Next Generation RAN
and its programmable structure

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5G NR

Outline

- Next generation of RAN
  - Cloud in RAN
  - New concept
- Physical Layer technologies
  - Massive MIMO in 5G
  - NOMA and OMA
- New Radio

Review

Concept of generations

- 0G Briefcase-size mobile radio telephones
- 1980s => 1G Analog cellular telephony
- 1990s => 2G Digital cellular telephony=> 200kbs
- 2000 => 3G High-speed digital cellular telephony=> 1Mbs
- 2010=> LTE (4G) faster IP-based “anytime, anywhere” => 100Mbs

- 3G ->LTE saw adoption of packet switching over circuit switching

Review

5G

- Operators see
  - Increasing OPEX and CAPEX
  - Slow increase in income, big increase in expectations
- Goals (versus 4G/LTE)
  - 1000× capacity growth
  - 10× spectral efficiency
  - 10× energy efficiency (OPEX down)
  - 10× data rate

How to achieve goals?

- New technologies
- New architectures
- Take ideas from
  - PHY – exploiting DSP & multiple antennas
  - cloud – centralization & commodity hardware
  - SDN – coordination & virtualization

Radio Access Network (RAN)

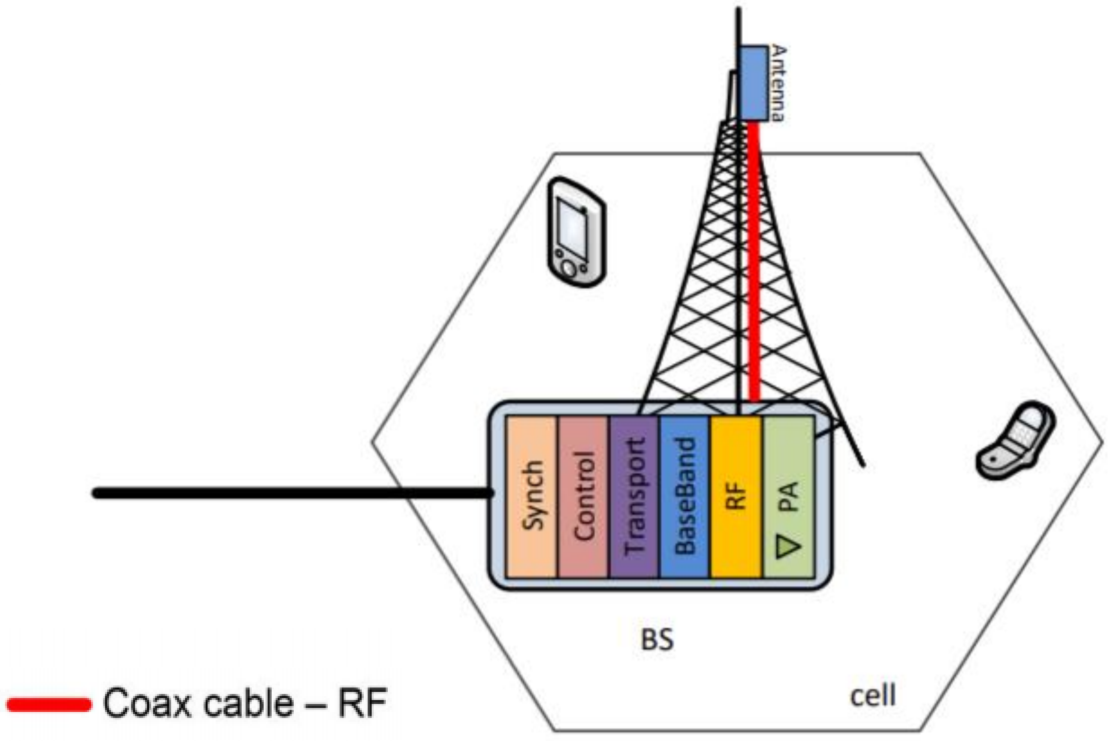
- Separation of functionalities
- Began with 3G
  - Radio equipment
    - Antenna, power amplifier, etc.
  - Signal processing
    - Physical layer (PHY)
    - Multiple access control (MAC)
    - Networking

Radio Part (RRH)

Base Band Processing (BBU)

Co-located RRH and BBU

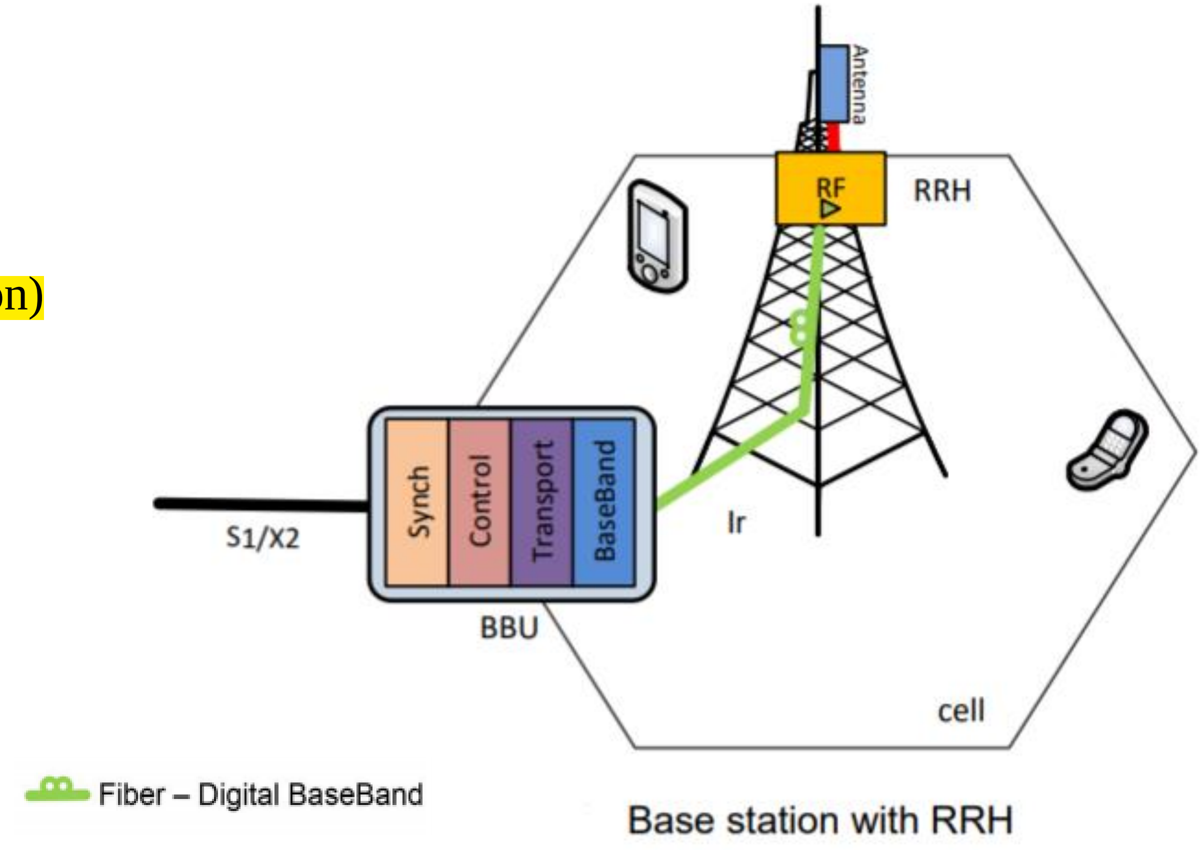
- Analog signal on coax limited to a few meters due to LOSS
- BBU at base of tower, for instance



Traditional macro base station

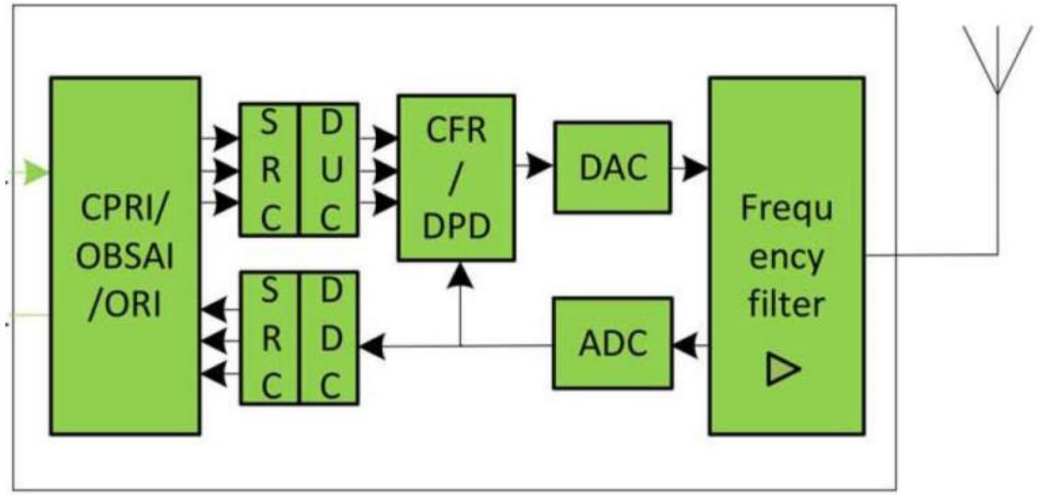
Distributed Antenna

- Fiber has very low loss
- Separation up to 40 km
- Limited by DELAY (processing and propagation)



Remote Radio Head (RRH)

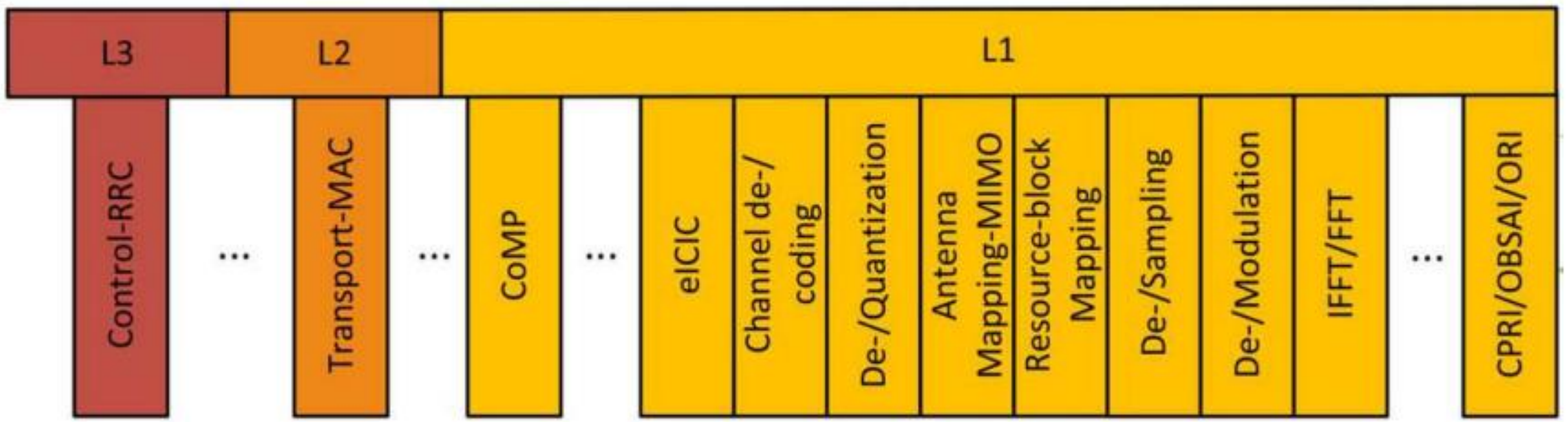
- Analog signal at high carrier frequencies



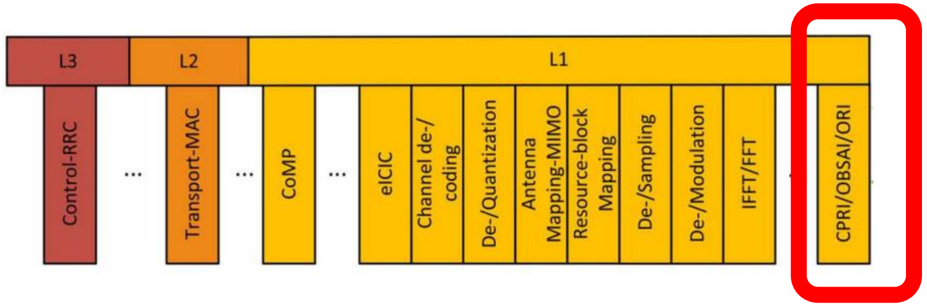
A. Checko, et al., "Cloud RAN for Mobile Networks—A Technology Overview," IEEE Communications Surveys & Tutorials, vol. 17, pp. 405-426.

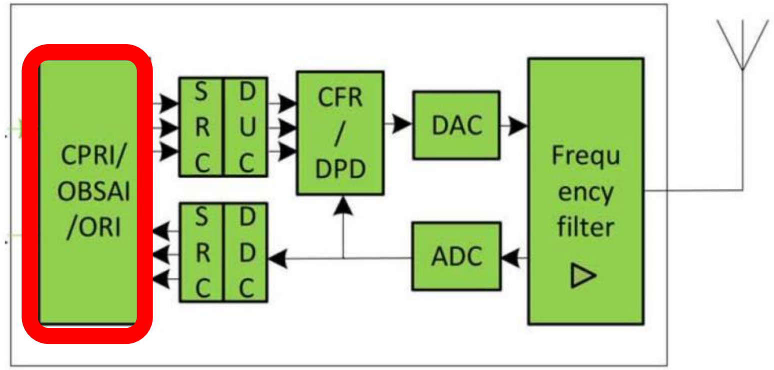
Baseband Unit (BBU)

- Digital signals that are manipulated by ASICs



Common Public Radio Interface (CPRI)





- Protocol for transmission of digital IQ data
- Supports FRONTHAUL traffic
- BBU
  - Specific modulation format, etc.
  - Digital baseband signal needs to become analog
    - Binary optical modulator
    - Digital to analog converter

C-RAN BBU leveraging

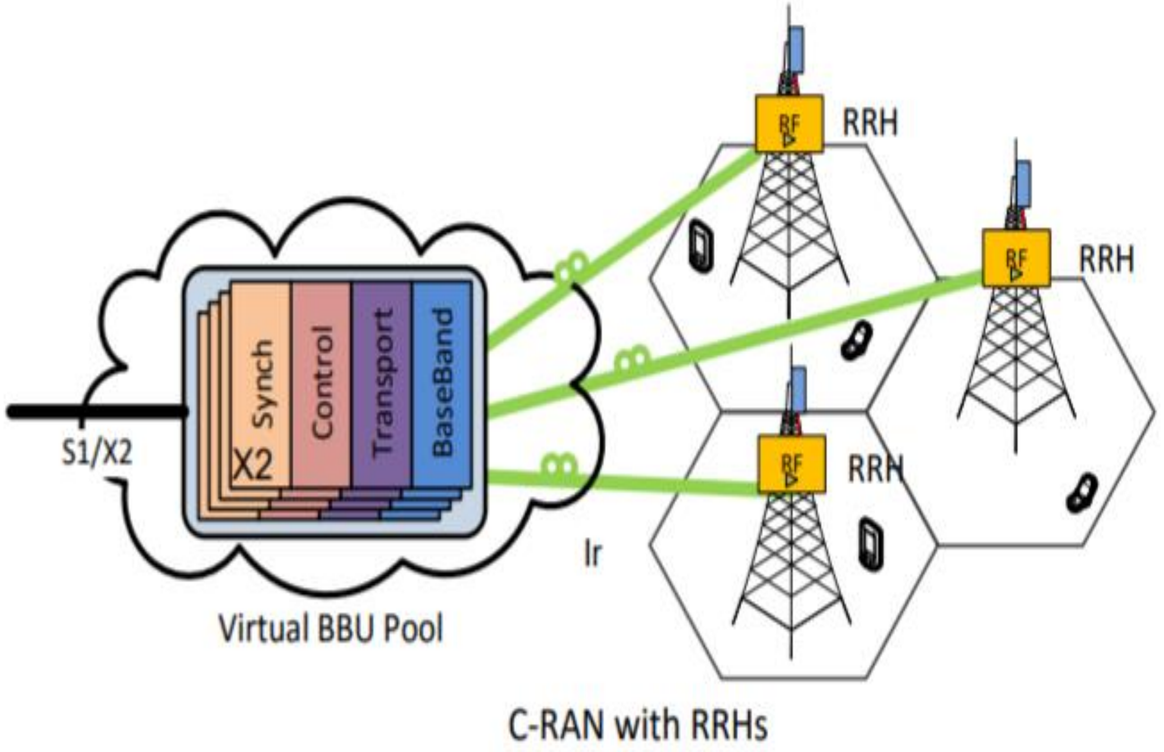
Radio access network

One BBU could service several RRH

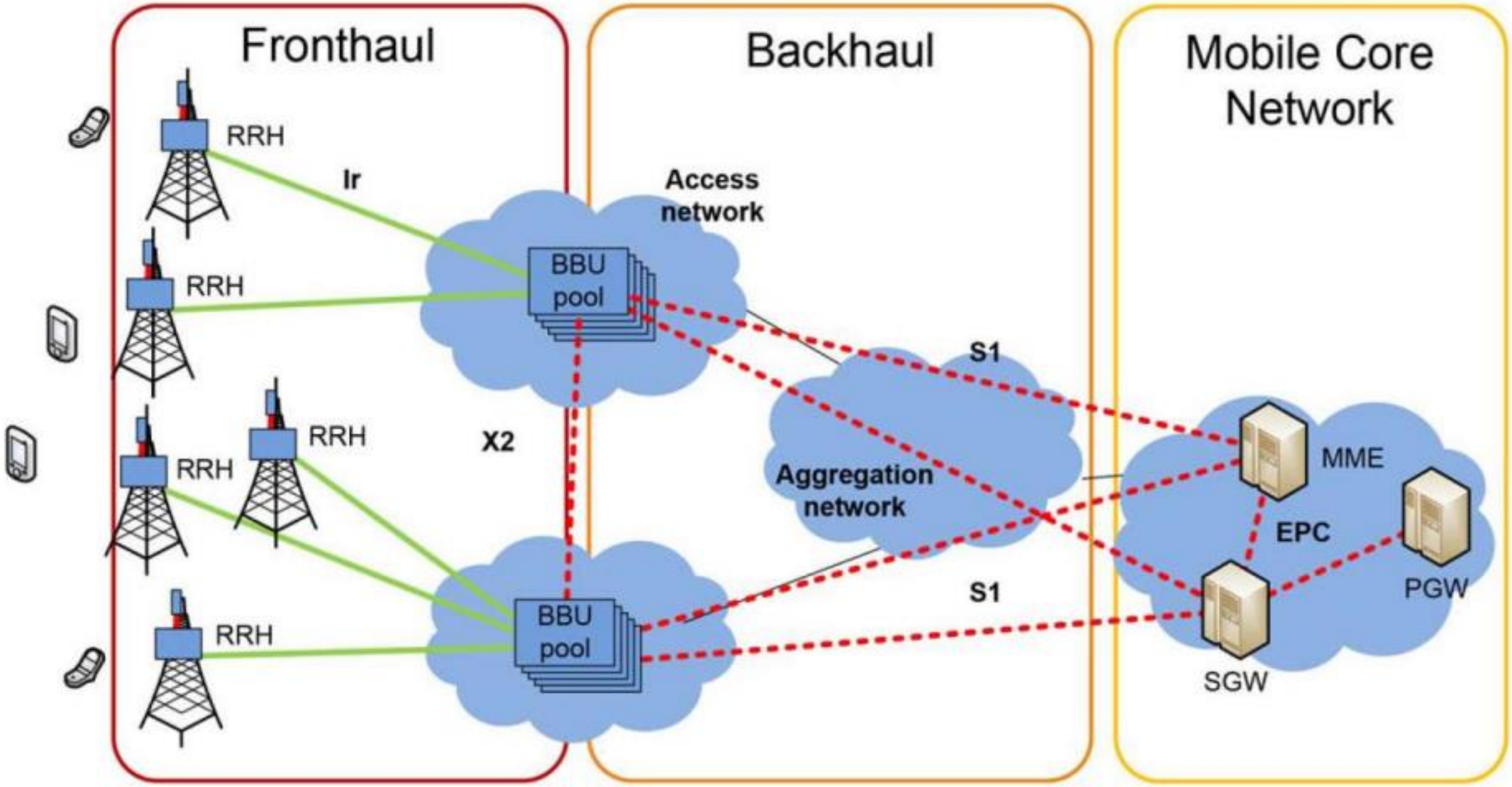
Go farther than separating the RRH & BBU

Exploit centralized BBU to achieve many more goals

RAN	CRAN
Advantages - Convenient location - Lower power consumption	Advantages - Centralization - Even lower power consumption
Disadvantages - Resources are underutilized	Disadvantages - Bandwidth requirements



Potential C-RAN architecture



Fronthaul

New Link between RRH and BBU pool

What does C stand for????

- Variously
  - Cloud
  - Centralized processing
  - Cooperative radio
  - Cooperative
  - Clean

- a cluster of general purpose processors for baseband processing
- compatible with virtualization of services

Economies of scale and coordination with centralization

coordination with centralization

Statistical multiplexing and ability to turn off unused RRH

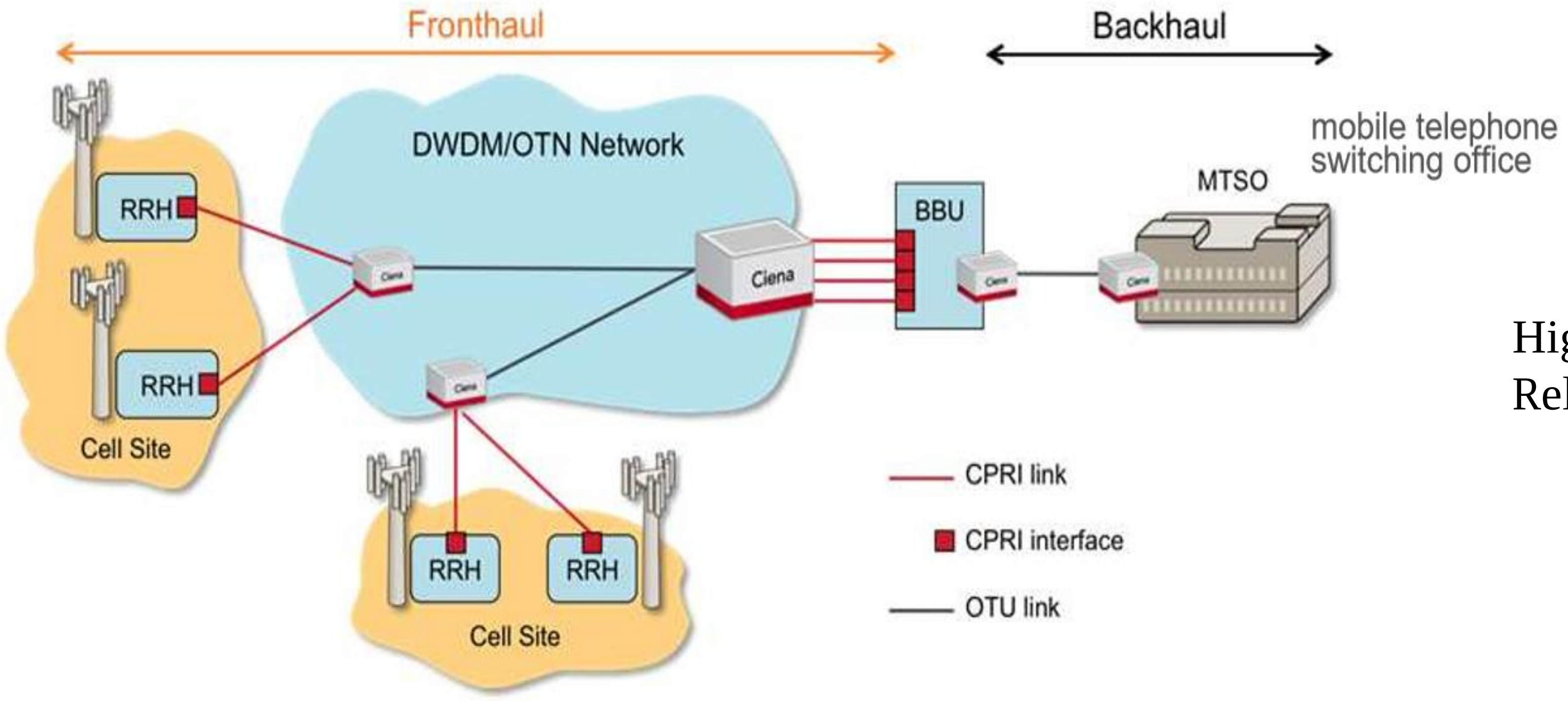
Why C-RAN?

- Non-uniform traffic
- Energy savings
- Maintenance & upgrades
- Increased capacity
- Reduced delay

Front-haul

Digital version of analog signal 1-12 Gbs

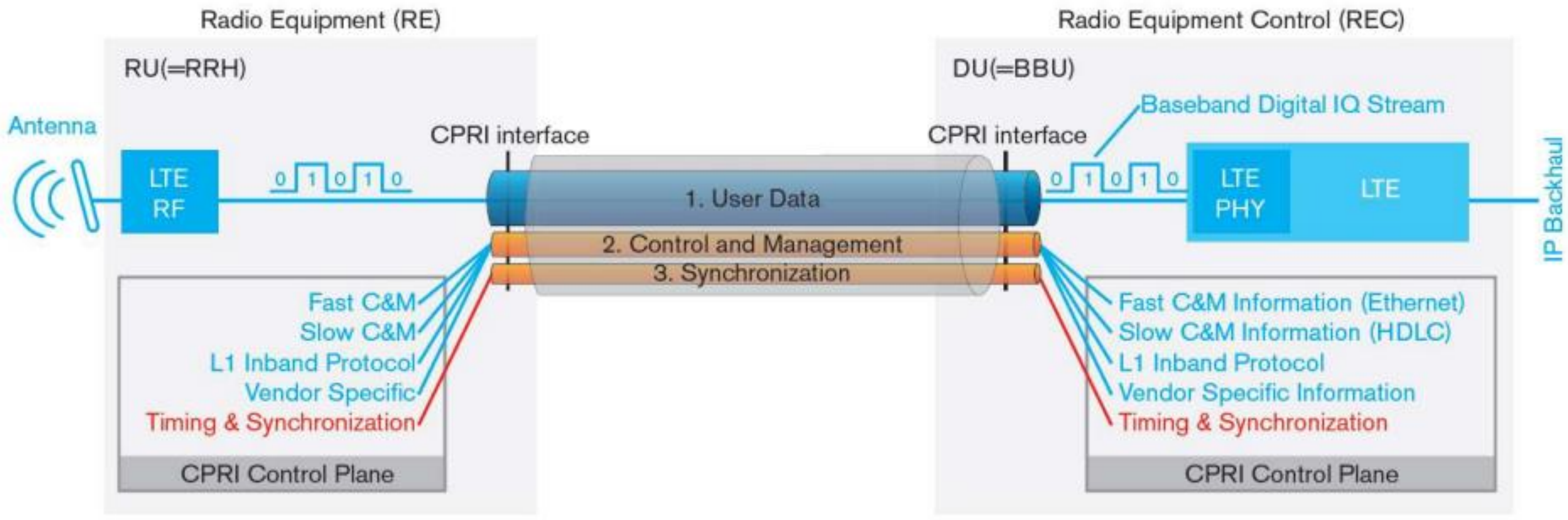
Digital data ~1 Gbs



High capacity with low delay and high Reliable link in Fronthaul

From Ciena primer on backhaul vs. fronthaul

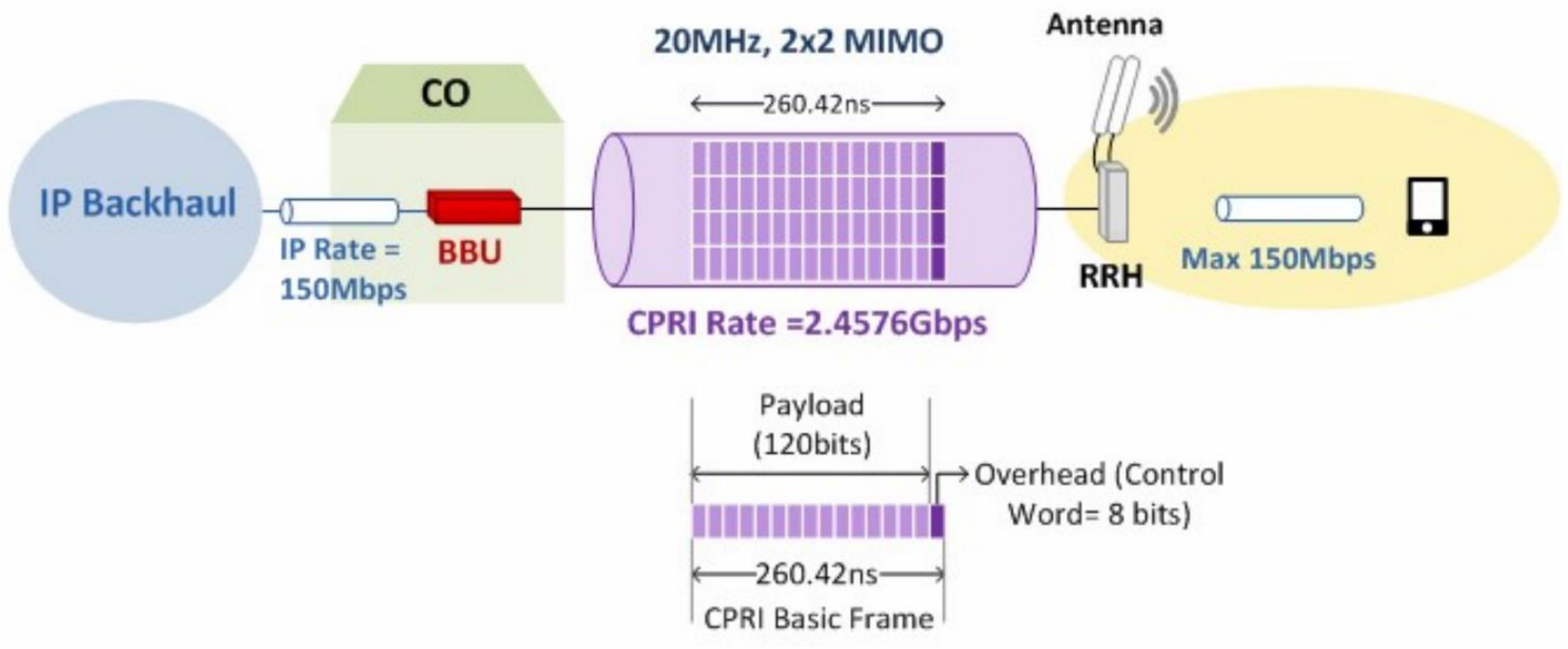
CPRI – Common Public Radio Interface



In-phase and quadrature created at radio
adapted to modulation format
adapted to frequency band

Dedicated Front-haul

- Typically dark fibers used



Why WDM is essential in C-RAN fronthaul networks? March 12, 2014 | By Steve Shin and Dr. Harrison J. Son

Cloud in RAN

Practical challenges

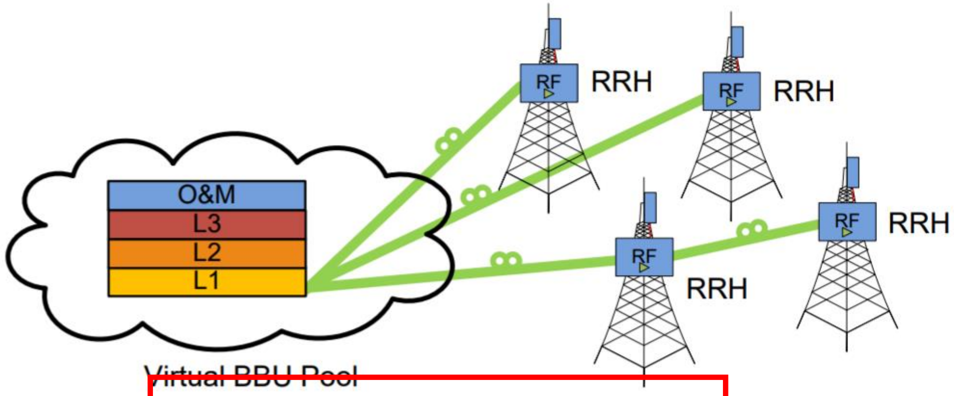
- Front-haul limitations
- Real time versus non-real time functions
- Centralized versus distributed structure

How to apply Complementary technologies

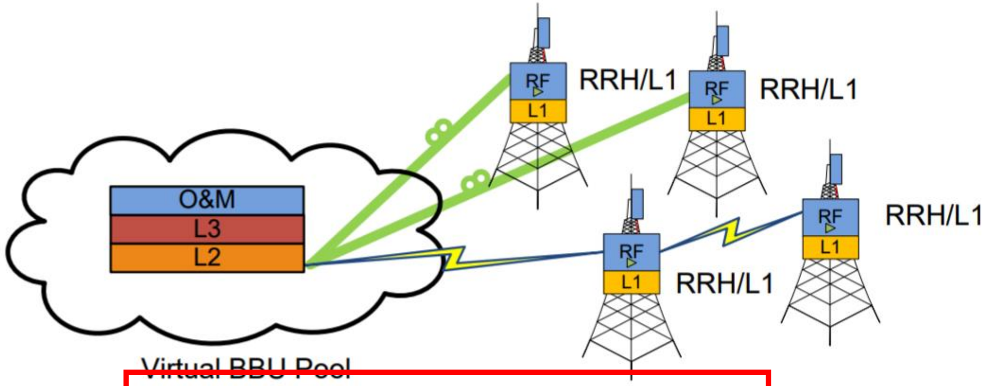
- UAV
- Caching
- New concepts (vehicular nodes)

How to serve three categories of services

- Tactile Internet services

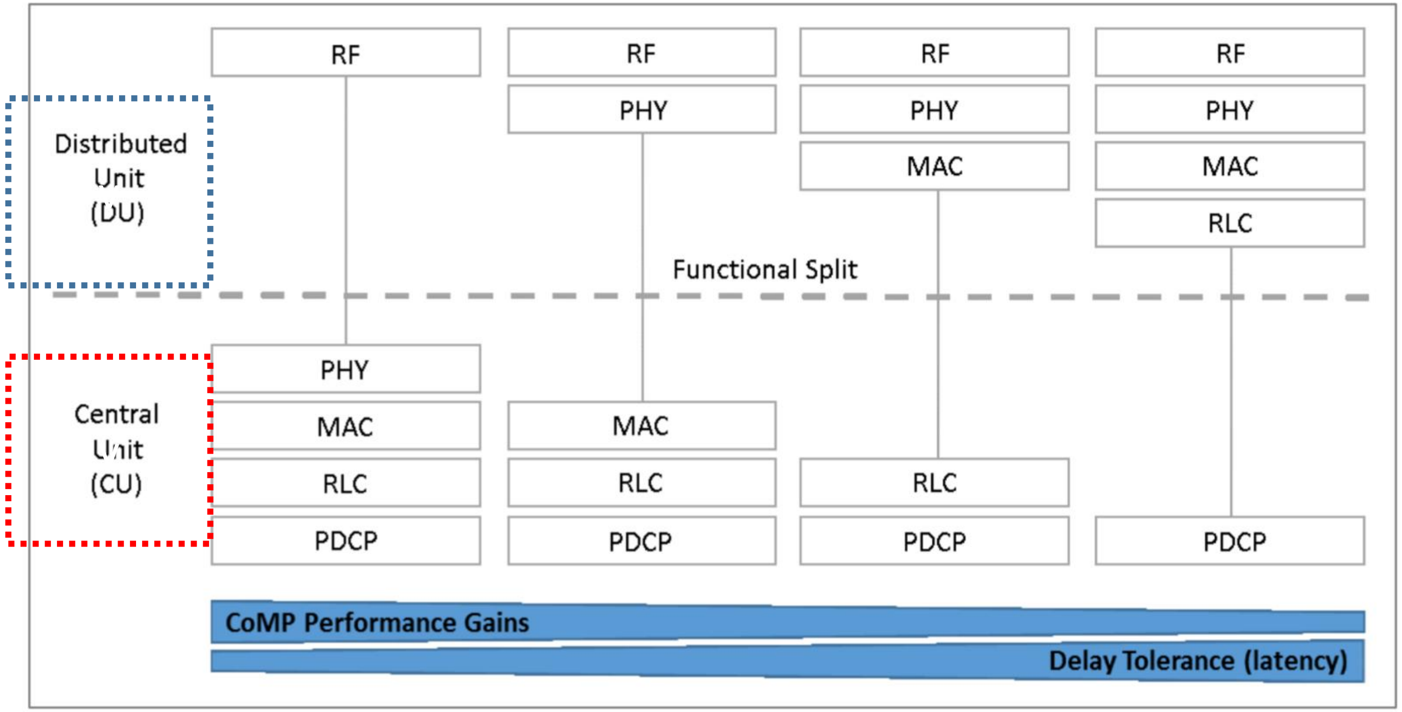


a) C-RAN: fullly centralized solution



b) C-RAN: partially centralized solution

Function Splitting

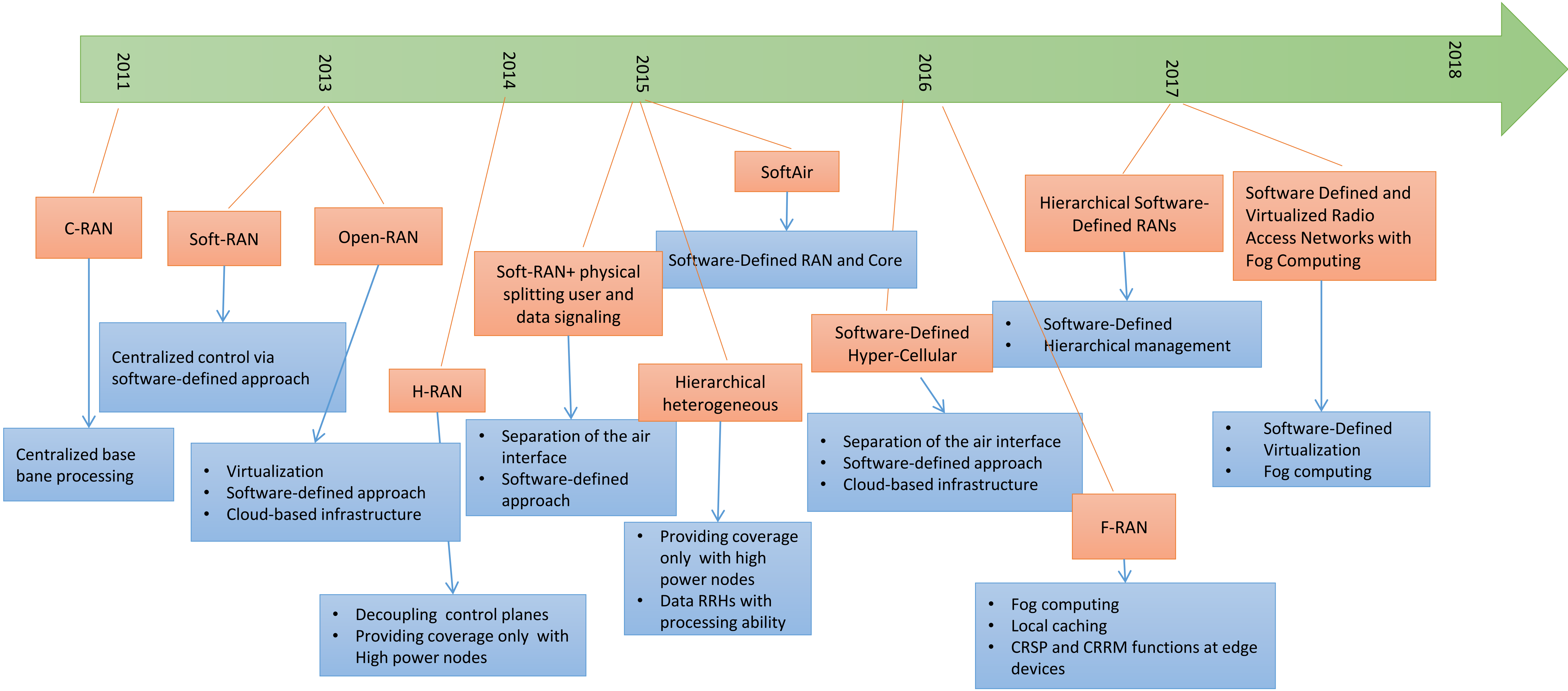


Source: Heavy Reading

Real time versus non-real time components

- Central cloud /unit for non-real time components
- Distributed units for real time components

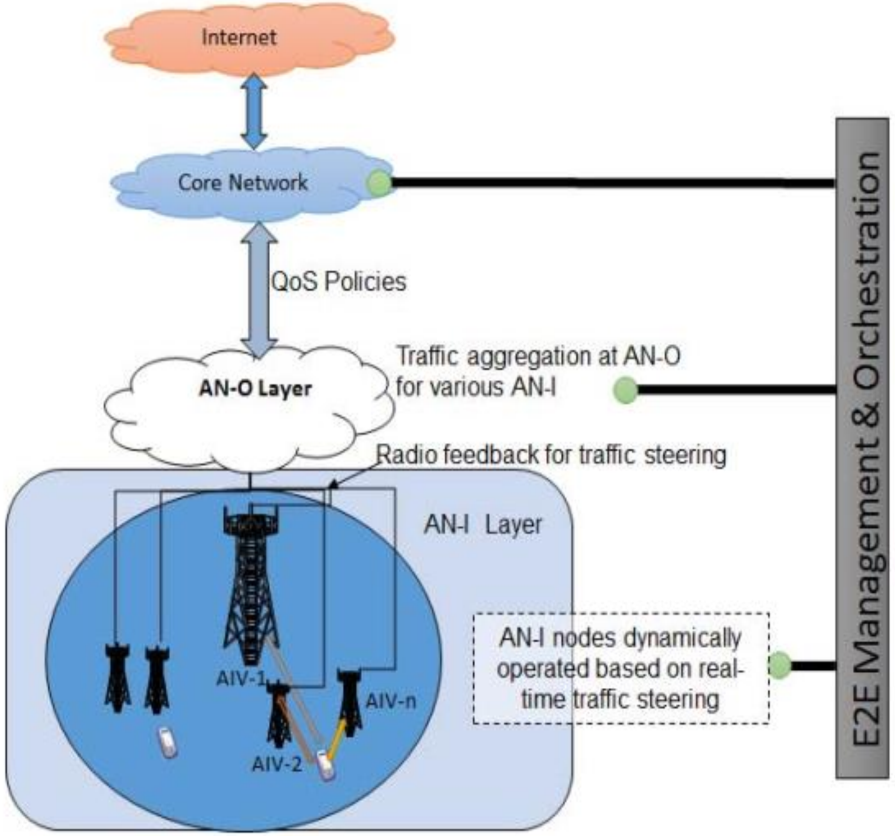
Time Line of 5G RANs



M. Baghani, S. Parsaeefard, T. Le-Ngoc, "**Multi-objective resource allocation in density aware designed of C-RAN in 5G**", 2018

New Trends in RAN Architecture

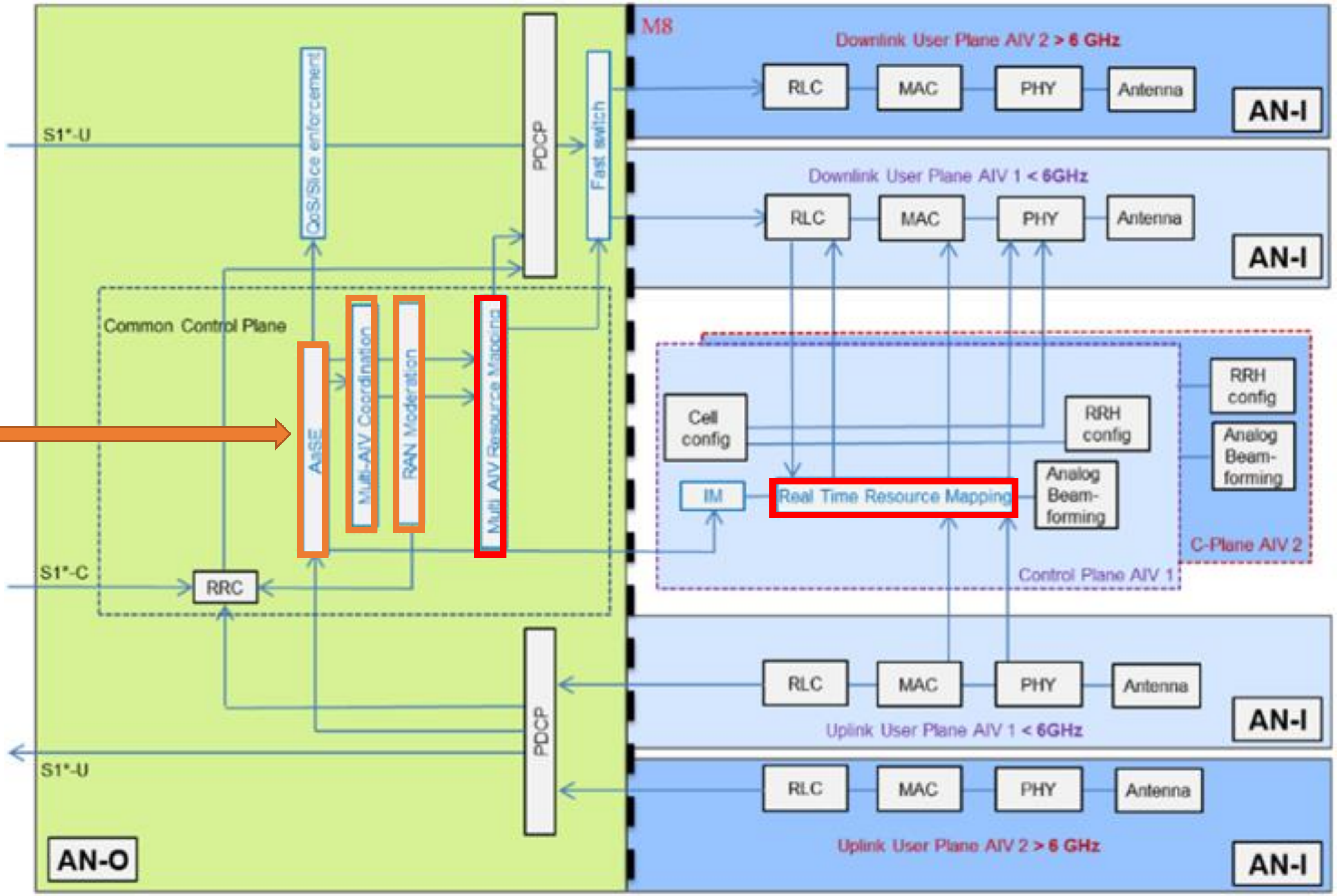
- RAN Enhancement
  - Access Network outer (AN-O)
  - Access Network Inner (AN-I)
- Air Interface Variant (AVI)
  - Multi-Band
  - Multi-Technology



METIS-II_D5.2_V1.1

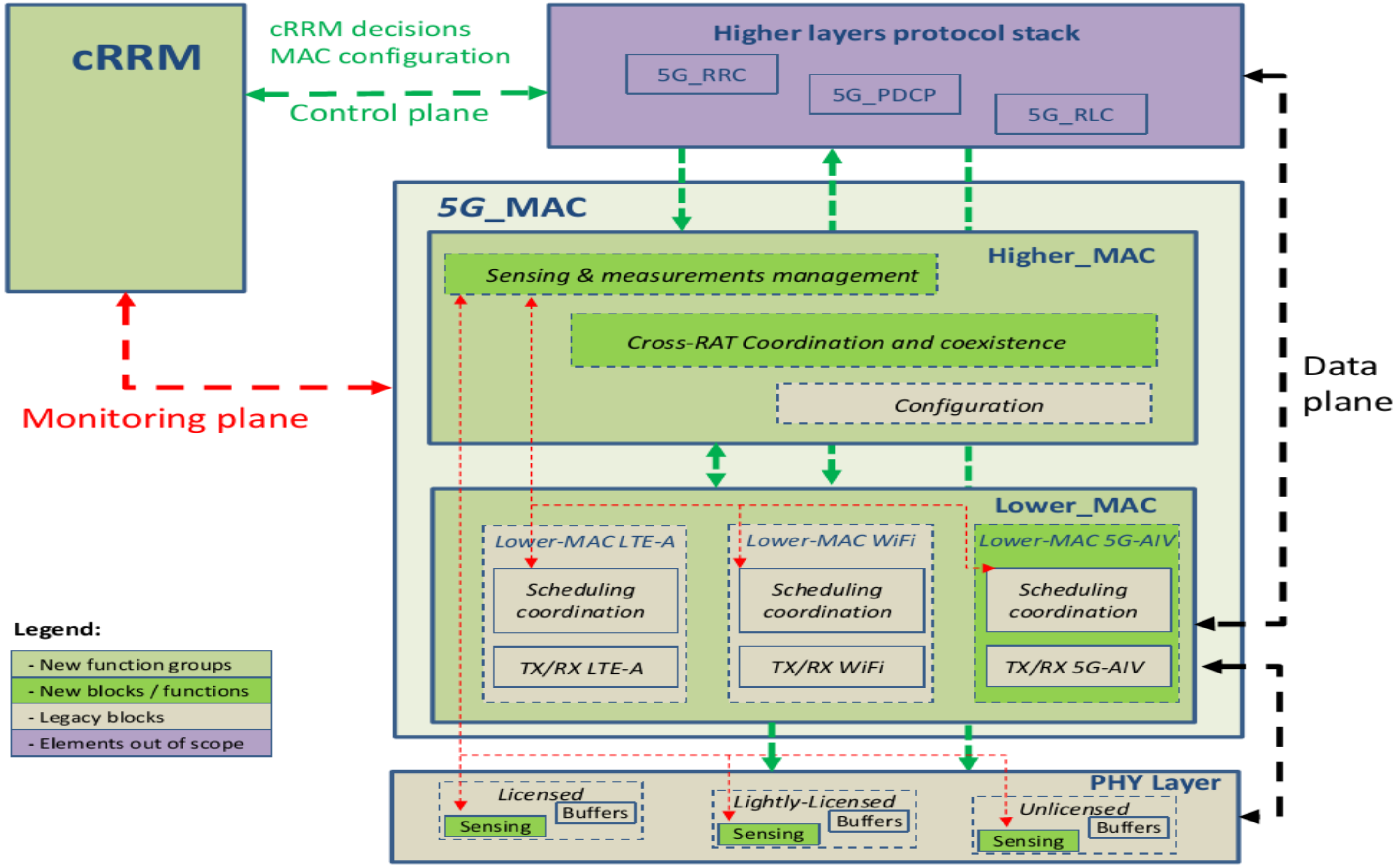
RAN Enhancement

Air interface variant agnostic slice enabler



Hierarchical CP Design in 5G RAN
5G-PPP-5G-Architecture-White-Paper-Jan-2018-v2.0

MAC Level Integration

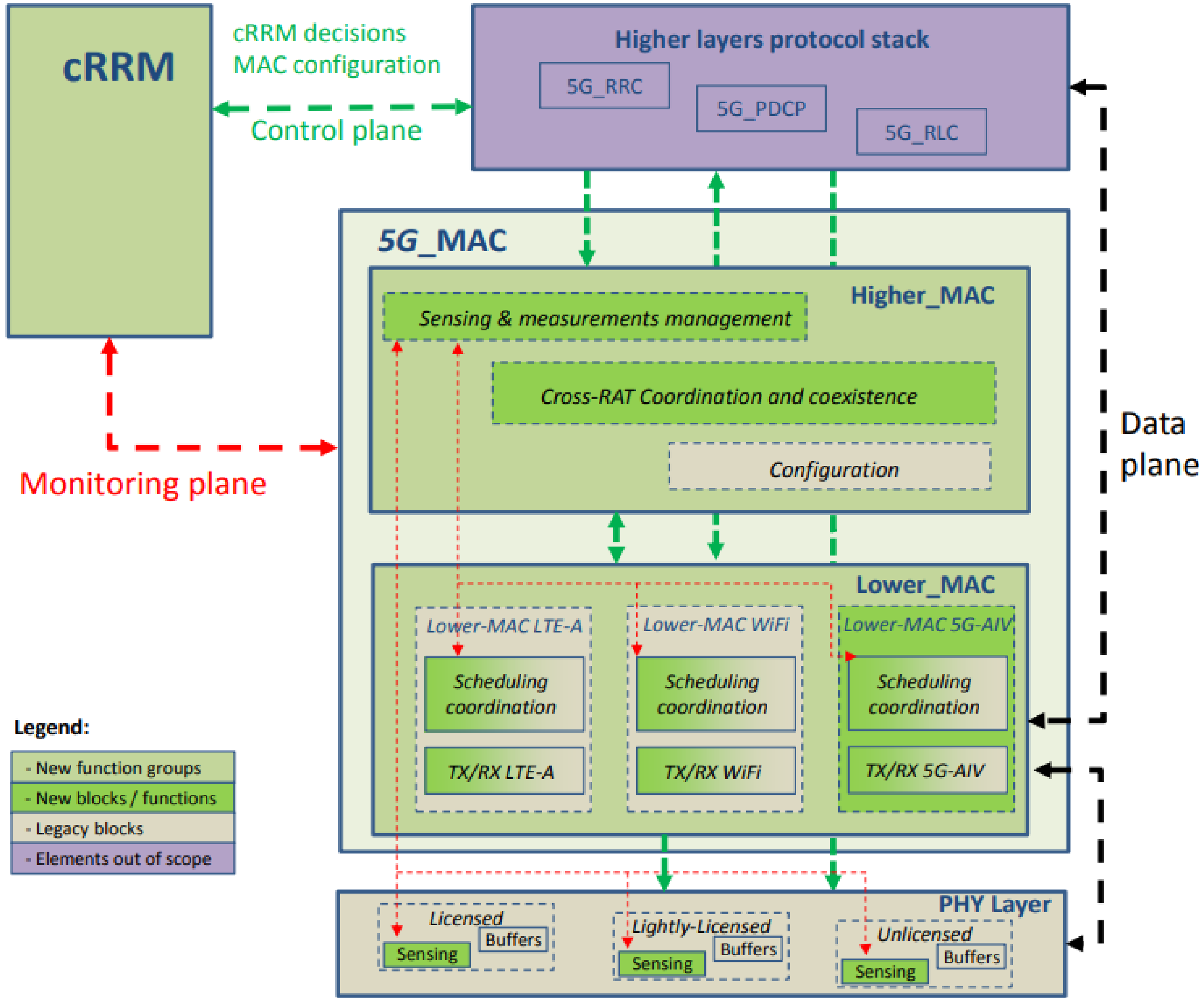


Multi-RAT design of 5G is leveraged by:

- The Extended Dynamic Spectrum Access (eDSA) MAC framework
- Centralized radio resource management (cRRM)

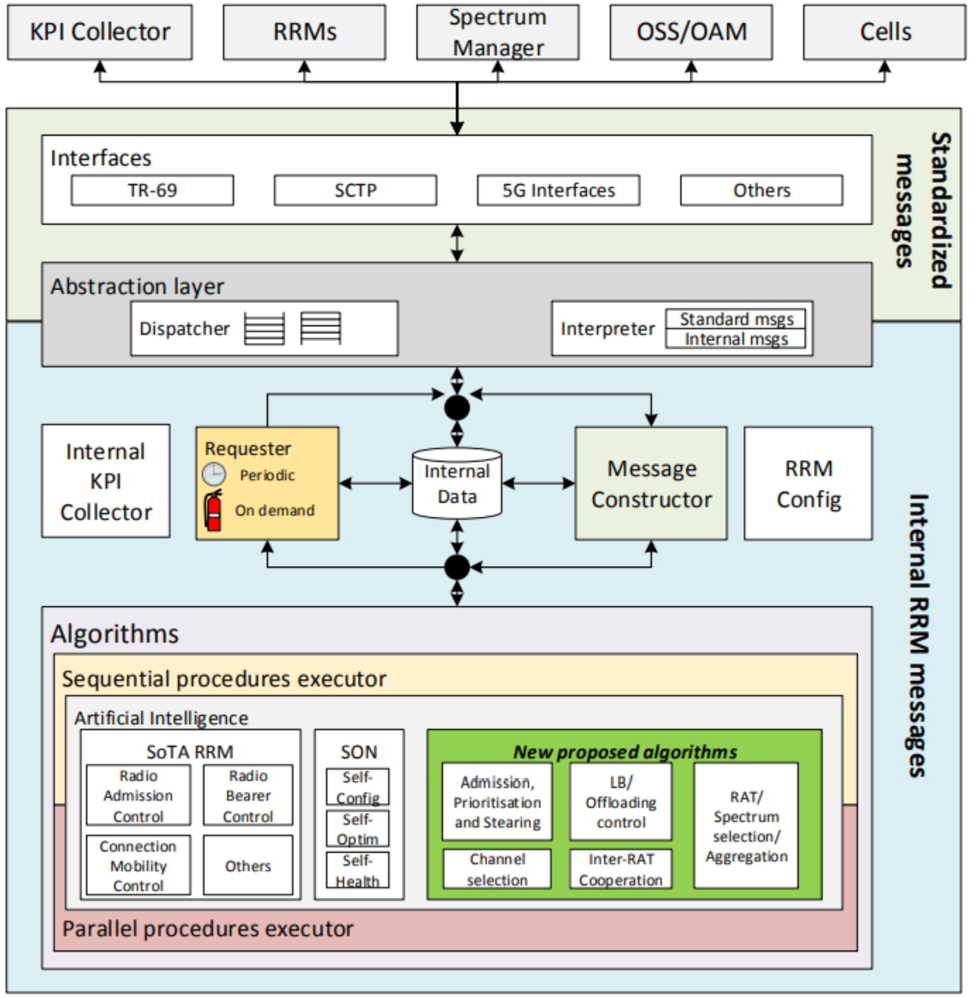
MAC Framework Architecture and functional blocks in 5G-PPP-5G-Architecture-White-Paper-Jan-2018-v2.0

eDSA MAC Framework Architecture and Functional Blocks



High-level RRM framework

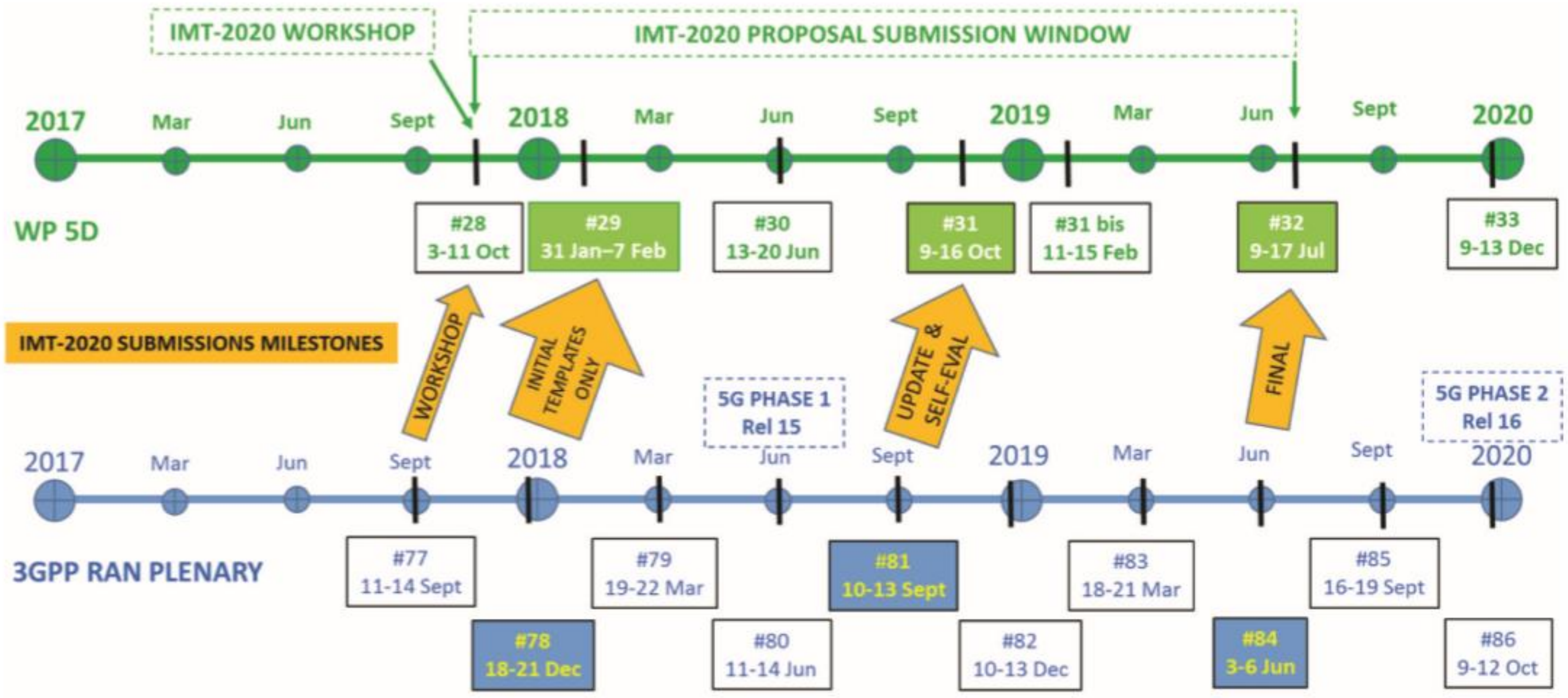
- Abstraction layer: manages the physical interfaces and translates physical messages through its SW abstraction layer
- Internal KPI collector: The RRM stores KPIs and reports them to the OSS.
- 6 New algorithms for eDSA



Other Concepts in RAN

- LTE and 5G RAN interworking
- Self backhauling
- Centralized versus distributed resource management units
- Multi-access Edge Computing (MEC) will leverage new vertical business segments and services for consumers and enterprise customers such as
  - Video analytics
  - Location services
  - Internet-of-Things (IoT)
  - Augmented reality
  - Optimized local content distribution
  - Data caching

5G New Radio (NR)
Physical Layer Overview and Performance

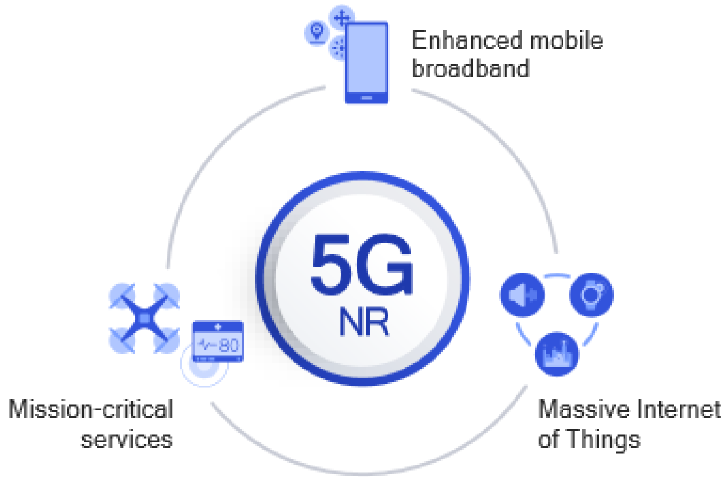


Overall time plan for 3GPPtechnology submissions to IMT2020.

3GPP standards and technology leadership

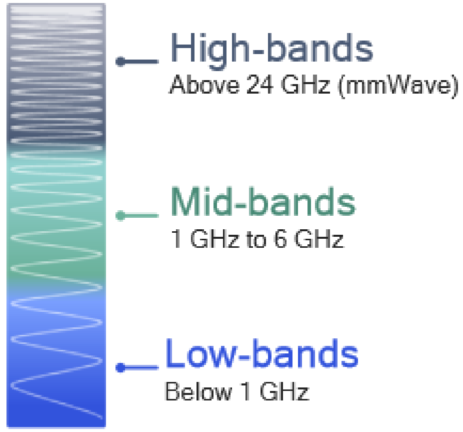
Our system-level inventions are foundational to 5G NR standard

Designing a unified, more capable 5G air 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

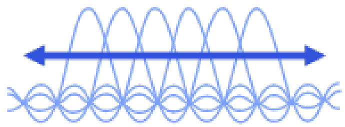
From macro to indoor hotspots, with support for diverse topologies

Learn more: www.qualcomm.com/5G-NR

3GPP Rel-15 establishes a solid foundation for 5G NR

For enhanced mobile broadband and beyond

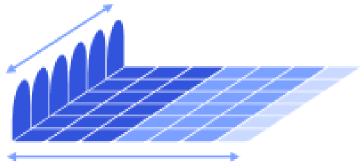
Scalable OFDM-based air interface



Scalable OFDM numerology

Efficiently address diverse spectrum, deployments/services

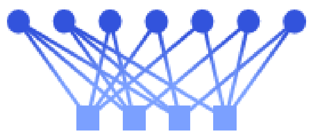
Flexible slot-based framework



Self-contained slot structure

Key enabler to low latency, URLLC and forward compatibility

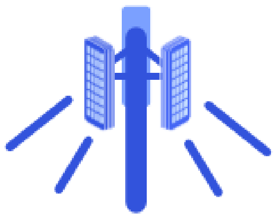
Advanced channel coding



Multi-Edge LDPC and CRC-Aided Polar

Efficiently support large data blocks and a reliable control channel

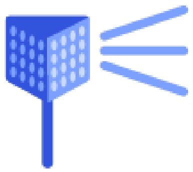
Massive MIMO



Reciprocity-based MU-MIMO

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

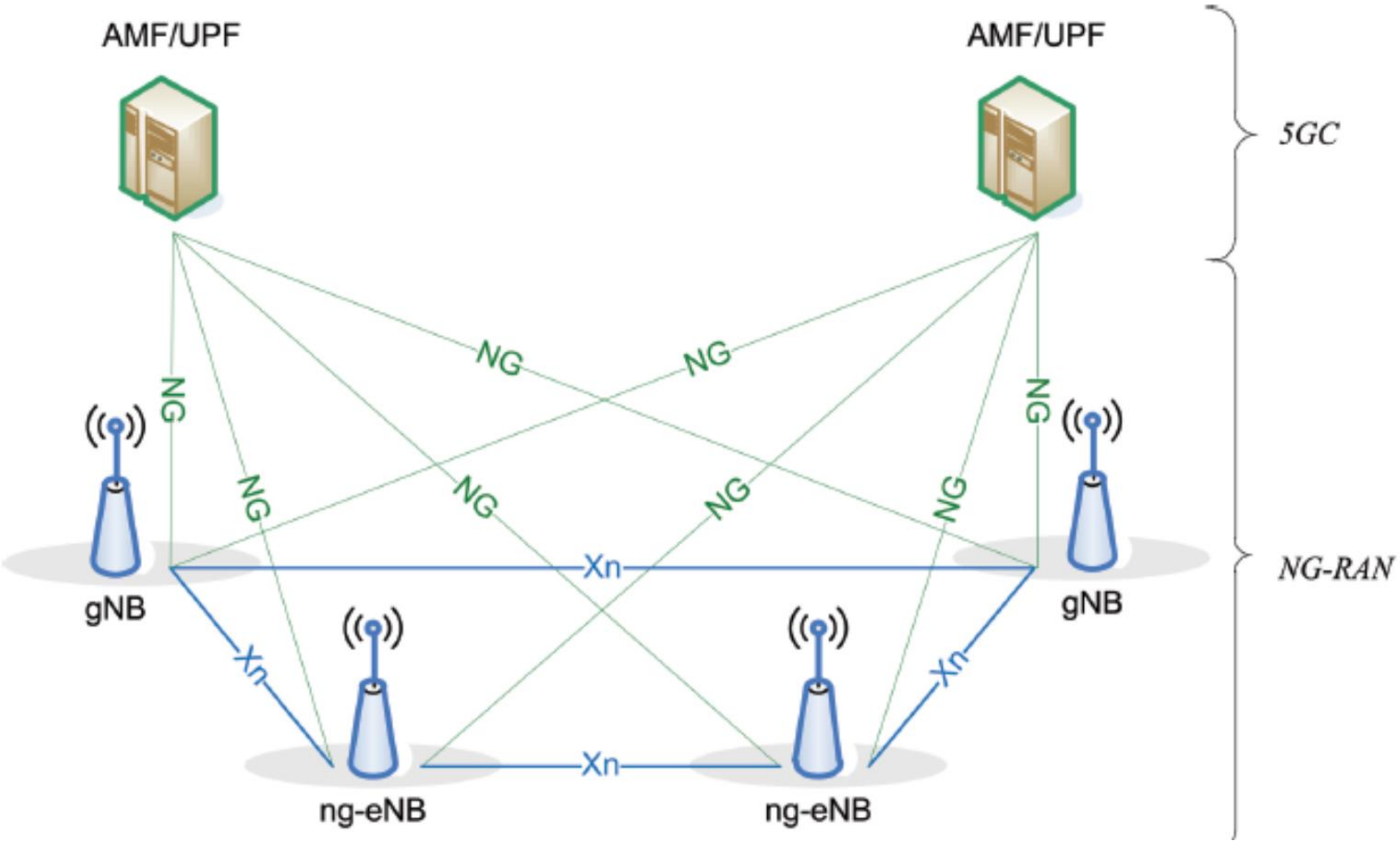
Mobile mmWave



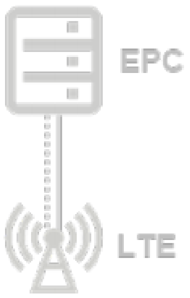
Beamforming and beam-tracking

Enables wide mmWave bandwidths for extreme capacity and throughput

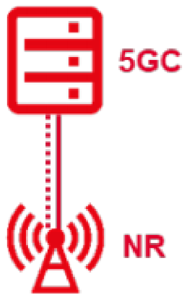
NG-RAN High Level Architecture



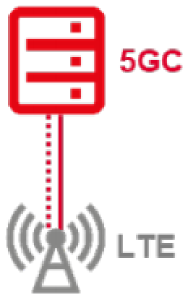
Overview of SA and NSA Options



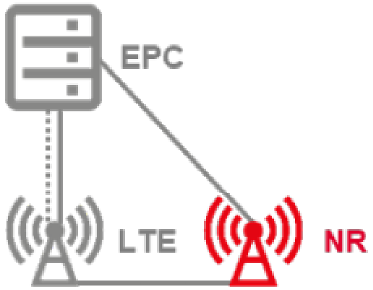
Standalone LTE under EPC (option 1)



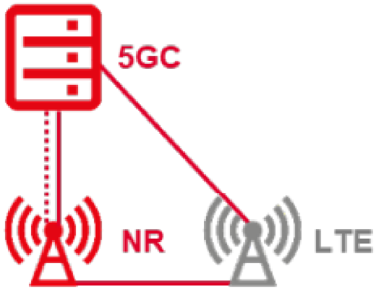
Standalone NR under 5GC (option 2).



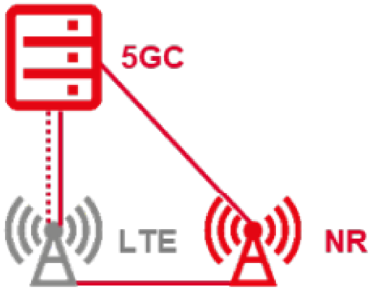
Standalone LTE under 5GC (option 5)



Non-standalone LTE and NR under EPC (option 3)

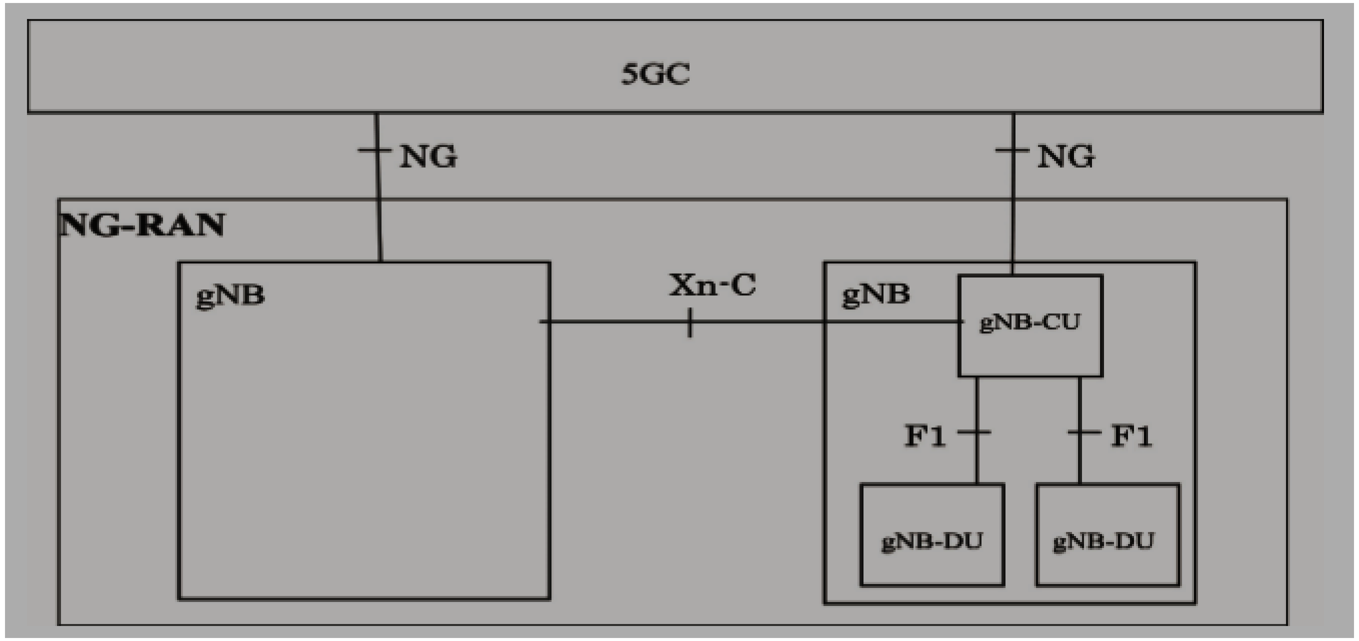


Non-standalone NR and LTE under 5GC (option 4).



Non-standalone LTE and NR under 5GC (option 7)

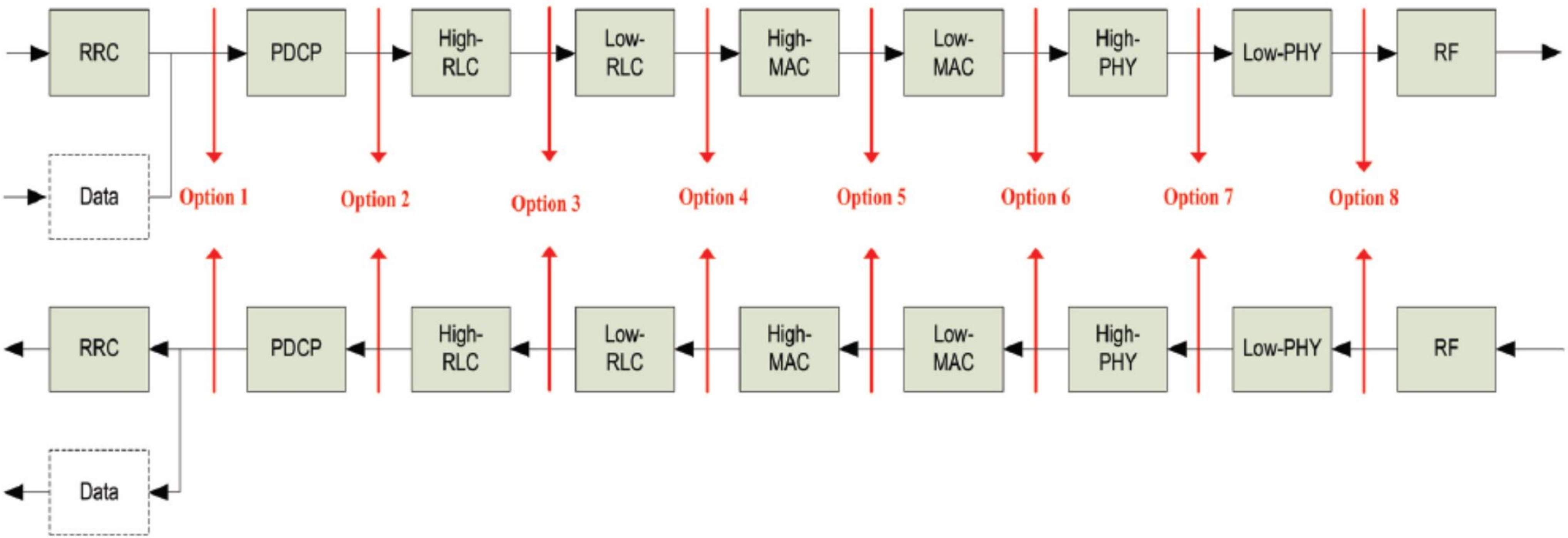
Higher Layer split of the gNB



Since the earliest phases of the NR study, however, it was felt that splitting up the gNB (the NR logical node) between

- Central Units (CUs)
- Distributed Units (DUs)
- *Some benefits in this regard were in fact identified already* in the early study phase, including:
    - *A flexible* hardware implementation allows scalable cost-effective solutions.
    - A split architecture allows coordination of performance features, load management and real-time performance optimization. It also enables virtualized deployments.

Functional Splitting



Frequency Bands in 5G/NR

- 3GPP *has defined a number of* 5G/NR (New Radio) frequency bands and these can be seen in Tables 1 to 3

Table 5G/NR – mmWave bands

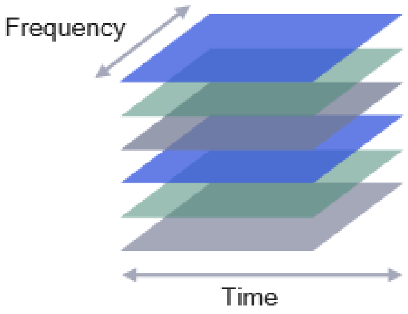
5G/NR – mmWave			
Band	Frequencies [GHz]	BW [MHz]	Duplex mode
n257	26.5–29.5	50–400	TDD
n258	24.25–27.5	50–400	TDD
n260	37.0–40.0	50–400	TDD
TBD	37.0–43.5	50–400	TDD

Table 2 5G/NR – spectrum below 6 GHz

5G/NR – Below 6 GHz			
Band	Frequencies [MHz]	BW [MHz]	Duplex mode
n77	3300–4200	10–100	TOD
n78	3300–3800	10–100	TOD
n79	4400–5000	40–100	TOD
n80	1710–1785/N/A	5–30	SUL
n81	880–915/N/A	5–20	SUL
n82	832–862/N/A	5–20	SUL
n83	703–748/N/A	5–20	SUL
n84	1920–1980/N/A	5–20	SUL

Pioneering tomorrow’s massive IoT technologies

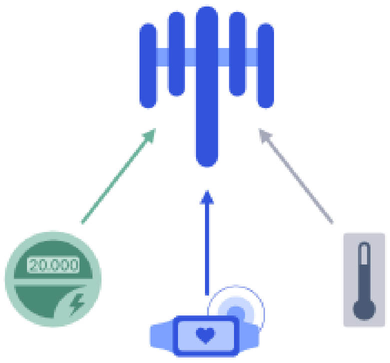
Applies to LTE IoT and 5G NR IoT evolution — potential for 3GPP Rel-16+



Non-orthogonal multiple access

Even higher connection density

- NOMA is part of 5G NR Rel-15 Study Item
- Can be either scheduled or grant-free
- Increases device density and network efficiency

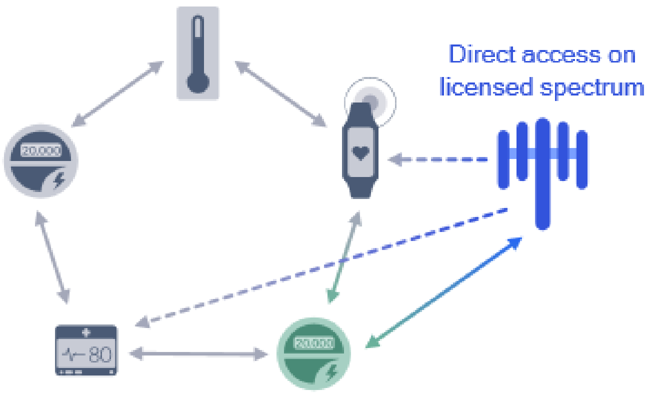


Grant-free uplink

Autonomous mode transmission

- Contention-based access for IoT devices
- For sporadic uplink of small data bursts
- Also key enabler of mission-critical communication

Mesh on unlicensed or partitioned with uplink licensed spectrum[1]



Mesh networking

Multi-hop mesh with WAN management

- For low-power devices with challenging placements
- Especially uplink data relayed via nearby devices
- Expands on LTE Device-to-Device (D2D)

Multiple Access Technologies

- Orthogonal multiple access (OMA): e.g., FDMA, TDMA, CDMA, OFDMA.
- Non-orthogonal multiple access (NOMA): to break orthogonally.
- Question: What is multiple access?
  - OMA versus NOMA
- A promising solution is to break orthogonality
  - PD-NOMA, SCMA, PDMA, LPMA, and MUSA are based on NOMA

Recent activities

Received a lot of attentions from academy, industries (DOCOMO, METIS, NGMN, ZTE, SK Telecom, ...), and standard bodies (3GPP-LTE)

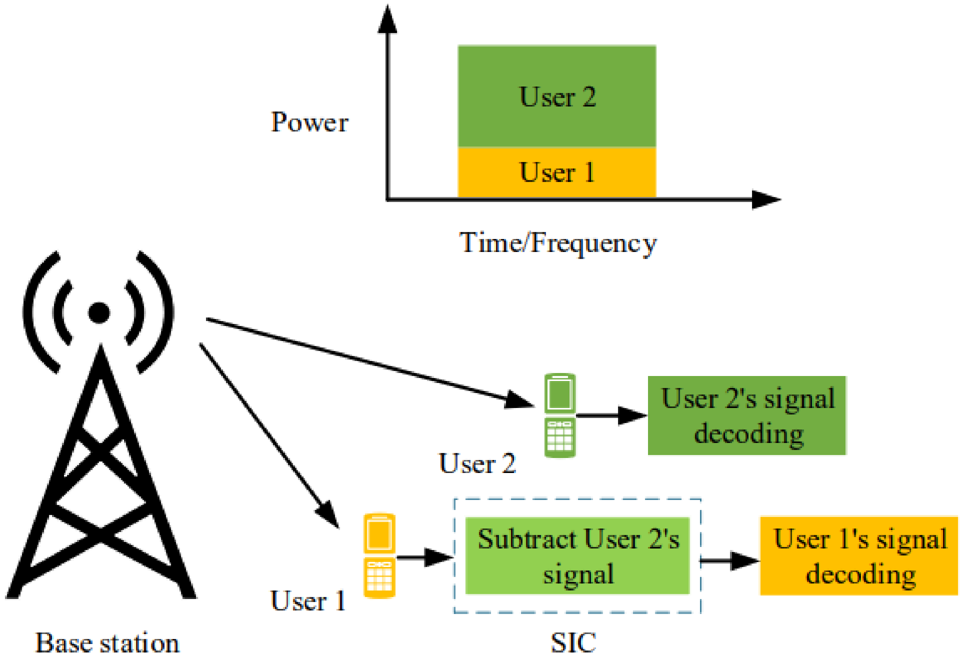
OFDMA versus NOMA

OFDMA	NOMA
• OFDMA is a scalable waveform with lower complexity receivers • OFDMA has a more efficient framework for MIMO spatial multiplexing which means higher spectral efficiency • OFDMA allows enhancements like windowing/filtering for enhanced localization • SC-FDM/SC-FDMA is well-suited for uplink transmissions in macro deployments • Widely applied in WiFi, LTE, WiMax	• Serve more than one user on the same time and frequency resource • Higher spectral efficiency (more data rate per Hz) • Benefit from the geographical distribution of users • Better serve cell edge users (users far from the base station) • Some applications need low data rate. A waste of resources to allocate dedicated time and frequency (Sensor readings , Inter-vehicle communications , Machine to machine communications)

NOMA Principle

- Key ideas:
  - All the users are served at the same time, frequency and code, *using different power levels for* distinguishing/separating them
  - Users with better channel conditions get less power
  - Successive interference cancellation is used at the receivers

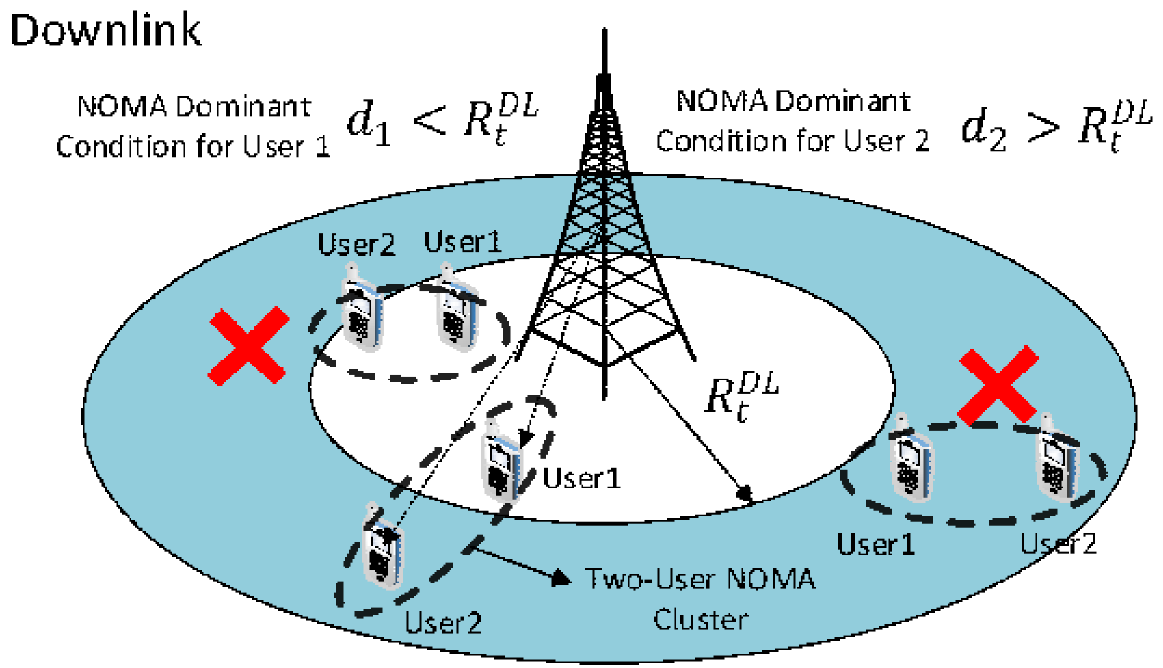
  - Consider the following two scenarios
    - If one user only needs to be served with a low data rate, e.g. sensors.
      - The use of OMA gives the sensor more than it needs
    - If one user has a very poor channel condition
    - The bandwidth allocated to this user via OMA is not used efficiently.



Downlink NOMA in a single cell with one BS and two users.

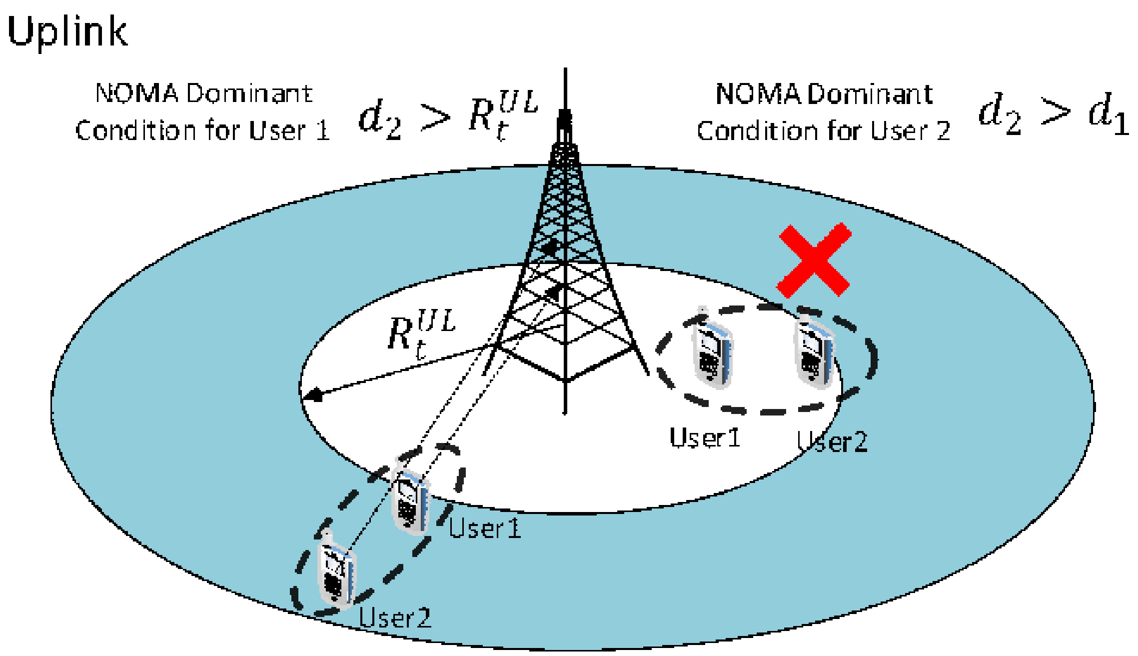
Down-link Transmission in NOMA

1) Downlink NOMA: In downlink, the BS transmits the superimposed signal $x = \sum_{i=1}^{U} \sqrt{p_i} x_i$, where x_i is the unit power message signal intended for user i, p_i denotes the power allocated for user i, and U denotes the total number of users in a NOMA cluster. The power allocated to a user depends on the powers of other users due to the BS total power constraint, $P_t = \sum_{i=1}^{U} p_i$, where P_t is the BS total power. The received signal at the i-th user is given by $y_i = h_i x + w_i$, where h_i represents the channel gain between the BS and user i, and w_i denotes the Gaussian noise (with power spectral density $N_{0,i}$) at the receiver for user i.



Up-link Transmission in NOMA

2) Uplink NOMA: In uplink, each user transmits its individual signal x_i with a transmit power p_i such that the received signal at the BS can be defined as $y = \sum_{i=1}^{U} \sqrt{p_i} h_i x_i + w$, where w denotes the receiver noise (with power spectral density N_0) at the BS. The power transmitted per user is limited by the user's maximum battery power. Different from downlink NOMA, all users can independently utilize their battery powers up to the maximum as long as the channel gains of the users are sufficiently distinct. If the channel gains are too close, power control can be used to boost up the performance of the user with better channel gain, while maintaining the performance of the users with weaker channel gains at a certain level.



Key Distinctions Between Uplink and Downlink NOMA

Implementation Complexity

- Downlink NOMA requires the implementation of sophisticated multi-user detection and interference cancellation schemes at the receiver of each user which is a cumbersome task provided the limited processing capability of users.
- In the uplink, it is relatively more convenient to implement multi-user detection and interference cancellation schemes on a centralized entity (i.e., BS).

Intra-cell/Intra-cluster Interference

The downlink intracell interference at a user is experienced on its own channel, i.e., a user with the strong downlink channel receives strong interference.

- The strong channel (which is interfering) and relatively high transmit powers allocated for the messages of weak channel users.
- The users with strong downlink channels are relatively more vulnerable to intra-cell interference. This is resolved by applying SIC at the users as will be explained later

Key Distinctions Between Uplink and Downlink NOMA

SIC at Receiver(s)

- In downlink NOMA, the strong channel users achieve throughput gains, by successively decoding and canceling the messages of weak channel users, prior to decoding their desired signals.
- In the uplink, to enhance the throughput of weak channel users, the BS successively decodes and cancels the messages of strong channel users, prior to decoding the signals of weak channel users.

Inter-cell interference

- Downlink multi-cell applications of NOMA will induce additional interference (from the neighboring co-channel BSs) at each individual user in a NOMA cluster.
- the downlink inter-cell interference received at each individual user in NOMA is same as in OMA.

NOMA & OMA Throughput

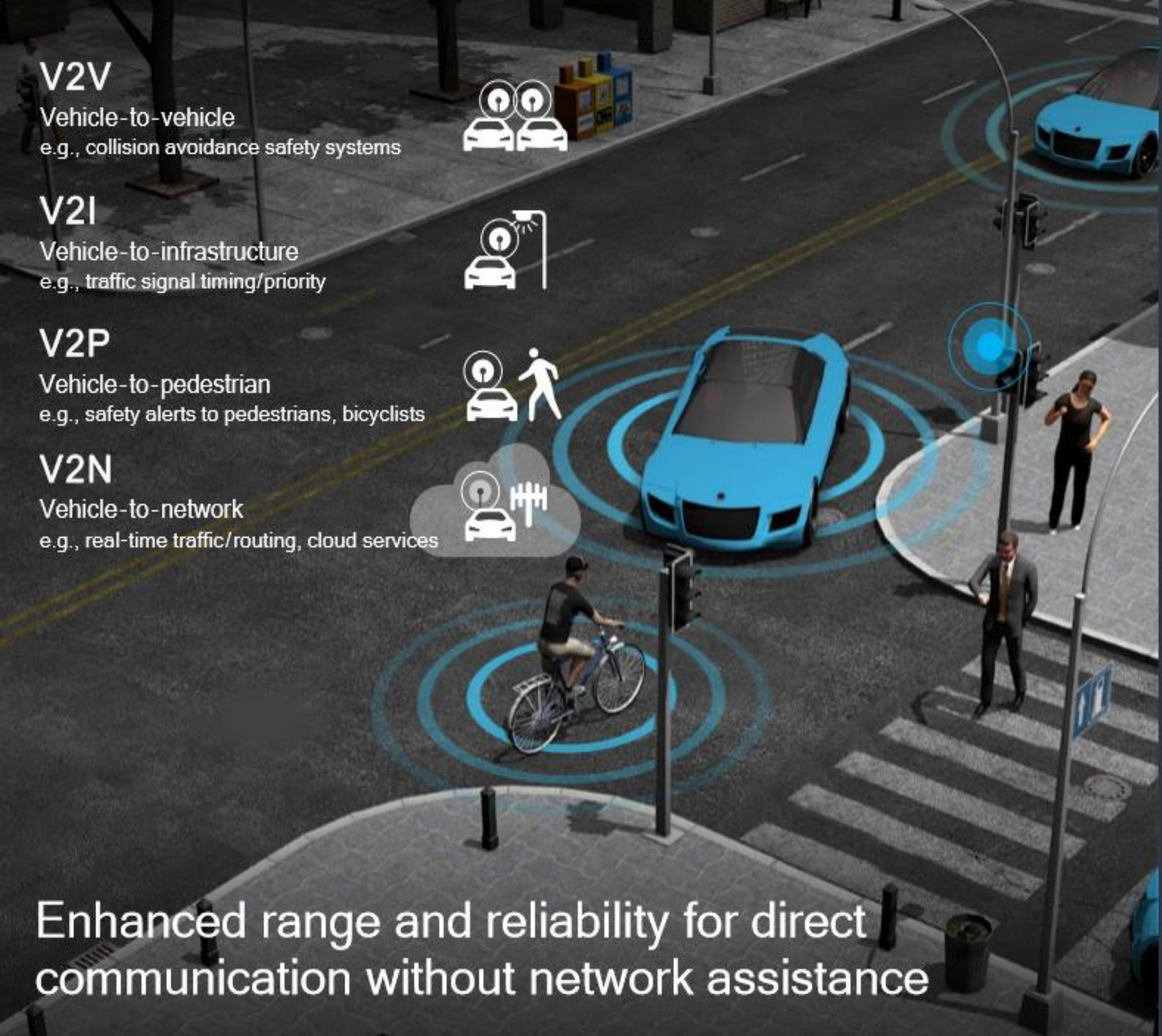
- System Set-up: Two users located at $d1$ and $d2$ such that $d1 < d2$ and h their average channel gains given by d-α 1 and $d-\alpha$ 2 , respectively.

$$C_1^{(\mathrm{noma})} = \log_2(1 + a_1 P d_1^{-\alpha})$$
$$C_2^{(\mathrm{noma})} = \log_2\left(1 + \frac{a_2 P d_2^{-\alpha}}{a_1 P d_2^{-\alpha} + 1}\right)$$

- For THD<A

$$C_j^{(\mathrm{oma})} = 0.5\ \log_2(1 + P d_j^{-\alpha}), \quad \forall j = 1, 2.$$

Hina Tabassum, Md Shipon Ali, Ekram Hossain, Md. Jahangir Hossain, and Dong In Kim , Uplink Vs. Downlink NOMA in Cellular Networks: Challenges and Research Directions



C-V2X

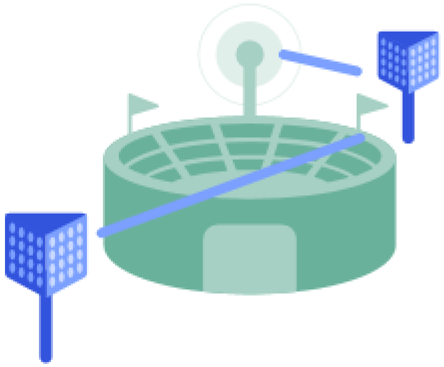
Establishes the foundation for safety use cases and a continued 5G NR C-V2X evolution for future autonomous vehicles

- C-V2X Release 14 completed in 2017
- 5G Broad industry support—5GAA
- Global trials started in 2017
- Our 1st announced C-V2X product in September, 2017

Learn more at: https://www.qualcomm.com/c-v2x

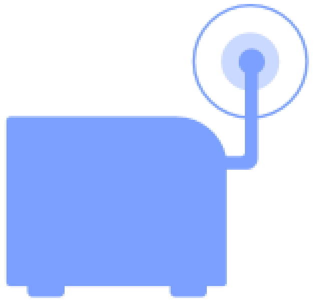
5G NR mmWave continuing to evolve beyond R15

Bringing new capabilities, new spectrum bands and new deployment opportunities



Integrated Access and Backhaul

Rel-15 Study Item on enabling easy/low-cost deployment of small cells using mmWave spectrum for access and backhaul



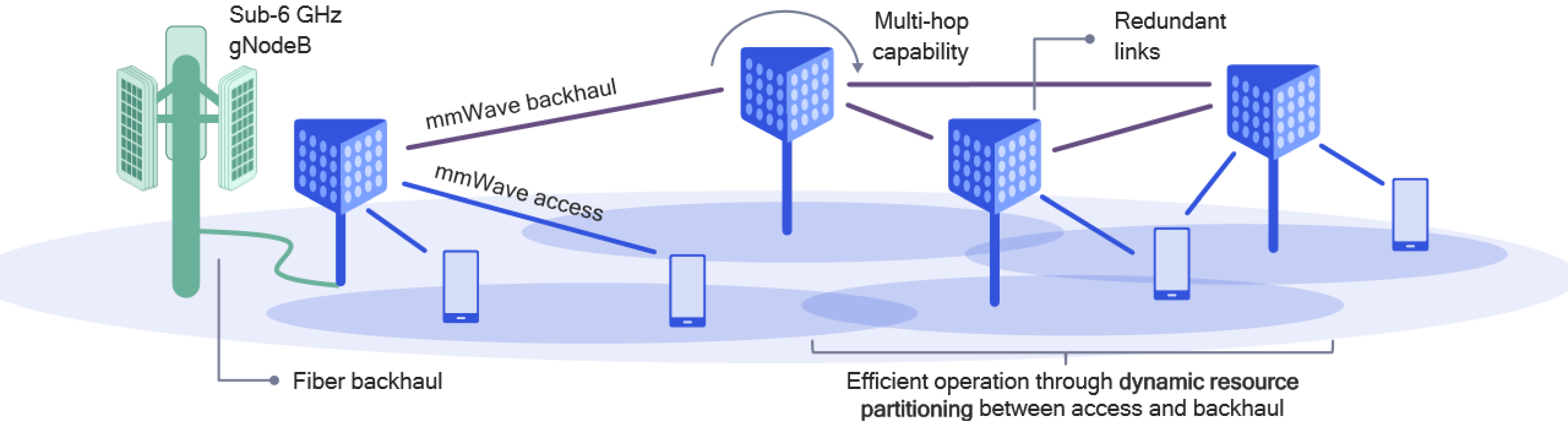
Unlicensed Spectrum

Rel-15 Study Item for both LAA and standalone operation (aka 5G MulteFire™) in sub-6 GHz and mmWave spectrum bands

Higher spectrum bands

Exploring the use of spectrum bands above ~40 GHz, including unlicensed spectrum in the 57 GHz to 71 GHz band

5G NR mmWave for cost-efficient dense deployments

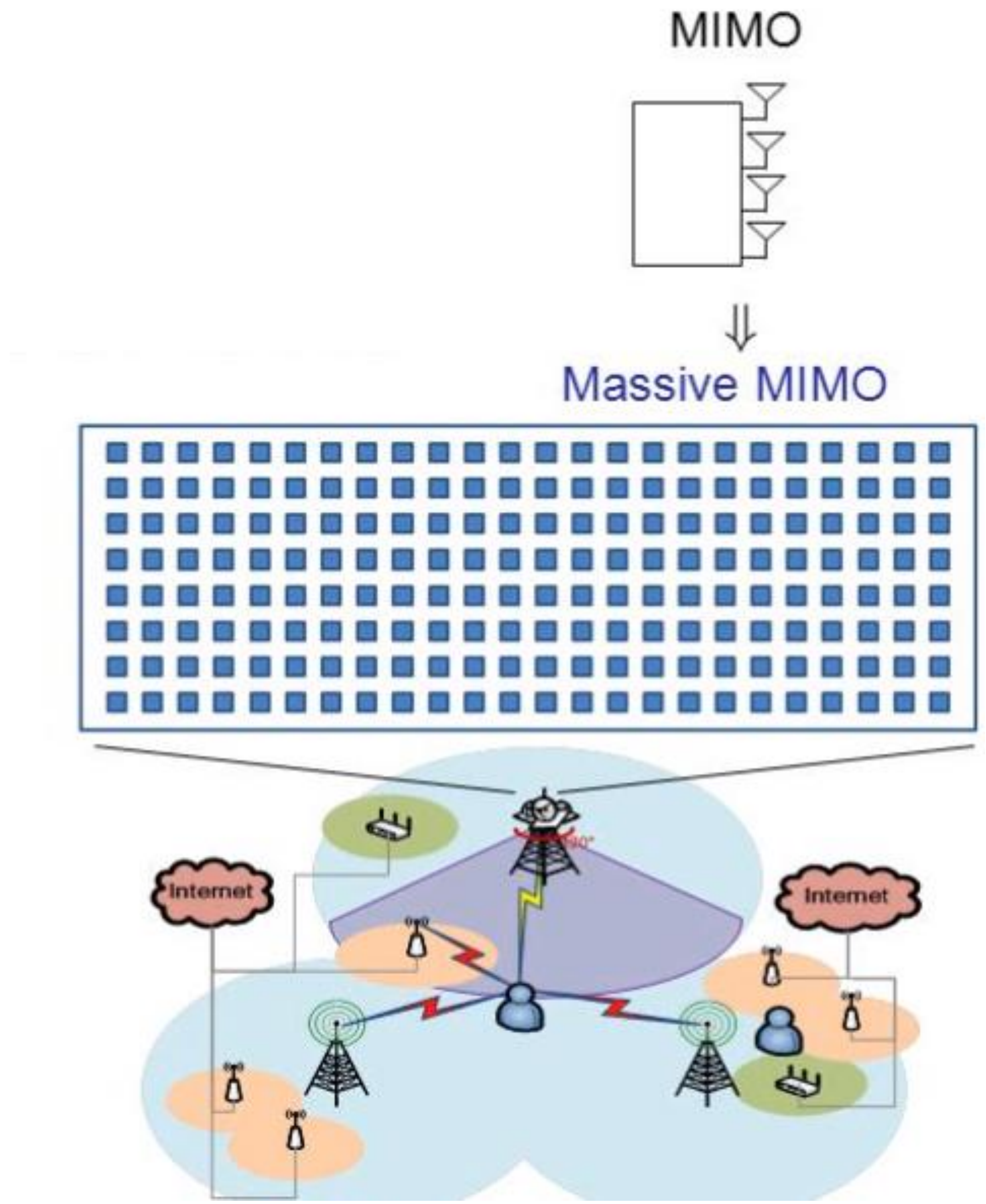


5G NR mmWave Integrated Access & Backhaul for cost-efficient dense deployments traditional fiber backhaul can be expensive for mmWave cell sites Improves coverage and capacity, while limiting backhaul cost

Massive MIMO

- Massive MIMO is an emerging technology which scales up MIMO by an order or magnitude.
- Antenna arrays with a few hundred elements

Rate ↑
Transmission reliability↑
Energy efficiency ↑

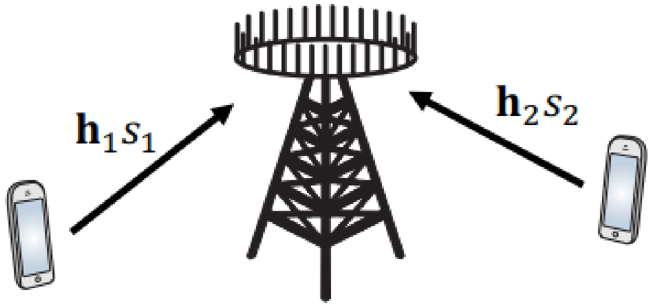


Massive MIMO

- Massive MIMO is the extension of traditional MIMO technology to antenna arrays having a large number (>>8) of controllable antennas
- Transmission signals from the antennas are adaptable by the physical layer via gain or phase control
- Enhance Coverage: High Gain Adaptive Beamforming
  - Path Loss Limited (>6GHz)
- Enhance Capacity: High Order Spatial Multiplexing
  - Interference-limited (<6GHz)

Asymptotic Channel Orthogonality

- Example: Uplink with i.i.d. Rayleigh Fading
  - Two users, send signals s_k for $k = 1,2$
  - Channels: $\boldsymbol{h}_k = [h_{k1} \dots h_{kM}]^T \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_M)$
  - Noise: $\mathbf{n} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_M)$
  - Received: $\mathbf{y} = \mathbf{h}_1 s_1 + \mathbf{h}_2 s_2 + \mathbf{n}$

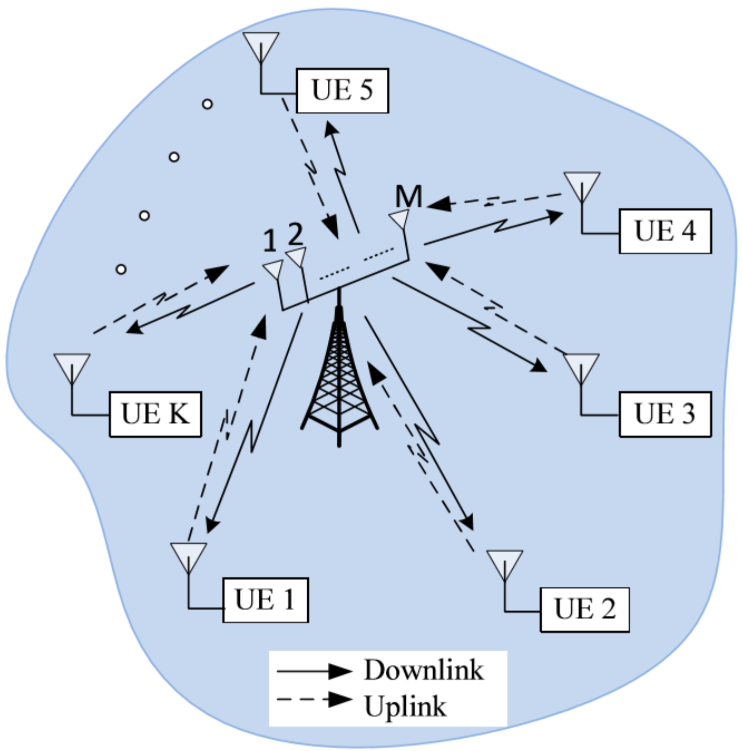


- Linear Detector $\mathbf{w}_1$ for User 1: $\tilde{y}_1 = \mathbf{w}_1^H \mathbf{y} = \boxed{\mathbf{w}_1^H \mathbf{h}_1} s_1 + \boxed{\mathbf{w}_1^H \mathbf{h}_2} s_2 + \boxed{\mathbf{w}_1^H \mathbf{n}}$
  - Maximum ratio filter: $\mathbf{w}_1 = \frac{1}{M} \mathbf{h}_1$
  - Signal remains: $\mathbf{w}_1^H \mathbf{h}_1 = \frac{1}{M} \|\mathbf{h}_1\|^2 \xrightarrow{M\to\infty} \mathrm{E}[|h_{11}|^2] = 1$
  - Interference vanishes: $\mathbf{w}_1^H \mathbf{h}_2 = \frac{1}{M} \mathbf{h}_1^H \mathbf{h}_2 \xrightarrow{M\to\infty} \mathrm{E}[h_{11}^H h_{21}] = 0$
  - Noise vanishes: $\mathbf{w}_1^H \mathbf{n} = \frac{1}{M} \mathbf{h}_1^H \mathbf{n} \xrightarrow{M\to\infty} \mathrm{E}[h_{11}^H n_1] = 0$

Asymptotically noise/interference-free communication: $\tilde{y}_1 \xrightarrow{M\to\infty} s_1$

Uplink Throughput of Massive MIMO

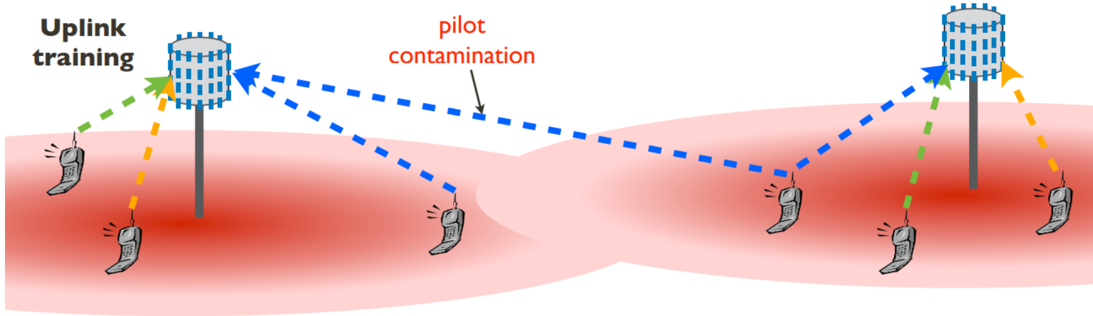
$$C_{UL} = \sum_{k=1}^{K} \log_2(1 + p_{u,k} M \beta_k),$$



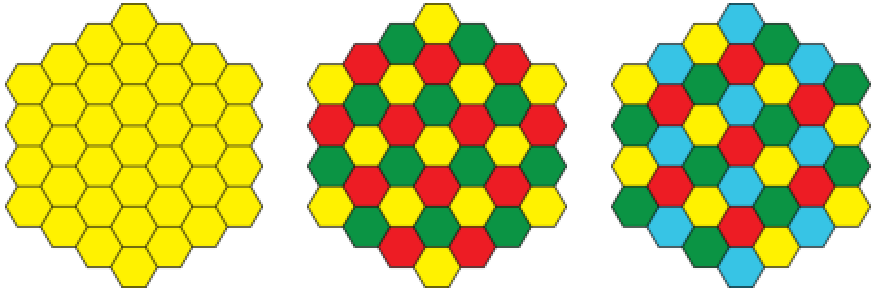
T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," IEEE Trans. Wireless Commun., vol. 9, no. 11, pp. 3590–3600, Nov. 2010.

Uplink Massive MIMO: Incomplete CSI Throughput

- BS Needs Channel Responses for Linear Processing
  - Estimate using $\tau_p \leq \tau_c$ pilot symbols
  - Must reuse pilot sequences in different cells
- Called: Pilot Contamination
  - BSs cannot tell some users apart
  - Recall: Noise and interference vanish as $M \to \infty$
  - Not interference between users with same pilot!



- Scalable Solution: Select how often pilots are reused
  - Pilot reuse factor $f \geq 1$
  - Users per cell: $K \leq \tau_p / f$
  - Higher f $\to$ Fewer users per cell, but interferers further away



Pilot reuse $f = 1$ *Pilot reuse* $f = 3$ *Pilot reuse* $f = 4$

Downlink Massive MIMO

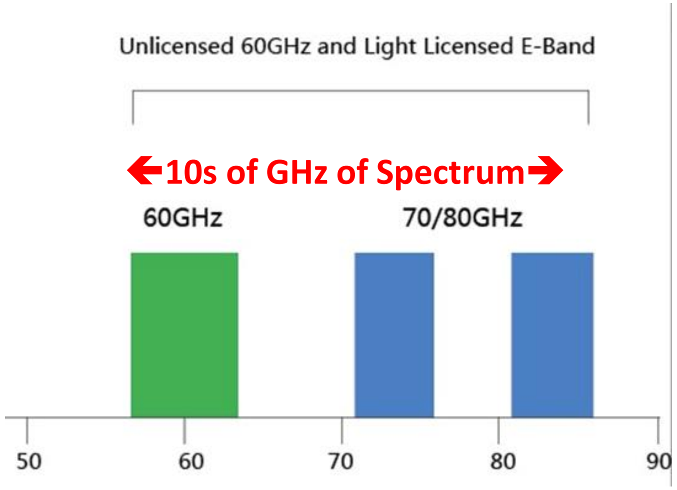
We consider a down-link transmission in 5G wireless network with a cloud radio access network (C-RAN) architecture as illustrated in Fig. II where a specific region is covered by a set of $\mathcal{J} = \{1, \cdots, J\}$ RRHs. Each RRH is equipped with a large number of antennas, i.e., $M_j \gg 1$ and connected to the C-RAN consisting of $\mathcal{B} = \{1, \cdots, B\}$ BBUs. The C-RAN is responsible to process the baseband signals for all RRHs in this region. A limited capacity front-haul link connects RRHs to the BBUs, serving a set of single-antenna users denoted by $\mathcal{N} = \{1, \cdots, N\}$ in this specific region.

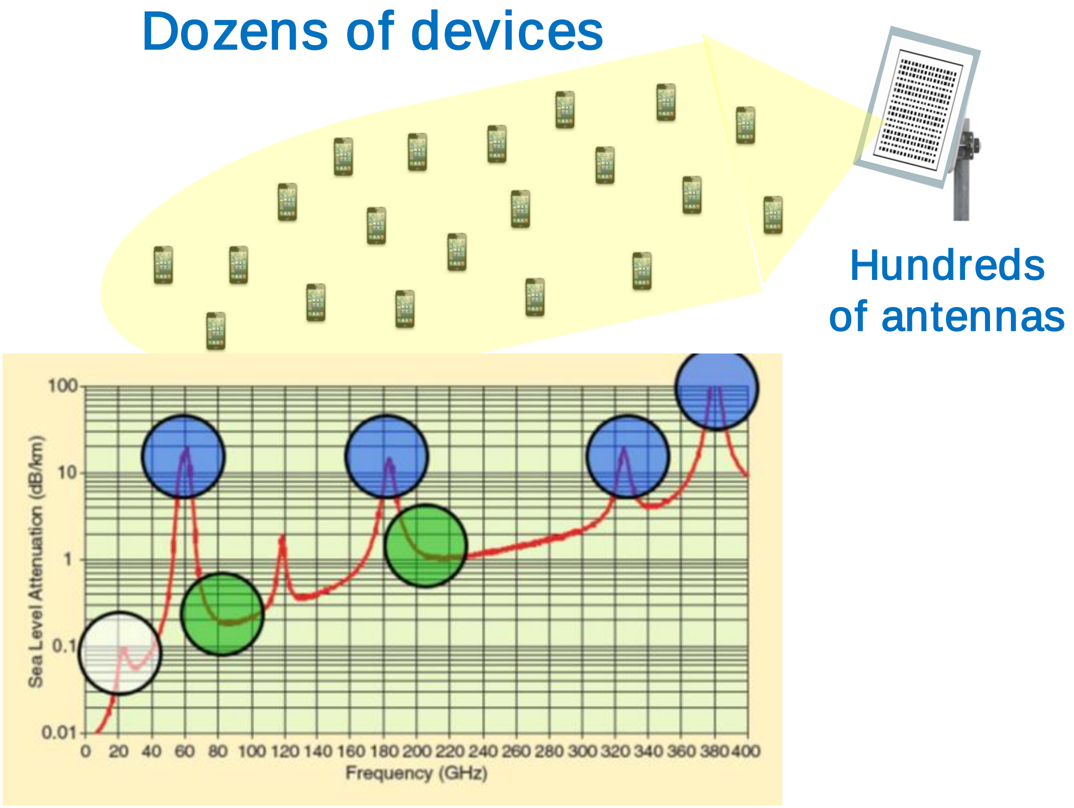
Let $g_{j,n}$ be the channel gain of user n to RRH j, and the number of simultaneously served users by a RRH j, be much smaller than the number of transmit antennas M_j.

$$R_{j,n}(\mathbf{P}, \boldsymbol{\alpha}, \mathbf{F}) = F_n \alpha_{j,n} \log(1 + (\frac{M_j - U_j + 1}{U_j} \frac{P_j g_{j,n}}{1 + \sum_{j' \neq j} P_{j'} g_{j',n}})),$$

D. Bethanabhotla, O. Y. Bursalioglu, H. C. Papadopoulos, and G. Caire, "User association and load balancing for cellular massive MIMO," in Information Theory and Applications Workshop (ITA), 2014. IEEE, 2014, pp. 1–10.

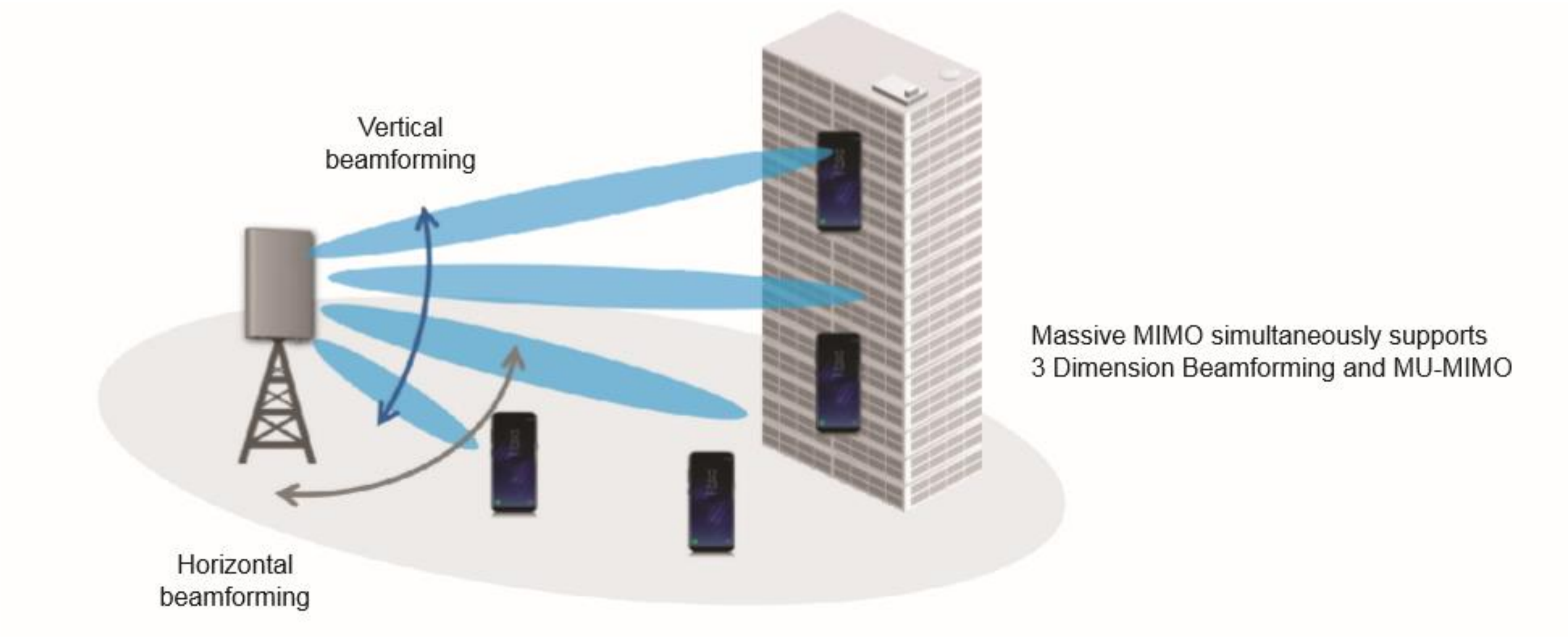
mmWave Massive MIMO





- mmWaves have large non-monotonic path loss
  - Channel model poorly understood
- For asymptotically large arrays with channel state information, no attenuation, fading, interference or noise
- mmWave antennas are small: perfect for massive MIMO
- Bottlenecks: channel estimation and system complexity
- Non-coherent design holds significant promise

3D Beam-forming



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Thank you