UNIVERSITÀ DELLA CALABRIA

Master Degree in Telecommunications Engineering

“Mobile Radio Networks” Class

5G: Radio Access Network & enabling technologies

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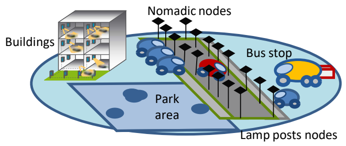

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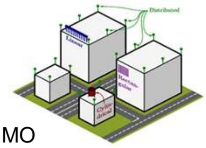

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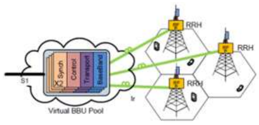
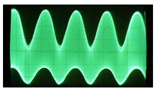
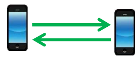


Cloud RAN (C-RAN)



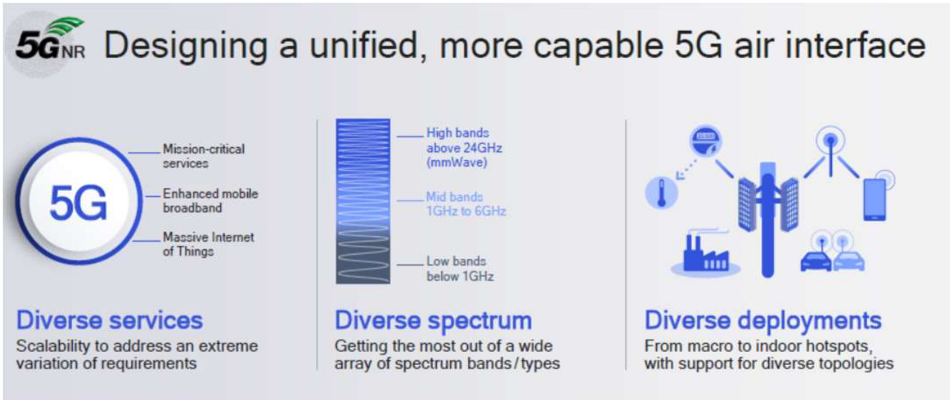
Air interfaces for new applications and reduced signaling



Mobile Device-to-device

J.G. Andrews, et al. "What will 5G be?." *IEEE Journal on Selected Areas in Communications* 32.6 (2014): 1065-1082.
F. Boccardi et al., "Five Disruptive Technology Directions for 5G", IEEE Communications Magazine, Feb. 2014

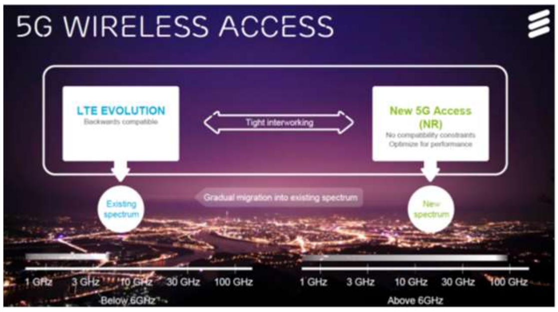
5G New Radio (NR)



QUALCOMM

5G Radio Access Network

- In LTE access network from Rel-8 up to Rel-14 the only available node is eNodeB (eNB)
- Two radio technologies have to be considered in 5G NG-RAN discussions:
  - LTE (from Rel-15 onwards) aka “eLTE”
  - New Radio (“NR”)

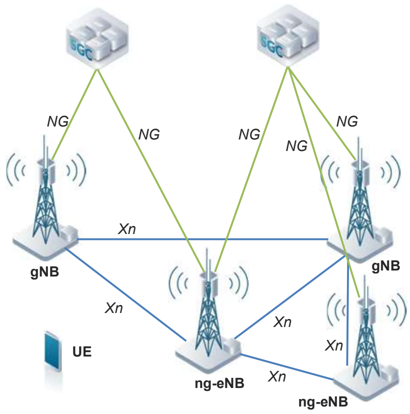


5G Radio Access Network

- NG-RAN provides both NR and LTE radio access.
- An NG-RAN node (i.e. base station) is either:
  - Next generation eNodeB (ng-eNB) – LTE access network from Rel-15 onwards
    - node providing LTE/E-UTRAN user plane and control plane protocol terminations towards the UE.
  - Next generation NodeB (gNB) – 5G access network from 3GPP Rel-15 onwards
    - node (i.e. a 5G base station) providing NR user plane and control plane protocol terminations towards the UE .

5G Radio Access Network

- The gNBs and ng-eNBs are interconnected with each other by means of the **Xn interface**.
  - The Xn interface is very similar to the LTE X2 protocol and it is used for:
    - mobility (i.e. handover),
    - multi-connectivity, and
    - SON (Self Optimized Networks).
- The gNBs and ng-eNBs are also connected by means of the **NG interfaces** to the 5G Core (5GC).



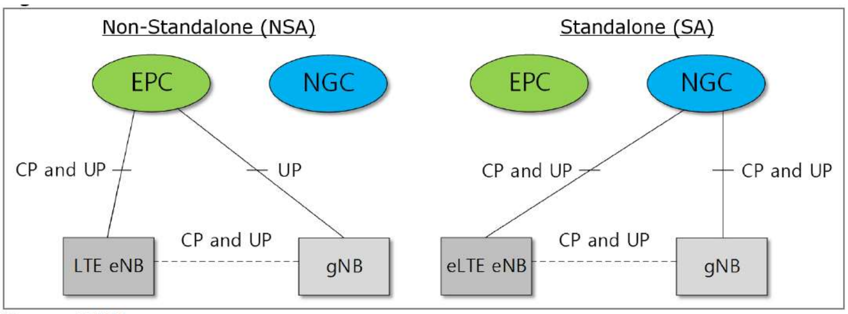
5G NR

- **Forward compatibility of NR** shall ensure **smooth introduction of future services and features** while efficient access of the earlier services and UEs in the same spectrum is still ensured.

- Two Core Network concepts have to be considered in the 5G discussions
  - EPC (with potential evolutions)
  - Next Generation Core («NGCN»)

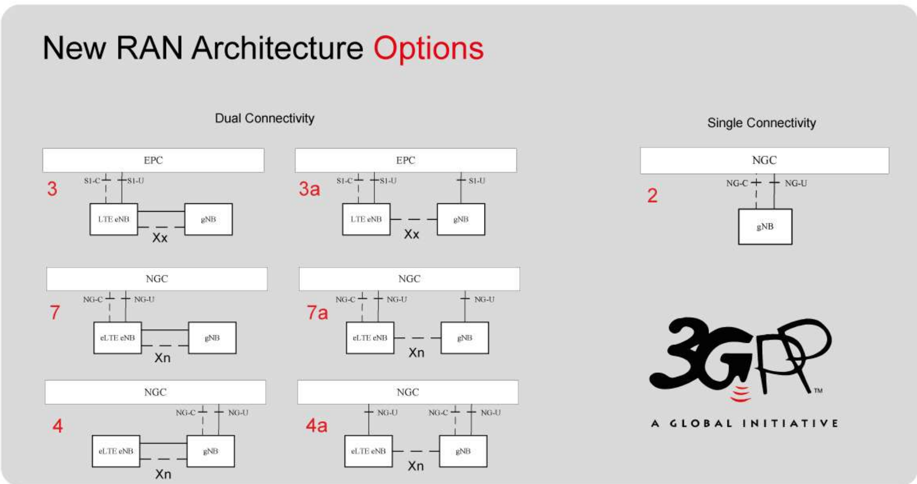
5G deployment

In Stand Alone (SA) a new core (NGC) is required (Phase 2, Rel. 16)

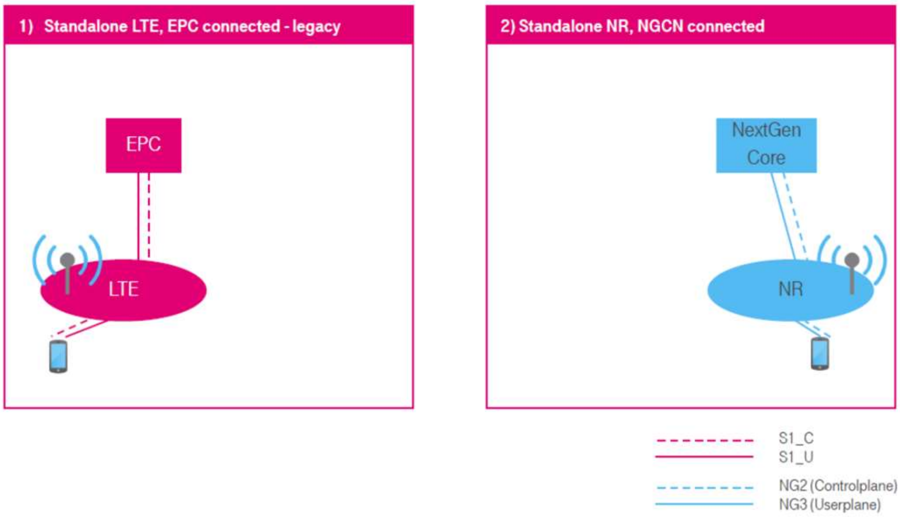


Source: 3GPP

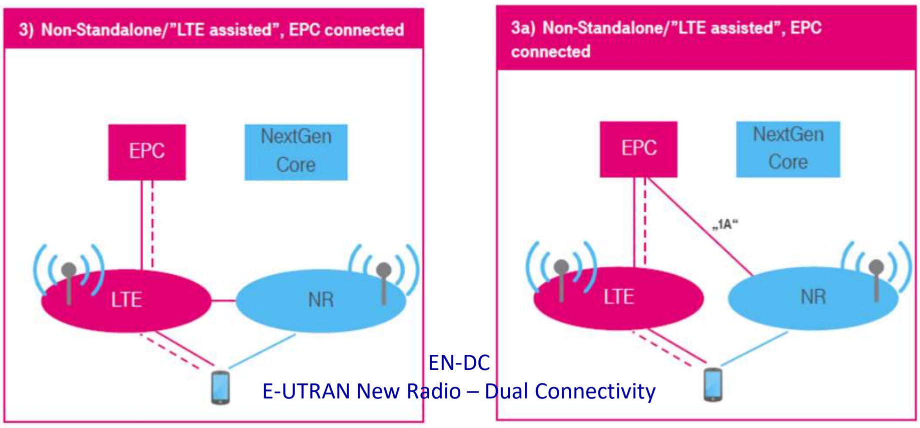
5G new RAN architecture options



5G new RAN architecture options



5G new RAN architecture options

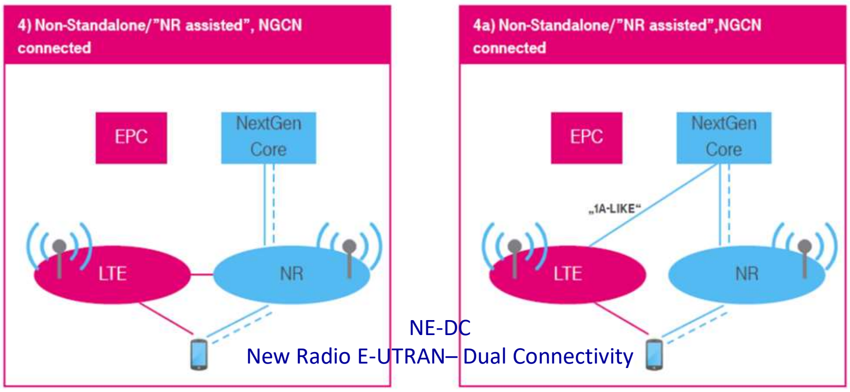


EN-DC
E-UTRAN New Radio – Dual Connectivity

In Non-Standalone (NSA):

- the 5G radio **(gNB) is co-located with the eNB** and connects to the 4G core, acting as **CP anchor**.
- **the 5G radio only acts as a secondary serving cell to boost throughput and capacity**.

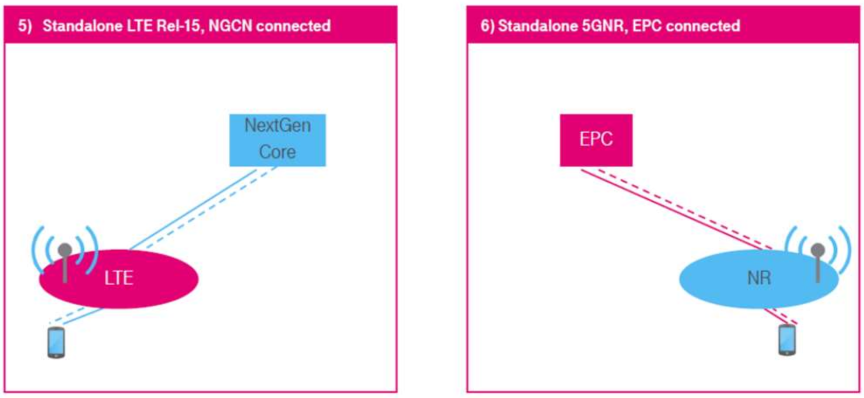
5G new RAN architecture options



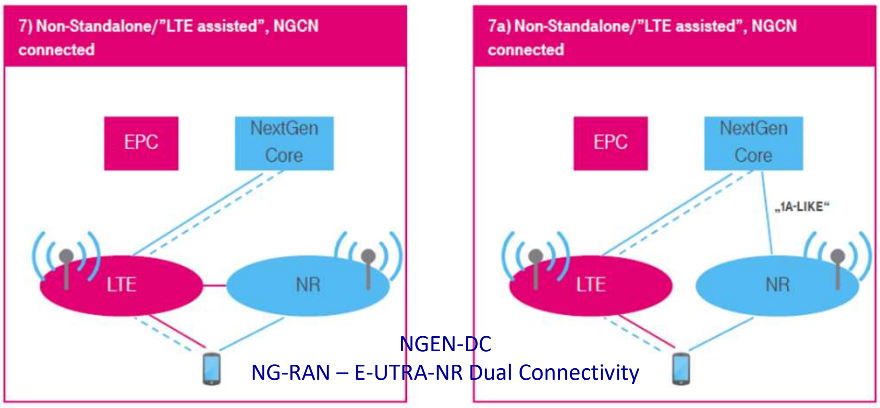
NE-DC
New Radio E-UTRAN– Dual Connectivity

configuration utilizing the 5GC, whereby the master RAN is a 5G gNB and the secondary RAN node is a 4G ng-eNB

5G new RAN architecture options

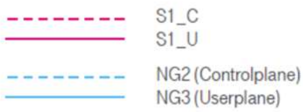


5G new RAN architecture options

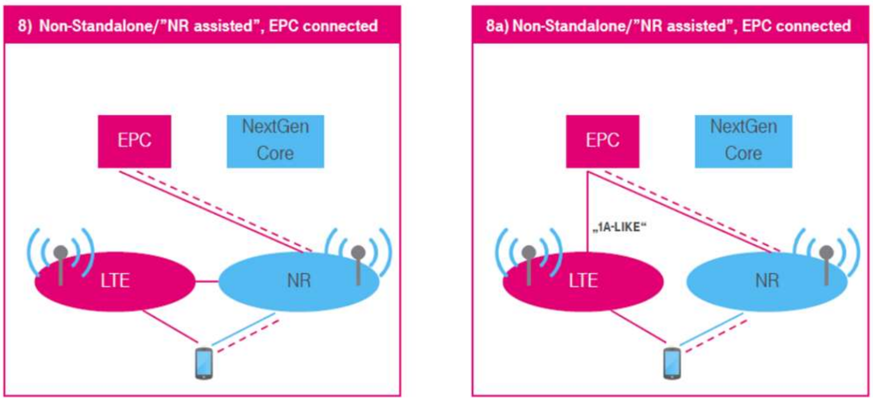


NGEN-DC
NG-RAN – E-UTRA-NR Dual Connectivity

configuration utilizing the 5GC, whereby the master RAN is a 4G ng-eNB and the secondary RAN node is a 5G gNB



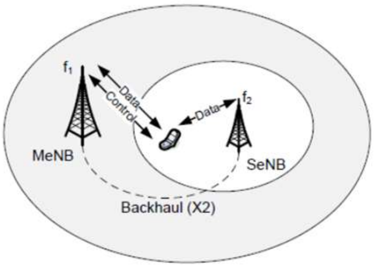
5G new RAN architecture options



5G new RAN architecture options

Dual Connectivity (DC) was introduced in 3GPP to allow a UE to simultaneously transmit and receive data on multiple component carriers from two cell groups via **master eNB (MeNB)** and **secondary eNB (SeNB)**

DC can **increase user throughput**, provide **mobility robustness, and support load-balancing among eNBs**



Dual Connectivity

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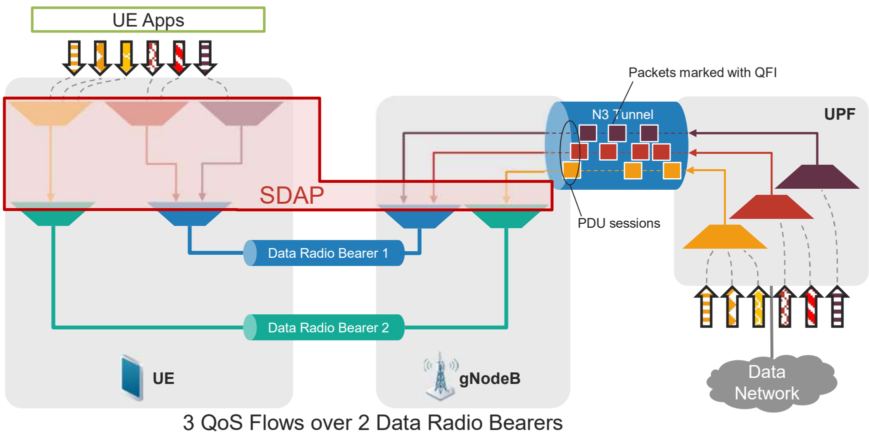
NG-RAN User Plane Protocol Stack

- **Service data adaptation protocol (SDAP)**:
  - New with respect to LTE
  - It aims to support the new flow based QoS model of the 5G core network.
    - Different QoS requirements for different IP flows of a PDU session.
    - Mapping (and filtering) of IP flows with different QoS requirements to radio bearers in both downlink and uplink sides.
    - Marking IP packets with QoS flow Identifier (QFI).
    - Classification filters are dynamically created by NAS procedures and support “reflective mapping” (i.e., downlink and uplink packets of a same flow are automatically mapped onto the same QoS flow).
  - A single protocol entity of SDAP is configured for each individual PDU session.

NG-RAN User Plane Protocol Stack



3 QoS Flows over 2 Data Radio Bearers

NG-RAN Protocol Stack

- **Packet data convergence protocol (PDCP):**
  - Similarly to LTE:
    - Header compression and decompression;
    - Security functions.
  - In addition to LTE:
    - data duplication over different transmission paths (i.e., radio bearers towards different gNodeBs) for URLLC (Ultra Reliable Low Latency) applications;
    - Integrity protection for user plane data.

NG-RAN Protocol Stack

- **Radio link control protocol (RLC)**
  - Very similar to the LTE RLC:
    - It aims to provide segmentation, in order to match the transmitted PDU size to the available radio resources, and error correction through ARQ.
  - Differently from LTE:
    - PDU concatenation is no more supported (to speed up the transmission process and reduce the packet latency).

NG-RAN Protocol Stack

- **Medium access control (MAC):**
  - Very similar to the LTE MAC
    - Multiplexing of data among different radio bearers.
  - Differently from LTE:
    - Enhanced to flexibly support multiple numerologies, bandwidth parts, beam relevant functions.
    - The MAC PDU consists of multiple MAC subPDUs. A MAC sub-header is now present within each subPDU (to reduce the reception latency).
    - The number of logical channels is expanded
    - Only asynchronous HARQ is supported,
    - The scheduling mechanism is further enhanced.

NG-RAN Protocol Stack

- **Physical Layer (PHY):**
  - Very similar to the LTE
    - OFDM is used.
  - Differently from LTE:
    - OFDMA is used also on the uplink side.
      - SC-OFDM can be supported, but it is not the default setting.
      - Enhanced support for Massive MIMO and Beam forming.

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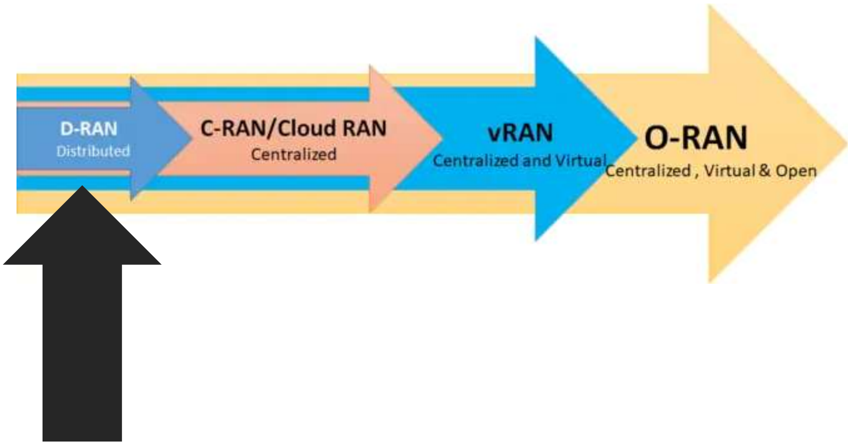
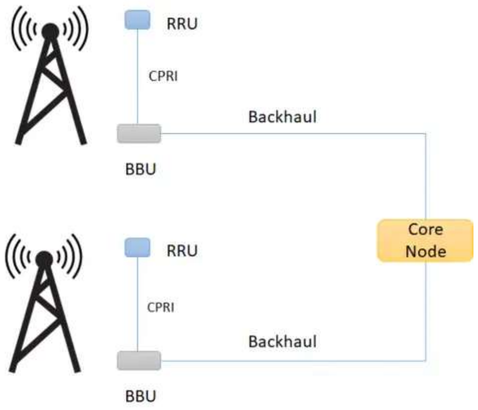
RAN evolutionary path



What is D-RAN?



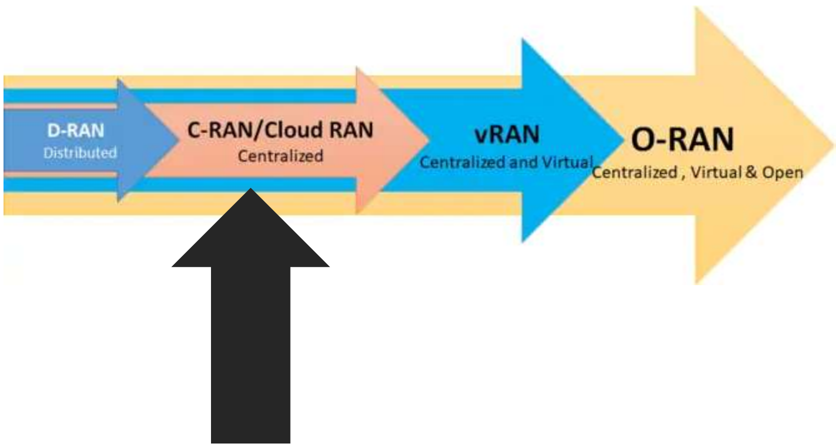
BBU: Baseband unit. Manages the whole base station, including operating/maintenance and signaling processing. It decides the **"CAPACITY"** of the system.

RRU: Remote Radio unit interfaces with an antenna on one end and BBU on the other. It connects to BBU through CPRI interface and converts RF signal into data signal and vice versa. Further, it does filtering and amplification of RF signal. In fact, it decides the "**COVERAGE**" of the system"

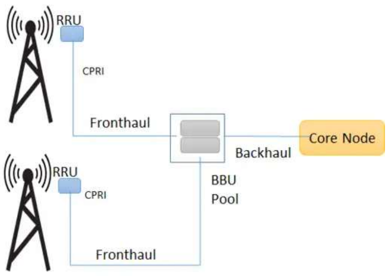
Antenna: It interfaces a cell phone wirelessly and transmits/receives RF signal. It decides the "**SHAPE"** of the coverage.

- D-RAN stands for "Distributed RAN"
- The RRU and BBU are **co-located at every cell site**. Each cell site with all its radio functions are distributed and connected back to the core network through backhaul.

Cloud-RAN (CRAN)



What is C-RAN / Cloud RAN



- C-RAN (Also CRAN) stands for Centralized RAN or Cloud RAN.
- In C-RAN (Cloud RAN) the BBU moves to a centralized location and the cell site only has the antenna and the RRU. A new interface called fronthaul is between the RRU and **BBU pool**.
- BBUs centralization
  - reduces deployment and maintenance cost per cell site.
  - In addition, it improves spectral efficiency and reduces inter channel interferences (centralized BBUs can share the resources dynamically among the multiple RRUs and joint scheduling and processing reduces inter-channel interference)

C-RAN / Cloud RAN

In the traditional architecture:
- ✓ RAN is made by many **stand-alone BSs**
- ✓ **radio and baseband processing functionality is integrated inside a BS**
- ✓ BSs designed to handle the **peak traffic (<u>overprovisioning</u>)**

CRAN in short: "a super BS with distributed antennas".
The processing of multiple BSs is located in one unit.

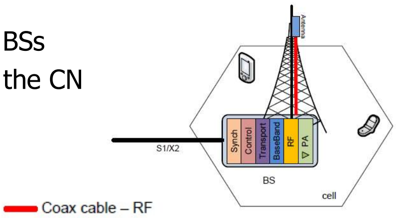
- **China Mobile** started to promote the idea of C-RAN publicly since April **2010**.
- **ZTE, IBM, Huawei, Intel** signed MoU on C-RAN collaboration on April 2010

A. Checko et. al. "Cloud RAN for Mobile Networks - a Technology Overview", IEEE Communications Surveys and Tutorials, 2015
"C-RAN The Road Towards Green RAN," China Mobile Research Institute, Tech. Rep., October 2011.

C-RAN / Cloud RAN

All-in-one BS

- In the **traditional architecture (used in 1G, 2G)**, **radio and baseband processing functionality is integrated inside a BS**.
- Antenna module generally located a few m-far from the radio module (coaxial cables to connect them exhibit high losses).
- BS cabinet placed in a **dedicated room** along with all necessary supporting facilities such as **power, backup battery, air conditioning, environment surveillance, and backhaul transmission equipment**.
- X2 interface is defined between BSs
- S1 interface connects a BS with the CN

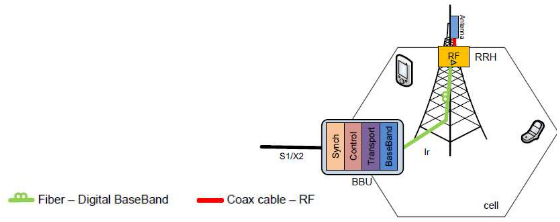


C-RAN / Cloud RAN

Distributed BS

In a **BS with Remote Radio Head (RRH**) architecture (largely used in 3G), it is separated into:

- a **radio unit** called **RRH** or **Remote Radio Unit** (RRU) that provides the interface to the fiber and performs digital processing, digital to analog conversion, analog to digital conversion, power amplification and filtering
- a **baseband signal processing** unit (**BBU)** or Data Unit (DU)

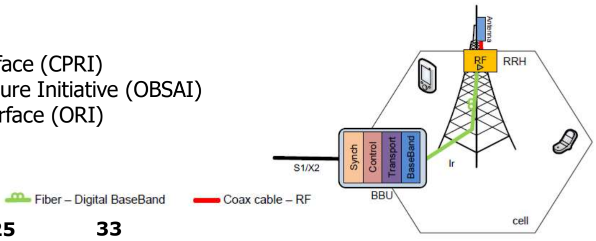


C-RAN / Cloud RAN

Distributed BS

- **RRH installed on the top of tower close to the antenna**, reducing the loss w.r.t. the traditional BS where the RF signal has to travel through a long cable from the BS cabinet to the antenna at the top of the tower.
- **BBU** in a more convenient, easily accessible place, enabling cost savings on site rental and maintenance instead of being close to the antenna.
- The **fiber link between RRH and BBU** allows more flexibility in network planning and deployment (few hundreds m or a few km long).

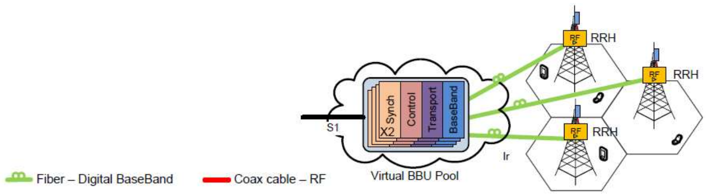
Ir:
- Common Public Radio Interface (CPRI)
- Open Base Station Architecture Initiative (OBSAI)
- Open Radio equipment Interface (ORI)



C-RAN / Cloud RAN

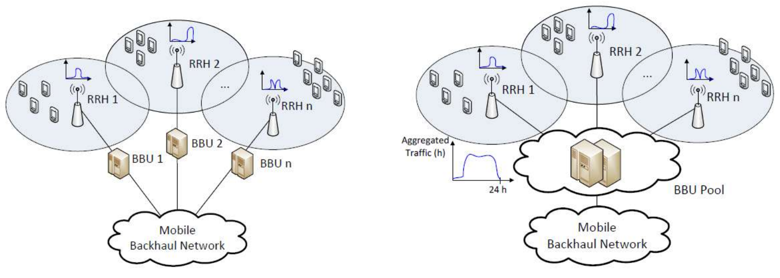
In **C-RAN**, in order to optimize BBU utilization between heavily and lightly loaded base stations, the **BBUs are centralized into one entity that is called a BBU/DU Pool/Hotel**.

- A BBU Pool is shared between cell sites.
- X2 interface in a new form, often referred to as **X2+** organizes inter-cluster communication.



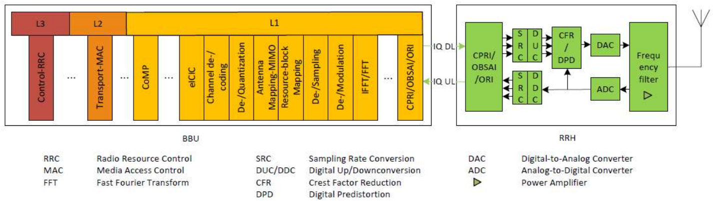
In C-RAN C can be interpreted as: Cloud, Centralized processing, Cooperative radio, Collaborative or Clean.

C-RAN / Cloud RAN



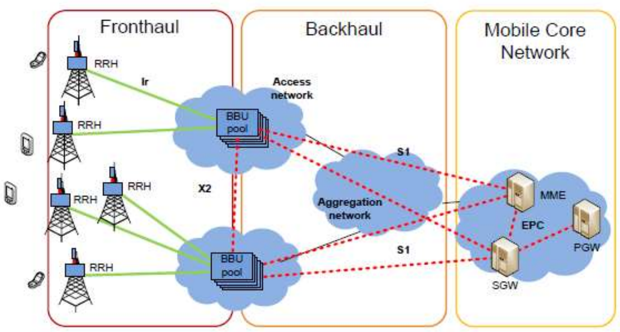
(a) RAN with RRH (b) C-RAN

BS functionalities



C-RAN / Cloud RAN

C-RAN LTE Mobile Network



Low-latency high bandwidth **optical transport links in the fronthaul** (**also mmwave wireless links**)

C-RAN / Cloud RAN

Cloud-RAN (CRAN): benefits

- Real-time virtualization capability based on open platform
- Adaptability to non-uniform traffic and scalability
- Increase of throughput, decrease of delays
- Ease in network upgrades and maintenance

C-RAN / Cloud RAN

Cloud-RAN (CRAN): benefits

- Real-time **virtualization** capability based on open platform:
  - traditional BS built on **proprietary HW**, where SW and HW are closed-sources and provided by one single vendor
  - C-RAN BBU pool built on **open HW**, like x86/ARM CPU based servers, plus interface cards to handle fiber link to RRH and inter-connection in the pool.
  - **Resources in the pool can be allocated dynamically** to BS software stacks, **from different vendors**, **according to network load**.
  - Real-time performance for C-RAN is at the level of **10 of μs vs 2 ms** usually seen in Cloud Computing environment.
- **Coordination**
- **Centralization**

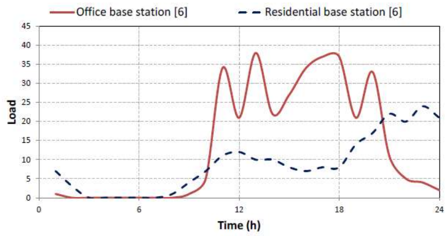
TCO: Total Cost of Ownership

C-RAN / Cloud RAN

Cloud-RAN (CRAN): benefits

- Adaptability to non-uniform traffic and scalability

- ❑ BSs are often dimensioned for busy hours (peak traffic load 10x > during off-the-peak hours), by wasting processing power in the areas from which the users have moved.
- ❑ Since in C-RAN baseband processing of multiple cells is carried out in the centralized BBU pool, the overall utilization rate can be improved.
- ❑ The required baseband processing capacity of the pool is expected to be smaller than the sum of capacities of single BSs.



C-RAN / Cloud RAN

Cloud-RAN (CRAN): benefits

- Increase of throughput, decrease of delays

- ❑ Signal processing from many cells can be done over one BBU Pool, easing the implementation and **reducing processing and transmitting delays**
- ❑ The time needed to **perform handovers is** reduced as it can be **done inside the BBU pool instead of between eNBs**.

C-RAN / Cloud RAN

Cloud-RAN (CRAN): benefits

- Ease in network upgrades and maintenance

- ❑ C-RAN capacity peaks and failure might be absorbed by BBU Pool automatic reconfiguration, therefore limiting the need for human intervention
- ❑ Whenever upgrades are really required, human intervention is to be done only in a **very few BBU pool locations**.

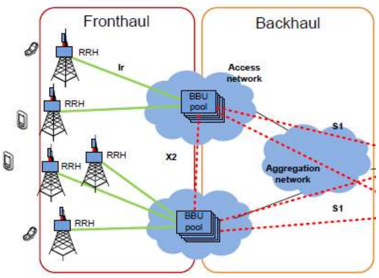
C-RAN / Cloud RAN

Cloud-RAN (CRAN): drawbacks

Cost of **leasing the fiber connection** to the site may increase **CAPEX**.

- ❑ Signal transported between RRHs and BBUs brings up a significant overhead
- ❑ The **installation and operation of transport network** causes considerable costs for operators.

CRAN typically **favored by operators with access to optical fiber and low-cost wireless front-haul** or in extremely high-density scenarios (e.g., sports stadium)

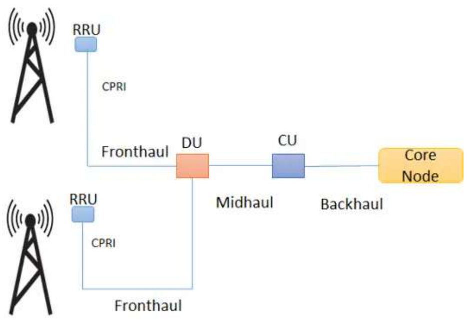


C-RAN / Cloud RAN

Cloud-RAN (CRAN): challenges

- High bandwidth, strict latency and jitter as well as low transport
- **BBU cooperation, interconnection and clustering**
  - Needed to support sharing the user data, scheduling at the BS and handling channel feedback information to deal with interference.
  - Co-location of many BBUs requires special **security and resilience mechanisms**.
  - Cells should be **optimally clustered** to be assigned to one BBU Pool, in order to reduce interference but also to prevent the BBU Pool and the transport network from overloading and to achieve optimal energy savings.
- Virtualization/cloud computing techniques
  - Dynamic processing capacity allocation is necessary to deal with a dynamically changing cell load (refer to NFV).

C-RAN / Cloud RAN with RAN splitting



Fronthaul: is the link between RRU and BBU (or RRU and DU). It has a strict latency requirements of 100 to 250 µs (one way)

Midhaul: is the link between DU and CU. It has relaxed latency requirements, which means we can place CU further closer to the core node.

DU: Distributed Unit runs the RLC, MAC, and parts of the PHY layer. We normally place DU closer to RRU.

CU: Centralized Unit handles the RRC and PDCP layers (and SDAP in case of 5G) . One CU can connect to multiple DUs, CU is co-located with DU or far from DU.

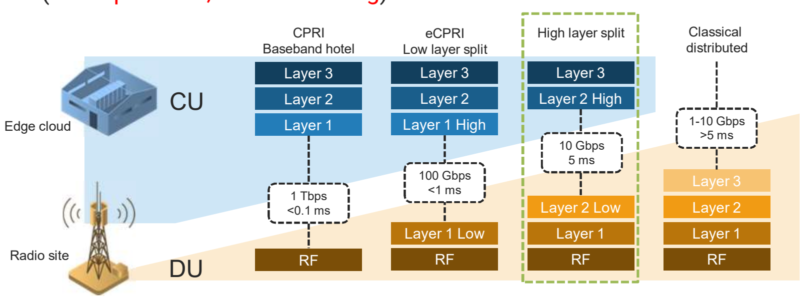
- In addition, a second option of the centralized RAN architecture has a further split in BBUs into DU and CU. Here, CU is further towards the core network resulting in a new interface called midhaul.

RAN Splitting

- Splitting up the gNB (the NR logical node) between **Central Units (CUs)** and **Distributed Units (DUs)** would bring different benefits:
  - 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.
  - Configurable functional splits enable adaptation to various use cases, such as variable transport latency.
- The choice of how to split NR functions in the architecture depends on radio network deployment scenarios, constraints and envisaged services.
- Several possible CU-DU split options have been considered, and 3GPP decided to adopt the "**High Level Split**" as base of specifications.

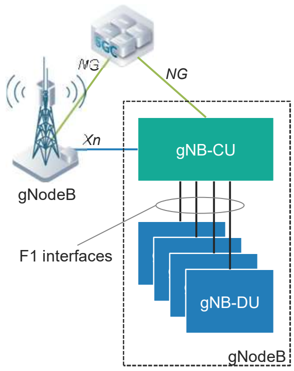
Interfaces for RAN splitting

- The 5G radio network includes new interfaces between the radio (distributed) unit and baseband (central) unit or edge cloud unit, with the aim of bringing more flexibility to the radio network deployment.
- Open interfaces in the radio network are supported by the ORAN Alliance (ref. Open RAN, in the following).



High Level Split (HLS)

- A gNB may then consist of a **gNB-CU** and one or more **gNB-DU**(s).
- The interface between gNB-CU and gNB-DU is called **F1 interface**.
- The NG and Xn-C interfaces for a gNB terminate in the gNB-CU.
- One gNB-DU may support one or more cells.
- The <u>internal structure of the gNB is not visible to the core network and other RAN nodes</u>, so the gNB-CU and connected gNB-DUs are only visible to other gNBs and the 5GC as a gNB.

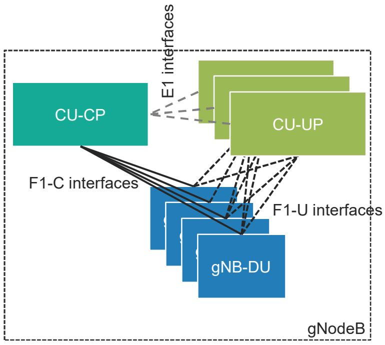


High Level Split (HLS)

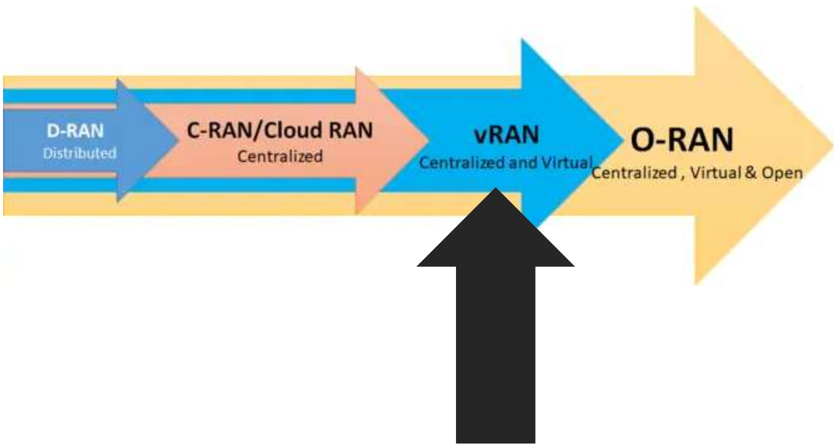
- The F1 interface :
  - supports signaling exchange and data transmission between the endpoints,
  - separates Radio Network Layer and Transport Network Layer,
  - enables the exchange of UE-associated and non-UE-associated signaling.
- The F1 interface functions are divided into:
  - **F1-C** (control-plane) functions: F1 Interface Management, System Information Management Functions, F1 UE Context Management Functions, RRC Message Transfer Function.
  - **F1-U** (user-plane) functions: Transfer of User Data, Flow Control Function (including management of the mobility among different DUs of the same CU).

High Level Split (HLS)

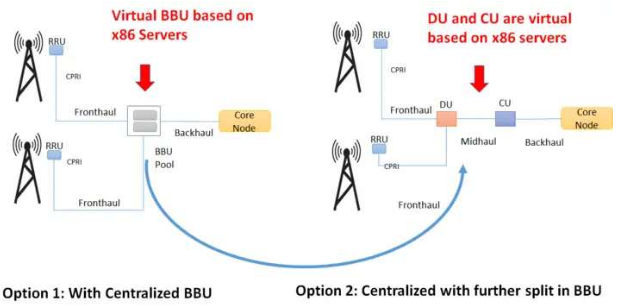
- The gNB-CU can be further separated into its CP and UP parts:
  - The **gNB-CU-CP**: it hosts the RRC and the control plane part of the PDCP protocol; it also terminates the E1 interface connected with the gNB-CU-UP and the F1-C interface connected with the gNB-DU
  - The **gNB-CU-UP**: it hosts the user plane part of the PDCP protocol and the SDAP protocol. The gNB-CU-UP terminates the E1 interface connected with the gNB-CU-CP and the F1-U interface connected with the gNB-DU.
- The interface between CU-CP and CU-UP is called **E1 interface**.



Virtual RAN

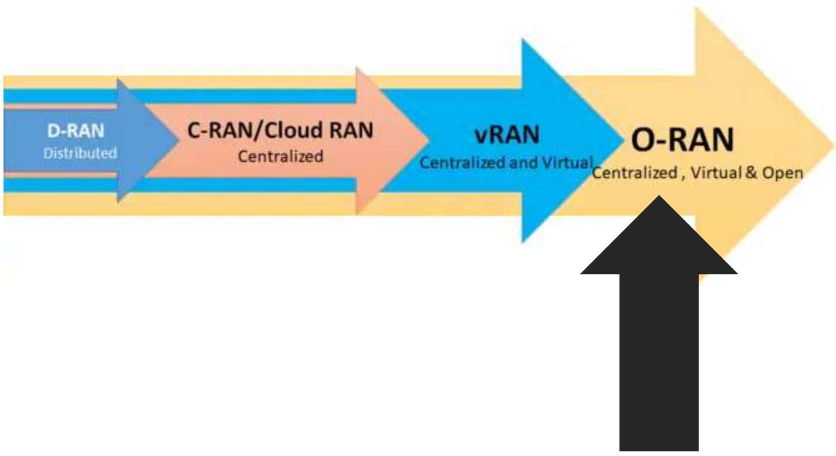


What is vRAN or Virtual RAN?

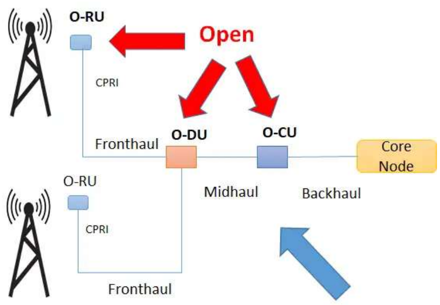


- vRAN decouples the SW from HW by virtualizing Network Functions. It uses virtualization technologies to deploy CU and DU over x86 server. (or virtual BBU on a server). S
- Difference: traditionally C-RAN uses proprietary hardware while vRAN uses Network Functions on the server platform. vRAN can be seen as a type of C-RAN.
- **Advantage**: Because of vRAN HW/SW decoupling flexibility, we can achieve scalability. This can cause a decrease in hardware costs and application agility as application can be upgraded easily or swapped altogether (which is not easier with traditional hardware).
- **Disadvantages**: vRAN puts servers to new limits because of the performance expectation.

Open RAN (ORAN)



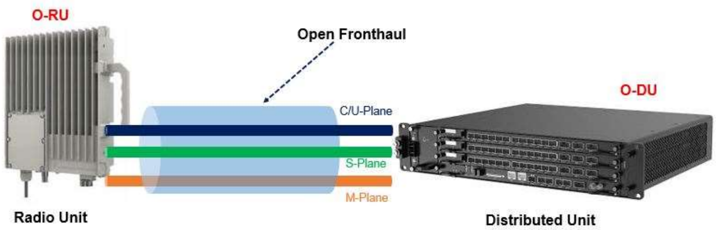
What is O-RAN or Open RAN?



- Open RAN/O-RAN (from O-RAN alliance) takes vRAN to the next level.
- The O-RAN alliance is working on specifications to open the interface between RRU and DU and further between DU and CU.
- This means that a customer can mix and match the components from different vendors without being locked to one vendor for all these three components, thus resulting in an open RAN network.
- These new open components as per O-RAN alliance's specs are called O-RU, O-DU and O-CU (where O stands for Open) which is actually a modular base station software stack on off-the-shelf server hardware.

5G Open RAN Fronthaul

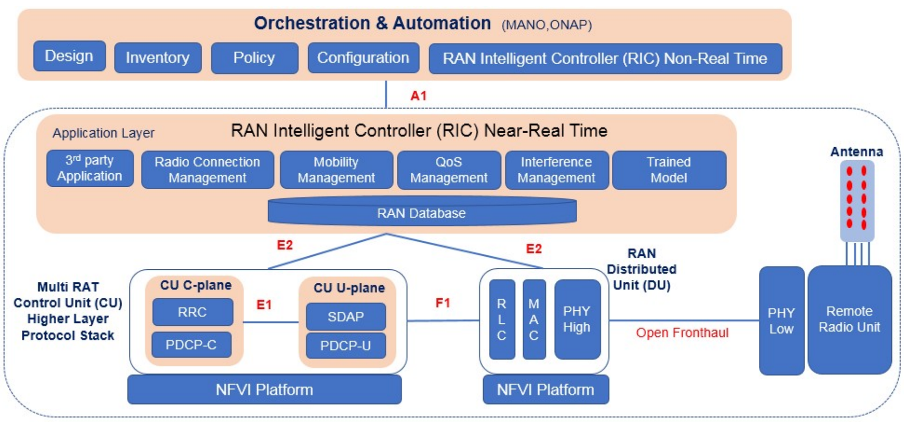
- In Open RAN network deployments, interface between DU and RU is known as Fronthaul. As shown in below picture, the fronthaul carrier, the fronthaul carries Control and User Plane (C/U) data, Sync and Management using eCPRI standard defined format.
  - C-Plane (Control Plane): Control plane messages define the scheduling, coordination required for data transfer, beam-forming etc.
  - U-Plane (User Plane): User plane messages for efficient data transfer within the strict time limits of 5G numerologies.
  - S-Plane (Synchronization Plane) : Synchronization plane is responsible for the timing and sync aspects between the O-DU and O-RU.
  - M-plane (Management Plane) : Management plane messages are used to manage the radio unit.



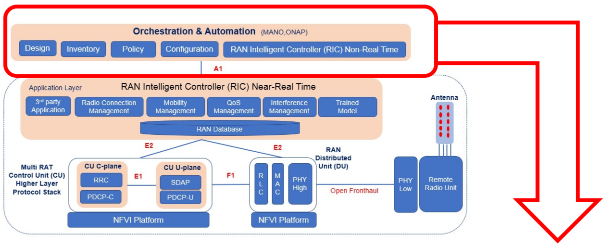
Open RAN (O-RAN) Reference Architecture

- The O-RAN Reference Architecture is designed to enable next generation RAN infrastructures.
  - is designed with the principles of intelligence and openness
  - is the foundation for building the virtualized RAN on open hardware, with embedded AI-powered radio control
- The architecture is based on well-defined, standardized interfaces to enable an open, inter-operable supply chain ecosystem in full support of and complimentary to standards promoted by 3GPP and other industry standards organizations.

Open RAN (O-RAN) Reference Architecture



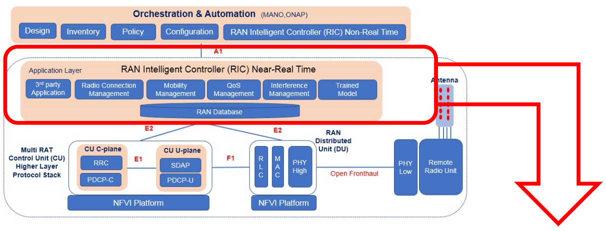
Open RAN (O-RAN) Reference Architecture



Orchestration/NMS layer with Non-Real Time RAN Intelligent Controller:

- Non-RT control functionality (> 1s) and near-Real Time (near-RT) control functions(<1s) are decoupled in the RIC
- Non-RT functions include service and policy management, RAN analytics and model-training for the near-RT RAN functionality
- The core algorithm of non-RT RIC is owned and deployed by network operators
- These algorithms provides the capability to modify the RAN behaviors based by deployment of different models optimized to individual operator policies and optimization objectives.

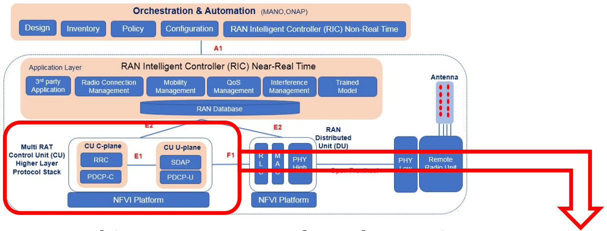
Open RAN (O-RAN) Reference Architecture



RAN Intelligent Controller (RIC) near-Real Time function layer:

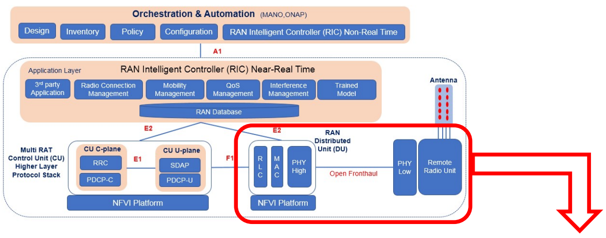
- next generation RRM with embedded intelligence (and optionally legacy RRM) resides within the RIC Near RT function layer
- The RIC near-RT is completely compatible with legacy RRM
- It provides new functions leveraging embedded intelligence, such as QoS management, connectivity management and seamless handover control.
- The RIC near-RT delivers a robust, secure, and scalable platform that allows for flexible on-boarding of third-party control-applications.
- RIC near-RT functions leverages a database called the Radio-Network Information Base (R-NIB) which captures the near real-time state of the underlying network
- It feeds various RAN measurements data, to the near-RT RIC to facilitate radio resource management
- It also provides initiate configuration commands to CU/DU.
- The near-RT RIC can be provided by 3rd-party players
- RIC near-RT receives an AI model from RIC non-RT and execute it to change the functional behavior of the network.

Open RAN (O-RAN) Reference Architecture



Multi-RAT CU protocol stack Function:
- The function of the Multi-RAT protocol stack supports 4G, 5G and other protocol processing.
- The basic functions of the protocol stack are implemented according to the control commands issued by the near-RT RIC module e.g. handovers
- Multi-RAT CU function shall be deployed on virtualization platform
- This virtualization provides a highly-efficient execution environment for CU and near-RT RIC, with the ability to distribute capacity across multiple network elements with security isolation, virtual resource allocation, accelerator resource encapsulation, etc. benefits

Open RAN (O-RAN) Reference Architecture



DU and RRU Function:
- The DU and RRU function includes real-time L2 functions, base band processing and radio frequency processing
- The interface between the DU and the RRU provides standard function segmentation, including the DU-RRU lower layer split interface (Open front-haul Interface), and the CU-DU higher layer split interface (F1)

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Air interface evolution

New radio numerologies

- In LTE a 1 ms transmission time interval (TTI) was considered static and inflexible.
- This could be a problem for low-latency-demanding device having to spend a whole millisecond in a waiting line to get the required radio resources.

- 5G base station (known as the gNB) will be able to allocate radio resources in a more flexible way.
- New numerologies are introduced !!

Air interface evolution

New radio numerologies

- As a first step, the sub-carrier spacing can be increased from 15 to 30 kHz.
  - This means that the resources in the frequency domain are doubled.
  - For some OFDM-mathematical reason it results in the OFDM-symbol being half as long.

- If you think of radio resources as rectangles, this means that the same amount of information can be sent in half the time using twice the frequency resources.
- Istead on a 1 ms long and 12×15 kHz 5G Resource Block, a higher (12×30 kHz) but shorter (0,5 ms) 5G RB can be used.
- Scheduling of radio resources now can be done on a 0,5 ms level!

Air interface evolution

New radio numerologies

- As a further step, we can increase the sub-carrier spacing one more step – or number.
- With a sub-carrier spacing of 60 kHz, the length of an OFDM-symbol decreases even more and radio resources management can be done on a 0,25 ms level.
- This can be taken further to 120 kHz sub-carrier spacing and a 0,125 ms TTI.

....but

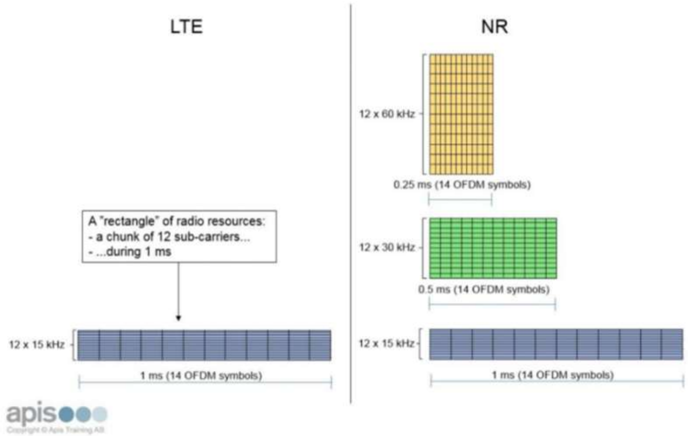
- Radio resource management on a 0,125 ms level is highly demanding on the gNB, and inecessary for a lot of 5G services.

  mix different numerologies on the same radio carrier in a dynamic way to support all types of more or less latency-sensitive services.

Air interface evolution

Actual meaning of numerology?

- refers to the formula for sub-carrier spacing in NR: $\Delta f = 15\ \text{kHz} * 2^n$, where n is the actual number referred to as "numerology".



Air interface evolution

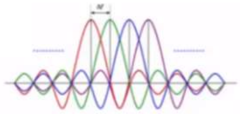
Resource Block in 5G

- In 5G, One NR Resource Block (RB) contains 12 sub-carriers in frequency domain similar to LTE.
- In LTE resource block bandwidth is fixed to 180 KHz but in NR it is not fixed and depend on sub-carrier spacing.

- Numerology μ =0, Δf = 15 KHz: One Resource Block is 180 KHz (15 x 12) in frequency domain and 1ms in time domain, Normal CP
- Numerology μ =1, Δf = 30 KHz: One Resource Block is 360 KHz (30 x 12) KHz in frequency domain and 0.5ms in time domain, Normal CP
- Numerology μ =2, Δf = 60 KHz: One Resource Block is 720 KHz (60 x 12) KHz in frequency domain and 0.25ms in time domain, Normal CP
- Numerology μ =3, Δf = 120 KHz: One Resource Block is 1440 KHz (120 x 12) KHz in frequency domain and 0.125ms in time domain, Normal CP
- Numerology μ =4, Δf = 240 KHz: One Resource Block is 2880 KHz (240 x 12) KHz in frequency domain and 0.0625ms in time domain, Normal CP

Air interface evolution

Variable Subcarrier Spacing



	Slot configuration 0				
Subcarrier spacing (kHz)	15	30	60	120	240
Symbol duration (no CP) (µs)	66.7	33.3	16.6	8.33	4.17
Nominal max BW (MHz)	49.5	99	198	396	397.4
Min scheduling interval (ms)	1	0.5	0.25	0.125	0.0625

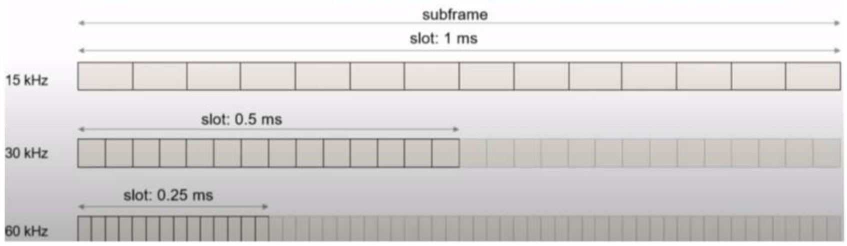
- This flexibility is required to support different services (eMBB, mMTC, URLLC) and to meet short latency requirements
- Increased subcarrier spacing can also help operation in mmWave frequencies

Source: MathWorks

Air interface evolution

Slots and OFDM Symbols

Subcarrier spacing (kHz)	Symbols/slot	Slots/frame	Slots/subframe
15	14	10	1
30	14	20	2
60	14	40	4
120	14	80	8
240	14	160	16



Source: MathWorks

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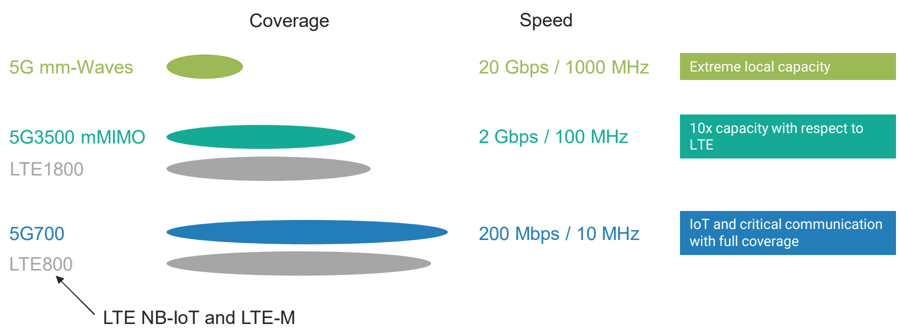
The 5G Spectrum

- 5G is the first radio system designed to support any spectrum between 400 MHz and 90 GHz.
  - Combination of high capacity, high data rates, ubiquitous coverage and ultra-high reliability.
- Low bands below 6 GHz are useful for wide area coverage and data rates up to a few Gbps.
- Reliable coverage is an important factor for IoT devices and for critical communication such as remote control or automotive communication.
- 5G can also be deployed on shared spectrum:
  - New possibilities for enterprises and industries to deploy their own private/local 5G.

The 5G Spectrum

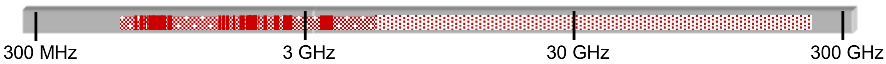


The 5G Spectrum

Millimiter wave (mmWave)

Millimiter wave

- Most mobile cellular systems are deployed in the sub-3 GHz spectrum
- 5G is expected to explore higher carrier frequency, such as millimeter-wave bands (30 to 300 GHz) characterized by:
  - large amounts of bandwidth, enabling very **high throughput**
  - very small wavelengths enabling a **large number of tiny antennas in a given device area**



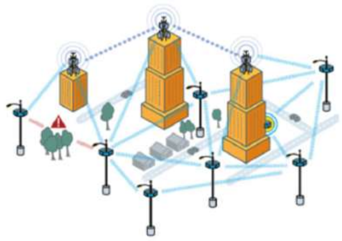
Y. Niu et. al., A Survey of Millimeter Wave (mmWave) communications for 5G: Opportunities and challenges, Springer, 2015

Millimiter wave (mmWave)

Millimiter wave

Due to the high costs, the technology so far has been used mainly for **high data rate indoor communications** and for **backhaul links**.

The usage of mmWave for cellular networks started to be investigated only in recent years.

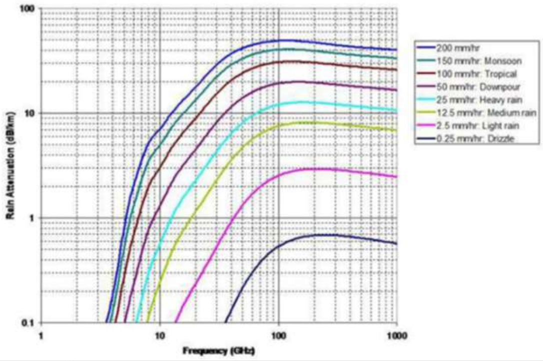


Y. Niu et. al., A Survey of Millimeter Wave (mmWave) communications for 5G: Opportunities and challenges, Springer, 2015

Millimiter wave (mmWave)

Millimiter wave: challenges

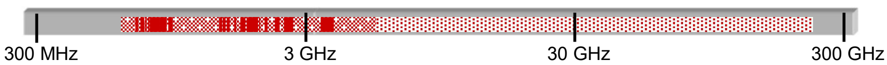
- atmospheric and rain **absorption**



Millimiter wave (mmWave)

Millimiter wave: challenges

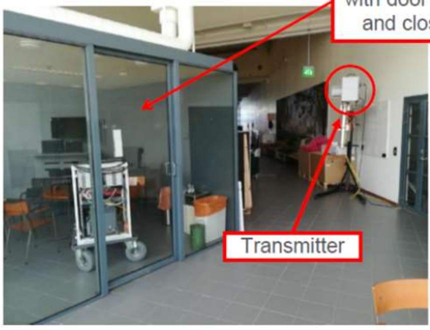
- large **path loss** (especially with NLoS propagation)
- signal **blocking** by various objects (furniture, foliage) and humans in the environment (e.g., blockage by a human penalizes the link budget by 20-30 dB)
- **highly varying channel state under mobility conditions**
- at high frequencies, different materials may produce **non-equal behavior on the signal propagation**



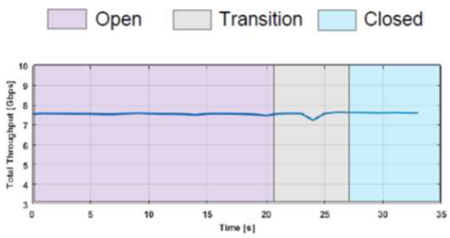
Millimiter wave (mmWave)

Millimiter wave: measurements

Test performed with door open and closed



Impact of glass



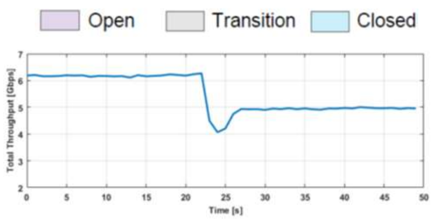
No evident signal loss and throughput degradation experienced

Millimiter wave (mmWave)

Millimiter wave: measurements

Tests performed with door open and closed

Impact of wood

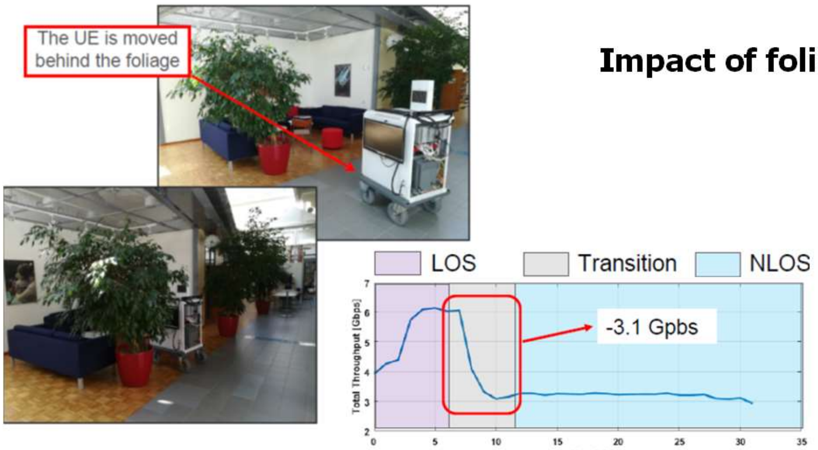


Throughput decreased from 6.2 Gbps to 5 Gpbs

Millimiter wave (mmWave)

Millimiter wave: measurements

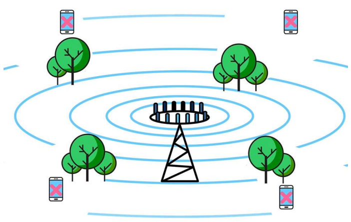
Impact of foliage

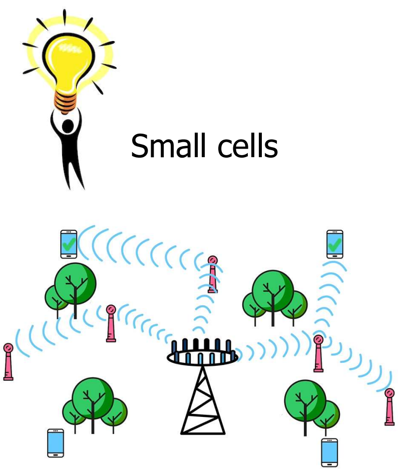


Throughput decreased from 6.3 Gbps to 3.2 Gpbs
Losses caused by the thickness and density of the foliage

Millimiter wave (mmWave)

Millimiter wave: challenges





Millimiter wave (mmWave)

Millimiter wave: solutions

An appropriate **beamforming** scheme to **focus the transmitted and/or received signal in a desired direction** in order to overcome the **unfavorable path loss** (especially with NLoS propagation) is one of the key enablers for cellular communications at mmWave frequency bands.

The **small wavelengths of mmWave frequencies facilitate the use of a large number of antenna elements in a compact form factor** to synthesize highly directional beams corresponding to large array gains.

Millimiter wave (mmWave)

Millimiter wave: challenges

The directional beam pattern improves the transmission range but it complicates communication protocol designs.

Communications between two devices are not possible if their beam directions are not pointing towards each other.

An efficient protocol that discovers the best beam direction pair between devices is very crucial that is called **beam training**.

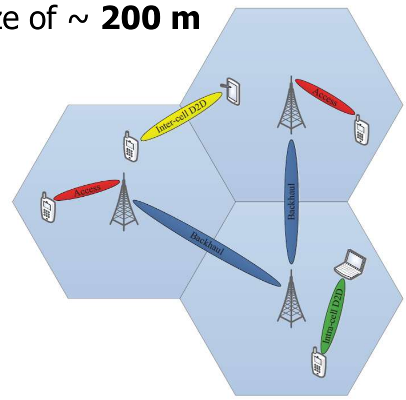
Beam training requires a search over all possible beamformer and combiner pairs.

The overhead due to beam training is generally higher when larger arrays are deployed.

Millimiter wave (mmWave)

Millimiter wave: applications

- Indoor environment
- Small cell access with cell size of ~ **200 m**
- Wireless backhaul with cell size of ~ **200 m**
- D2D communications



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Spectrum options

Spectrum options

Spectrum options

- Cellular systems have always relied on dedicated licensed spectrum and typically use frequencies below 6 GHz due to the favorable propagation conditions
- 5G will still rely on it to provide high-quality connectivity with very high availability but will also move to higher unconventional bands
- It will be extended to operate with more flexible spectrum assignment
  - **Licensed Spectrum Access (LSA)** will enable spectrum sharing among industries;
  - Licensed-unlicensed spectrum combinations can be operated through **Licensed Assisted Access (LAA)**

Spectrum options

LTE-Unlicensed

Spectrum in licensed bands for LTE is limited and expensive.

To address the increasing data traffic demands 3GPP is investigating how to exploit ISM bands at 5GHz and other radio access technologies (RATs) and how to take advantage of LTE technologies in unlicensed bands (**LTE-U**).

LTE in unlicensed bands is a.k.a. License assisted access (**LAA**) which naturally integrates the unlicensed spectrum in the overall LTE network.

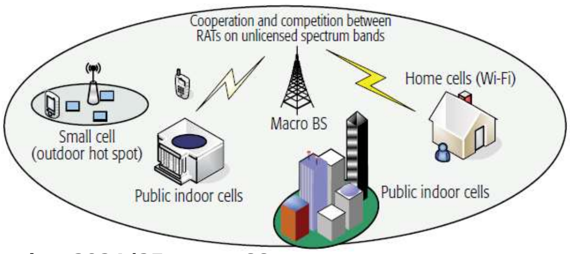
3GPP started to work on LAA since Release 13.

Spectrum options

LTE-Unlicensed

Enabling LTE-U in unlicensed shared spectrum faces some critical challenges. The primary indispensable challenge is the **fair coexistence mechanism design among different RATs**.

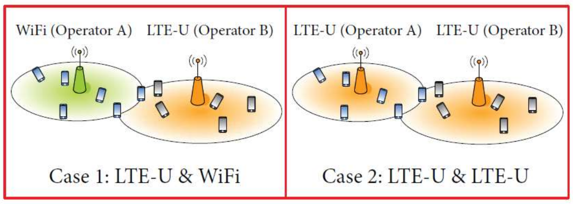
<u>Target</u>: LTE-U/LAA should not impact Wi-Fi services more than an additional Wi-Fi network deployed on the same carrier.



Spectrum options

LTE-Unlicensed

The barrier for efficient coexistence is the lack of inter-RAT coordination and mutual interference management when sharing the same unlicensed spectrum.



Currently, the resource allocation functionalities for different RATs are **performed independently**; the **interference management mechanisms are RAT-specific with significantly different MAC and PHY protocols**, making the inter-RAT coordination quite challenging.

Spectrum options

LTE-Unlicensed

LTE Vs Wi-Fi

<u>They are operated by different operators</u>.

The LTE system adopts a **centralized MAC protocol**, which always allocates one resource unit to the user that can maximize the target metric in every subframe.

The Wi-Fi systems use a totally different MAC protocol based on the **distributed coordination function (DCF)** which is a contention-based mechanism that adopts carrier sense multiple access with collision avoidance (CSMA/CA). Before transmission, the node will first listen to the intended channel. If the interference level exceeds a threshold, the node will back off for a random time.

Thanks to channel sensing, the collision probability is reduced at the expense of lower channel utilization.

Spectrum options

LTE-Unlicensed

LTE Vs Wi-Fi

Besides the MAC protocol, the two systems have different physical layer features.

LTE employs orthogonal frequency division multiple access (OFDMA).

The system bandwidth is divided into a series of physical resource blocks (PRBs), each composed of 12 OFDMA subcarriers. **Different PRBs can be scheduled to different users in the same subframe, thus achieving multi-user diversity gain**.

Wi-Fi system adopts orthogonal frequency division multiplexing (OFDM) in the physical layer, however, it allows **only one user to occupy the whole channel at one time**, the bandwidth of which is usually 20 MHz.

Spectrum options

LTE-Unlicensed

LTE Vs Wi-Fi

Although the available unlicensed bandwidth is relatively abundant, it is still possible that sometimes no clean channel is available so that LTE-U and Wi-Fi have to share the same channel.

This may happen due to an **ultra-dense small cell deployment**, bandwidth range regulations for one operator.

Since LTE has shown dominant system performance over Wi-Fi in the co-channel scenario, some restrictions need to be imposed upon LTE resource allocation in order to protect the Wi-Fi performance.

TDM should be leveraged to avoid interference.

Spectrum options

LTE-Unlicensed

Listen-before talk (LBT)

LBT requires the LTE-U device to periodically stop the channel occupancy and detect the activities of other channel occupants in a scale of milliseconds.

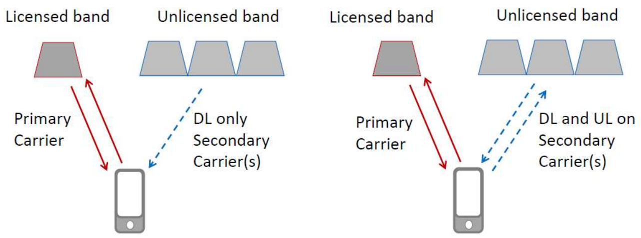
Before transmission, the LTE-U UE or BS **needs to first listen to the target channel to detect the energy level for a period called clear channel assessment (CCA) period**.

Only if the interference level is below a predefined threshold, the UE or BS can occupy the channel.

Spectrum options

Focus will be on **Licensed-Assisted Aggregation (LAA)** operation to aggregate a primary cell - using licensed spectrum - to deliver critical information and guaranteed QoS, and a secondary cell - using unlicensed spectrum - to opportunistically boost data rate.

The secondary cell operating in unlicensed spectrum could be configured either as **downlink-only cell** or contain **both uplink and downlink**.



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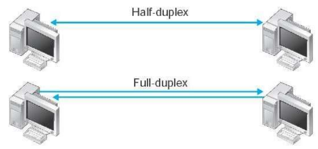
Full-duplex (FD) communications

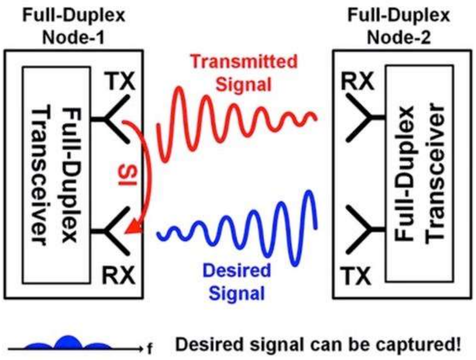
- FD is attracting more and more attention with the advent of 5G
- Sometimes they are considered as **beyond 5G technology**
- FD systems, unlike half-duplex (HD), **<u>can simultaneously transmit and receive signals over the same channel</u>**
- They can **ideally double the capacity of wireless systems**
- Such benefits can be achieved if **self-interference** (SI), due to the transmitted signal, **can be effectively canceled**



A. Sabharwal, et al. "In-band full-duplex wireless: Challenges and opportunities." *IEEE JSAC* 32.9 (2014): 1637-1652.
D. Kim, "A survey of in-band full-duplex transmission: From the perspective of PHY and MAC layers." IEEE Comm. Surveys & Tutorials 17.4 (2015).

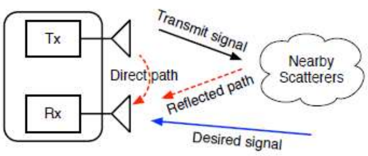
Full-duplex (FD) communications

- **SI can be much higher than the signal from a nearby transmitter** which can be several meters far from the receiver and, hence, subject to attenuation due to path loss and fading phenomena

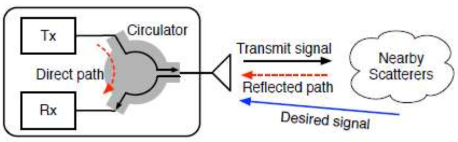


Full-duplex (FD) communications

Simultaneous transmission and reception (STR)



(a) Separate-antenna full-duplex



(b) Shared-antenna full-duplex

Contents

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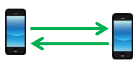
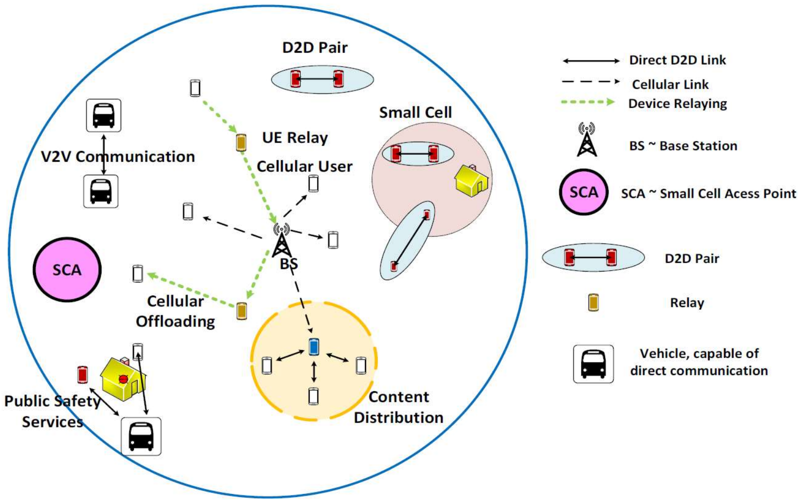
Device-to-device (D2D) communications

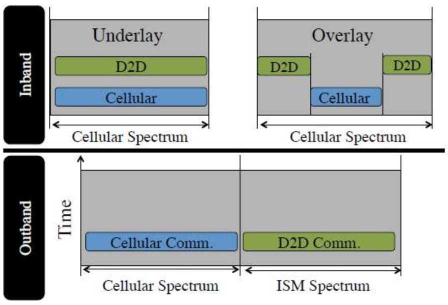
- D2D supports direct communication between devices that are in proximity without passing through the eNodeB; this paradigm well suits **localized communications** (e.g., public safety, V2V communications);
- **The reduction in the number of hops** achieved bypassing the eNodeB **reduces latency**;
- The **device proximity** allows to achieve **higher data rate, lower power consumption, and increased reliability**;
- When cellular and D2D links share the same radio resources (underlay mode), then the frequency reuse brings higher spectral efficiency that comes with no additional spectrum costs.
- It allows **offloading the infrastructure**



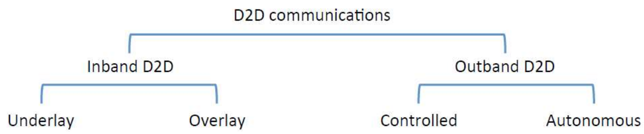
Device-to-device (D2D) communications



Device-to-device (D2D) communications



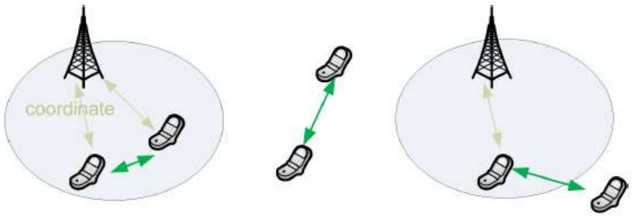
- D2D can be supported on the same cellular spectrum (i.e., *inband*) or on unlicensed spectrum (i.e., *outband*).
- In **underlay case**, cellular and D2D communications *share the same radio resources (interference between D2D and cellular users)*.
- In **overlay**, D2D links are given *dedicated cellular resources*.



A. Asadi, Q. Wang, and V. Mancuso. "A survey on device-to-device communication in cellular networks." *IEEE Communications Surveys & Tutorials* 16.4 (2014): 1801-1819.

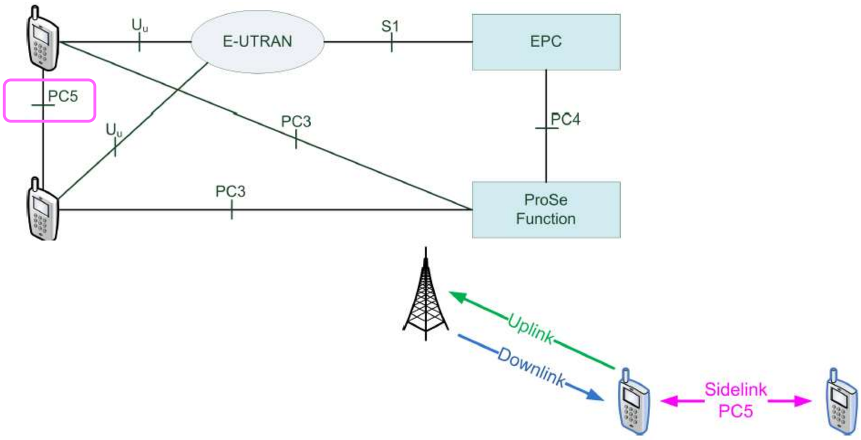
Device-to-device (D2D) communications

- In 3GPP Release 12, device to device communication, or ProSe (**Proximity Services**) communication, is limited to the public safety usage.
- ProSe optimized for multicast/broadcast transmissions, under low density scenarios, in presence of mainly static nodes



Device-to-device (D2D) communications

- ProSe architecture in 3GPP



Device-to-device (D2D) communications

	Inband		Outband	
	Underlay	Overlay	Controlled	Autonomous
Interference between D2D and cellular users	✓	×	×	×
Requires dedicated resources for D2D users	×	✓	×	×
Controlled interference environment	✓	✓	×	×
Simultaneous D2D and cellular transmission	×	×	✓	✓
Requires inter-platform coordination	×	×	✓	✓
Requires devices with more than one radio interface	×	×	✓	✓
Introduces extra complexity to scheduler	✓	✓	✓	×

A. Asadi, Q. Wang, and V. Mancuso. "A survey on device-to-device communication in cellular networks." *IEEE Communications Surveys & Tutorials* 16.4 (2014): 1801-1819.