Survey on 5G Second Phase RAN Architectures and Functional splits

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***Abstract*—The Radio Access Network (RAN) architecture evolves with different generations of mobile communication technologies and forms an indispensable component of the mobile network architecture. The main component of the RAN infrastructure is the base station, which includes a Radio Frequency unit and a baseband unit. The RAN is a collection of base stations connected to the core network to provide coverage through one or more radio access technologies. The advancement towards cloud-native networks has led to centralizing the baseband processing of radio signals. There is a trade-off between the advantages of RAN centralization (energy efficiency, power cost reduction, and the cost of the fronthaul) and the complexity of carrying traffic between the data processing unit and distributed antennas. 5G networks hold high potential for adopting the centralized architecture to reduce maintenance costs while reducing deployment costs and improving resilience, reliability, and coordination. Incorporating the concept of virtualization and centralized RAN architecture enables to meet the overall requirements for both the customer and Mobile Network Operator. Functional splitting is one of the key enablers for 5G networks. It supports Centralized RAN, virtualized Radio Access Network, and the recent Open Radio Access Networks. This survey provides a comprehensive tutorial on the paradigms of the RAN architecture evolution, its key features, and implementation challenges. It provides a thorough review of the 3rd Generation Partnership Project functional splitting complemented by associated challenges and potential solutions. The survey also presents an overview of the fronthaul and its requirements and possible solutions for implementation, algorithms, and required tools whilst providing a vision of the evaluation beyond 5G second phase.**

***Index Terms*—eCPRI, Functional Splitting, Open RAN, Centralized RAN, Virtualized RAN, BBU, CU, DU, 5G Second Phase.**

I. Introduction

This work was supported by FCT/MCTES through national funds and when applicable co-funded EU funds under the project UIDB/50008/2020, ORCIP (22141-01/SAICT/2016), COST CA 20120 INTERACT, SNF Scientific Exchange-AISpectrum (project 205842) and TeamUp5G. TeamUp5G has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie ETN TeamUp5G, grant agreement No. 813391.

Each generation of mobile communication technologies (1G, 2G, 3G, 4G and 5G first phase) has enabled the telecommunications operators to upgrade their network and renew its infrastructure to fulfil service provision and their customer's demands. However, decreasing costs, reducing energy consumption and improving the service have been limiting network operation. A shift towards novel radio access technologies is thus in order. Fifth Generation (5G) contributions are gradually going through the commercialization phases. With the 3rd Generation Partnership Project (3GPP) Release 16 [1], the second phase of 5G is introduced to define the transformative and evolutionary features and capabilities of Radio Access Network (RAN). The second phase of 5G intends to enhance the battery life, performance and support multitude of applications and services. While the first phase of 5G Networks is already commercialized globally, there are still few customers with 5G User Equipments (UEs). Meanwhile, operators have not yet solved many outstanding issues, for example, adopting a cost-effective architecture that effectively addresses the current ultra densification issue that hinders every Mobile Network Operator (MNO) [2].

With the evolution of 5G applications and services, new RAN architectures and protocols are emerging. Network densification is among the potential contenders for increasing the network capacity [3], [4]. The introduction of virtualization is transforming the communication networks and the RAN architectures including the Radio Units (RU) and the Base Band Units (BBUs) which were usually at the cellular Base Stations (BSs). The 3GPP [5] has defined the idea behind virtualization of network functions and functional splitting in order to promote RAN centralization by while reducing the total cost of densification. In the new RAN architecture, the functionalities of 5G BBU are split into several functional blocks, such as the Centralized Unit (CU), the Distributed Unit (DU) and the RU, forming the key building blocks of the Next Generation RAN (NG-RAN). The idea is to support flexible, cheap, energy efficient and straight forward Remote Radio Heads (RRHs) that provide extensive benefits, such as joint processing of radio signals, load balancing, network extensions, and power reduction. Figure 1 presents the NG-RAN concept. The splitting up of the functionalities at the BBU significantly reduces the transport rate requirements. Enhanced Common Public Radio Interface (eCPRI) protocol in the fronthaul transport should provide a cost-efficient enhancement of the performance [3].

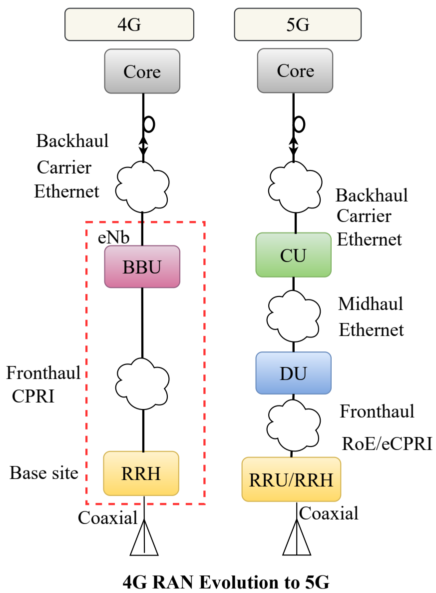

Fig. 1: The evolution of 4G RAN to 5G.

Since the beginning of 4G deployments, there are many works describing and analyzing the various functional split options. In 2018, Larsen et al. [6] gave "*an overview of where the most effort has been directed in terms of functional splits, and where there is room for further studies*". This contribution aimed to provide an update while being self-contained. The contribution exposes recent tools, emulators, simulators, and analysis of the impact of functional splitting. Furthermore, some detailed comparisons of these splits are reported together with the discussion of and their pros and cons with within different use cases are reported.

This work addresses tools that enable to analyze and choose the best functional split options according to their own requirements. Comparative graphs are provided, and it is shown how many researchers are using these tools. The published real-time implementations of the functional splits are also identified. An analysis and our vision on the RAN fronthaul, midhaul and backhaul evolution are included.

The remaining of the survey is organized as shown in Figure 2. Section II starts by presenting several definitions and then introduces our current overview of the RAN terminology from 3GPP, Open RAN and other sources. Section III describes the current research status on the functional splitting, and explains each split, in detail while summarizing the essential aspects, from theory to implementation, algorithms, and tools (simulators or emulators) requirements. Section IV addresses ongoing research on front/mid/backhaul and explains the shift from Common Public Radio Interface (CPRI) to the enhanced CPRI (eCPRI). Section V examines the recent advancements in RAN architectures. We discuss virtualized RAN (vRAN) and Open Radio Access Network (OpenRAN) conceptual architectures in detail and how they evolved, and address the main implementation challenges and opportunities in Section VI. Finally, conclusions are drawn in Section VII.

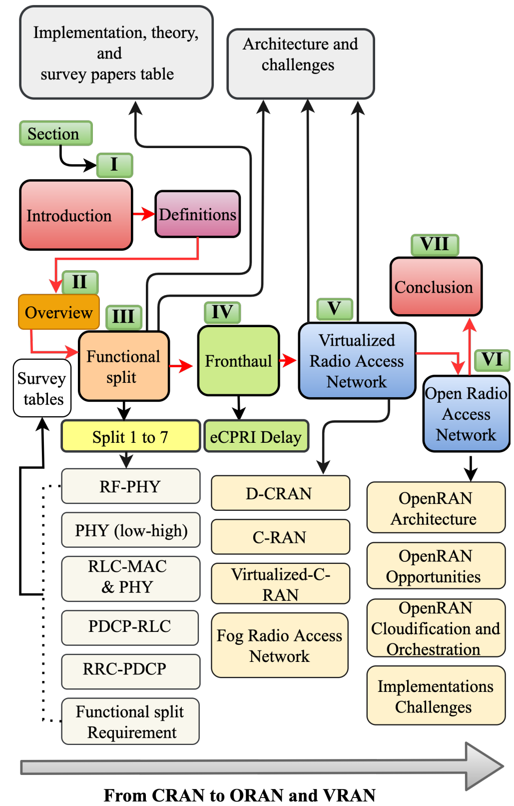

Fig. 2: Overall structure of the survey, with details of sub sections of the paper.

II. Overview

A. *Overview of O-RAN Fronthaul*

Fronthaul indicates the connection between the multiple RRHs and the centralized BBUs, facilitating a more expansive coverage range and faster data transmissions. As defined by the Open RAN Alliance (O-RAN) fronthaul specification [7], the fronthaul interface is defined as Open Fronthaul when it acts as an interface between the multi-vendor DU and RU by the defined signaling and control formats [8]. The open fronthaul architecture defines the Open RAN Distribution Unit (O-DU) and the Open RAN Radio Unit (O-RU) entities as logical nodes for accommodating RLC/MAC/High-PHY layers and Low-PHY with RF processing based on lower layer functional splits respectively.

1) Operational Planes: The O-RAN Fronthaul defines four different operational planes, as shown in Figure 3(a) [7]–[9].

- **Control Plane (C-Plane):** It establishes the control between the DU and RU, in real-time, and transmits messages defining the scheduling information, data transfer coordination requirements, FFT size, length of the cyclic prefix, subcarrier spacing, beamforming and downlink precoding configurations, among other functionalities.

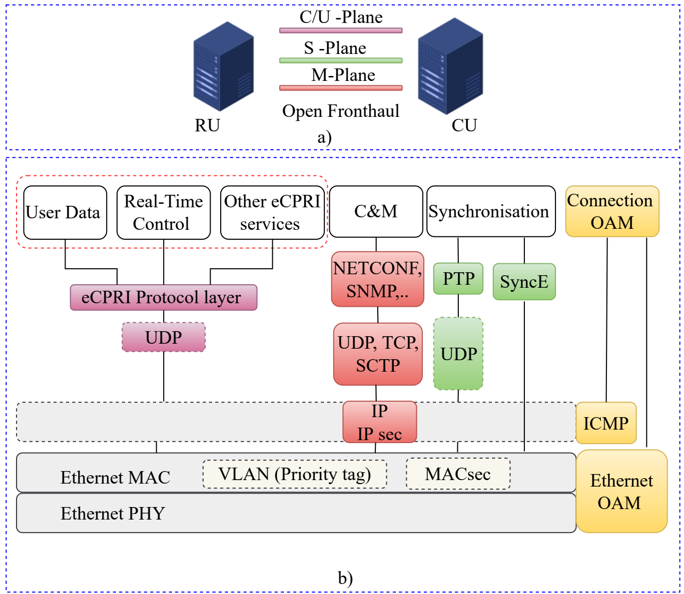

Fig. 3: Typical fronthaul protocol stack considered by the O-RAN ALLIANCE and eCPRI to support: user and control planes, other eCPRI services, Control and Management (C&M), synchronization (PTP or SyncE over UDP or directly over Ethernet) and operation and maintenance [10]. This survey focus on the user and control planes.

- **User Plane (U-Plane):** It characterizes the frequency domain's In-band and Quadrature (IQ) sample data transfer between the DU and RU in the frequency domain. The U-Plane transmits messages containing Downlink (DL)/ Uplink (UL) user data (PDSCH/ PUSCH), DL/UL control channel data (PDCCH/ PUCCH), and Physical UL PRACH (connection request purpose) data, among other, to the RU, before the transmission initiates. Additionally, The U-Plane also supports data compression and DL data precoding.
- **Synchronization Plane (S-Plane):** It is responsible for synchronizing and aligning the time, frequency, and phase clocks between the DU and the RU. S-Plane uses different sync profiles like the IEEE 1588 PTP packets, Synchronous Ethernet (SyncE), Physical Layer Frequency Signals (PLFS), among other to control the timing and synchronization aspects.
- **Management Plane (M-Plane):** It manages the RU, and facilitates functionalities for fault, configuration, accounting, performance, and security (FCAPS) required by the other operational planes, and supports C/U Plane IP and delay management. M-Plane eliminates dependency on the vendor's RU to support a multi-vendor OpenRAN infrastructure.

2) Protocol Stack: The O-RAN Fronthaul (FH) specifications [7] enlist guidelines and blueprint for implementing the four operational planes: Control, User, Synchronization, and Management planes. Figure 3(a) and (b) illustrate the O-RAN FH protocol stack for the 4 different operational planes. The functions of the operational planes are explained in the above section. The O-RAN Fronthaul Interface (FHI) library [8] supports IQ sample transmissions, O-RAN packets generation, appending IQ samples in the packet payload, and extracting IQ samples from O-RAN packets for split 7.2x based O-RAN architecture [8] [9]. The O-RAN FHI library constitutes of (i) O-RAN specific packet handling functionality (src), (ii) Ethernet and the supporting functionality (ethernet), and (iii) Set of header files to support external functions and structures. The C/U-Plane transmits eCPRI or Radio over Ethernet (RoE) essential data over the Ethernet or the UDP/IP protocol stack. The S-Plane transmits the Precision Time Protocol (PTP) and SyncE essential data over the Ethernet. The Management-Plane (M-Plane) transmits Network Configuration (NETCONF) signals over Ethernet with TCP/IP with Secure SHell (SSH).

B. Definitions

Essential definitions of the RAN architecture and functional splitting are as follows:

- **Backhaul:** is the connection to the internet or the core [11].
- **BBU:** baseband unit transports a baseband frequency or a unit that processes baseband [12].
- **Core network:** offers different services to the customers who are interconnected by the access network, or it is the site among the external networks and radio network [13].
- **CPRI:** Common Public Radio Interface is the interface specification for the fronthaul, i.e., between the radio equipment and radio equipment control of radio base stations, considers for wireless cellular networks.
- **CU and DU:** the 5G gNodeB (gNB) is divided into two physical entities CU and DU, generally CU provide support to higher layers and DU provides support for the lower layers [14].
- **eCPRI:** enhanced CPRI for th is the interface specification be radio equipment and radio equipment control

of radio base stations, considered for wireless cellular networks.

While the eCPRI is the enhanced version of CPRI and its connecting enhanced radio equipment and enhanced radio equipment control through fronthaul transport network and is used for 5G systems [15], [16].

- **Functional split:** it is the set of techniques proposed by 3GPP, that divide the network functions to different part to improve overall system performance [17].
- **Fronthaul:** is commonly the link among the the controller and the radio head or small cell. Also, it is the link between the radio head and UE device. It is considered as the end link [11].
- **Midhaul:** is the link between the controller the radio head that provides information to the next link [18].
- **Network Function Virtualization (NFV):** facilitates the virtualization of the network services, such as routers, firewalls, and load balancers, packaged as Virtual Machines (VMs) to enable that allow the mobile service providers may run their network on standard servers instead of proprietary hardware solutions [19].
- **RAN:** is the mobile network part connecting the end-user devices by sending information via radio waves over the Internet. It performs complex processing and handle the increasing demand based on the user-specific services [20].
- **Virtualized RAN (vRAN):** virtualized RAN virtualizes the RAN functions to promote agility in RAN deployment and management offered by the service providers. vRAN eliminates the dependency on proprietary solutions and enhances flexibility in hardware, software and system integration [21].
- **Remote radio head:** is the remote radio transceiver which maintain the connection to radio base station unit via electrical or wireless interface [22].
- **Software-defined network:** facilitates network service management and faster configuration based on the software. It separates the CU and DU and centralizes the network control and configurations [23].
- **Virtual Machines:** are the computing-enabled resource virtualization of a physical systems to execute and deploy programs and applications [24].
- **OpenRAN:** defines interoperability of open hardware, software, and interfaces for the wireless cellular networks. OpenRAN disaggregates the RAN to facilitate an open user and control plane with incorporated synchronization and management plane [25].

C. Introduction to RAN functional splits

Among many organisations contributing to the xG cellular mobile telecommunication standards, the ITU and 3GPP are instrumental. The increasing complexity of the RAN and its management, the virtualization of network functions, the hope to deploy Artificial intelligence (AI) powered distributed networks, the benefits of open interfaces, and the potential to propose innovative connectivity-based services led many organisations and companies to push toward open RAN standard, including, maybe unsurprisingly to some readers, Facebook and Google.

Late 2020, the 2018-founded O-RAN ALLIANCE and the 2006-founded Next Generation Mobile Networks (NGMN) Alliance signed a cooperation agreement to *decompose* the RAN. As explained in the next paragraphs, RAN decomposition, radio network dis-aggregation, base station dis-aggregation and RAN functional splits are somewhat similar terms used when addressing the challenges of 4G and beyond RANs.

The NGMN Alliance is formed by service providers and has defined and developed many RAN topologies to model demand-service-cost-performance statistics. Distributed RAN (D-RAN) and Centralized RAN (C-RAN) are dominant examples of the newly defined topologies based on the requirements. D-RANs demonstrate the lowest latency using Baseband Unit (BBU) at the cell site while requiring usually acceptable transport capacity. The C-RAN solutions propose centralized BBUs and thus require a high-performance transport layer. The C-RAN eliminates the requirement of configuring the individual cell site based on BBU's capacity [26], [27]. The C-RAN architecture is shown in Figure 4. The C-RAN consists of the Remote Radio Heads (RRHs) at cell sites connected via a FH network to BBUs in a BBU Pool (Farm or Hotel depending on the authors). The BBU Pools are connected to the Core Network via the backhaul (BH) network. The C-RAN topology eases the load balancing among the BBU computing resources [27].

Each RRH carries out radio functions, mainly at the physical layer, and is located at the cell site defining the mobile service coverage area. The BBUs are remotely located in BBU Pools and are responsible for processing the radio signal [28]. A BBU is executing and processing radio functions, for example, modulation, channel estimation, Fourier transforms, and error correction. The FH network should provide a low-latency high bandwidth transport for user and control data and synchronization, unless satellite-based synchronization at each cell site is preferred. Besides, it should also provide control and management of the radio equipment.

The CPRI and eCPRI standards specify the fronthaul connecting the BBU and RRHs (Figure 4).

Most 2G and 3G cellular sites were deployed with a base station hosting both the BBUs and the Radio Units (RU), also called Radio Heads (RH) near the cell site mast and with coaxial cables to link the RUs and the antennas on the mast. The concept of separating the BBUs and RRHs with a point-to-point radio transmission or an optical fiber was first introduced in 3G. The BBU-RRH links are called the fronthaul (FH) links. In 2003, several equipment manufacturers defined the open CPRI specifications to transport, over the FH, I/Q user data, synchronization data and Control & Management data. The CPRI v7.0 was specified in 2015 [29]. The CPRI signals can be transported over an electrical cable but are usually transported over an optical fiber less than 2km although the link could be as long as 20 km [30], [31]. The CPRI line bit rate ranges from 1.288 Gbps to 24.3302 Gbps supporting one to twenty four (20 MHz 4G LTE signal). CPRI is a constant bit rate Time Division Multiplex (TDM) stream. Synchronization and accurate timing can be insured using global navigation satellite

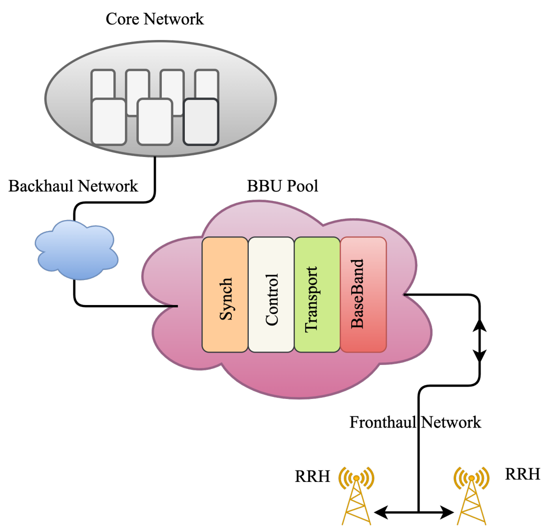

Fig. 4: C-RAN architecture: the BBU and RRH are connected through the fronthaul while BBU and core network are connected through backhaul.

system, e.g., GPS, Galileo, QZSS, NavIC, and BeiDou, or via the CPRI link using the synchronous property of TDM signal, or PTP (IEEE 1588v2) or SyncE (ITU-T G.826x). All details can be found in the CPRI specifications [29]. Note that eCPRI, presented next, is replacing CPRI for the 4G and 5G FHs.

In 2017, the enhanced CPRI (eCPRI) [32], [33] specifications started to be designed to enable 5G FHs to be carried using a continuous bit rate over dark fiber, WDM, and even Ethernet. In 2019, Ericsson, Huawei Technologies, NEC and Nokia updated the eCPRI specification enabling flexible deployments of FHs. The eCPRI allows splitting the physical layer to allow data FH bit rate raising from the CPRI maximum bit rate of 25 Gbps to any available bit rate, e.g., 100 Gbps [34]. The eCPRI also enables to analyze and prioritize traffic. The eCPRI splits are denoted A to E and the mapping to 3GPP splits is given in Figure 5 [33].

Despite the efficiency of the eCPRI, massive MIMO will impose high line rates requiring the use of Dense Wavelength Division Multiplexing (DWDM) if the processing for each MIMO antenna is kept at the BBU. In an experimental setup in 2020, Le et al. [35] demonstrated that *"an aggregated [5G] radio bandwidth of 25.6 GHz was transmitted on a single optical wavelength over 40 km without fiber chromatic dispersion compensation"*. Note that the distance of 40 km leads to a latency of 133 μs, below the maximum latency of 250 μs on the eCPRI fronthaul [36].

The C-RAN architecture was introduced for 4G. C-RAN places the BBUs in a centralized BBU pool (hotel or farm) [6]. Some advantages of the centralized radio signal processing of C-RAN are as follows:

- To share the BBUs resources on-demand depending on the traffic load on the attached RRH in the served cells: in the simplest scheme, BBUs can be launched or turned off as needed, and more complex schemes could optimize the resources allocated to BBUs while reducing energy consumption using AI techniques;
- To simplify or enable radio processing features requiring cooperation between cell sites, such as advanced interference management, fast handover, Coordinated Multipoint (CoMP) transmission and reception;
- To virtualize some or all functions required from the BBUs;
- To simplify upgrades.

The C-RAN architecture with its BBUs and RRHs shown in Figure 4 is identified as one of the 5G enablers. Nevertheless, it is challenging to reach the high-capacity requirement of the FH network when centralizing the base band units for multiple antennas, especially for MU-MIMO. Some challenges have been addressed by the CPRI discussed in the next subsection. To reduce the load over the fronthaul, researchers are investigating techniques to maintain the benefits of the C-RAN and further reduce the burden on the FH link. Heterogenous Cloud RAN (HCRAN) and Fog RAN (F-RAN) have been described to mitigate some C-RAN challenges [37]–[39]. Some details will be provided in the following sections. It is recalled that, in 5G and beyond, the Baseband Units (BBUs) functionalities are splitted between Control Units (CUs) and Distributed Units (DUs) as shown schematically in Figure 1.

1) 3GPP, CPRI and eCPRI Functional Splits: 3GPP has defined eight functional split options. They include further sub-splitting possibilities in the lower and higher physical layer [40]. DU's functions are highly near to the user and will be placed at the antenna side. The functions in the CU will benefit from the centralization processes as well as from the high processing powers within a data center. The functional splits proposed by 3GPP and eCPRI, Small Cell Forum and NGMN are presented in Figure 5 [33]. To improve the CPRI requirements, several higher-layer functional splits are proposed in the literature [41]. The proposal from [40] shifts the radio processing responsibility from the BBU to the RRH while reducing the burden of the FH. According to our research, the most beneficial and popular split is the option seven Physical (PHY) layer, and its underlying intra splits. Besides, split seven has further sub-splits that involve moving Inverse Fast Fourier Transform (IFFT), resource mapping, precoding, and cyclic prefix addition, functionalities to RRH, which efficiently reduce the load over the FH.

Split six is the Media Access Control (MAC) split, known as MAC-PHY split. It moves the RF and PHY and other functionalities to the RRH. Split option two is the split between the Packet Data Convergence Protocol (PDCP) and Radio Link Control (RLC). In this split, the network layer/PDCP functionality is kept in the BBU while all the other processing functionalities (RLC, MAC, PHY, and RF) shift to the RRH. Option 1 to Option 6 are well-thought-out to comprise the higher layer splits [2].

Different splits have been defined in the eCPRI specification [43]. eCPRI has introduced splits named A, B, C, D, I_D, II_D, I_U, and E [42].

When presenting the split, the DL is usually considered first and the split is said to be between higher layer functions at the CU and lower layer at the DU. A single split defines: (1) a BH between the Core and combined CU/DUs, and (2) a FH between each CU/DU and RUs. Double split introduces a

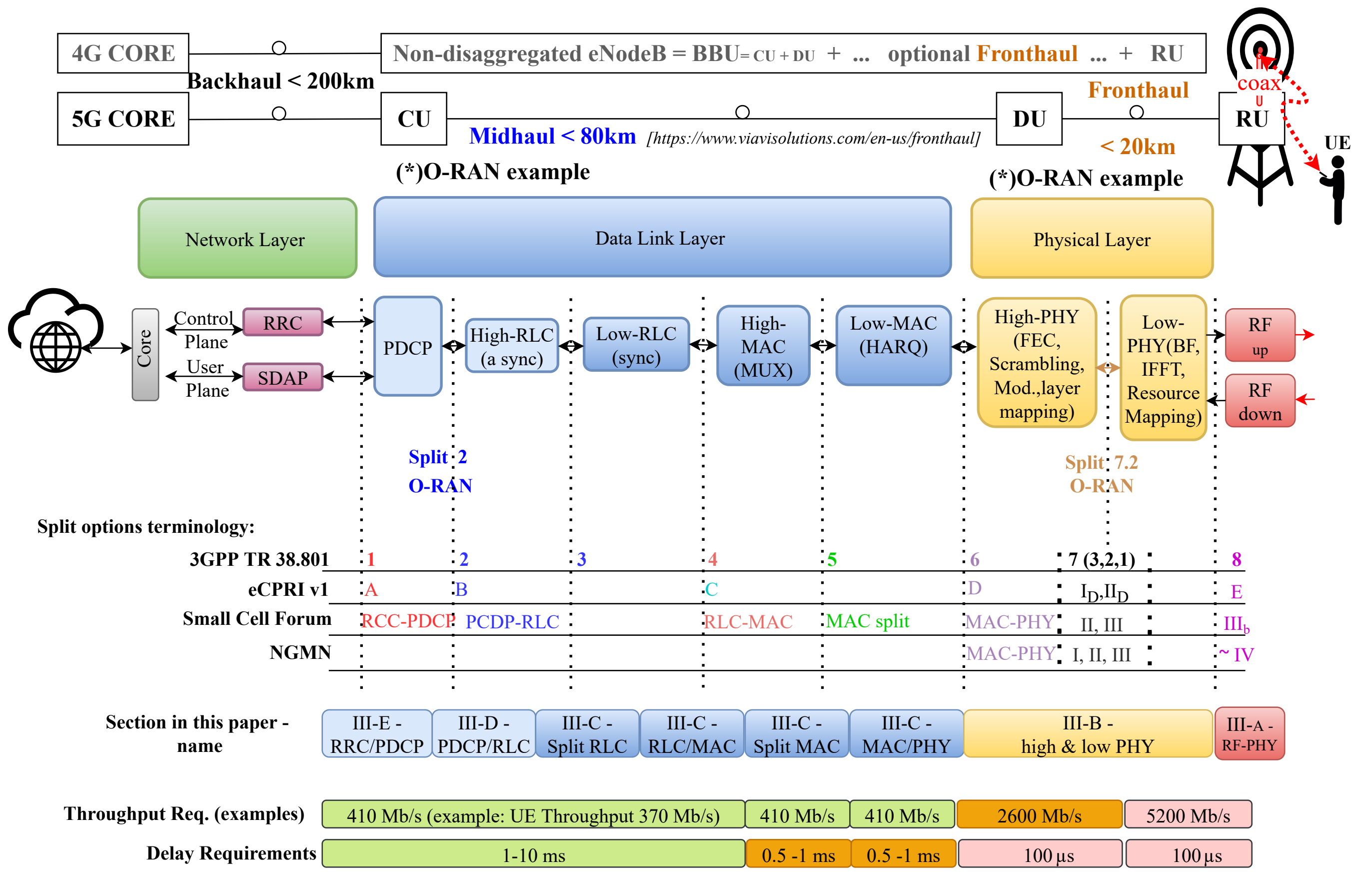

Fig. 5: Different functional splits proposed by 3GPP [33], eCPRI, Small Cell Forum and NGMN [42] with different names.

Midhaul (MH) between each CU and the DUs. A very good overview from Huber&Suhner show the detailed architecture and the elaborate terminology related to functional splits [44].

The mapping between eCPRI and (3GGP) splits is as follows:

- eCPRI A (3GPP 1), between user Data (IP in 4G) or Radio Resource Control (RRC) and Packet Data Convergence Protocol (PDCP);
- eCPRI B (3GPP 2), between PDCP and RLC (Radio Link Control);
- no eCPRI split for the 3GPP split 3 separating the RLC high and low (segmentation);
- eCPRI C (3GPP 4), between the RLC and MAC (Medium Access Control), i.e., the multiplexing controlled by a scheduler;
- no eCPRI split for the 3GPP split 5 separating the MAC multiplexing and MAC HARQ (in 5G NR, HARQ is asynchronous in DL and UL but in 4G/LTE, HARQ is asynchronous in the DL and synchronous in the UL);
- eCPRI D (3GPP 6), between the MAC (HARQ) and MAC-PHY (Forward Error Correction, Rate Matching and Scrambling, all bit processing before/after modulation/demodulation);
- eCPRI I_D (3GPP 7.3) for the DL only (subscript D) between Scrambling and Modulation/Layer Mapping/Precoding;
- eCPRI II_D (3GPP 7.2) for the DL only between the Precoding (N symbols per antenna) and the Resource Element Mapping to each sub-carrier and beamforming Port Expansion (if any); for the UL: the corresponding eCPRI split is called I_U between the Resource Element Demapping and the channel estimation and other received signal processing steps before demodulation;
- no eCPRI split for the 3GPP split 7.1 between the signal and the iFTT (for OFDM processing) and addition of the Cyclic Prefix (to mitigate the multipath effects), in the DL;
- eCPRI E (3GPP 8) between the Cyclic Prefix insertion or removal and the RF (Radio Frequency) transmission in the DL or UL, respectively.

More details are provided in the next section.

As discussed in [45], data link layer splits (3GPP 1 to 6) offer gains in performance concerning CoMP, interference mitigation, scheduling and Radio Resource Management (RRM), and resource sharing, as more functionalities are centralized in the CU. Moreover, the CU can be connected to many DUs, controlling various cells in a reasonably large area.This change in the classical architecture improves and advances RRM and scheduling algorithms. However, this solution increases the complexity of the fronthaul interface and implies a potentially considerable increase in the latency and throughput. As a consequence, OpenRAN provides split

TABLE I: Number of split options proposed by 3GPP.

Split Number	Split Name	Covered in section III
8	RF-PHY	B
7	High-Low PHY Split	C
6	RLC-MAC, and PHY Split	D
5		
4		
3	PDCP-RLC	E
2		
1	RRC-PDCP	E

option 7.2 (precoding/Resource Ethernet, RE, Mapper) only while avoiding split option 8 (digital/analog IQ symbols), e.g., tens of Gbps at mmWaves transmission transported for, say, 64 antennas would be very challenging to be carried on the fronthaul as terabits per second might be required. However, a macrocell site with some microcells could be served using centralized BBUs.

According to 3GPP, there is market demand for two somewhat different split option opportunities. On the one hand, the first one consists of options 6, 7, and 8 (low level). It it targets the operators with sufficient fiber fH transport. On the other hand, options 1, 2, 3, and 5 (high level) splits may be deployed by operators that do not have fiber fronthaul transport yet or need to postpone investment in fiber transport.

2) Open Radio Access Functional Splits: The introduction in 2016 of the open standards for RAN formed the basis for implementing functional splits [46], [47]. The split options rely on the available transport links and network services. Hence, using open standards makes the implementation and assignment of network functions flexible. Open Radio Access Network (OpenRAN) has been proposed to transform traditional communication systems towards an open, intelligent, virtualized and fully interoperable RAN [48]. The OpenRAN Alliance (O-RAN), created in 2018, is a group aiming at enabling RAN key solutions based on general-purpose hardware and software-defined technology that can be open from different perspectives [49]. The main aim of the O-RAN openness is to break the vendor lock-in, proprietary execution of the software, underlying hardware, by launching open standard RF interfaces that increase operational savings using vRAN and C-RAN. The RAN openness will provide flexible deployment and access of BBUs, CUs, DUs and RRHs from different vendors to shape adaptable and scalable RAN networks. OpenRAN made network architecture flexible by adding FH and MH transport by offering alternatives to service providers.

OpenRAN concepts intend to enable any split to create flexible RAN architecture. In 2021, the O-RAN ALLIANCE defined a low-level split option 7.2x, between 7.2 and 7.1, i.e., between the 1-subcarrier by 1-symbol resource element de-mapper and the beamforming port reduction-expansion. Split 7.2x include fronthaul de-compression techniques of IQ signals.

III. 3GPP Functional Splits

A. Naming Conventions

This section provides a detailed overview of the conceptual aspects of the 3GPP functional splits by analyzing and explaining the algorithms associated with each split. For the sake of of understanding and cross-reference, we provide a naming convention for the 3GPP-defined splits in Table I. Detailed charts and tables are added for comparison among different simulators. Moreover, simulators/emulators that are frequently considered for functional splitting implementation are discussed. Tables II, III, IV and V show specific simulators/emulators/analytical approaches.

B. RF-PHY Split (option 8)

Split eight was initially considered based on the traditional C-RAN design: the CPRI or another standard is used to link the BBU and Remote Radio Head or Unit (RRH/RRU) support [50]. Currently, the deployment of split option 8 is indeed still advantageous in some use cases.

Split option 8 is based on the CPRI industry-standard interface. CPRI provides the complete split-up of the Radio Frequency (RF) from the PHY layer to all-out virtualization gains. All the protocol layers from the PHY layer and above are centralized, resulting in a very compactly synchronized RAN, as shown in Figure 6. The placement of only the RF sampler and up-converter in the DU gives a precise and simple DU. This method enables the existence of several functions such as mobility and efficient management of the resources [51].

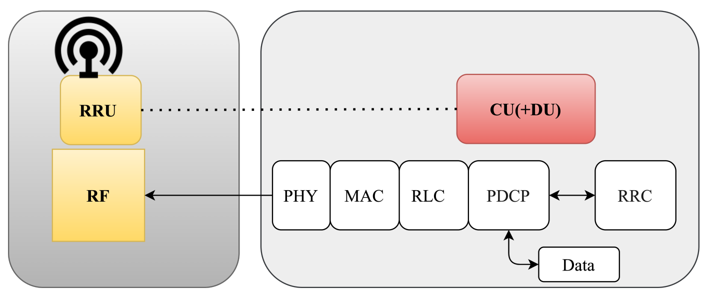

Fig. 6: RF-PHY split architecture.

Bitstream over the FH link is continuously using split eight, and depends on the scales for the count of antennas [51]. This architecture moves New Radio (NR) functions from central to distributed structure. Its advantages are as follows [50]:

- It provides a flexible hardware implementation that supports scalable cost-efficient solutions;
- The split between central and distributed units allows feature coordination, real-time performance optimization, and load management.

Moreover, the DU can assist multiple radio units in handling the digital signal processing and optimize the network traffic.

Field Programmable Gate Array (FPGA) is claimed to be one of the cheapest and possible selections for the implementation of split 8 [52], [53]. FPGAs consider the digital processing assignments in DU but they can correspondingly

TABLE II: Literature review on RF-PHY split.

Concepts/Algorithm/Consideration	Simulator/Emulator /Analysis
Encapsulating CPRI over Ethernet (CoE), stringent CPRI desires like delay & jitter to make CoE a certainty, considered PHY & RF split option 8 [52]	FPGA-based Verilog MATLAB Simulink
Latency is mathematically analyzed using queuing theory, and closed-form formulas [56]	Mathematical analysis
Development of virtual network architecture while considering flexibility to choose the suitable functional split for small cell [57]	MATLAB
Virtualized multi-layer cellular network [58]	Numerical model analysis
Real-time implementation of functional split among RRH and BBU, to balance the transmission throughput among RRHs and BBUs [53]	FPGA, MATLAB and Simulink
Software solutions offering 5G NR protocols to implement the 3GPP Split 8 [54]	IS-Wireless gNodeB
Theoretical & mathematical concepts on split 8 [59], [60], [61], [62], [51], [63], [64], [65], [66], [67], [68]	Analysis

integrate analog sub-systems. gNodeB [54] from IS-Wireless (ISW) [55] is a software solution that can be deployed on either physical or virtual resources. ISW-gNodeB is a 3GPP-compliant implementation of the 5G-NR base station and enables any protocol stack cutting option. An ISW-gNodeB consists of independent Network Functions (NF), which implement 3GPP-compliant NR RAN protocols namely: PHY, MAC, RLC, PDCP, SDAP, RRC, NRAP. The ISW-gNodeB Network Functions can run together or independently and can be deployed on either physical (e.g., a small cell chipset) or virtual resources (e.g. dedicated COTS server or shared cloud resources).

Table II shows a set of characteristics for the RF-PHY split and indicates whether simulations, emulations, or analytical approaches have been conducted by researchers from the indicated reference.The PHY layer is shown in Figure 7.

C. *High-Low PHY Split (option 7)*

As shown in Figure 7, the physical layer is split in the High-PHY and Low-PHY. The low-PHY stays in the RUs while the high-PHY stays in the DUs, and handles the Forward Error Correction (FEC), among other functionalities.

The 3GPP option 7 split has centralization benefits through MIMO, Carrier Aggregation (CA), and Coordinated Multi-Point (CoMP) [69]. CoMP is seen as a significant candidate for 5G in terms of system performance improvement, and is separated into two classes: MAC sub-layer coordination and PHY layer coordination. CoMP include joint transmission and joint reception.

Figure 7 presents the functions of the PHY layer in the DL direction, and presents the data information that is exchanged between the different blocks. The transport block is the input to the PHY layer from the MAC sub-layer on the top. As we can observe, the PHY layer's overall procedures transform the transport block received from the MAC sub-layer into In-phase and Quadrature (IQ) symbols, as shown on the top of Figure 7. The transport blocks are encoded and segmented into block segments and then passed through the rate matching block. Next, the rate-matched codewords are scrambled. The scrambled codewords are then passed through the modulation mapper, where the bits are converted into symbols, according to the modulation order. Then, the layer mapping block takes the modulated symbols into account and maps them into one or various transmission layers [70]. The precoding block then precodes the symbols on each layer before transmission through the desired antenna ports occurs. The resource element (RE) mapper is responsible of mapping the antenna symbols into resource elements, converting them into subcarriers. These subcarriers pass through the IFFT block [71], which produces the IQ symbols in the time domain. Finally, the Cyclic Prefix is attached. This split is detailed in Table III.

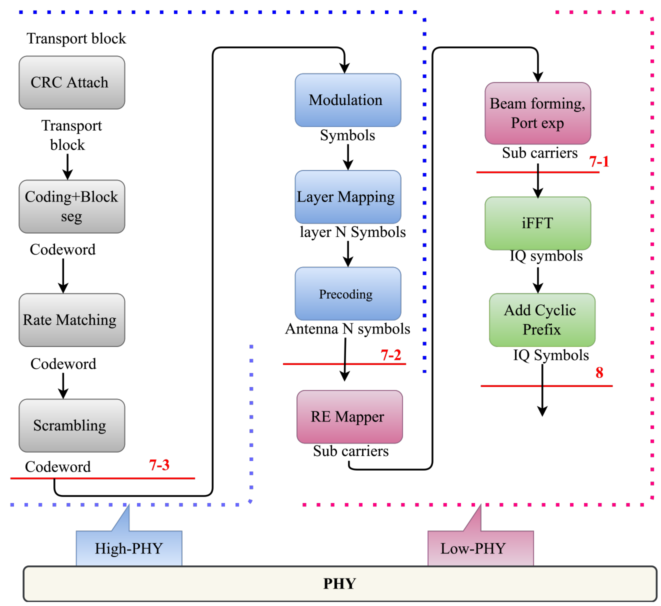

Fig. 7: 3GPP split 7: detailed splits 7.3, 7.2, 7.1 and 8 in this (conventional although strange) order considering the DL and the 4G/LTE protocol stack (5G NR is the same at this level of detail).

In split option 7, the PHY layer functions are defined between the DU and CU [36]. The PHY split has further sub-splits, namely 7.1, 7.2 and 7.3. These splits are enhanced in [72] [73]. Split seven's UL and DL bandwidth mathematical expression is presented in [36], [74]. Figure 7 shows the PHY layer procedures/blocks according to the Long Term Evolution (LTE) protocol stack. Figure 7 presents the functional split proposed in [6]. All the three sub-options of the PHY layer keep the Fast Fourier Transform (FFT)/IFFT in the DU to reduce the FH bit rate [70], [57].

In the split 7 of the PHY layer, the IFFT transformations and the Cyclic Prefix insertion are computed in the DU [75]. Compare to split 7.1, the split 7.2 further reduces the bit rate over the FH by keeping two more functionalities at the DU: resource elements mapping and beamforming. Option 7.3 keeps even more PHY functionality at the DU, resulting in a complex DU and lower achievable bit rates: grey and blue functions in Figure 7. Each split has its benefits and drawbacks, as shown in Figure 8. The splits 7 are considered as the best compromises for the FH bit rate requirements versus advantages due to centralization. Hence, splits 7 are the strongest candidates to achieve high capacity in ultra-dense networks [76] and the FH bit rate is dropped to values comparable to eCPRI.

Splitting options 7.2, 7.3, 6 or below should be used to avoid considerable bit rates on the FH between the RU and DU. Table V contains additional details on the 7.x splits.

The PHY latency requirements are stringent due to the need for coordination from the upper layers. As elaborated in [77], the round-trip latency of 5 ms is required for Hybrid Automatic Repeat Request (HARQ), located in the MAC sub-layer. The comparison of PHY latency with the latency in splits from other layers is defined in [78]. These latency requirements limit the distance between CU and DU to 40 km of optical fiber [78], and from 15 to 20 km of dark fiber connectivity [79]. Note that splits 7.x requires the shortest CU-DU distances. Much longer CU-DU distances ($<$ 200 km) can be achieved using for example split 2 as discussed later and shown in 5. More details are out of the scope of this introductory survey.

The one-way latency is defined in [41] by considering the PHY layer's ideal or near-ideal characteristics. Timing and other frame and subframe requirements are explained in [80]. Because of the automatic repeat request placement within CU, the PHY split options are reliable even with non-ideal transmission conditions. It is possible to relax the FH requirements in terms of latency and bandwidth, by considering the PHY and RF splits as the baseline. For example, to keep a processing FFT/IFFT block and subcarrier mapping/demapping at the DU reduces the FH bandwidth requirements by a factor of 2.5 [57]. By performing the IFFT/FFT function at DU, the cyclic prefix is removed from the Baseband signal, and only the received signals of the allocated Physical Resource Blocks (PRBs) are forwarded to the CU pool.

D. RLC-MAC, and PHY split (options 6, 5 and 4)

The MAC sub-layer, green box, in Figure 9 is an interface to the RLC layer: blue box. The MAC layer sends or receives the data from layer 1 using transport channels [95], while logical channel services provide the data transfer to or from the RLC sub-Low layer. There are 2 logical channels classified as traffic and control channels [96]. Data on a transport channel is organized into dynamic-sized transport blocks, whereas transport formats determine the configuration of the transport block.

Based on the Protocol Data Units (PDUs) delivered from the RLC sub-layer towards the MAC, MAC Service Data Units (SDUs) are configured and later converted to MAC PDUs, which are provided later on in a form of transport blocks to the PHY layer. Each transport block is transmitted in a single transmission time interval in the MAC sub-layer. The MAC sub-layer details for multiple underlying UE MAC entities, are explained in [95]. The MAC sub-layer has a set of functionalities defined in [97]. The 3GPP sets rules for mapping the logical channel traffic to transport block are addressed in [97].

TABLE III: Literature review on the PHY (High-Low) split.

Concepts/Algorithm/Consideration	**Simulator/Emulator /Analysis**
Exploited functional split at PHY & utilize it to serve RAN in capacity-limited scenarios [81], [82]	MATLAB
Implementation of split 7 by using Open Air Interface (OIA) & considering NR [83]	Open Air Interface (OAI)
Prototyping & validation of a DU Lower PHY transmission chain, for 5G and NR [84]	FPGA, MATLAB and Simulink
Design of an adaptive RAN that switches between two different centralization options at runtime, switch from MAC-PHY to PDCP-RLC without service interruption [85]	srsLTE, USRP B200 1 Gb/s Ethernet link
Splitting for efficient FH, to enable the consumed bandwidth with cooperative radio, intra-PHY functional split C-RAN architecture and 7.1, 7.2 and 7.3 splits [76]	OAI
MAC-PHY split generation to find an amount of overhead traffic on the DL [86]	srsLTE
5G-NR DU & CU, UL receivers implementation [87]	FPGA, MATLAB and Simulink
Complexity of the RRU with 5G NR considering functional split option 7.2 [88]	FPGA
The software solution to implement stack cutting option defined by 3GPP at split option 7, between RU and DU, [54]	gNB (ISW)
Survey papers, theoretical & mathematical concepts [76], [86], [87], [88], [89], [90], [91], [92], [57], [93], [94]	Mathematical & theoretical analysis

The MAC sub-layer handles the resource scheduling. It plays a fundamental role in the implementation of Carrier Aggregation (CA) techniques. The MAC Layer generates one transport block per transmission time interval (TTI) per component carrier. The MAC sub-layer shares the MAC packet data units and control elements over different component carriers. Each component carrier within the MAC sub-layer has its own HARQ entity. All the cells involved in CA within the cell group are under a single MAC entity. Authors in [98] and in [99], [100], [101] addressed the aspects of CA and Dual Connectivity (DC) with respect to the MAC sub-layer. Due to the execution per TTI, the MAC scheduler requires very low latency and low jitter [102]. The NGNM Alliance [103] warns that placing the MAC functions in a CU-pool (split 5 or 4) can limit the CoMP functions performance.

The functional split options 1 to 5 have relaxed latency requirements on FH, as the HARQ processing and other time-critical functions are placed in the DU close to the antennas. According to [63], setting the MAC in the CU pool will ease the use of LTE-Advanced in unlicensed bands.

With split 5, low and high RLC, PDCP and RRC will be in CU, and the low MAC (HARQ, multiplexing/scheduling) will be in DU. Functions like scheduling decisions can be performed at CU, for example, inter-cell interference coordination, CoMP. With split 5, the HARQ, a MAC time-critical processing tasks are computed at DU [73]. The split 5, with the High MAC containing multiplexing and scheduling decision at the CU, simplifies the MAC management by the mobile

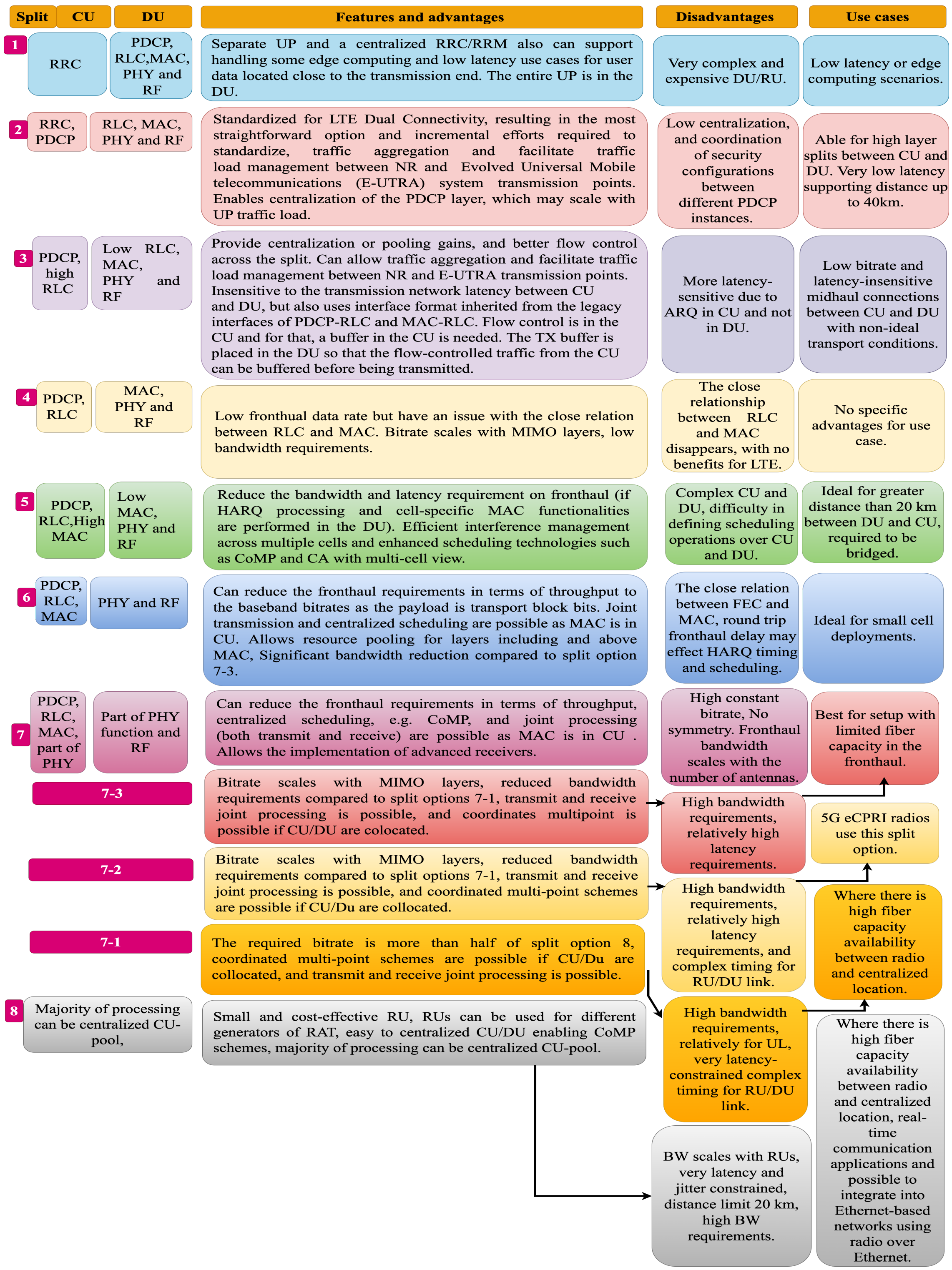

Fig. 8: Advantages and disadvantages in the perspective of this survey.

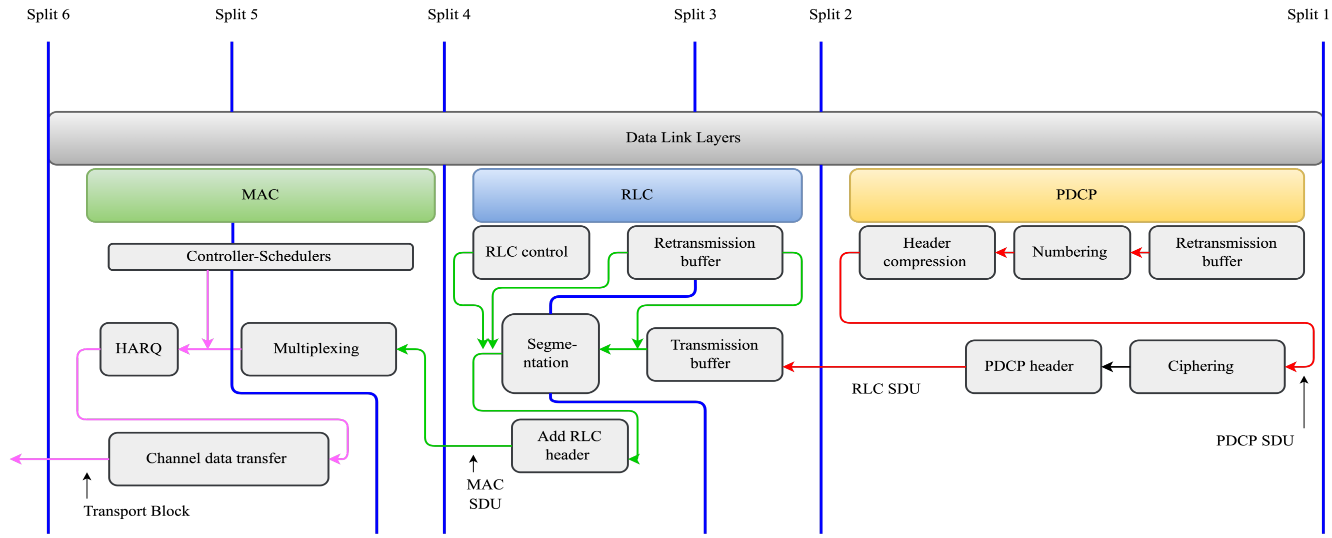

Fig. 9: Architecture of split 1 to split 6 of the data link layer: from PDCP to RLC to MAC in the downlink.

network operator [104].

The split 6 or MAC-PHY split and its resulting reduced FH bit rate requirements are addressed by 3GPP in [105], [106]. The split 6 (MAC-PHY) specifies the transport of MAC PDUs instead of IQ-data blocks. The split 6 is advantageous compared to CPRI as it decreases the fronthaul capacity requirement: for example, [105] reported a fronthaul bit rate of about 137 Mbps for the split 6 while split 8 requires over a 100 times more: 14700 Mbps for 4G. For 5G: 7 Gbps (split 6) is required instead of 157 Gbps (split 8).

The Small Cell Forum favors the Split 6 to reduce costs of 4G and 5G small cell deployments. The Small Cell Forum publishes the so-called 5G network Functional Application Platform Interface (5G nFAPI). The 5G nFAPI extends for 5G the functional split between the MAC and PHY functions to enable virtualization of the MAC function. The nFAPI support communication between the Virtual Network Function (VNF) handling the MAC sub-layer in the DU and the Physical Network Function (PNF) in the RU. Note that the Small Cell Forum refers to S-DU and S-RU instead of DU and RU [107].

Table IV provides a glimpse on several papers discussing the split 6 to 4, i.e., the MAC (High-Low) and PHY splits.

E. PDCP-RLC split (3GPP options 3 and 2)

The 3GPP defines the split 2 as the split between the Radio Link Control (RLC) in the DU and Packet Data Convergence Protocol (PDCP) in the CU [121]. The 3GPP Split 3 separates the RLC by keeping the segmentation (Low RLC) at the DU and the other RLC functions (High RLC) at the CU [121]. split option 3 is further studied in [121].

The PDCP maintains the real-time operation using a buffer at the RLC level. Every incoming packet from the user plane, i.e., the Internet Protocol (IP)+SDAP packet is processed by the PDCP. The PDCP handles packet buffering and retransmission, layer 2 numbering, header compression, ciphering, and integrity protection before the RLC in the downlink. The RLC handles bufferization, segmentation, and ARQ retransmissions.

TABLE IV: Literature review on split between MAC (High-Low) and PHY split

Concepts/Algorithm/Consideration	**Simulator/Emulator /Analysis**
To minimize the intercell interference and the FH bandwidth utilization by dynamically selecting the appropriate functional split option considering PHY-MAC split [108]	MATLAB
Trade-off between bandwidth and RRU complexity for different splits [88]	FPGA
Optimization of processing & bandwidth resource usage, minimizing the overall energy consumption compared to i) cell-centric, ii) distributed and iii) centralized Cloud-RAN approaches [109]	Open Air Interface (OIA)
Examine Ethernet as FH work in C-RAN, with focusing on the MAC and PHY split [110]	Open Air Interface
Theoretical & mathematical concepts [80], [111], [112], [113], [114], [115], [116], [104], [117], [118], [119], [120]	Analysis

According to [63], the PDCP centralization in the CUs, i.e., the 3GPP split 2, is a 5G enabler. The delay sensitive processing of ARQ retransmissions is kept at the DU which can be close to the RU.

According to [122], one PDCP traffic flow is considered per radio bearer. The traffic Split 2 is organized into several flows. Each flow can be directed to various access nodes and support multiple types of connectivity. According to [41], split 2 keeps real-time support in the DUs, resulting in a relaxed CU-DU link requirement.

Figure 11 compares the bit rate among different functional spitting options in uplink and downlink. Table V contains additional details on the PDCP-RLC split (split 2).

The PDCP handles both the NAS/RRC messages for the Control Plane. (CP), and the IP/SDAP for the 5G User Plane (UP). Thus, the CU is composed of two logical components, one for the CP and one for the UP as defined in the context of Software Defined Network (SDN). Some authors use the

TABLE V: Literature review on PDCP-RLC split.

Concepts/Algorithm/Consideration	Simulator/Emulator /Analysis
Different functional splits implementation in the cloud-RAN [122]	Open Air Interface (OIA)
The CU/DU CP split at the RRC/RLC [123]	OIA/SDR
Split buffering between the RLC & PDCP layers. PDCP buffer with per-flow queues, and applied to the RLC buffer a new dynamic sizing mechanism that enforces the shortest queuing delay and is compatible with the existing configuration of the RLC connection [124]	OIA
C-RAN based architecture allows the selection dynamic switching of different HetNets in the RAN [125]	Open Air Interface (OIA)
Software solution to offer NR RAN protocols such as PHY, MAC, RLC, PDCP, SDAP, RRC, NRAP in Option 2, between DU and CU, [54]	gNB (ISW)
Surveys, theoretical & mathematical concepts [126], [127], [128], [129], [126], [130], [131], [132], [133], [134], [135], [136], [137], [138]	Analysis

term CU/CP split but this should not be confused with the functional splits discussed here. Based on the functional split requirements, all the network functions at the CU are organized as either part of the CP or UP [9].

In the RRC-PDCP (3GPP option 1) split, the whole processing for the control and user planes is placed in the DU. Split 1 is thus not very different from the usual Core-BBU-RRH. As the processing of the user data is now near the transmitter there is an advantage for caching. However, features like intercell coordination are not supported in this split 1 option. Consequently, split 1 is not advantageous if many cells are connected to a CU pool [6], [139].

The control and user plane splitting are designed and implemented in [62]. The RRC in the DU handles the control plane functions in this split 1 while the user plane functions are handled by the new 5G Service Data Adaptation Protocol (SDAP) to handle new services beyond IP for 4G. Authors from [140] show that the split option 1 (also called PDCP/RRC) requires low control plane overhead, which benefits load balancing and mobility management using virtualization. In [141], complete and partial scheduling processes are performed at the RRC.

F. Functional Splits Requirements

The maximum latency requirement of each split option is shown in Figure 10. The splits 8 to 5 require a latency less than 1 ms because more processing at DU. Splits 3 and 2 require a latency of 5 ms or more, which is higher than in splits 8 to 4 because there are less functions at CU. Split 1 has the less tight requirement, i.e., 10 ms.

The DL and UL data rate of different splits. Figure 11 compares data rates according to the Small Cell Forum. One can see that all the considered references suggest higher fronthaul bit rate between split options 5 to 8. High and low mmWave band communications perform better for split option 7.1 and 7.2 compared to 5G/ band of less than 6 GHz. Overall the split options 8, 7.1 and 7.2 provide higher bit rate over the FH.

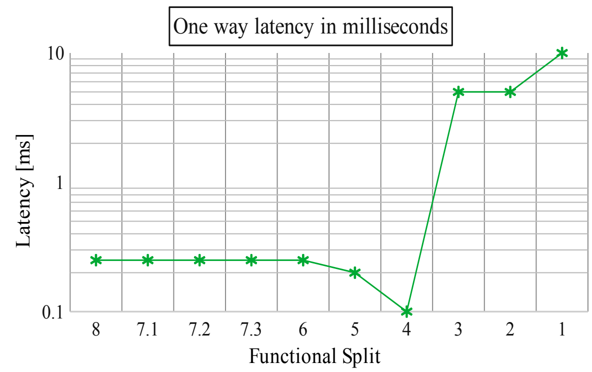

Fig. 10: Latency for different functional splits [41], [142].

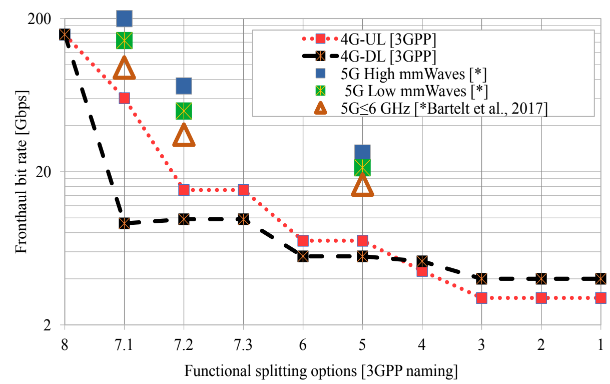

Fig. 11: Fronthaul bit rate (log scale) for different split options according to 3GPP [142], [143], Small Cell Forum [41] and Larsen et al. [6] for 4G (lines), and according to [*]Bartelt et al. for 5G sub 6 GHz (triangles) and near mmWave bands (squares) [144].

Figure 12 presents a comparison of different simulators/emulators considered for the implementation of the splits by other researchers.

Mainly the Physical (PHY) layer split implementation is analyzed, and authors considered FPGAs (62%, i.e., 31 out of the 50 papers considered here) and MATLAB (60%) For overall split implementation and testing in different scenarios, Software Radio Systems (30%),(srsLTE, now srsRAN) and (20%) OAI have been considered, among others. This analysis is based on the research papers listed in the tables from this survey.

IV. Fronthaul

Figures 1 and 4 show the FH network link, usually formed by optical fibers or wireless connections, from the BBUs or DUs to the radio equipment (RRHs, RRUs or RUs) linked via coaxial cables to the antennas, as discussed in , e.g., [69]. The FH carries the data, control, synchronization and operation & maintenance signals. 5G developments challenges current FH transport and next-generation FH interface, radio-over-fiber, and xHaul were investigated in [32], [145]–[147]. Some more details are mentioned in the next sub-sections.

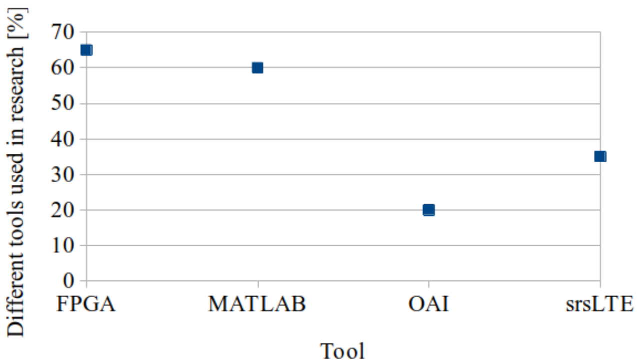

Fig. 12: Different simulators used for implementing functional splits.

A. Requirements and Standardization Bodies

The FH requires high data rate, low latency, low jitter, and low packet loss. The data rate for CPRI is 2.46 Gbps in LTE Networks while the eCPRI capacity reaches more than 10 Gbps [69], [148], [149].

The traditional approach for the transport layer is not expected to continue within 5G and beyond. Instead, next-generation networks require integrated BH and FH technologies that can minimize Operational Expenditure (OPEX) and Capital Expenditure (CAPEX). Authors from [146] present the architecture integrating FH and BH in a shared packet-based network defined as the Xhaul. In fact, the research community has shown that operators are getting more interest in the FH. In a survey of global operator 2020 [150], it is reported that 46% of FH support will be needed for functional split implementation.

Realistic functional split implementation require standards and virtualization. The European Telecommunications Standards Institute (ETSI) is one of the international bodies that is very active in standards related to virtualization and centralized RAN concepts. According to ETSI, base stations are held in cloud computing centers. With virtualization, the BBU, usually located at the base station sites can be moved to data centers, providing the opportunity for easier load balancing. Virtualization of RAN functions facilitates the distribution and shift of the functions across data centers, providing enhanced load balancing and advanced cooperation between antenna sites.

B. Delay

The FH architecture must satisfy specific 5G end-to-end delay to offer time-critical 5G services, such as URLLC. Some envisioned 5G applications could require delays as low as 1 ms. The FH transport within the PHY layer corresponds to options D and E in eCPRI I [151], i.e., 3GPP split 6, 7 and 8. In this context, the HARQ protocol limits the maximum delay between the BBU (or DU) and RRH. For example, after transmitting three 1 ms subframes, the UE sends a positive or negative acknowledgement in the fourth subframe. All the processing at the BBU or DU must be finalized and the frame is created before three subframes, i.e., 3 ms [152].

In [153], the suggested processing time of the BBU is 2754 μs. The 3 ms HARQ limit implies a FH path round-trip time of 246 μs. Thus, the maximum FH one-way latency is 123 μs, or about 24 km assuming, as usual, a propagation speed of 200 m/μs.

Other authors, such as [152], [154], [155] and IEEE 802.1CM, consider a slightly stricter requirements for the delay, i.e., 100 μs for one way communications. This 100 μs maximum delay results from a breakdown of the HARQ processing which ensures the best performance for the FH. Delays longer than this target would degrade the performance of the radio network [152]. In the transmission path using optical fiber, the delay is close to 5 μs/km. Consequently, the maximum distance must be less than 20 km to accomplish the 100 μs highest end-to-end one-way delay limit.

C. eCPRI

In LTE-Advanced, FH connections could use the CPRI protocols, while for 5G NR, eCPRI has been introduced [32]. Going toward the 2nd phase of 5G and beyond, more and more operators might consider the C-RAN architecture. With 4G, 5G NR and dual connectivity, the fronthaul network will carry an amount of traffic which is challenging the CPRI interface.

Currently, for 4G, several Telcos use the CPRI interface for their FH connections. CPRI is a point-to-point interface and considers that operators will use the same vendors at each end of the FH. In turn, the eCPRI interface is open and supports virtualization options, like software-defined network and network functions virtualization. eCPRI is claimed to provide more flexibility to operators to complement networks with shared equipment, improve bandwidth efficiency, and simplify deployments. However, unlike the CPRI, eCPRI neither supports end-to-end synchronization. eCPRI supports and recommends the PHY splitting. Besides, to reduce cost, eCPRI allows deployments using Ethernet transport technology.

In [156], the CPRI to eCPRI replacement have been implemented. Based on the specification of eCPRI, data has been encapsulated in eCPRI format to create eCPRI packets. The system in [156] supports the raw Ethernet header, in which the payload contains one eCPRI message.

1) eCPRI Protocol Planes: The eCPRI specification defines three protocol planes between the eCPRI Radio Equipment (eRE): RU, RRU or RRH and eCPRI Radio Equipment Control (eREC): DU. The first is the user plane, the second is the control and management plane while the third is synchronization plane. Some details are provided as follows:

- The user plane data protocol deals with user data. The real-time control information and related eCPRI services depend on the functional split implementation for the user data;
- The control and management involve non-time-based data flows within eCPRI nodes;
- The synchronization plane carries time-critical information essential for frame and time alignment, utilizing protocols such as precision time protocol (PTP) and SyncE.

2) eCPRI Frame: the eCPRI framing is supported by an Ethernet frame whose sections are transported by using separate layers of the Ethernet frames. The eCPRI message (header) contains four sections, while the reserved portion keeps the payload. Details are as follows:

- The eCPRI protocol revision contains 4 bits.
- C is one bit and shows the eCPRI concatenated message. If it is 0, it indicates that the alternative frame of the same group follows. Otherwise, if it is one, it shows the last frame of the concatenated group.
- The message type section contains 8 bits and the payload size contains 16 bits that follows the eCPRI (message) header. There are eight different payload types carried in the eCPRI frame payload, that includes IQ data transfer, bit sequence transfer, real-time control data, generic data transfer, remote memory access, one-way delay management, remote reset, and event indication. These message types are defined as follows [157]:
  - **eCPRI Message Type 0 - IQ Data Transfer** specifies the time/ frequency domain - IQ sample transfers between eREC (BBU) and eRE (RU), with the vendor-defined structure for the payload;
  - **eCPRI Message Type 1 - Bit Sequence Transfer** specifies the transfer of user data between eREC and eRE;
  - **eCPRI Message Type 2 - Real Time Control Data** specifies the vendor-specific real-time control messages associated with user data (IQ samples, bit sequence) between eCPRI nodes (eREC and eRE);
  - **eCPRI Message Type 3 - Generic Data Transfer** specifies the transfer of the user plane and control messages for generic data transfer and data synchronization;
  - **eCPRI Message Type 4 - Remote Memory Access** allows read/write action from/to opposite eCPRI nodes at a specific memory address using remote units. This service facilitates different read/write accesses depending on the driver routines and hardware implementation;
  - **eCPRI Message Type 5 - One-Way Delay Measurement** estimates the one-way delay between two eCPRI-ports, unidirectional. The local time is sampled by the sender, including a Compensation Value (CV), while the receiver, time stamps the message on arrival and reverts it to the sender with an internal CV;
  - **eCPRI Message Type 6 - Remote Reset** is used when one eCPRI node requests a reset of another node. eREC sends the request to initiate an eRE reset;
  - **eCPRI Message Type 7 - Event Indication** is used to inform the end of a link fault.

V. Virtualized Radio Access Network

This section first recalls some basics related to virtualization and discuss then virtualized RAN.

A. Network Functions Virtualization and Software-Defined Networking

NFV and Software-Defined Networking (SDN) is considered a key pillar of 5G. SDN and a key protocol called OpenFlow are promoted by the 2011-founded Open Networking Foundation (ONF). The operator-driven SDN & OpenFlow proposal led to the creation within the ETSI of the NFV Industry Specification Group (ISG).

The 3GPP 5G architecture defines several core Network Functions (NFs), such as the Session Management Function (SMF) controlling the User Plan Function (UPF) via the N4 interface. By separating the SMF/controller from the UPF/packet forwarding element, the 3GPP 5G architectures follow the SDN concept of separating the control from the user traffic switching, a concept appropriately short named by 3GPP as CUPS (Control/User Plane Separation). CUPS was introduced by 3GPP for 4G and 5G.

To satisfy mobility requirements in the core network, the controlling protocol running over the N4 interface between the control plane (SMF) and the User Plane Function (UPF) is not OpenFlow but the Packet Forwarding Control Protocol (PFCP).

The RAN's Access and Mobility Management Function (AMF) are linked to the 5G base station (gNBs), forming the RAN via the N2 interface. The gNBs are interconnected via the Xn interface. Mainly for access and handovers, the protocols over N2 and Xn are NGAP and XnAP, respectively, for the control plane and GTP-U for the user plane. Additional RAN controls and the virtualization of the controllers are not standardized and led to initiatives from operators and vendors to improve the RAN.

Virtualization techniques can be adapted to perform RAN enhancements. Virtualization technology separates the software from the hardware, i.e., the network and computing resources from the physical resources. The primary purpose of virtualization is to incorporate scalable and flexible solutions like efficient resource and cost management, load balancing, automatic scaling, operation and control procedures, and, it is often claimed to enable the introduction of Artificial Intelligence and Machine Learning based control. Virtualization allows MNOs to engineer the network by centralizing the network equipment to high-volume industrial servers, switches, and storage, among others, so-called Commercial Off-The-Shelf (COTS) equipment such as x86 physical machines or P4-devices. The centralized units, BBU, CU or even DU in the context of RAN, may reside at the data centers, and/or at so-called Point-of-Presence (PoP) or at or near the users premises, e.g., in the case of Private 5G [158].

B. Distributed RAN and Centralized RAN

The D-RAN concept is presented to understand basic virtualization. Each cell site is composed of isolated RRU and BBU subsystems in a D-RAN architecture. The RRU unit is connected to the assigned BBU through the FH connection using CPRI. Cells are equipped with radio functions and connected to the core network via the backhaul. Figure 13 presents the basic D-RAN architecture. Depending on the network requirements, network resources are allocated dynamically by the BBU [159]. The BBU, or more realistically, some parts of the BBU, may run on VMs. VMs and co-locating the BBUs led to the C-RAN architecture presented below.

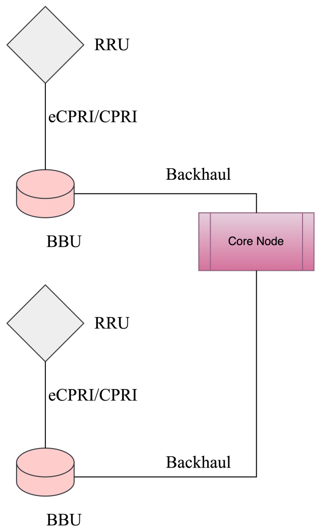

Fig. 13: D-RAN architecture: the classical setup with the antennas, RRU and BBU at each base station site. The short RRU-BBU fronthaul link remains proprietary although CPRI is used. The backhaul is connected to a core node, usually over optical fiber or point-to-point microwave link.

The fundamental of C-RAN architecture is to separate all BBUs from their RRU subsystems and move the BBUs to a centralized, shared, possibly virtual pool. The BBU subsystem is centralized in C-RAN. Each C-RAN cell site is composed of antennas and the RRU subsystems. Figure 4 shows the basic C-RAN architecture. In C-RAN, network-related resources are kept at the edge, at the RRUs, and the core functionalities reside in the BBUs in the cloud. As a result, C-RAN networks are more flexible and, in some cases, more accessible to deploy and maintain than the classic D-RAN if the FH bit rate is supported.

In generic terms, C-RAN implementations are based on Cloud Computing. Cloud Computing is the services provided by clusters of networked elements which may or may not be user-administered. In the context of cellular networks, Cloud Computing allows Mobile Network Operators to store large volumes of data generated by the devices and network while ensuring cost-effective sharing of required computing resources. In other words, C-RAN, like Cloud Computing, could ease the on-demand availability of the networked data for RAN optimization. Sharing the COTS computing power and storage between BBU and end-users seems evident initially but might be very challenging to implement practically and securely.

C-RAN, like Cloud Computing techniques, presents challenges such as increased latency, potential traffic congestion, increased data processing time (if the computing resource is unavailable), and communication costs. To mitigate some challenges of Cloud Computing, Virtualization, Edge-Computing, and Fog Computing could be presented as solutions.

C. Virtualized or Virtual RAN

MNOs migrate the data center to Mobile Edge Computing (MEC) to achieve high performance at the user end while supporting many devices. MEC reduces latency and offers high data capacity. They are incorporating NFV and SDN technologies with C-RAN to help virtualize the RAN functions and resources and are thus called "virtualized-C-RAN" or "vC-RAN". vC-RAN implementation is related to specific characteristics of the wireless access network, like time-varying channel conditions, interference, UE distribution, and mobility. Appropriate resource allocation, optimized interference management, etc., are challenging from the MNOs' perspective. The author from [160] proposed the concept of the virtualized base station to facilitate the virtualization of the computing resources of a BS in vC-RAN. The virtualized BS executes multiple protocol stacks of a BS in software while sharing the radio equipment at the hardware end. MNOs have been implementing techniques to achieve enhanced energy efficiency and decreased OPEX, as discussed in [160].

The virtual RAN (vRAN) isolates the software from the hardware by implementing the network virtualization functions. vRAN separates the RRU from BBU on a General-Purpose Processing (GPP) unit and implements functionalities in software. vRANs are composed of centralized pools of BBUs, virtualized RAN control functions, and optimized service delivery protocols. vRAN could offer several advantages over conventional RAN deployments, such as scalability, flexibility, faster upgrade cycles, resource pooling gains, and centralized scheduling.

D. Fog Radio Access Networks

Centralizing the BBUs far from the base station sites might raise concerns about optimizing local RAN problems such as handovers, local interferences, and services to static users.

Edge Computing and Fog Computing solutions have probably inspired the terms Mobile Edge Computing (MEC) mentioned earlier, and F-RAN presented very briefly. Fog Computing forms a distributed computing environment that enables storage and data processing at the network edge [161]. The RAN architecture that enables fog computing is known as Fog-RAN, F-RAN, or F-RAN [162], [163]. F-RAN aims to facilitate the processing the generated raw data at the computing units at the user end or closest proximity. Hence, FRAN forwards processed data instead of raw data, resulting in a decreased requirement for high bandwidth and QoS enhancement [164]. Thus, F-RAN, CRAN, HCRAN [38], [39], [165], and other cloud-based RAN will certainly be revisited and further improved. In the evolution of the RANs, the OpenRAN has gained particular attention. OpenRAN is discussed in the following section.

VI. Open Radio Access Networks

The terms Open RAN, OpenRAN, O-RAN, and ORAN can all be found in the literature. However, we cannot claim to present a unique definition for each of these terms. The industry-focused Telecom Infra Project (TIP) initiated an Open RAN MoU Group in 2020 to "supports the development of disaggregated and interoperable 2G/3G/4G/5G NR Radio Access Network (RAN) solutions based on service provider requirements", quoted from [166]. The O-RAN ALLIANCE was founded in February 2018 by AT & T, China Mobile, Deutsche Telekom, NTT DOCOMO, and Orange. It was established as a German entity in August 2018. Since then, O-RAN ALLIANCE has become a worldwide community of mobile network operators, vendors, and research & academic institutions operating in the Radio Access Network (RAN) industry", quoted from o-ran.org. The TIP OpenRAN and O-RAN ALLIANCE are joining forces to promote Open RAN.

A. Working Alliances and Groups

The O-RAN ALLIANCE [48] specifies open industrial standards for RAN interfaces that support interoperability. The preeminent intention for supporting new OpenRAN and vRAN architectures is to detach individual base station components and facilitate independent interactions. OpenRAN assures interoperable RAN elements, hardware, and software, from different vendors. Open RAN promotes 3GPP based vRAN architectures and provides MNOs with capabilities to overcome the challenges with proprietary hardware and software. The vRAN technologies aim to foster the development of OpenRAN standards by specifying open interfaces between the DU-CU and BBU. The DU/CU/BBU separation is based on the concept of the functional splits [167] and is claimed to enhance security and flexibility and reduce CAPEX and OPEX costs. The DU/CU/BBU separation should provide MNOs with opportunities to allocate the functional blocks to maximize performance. OpenRAN will empower smaller MNOs and vendors to introduce their services and network customization based on requirements and needs [48].

Different working alliances towards OpenRAN are mentioned in Figure 14 [168]–[173]. These individual alliances and collaborations mainly drive openness and interoperability in the RANs from 2G to 5G systems. The OpenRAN initiatives provide software and hardware solutions to support implementing an open and intelligent RAN. The O-RAN ALLIANCE specifications allow for building an open and modular RAN architecture based on 3GPP and disaggregated base station software. The O-RAN ALLIANCE has its own defined working groups to achieve the mission and vision of the Alliance. The different OpenRAN working groups are summarized in Figure 15 [174].

B. OpenRAN Architecture

According to [175], [176], OpenRAN focuses on three specific areas, namely: (a) separating the CU RAN from UP, (b) creating a modular or disaggregated base station software stack using COTS hardware, and (c) Open Interfaces. OpenRAN mainly defines the concept of open architecture, enabled by well-defined interfaces between the different elements of the RAN. OpenRAN also defines the integration of machine learning and artificial intelligence techniques in the RAN [177]. All OpenRAN components must support the same Application Programmable Interface (API), allowing OpenRAN-based 5G

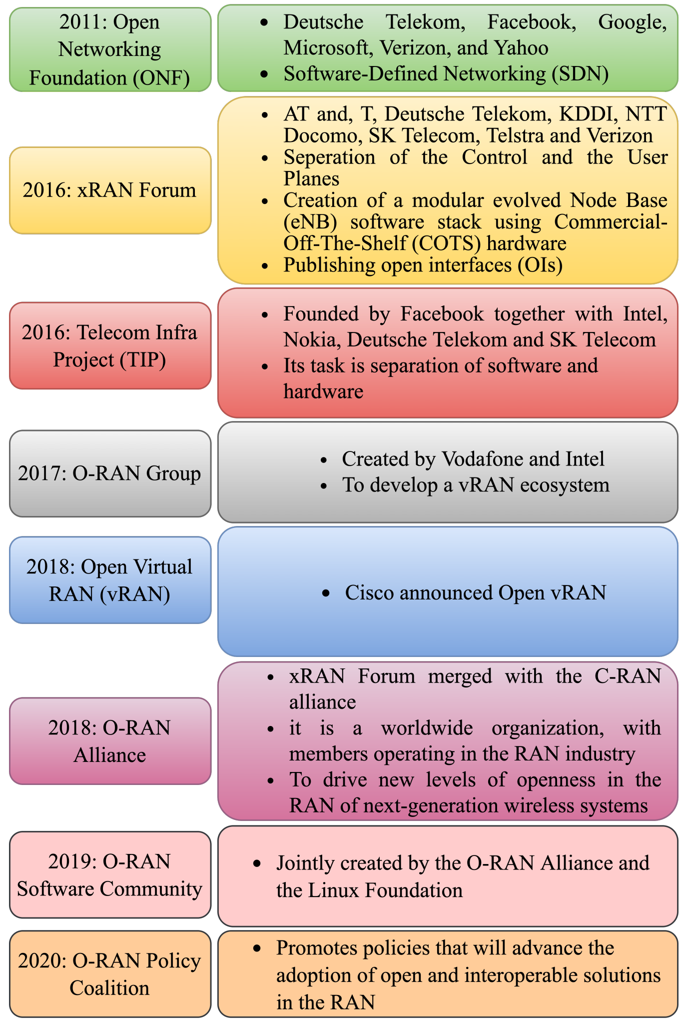

Fig. 14: Summary of initiatives and organization working towards OpenRAN architecture and infrastructure.

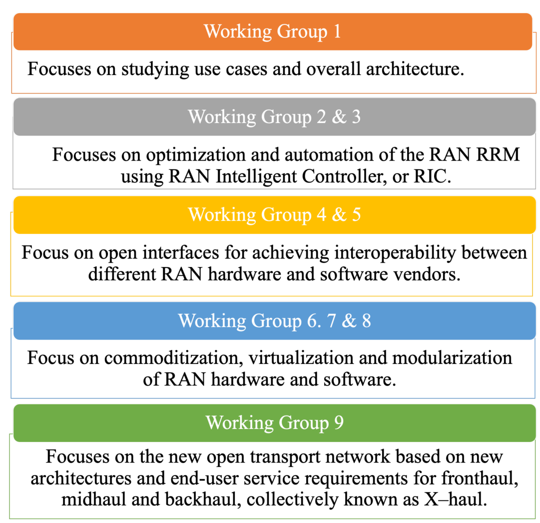

Fig. 15: Different OpenRAN working groups and associated tasks for developing new RAN architecture.

deployments to integrate elements from multiple vendors and make it possible to utilize COTS hardware.

In March 2019, the O-RAN ALLIANCE defined the functional splits between the BBU and RRU to embed FH functional requirements. The O-RAN ALLIANCE defined a reference architecture to support next-generation open virtual RAN infrastructures with intelligent radio [48]. The reference architecture describes well-defined interfaces to facilitate an open, interoperable supply chain ecosystem with respect to the 3GPP and other industry standards organizations. Figure 16 shows the reference OpenRAN architecture.

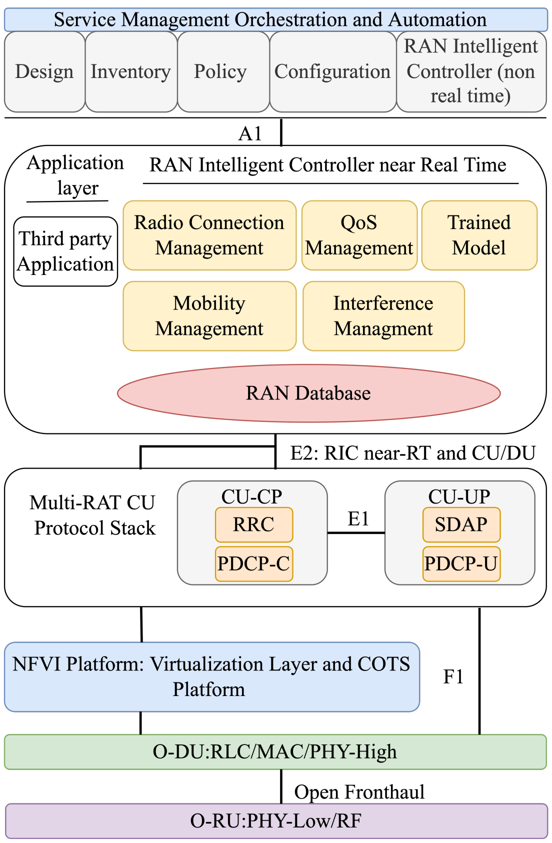

Fig. 16: OpenRAN architecture as defined by the O-RAN ALLIANCE to achieve an OpenRAN infrastructure.

The splits of the O-RAN architecture are basically organized as follows:

- **For the fronthaul** - the 3GPP split 7.2 or Low Layer split between the so-called O-RU and O-DU (O for O-RAN);
- **For the midhaul** - the 3GPP split 2 or PDCP/split between the O-DU and O-CU. Note that the CU-CP (Control Plane) and the CU-UP (User Plane) are explicitly mentioned in the O-RAN architecture.

Similarly in essence to an SDN architecture, the forwarding elements (O-DU, O-CU-CP and O-CU-UP) are controlled by two so-called RAN Intelligent Controllers (RICs). Two RICs are needed to take into account two time scales required for efficient RAN functions, as follows:

- A near-Real Time (near-RT) RIC to handle control from 0.1 to 1 second;
- A non-Real Time (non-RT) RIC to handle control above 1 second.

O-RAN ALLIANCE advocates the use of virtualization. Hence, it specifies the so-called Service Management and Orchestration Framework, which contains the non-RT-RIC function. The non-RT-RIC communicates with the near-RT RIC, with an interface called A1, and with the O-DU and O-CUs, via O1. The near-RT control and optimization of OpenRAN elements and resources are performed through compact data collection and control over a new E2 interface (not specified by 3GPP for the DUs and CUs). The non-Real Time RIC implements control and optimization of RAN elements and resources. The non-Real Time RIC is anticipated to incorporate specific AI/ Machine learning (ML) workflow, which involves training modules and provides policy-based guidance for applications in the non-RT-RIC [177].

The O-CU element handles the RRC for the control plane and the Service Data Adaption Protocol (SDAP) for the user plane and the PDCP. The O-CU-CP hosts the RRC and the control-plane part of the PDCP protocol, while the O-CU-UP hosts the SDAP protocol and the user-plane part of the PDCP protocol. The PDCP streams are exchanged to the O-DU via the MH, which could be physically or virtually almost anywhere in the Open Cloud. MH distances up to 80 km have been reported earlier in this survey, but it remains to be seen how vendors, service providers and operators use O-RAN for their use cases.

The O-DU contains the RLC/MAC/High-PHY layers. The O-RU contains the Low-PHY layer and RF processing based on a lower layer functional split. The fronthaul link (RU-DU link specified by the so-called LLS-C/U/S interface) should be less than about 20 km, as reported in the first figure of this survey.

The virtualization platform, or Open Cloud, which hosts the O-DU, O-CU, and RICs, should handle the multi-RAT CU protocol stack and support many protocol processing for 4G or 5G. The virtualization platform isolates the blocks and performs virtual resource allocation [48]. Obviously, a lot of work remains for the operators and vendors to implement and exploit the O-RAN ideas. Major operators and vendors are working hard to make intelligent RAN a reality.

C. OpenRAN Opportunities

OpenRAN benefits from the advancing RAN architectures toward interoperability and intelligence. OpenRAN holds enormous opportunities for both the user and the operators. OpenRAN defines new technical solutions and business models to tackle in- creasing costs, complex deployments, and many more by incorporating software and hardware disaggregation through open interfaces [178]. In the white paper published by O-RAN ALLIANCE on use cases and deployment scenarios [179], an initial set of OpenRAN use cases is introduced, which benefits from the advances in open architectures and shows high business value. The OpenRAN ecosystem utilizes AI and ML capabilities at the back-end blocks of the architecture to facilitate an open and intelligent multi-vendor network.

In real-time, ML and AI algorithms are applied to manage and control RAN performance, configurations, and optimization for the envisaged use cases in target deployment scenarios. The use cases are categorized based on the application area, and requirements [179].

Each use case has its focus area, well-defined purposes, and requirements [179]. The concept of white-box hardware as the base site will motivate an economical 5G deployment. The so-called white-box Base Stations focus on UL and DL processing, RF conversions, and gateways. Most of the use cases are defined based on the incorporated AI techniques. They cover comprehensive range of applications, from traffic steering, Service Level Agreement (SLA), dynamic handover management for Vehicle-to-Everything (V2X) to enhanced user services and experiences through optimized resources. Within various Unmanned Aerial Vehicles (UAVs)-based use cases, applications are introduced envisaging OpenRAN and open interfaces. The context-based dynamic handover management for the V2X use case focuses on supporting frequent handover requests in high-speed heterogeneous environments. A summary of the categorized use cases is presented in Figure 17. The O-RAN ALLIANCE website hosts many impressive demonstrations of current and future OpenRAN capabilities [180].

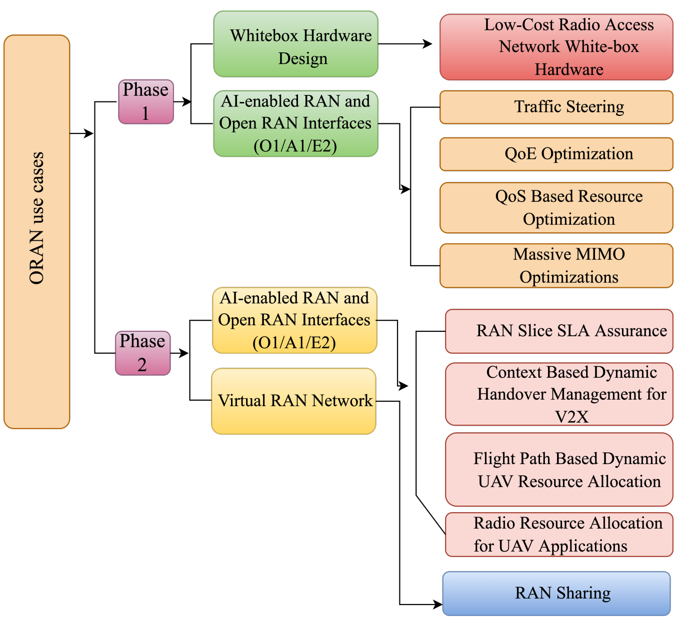

Fig. 17: Summarized OpenRAN use cases criterion as defined by the ORAN ALLIANCE to validate OpenRAN development.

D. Open RAN Cloudification and Orchestration Platform

The O-RAN ALLIANCE has defined and sketched requirements for open cloud architecture and various deployment scenarios, as discussed in [179]. The so-called Open-Cloud (OCloud) is an O-RAN cloudification and orchestration platform that classifies deployment options to expedite the cloudification of OpenRAN virtualized network elements. The OCloud provides a cloud computing platform encompassing physical nodes to execute applicable functionalities related to management and orchestration. The orchestration facilitates BBU resource pooling and cloudification, which should help maximize the operational improvement/cost ratio.

1) OCloud Architecture: OpenRAN cloudification architecture is based on the reference architecture provided by ETSI NFV Architectural Framework [181], which includes appropriate COTS hardware that enables abstraction through virtualization. The ETSI NFV Architectural Framework implements VM on the servers that facilitate Virtual Network Functions (VNFs) in the cloud. The Virtual Infrastructure Manager (VIM) acts as the control plane in OCloud and manages different servers as a single distributed system [179]. The VNFs mainly provide the interfaces and virtualized open planes (O-DU, O-CU, NRT-RIC), along with the MEC applications and the 5G User Plane Function (UPF).

2) OCloud Deployment: OCloud defines a hierarchical deployment model comprising different modules, like regional cloud and edge cloud, hosted at independent or dependent levels. Figure 18 presents a hierarchical cloud deployment where each Edge Cloud, monitoring individual cell sites, is connected to the Regional Cloud (different traffic flows are represented by different colours). The VNFs are either implemented in the proprietary network element or on the OCloud component. Based on the different deployment scenarios in [179], the functionalities and hosting of O-DU and O-CU vary.

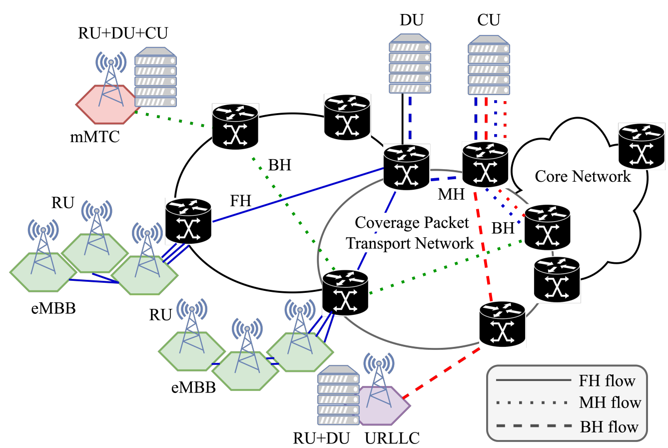

Fig. 18: A typical layout of a RAN infrastructure [6], [182].

E. Implementation Challenges

One of the main challenges in O-RAN is to integrate the multi-vendor model and seamless interoperability between the services and the equipment they provide. The RAN virtualization can bring concerns about the capacity of the FH link in order to host several virtual BSs while maintaining the latency requirements between the RRH and BBUs. Implementing the functional splits can be challenging, affecting the FH network's bit rate and latency.

Open architecture also imposes several challenges on security aspects at various levels. The OpenRAN standards and 3GPP specifications have evolved in hand to facilitate RAN-functional splits resulting in RAN virtualization. At the deployment and implementation side, there is stil a gap on clearly defining vRAN specifications and on how the software and hardware parts are deployed [45].

RAN virtualization to support high data rate, low latency and high availability 5G and beyond requirements are certainly very challenging for researchers and practitioners.

VII. Conclusion

This survey comprehends an extensive literature review on different functional splits proposed by 3GPP and the O-RAN ALLIANCE. A practical approach to the functional split requirements and implementation was provided. As a result of RAN splitting and virtualization, network deployments are more flexible and facilitate the creation of a multi-vendor marketplace for different radio and network components that are different from the traditional business models. By creating various interfaces between layers through splitting, new hardware and software products can be designed and fabricated while guaranteeing interoperability between elements produced by different manufacturers. The main advantages, disadvantages, and challenges are discussed. Each functional split is described in detail, and the underlying challenges are identified. Broadband access will be enhanced, and ultra-reliable low latency communications (URLLC) and massive Machine Type Communications will be supported. URLLC will enable applications like self-driving cars or coordinated autonomous UAVs, e.g., in a disaster-resilient swarm of coordinated drones participating in rescue missions. Expected 5G and beyond reliability and resilience are commonly cited to enable remote surgeries with physicians commanding high-precision robots from remote hospitals in real-time and to support high-speed nano-robot communications for in-body healthcare applications. More realistically, 5G and beyond will serve the needs of the industry 4.0 and beyond.

Moving the processing functionalities from the RRHs to the DUs and CUs may be advantageous as the RAN architecture evolve and leads to an economy of scale. Many functional splits, serving various use cases, have been devised but have limitations. For example, the 3GPP split option 8 requires a data rate much higher than the total user data rate and a distance between CU and DU lower than 20 km. The split option 7.2 has been preferred by the O-RAN ALLIANCE. Different splitting implies different data rates and latency requirements.

For example, to implement split option 6, the PHY and RF are in the DU, while the MAC is in the CU. The MAC layer performs functionalities like the computation/calculations and operations in CU considering software, whereas the RF (DU) takes care of the rest of the functionalities, resulting in high hardware costs.

Various standardization bodies are actively working to provide energy-efficient, reliable, and economic solutions by allowing BBUs to support multi-RF units.

The final part of the survey discussed the RAN evolution from C-RAN to OpenRAN. The virtualization functions have been examined. The O-RAN ALLIANCE architecture was discussed while addressing how it may serve future stakeholders for 5G and beyond RAN. The O-RAN ALLIANCE intends to support diversified 4G to 5G and beyond use cases by developing the specifications and architectures with new open interfaces to control the DU and CU with the so-called RAN Intelligent Controller. State-of-the-art technologies for incorporating various split options were discussed. Some relevant solutions allow splitting, such as split eight implementations using FPGA (hardware) [52], [53], gNodeB from ISW (software) [55] have been presented. The ISW-gNodeB consists of independent network functions to implement PHY, MAC, RLC, PDCP, SDAP, RRC, and NRAP protocols.

The survey shed light on the various RAN architectures and deployment scenarios, providing a vision of the functional splits, underlying opportunities, and evolution challenges. We provided detailed literature to justify the emergence of functional splits as an enabler for beyond 5G networks. In addition to the overview of functional splits, we also summarized the concept of virtualization and O-RAN ALLIANCE architecture. However, we did not address Massive MIMO, CoMP, and mmWaves, concerning functional splits in the scope of this survey.

Academia, industry, and research organizations are working toward an OpenRAN infrastructure to support RAN disaggregation. The O-RAN ALLIANCE implements different intelligent processing algorithms to deploy flexible, and economic networks. Integrated access backhauling, edge processing with cloud and virtualized (also Fog) RAN are certainly open research areas that have the potential to incorporate intelligence into the network while supporting 5G second phase and 6G deployments.

VIII. Acronyms

3GPP	3rd Generation Partnership Project
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
AI	Artificial Intelligence
AMF	Access and Mobility Management Function
API	Application Programmable Interface
ARQ	Automatic Repeat Request
BB	Base Band
BBU	Base Band Unit
BS	Base Station
BH	Backhaul
CA	Carrier Aggregation
CAPEX	Capital Expenditure
CoMP	Coordinated Multi-point
COTS	Commercial-Off-The-Shelf
CP	Control Plane
CPRI	Common Public Radio Interface
C-RAN	Centralized Radio Access Network
CU	Centralized Unit
CV	Compensation Value
DC	Dual Connectivity
DL	Downlink
D-RAN	Distributed RAN

DU Distributed unit
DWDM Dense Wavelength Division Multiplexing
eCPRI Enhanced Common Public Radio Interface
eRE eCPRI Radio Equipment
eREC eCPRI Radio Equipment Control
E-UTRA Evolved Universal Mobile telecommunications
ETSI European Telecommunications Standards Institute
FCAIS Fault Configuration Accounting Performance and Security
FEC Forward Error Correction
FFT Fast Fourier Transform
FH Fronthaul
FHI Fronthaul Interface
FPGAs Field Programmable Gate Array
F-RAN Fog RAN
GPP General Purpose Processing
gNB gNodeB
GTP-U General Packet Radio Service Tunnelling Protocol
HARQ Hybrid Automatic Repeat Request
HRAN Heterogeneous Cloud RAN
IFFT Fast Fourier Transform
IP Internet Protocol
IQ In-phase and Quadrature
ISW IS-Wireless
ISG Industry Specification Group
ITU-T International Telecommunications Union - Telecommunications Sector
LTE Long Term Evolution
MAC Media Access Control
MEC Mobile Edge Computing
MH Midhaul
MIMO Multiple-Input Multiple-Output
ML Machine Learning
MNO Mobile Network Operator
NETCONF Network Configuration
NF Network Functions
nFAPI network Functional Application Platform Interface
NFV Network Functions Virtualization
NGMN Next Generation Mobile Networks
NG-RAN Next Generation RAN
NR New Radio
NRT Near-Real-Time
nRT non-Real-Time
OAI Open Air Interface
O-CU-CP OpenRAN Central Unit Control Plane
O-CU-UP OpenRAN Central Unit User Plane
O-DU OpenRAN Distributed Unit
ONF Open Networking Function
OpenRAN Open Radio Access Network
OPEX Operational Expenditure
O-RAN OpenRAN ALLIANCE
O-RU Open Radio Unit
PDCCH Physical Downlink Control Channel
PDCP Packet Data Convergence Protocol
PDSCH Physical Downlink Shared Channel
PDUs Protocol Data Units
PFCP Packet Forward Control Protocol
PHY Physical
PLFS Physical Layer Frequency Signals
PNF Physical Network Function
PoP Point-of-Presence
PRACH Physical Random Access Channel
PRBs Physical Resource Blocks
PTP Precision time Protocol
PUCCH Physical Uplink Control Channel
PUSCH Physical Uplink Shared Channel
QoS Quality of Service
RAN Radio Access Network
RAT Radio Access Technology
RE Resource Element
RF Radio Frequency
RH Remote Head
RIC RAN Intelligent Controller
RLC Radio Link Control
RoE Radio over Ethernet
RRC Radio Resource Control
RRM Radio Resource Management
RRH Remote Radio Head
RRU Remote Radio Unit
RTT Round Trip Time
RU Radio Unit
SDAP Service Data Adaption Protocol
SDN Software- Defined Networking
SDU Service Data Unit
SLA Service Level Agreements
SMF Session Management Function
SON Self-Organizing Networks
SR Sample Rate
srsLTE Software Radio Systems LTE
SSH Secure SHell
SyncE Synchronous Ethernet
TCP-IP Transmission Control Protocol/Internet Protocol
TDM Time Division Multiplexing
TIP Telecom Infra Project
TTI Transmission Time Interval
TTM Time-to-Market
UAV Unmanned Aerial Vehicle
UE User Equipment
UL Uplink
UPF User Plane Function
URLLC Ultra-Reliable and Low Latency Communications
V2X Vehicle-to-Everything
vBBU Virtual BBU
vC-RAN virtualized - C-RAN
VM Virtual Machine
vRAN virtualized Radio Access Network
WDM Wavelength Division Multiplexing

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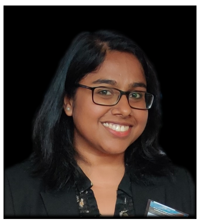

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