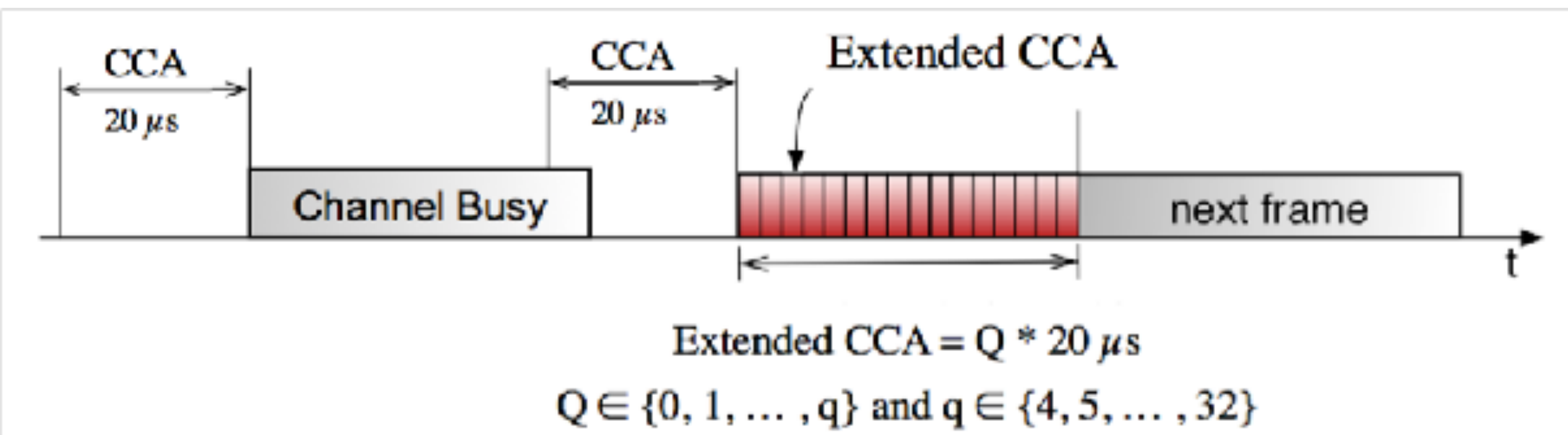
- Two modes of operation
- LTE-U
  - Duty cycling at time scales of tens of ms
  - Can be realized today: switch on/off unlicensed carriers
  - Short-term unfairness to WiFi, higher latency



Source: Cable labs

LTE-WiFi Co-existence

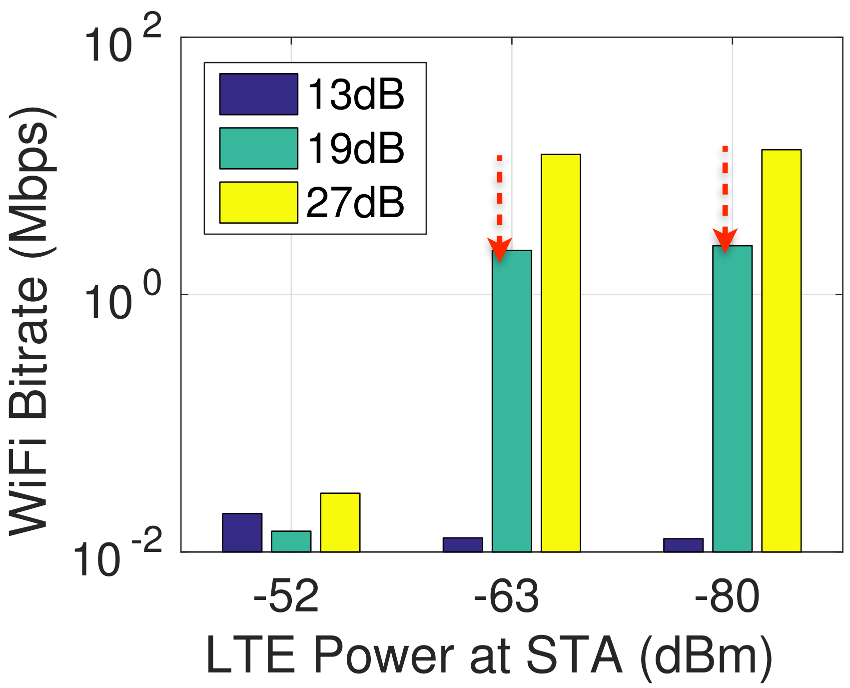
- LTE-U
  - Duty cycling at time scales of 100 ms
  - Short-term unfairness to WiFi, higher latency
- LAA-LTE: License assisted access
  - Energy sensing CCA; Operation at 1-10 ms granularity
  - Modification to LTE specification for Listen-before-Talk

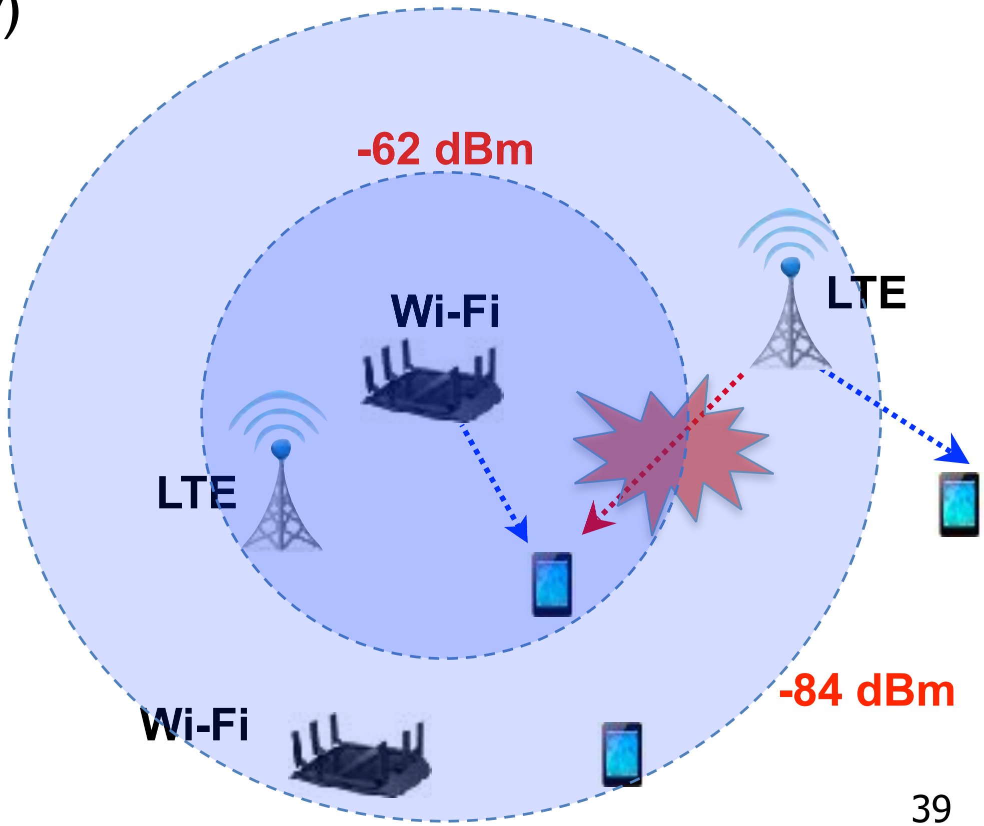


Source: Cable labs

Un-resolved Challenges

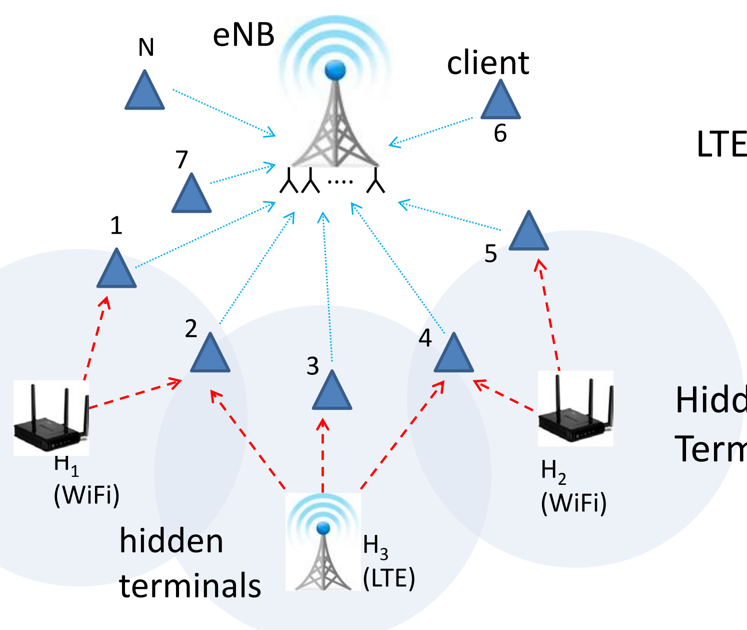
- Im-balanced channel access between LTE and WiFi
  - WiFi detects/notifies other WiFi through "WiFi carrier" sensing/notification (-84 dBm sensitivity)
  - WiFi-LTE detect each other through "energy" sensing alone (-62 dBm sensitivity)

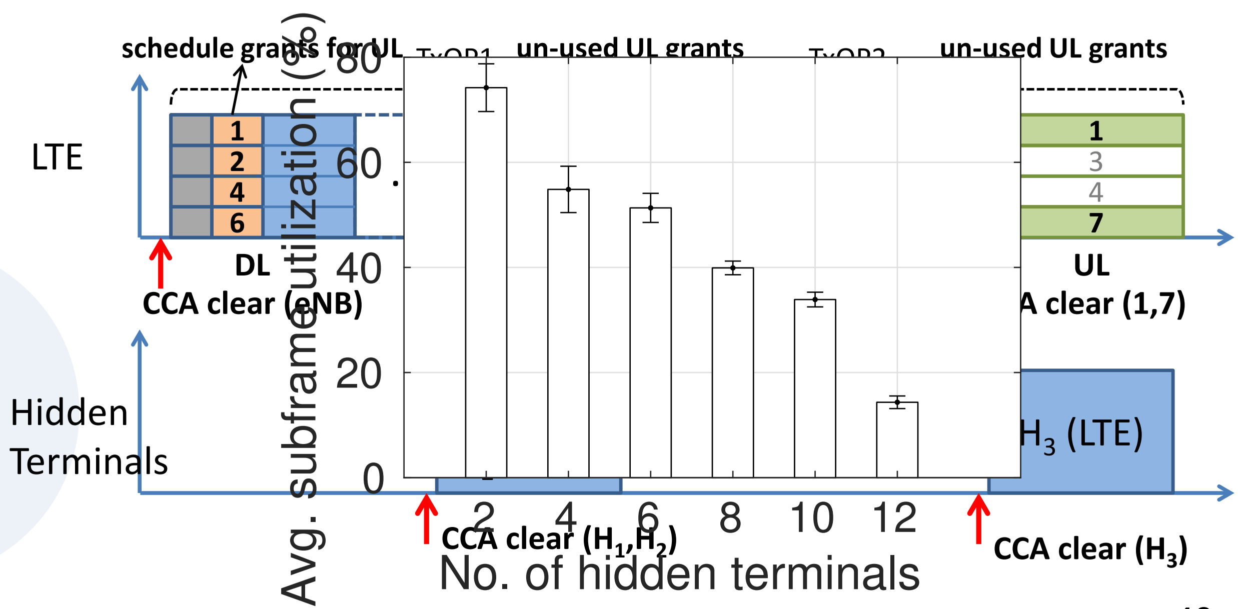




Un-resolved Challenges

- In-efficient LTE operation in unlicensed spectrum
  - Conflict between concurrency and asynchronous interference
    - Synchronous, multi-user transmissions increase capacity
    - Lead to utilization loss in the presence of asynchronous interference (from WiFi and LTE)
  - Pronounced impact on uplink, where eNodeB schedules all UL transmissions





Access Recap

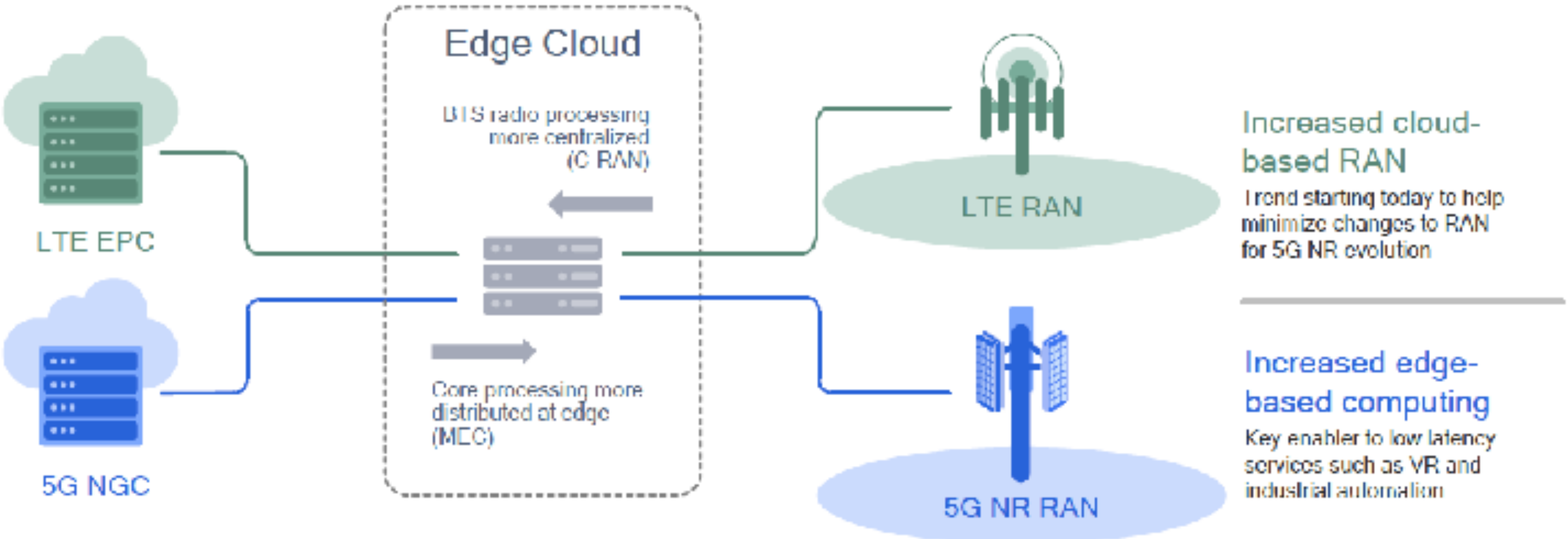
- Dual connectivity for non-standalone access (LTE+NR)
  - Stepping stone for standalone NR
- Flexible frame structure enables diverse services (eMBB, MTC, IoT, URLLC)
- Room for future access and services
  - Non-orthogonal multiple access (NOMA), C-V2X, wireless industrial ethernet, grant-free UL, mesh

- Shared spectrum: important access model in 5G
  - Boundaries between synchronous (e.g. LTE, NR) and asynchronous (e.g. WiFi) access models will get blurred
- Deeper understanding to realize converged access
  - Several interesting and important problems

(III) Network

SDN in Wireless Access, Network Slicing

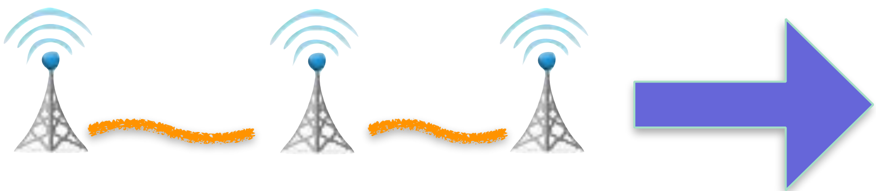
Network Evolutions

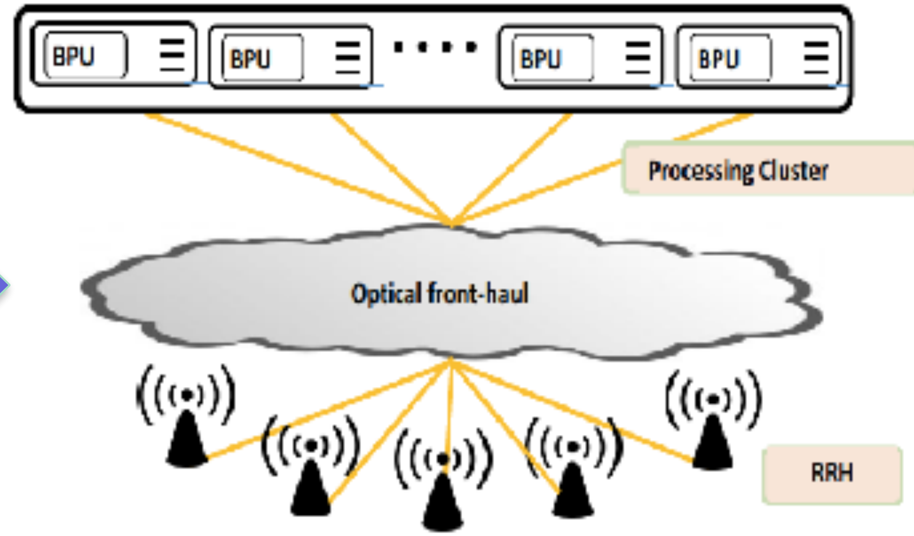


Source: Qualcomm

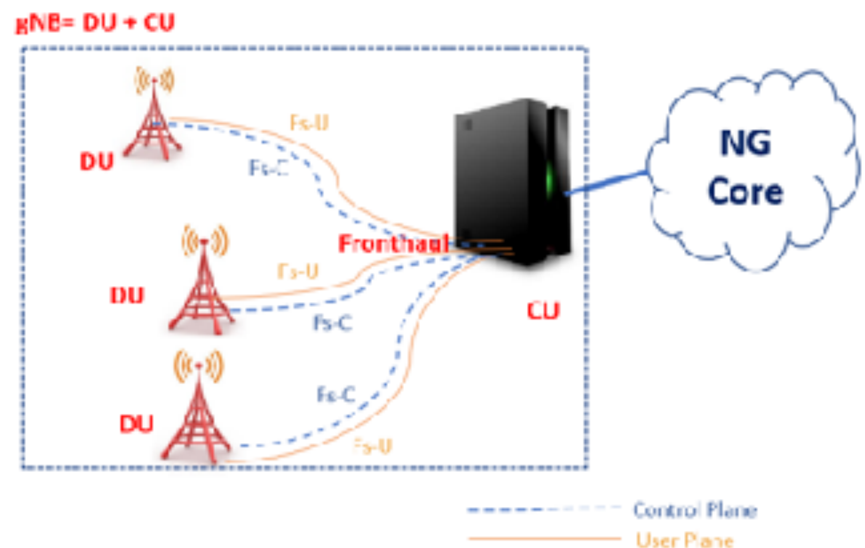
- Two trends aid in evolution from non-standalone to standalone access
  - Cloud-based RAN and mobile edge computing

Cloud-RAN Architecture

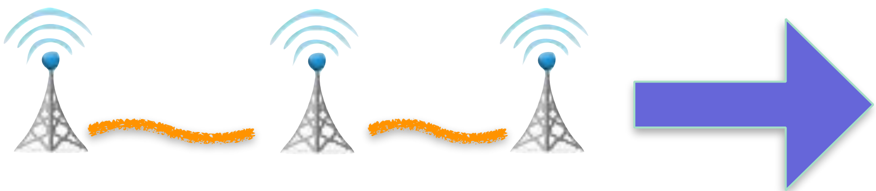


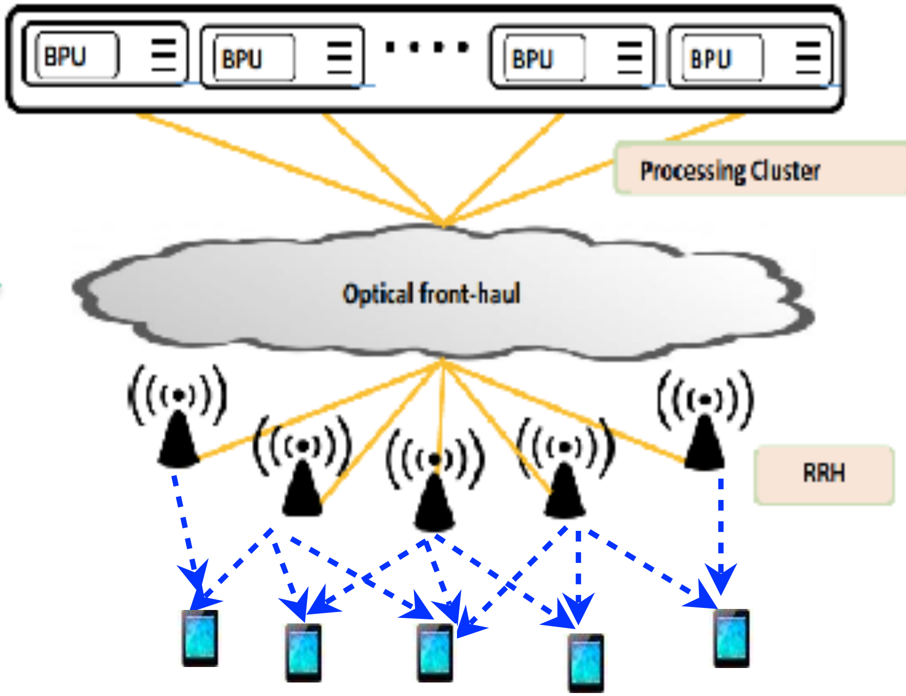


- Decouple processing from transmission
- Baseband unit (BBU) pool
  - Centralized processing
- Remote radio/antenna head
  - Cost and power efficient
- Front-haul network
  - Optical, heterogeneous



Cloud-RAN Architecture

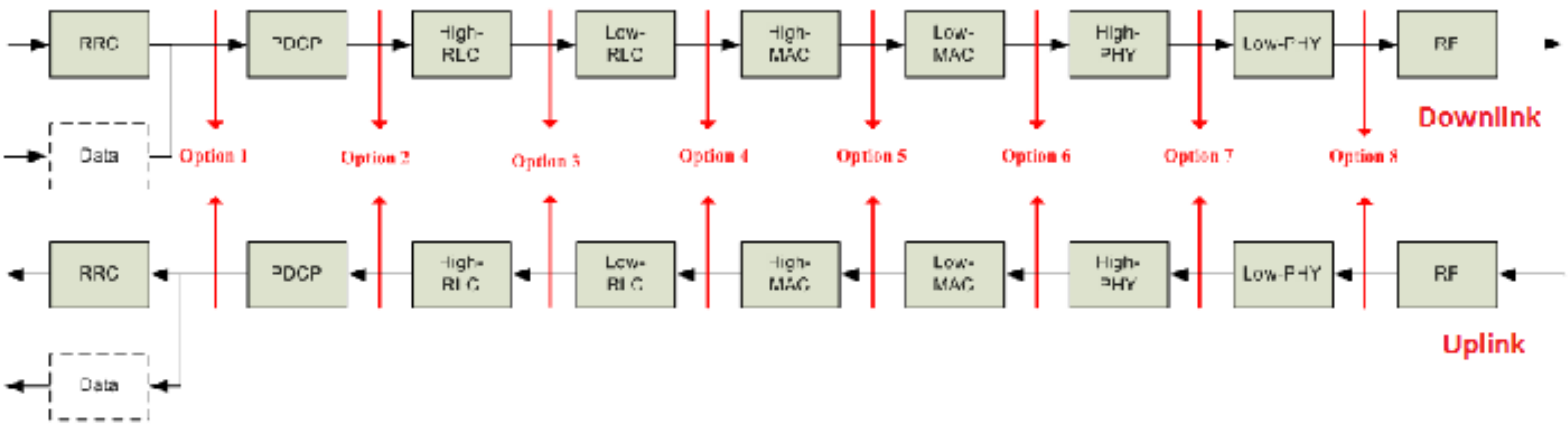




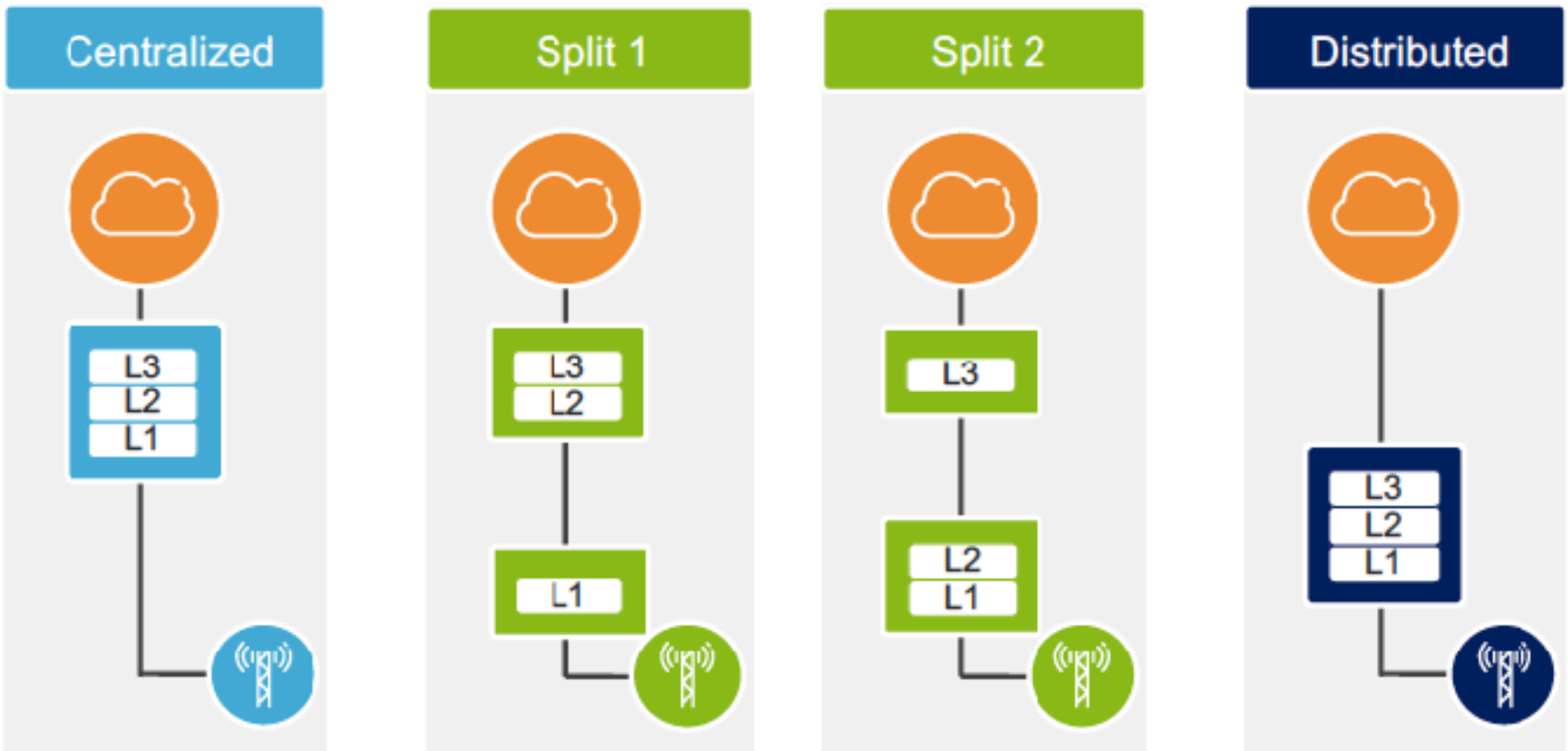
- Several benefits
  - Capex/Opex savings: simplified cell-sites
  - Cooperative interference management
  - Better compute management
- Attractive for high-density deployments (eg. stadiums, convention centers, etc.)

C-RAN Split Options

- 8 different functional split options
  - Front-haul bandwidth vs. performance and RRU complexity
  - Popular options: Options 1, 2 (low front-haul requirements), options 7, 8 (low RRU complexity and higher system performance)



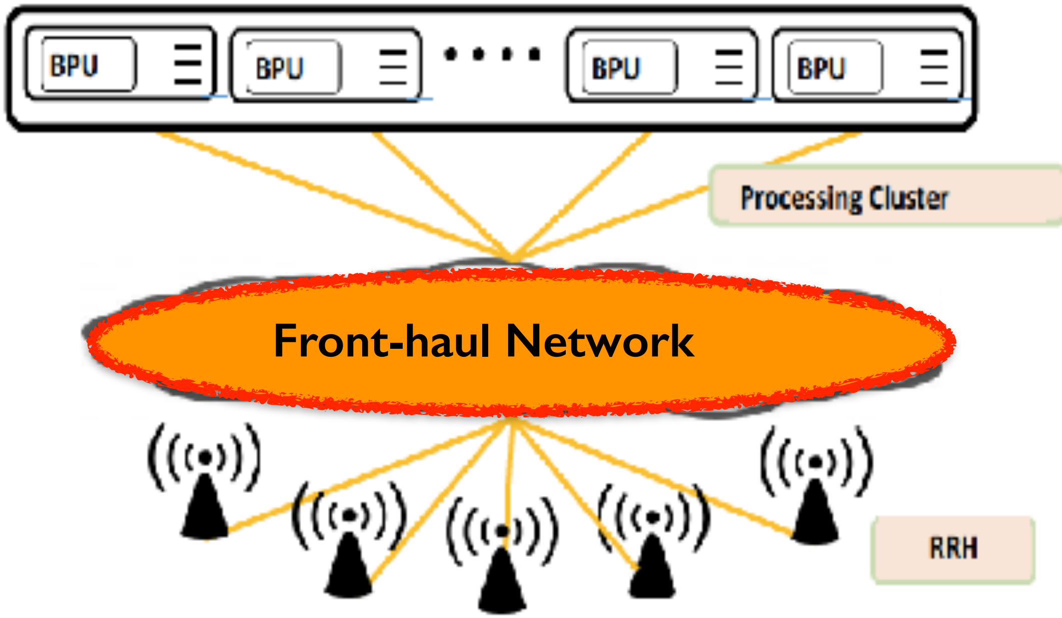
Some Popular Split Options



Source: Ericsson W.P. on Cloud RAN

Realize C-RAN's True Potential

- Key: handle diverse traffic and user profiles
  - Unicast vs. multicast traffic
  - Mobile users vs. static users
  - Spatio-temporal traffic load variations

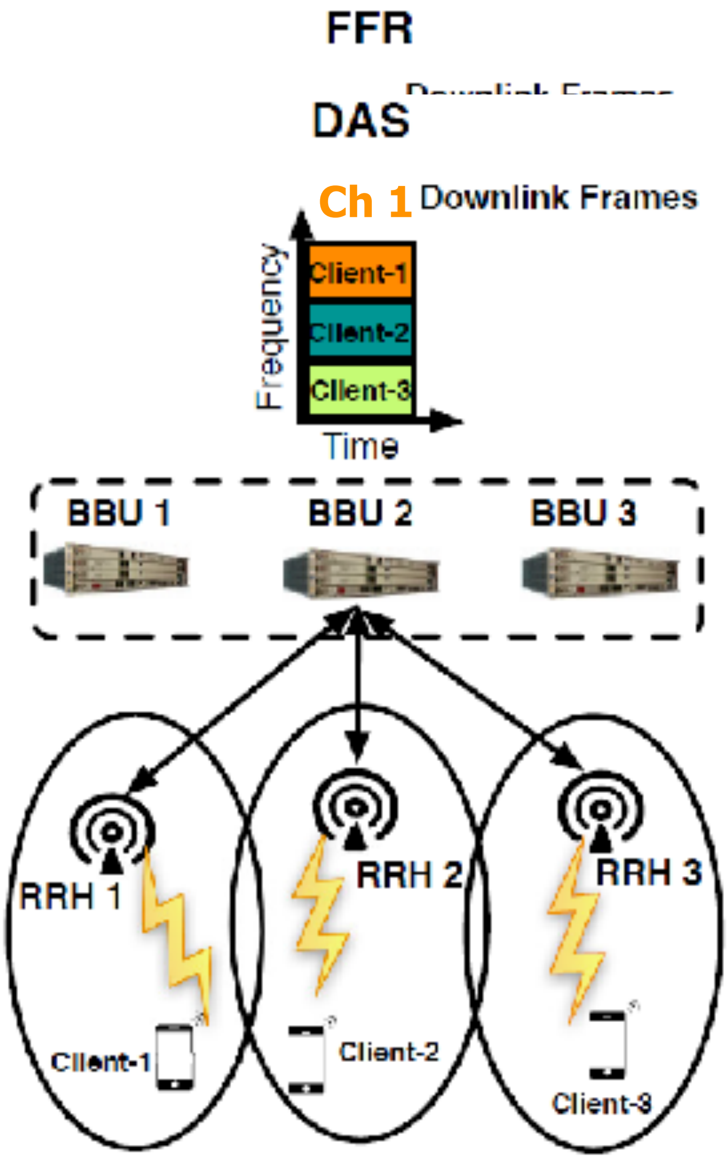


➢ Orchestrate the unique component of a C-RAN: the front-haul that maps BBU signals to RRHs

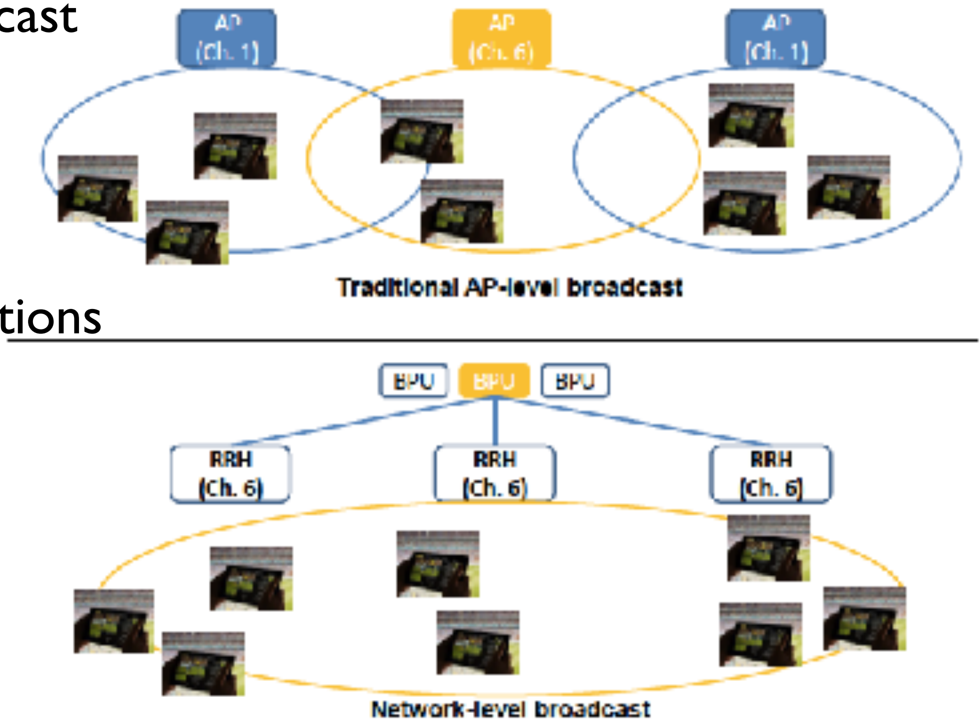
- Optimize performance and energy
  - Improved user performance in RAN
  - Intelligent use of BBU resources in BBU pool

Strategies and Configurations

- One-one logical mapping on front-haul
  - Currently used configuration
  - Different frames to different small cells
  - Strategy: frequency reuse (FFR) in LTE, spatial reuse in WiFi
- One-many logical mapping on front-haul (Options 7, 8)
  - A complementary configuration
  - Single frame sent to multiple small cells
  - Strategy: Distributed Antenna System (DAS)



Characteristics

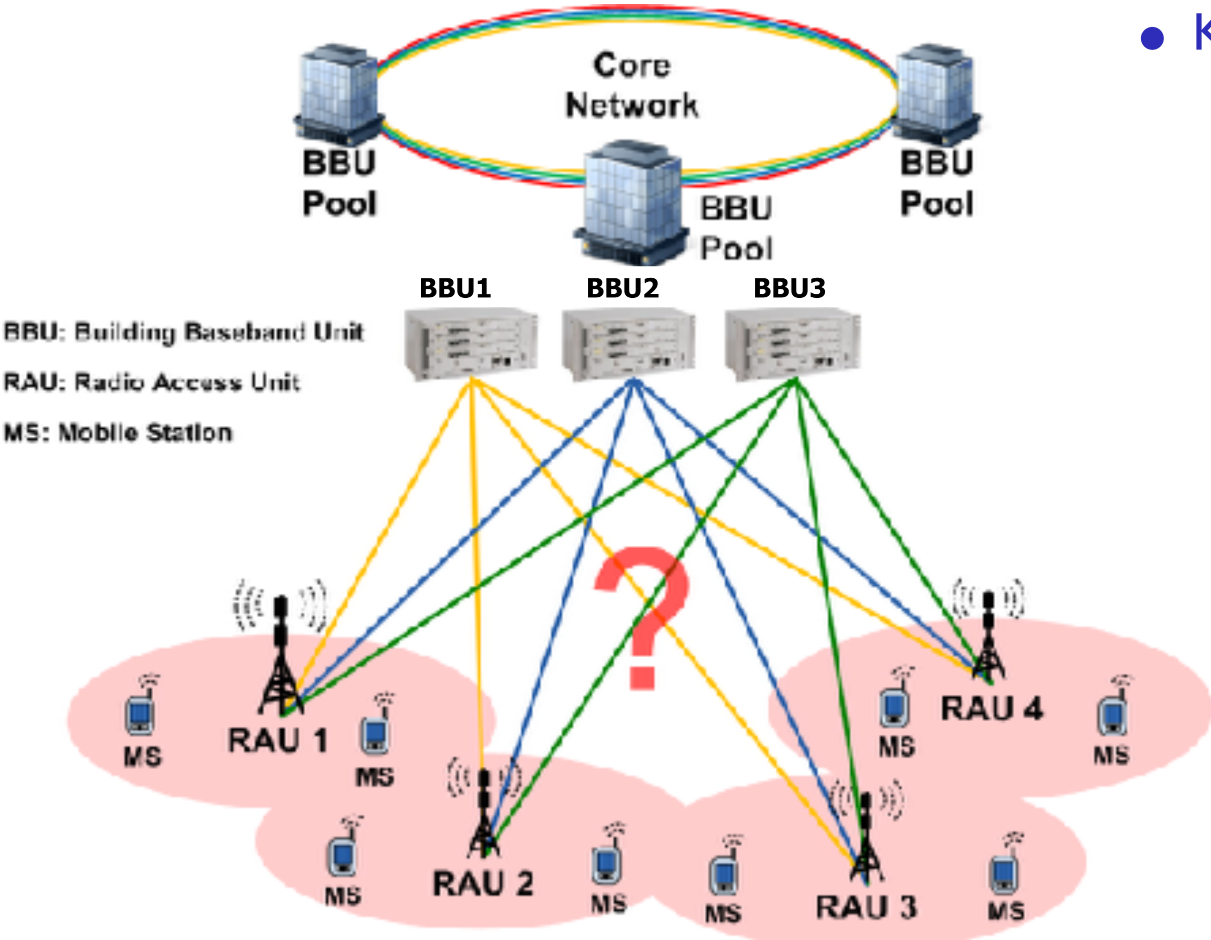


- Capacity
  - FFR better suited for high, unicast traffic demand
- Mobility management
  - DAS reduces handoff interruptions
- Multicasting capability
  - DAS provides network-wide multicasting capability
- Compute/energy-efficiency
  - DAS is compute/energy-efficient

➢ Dynamic combination of strategies, i.e. a reconfigurable front-haul

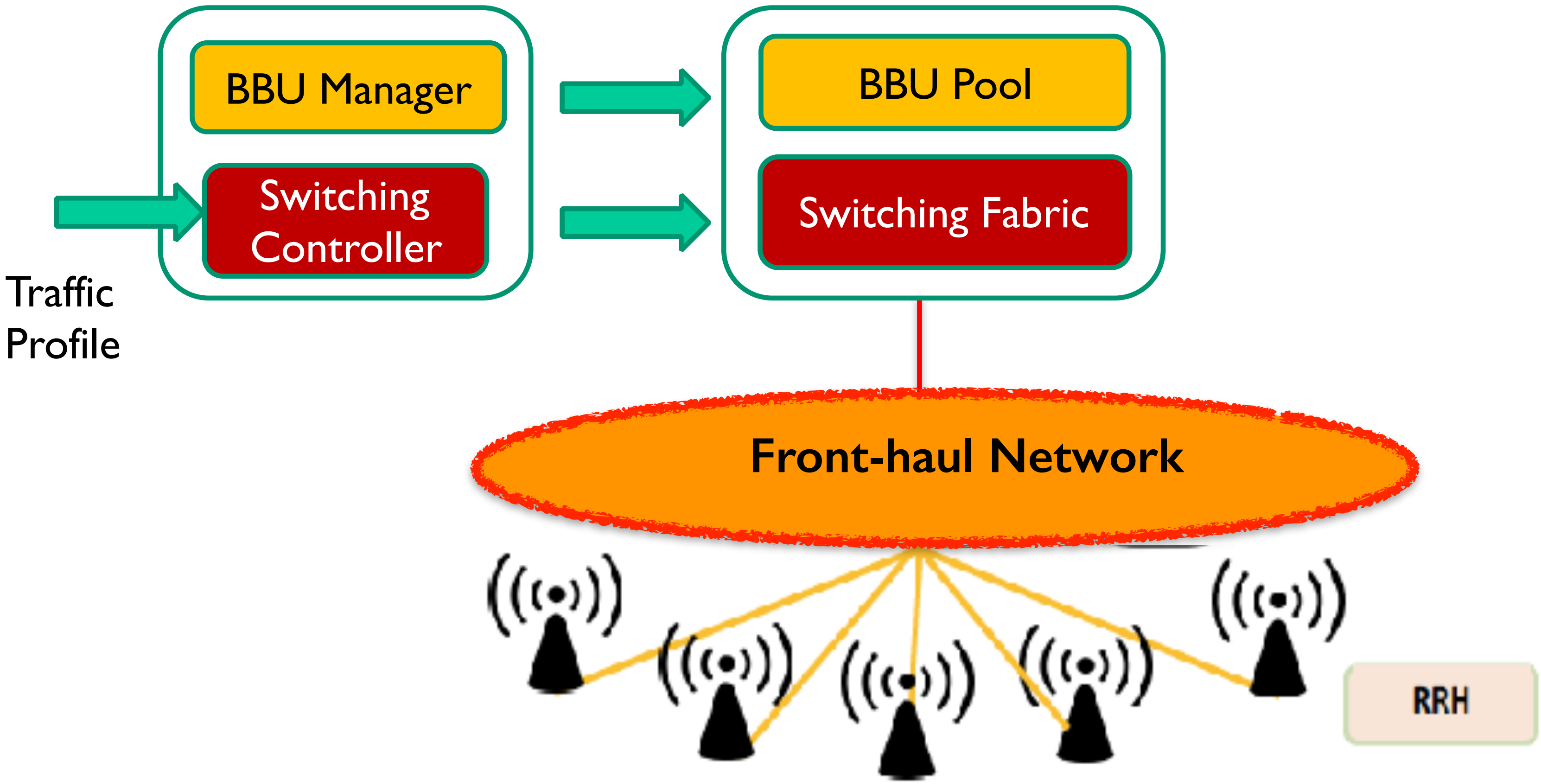
C-RAN System with SDN Transport

- C-RAN with a software-defined front-haul (SDF) transport network



- Key features
  - Different transmission strategies through appropriate front-haul configurations
  - Caters to spatial and temporal variations in traffic/user profiles
  - Optimizes for performance and energy
  - Customizes configurations for services (MBB, IoT, URLLC), operators and technologies (LTE, 3G, WiFi)

C-RAN Architecture with SDF



Objectives for Reconfiguration

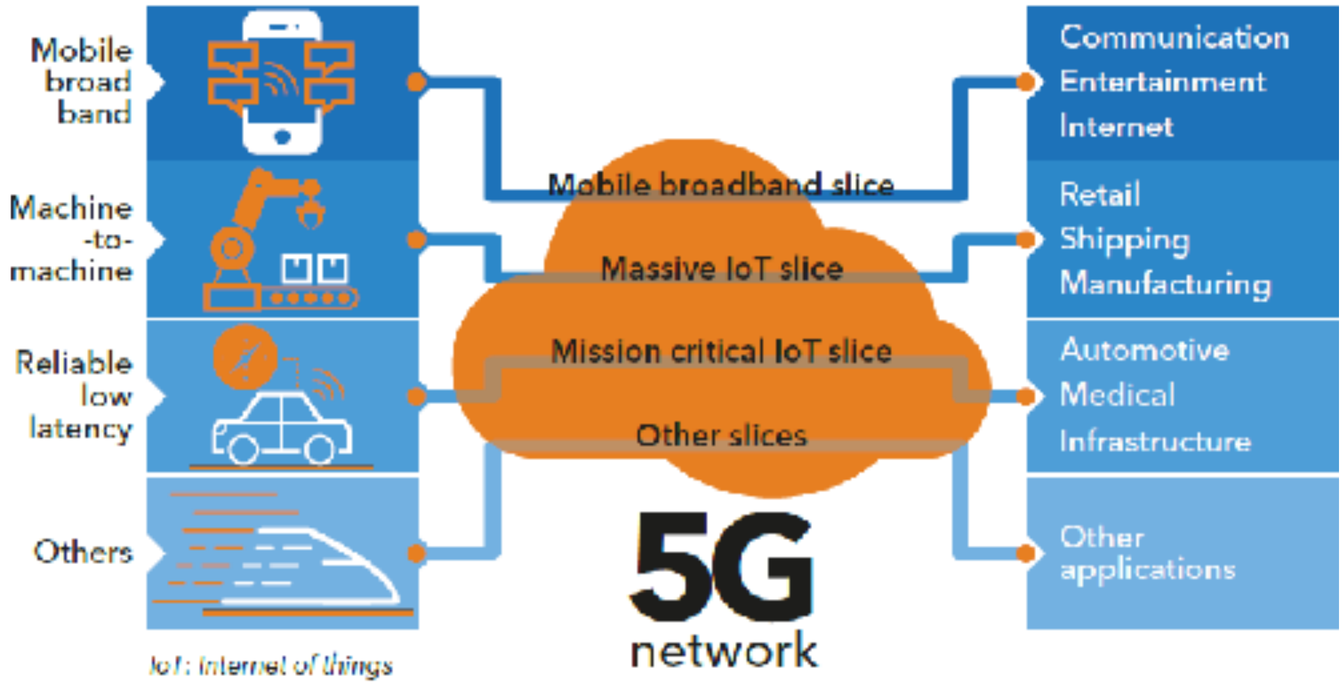
- Compute/energy-focused objective (LTE)
  - Determine configuration (Γ) that sustains as much traffic demand (D) as an optimal scheme, while minimizing the BBU resource units (RU) used in the pool

$$\min_{\Gamma} RU_{\Gamma}, \text{ subject to } D_{\Gamma} \geq \lambda \cdot D_{OPT}$$

- Throughput-focused objective (WiFi)
  - Determine configuration (Γ) that maximizes the amount of traffic demand (λ) supported in the network for a given number of BBU units (R)

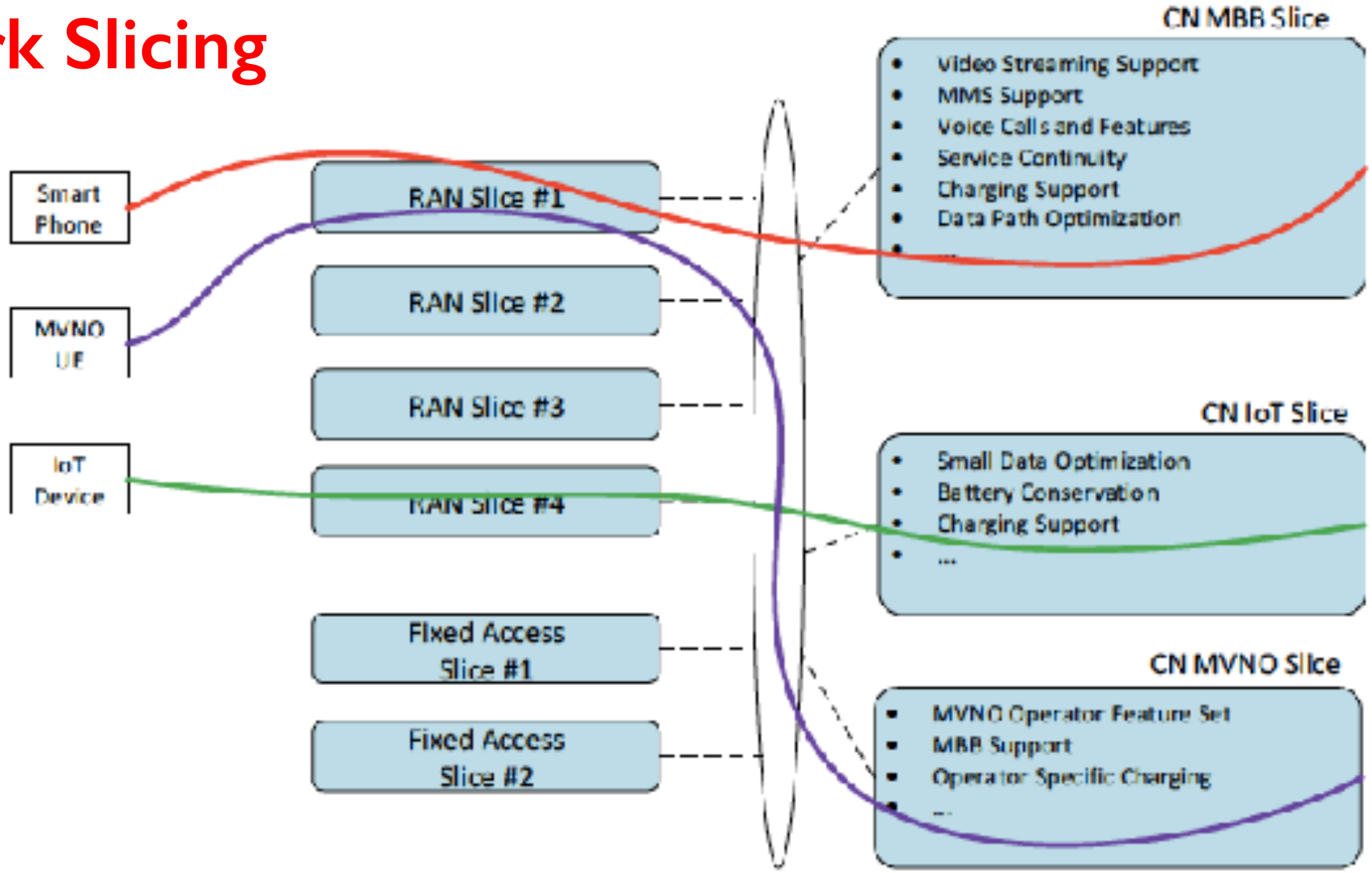
$$\max_{\Gamma} \lambda_{\Gamma}, \text{ subject to } RU_{\Gamma} \leq R$$

Network Slicing



- Key component in helping a single 5G physical network cater to diverse services "simultaneously"
- Creates multiple logical slices of a single physical network

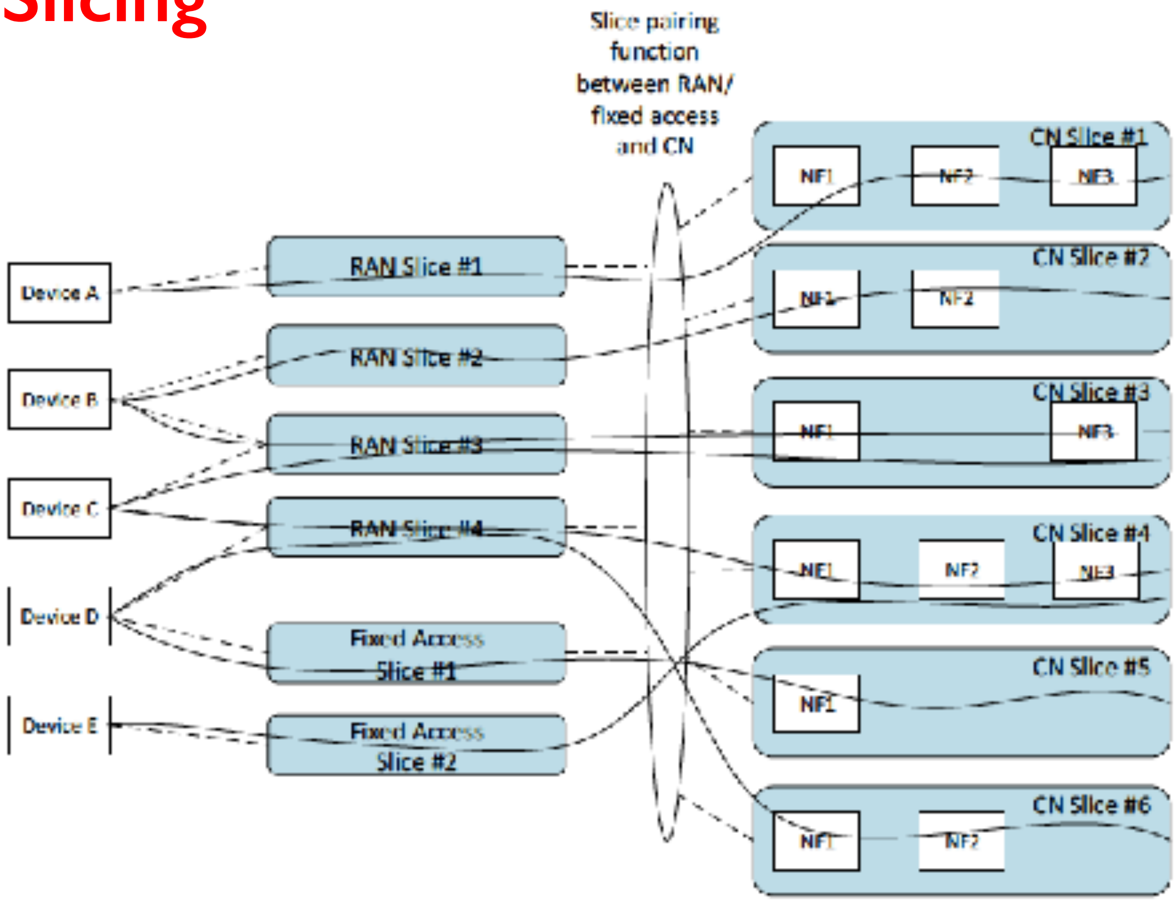
Network Slicing



Source: 5G Americas

- Each slice corresponds to slicing both RAN and core resources
- Each slice can be configured to suit different application requirements
  - Different QoS, charging, performance, etc. features

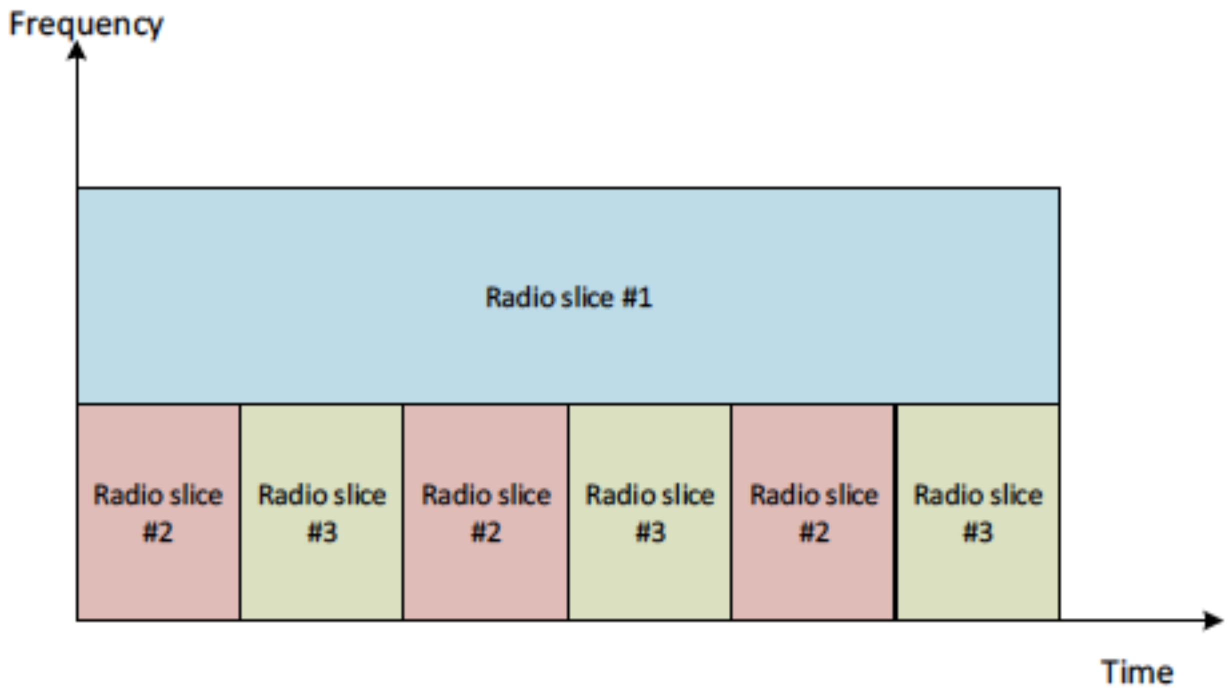
Network Slicing



Source: 5G Americas

- A device can belong to multiple slices
- In addition to RAN and core, access network (e.g. fronthaul transport in C-RAN) can also be sliced

RAN Slicing

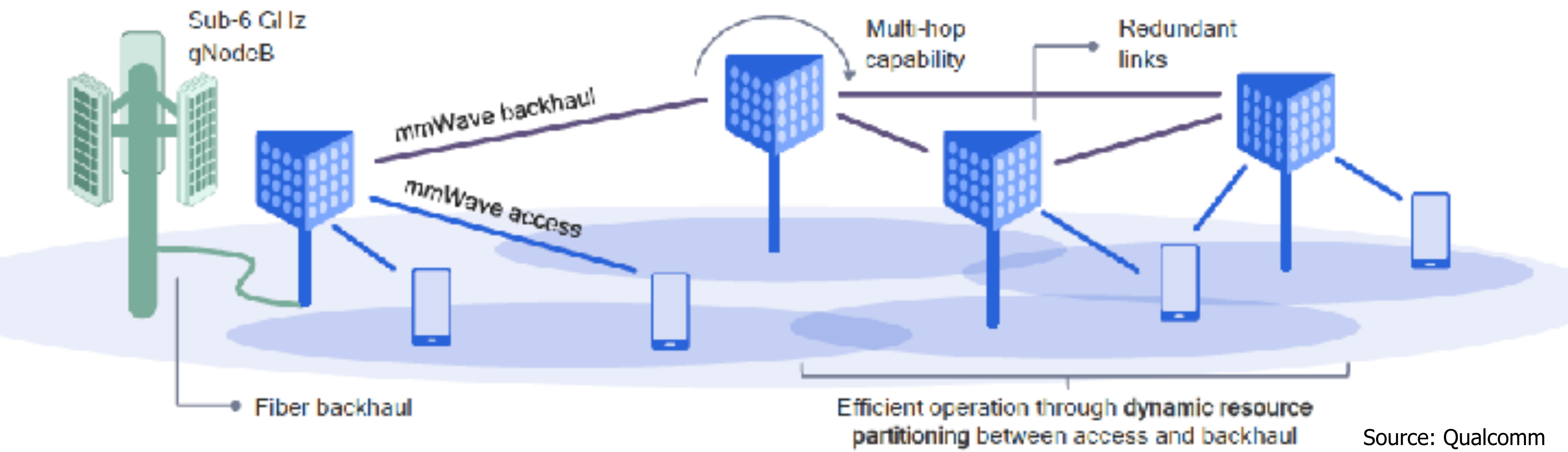


Source: 5G Ameicas

- Virtualizing the RAN spectrum
- Slice Scheduling
  - Scheduling resources (time, frequency, spatial) across slices
- Admission control for slices
- Single-cell and multi-cell RAN slicing

Network Recap

- Software-defined networking plays an important role in 5G network deployments
- SDN + network slicing (virtualization) enables flexible orchestration of RAN + transport + core network



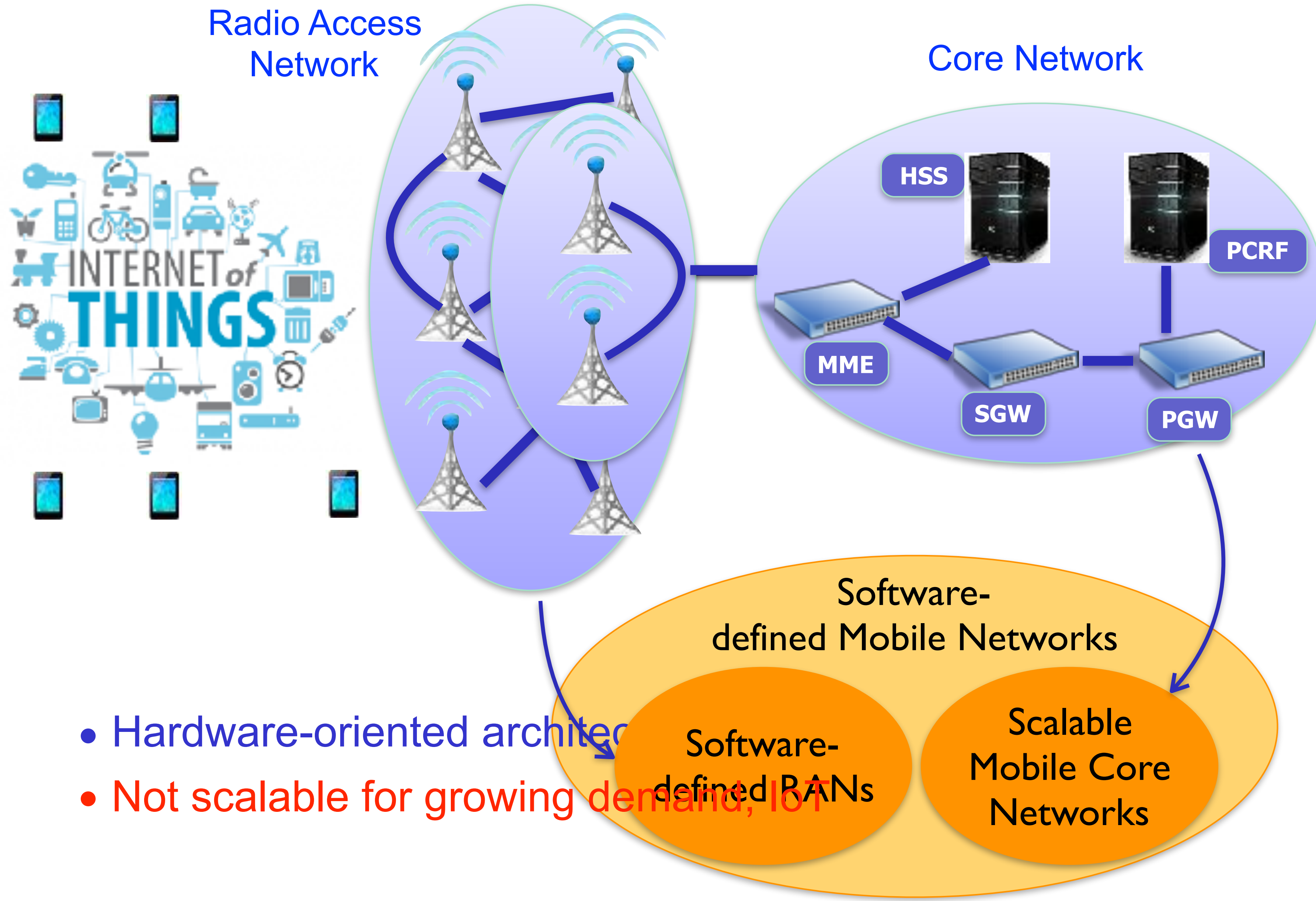
Source: Qualcomm

- Helps realization of integrated access and backhaul in mmWave spectrum
- New business models and expansion of 5G ecosystem

(IV) Computing

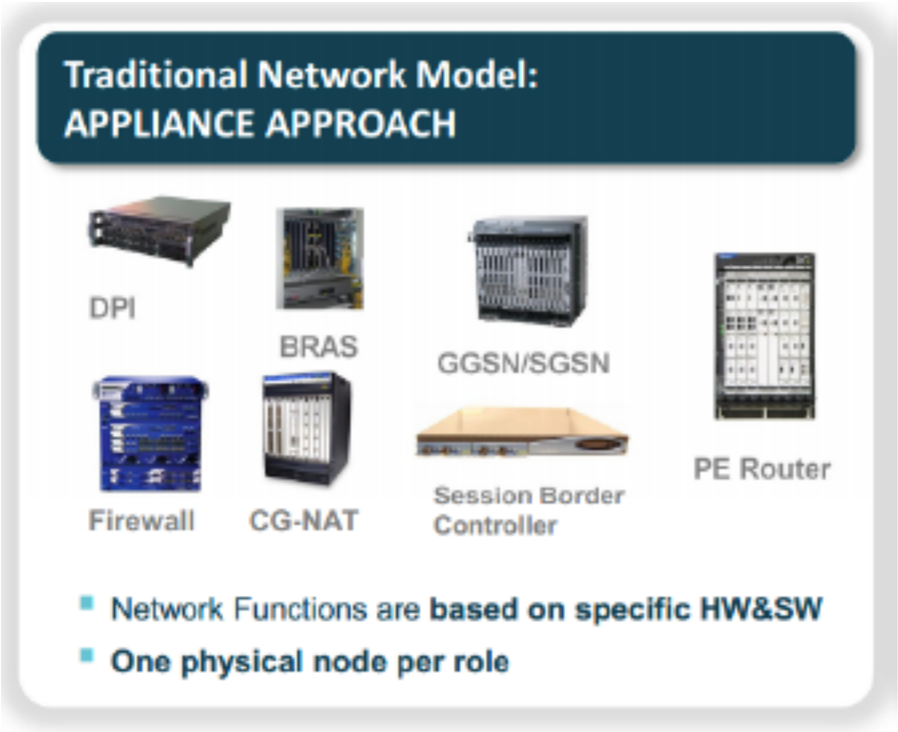
NFV for core slicing, Mobile edge computing

Confluence of Connectivity and Computing



- Hardware-oriented architec
- Not scalable for growing demand, IoT

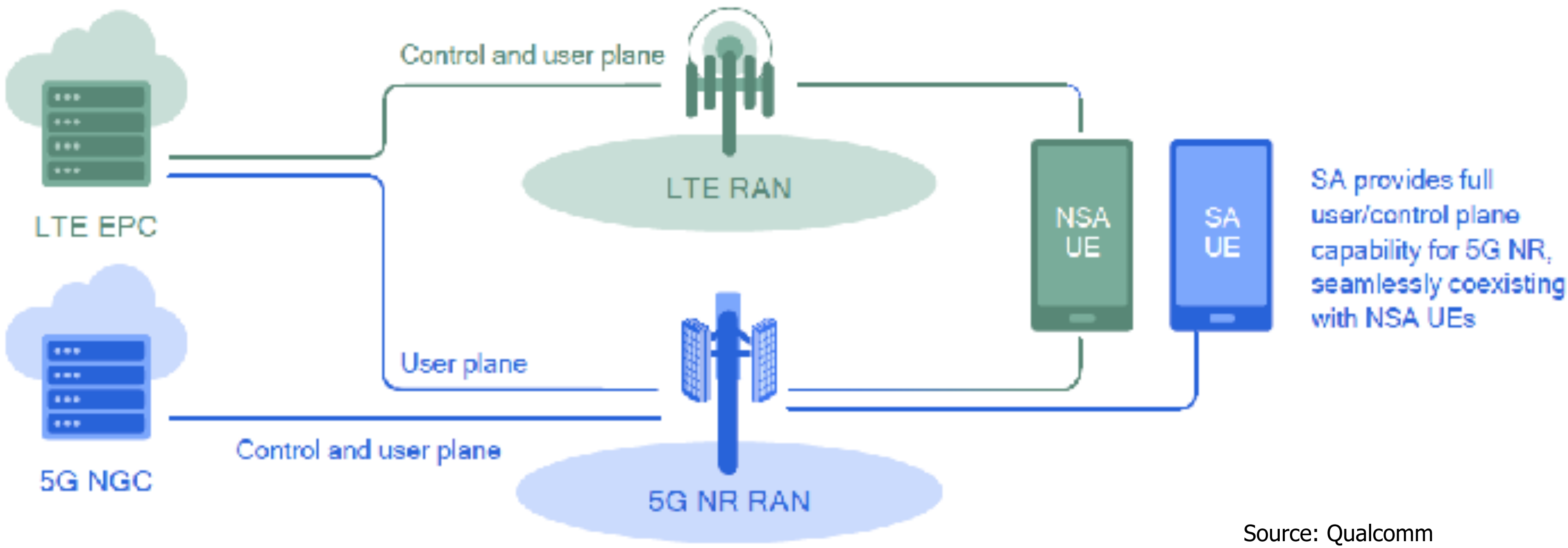
Today's Core Networks



Source: Telefonica, I+D, NFV

- Complex and cannot scale easily
- Launching new services is difficult and time consuming
- Procurement and operation is expensive

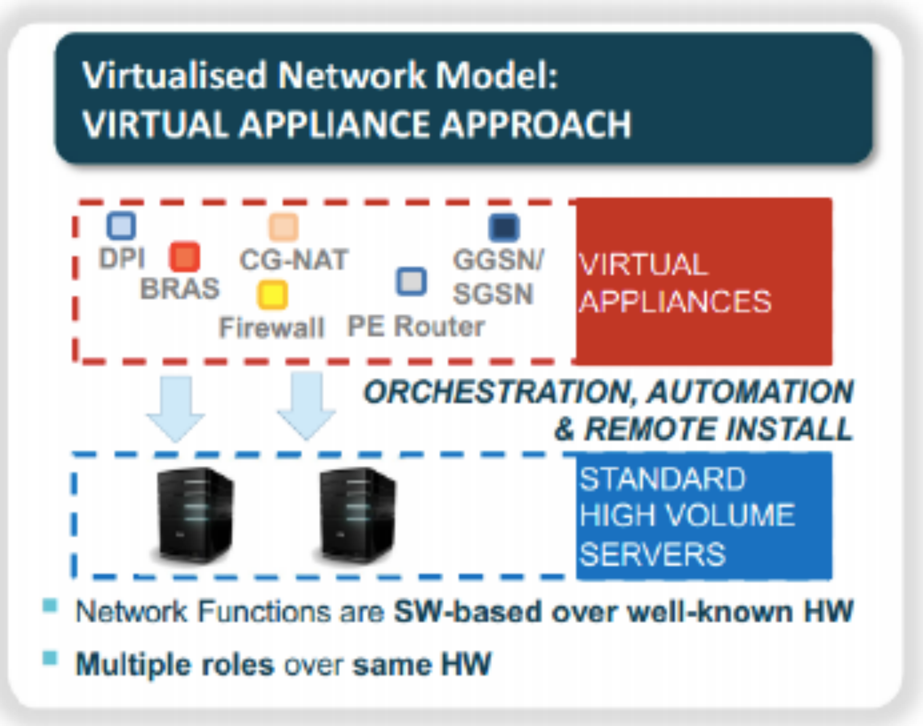
5G Next Generation Core (NGC)



Source: Qualcomm

- 5G standalone NR relies on NGC
- Leverages SDN/NFV to create optimized network slices
- Flexible business models, deployments
- Dynamic creation of services

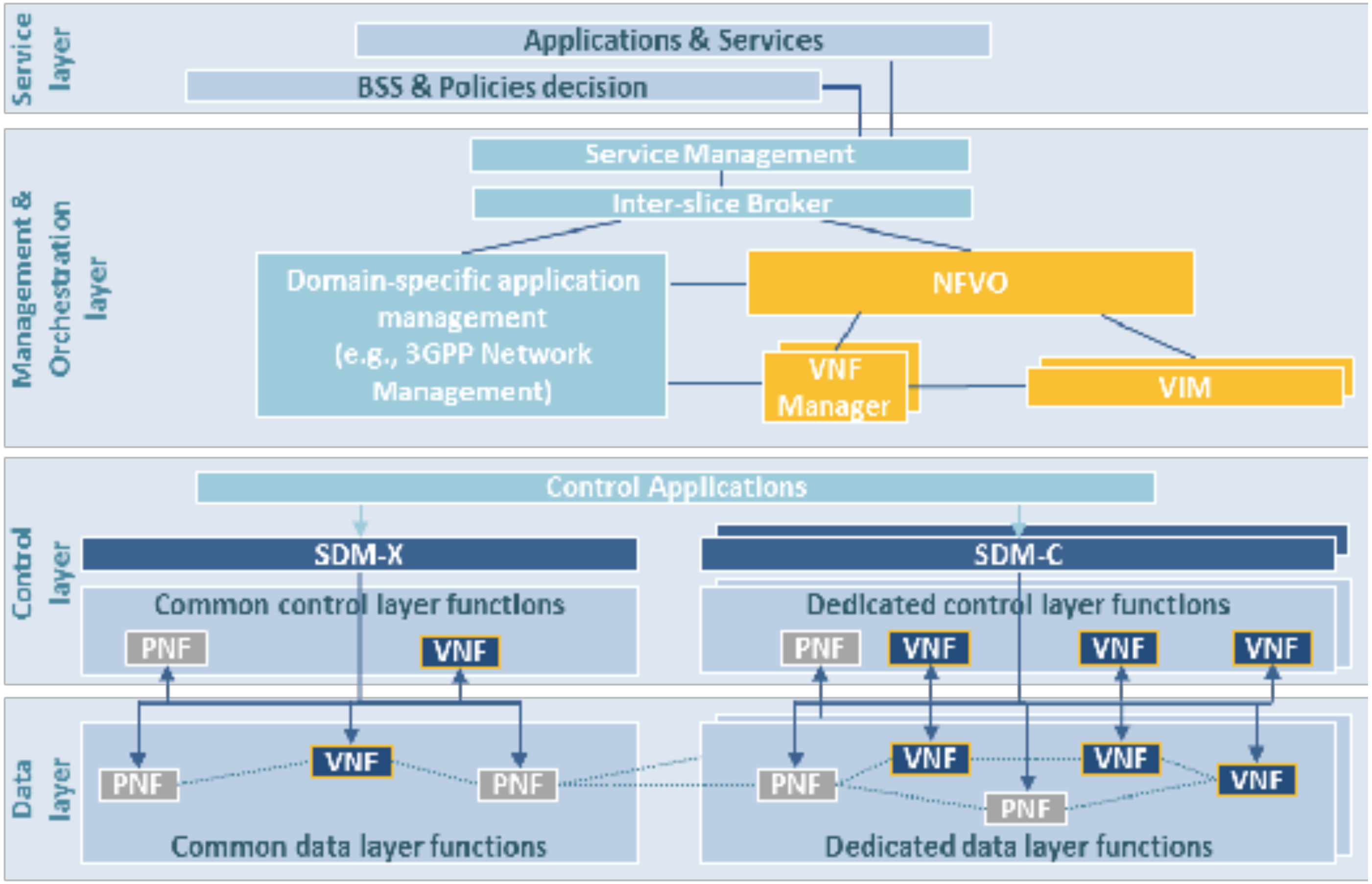
5G: Virtualized Core



Source: Telefonica, I+D, NFV

- Network Function Virtualization
  - Flexible use of logical resources, decoupled from physical resources
  - Dynamic scaling, programmability, orchestration
  - Performance, multi-tenancy, automation

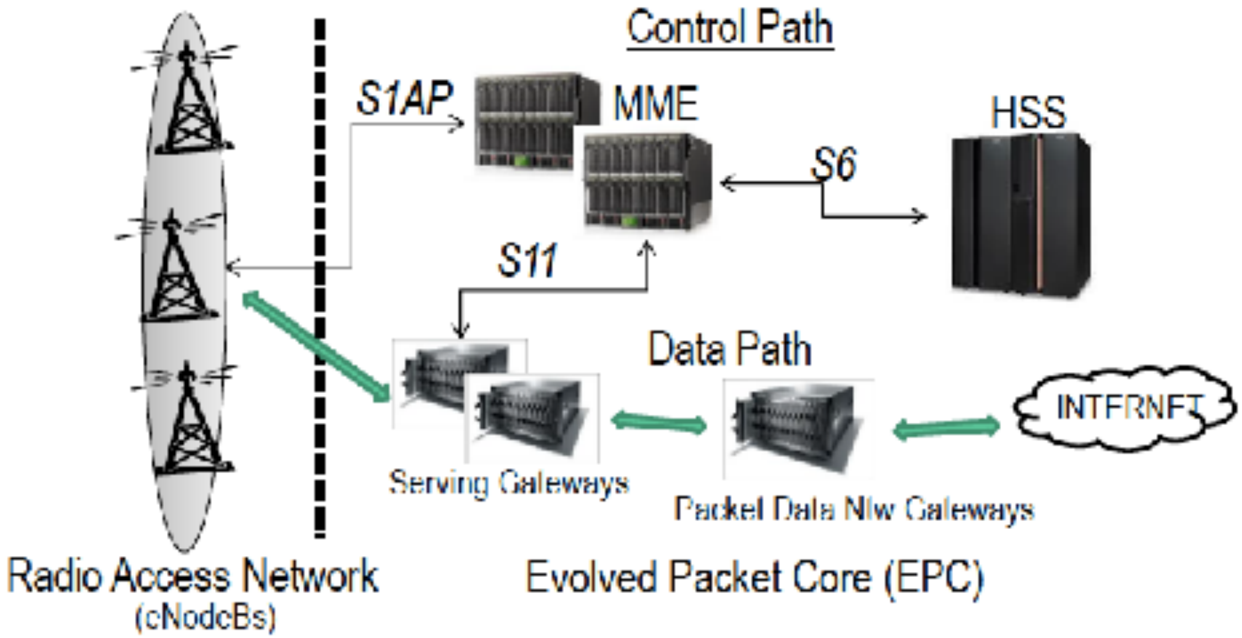
Scaling the Mobile Core



Source: 5G PPP

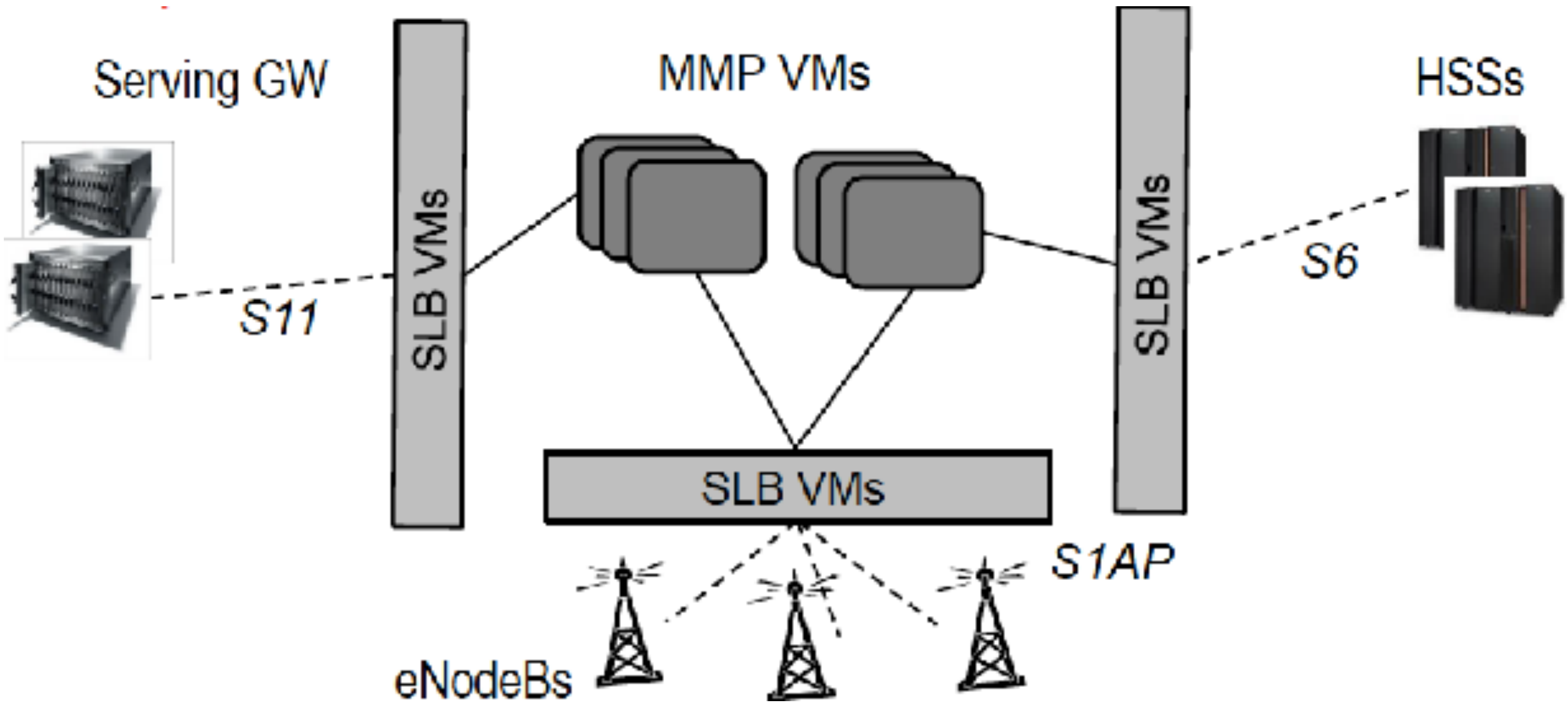
- SDN: decoupling control and data plane
- NFV: virtualization of control and data plane network functions

Scaling the Control Plane



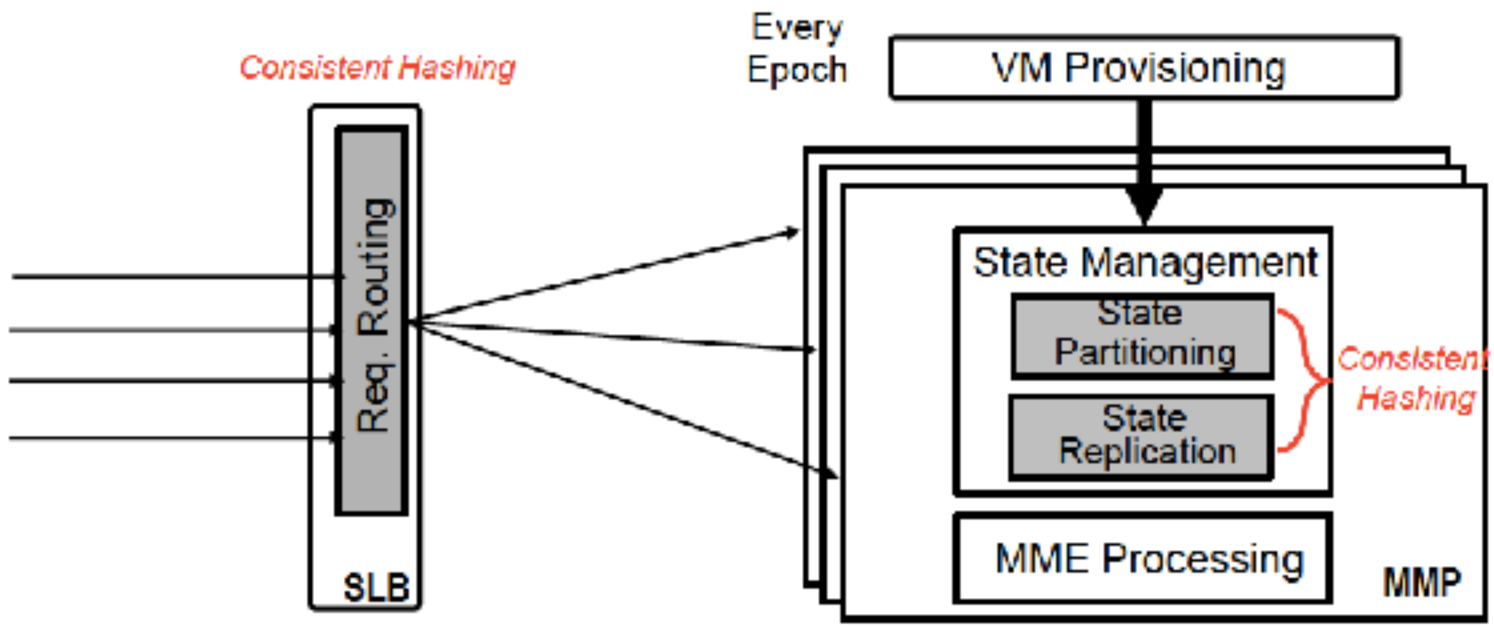
- Mobility Management Entity (MME)
  - Main control plane entity: overload affects user experience (connectivity and handover delays)
  - Static configurations limit flexibility and efficiency: cannot scale to the density of IoT connections

Virtualizing the Control Plane



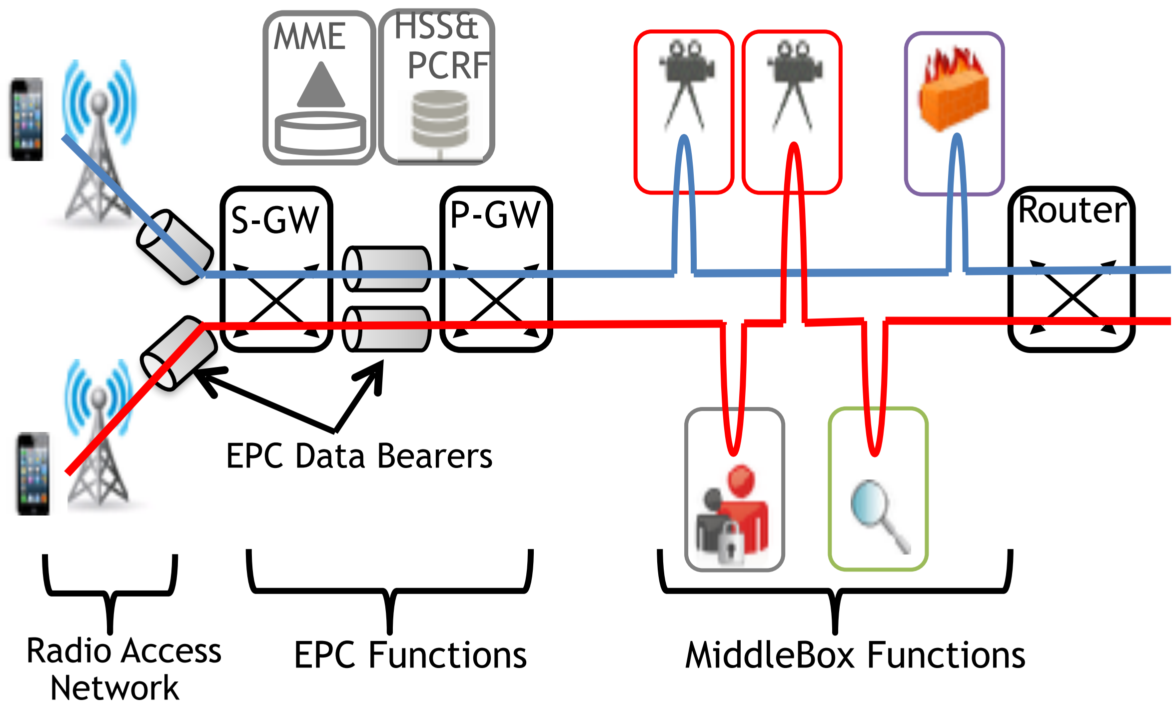
- Standard interfaces decoupled from MME device management
  - MME processing (MMP) entities store device state and process requests
  - Software load balancers forward requests from devices, SGW, HSS to the appropriate MMP VM

Virtualizing the Control Plane



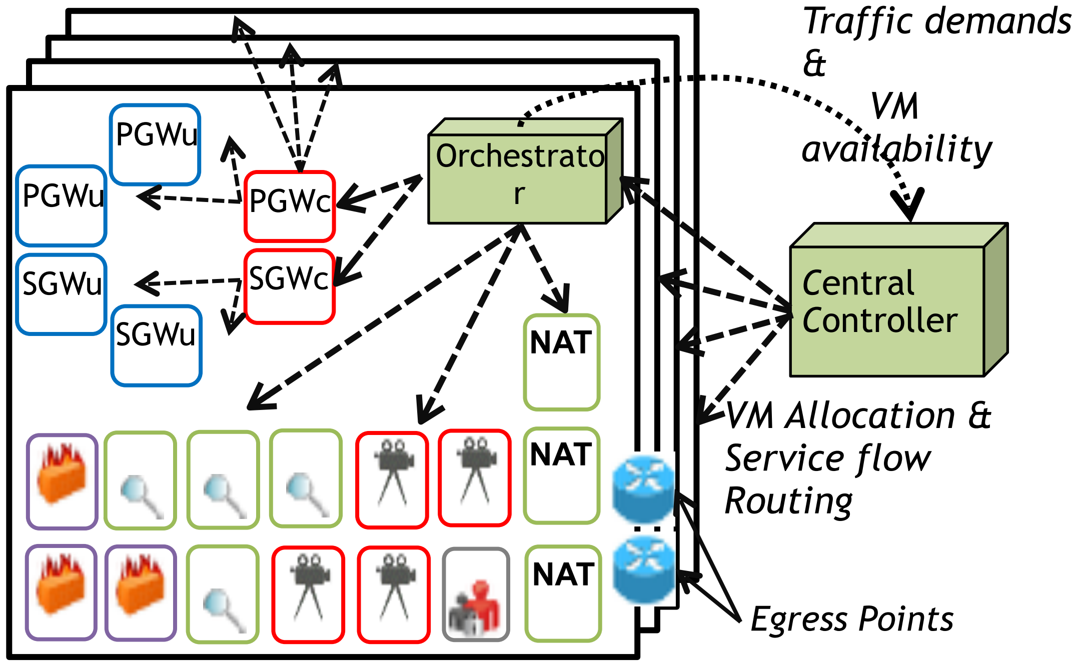
- Device state partitioned and replicated across VMs
- VMs provisioned based on perceived traffic load
- Concepts from distributed data stores can be leveraged for state management

Scaling the Data Plane



- Flexible provisioning of data plane gateway elements
- Agile routing and forwarding between gateway elements
- Service chaining of gateway elements and other IP middle boxes (firewall, transcoding, DPI, etc.) - critical for network slicing

Scaling the Data Plane



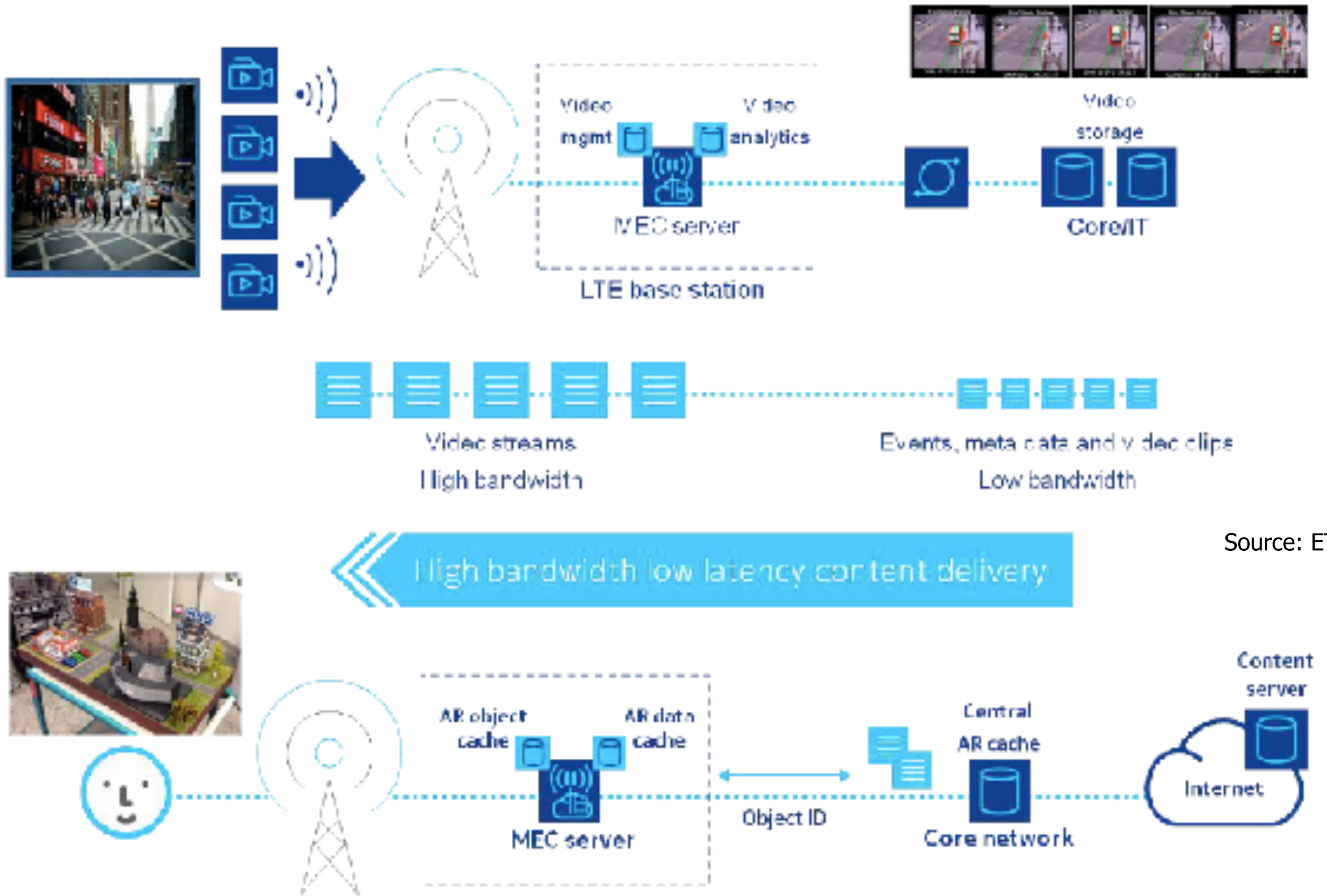
- Effective multiplexing of resources both within and across remote datacenters
- Network functions span both data plane gateway elements as well as other IP middle box functions

Mobile Edge Computing

- Emergence of continuous interactive (CI) mobile applications at scale
  - AR/VR, face recognition, autonomous driving

- Common characteristics
  - Highly responsive (~100ms)
  - Computationally intensive

MEC Use Cases



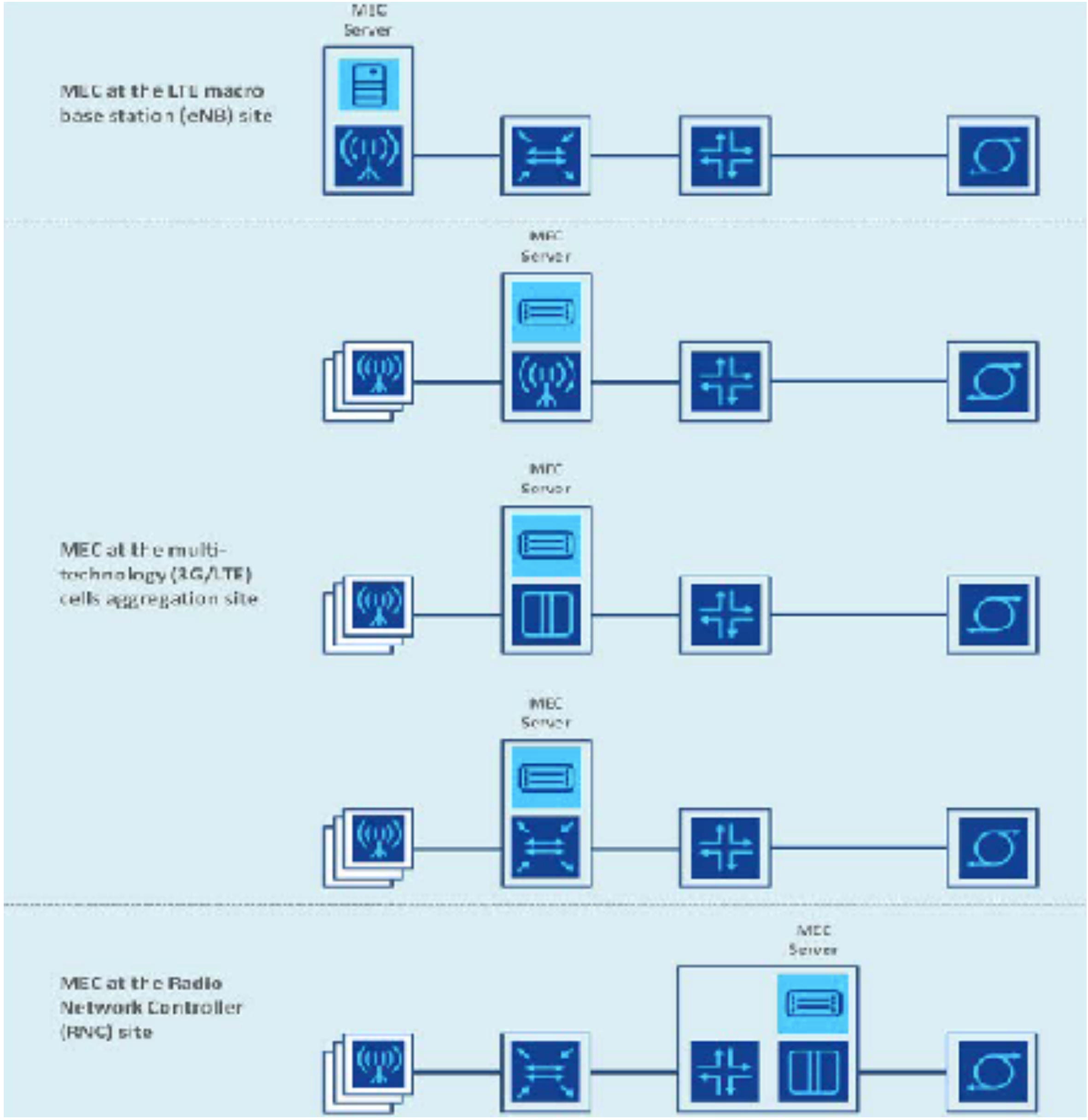
Source: ETSi, MEC W.P.

- Several use cases: video analytics, mobile AR, etc.

MEC Advantages

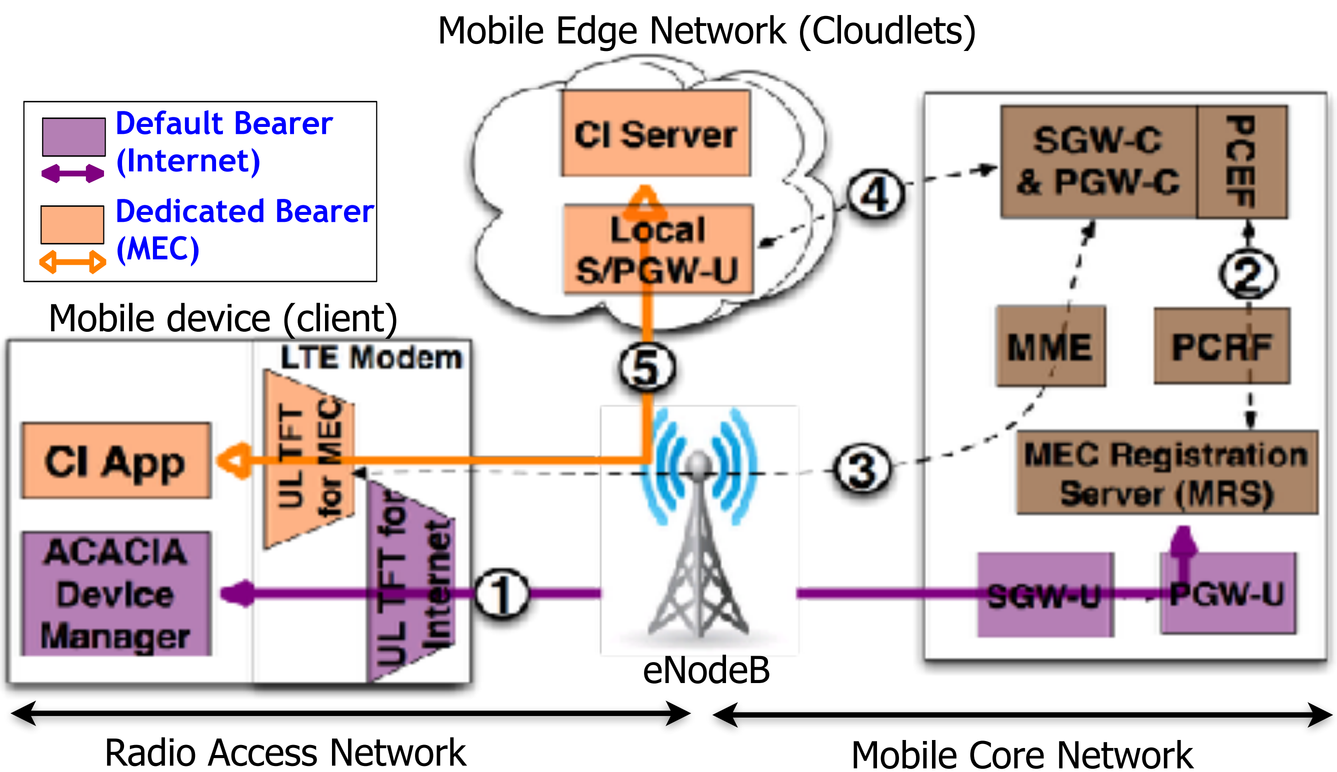
- Moves IT and computing capabilities to edge of core network to increase responsiveness of applications and services
- Leverages proximity to RAN edge to deliver ultra-low latency and high bandwidth
- Proximity, context and agility create opportunities for multiple players (mobile operators, service providers, OTT players, etc.)
- SDN and NFV enable mobile edge computing (MEC)

MEC Deployment Scenarios



Source: ETSI, MEC W.P.

MEC Orchestration



- SDN/NFV orchestrated mobile core/edge network
  - Scalable, low-latency control plane sets-up policies
  - LTE QoS bearers to set-up new flow to closest CI server
  - Deploy multiple G/W data elements, route to closest element
- eNB scheduler prioritizes bearer with spectrum virtualization

Computing Recap

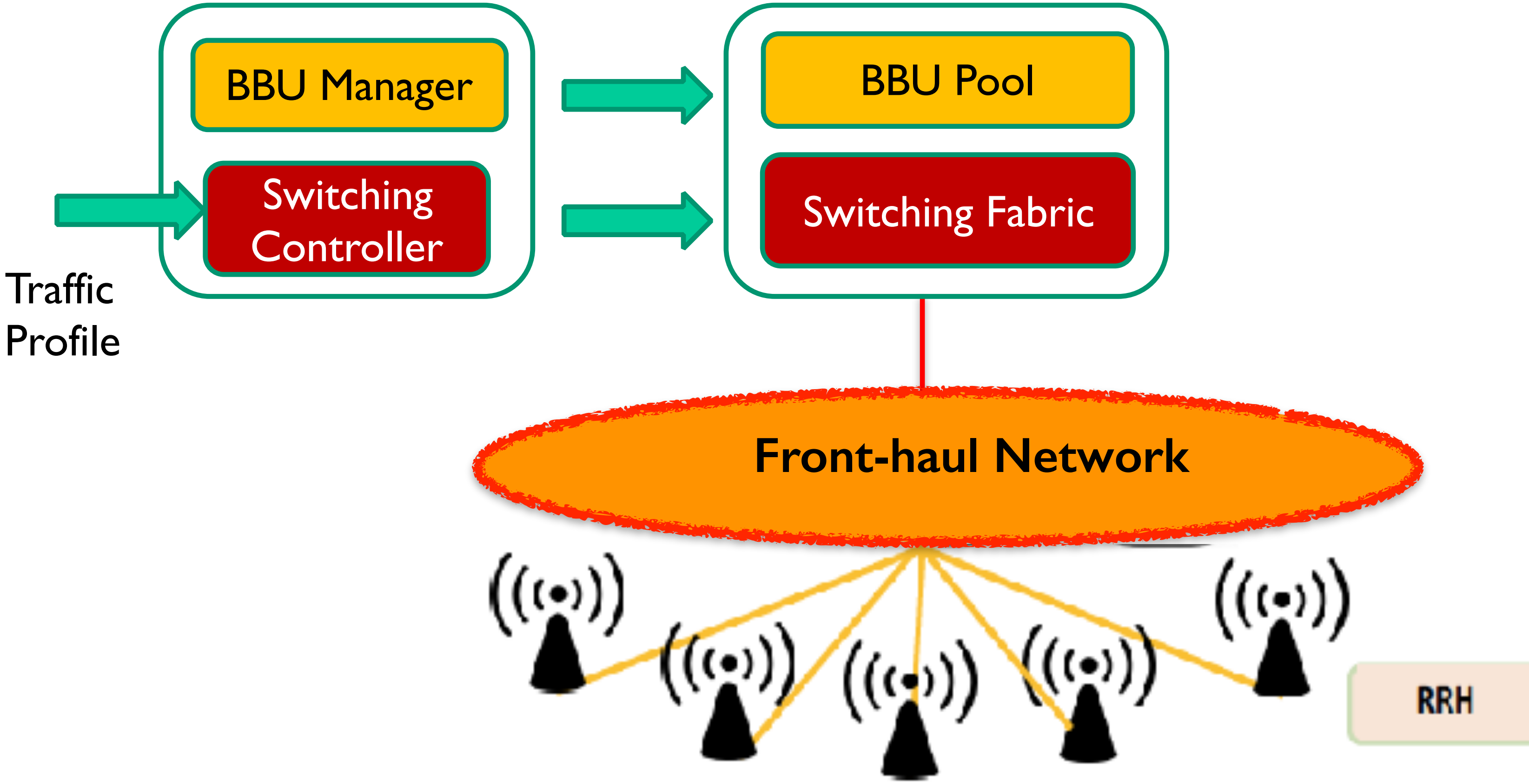
- Next Generation Core (NGC) will heavily leverage SDN/NFV to create dynamic network slices that cater to diverse services
  - Both control and data planes will be capable of flexible scaling
- Computing will move closer to the edge to cater to bandwidth/latency-intensive interactive services
- Hybrid models of cloud and edge computing will be leveraged as appropriate for hosted services

Roadmap

- Drivers of 5G
  - Single network caters to diverse use cases, which is revolutionary
- Building Blocks: Evolution at Multiple Layers
  - Radio
  - Access
  - Network
  - Computing
- Case Studies
  - SDN in wireless access
  - Mobile augmented reality through edge computing
  - LTE in the Sky: UAVs for on-demand LTE connectivity

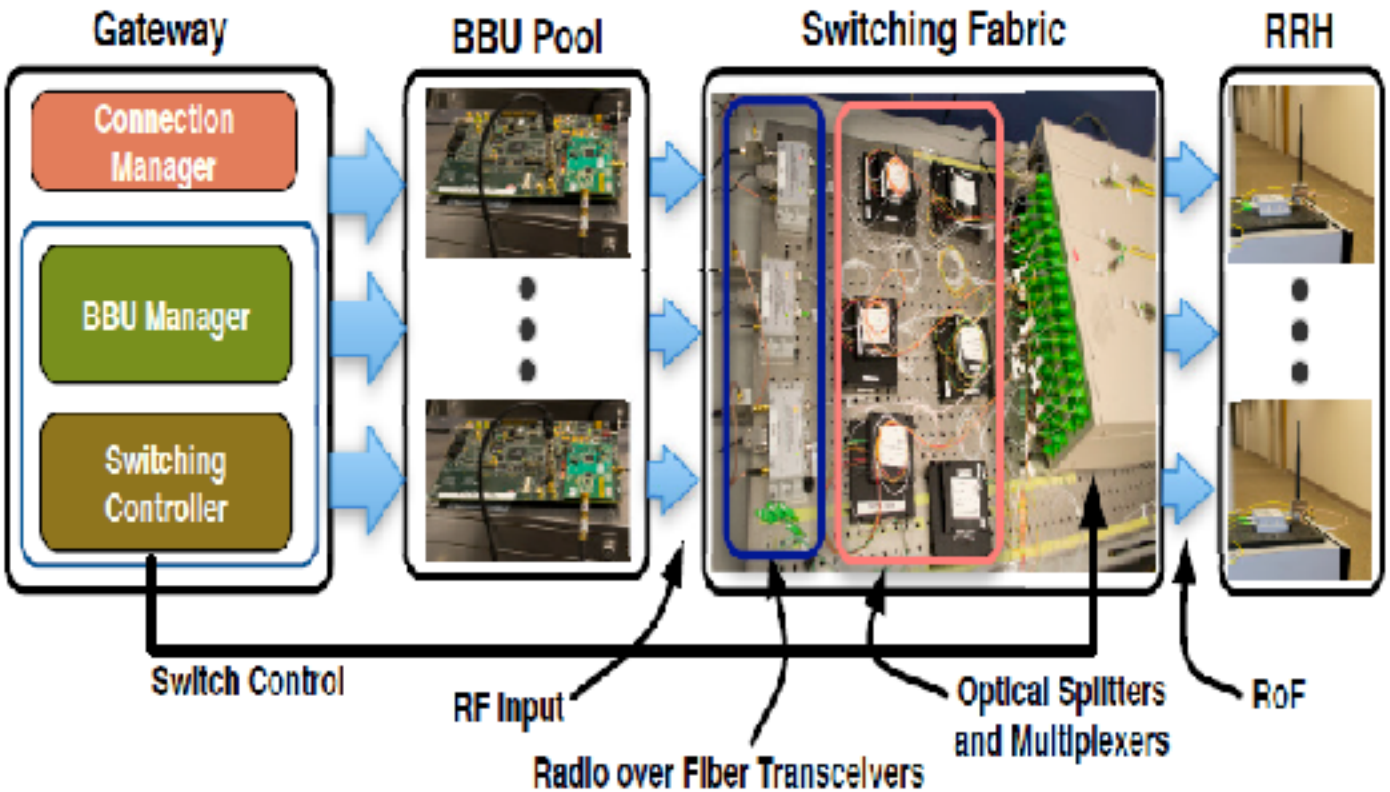
(1) SDN in Wireless Access (2012)

FluidNet C-RAN Architecture



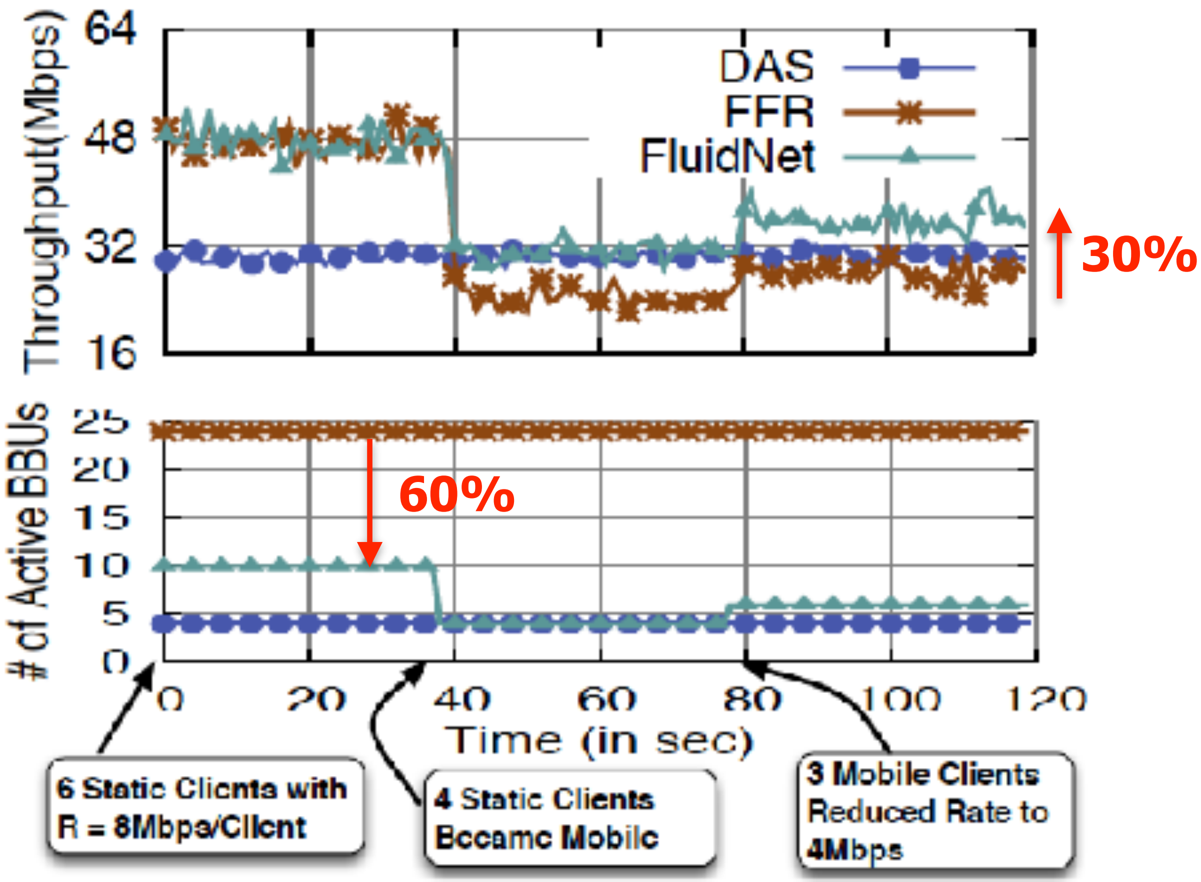
- FluidNet: A C-RAN architecture with software-defined front-haul

FluidNet Prototype



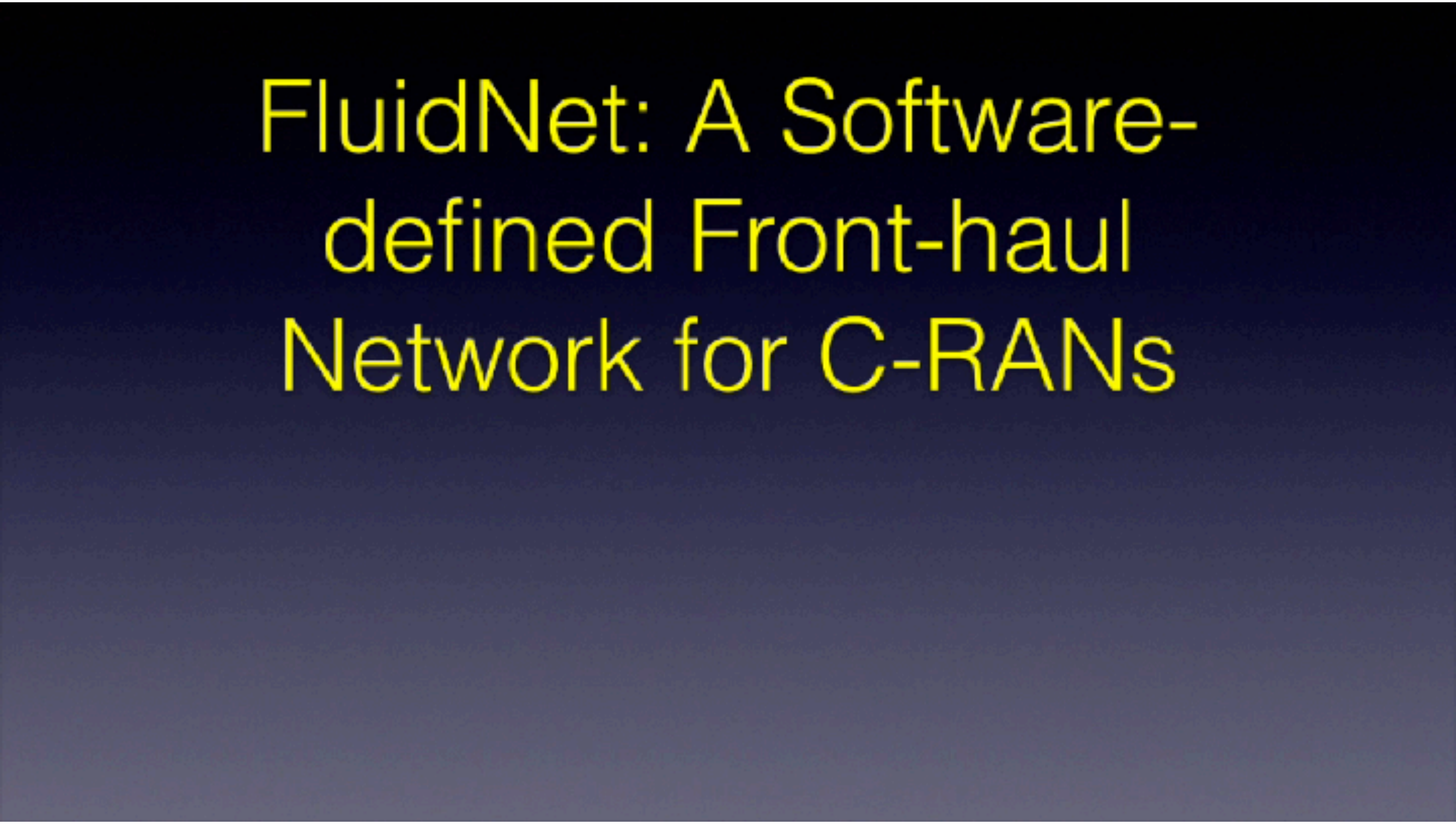
- Small-scale C-RAN test-bed based on WiMAX/LTE
  - 6 WiMAX/LTE eNBs, 6 RRHs, 6 WiMAX/LTE clients; single sector with 6 small cells
  - Four 5 MHz carriers; net 20 Mhz bandwidth; 24 logical BBUs
  - Front-haul: Radio-over-Fiber (analog RF) transport using WDM
  - Software-defined optical switching for front-haul configuration

Adapting to Traffic & User Dynamics



- FluidNet adapts its front-haul configurations to traffic dynamics
- Outperforms FFR performance at less than half its BBU consumption

Demo



(2) Mobile augmented reality through edge computing (2015)

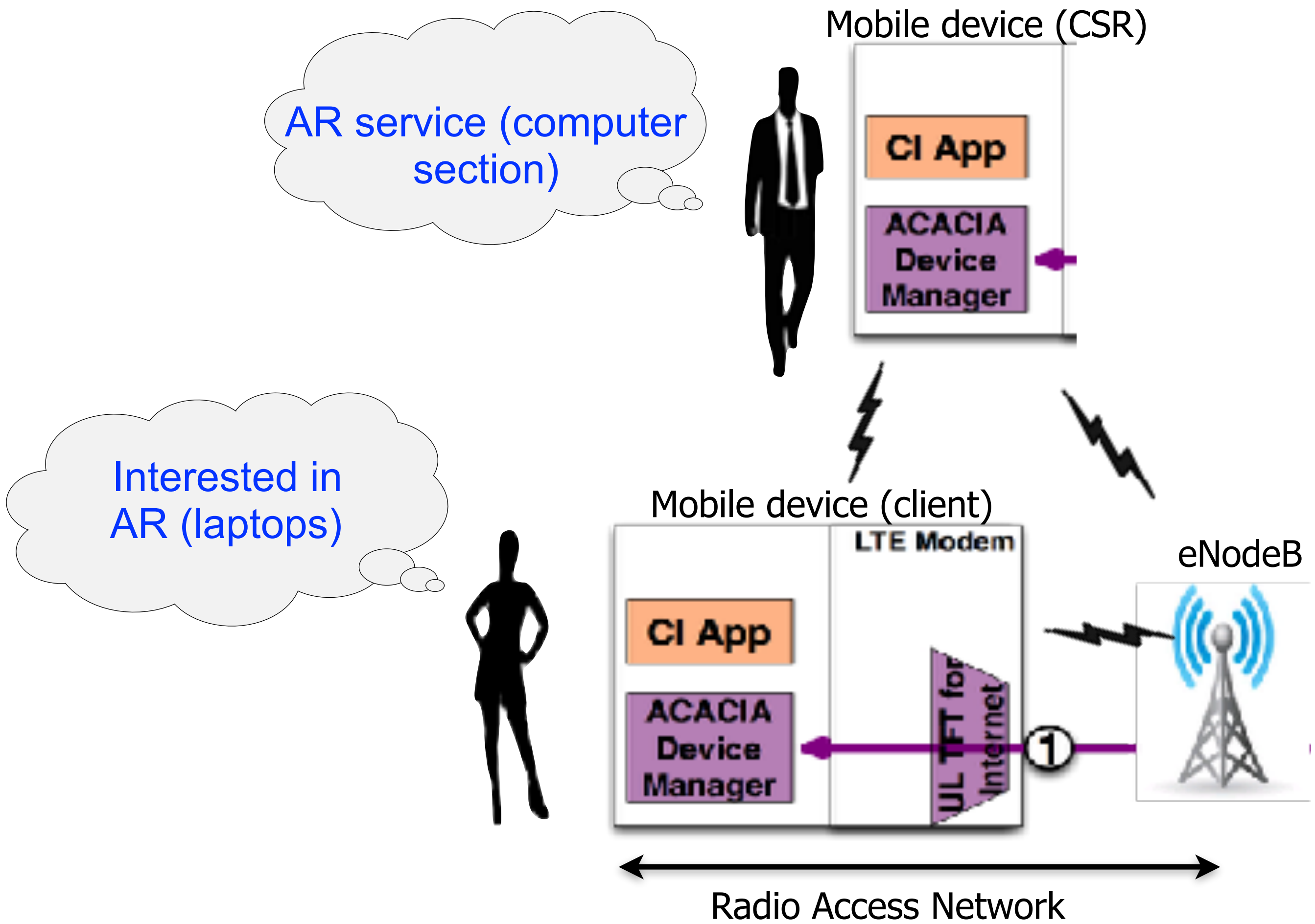
Vision-based Mobile AR Applications

- Focus camera on objects (retail application)
- Get real-time object info (price, reviews, etc.) overlaid on camera feed

Making it Happen with LTE

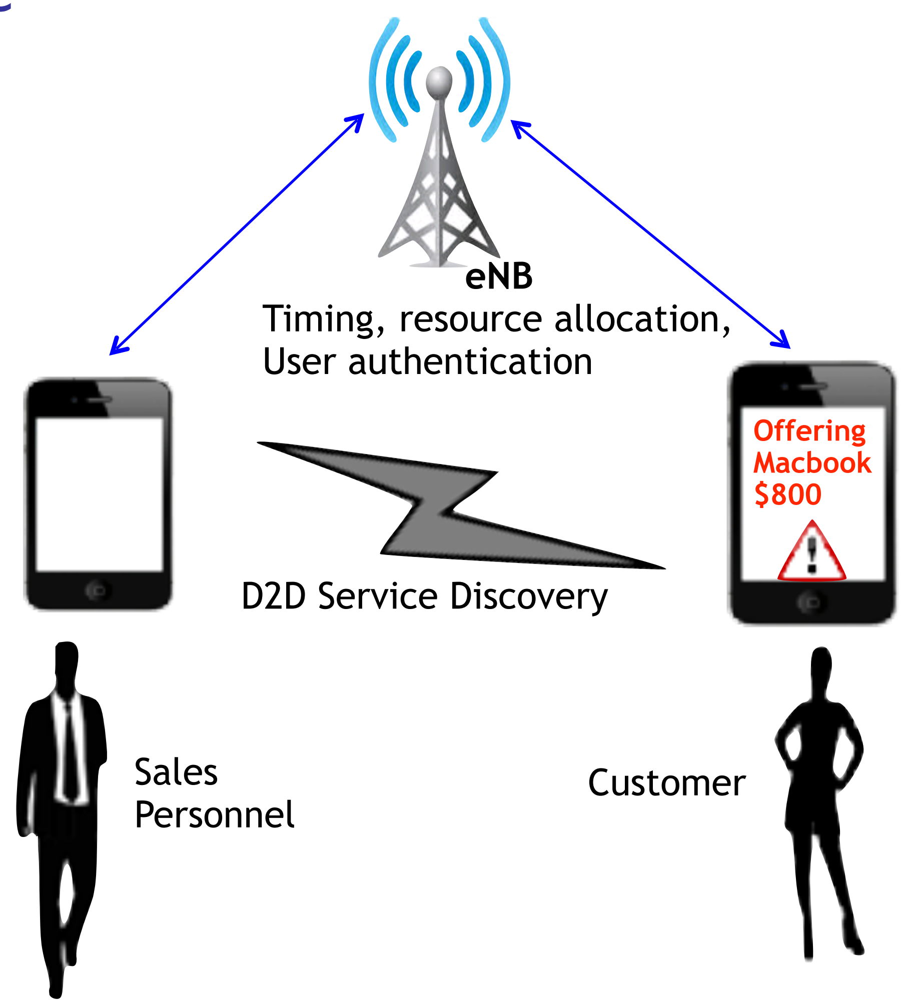
- A holistic approach that integrates device, network and application
- ACACIA: A service abstraction framework that orchestrates client, network and application jointly
  - Key Ingredient: User context
  - Optimize both network handling and application processing

(i) Context-based Service Discovery

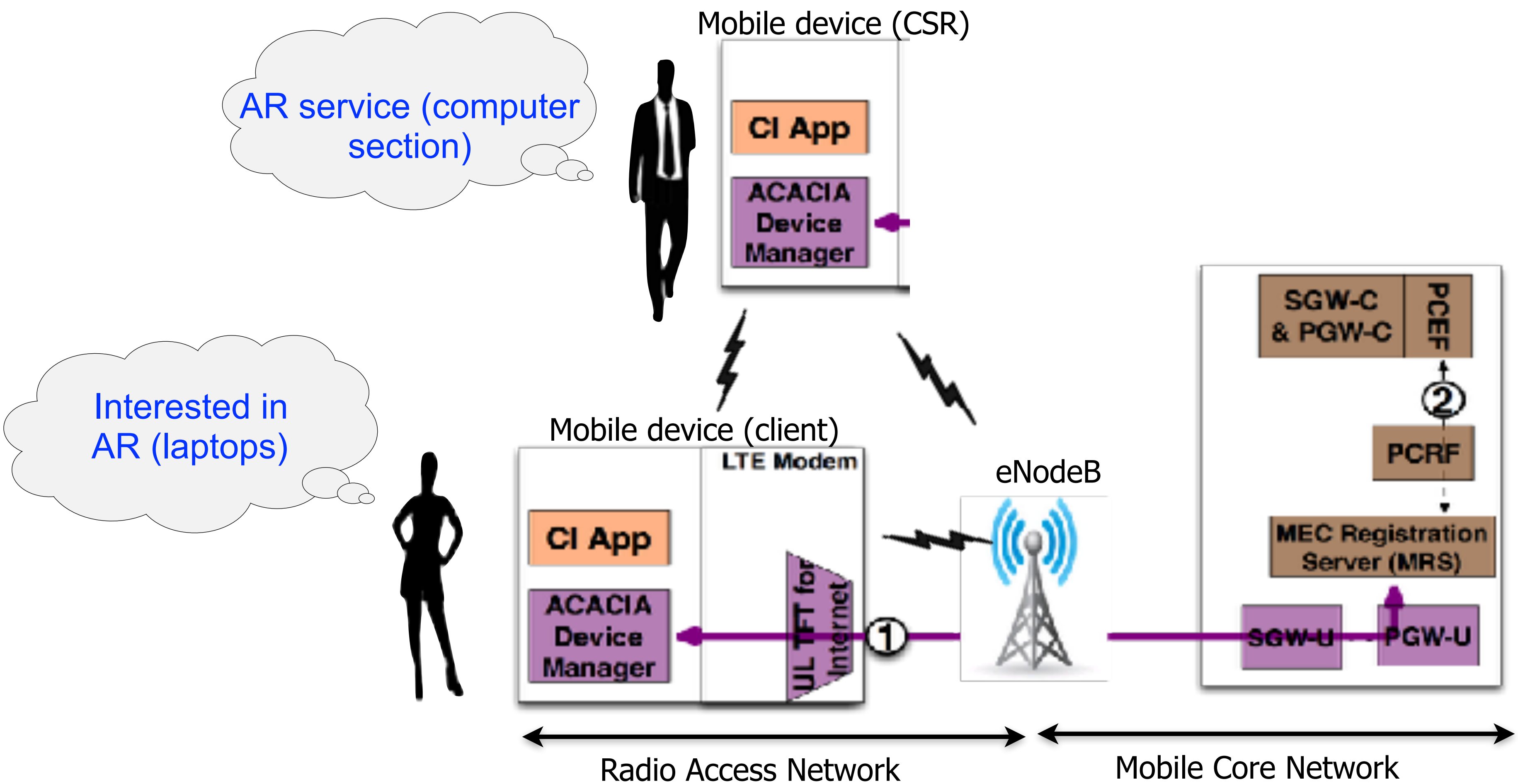


(i) Context-based Service Discovery

- D2D (LTE-direct) service discovery
  - Leverage LTE infrastructure
  - Pub-Sub system at physical layer
  - Filter by user interests
  - Good range, scalability

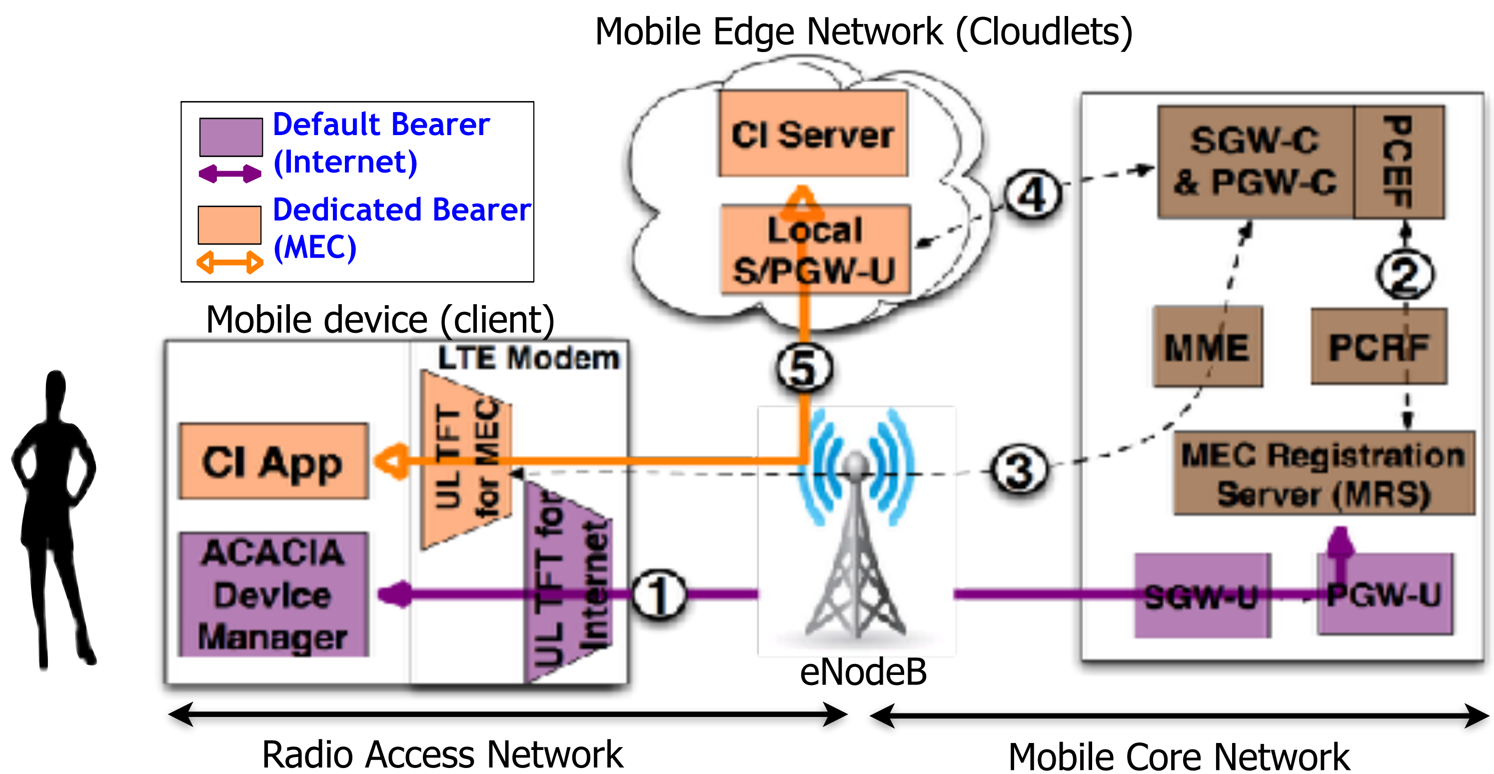


(ii) Context-aware Traffic Classification



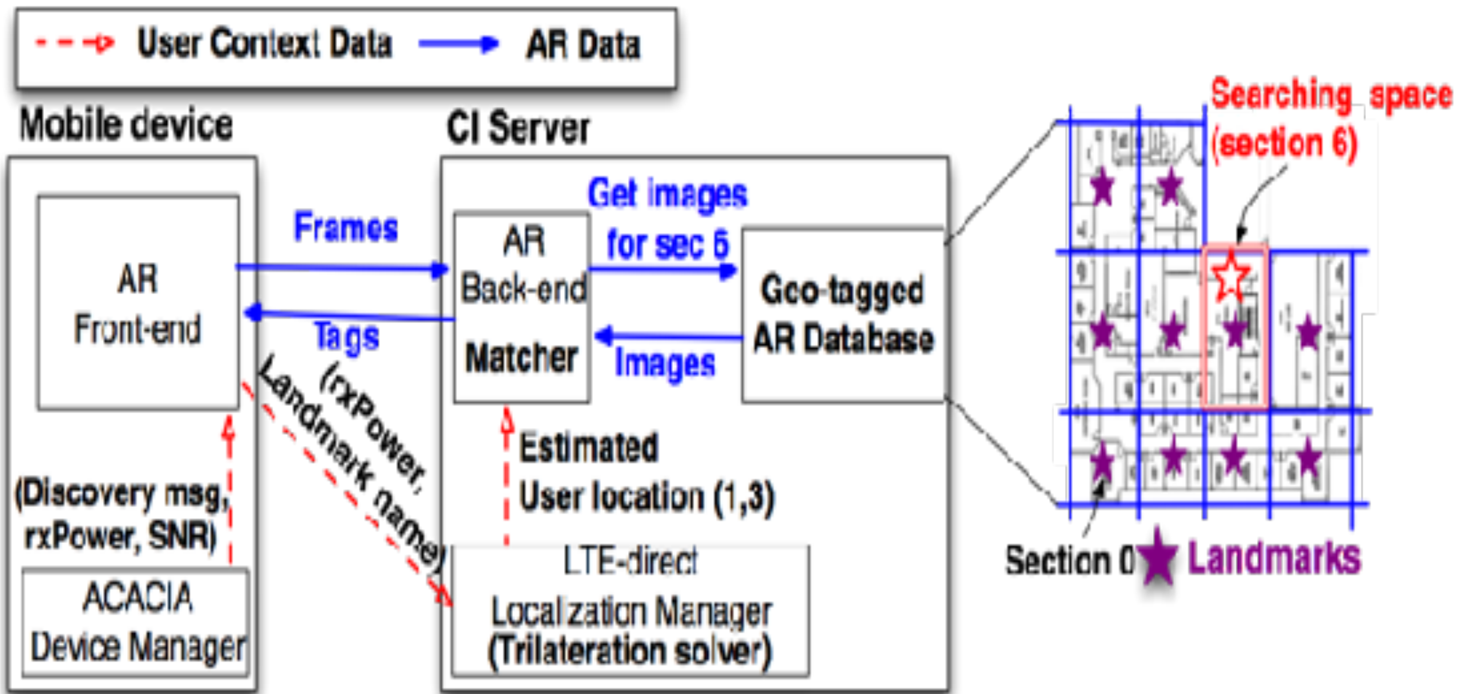
- Client requests connectivity to CI server
- CI traffic classified at client (source)

(iii) ACACIA Mobile Edge Network



- SDN/NFV orchestrated mobile core/edge network
  - Scalable, low-latency control plane sets-up policies
  - LTE QoS bearers to set-up new flow to closest CI server
  - Deploy multiple G/W data elements, route to closest element
- eNB scheduler prioritizes bearer with spectrum virtualization

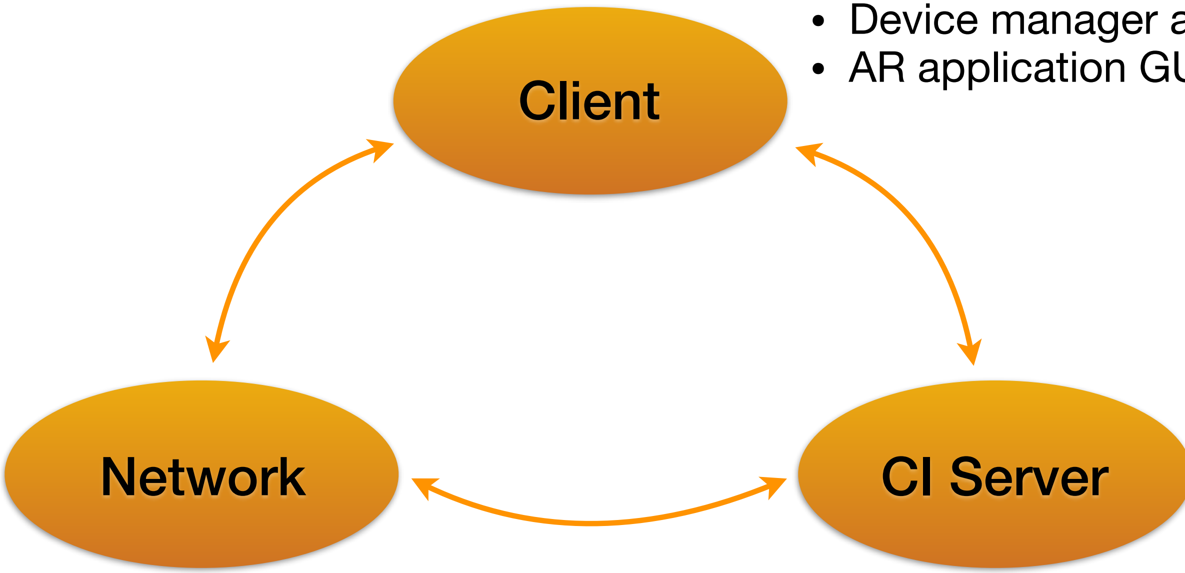
(iv) Context-aware Application Optimization



- Context speeds up object detection
    - Localize client using proximity to presence points
    - Geo-tagged DB of objects; targeted search using client location
- Object detection refines client location

ACACIA Prototype (2015)

- D2D service discovery
- Device manager as Android service
- AR application GUI



- OpenEPC extension for dedicated flows
- Data plane routing using Open vSwitch, Ryu SDN controller

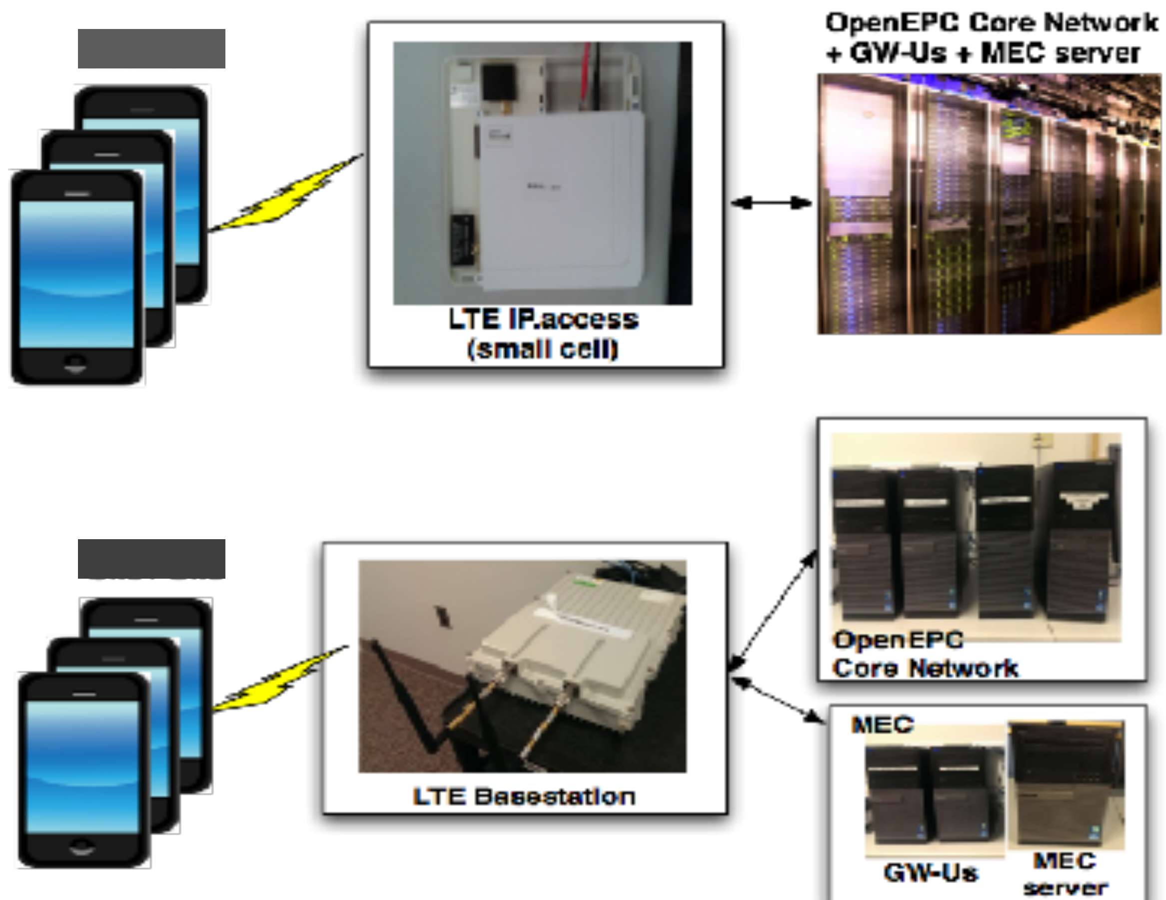
- OpenCV (Surf) for object detection
- Geo-tagged database
- Client localization

Network Set-up

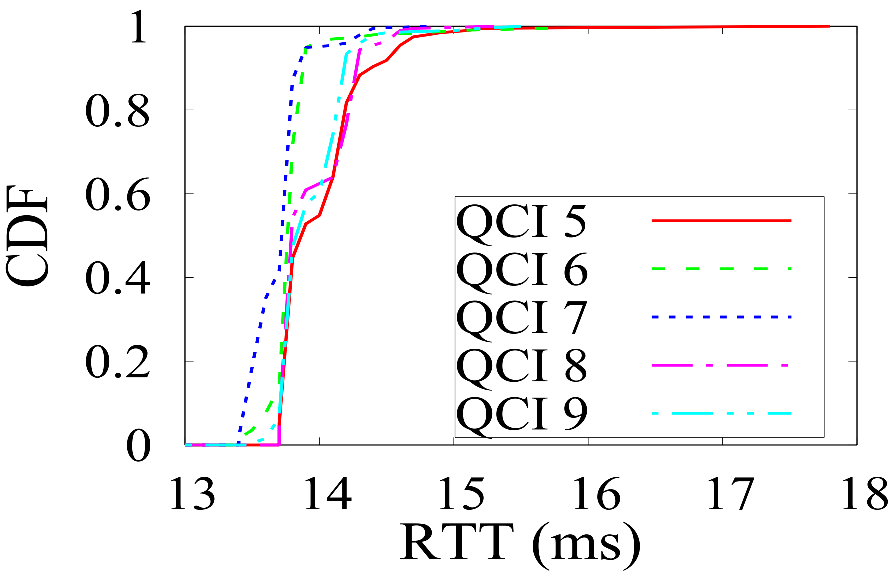
- Two mobile network test-beds

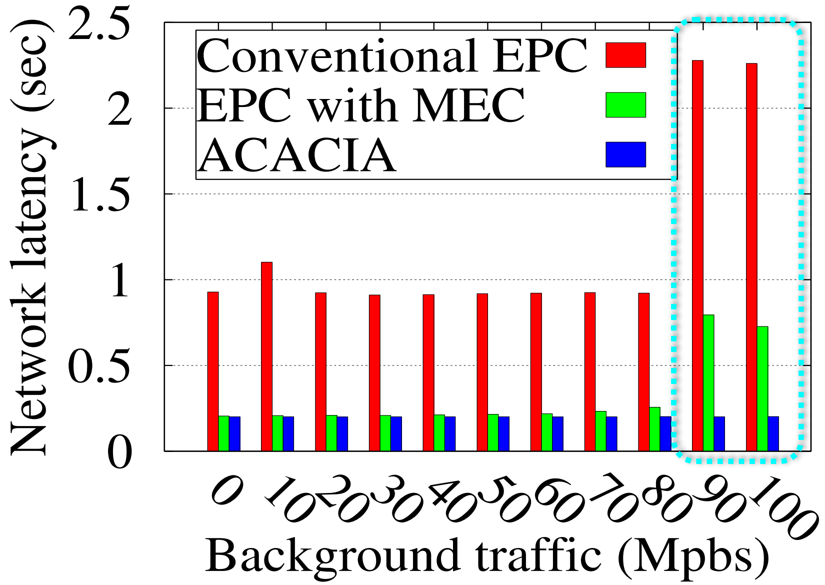
One+ one, Nexus 5,
Huawei dongle

One+ one, Nexus 5,
Pantech dongle



Network Latency

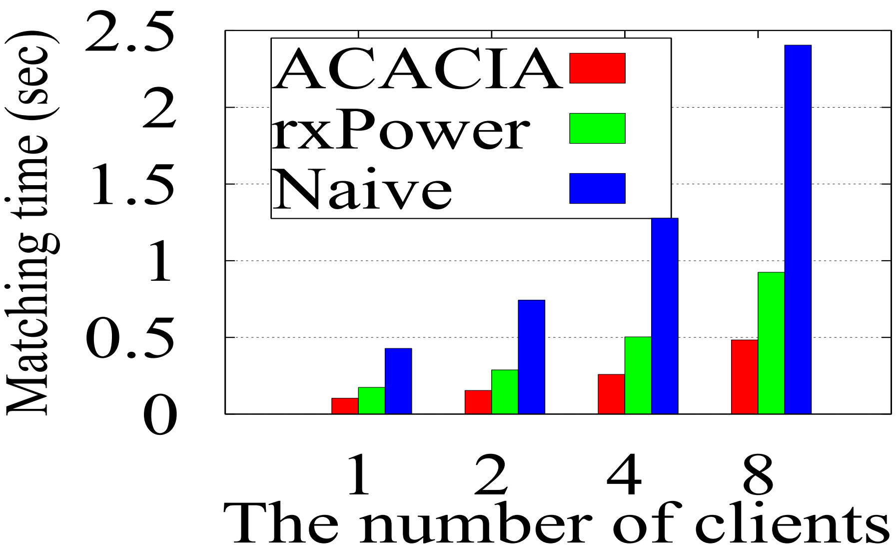


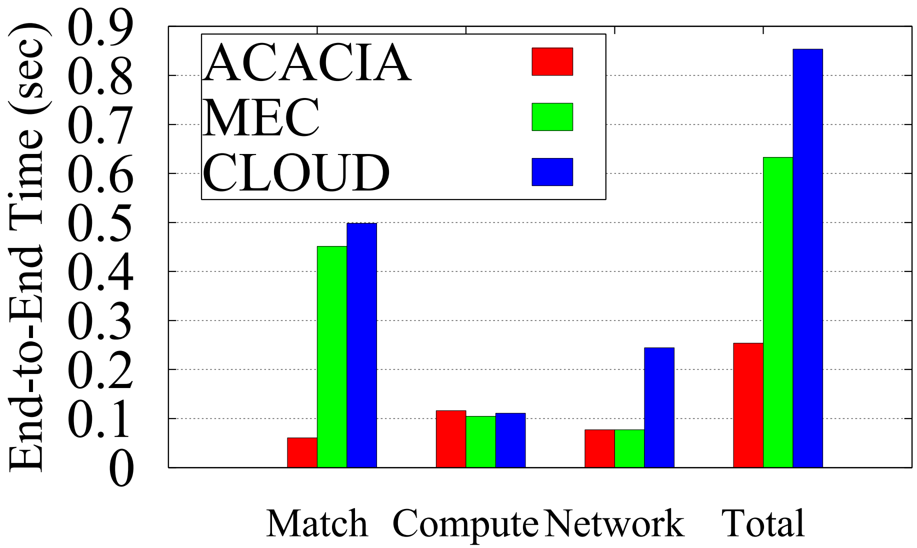


ACACIA RTT (~14 ms) << LTE RTT (>70 ms)

- Location: MEC helps - 14ms RTT (12ms in access, 1.6ms in core)
- Traffic isolation critical to avoid core network bottleneck

Application and End-End Latency





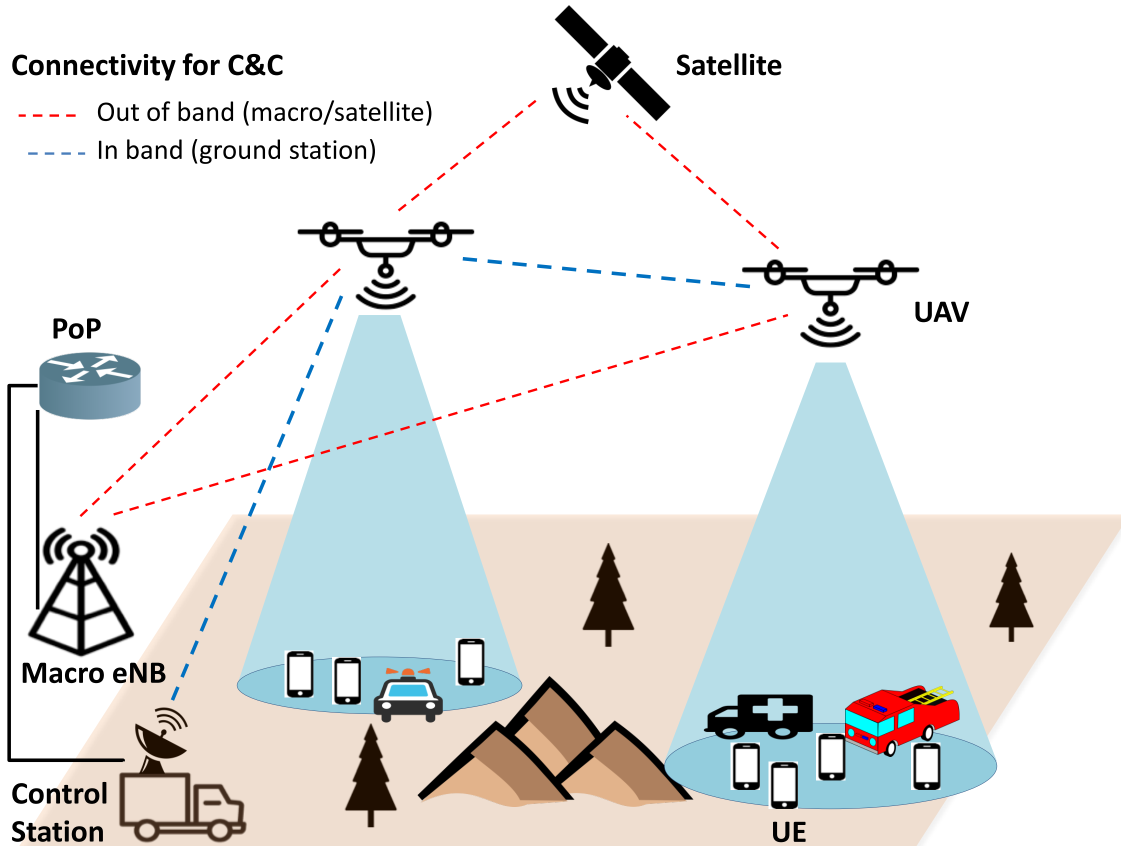
(5 sections, 21 subsections,>200 objects)

- Geo-tagged DB with location-based matching
  - Better scaling with multiple clients: 5x reduction
- End-end: 3x reduction (~200ms) from network and application optimization

Demo

(3) LTE in the Sky: UAVs for on-demand LTE Connectivity (2017)

Airborne LTE Network for Public Safety



- Low-altitude UAV networks provide "on-demand" LTE connectivity
  - Serve as augmenting hot-spots or stand-alone networks

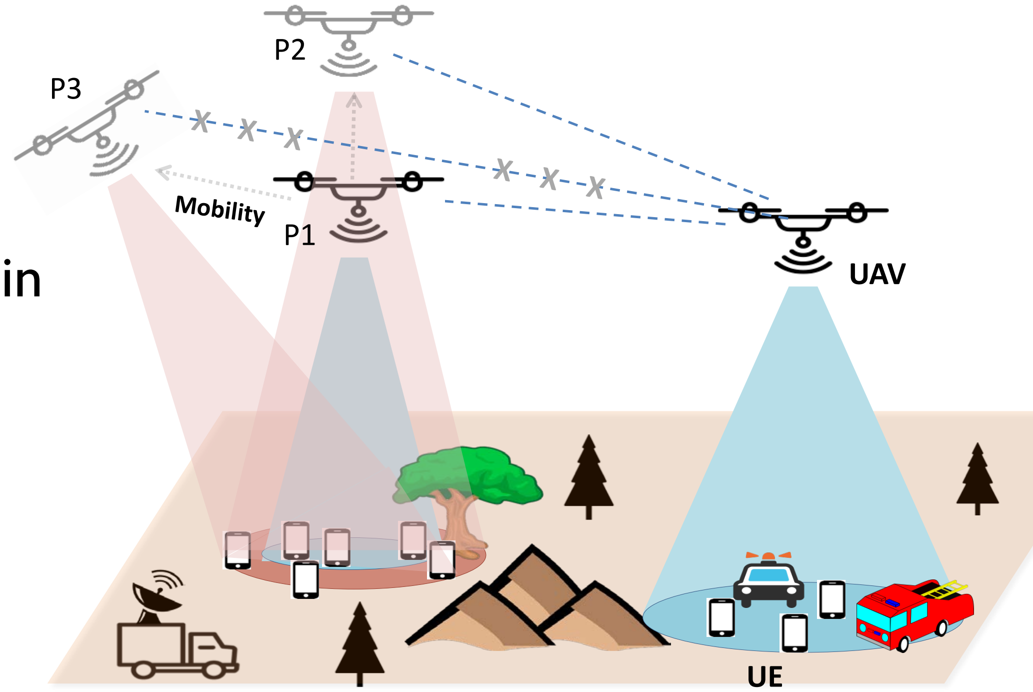
Deployment Challenges



- Solutions today are "tethered"
  - Only LTE radio on UAV; EPC on the ground
  - UAV tethered by wire to ground for power
- Need to deploy both LTE RAN (BS) and Core on UAV for "un-tethered" operation
  - Resource-constrained UAV platforms
  - Re-architect core network for UAV deployment

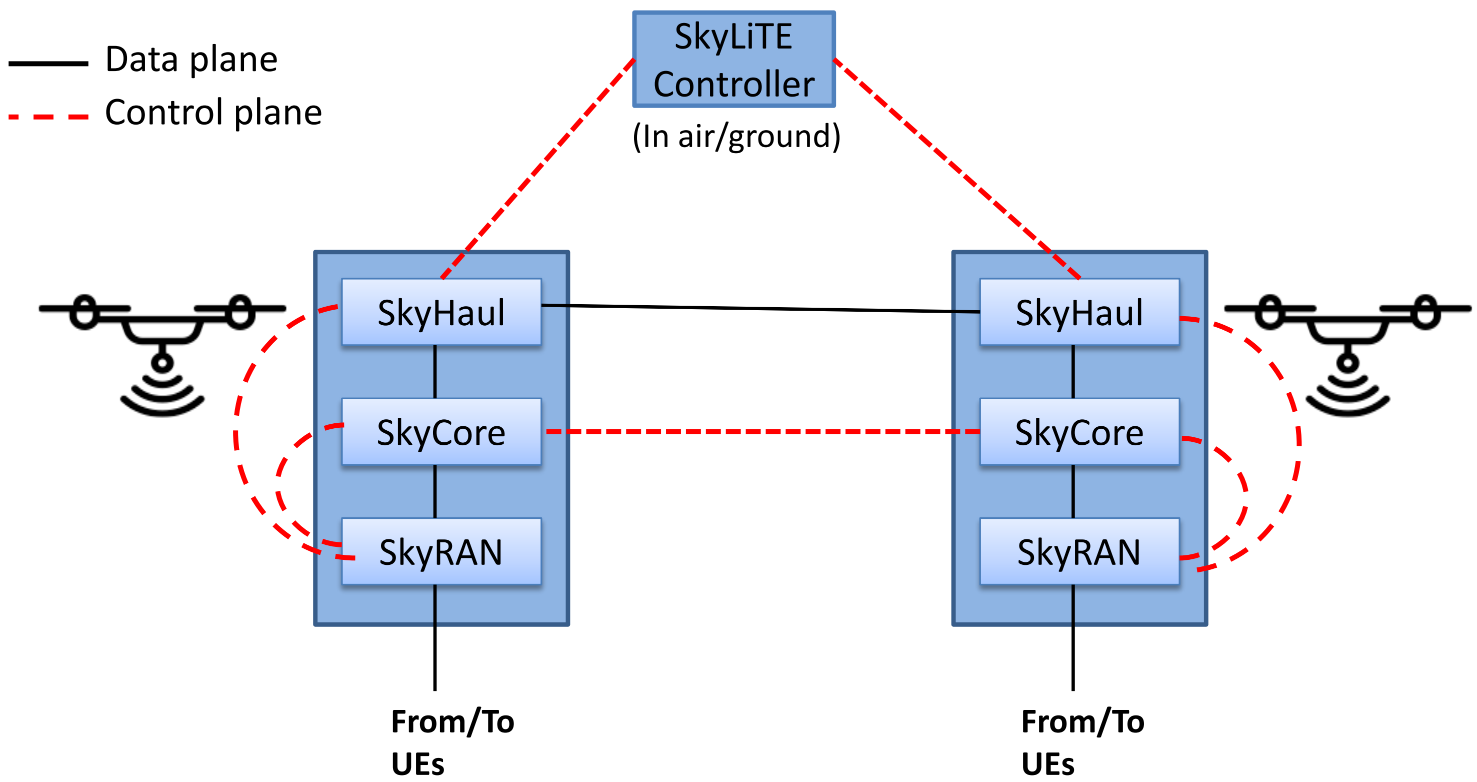
Connectivity Challenges

- RAN
  - Optimize connectivity for multiple UEs jointly
  - Radio conditions vary significantly based on terrain
- Backhaul
  - Multiple UAVs needed for coverage
  - RAN and backhaul optimization inter-twined



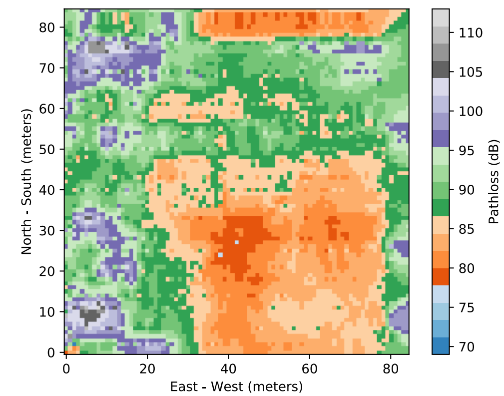
- Core
  - On-ground design becomes bottleneck due to wireless RAN-Core link

SkyLiTE: An E2E Multi-UAV Network for LTE Connectivity (2017)

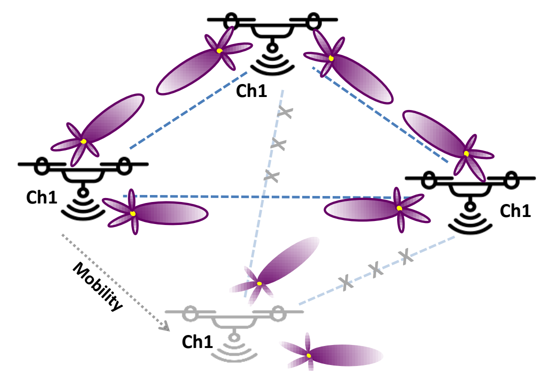


SkyLiTE Building Blocks

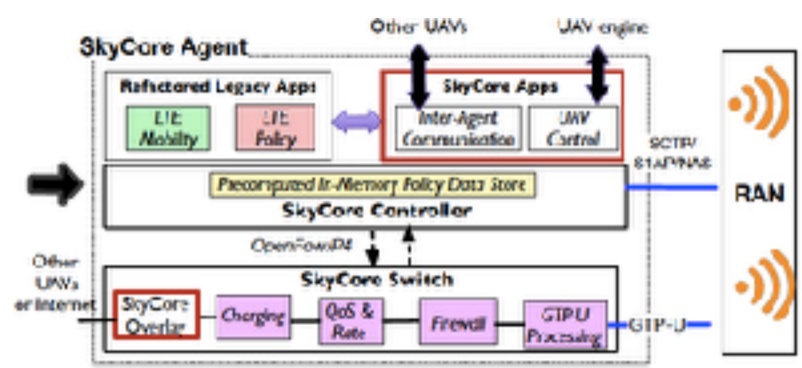
- SkyRAN
  - Self-organizing mechanisms for collecting measurements, generation of RF maps for optimized UAV placement



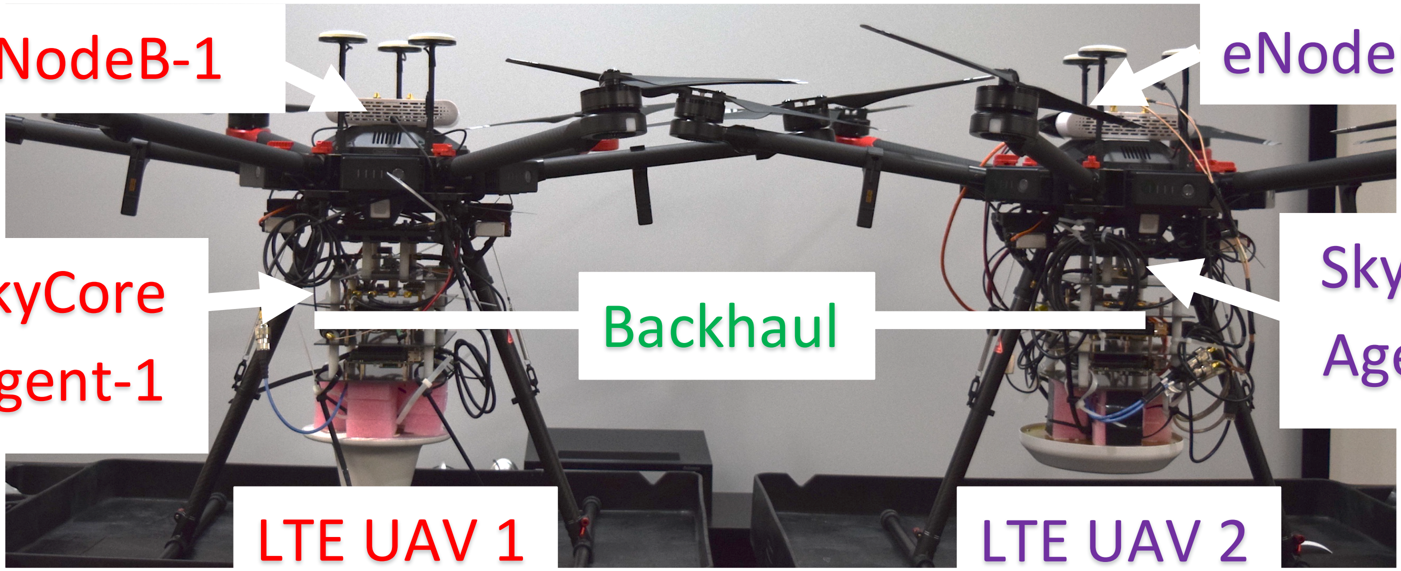
- SkyHaul
  - mmWave self-adapting mesh backhaul; beamforming and tracking, jointly optimized with SkyRAN



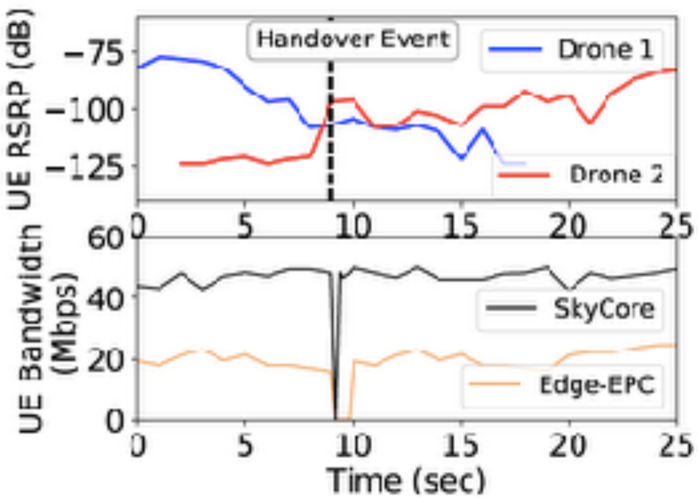
- SkyCore
  - Novel edge EPC agent (SDN/NFV) architecture for handling resource constraints and mobility



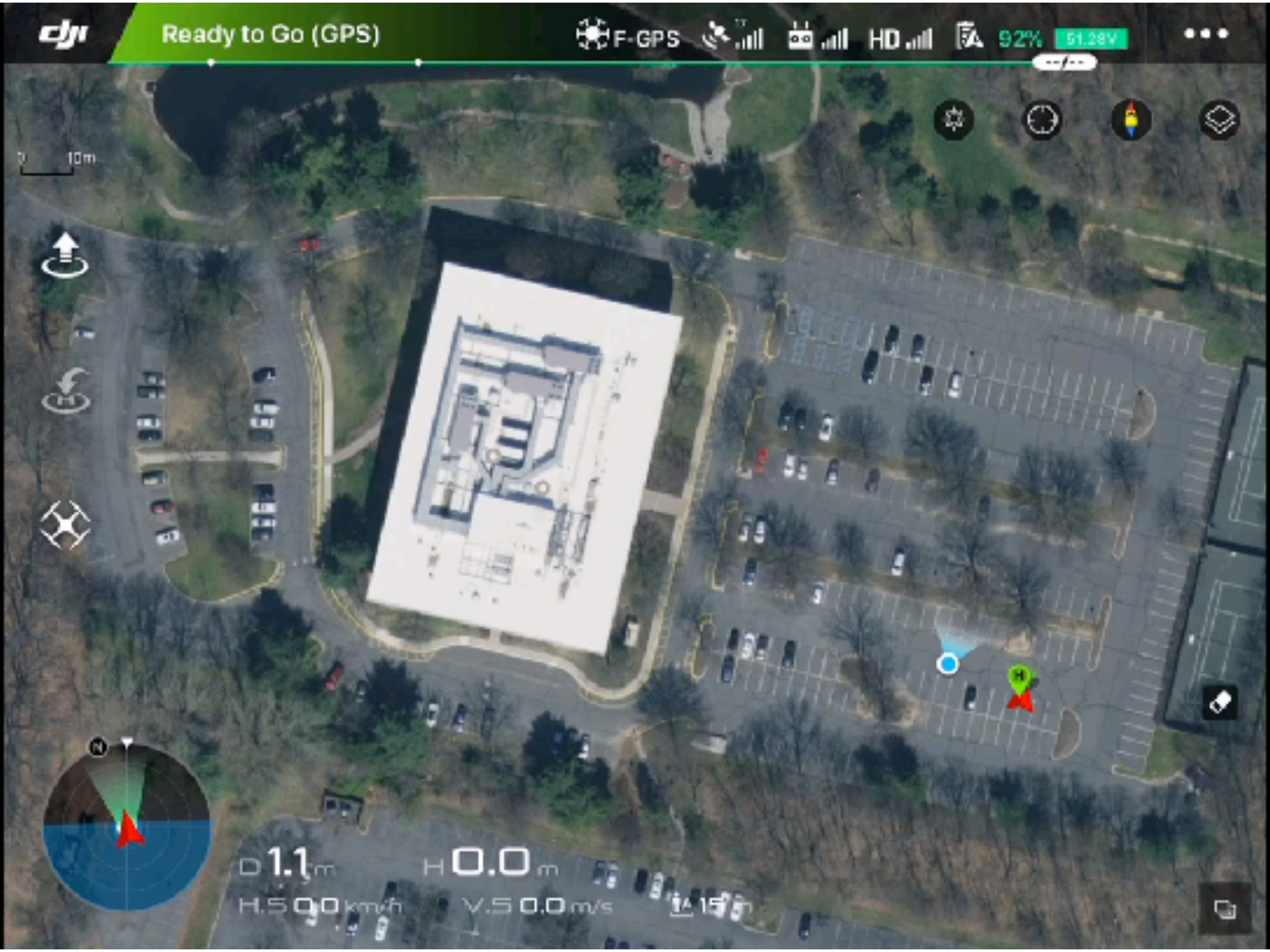
SkyLiTE Prototype Sytem



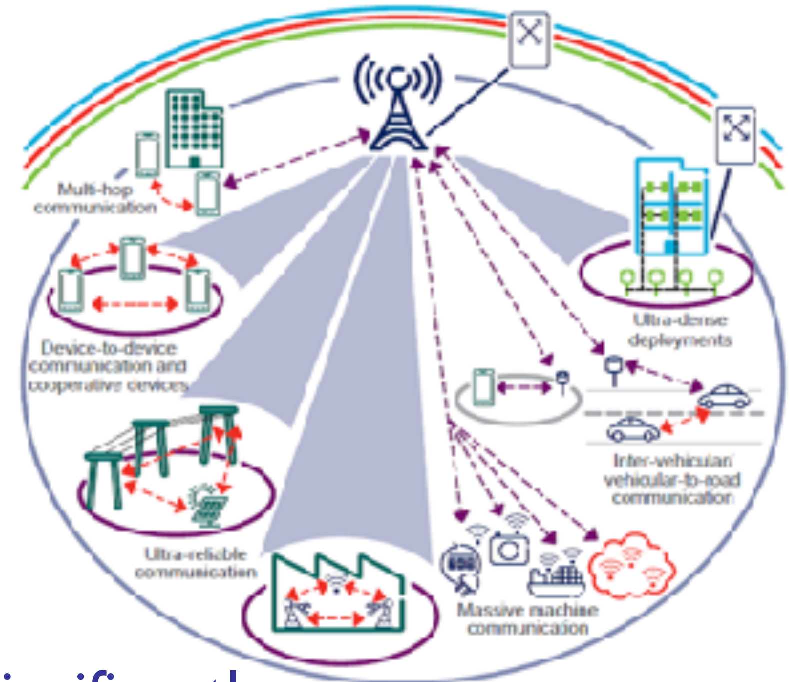
- 4 UAVs with ~150-200m ISD
- Seamless UE mobility across UAVs



Demo



Summary



- New class of diverse mobile application and services drive 5G
  - Real-time immersive experience, IoT, cyber-physical systems
- 5G wireless networks are evolving significantly
  - Confluence of Connectivity, Computing and Experience
  - Role of AI in heterogeneous network orchestration
    - Automate connective-computing decisions to cater to heterogeneity in network/device capabilities
- 5G's capabilities will in turn spawn a lot of novel, revolutionary services!
- Stay tuned!

References

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Thanks!

Questions/Comments?

Tag cloud of research areas

Info/Demos: https://sites.google.com/view/karthik-s/home/research