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

行動邊緣計算
可推廣教材模組

單元-05：雲端無線接取網路與邊緣計算

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Outline

- C-RAN and MEC
- Radio Access Network
- Cloud Radio Access Networks
- Centralized / Cloud RAN (C-RAN)
- Techniques for C-RAN
- C-RAN Fronthaul and Backhaul Architecture
- C-RAN Transport Network Techniques
- Mobile Backhaul

C-RAN and MEC

C-RAN Features (1/2)

- The physical layer communication functionalities are decoupled from the distributed BSs and are consolidated in a virtualized central processing center.
- With its centralized nature, it can be leveraged to address the capacity fluctuation problem and to increase system energy efficiency in mobile networks
- C-RAN can provide new opportunities for IoT, opening up a new horizon of ubiquitous sensing, interconnection of devices, service sharing, and provisioning to support better communication and collaboration in a more distributed and dynamic manner.

C-RAN Features (2/2)

- The integration of cloud provider, edge gateways, and end devices can support powerful processing and storage facilities to massive IoT data streams (big data) beyond the capability of individual “things” as well as provide automated decision making in real time.
- Thus, the C-RAN and IoT convergence can enable the development of new innovative applications in various emerging areas such as smart cities, smart grids, smart healthcare, and others aimed at improving all aspects of human life.

C-RAN vs. MEC

- C-RAN
  - full centralization principle entails the exchange of radio signals between the radio heads and cloud processing unit
  - stringent requirement to the fronthaul connections in terms of throughput and latency
- MEC
  - useful in reducing latency
  - improving localized user experience
  - the amount of processing power and storage is orders of magnitude below that of the centralized cloud in C-RAN.

Features: MEC vs. C-RAN

	MEC	C-RAN
Location	Co-located with base stations or aggregation points.	Centralized, remote data centers.
Deployment planning	Minimal planning with possible ad hoc deployments.	Sophisticated.
Hardware	Small, heterogeneous nodes with moderate computing resources.	Highly capable computing servers.
Fronthaul requirements	Fronthaul network bandwidth requirements grow with the total amount of data that need to be sent to the core network after being filtered/processed by MEC servers.	Fronthaul network bandwidth requirements grow with the total aggregated amount of data generated by all users.
Scalability	High	Average, mostly due to expensive fronthaul deployment.
Application delay	Support time-critical applications that require latencies less than tens of milliseconds.	Support applications that can tolerate round-trip delays on the order of a few seconds or longer.
Location awareness	Yes	N/A
Real-time mobility	Yes	N/A

Mobile Edge Orchestration (1/2)

- Mobile devices: limited resources (e.g., battery, CPU, memory)
- Computation-intensive applications are expected to work seamlessly with real-time responses
  - computer vision
  - machine learning
  - artificial intelligence
- Traditional way of offloading computation to the remote cloud often leads to unacceptable delay (e.g., hundreds of milliseconds) and heavy backhaul usage.

Mobile Edge Orchestration (2/2)

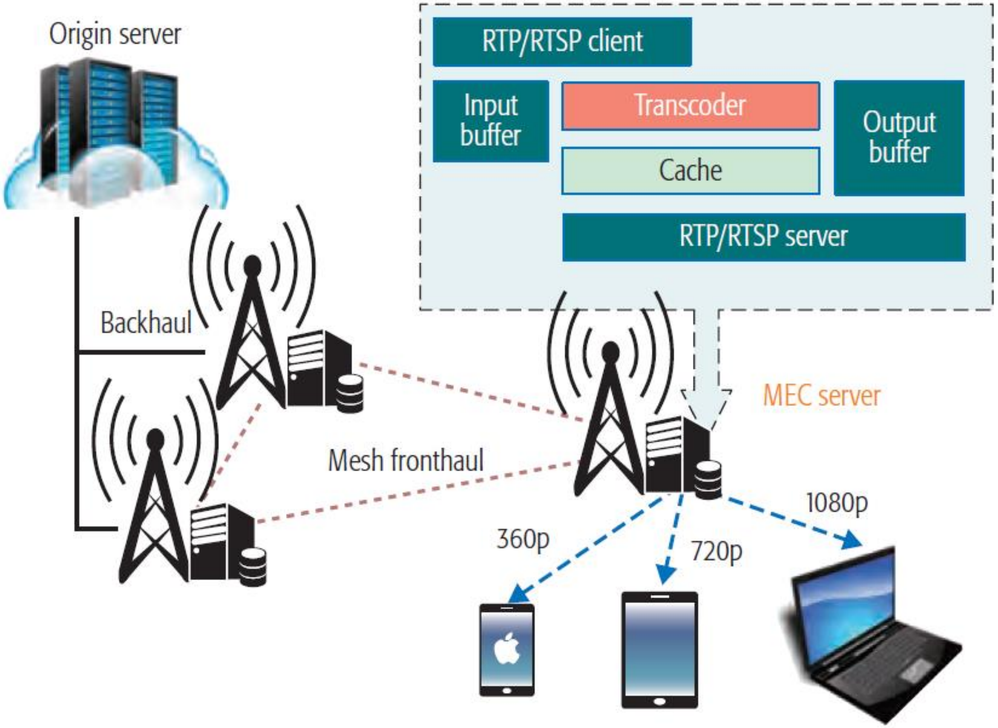
- Due to its distributed computing environment, MEC can be leveraged to deploy applications and services as well as to store and process content in close proximity to mobile users.
- MEC would enable applications to be split into small tasks with some of the tasks performed at the local or regional clouds as long as the latency and accuracy are preserved.

A Distributed Computing Framework

- A hierarchical architecture consisting of:
  - **End user**: implies both mobile and static end-user devices such as smartphones, sensors, and actuators
  - **Edge nodes**: the MEC servers co-located with the BSs
  - **Cloud node**: the traditional cloud-computing server in a remote data center

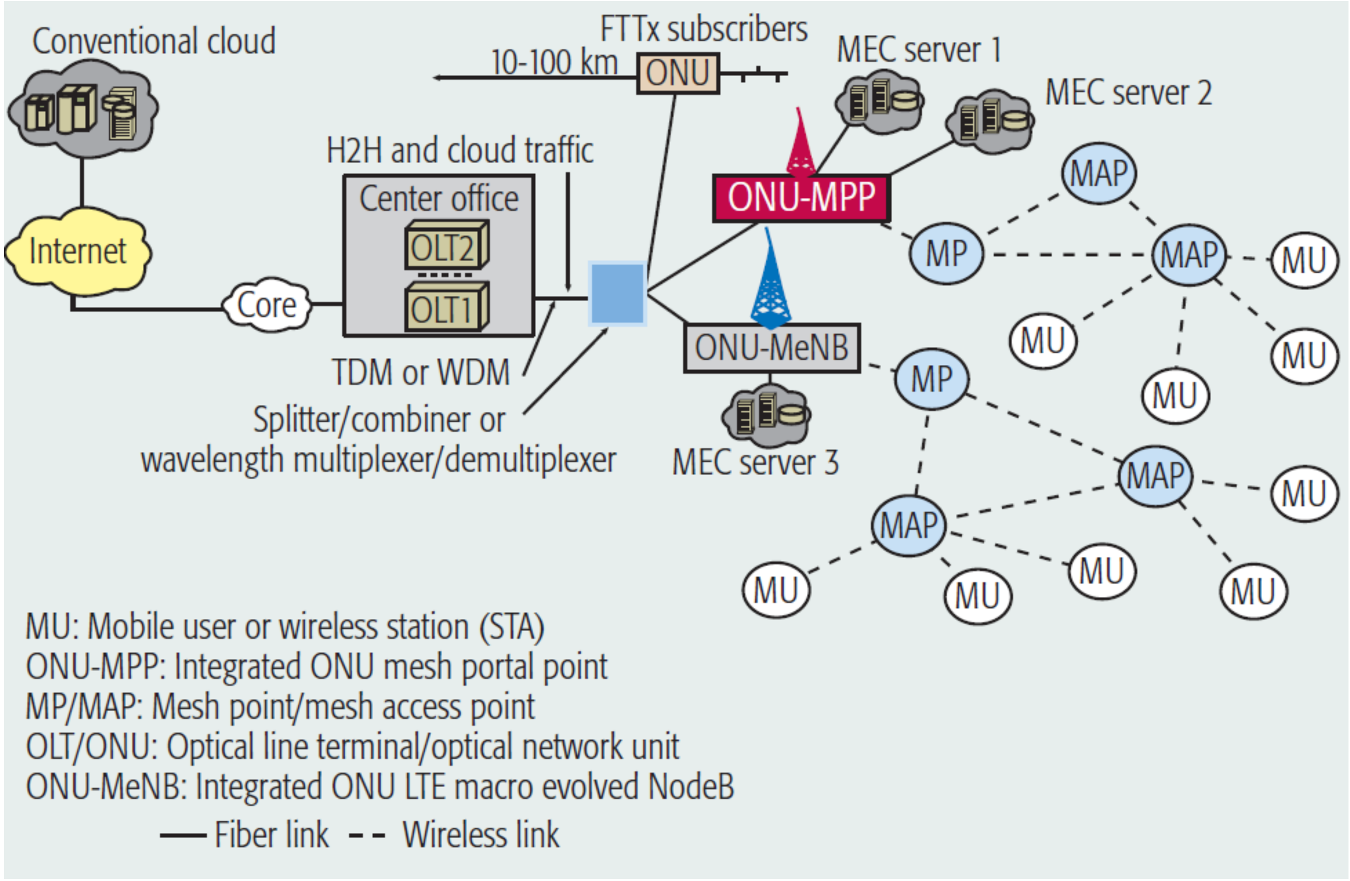
Example I

- A collaborative video caching and processing framework deployed on an MEC network



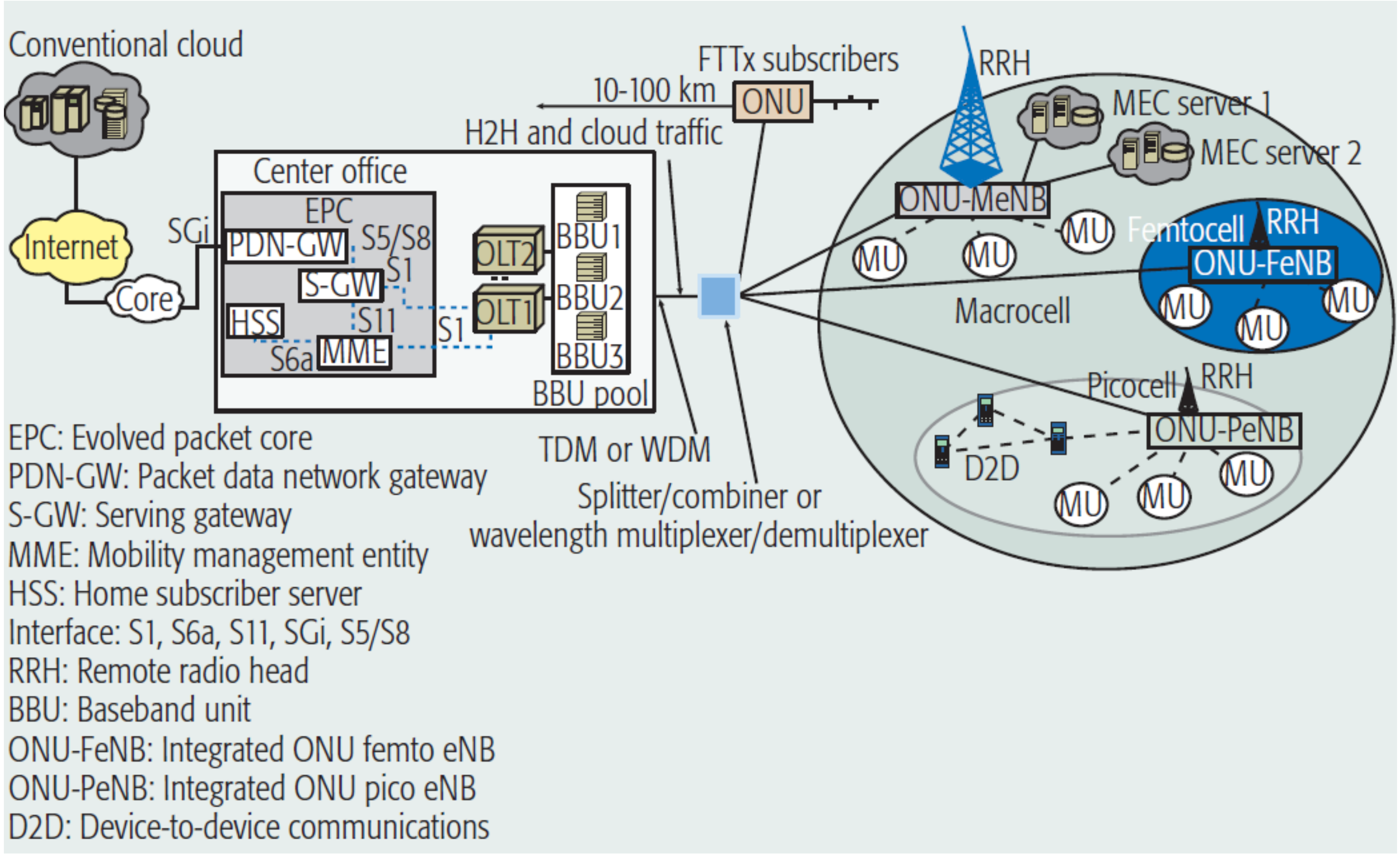
Example II (a):
MEC over FiWi Network Architectures

- MEC over Ethernet-based FiWi networks and MEC over 4G LTE-based FiWi networks



Example II (b):
MEC over FiWi Network Architectures

- Coexistence of MEC and C-RAN over FiWi enhanced 4G LTE HetNets



Challenges and Open Research Issues

- The decentralization of cloud computing infrastructure to the edge introduces new challenges and open research issues
  - Resource Management
  - Interoperability
  - Service Discovery
  - Mobility Support
  - Fairness
  - Security

Radio Access Network

Radio Access Network (RAN)

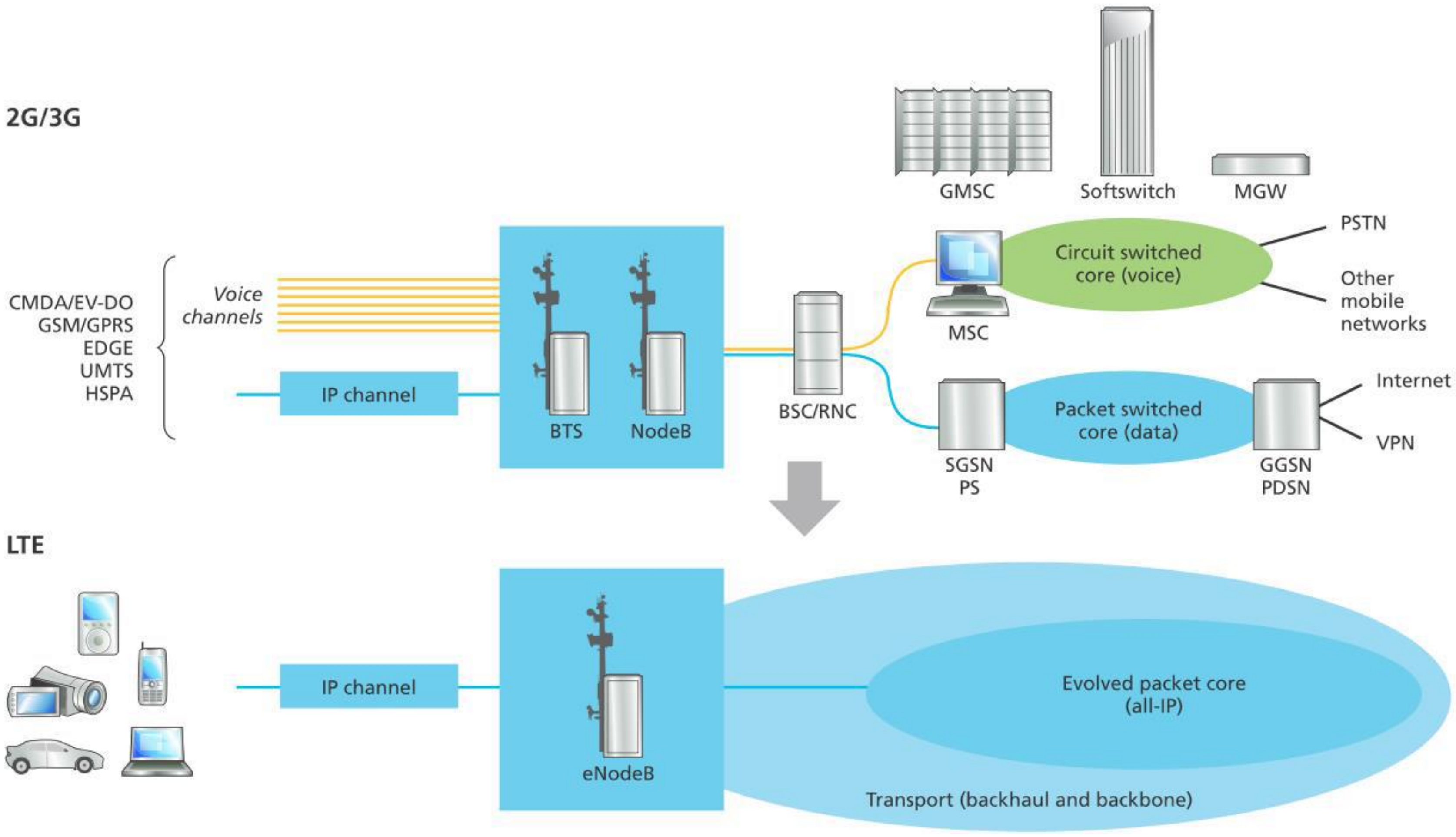
- A radio access network (RAN) is part of a mobile telecommunication system.
- RAN implements radio access technology.
- It resides between a user equipment (UE) and the core network (CN).
  – UE: a mobile phone, a computer, or any remotely controlled machine
- Depending on the standard, mobile phones and other wireless connected devices are known as UE, terminal equipment, or mobile station (MS), etc.

Mobile Communications Networks

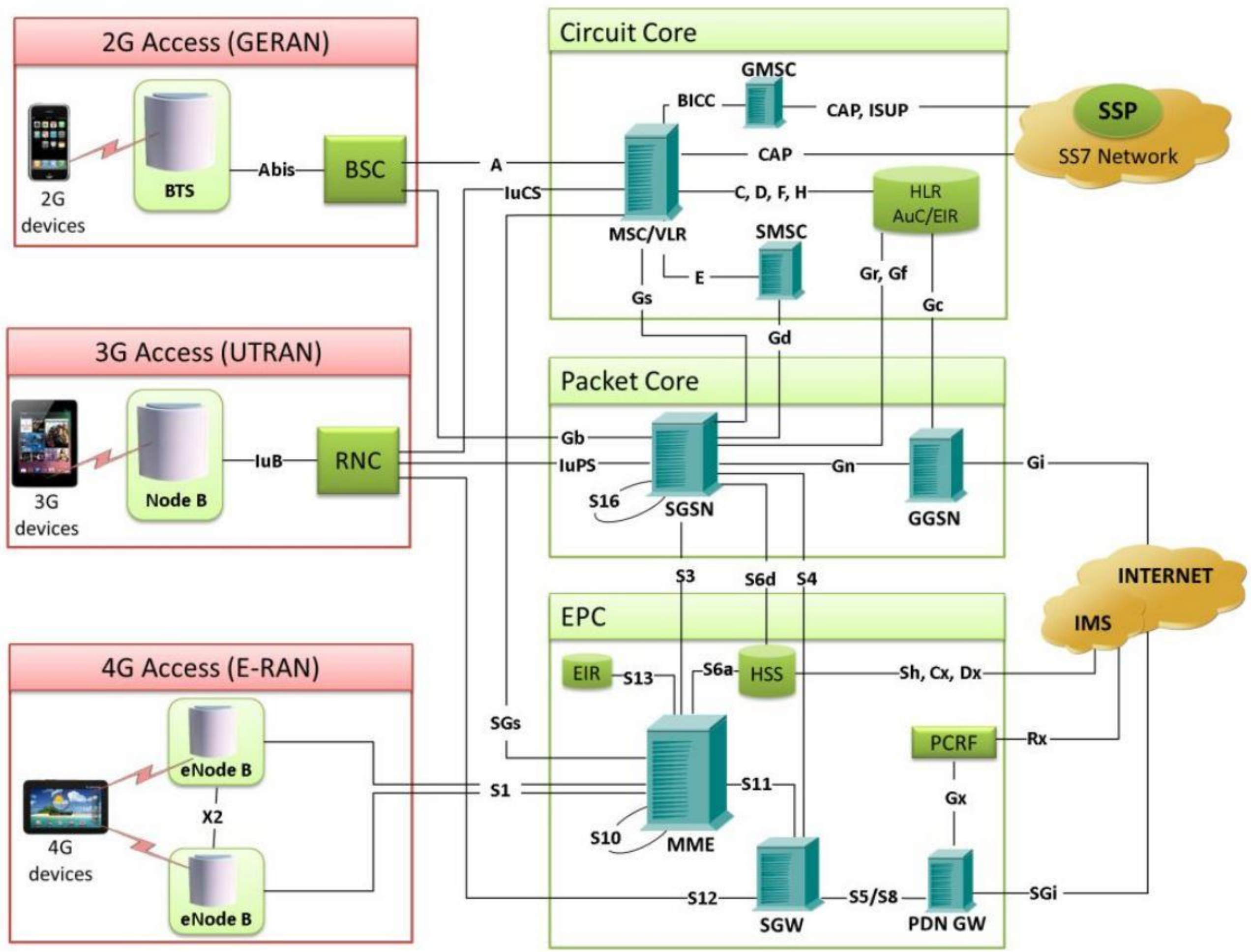
```
        CN
      /    \
     /      \
  RAN        RAN
  / \        / \
UE   UE    UE   UE
```

Types of Radio Access Networks

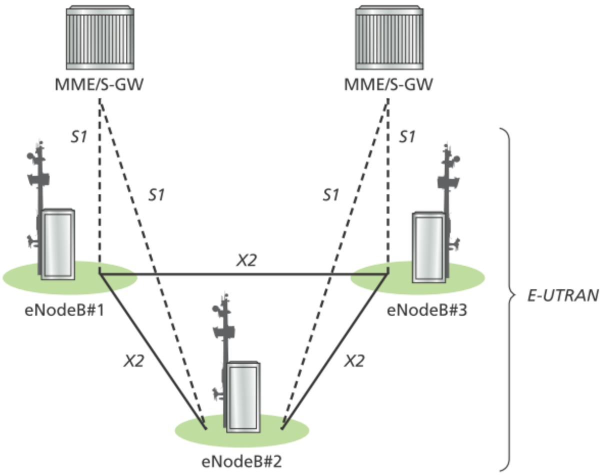
- **GRAN**: GSM radio access network
- **GERAN**: essentially the same as GRAN but specifying the inclusion of EDGE packet radio services
- **UTRAN**: UMTS radio access network
- **E-UTRAN**: The Long Term Evolution (LTE) high speed and low latency radio access network

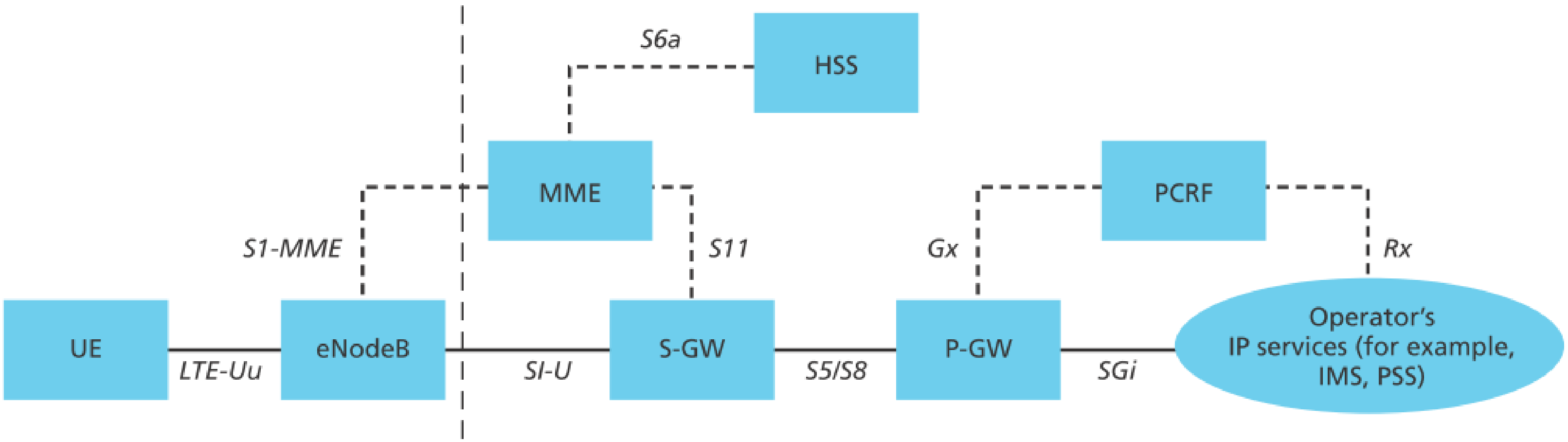

2G/3G
GMSC
Softswitch
MGW
PSTN
Circuit switched core (voice)
Other mobile networks
CMDA/EV-DO
GSM/GPRS
EDGE
UMTS
HSPA
Voice channels
MSC
BSC/RNC
IP channel
BTS
NodeB
Internet
Packet switched core (data)
VPN
SGSN PS
GGSN PDSN
LTE
IP channel
eNodeB
Evolved packet core (all-IP)
Transport (backhaul and backbone)

Radio Access Network (RAN) and Core Network (CN)



Interfaces between LTE Elements





Cloud Radio Access Networks

Meeting Traffic Demand (1/2)

- Mobile broadband is approaching a point where cellular infrastructure – originally designed for mobile telephony – is a viable substitute for fixed broadband in many markets.
- The mass adoption of smartphones and other connected devices is increasing the need for higher data rate, more application coverage, lower latency and greater capacity in mobile broadband networks.

Meeting Traffic Demand (2/2)

- Mobile networks are evolving quickly in terms of coverage, capacity and new features.
- Evolution regarding new requirements
  - Latency
  - Traffic volumes
  - Data rates
- Downlink 100Mbps everywhere and 1-10Gbps locally, with a latency of less than 1ms.

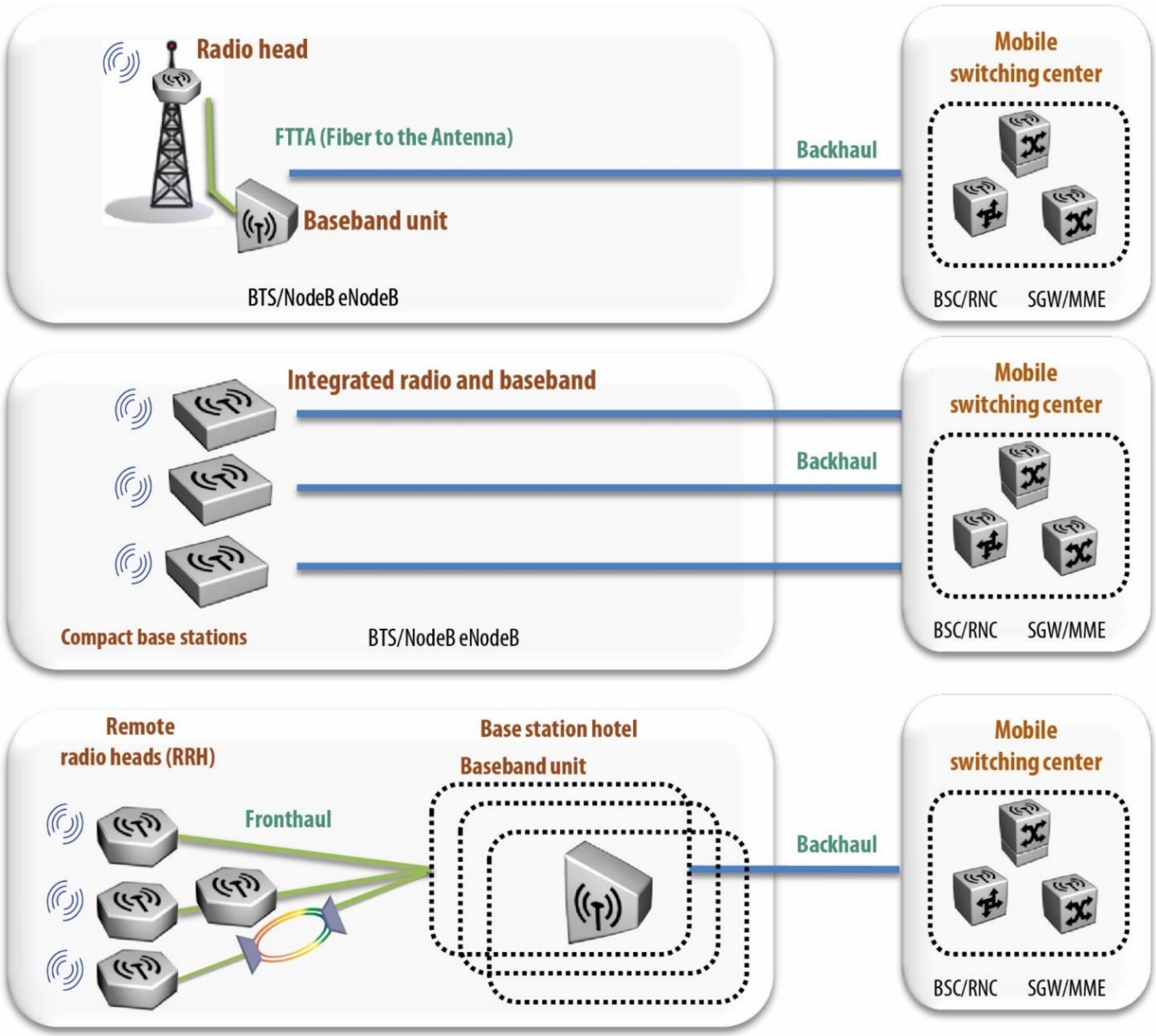
Features and Trends of 5G Networks

5G Expectations and Features	Trends/Proposals
Capacity and throughput improvement, high data rate (~1000x of throughput improvement over 4G, cell data rate ~10 Gb/s, signaling loads less than 1~100%)	Spectrum reuse and use of different band (e.g., mm-wave communication using 28~GHz and 38~GHz bands), multi-tier network D2D communication, C-RAN, massive-MIMO
Reduced latency (2 to 5 ms end-to-end latencies)	Full-duplex communication, C-RAN, D2D communication
Network densification (~1000x higher mobile data per unit area, 100~10000x higher number of connecting devices)	Heterogeneous and multi-tier network
Advanced services and applications (e.g., smart city, service-oriented communication)	C-RAN, network virtualization, M2M communication
Improved energy efficiency (~10x prolonged battery life)	Wireless charging, energy harvesting
Autonomous applications and network management, Internet of Things	M2M communication, self-organizing and cognitive network

HossainHasan2015

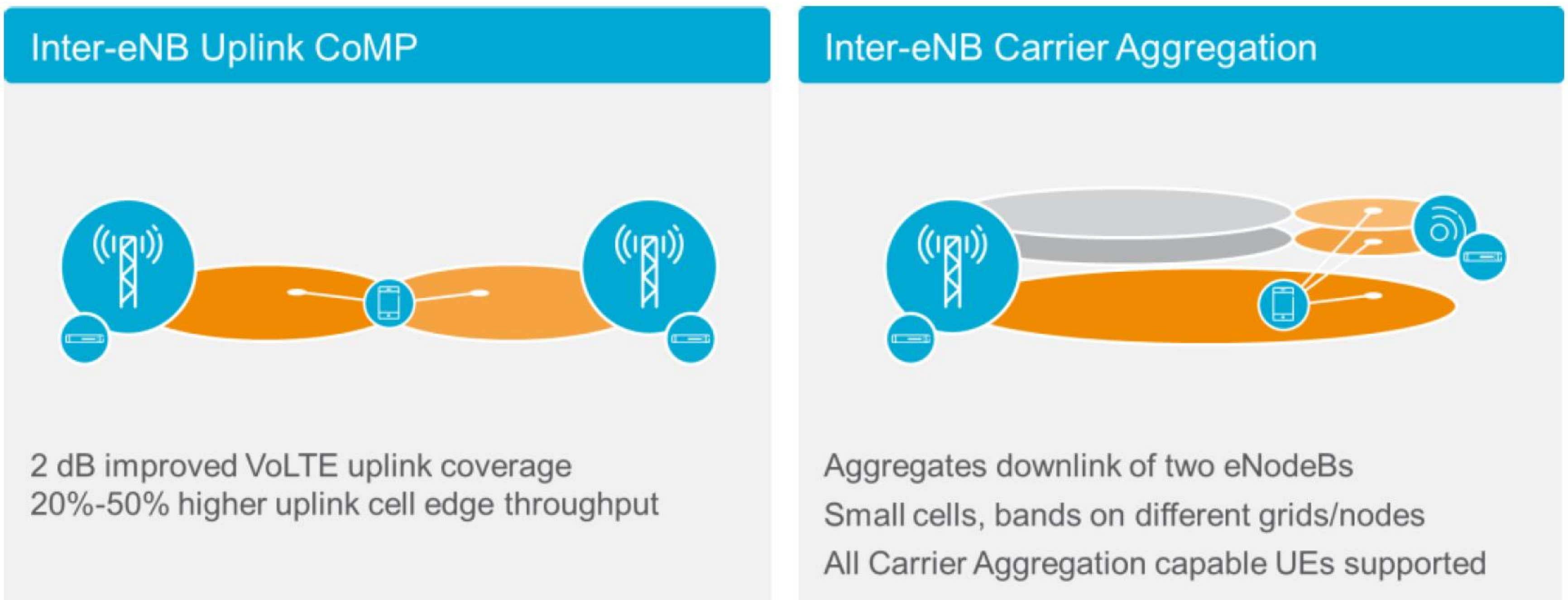
Centralized / Cloud RAN (C-RAN) : Architecture

Evolution of Cellular Networks



Current RAN Architectures

- **Distributed Baseband (Baseline X2 coordination)**

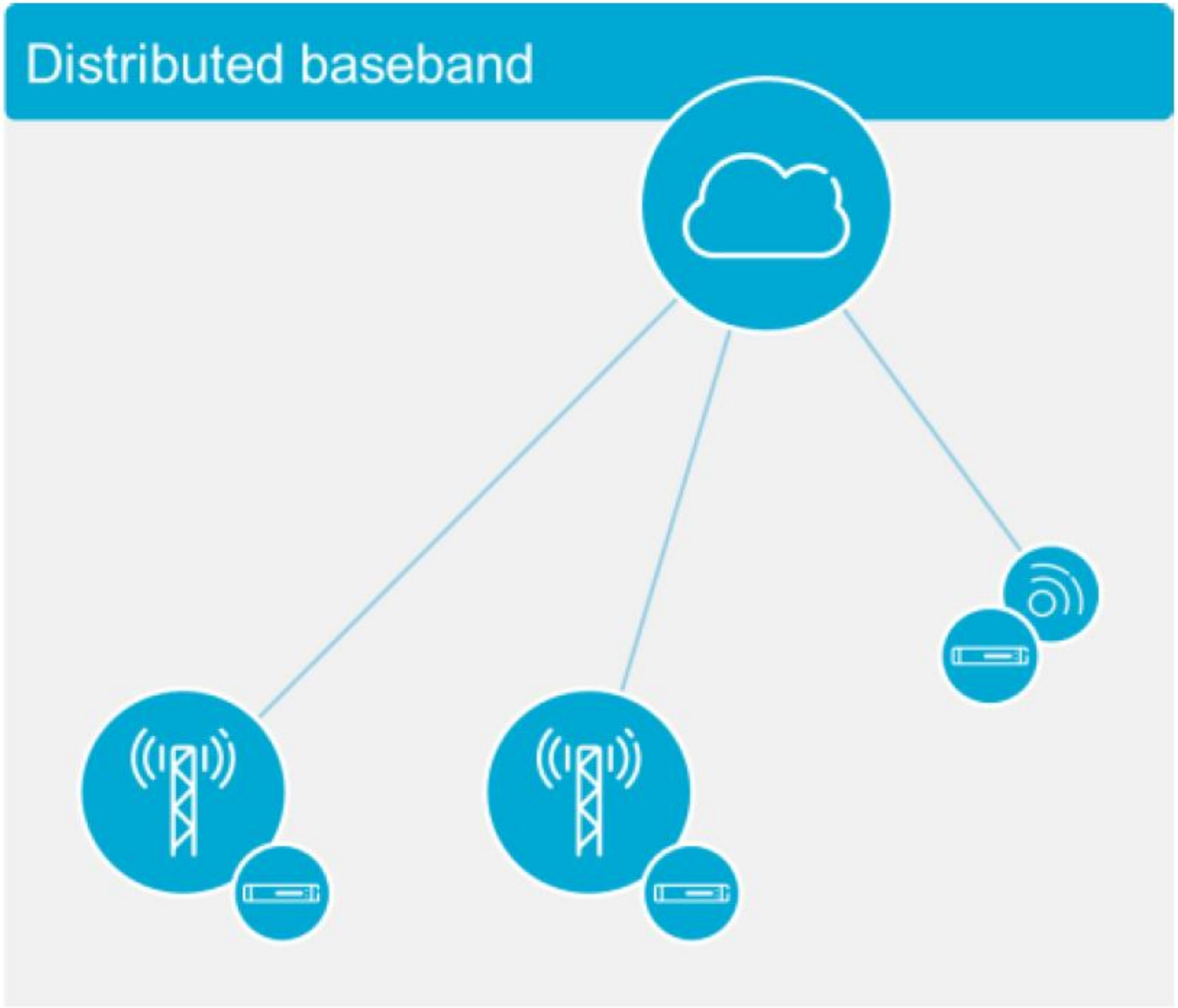


Baseline X2 coordination features include Automatic Neighbor Relations (ANR) and Reduced Handover Oscillations, Load Balancing, etc.

Distributed Baseband (1/2)

- Today, most LTE networks use a distributed baseband deployment only.
- The LTE flat architecture enables quick rollout, ease of deployment and standard IP-based connectivity.
- With the collaboration between base stations over the IP-based X2 interface, LTE handovers remain seamless from a user perspective. (Basic mobility and traffic management)
- The X2 coordination supports
  - carrier aggregation (CA)
  - coordinated multipoint reception (CoMP)

Distributed Baseband (2/2)



Different Stages of C-RAN Deployment (1/2)

Stage 1: Centralized RAN

- baseband units are deployed centrally supporting many RRHs.
- However, resources are not pooled, nor virtualized.

Different Stages of C-RAN Deployment (2/2)

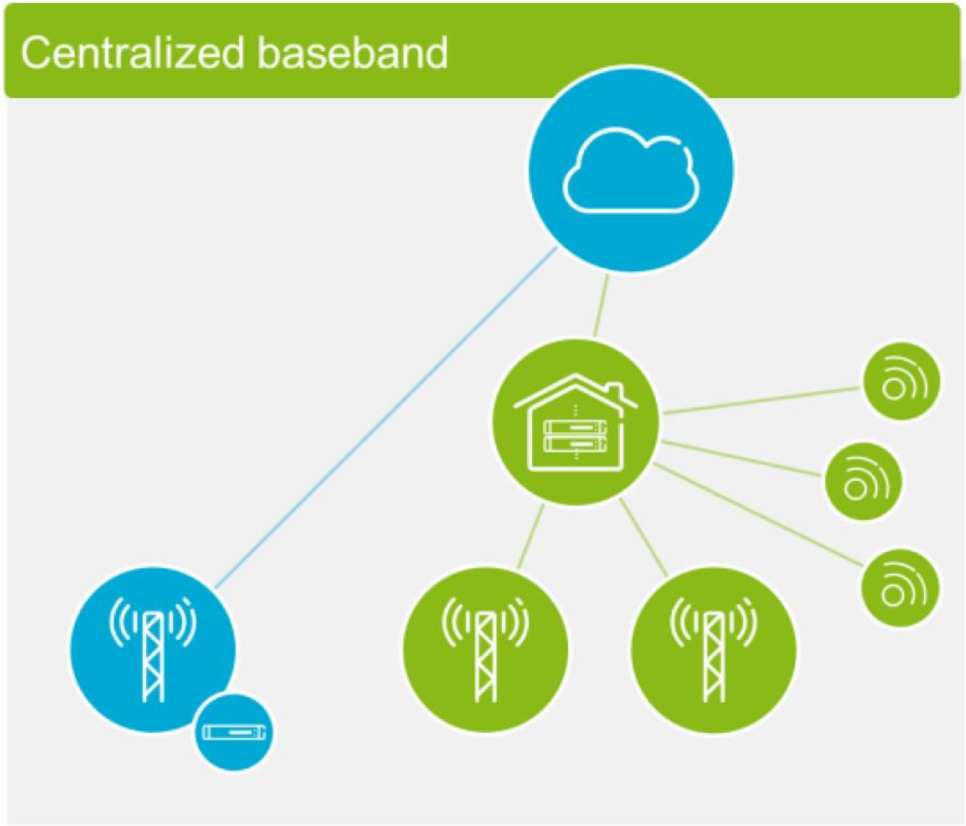
Stage 2: Cloud RAN

- Phase 1
  - Baseband resources are pooled.
  - Baseband processing is done using specialized baseband chip - DSPs
- Phase 2
  - Resources are virtualized, using GPP, thereby leveraging full benefits of C-RAN.
  - Sometimes this deployment is referred to as V-RAN, standing for Virtualized-RAN.

Centralized Baseband (1/2)

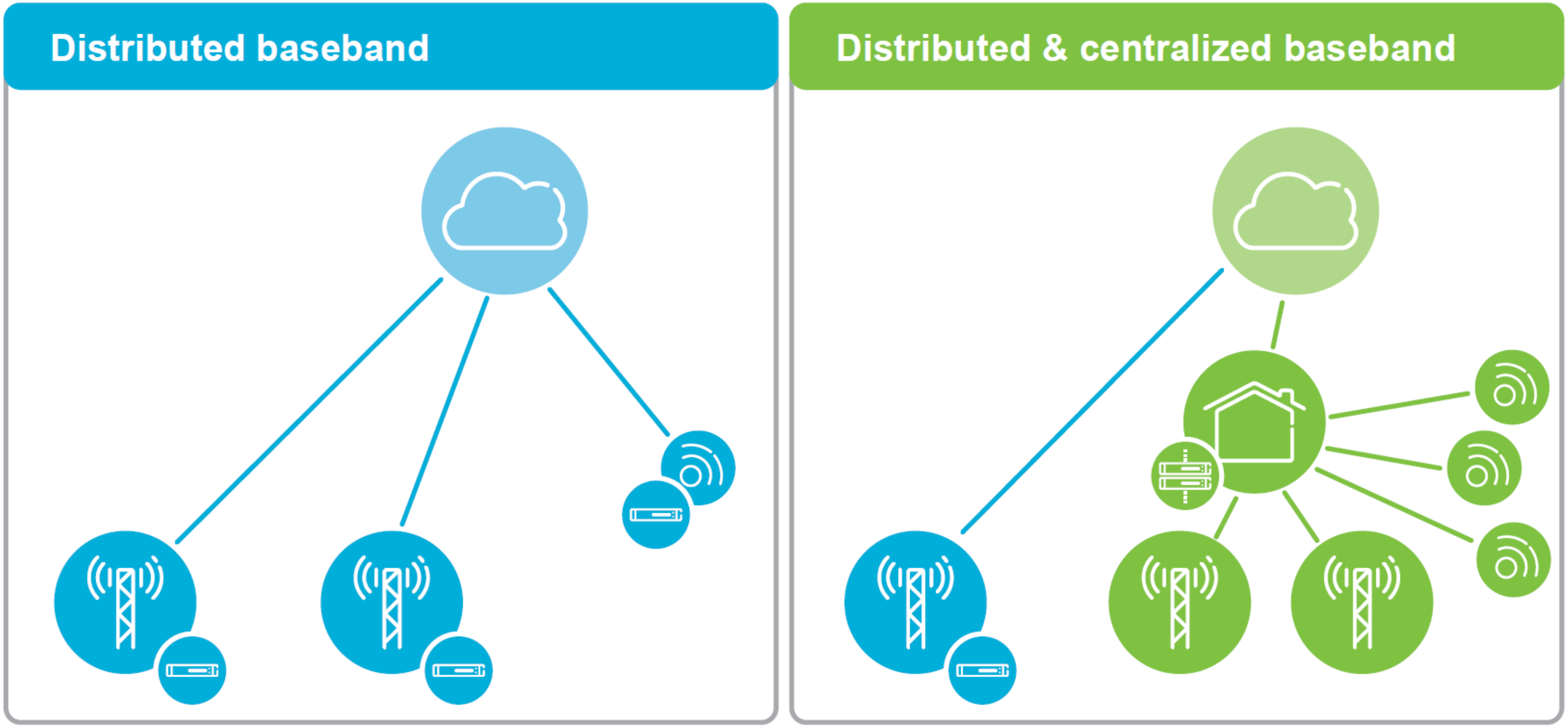
- In a fully centralized baseband deployment, all baseband processing (including RAN L1, L2 and L3 protocol layers) is located at a central location that serves multiple distributed radio sites.
- The transmission links between the central baseband units and distributed radio units use CPRI fronthaul over dedicated fiber, ethernet or microwave links.
- This CPRI fronthaul requires tight latency and large bandwidths.
- In many situations, CPRI connectivity requirements will be too strict for Centralized RAN architectures to be affordable.

Centralized Baseband (2/2)

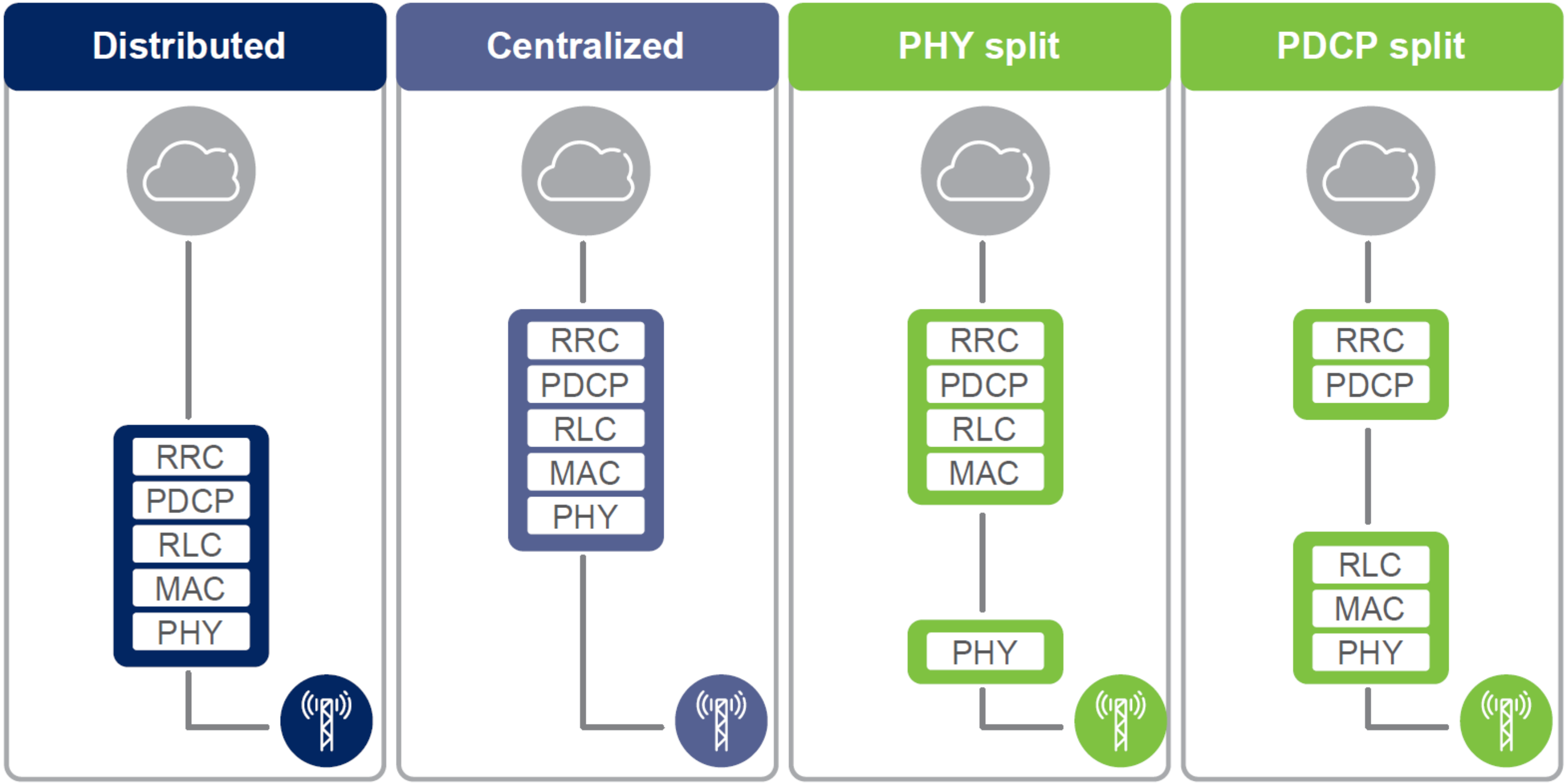


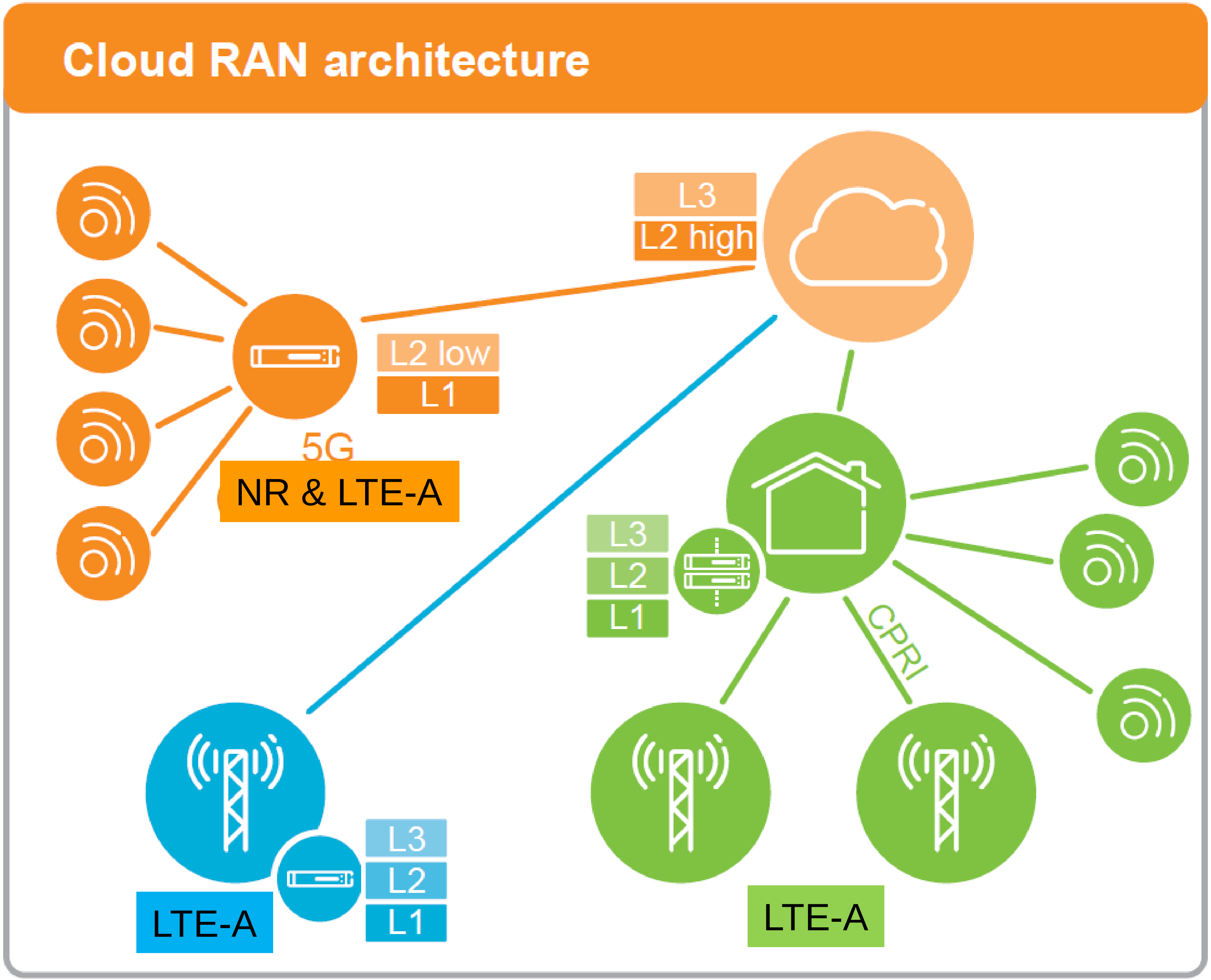
Centralized baseband deployment (green) complementing a distributed baseband deployment (blue)

Comparison

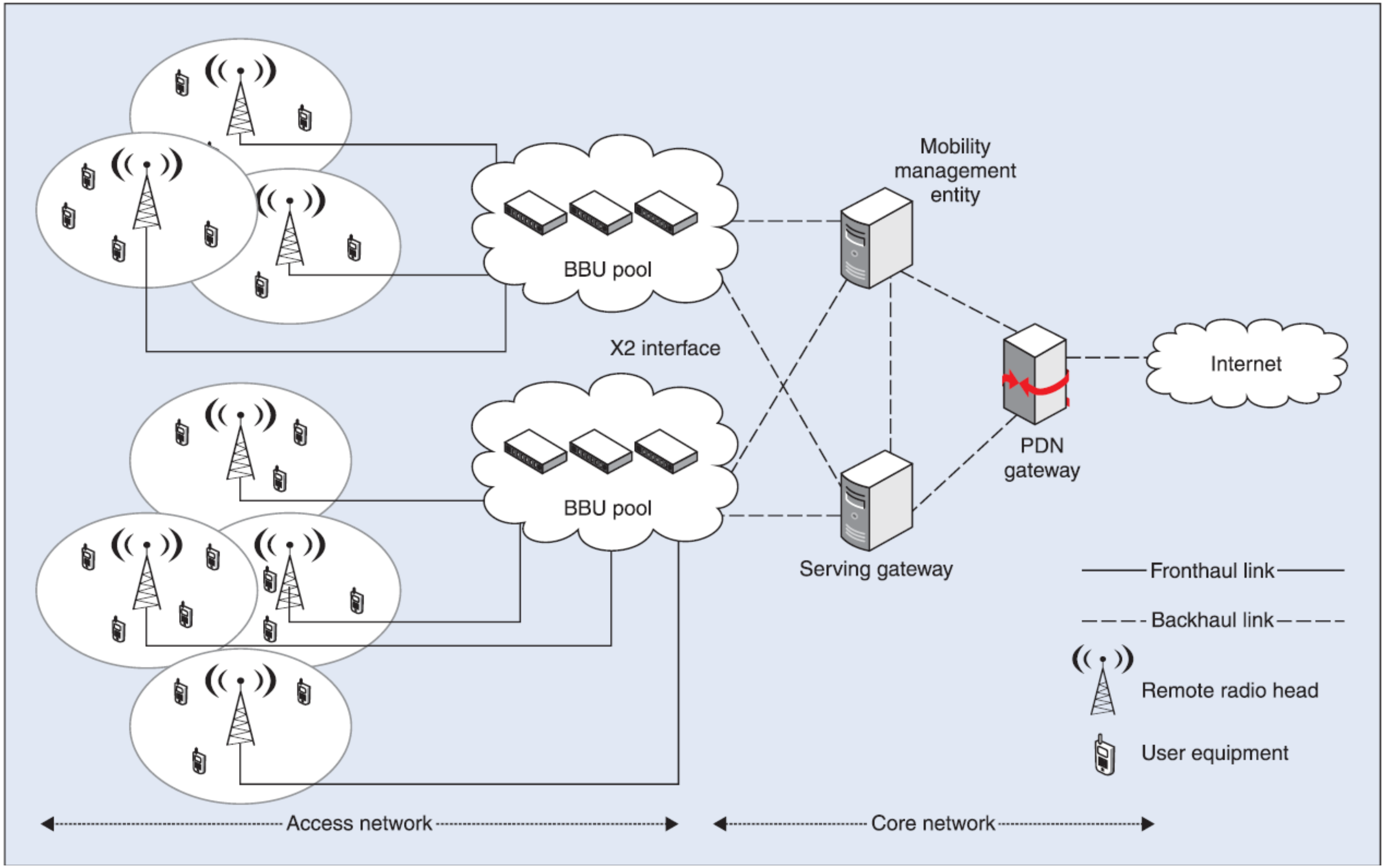


Selective Centralization in Cloud RAN




Cloud RAN architecture
L3
L2 high
L2 low
L1
5G
NR & LTE-A
L3
L2
L1
CPRI
L3
L2
L1
LTE-A
LTE-A

An LTE-A System Enhanced with Cloud RAN



Benefits of Using C-RAN

- The benefits of combining virtualization, centralization and coordination
  - Resource pooling
  - Scalability
  - Layer interworking
  - Spectral efficiency
- ➢ Building cost-, spectrum- and energy-efficient networks that offer a seamless user experience

Features of Cloud RAN

- Scalability
- Energy/power savings
- Increased throughput
- Reduced delay
- Adaptability to dynamic traffic
- Reduced CAPEX/OPEX
- Easier network management

Fundamental Challenges of Cloud RAN

- BBU management
  - Cooperation
  - Interconnection
  - Clustering
- Energy-aware scheduling
- Fronthaul-aware resource allocation

Techniques for C-RAN

Architecture Issues on Cloud RAN

- The C-RAN system architectures proposed by the industry are focused on different functional splits, in which the tradeoff between implementation complexity and performance gains is concerned.
- The C-RAN system architecture evolution to heterogeneous cloud radio access networks (H-CRANs) and fog computing based radio access networks (F-RANs) is highlighted in the research community.

Key Techniques in PHY for C-RAN

- The fronthaul compression in both uplink and downlink
  - Quantization
  - Compressive sensing (CS)
  - Spatial filtering
- Large-scale collaborative processing (LSCP)
  - Linear LSCP with/without perfect CSIs
  - Nonlinear sparse LSCP
- Channel estimation
  - superimposed training
  - segment training
  - Semi-blind channel estimation

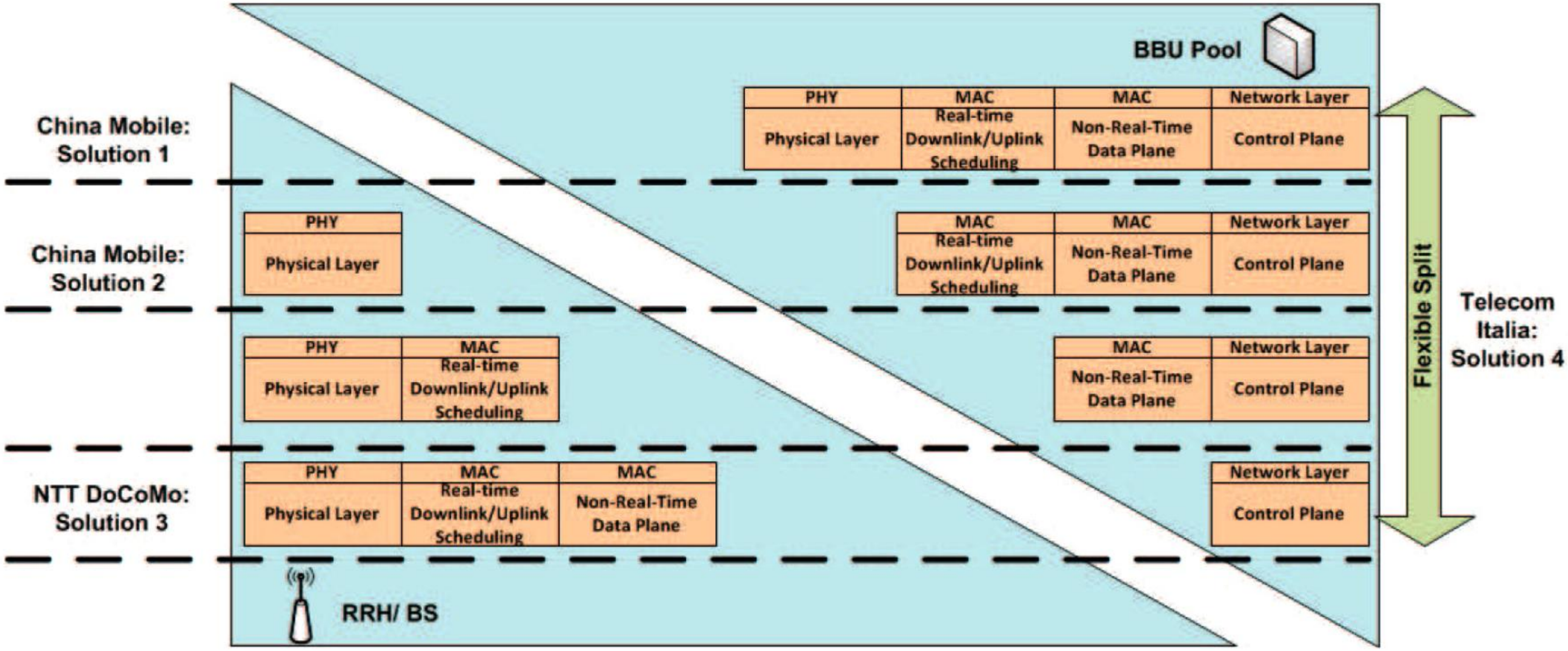
Cooperative Radio Resource Allocation (CRRA) for C-RAN

- Static CRRA without considering queue state information (QSI)
  - Classic non-convex optimization approaches
  - Game model based approaches
- Dynamic CRRA with queue-awareness
  - Equivalent rate approach
  - Lyapunov optimization approach
  - Markov decision process approach

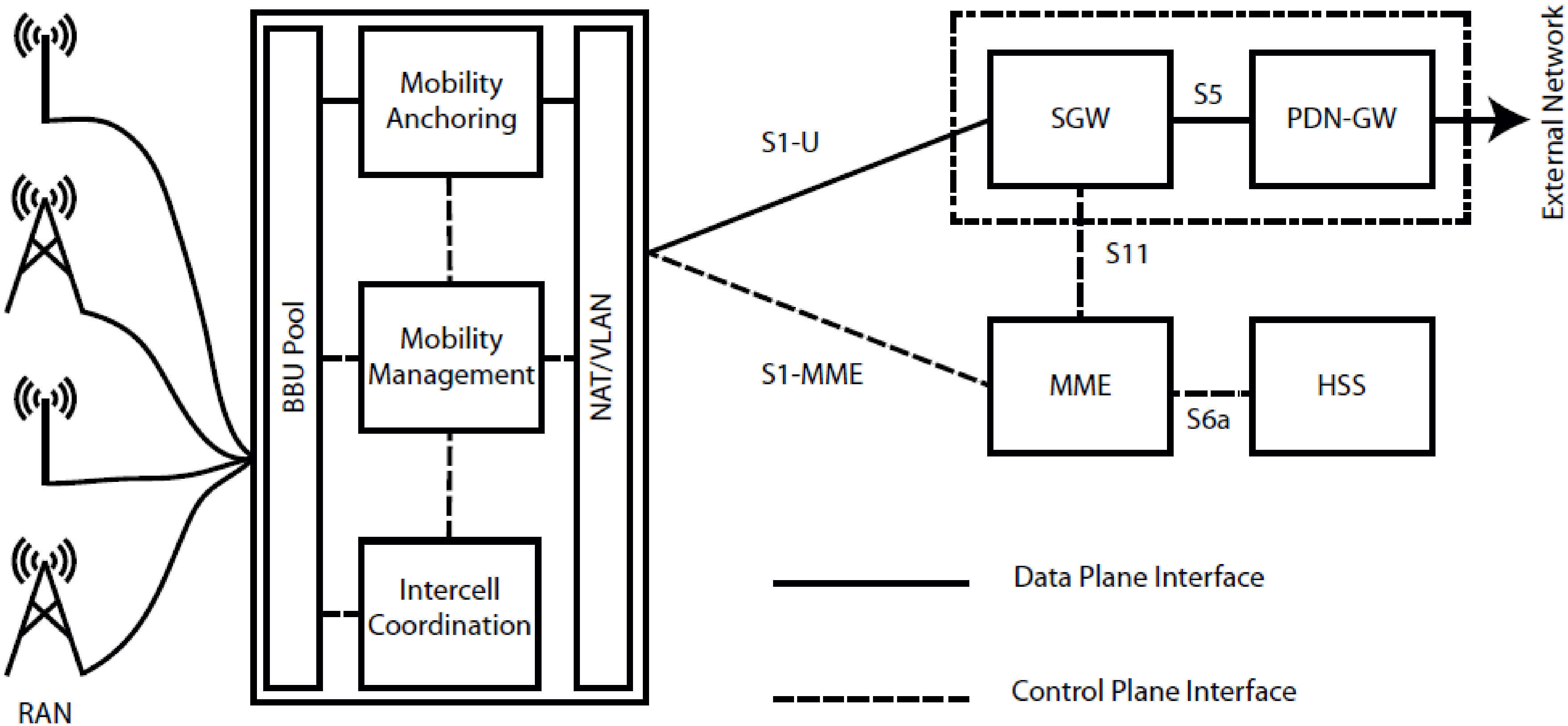
Other Issues on Cloud RAN

- Edge cache
- Big data mining
- Social aware device-to-device (D2D) communication
- Cognitive radio (CR)
- Software defined network (SDN)
- Physical layer security
- Trial tests

Functional Split of C-RAN

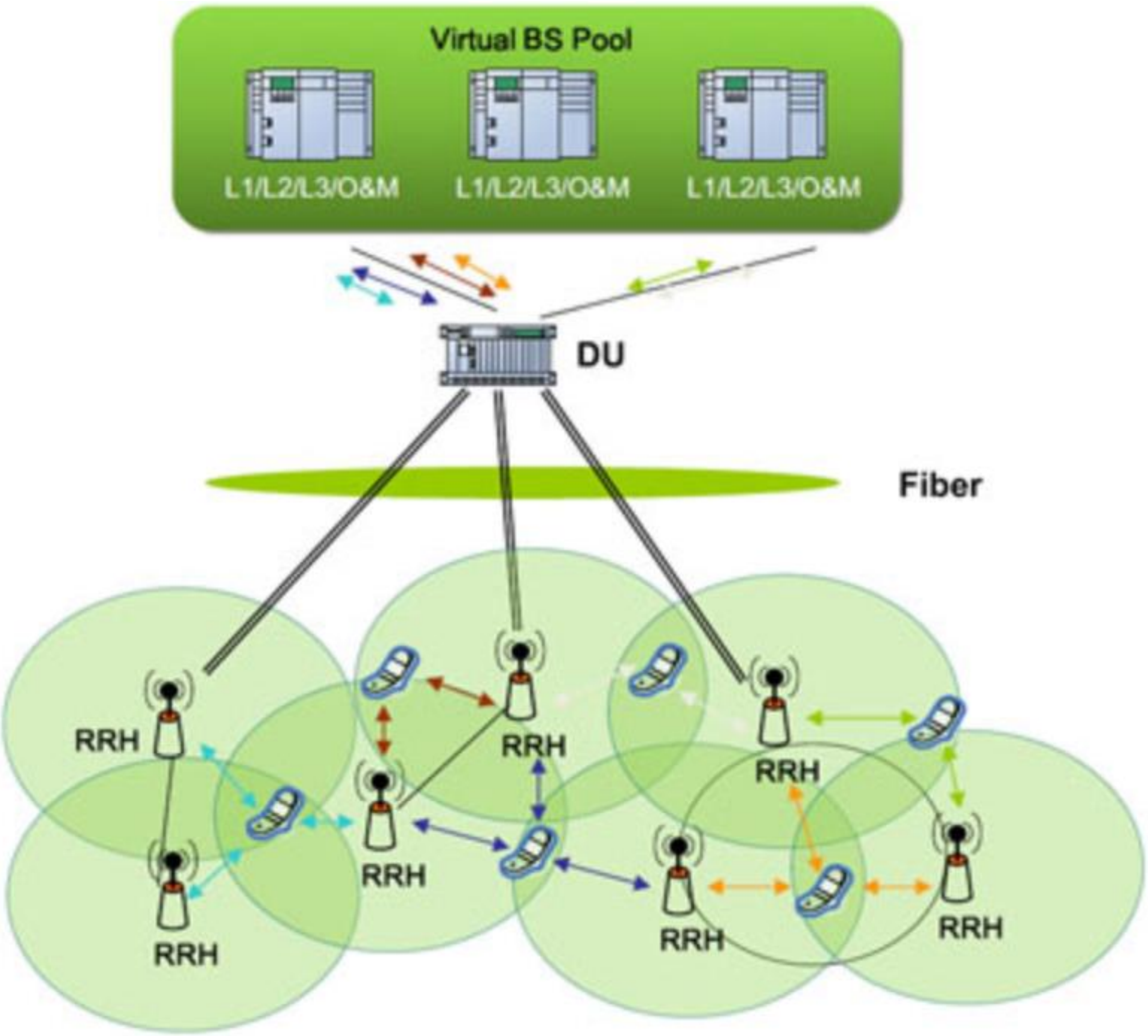


New Architecture and Functions/Elements in a C-RAN eNodeB



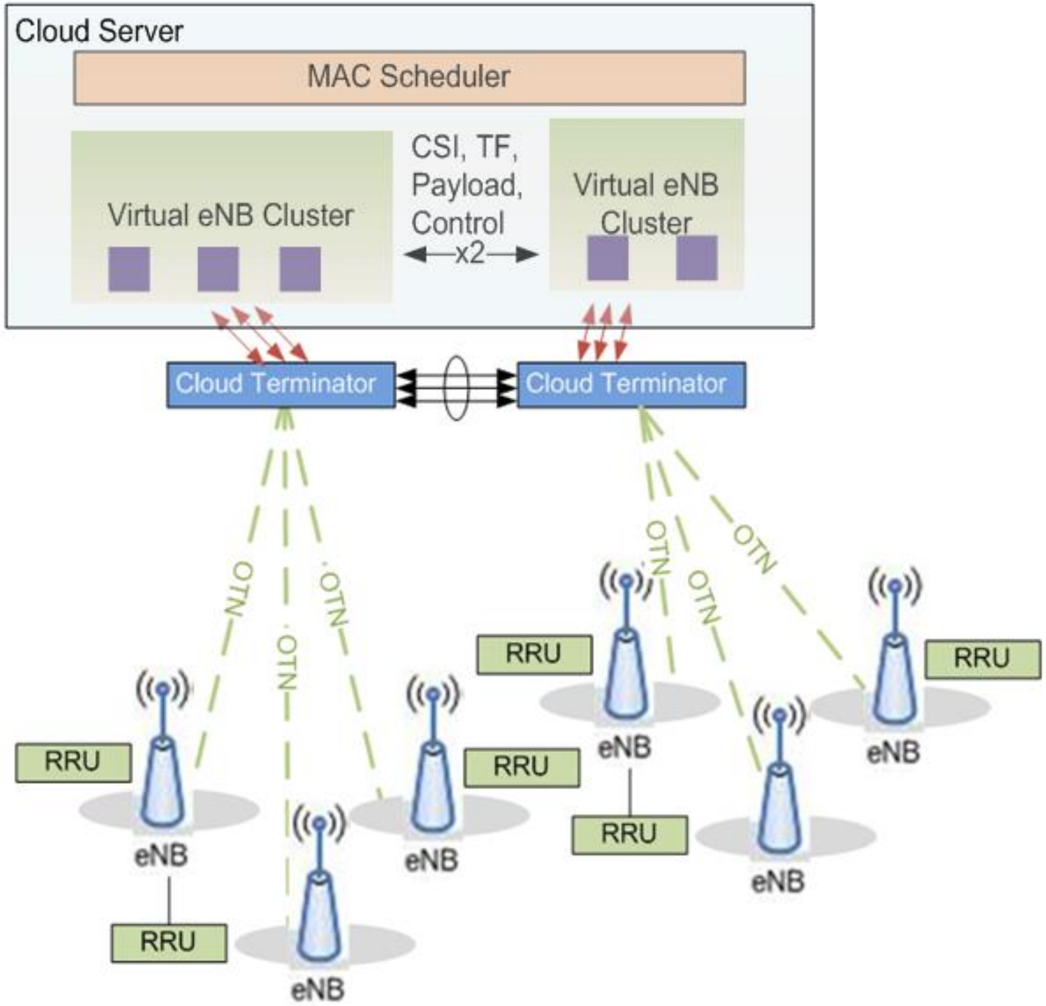
Source: Dawson, Edinburgh

Coordinated Multipoint (CoMP)



Source: CNL, Korea

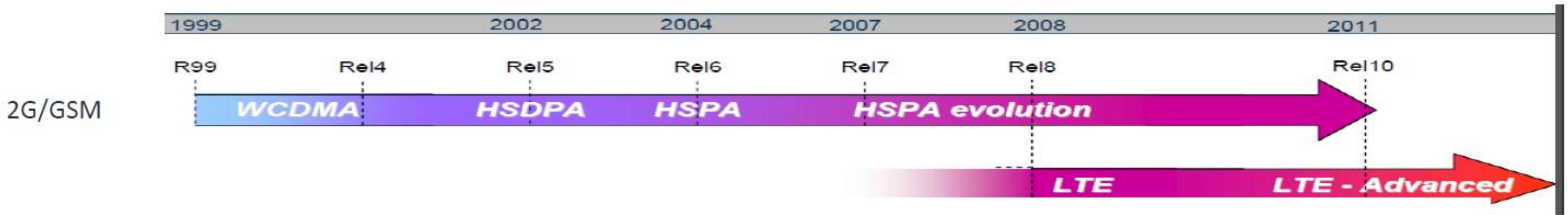
Cloud Server

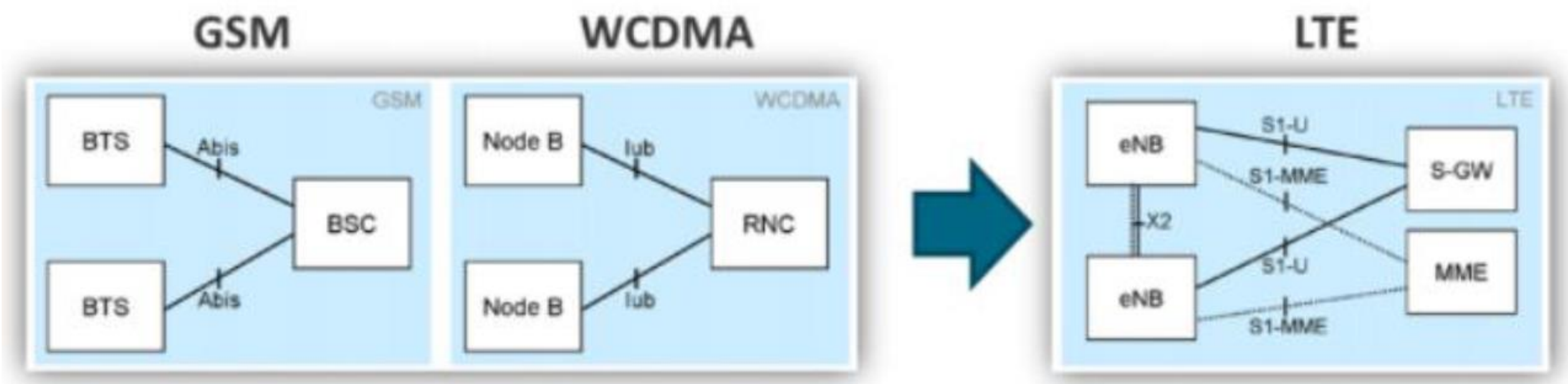


Source: Intel

Fronthaul and Backhaul Architecture

Evolution of Backhaul Networks





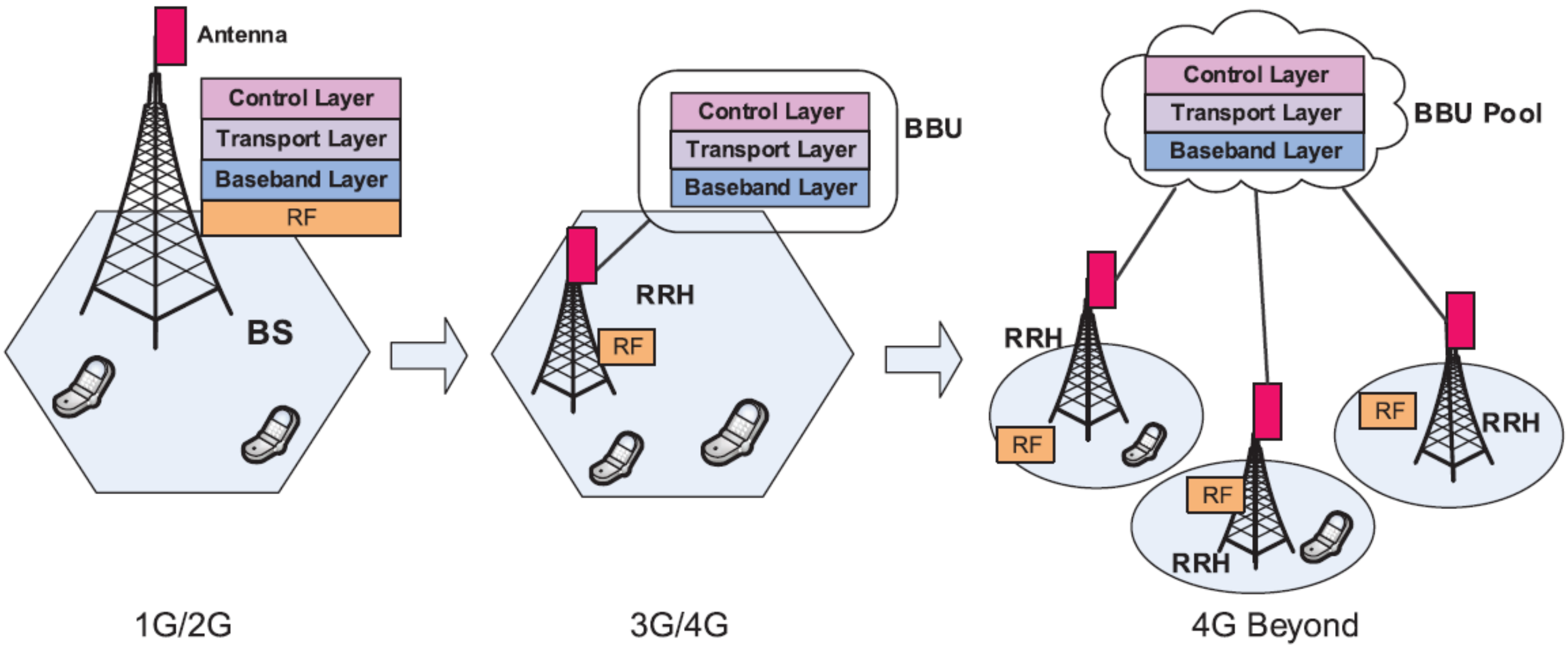
ATM Backhaul Only

Started as ATM, IP became an alternative in R5

All IP Backhaul

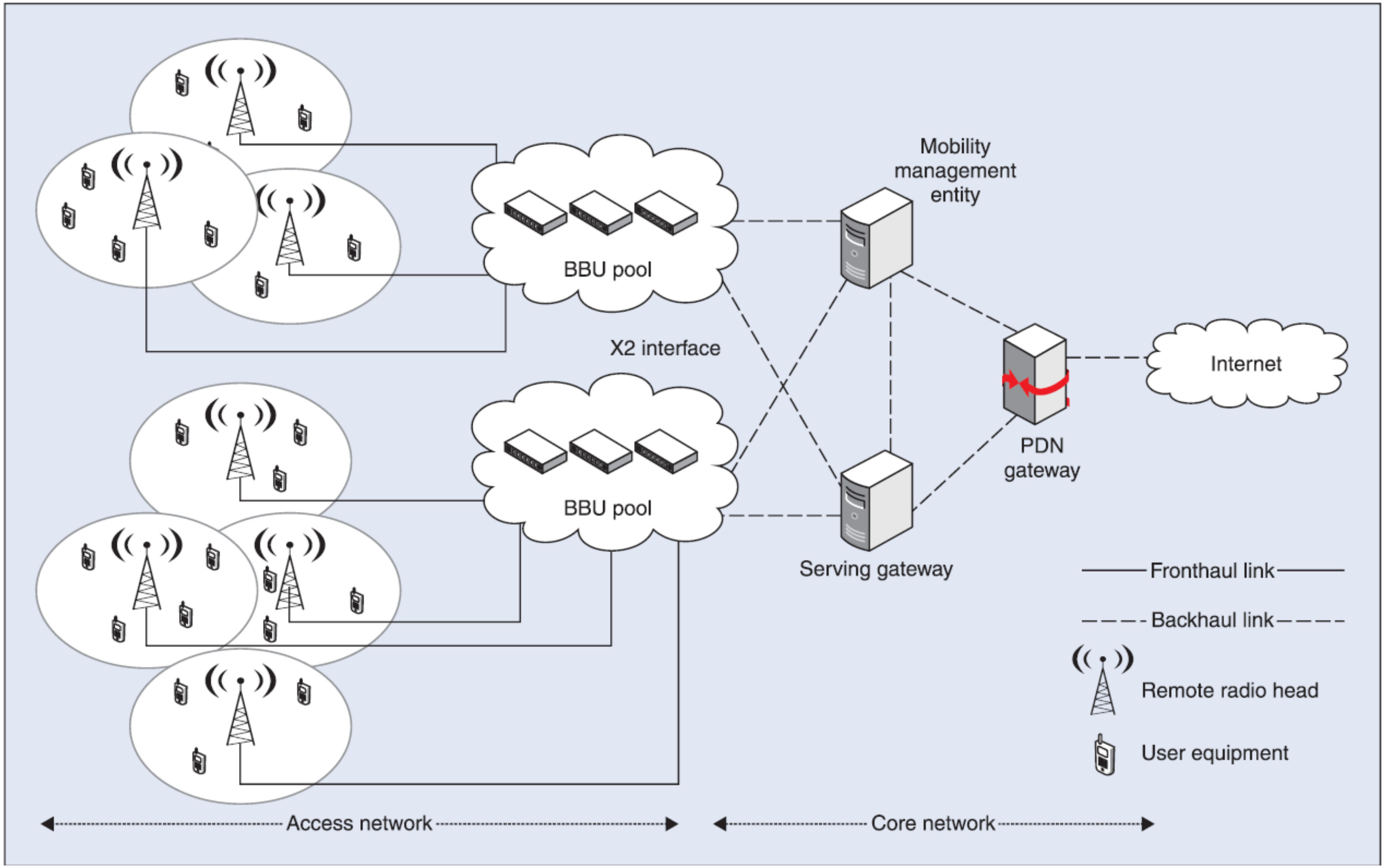
Right now there is no anticipated migration of backhaul to anything else

Evolution of Base Stations in RAN

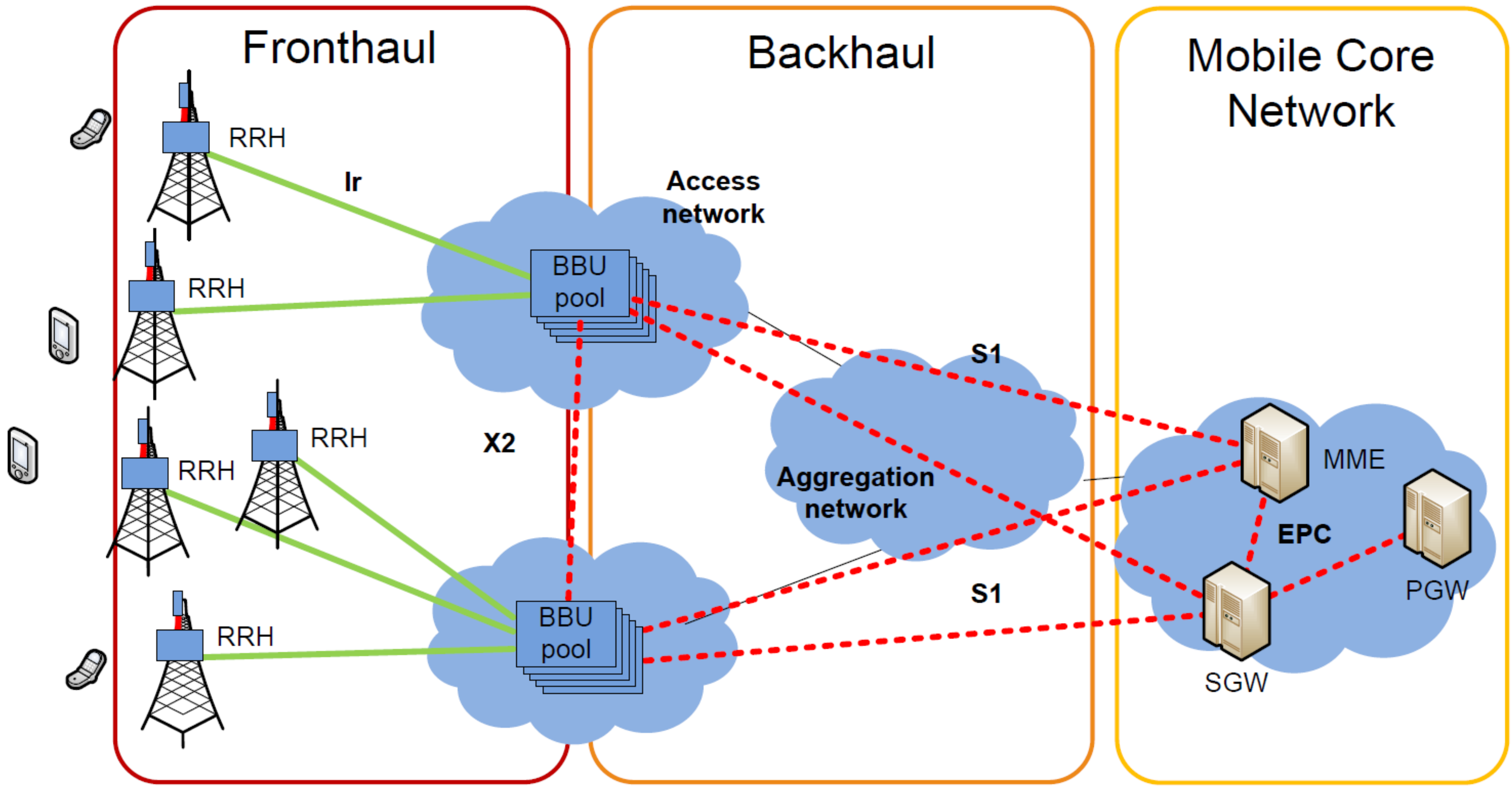


Peng2016

An Cloud-RAN based System

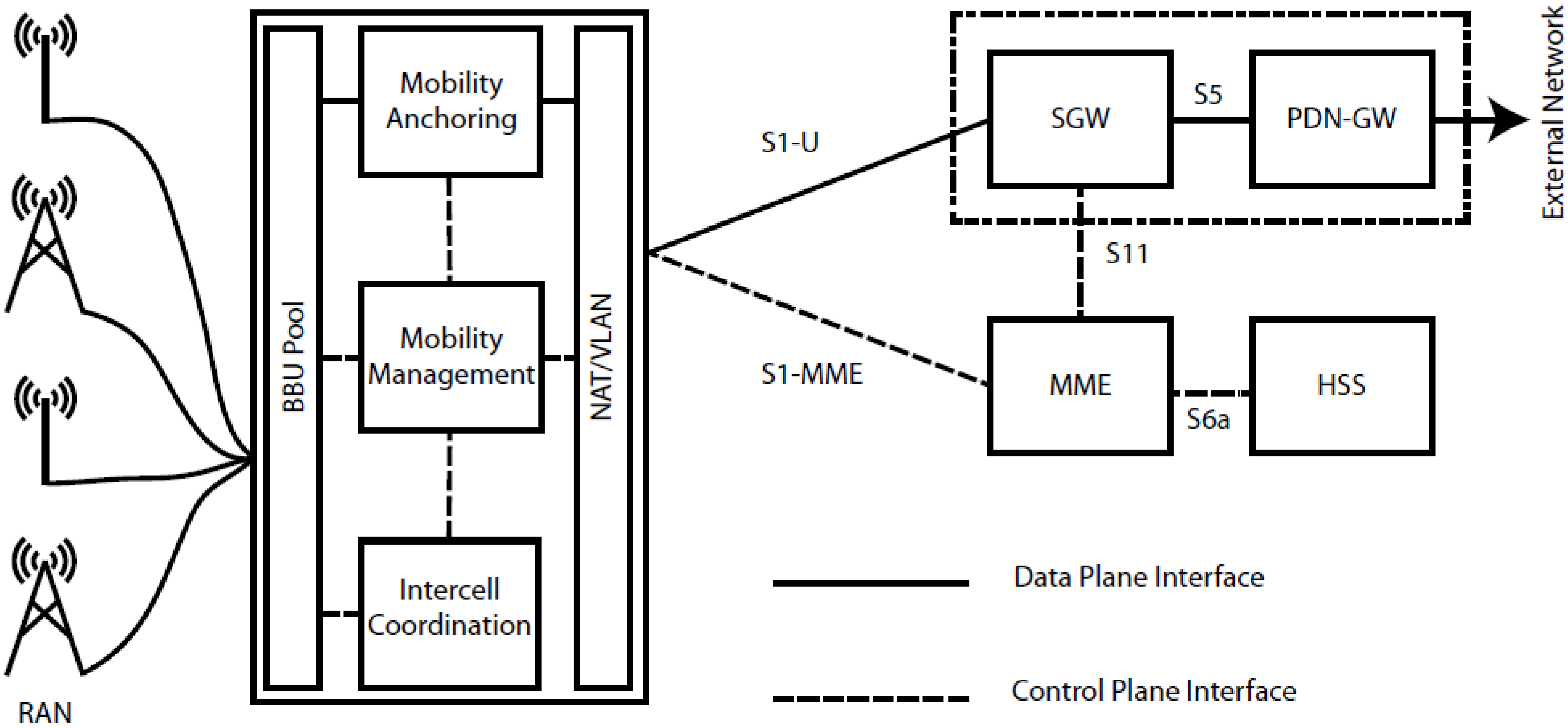


C-RAN LTE Mobile Network



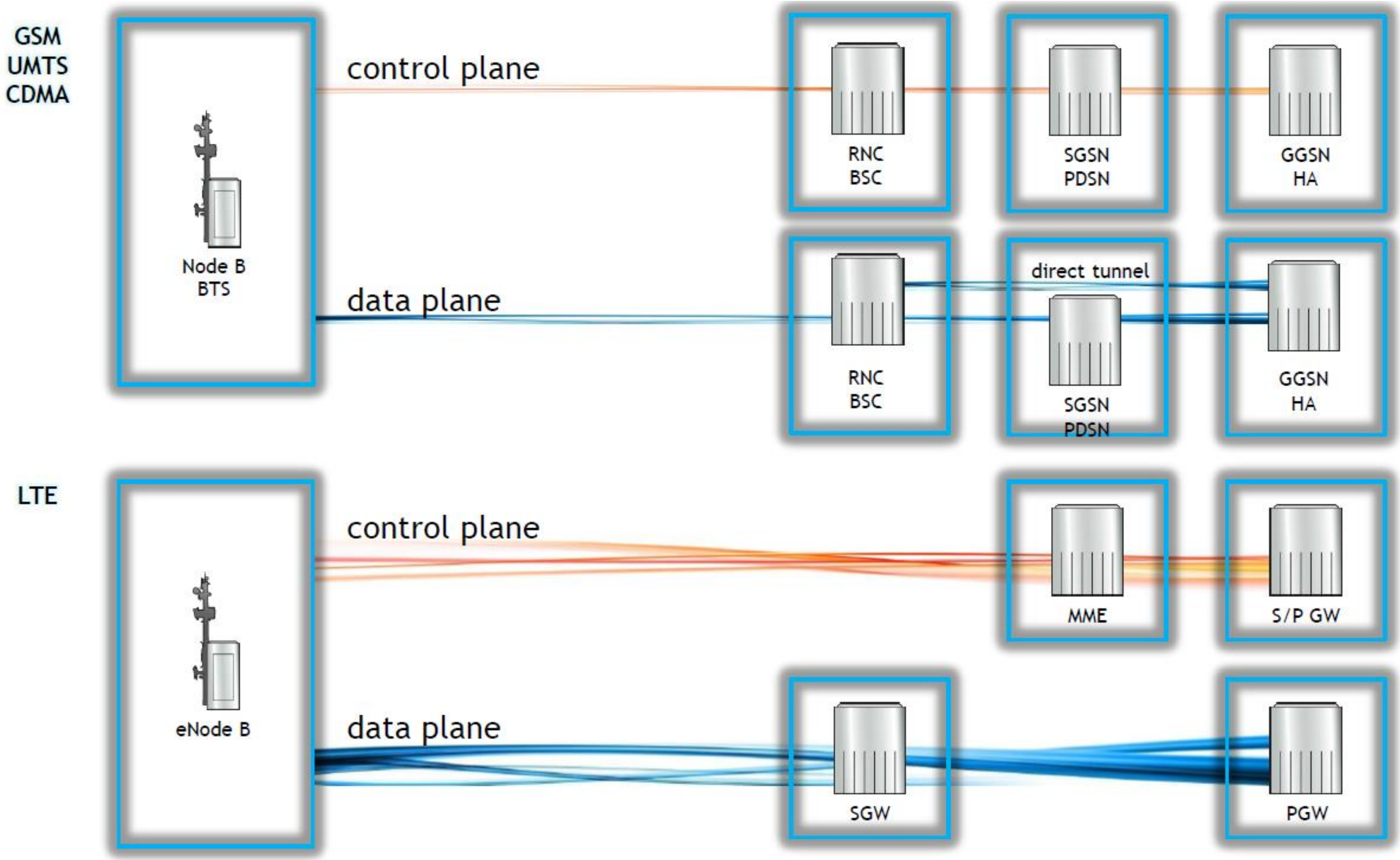
Checko2015

Architecture and Functions/Elements in a C-RAN eNodeB



Source: Dawson, Edinburgh

Backhaul:
Control Plane and Data Plane



COMPARISON BETWEEN TRADITIONAL BASE STATION, BASE STATION WITH RRH AND C-RAN

Architecture	Radio and baseband functionalities	Problem it addresses	Problems it causes
Traditional base station	Co-located in one unit	-	High power consumption Resources are underutilized
Base station with RRH	Spitted between RRH and BBU. RRH is placed together with antenna at the remote site. BBU located within 20-40 km away. Generally deployed nowadays	Lower power consumption. More convenient placement of BBU	Resources are underutilized
C-RAN	Spitted into RRH and BBU. RRH is placed together with antenna at the remote site. BBUs from many sites are co-located in the pool within 20-40 km away. Possibly deployed in the future	Even lower power consumption. Lower number of BBUs needed - cost reduction	Considerable transport resources between RRH and BBU

Checko2015

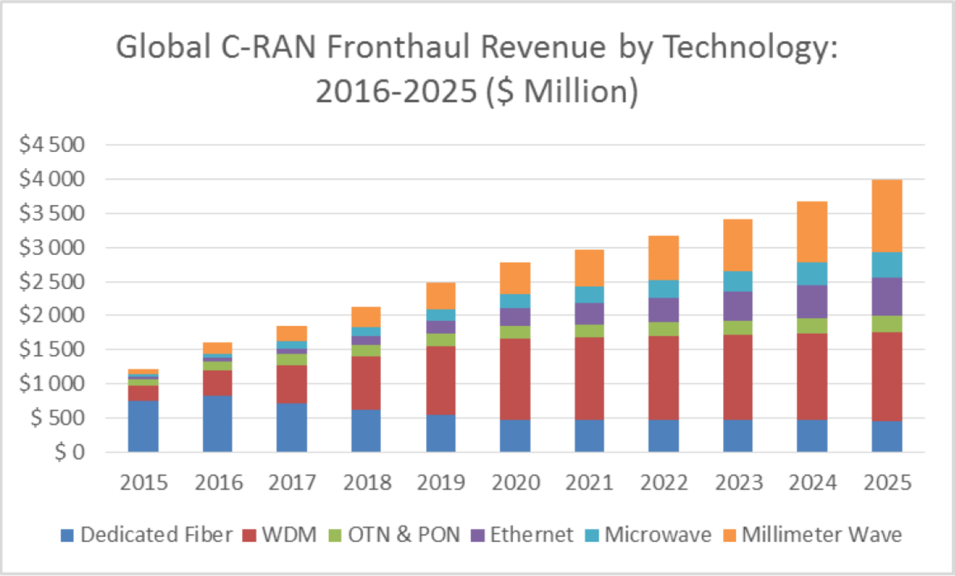
C-RAN Transport Network Techniques

Trends/evolution of mobile transport networks

- More capacity is needed in mobile transport networks
  - Fiber becomes the media for mobile transport networks
  - Macro cells become more dense
  - Small cells are introduced
  - Multiple technologies, frequencies, cell sizes and network architectures are mixed
    - LTE-Advanced address multi-antenna techniques
  - Het-Nets are being deployed
  - Mobile Fronthaul networks to bridge distance between antenna and base station

WDM is growing to be the preferred C-RAN technology

- WDM is the preferred C-RAN technology from 2018 and beyond
  - 33,86% CAGR - 2016-2030
- Dedicated fiber is dropping off
- Ethernet is starting to win traction around 2020

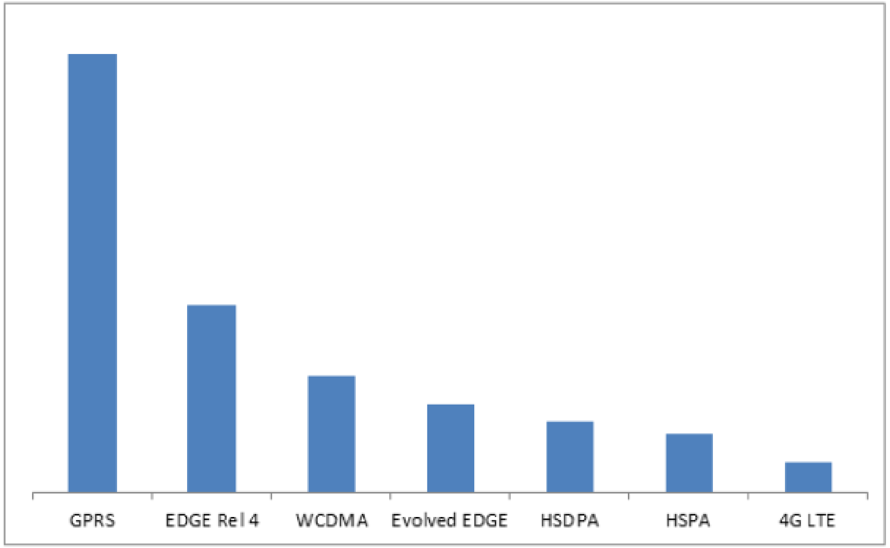


Source: SNS Research, 2016

Latency

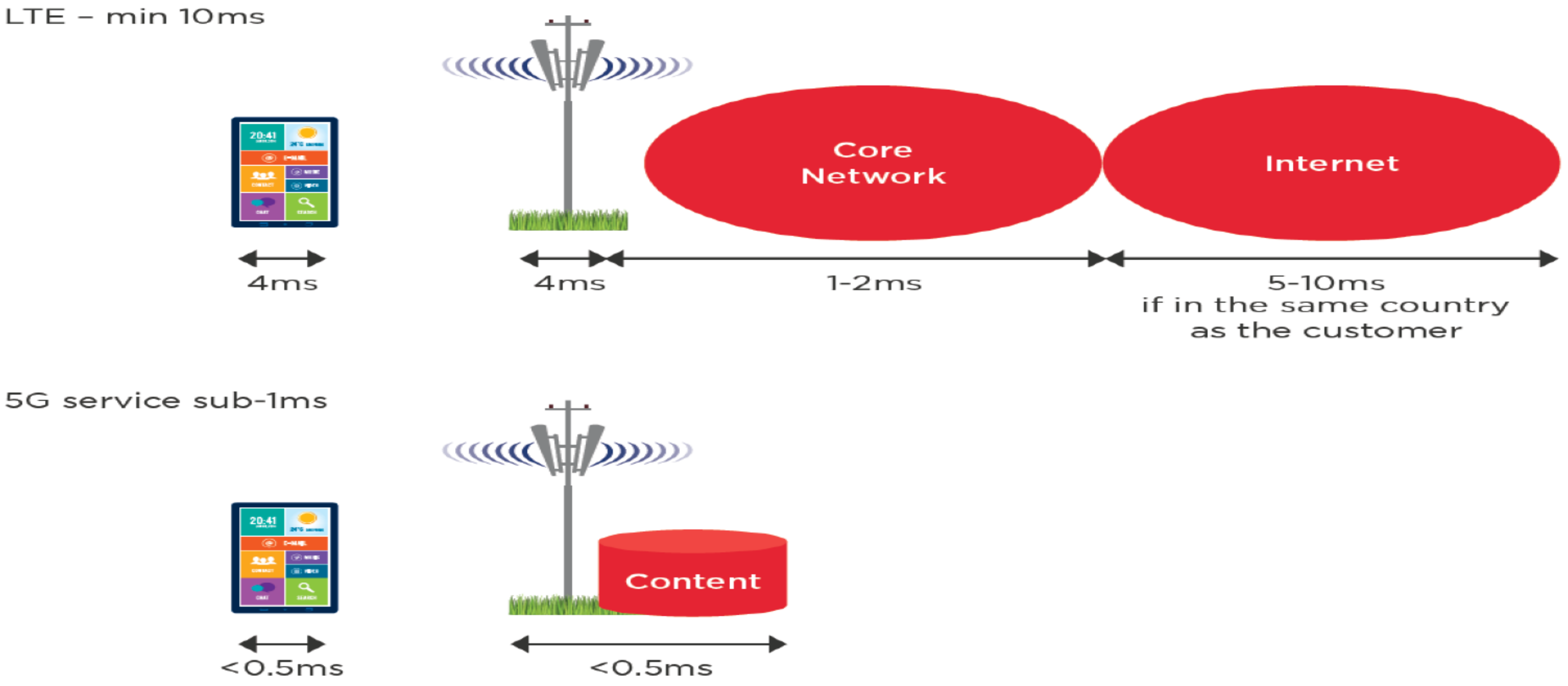
- The low latency requirement in LTE networks attracts development of new applications requiring real-time treatment
  - 4G/LTE is now about half lag time as HSDPA
  - Government, healthcare and other markets and industries are attracted to mobile networks
  - Examples: Real-time video surveillance, distance learning, expanded telemedicine, public safety

Comparing lag times
of the mobile network standards



Source: Backhaul Forum 2014

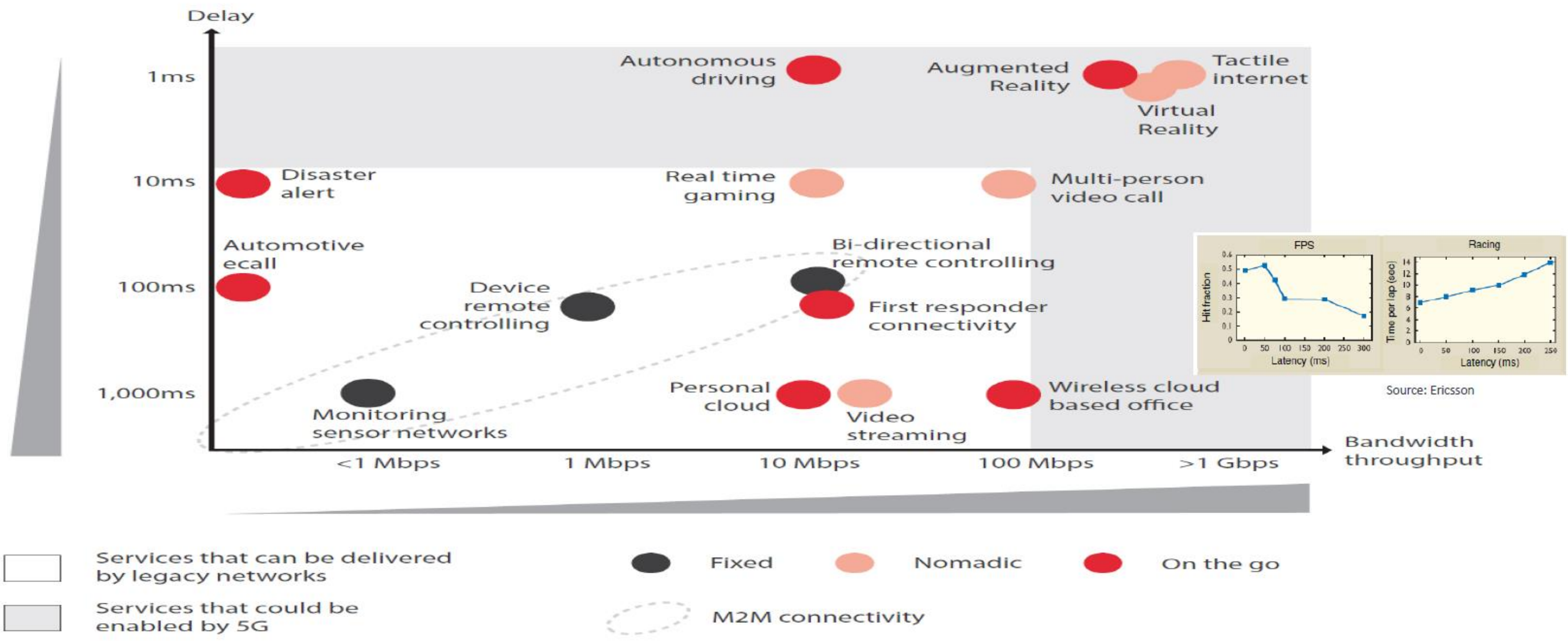
Latency performance



5G technology requirements

- Requirements are driven by the internet of things
- 1-10Gbps connections to end points in the field
- 1 millisecond end-to-end round trip delay (latency)
- 1000x bandwidth per unit area
- 10-100x number of connected devices
- (Perception of) 99.999% availability
- (Perception of) 100% coverage
- 90% reduction in network energy usage
- Up to ten year battery life for low power, machine-type devices

Latency and bandwidth

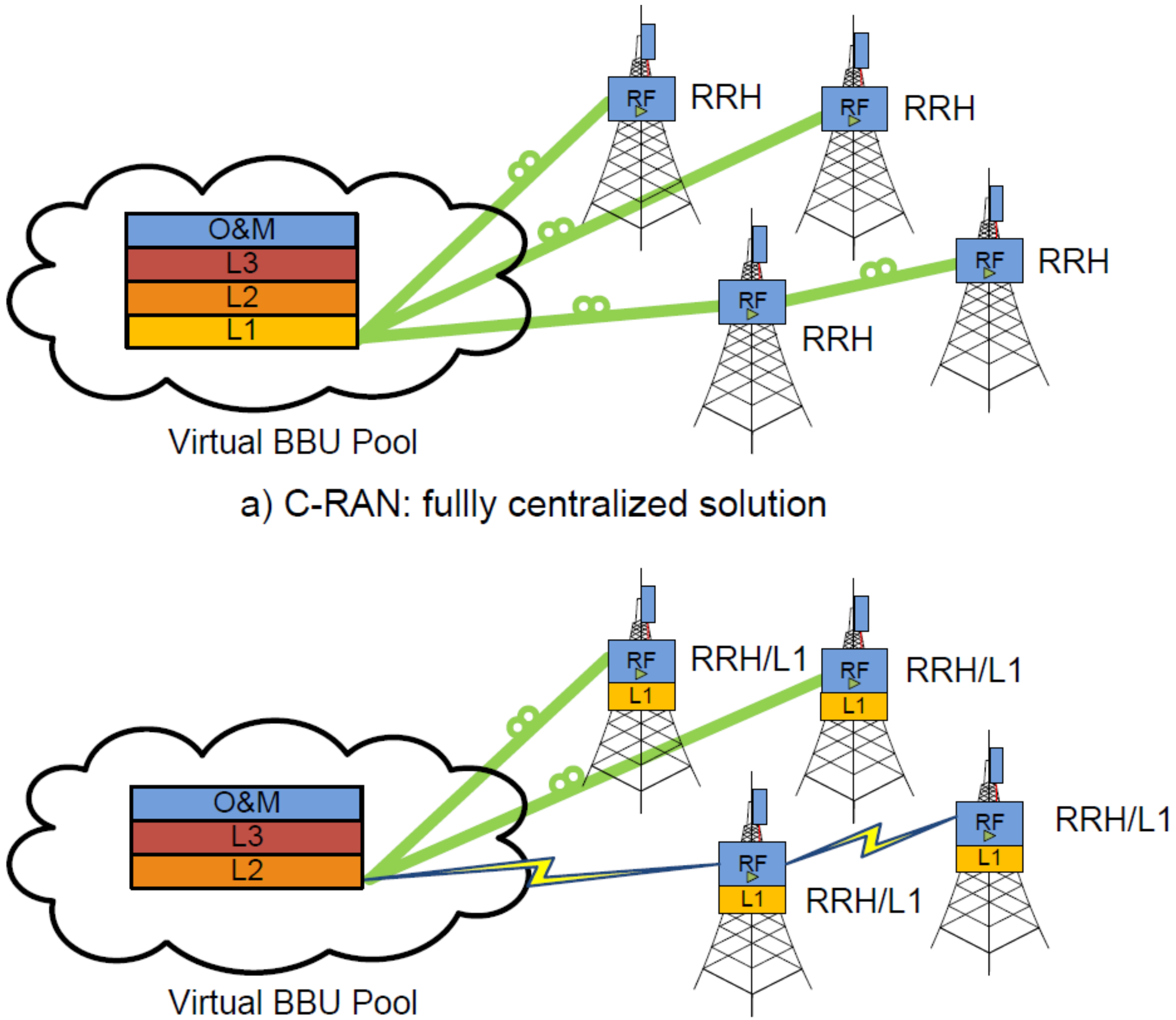


Transport Network Techniques

- Physical layer architecture
- Physical medium
- Transport network standards
- Transport network devices needed to support or facilitate deployments
- IQ compression techniques

**The main focus here is on the fronthaul transport network.

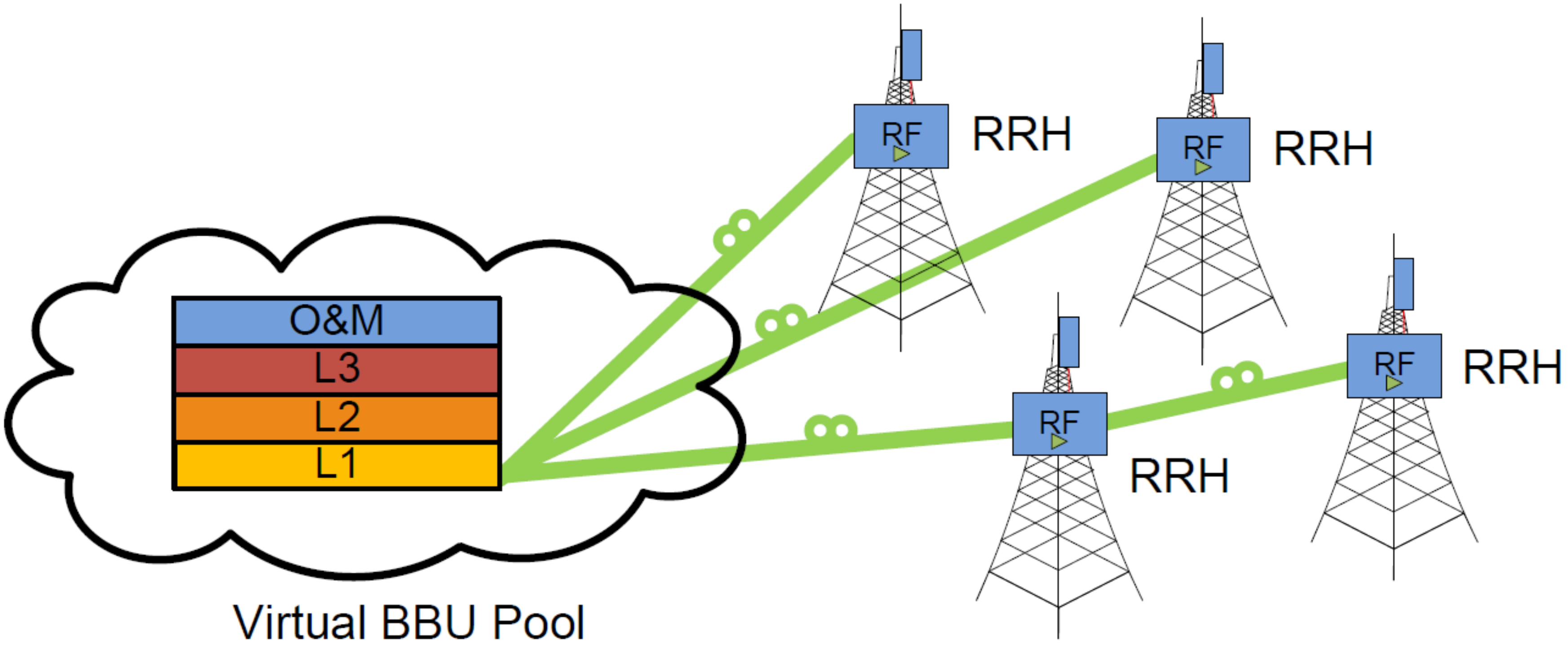
PHY Layer Architecture in C-RAN



b) C-RAN: partially centralized solution

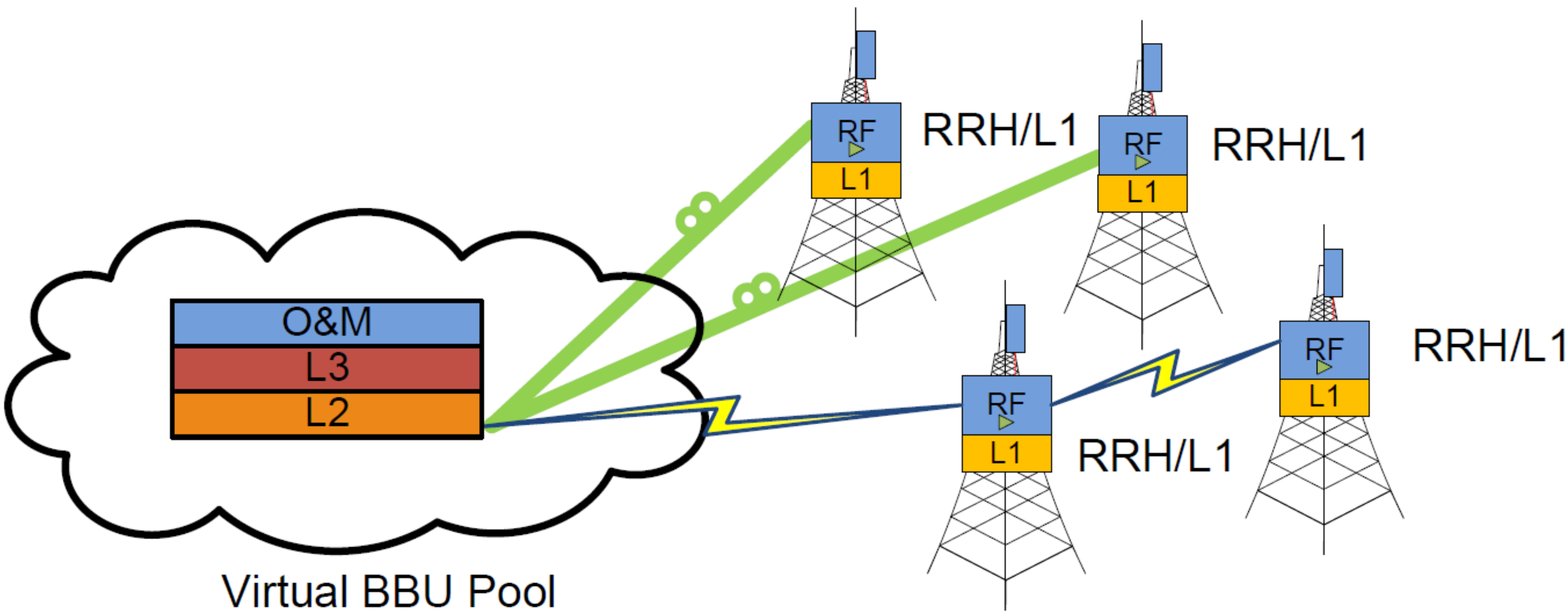
C-RAN: Fully Centralized Solution

- L1, L2 and L3 functionalities reside in the BBU Pool.
- This solution intrinsically generates high bandwidth IQ data transmission between RRH and BBU.



C-RAN: Partially Centralized Solution

- L1 processing is co-located with the RRH, thus reducing the burden in terms of bandwidth on the optical transport links



C-RAN: Partially Centralized Solution (cont'd)

- This solution is less optimal
  - resource sharing is considerably reduced
  - advanced features such as CoMP cannot be efficiently supported
- CoMP benefits from processing the signal on L1, L2 and L3 in one BBU Pool instead of in several base stations.
- Other solutions in between the two discussed above
  - only some specific functions of L1 processing are co-located with the RRH, e.g., L1 pre-processing of cell/sector specific functions, and most of L1 is left in the BBU.

Physical Medium (1/3)

- Only 35% of base stations were forecasted to be connected through fiber, and 55% by wireless technologies, the remaining 10% by copper on a global scale in 2014.
- The global share of fiber connections is growing. In North America the highest percentage of backhaul connections were forecasted to be done over fiber - 62.5% in 2014.

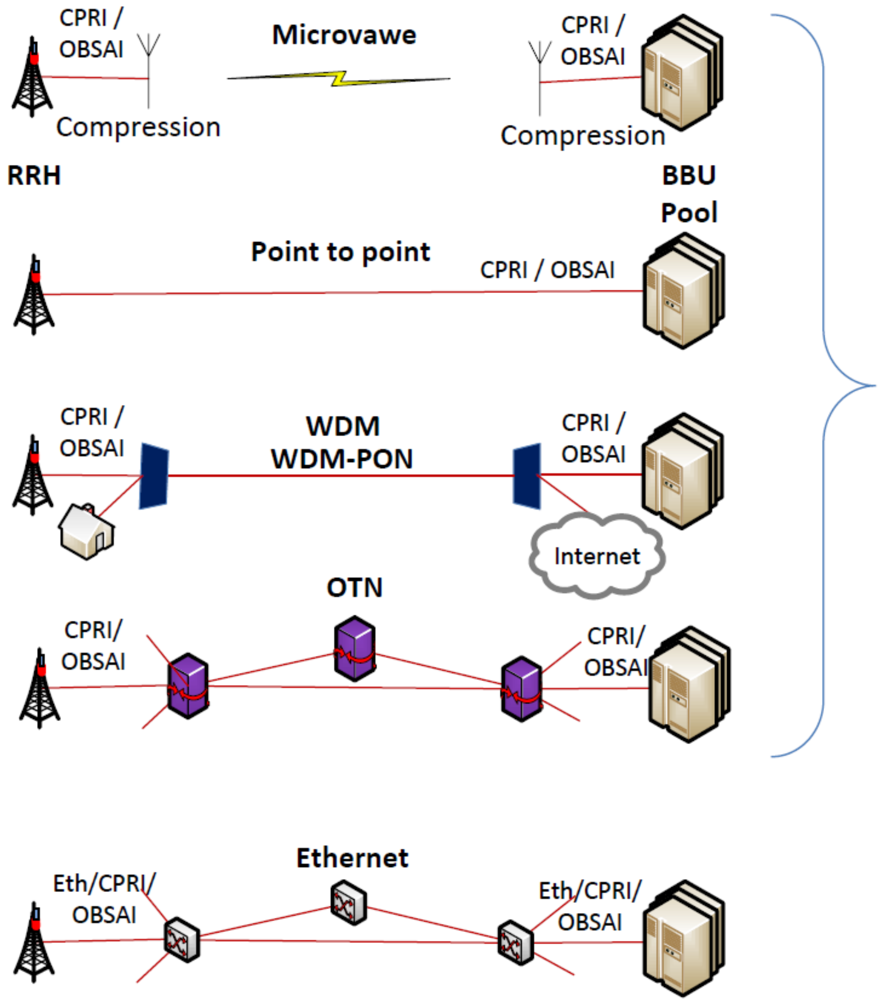
Physical Medium (2/3)

- Fiber links allow huge transport capacity, supporting up to tens of Gbps per channel.
- 40Gbps per channel is commercially available, while future systems will be using 100Gbps modules and higher, when their price and maturity will become more attractive.
- Typical microwave solutions offer from 10 Mbps-100 Mbps up to 1Gbps range, the latter available only for a short range (up to 1.5 km). Therefore, 3:1 compression would allow 2.5Gbps data to be sent over such 1Gbps link.

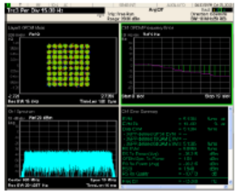
Physical Medium (3/3)

- Wi-Fi can potentially be used for fronthauling.
  - For small cells wireless backhaul deployment, Wi-Fi is seen as a possible solution. (The Wi-Fi IEEE 802.11ad can achieve the maximum theoretical throughput of 7Gbps.)
- The copper links is not taken into account for C-RAN
  - Digital Subscriber Line (DSL) based access can offer only up to 10-100 Mbps.
- Conclusions:
  - Full C-RAN deployment is currently only possible with fiber links between RRH and BBU Pool.
  - In case C-RAN is deployed in a partially centralized architecture, or when compression is applied, microwave can be considered as a transport medium between RRHs and BBU Pool.

Transport Network



Technology is ready
(capacity not necessarily)



Transport Network: Point to Point Fiber

- Point to point fiber is a preferred solution for a BBU Pool with less than 10 macro base stations, due to capacity requirements.
- The solution consumes significant fiber resources, therefore network extensibility is a challenge.
- New protection mechanisms are required in case of failure, as well as additional mechanisms to implement O&M are needed.
- CPRI products are offering 1+1 backup/ring topology protection features. If fiber is deployed with physical ring topology it offers resiliency similar to SDH.

Transport Network: WDM/OTN

- Wavelength-division multiplexing (WDM)/Optical Transport Network (OTN) solutions are suitable for macro cellular base station systems with limited fiber resources, especially in the access ring.
- The solution improves the bandwidth on BBU-RRH link, as 40-80 optical wavelength can be transmitted in a single optical fiber, therefore with 10Gbps large number of cascading RRH can be supported, reducing the demand on fiber.
- Optical Transport Network (OTN)
  - provide a way of supervising client's signals,
  - assure reliability compared with Synchronous Optical NETworking (SONET)/SDH network
  - achieve carrier grade of service
  - efficiently supports SONET/SDH as well as Ethernet and CPRI.

Transport Network: Carrier Ethernet

- Carrier Ethernet transport can also be directly applied from RRH towards BBU Pool.
- In that case, CPRI-to-Ethernet (CPRI2Eth) gateway is needed between RRH and BBU Pool.
  - CPRI2Eth gateway needs to be transparent in terms of delay.
  - CPRI2Eth gateway should offer multiplexing capabilities to forward different CPRI streams to be carried by Ethernet to different destinations.
- The main challenge in using packet passed Ethernet in the fronthaul is to meet the strict requirements on synchronization, syntonization and delay.

Transport Network: Carrier Ethernet (cont’d)

- Synchronization refers to phase and syntonization to the frequency alignment, respectively.
- Base stations need to be phase and frequency aligned in order to, e.g., switch between uplink and downlink in the right moment and to stay within their allocated spectrum.

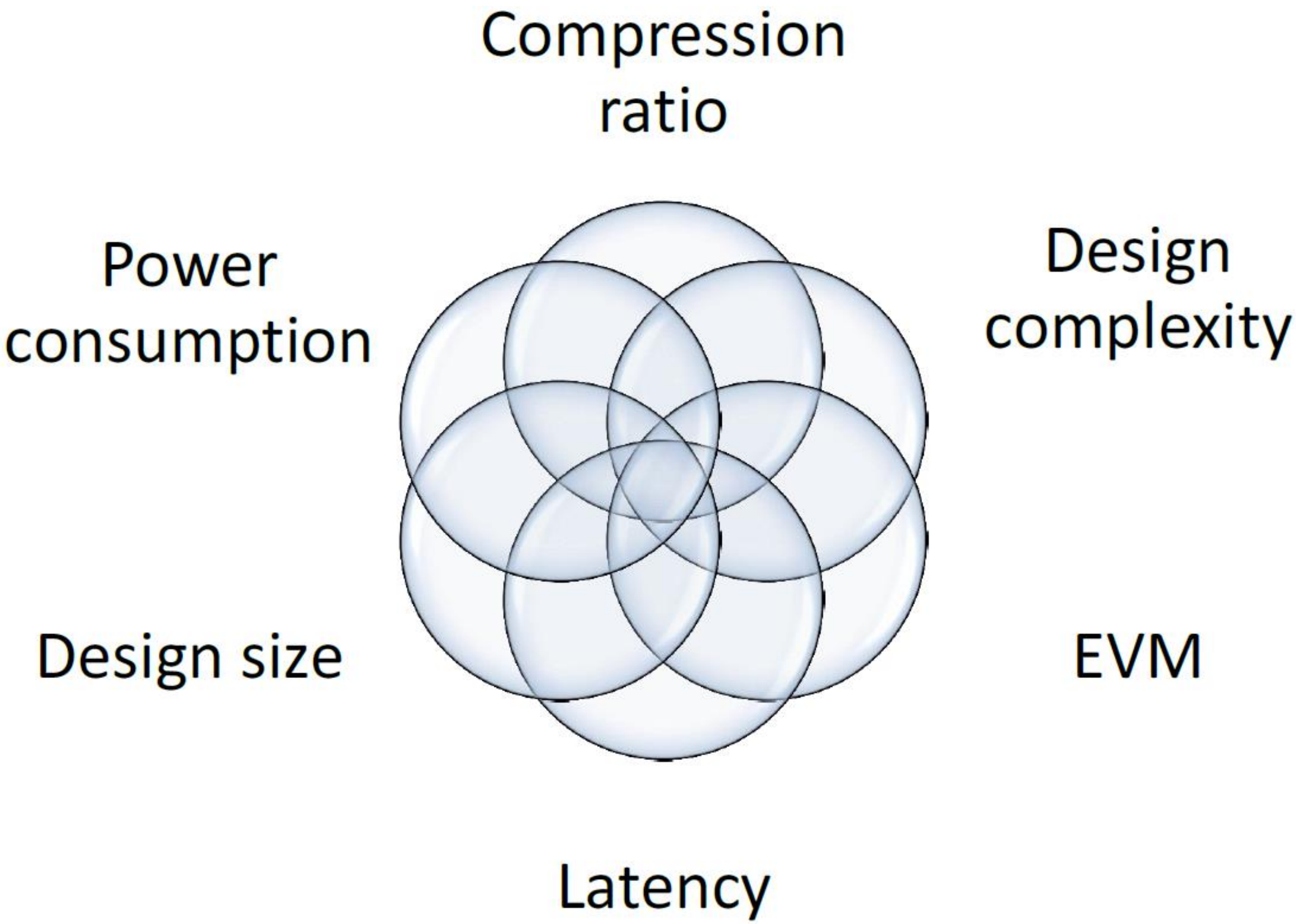
Transport Network Equipment for Usage in C-RAN

- CPRI2Ethernet gateway
  - If Ethernet is chosen as a transport network standard, CPRI2Eth gateway is needed to map CPRI data to Ethernet packets at the interface of RRH towards BBU Pool.
- IQ data routing switch
  - It is based on a Fat-Tree architecture of Dynamic Circuit Network (DCN) technology.
- CPRI mux
  - A device aggregates traffic from various radios and encapsulates it for transport over a minimum number of optical interfaces.
- x2OTN gateway
  - If OTN is chosen as a transport network solution, CPRI/OBSAI to OTN gateway is needed to map signals from two standards.

IQ Compression Schemes and Solutions

- In C-RAN the data rate at the fronthaul link can be 12 to 55 times higher compared to data rate on the radio interface, depending on CPRI IQ sample width and modulation.
- RRHs transmit raw IQ samples towards BBU cloud, therefore, an efficient compression schemes are needed to optimize huge bandwidth transmission over capacity-constrained links.
  - non-linear quantization
  - frequency sub-carrier compression
  - IQ data compression

Tradeoff on
Choosing IQ Compression Schemes



Security

Table 2.4: Comparison of IQ compression methods. Compression ratio 33% corresponds to 3:1

Method	Techniques applied	Compression ratio	EVM
[22]	Not available	44%	Not available
[89]	removing redundancies in spectral domain preforming block scaling usage of non-uniform quantizer	28% 23% 17%	3% 4% 8%
[90]	removing redundancies in spectral domain preforming block scaling usage of non-uniform quantizer	52% 39% 30%	$<$ 1.4% $<$ 1.5% $<$ 2.5%
[91]	adaption of dynamic range of the signal removal of frequency redundancy IQ compression	50% 33% 25%	0.5% 3% 8%
[92]	removal of frequency redundancy optimized control information transmission IQ compression user detection	33% (100% cell load) 7% (20% cell load)	Not available
[93]	self-defined robust method performed jointly with base station selection algorithm	Not available	Not available

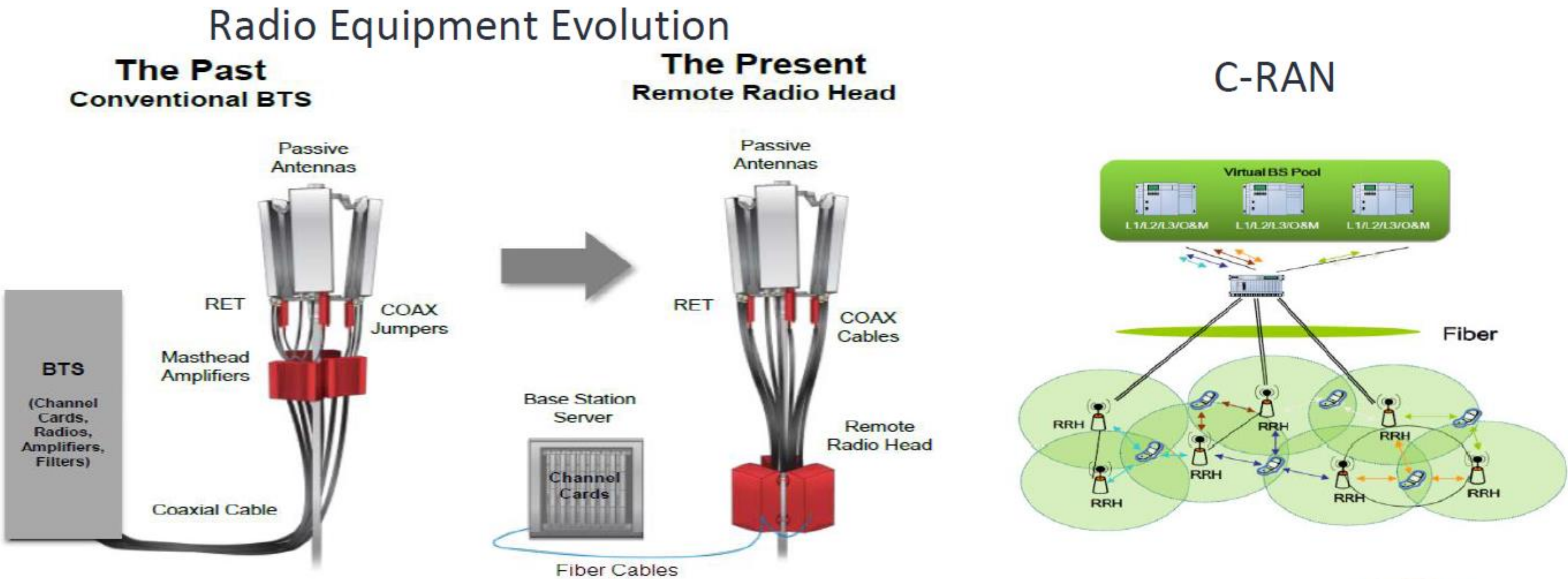
- Compression of 33% is achieved by all the algorithms for which the ratio was available.
- In order not to lose the cost benefit of BBU Pooling for transport network, operator needs to either own substantial amount of fiber or use an IQ compression scheme.

Mobile Backhaul

Trends in mobile networks impact mobile backhaul

- Need to enhance and improve existing mobile backhaul
- Capacity requirements: new technologies are required
- More stringent accuracy requirements needed to support new functionality, like coordinated multipoint (CoMP) and enhanced inter-cell interference coordination (eICIC)
  - Synchronization becoming one of the most important criteria
  - Phase and time synchronization is required for LTE-Advanced
- SLA assurance and end-to-end performance is important
- Support for multiple radio access architectures

Evolution to Fronthaul Architectures



Everything at the Antenna

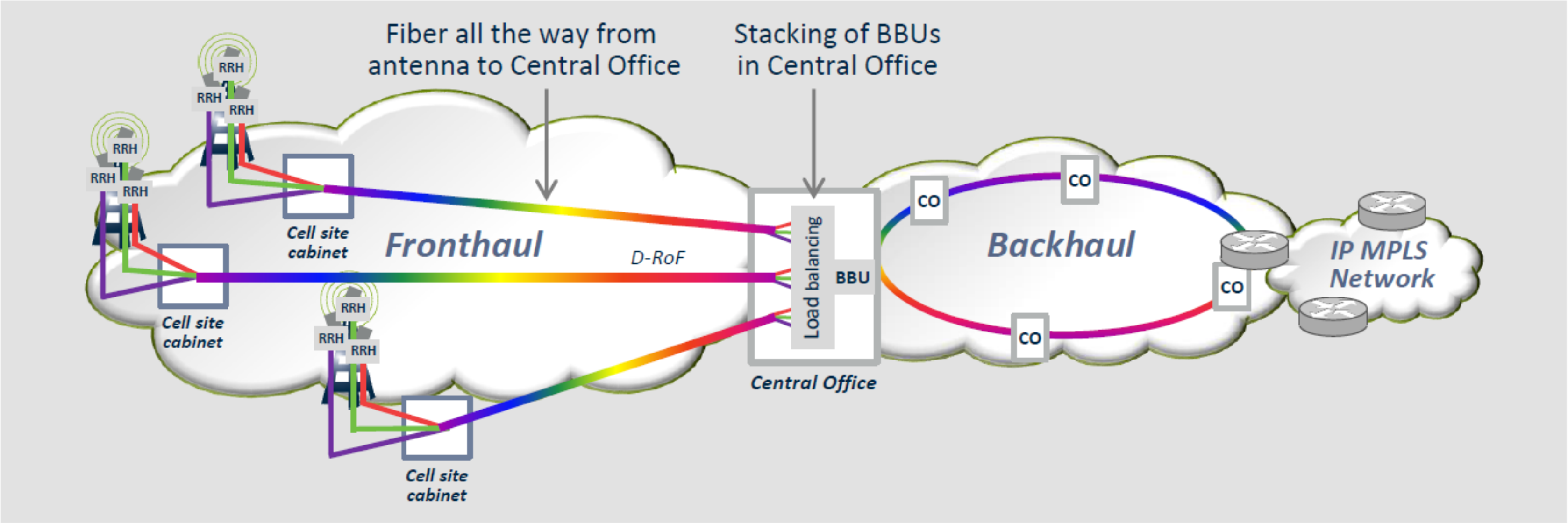
Move to BBU Hotels

BBU Collaboration C-RAN

Virtualization

Network Architecture Evolution

Overall Architecture



Source: GSMA

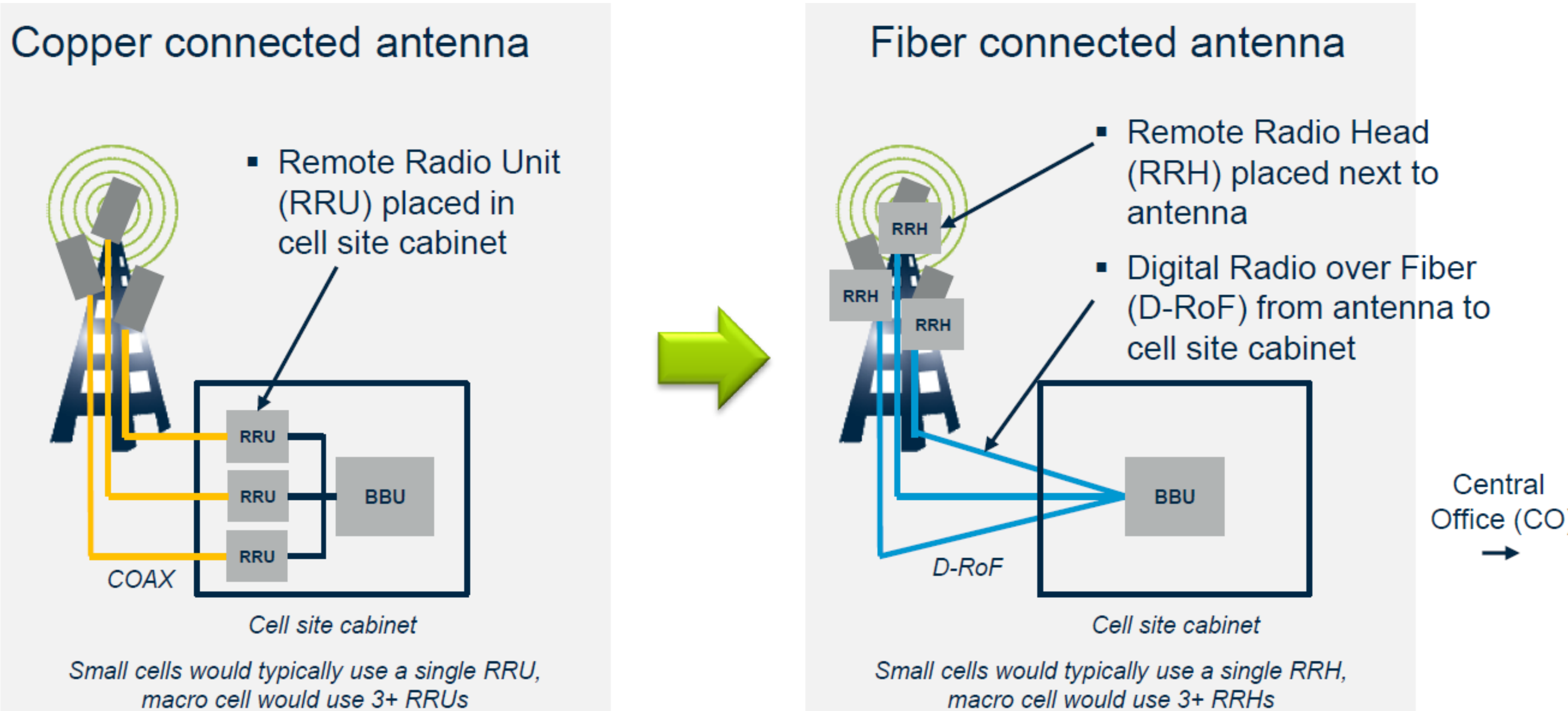
BENEFITS:

- Increased security of CO
- Saves space in the cell site
- Lower total OPEX
- Enables X2 optimization
- Supports LTE-A evolution

- Less interfaces to backhaul / core
- CAPEX saving due to lower number of BBUs
- Simplification of mobility management

RRH: Remote Radio Head
BBU: Base Band Unit
D-RoF: Digital Radio over fiber (CPRI/OBSAI)

Distributed Base Station Architecture



Benefits: Save energy!

BBU Centralization – Centralized-RAN

- Additional Benefits:
- Saves even more energy!
- Increased security of CO (no need for IPSec)
- Saves space in the cell site
- Lower total OPEX
- Enables X2 optimization
- Supports LTE-A evolution