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REVIEW

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Realizing 5G vision through Cloud RAN: technologies, challenges, and trends

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Abstract

Achieving the fifth-generation (5G) vision will introduce new technology innovations and substantial changes in delivering cutting-edge applications and services in current mobile and cellular networks. The Cloud Radio Access Network (C-RAN) concept emerged as one of the most compelling architectures to meet the requirements of the 5G vision. In essence, C-RAN provides an advanced mobile network architecture which can leverage challenging features such as network resource slicing, statistical multiplexing, energy efficiency, and high capacity. The realization of C-RAN is achieved by innovative technologies such as the software-defined networking (SDN) and the network function virtualization (NFV). While SDN technology brings the separation of the control and data planes in the playground, supporting thus advanced traffic engineering techniques such as load balancing, the NFV concept offers high flexibility by allowing network resource sharing in a dynamic way. Although SDN and NFV have many advantages, a number of challenges have to be addressed before the commercial deployment of 5G implementation. In addition, C-RAN introduces a new layer in the mobile network, denoted as the fronthaul, which is adopted from the recent research efforts in the fiber-wireless (Fi-Wi) paradigm. As the fronthaul defines a link between a baseband unit (BBU) and a remote radio unit (RRU), various technologies can be used for this purpose such as optical fibers and millimeter-wave (mm-wave) radios. In this way, several challenges are highlighted which depend on the technology used. In the light of the aforementioned remarks, this paper compiles a list of challenges and open issues of the emerging technologies that realize the C-RAN concept. Moreover, comparative insights between the current and future state of the C-RAN concept are discussed. Trends and advances of those technologies are also examined towards shedding light on the proliferation of 5G through the C-RAN concept.

Keywords: 5G, Cloud Radio Access Network, Common Public Radio Interface, Network function virtualization, Software-defined networking

1 Introduction

Mobile networks are rapidly evolving while the industry is struggling to keep up with the rising demand of connectivity, data rates, capacity, and bandwidth. By 2021, it is estimated that 10 billion devices will be connected to mobile networks worldwide [1], while the global data traffic will rise to 49 EB per month. Future fifth-generation (5G) mobile networks are designed considering the following fundamental requirements: massive connectivity, different traffic types, extremely high data rates, very high capacity, support for applications and services with very diverging requirements, energy-efficient communications, and flexible and effective spectrum utilization.

Previous generations of mobile networks included standard deployment schemes and fixed radio parameters (e.g., frequency and power). However, 5G introduces substantial changes on many levels. It utilizes a broader spectrum, using multiple access technologies, new deployment schemes (e.g., ultra-dense heterogeneous deployment), and advanced waveforms combined with novel coding and modulation algorithms.

The rapid proliferation of smart devices, along with the exponential rise in data traffic, creates a significant burden on current mobile networks. As current mobile network capacity is reaching its Shannon limit, operators try to satisfy these requirements by deploying more base stations (BSs), creating thus a complex structure of ultra-dense

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heterogeneous networks. However, the mass deployment of ultra-dense BSs increases operators' capital expenditure (CAPEX) because of the costs for site acquisition, planning, and hardware equipment, as well as operating expenditure (OPEX) due to maintenance and power usage costs. As legacy Radio Access Network (RAN) is becoming expensive and inadequate in satisfying the demands of future mobile trends, mobile operators are faced with the challenge of devising new RAN architectures.

Concepts such as cloud computing and virtualization technologies are of paramount importance [2–4] since they are deemed as candidate enablers for the new RAN technologies. Cloud computing is a compelling concept for enabling ubiquitous and on-demand access to a shared pool of scalable computing resources (e.g., network, storage, and applications). Virtualization is realized through two complementary technology concepts: network function virtualization (NFV) [5, 6] and software-defined networking (SDN) [7, 8]. SDN enables network programming and provides network intelligence, while NFV leverages virtualization technologies to virtualize network functions.

Cloud-RAN (C-RAN) [9–11] is an innovative RAN technology based on the aforementioned concepts. In C-RAN, operators can deploy mobile networks more rapidly using different access technologies while sharing the same infrastructure. To this end, the deployment cost is reduced, the network resources are effectively utilized, and the maintenance cost is low.

This work aims at presenting the key points of the C-RAN architecture subject to the latest technologies and challenges. The C-RAN enabling technologies have been extensively investigated in multiple studies. However, to the extent of our knowledge, this is the only work that compiles the challenges and open issues of all C-RAN components with respect to the 5G mobile networks. The rest of the paper is organized as follows. Table 1 lists all the acronyms used throughout the article. Background concepts related to the C-RAN implementation are presented in Section 2. Section 3.1 provides an overview of C-RAN architecture and identifies its key components. Section 3.2 presents C-RAN state-of-art implementations. In Section 3.3, research challenges and open issues are discussed on C-RAN developments. Section 3.4 discusses future trends and advancements. Finally, Section 4 concludes this paper.

2 Background

This section is devoted to presenting the background of the four main technologies behind C-RAN, namely the SDN concept, the NFV technology, the network virtualization and slicing, and the Common Public Radio Interface (CPRI) [12] which is the most widely used fronthaul interface in the C-RAN architecture.

Table 1 List of acronyms

Acronym	Definition
5G	Fifth generation
A/D	Analog to digital
API	Application programming interface
BBU	Baseband unit
BS	Base station
CAPEX	Capital expenditure
CN	Core network
CoE	CPRI over Ethernet
CoMP	Coordinated multipoint
CPRI	Common public radio interface
C-RAN	Cloud radio access network
D/A	Digital to analog
ETSI	European telecommunications standards institute
FFT	Fast fourier transform
F-RAN	Fog RAN
HARQ	Hybrid automatic repeat request
H-RAN	Hybrid RAN
IIoT	Industrial Internet of Things
IoT	Internet of Things
ISG	Industry specification group
KPI	Key performance indicator
LTE	Long-Term Evolution
MIMO	Multiple input-multiple output
mmWave	Millimeter wave
NFV	Network function virtualization
NFV MANO	NFV management and orchestration
NFVI	NFV infrastructure
OFDM	Orthogonal frequency-division multiplexing
ONOS	Open network operating system
OPEX	Operating expenditure
ORI	Open radio interface
RAN	Radio access network
RE	Radio equipment
REC	Radio equipment controller
RF	Radio frequency
RRU	Remote radio head
SDMN	Software-defined mobile network
SDN	Software-defined networking
T-SDN	Transport SDN
VBBS	Virtual big base station
VBS	Virtual base station
VNF	Virtualized network function
WDM	Wavelength-division multiplexing
WSN	Wireless sensor network

2.1 Software-defined networking

SDN has been primarily introduced for datacenter usage, aiming to deliver flexibility in network deployment, operation, and management [13]. The rationale behind SDN is twofold: it separates the data plane from the control plane and it introduces novel network control functionality based on abstract network representation. The control decisions are removed from the hardware, and the network intelligence is logically centralized. Network management and operation are simplified through SDN, as forwarding and routing instructions are configured by SDN controllers.

An overview of the SDN architecture is shown in Fig. 1. The application plane consists of the network applications (e.g., monitoring and security) and communicates with the control plane through the northbound interface. The control plane consists of the SDN controllers (e.g., Open Network Operating System (ONOS) [14] and OpenDayLight [15]) which govern the network devices. The devices are resided in the data plane. The communication between control and data planes is accomplished through the southbound interface. OpenFlow [16] is a widely adopted protocol for control and data plane communication. The data plane consists of switches and routers which forward the packets based on the configuration sent from the controllers.

2.2 Network function virtualization

Network function virtualization (NFV) is an emerging paradigm, which aims at offering new ways in designing, deploying, and managing modern network services [17]. The main idea behind the NFV concept is to leverage virtualization technologies and decouple, thus, the network functions from the physical equipment that accommodates them. This approach enables the concentration of network equipment and services in data centers, where network functions run as software applications on general-purpose processor platforms. Furthermore, network functions can be relocated at different network locations without purchasing and installing new network equipment.

NFV architecture is shown in Fig. 2. A virtualized network function (VNF) is an implementation of a network function (e.g., router and firewall) deployed on virtual resources provided by the NFV infrastructure (NFVI). The NFVI contains the hardware and software resources in which VNFs are deployed. It is composed by virtual and physical resources of storage, computation, and network. The hypervisor is responsible for the mapping between the virtual and physical domains. The NFV management and orchestration (NFV MANO) [18] framework is responsible for VNF management and mapping between virtual and physical resources.

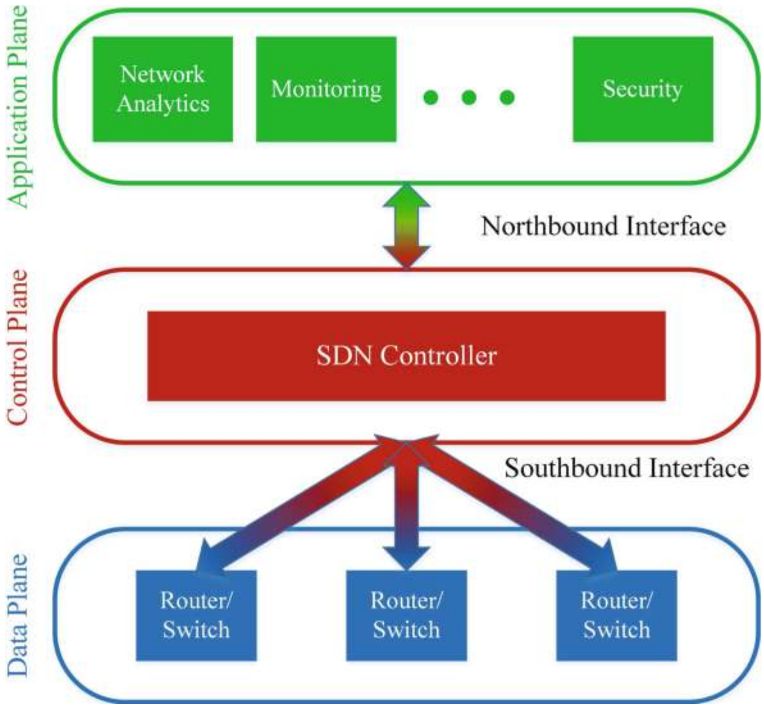

Fig. 1 SDN architecture in a three-layer approach

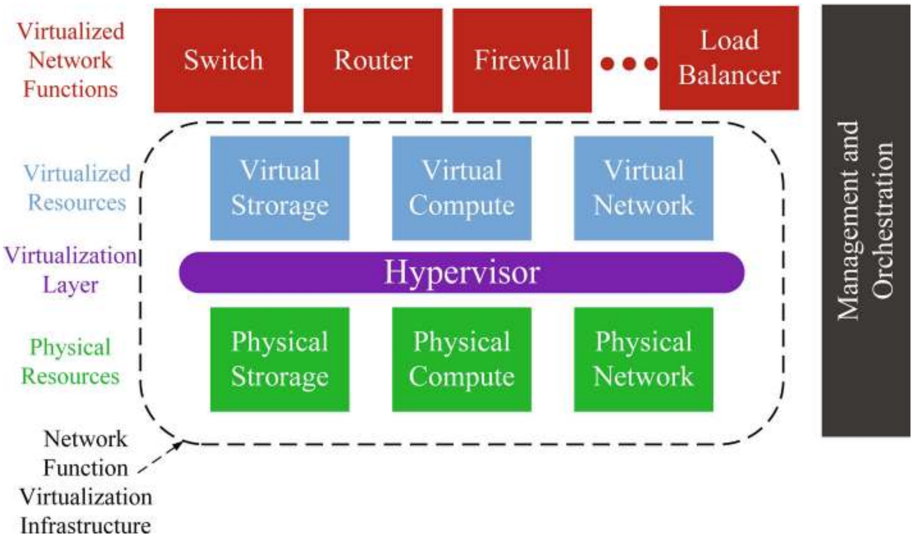

Fig. 2 NFV architecture

2.3 Network virtualization and slicing

Network virtualization allows operators to form their own virtual networks. This is achieved through the concept of network slicing, which allows network operators to create end-to-end virtual networks which share the same physical infrastructure. A network slice is a virtual network created on top of a physical infrastructure in a way that the network operator believes that it performs on its own dedicated physical network.

The heterogeneity of modern service requirements are illustrated in Fig. 3. Five key characteristic application scenarios are highlighted, namely sensor, vehicular, industrial, smartphone, and health paradigms. In addition, five key metrics are presented subject to the aforementioned scenarios, namely end-to-end latency, data rate, bandwidth, mobility, and number of connections per cell. Sensor applications require a massive number of connections, very low data rate and bandwidth, and very low mobility. On the contrary, vehicular applications require support for very frequent handovers. Industrial applications are characterized by extremely low latency and high data rate and bandwidth. Smartphones are the most widely used scenario with high overall requirements. Health applications are an important category, containing critical applications. They are characterized by low latency, medium bandwidth and data rate, and low mobility.

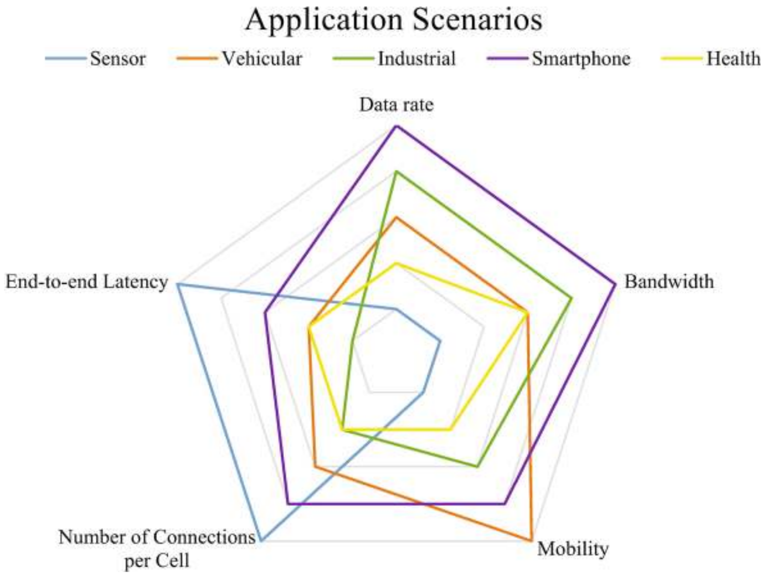

Fig. 3 Application scenarios

Figure 3 highlights the necessity of incorporating network slicing, as virtual networks tailored to specific requirements have better performance than typical multipurpose networks. Moreover, a network slice can be modified, depending on service requirements and number of users. Slices are also isolated to each other, which enhances reliability and security, as configurations of different slices do not affect each other.

2.4 Common Public Radio Interface

CPRI is the standard interface that enables the communication between the radio equipment (RE) and the radio equipment controller (REC) [19]. Point-to-point fiber is the most used physical transport technology for CPRI due to its low cost and ease in installation. Data are transmitted in the form of in-phase and quadrature signal (I/Q) flows, where each flow reflects the sampled and digitized radio signal of one carrier at one antenna element. The standard specification defines hierarchical framing with three layers so as to match the 3GPP Long-Term Evolution (LTE) framing. The first layer is a CPRI basic frame, which is transmitted every $TC = 260.416$ ns, based on the 3.84-MHz clock rate. This basic frame consists of 16 words, where word length depends on the CPRI configuration. The second layer is known as hyper-frame. It is a collection of 256 basic frames transmitted every $256 \times TC = 66.67$ ms, which is the LTE symbol time [20], using orthogonal frequency-division multiplexing (OFDM) [21]. Finally, the third layer is a collection of 150 hyper-frames, which are created every 10 ms. The third layer carries the I/Q samples of a whole LTE frame.

3 Review

3.1 Cloud-RAN

C-RAN is based on the concepts of centralization and virtualization. It intends to improve the overall network performance. It also reduces expenditures by leveraging the network resources. Using cloud servers, operators can scale up their deployments more rapidly, allowing different radio access technologies to share the same physical network infrastructure. The rest of this section provides an overview of the C-RAN architecture, its components, and the advantages over traditional RAN.

In a C-RAN architecture, the LTE base station consists of the baseband unit (BBU) and the remote radio head (RRH). The BBU performs baseband processing and provides higher layer functionality and communication with the core network. The RRH is responsible for radio functions, signal processing, modulation, analog-to-digital (A/D) and digital-to-analog (D/A) conversion, and power amplification.

The basic C-RAN architecture consists of three main parts: the BBUs, the RRHs, and the fronthaul. The C-RAN architecture is shown in Fig. 4. BBUs are virtualized and centralized into one entity called BBU pool, which is often located at a data center, while RRHs are located at remote sites. A RRH is not attached to a single BBU and can be logically connected to any BBU from the BBU pool. The BBU pool consists of many BBUs which are deployed on servers with high-processing power. The BBUs operate as virtual base stations (VBSs), which perform the baseband processing functions (e.g., fast Fourier transform (FFT)/inverse FFT, modulation/demodulation, encoding/decoding, radio scheduling, hybrid automatic repeat request (HARQ) management, and radio link control). These functions are software defined and they run as applications. Data from the BBU pool are transported to the RRHs through a low-latency and high-bandwidth interface called fronthaul.

RRHs transmit the RF signals to UEs, and they are responsible for radio frequency (RF) amplification, filtering, and A/D and D/A conversion. As most of the processing functions are executed in the BBU pool, RRHs are relatively simple and can be widely deployed in a cost-efficient manner.

In the initial C-RAN architecture, almost all baseband functionalities are moved to BBUs, while the RRHs act as a simple RF front-end. This split can achieve the highest processing gain but requires very high fronthaul bandwidth. Rather than offloading all baseband processing to the BBU, it is possible to keep a subset of these functions in the RRH [22]. The split can occur on any protocol layer. However, there are certain timing and capacity requirements on inter-layer communication. The fronthaul link is a critical factor influencing the split level. Higher link quality and capacity allow a higher degree of centralization, by moving more of the lower layer functions to the cloud. This means that a trade-off between full centralization and fronthaul requirement satisfaction appears. C-RAN has several advantages over traditional RAN as described below:

Advanced processing techniques: As BBUs are located in powerful data centers, they have access to higher processing resources. Advanced processing techniques can be easily implemented by leveraging these processing resources. Coordinated multipoint (CoMP) [23] processing is an effective technique to increase signal-to-interference-plus-noise ratio (SINR), mitigate interference, and improve overall network throughput.

In [24], the authors aim to mitigate cell edge interference by adopting a clustered CoMP transmission scheme. Another approach to mitigate interference, by dividing low- and high-mobility devices into clusters, was presented in [25]. The authors in [26] proposed an optimization framework for interference processing. In particular, the radio interference processing is formulated as short-term precoding and long-term user-centric RRH clustering sub-problems. Hekrdla et al. [27] proposed a novel

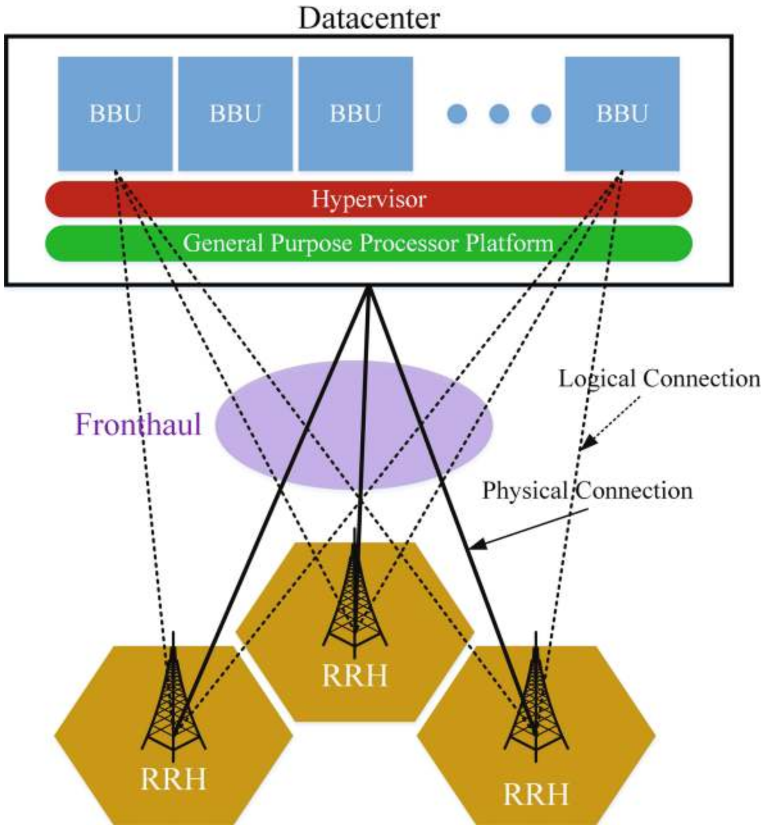

Fig. 4 C-RAN architecture

mechanism between multiple operators for downlink interference cancellation precoding. Inter-operator interference is canceled by adopting the regularized block diagonalization precoding to avoid user-sensitive data exchange between operators. Intra-operator interference is mitigated using Tomlinson-Harashima precoding with transmission power control.

BBU scaling: BBUs are dynamically scaled according to the network requirements. For example, when there is an increase in network traffic, a virtual BBU can be scaled up to utilize more computing resources. In addition, in case of future network extensions, more virtual BBUs can be instantiated. A novel resource optimization algorithm which takes into account thermal and computing resource models was developed in [28]. Optimization is achieved by allocating the maximum load to BBU under thermal constraints. The optimization problem is solved using Lagrange multiplier with Kuhn-Tucker condition. In [29], Zhang et al. aimed at minimizing the total amount of computing resources needed, while balancing the allocated computing resources among BBUs. The optimization is formulated as a bin-packing problem and solved using a heuristic genetic algorithm.

The authors in [30] studied the minimization of the number of active BBUs that are required to serve the users. They consider the problem as a special case of multidimensional bin-packing problem, where each BBU is viewed as bin and each virtual machine is viewed as item. A similar approach was presented in [31]. The authors solve the bin-packing problem using the best-fit decreasing method, by jointly considering RRH resources and BBU scheduling.

Pompili et al. [32] proposed an elastic resource utilization framework that aims to satisfy fluctuations in per-user capacity demands. They also introduced the idea of BBU clustering and discussed its advantages. The authors in [33] proposed a scheme for inter-BBU load balancing in the BBU pool. The scheme involves a controller which implements the inter-BBU management based on BBU load threshold.

Energy efficiency: By having BBUs located at the data centers, the overall network energy consumption is decreased. This is attached to the fact that the cell sites only include the RRHs, which have limited energy consumption. Energy efficiency can also be increased by dynamically managing (e.g., activation and operation) BBUs depending on the data traffic demand and network load [34, 35]. Joint power control and user scheduling techniques can highly augment energy efficiency as well [36]. Yu et al. [37] formulate the C-RAN energy saving problem as a joint resource provisioning problem. Based on the traffic load, users and BBUs are assigned to specific RRHs, so the energy consumption of the entire system is minimized. The authors in [38] proposed a BBU-RRH assignment scheme that improves energy efficiency based on graph partitioning and rejoining. Also, ultra-dense deployment reduces the distance between RRH and user, leading to high achievable data rates with low power consumption [39]. The work in [40] presented a tunable distance-based power control mechanism, which improves energy efficiency by reducing the energy consumed in the network nodes.

An energy-efficient algorithm through the cloud-based workload consolidation model was proposed in [41]. In the proposed algorithm, workloads are distributed among virtualized BBUs that operate at full utilization, while idle ones are turned off to reduce energy consumption. The authors in [42] focused on network energy efficiency through dynamic RRH activation and sparse beamforming. In particular, they transform the energy efficiency maximization problem into a concave-convex functional program based on weighted minimal mean square error technique and group sparsity theory.

Li et al. [43] designed a novel energy effective deployment scheme. The proposed scheme dynamically selects a subset of RRHs according to traffic demand and RRH capabilities. The RRH subset determination problem is formulated as a multi-choice, multidimensional knapsack problem. The work in [44] formulated the RRH selection problem as a trade-off between the minimization of power consumption and transmission power, while satisfying a series of network constraints (i.e., spectrum limitations and traffic requirements). An efficient local search algorithm was also proposed to address the formulated problem.

Resource scaling: In order to achieve optimal spectrum efficiency, mobile devices should be attached to the BS at the best link quality [45]. C-RAN enables ultra-dense RRH deployment, providing mobile devices with more options for connection, while enabling reuse of time-frequency resources. Provisioning of wireless resources is optimally adapted to the actual needs of operators and subscribers. By exploiting centralized network intelligence, real-time resource allocation can be implemented in order to adapt to network conditions and user needs [46].

Aiming to improve spectrum efficiency and decrease interference, the authors in [47] proposed a joint clustering and spectrum sharing scheme. They group virtualized BSs into clusters and divide the frequency band into 13 sub-bands. The sub-bands are allocated to mobile devices based on their position.

The authors in [48] proposed a novel approach based on a coalition formation game to improve the spectrum efficiency, by having the RRHs negotiating with each other reduce mutual interference.

Big data analytics: Datacenter processing resources can also be used for big data analytics. By analyzing massive amounts of user and network data, operators can extract valuable findings regarding network performance and quality of service. Proactive caching (e.g., popular videos, images, and location-based content), based on user behavior prediction, significantly improves user experience and reduces network load [49]. Data collection can also be combined with machine learning techniques leading to a more intelligent, self-adaptive, and secure network [50, 51].

An overview of the available mobile big data along with a big data analytics-enabled network architecture was proposed in [52]. Authors divide the data into four categories, namely application, user, network, and link data. Application data describe features of applications such as content popularity and service types. User data include user behavior, preferences, location, and mobility. Network data contain configurations, signal strength, traffic load, and interference information. Finally, link data cover physical channel information such as path loss, shadowing, and channel statistics.

A similar classification approach was presented in [53]. Data are classified into four categories, namely flow record data, network performance data, mobile terminal data, and additional data. Flow record data are obtained through deep packet inspection and contain the main attributes during a data session. Network performance data mainly include key performance indicator data and statistical information. They are used to evaluate the network performance and the quality of service metrics. Mobile terminal data contain information about the mobile devices, such as device information, authentication information, cell identification, signal strength, and data rates. Additional data can be used to build a subscriber profile for billing and data plan information.

The authors in [54] proposed a network optimization framework using big data analytics. They also discuss how the mobile big data are collected, stored, analyzed, and applied towards network optimization. In the same way, Zhang et al. [55] discussed how big data analytics can be exploited to improve network performance in aspects of network management, deployment, operation, and service quality. By analyzing real-time network state information, faults and anomalous behaviors can be predicted and mitigated. Spatial traffic load statistics can be obtained from data analysis in order to determine the appropriate deployment of BSs. Real-time data traffic analysis can extract traffic patterns in order to dynamically adjust the BSs resources, reducing energy consumption and improving network operation. Finally, user quality of service can be improved, by generating user behavior patterns based on mobility and content data.

Lower costs: Capital and operating expenditure can be reduced, as the BBUs are concentrated in data centers and the installation of RRHs requires less hardware. Moreover, software and hardware upgrading becomes easier and less expensive [56].

3.2 C-RAN solutions

This section lists, in chronological order, notable C-RAN solutions that have been developed over the recent years. A discussion is also included at the end of this section.

SoftRAN [57] is considered as one of the earliest proposals in cloud and virtualization concept integration. All physical BSs are considered simple radio elements with minimal control logic that form a virtual big BS (VBBS). VBBS performs resource allocation, mobility, load balancing, and other control functions. A logically centralized entity, i.e., the controller, maintains a global view of the RAN and makes control plane decisions for all the RRHs.

In SoftAir [58], the control plane consists of network management and optimization tools and it is implemented on the network servers. The data plane consists of software-defined BSs in the RAN and software-defined switches in the core network. Control and logic functions are realized in software and executed on general-purpose processing platforms. The proposed architecture offers (i) programmability of the nodes, (ii) cooperation of nodes for enhancing network performance, (iii) open interface protocols, and (iv) an abstract view of the whole network based on information collected from BSs and switches.

FluidNet [59] aims at providing intelligent configuration of the fronthaul. FluidNet's algorithms determine configurations that maximize the traffic demand satisfied on the RAN, while simultaneously optimizing the computation resource usage in the BBU pool.

FlexRAN [60] is a flexible and programmable software-defined RAN platform, which separates control from the data plane through a custom application programming interface (API). The main components are the FlexRAN master controller and the FlexRAN agent. Each agent corresponds to a BS and is connected to the master controller. The FlexRAN API enables a two-way interaction between agents and the master controller. Agents act as local controllers and send network state information to the master controller. Also, the master controller sends control commands to the agents based on its knowledge of the entire network state.

FlexCRAN [61] incorporates an architectural framework that implements a flexible functional split, using Ethernet as fronthaul link. The authors also introduced the key performance indicators (KPIs) of a C-RAN and evaluated the proposed architecture through an OpenAirInterface-based implementation.

Most of the aforementioned efforts are focused on the RAN part of the mobile network. SoftRAN and FlexRAN handle interference and handover management aspects. FluidNet and FlexCRAN discuss the importance of a flexible fronthaul in the context of the C-RAN. SoftAir is the only work that is focused on both RAN and core network (CN) parts of the mobile network. As a final note, FluidNet presents an IEEE 802.16-based implementation, while FlexRAN and FlexCRAN present an OpenAirInterface LTE implementation.

3.3 Challenges and open issues

In the previous sections, we presented an overview of the C-RAN architecture and novel solutions. Still in its infancy, it has many benefits but there are also several challenges and open issues that need to be further investigated in order to fully realize its potential. In the following sections, we provide the challenges associated with each of the C-RAN enabling technologies. Table 2 presents comparative insights between the current and the future state of the C-RAN technology. In the following, a discussion is provided on the C-RAN challenges and the open issues.

3.3.1 Software-defined network

The SDN concept is extended in order to support mobile communications. As software-defined mobile network (SDMN) is a new notion and its specifications are still open, common SDN is used as a reference model for SDMN design. There are critical issues that need to be addressed to achieve seamless integration in the RAN [62].

Architecture redesign: SDMN is different from conventional SDN, as mobile networks have fundamental differences from wired networks. For example, the wireless access domain is challenging because of the massive number of devices and the heterogeneity of the modern mobile networks. Complex radio environments, which affect link reliability and quality, should also be taken into consideration while designing the SDMN architecture.

Controller placement: The controller placement heavily affects the network performance. Controller placement problem [63] aims at finding the optimal number of SDN controllers as well as their location in order to minimize the overhead latency and enhance the network reliability. As stated before, SDMN architecture will introduce additional constraints and requirements in the controller placement problem.

Cognitive radio integration: Cognitive radio [64] is a promising approach in wireless communication engineering. Cognitive radio can monitor and dynamically reconfigure physical radio characteristics based on the environment variability. Centralized network intelligence

Table 2 Current and future state of C-RAN

Concept	Challenge	Today	Future
Software-defined networking	Architecture redesign	Straightforward architecture using wired technologies (i.e., Ethernet) for interconnections.	Complex architecture using wireless technologies. Radio environment affects link reliability and quality.
	Controller placement	Controllers are strategically placed in order to minimize latency. Increasing the number of controllers also increases control overhead.	Wireless communications introduce additional requirements in placement. Also, reliability becomes more critical because of the heterogeneity of the wireless environment.
	Cognitive radio integration	Controllers maintain a high-level network intelligence to achieve better network control.	Network control is enhanced by adding radio environment intelligence to controllers.
	Mobility management	As the current SDN is used for conventional wired networks, there is no need for mobility management.	Mobility management is important, as users should experience minimal disruptions in their communications.
Network and function virtualization	Performance optimization	Hypervisors such as Kernel-based Virtual Machine (KVM) and Xen [99] are used for virtualizing resources.	Utilize hypervisors optimized for extremely low overhead and latency.
	Network isolation	Each virtual network configuration and customization is independent from others.	Each virtual network configuration and customization is independent from others.
	Resource allocation	Virtual machines access the physical resources through the hypervisor. Computation, storage, and network resources are the most common physical resources.	Spectrum availability is an additional resource feature that has to be managed. Moreover, device mobility makes resource allocation more challenging.
	Slice management	Slices are scaled depending on service requirements.	Slicing in 5G mobile networks is more challenging as there are many operators sharing the same infrastructure and more diverging service requirements.
Fronthaul	Data reduction	CPRI uses raw I/Q samples, requiring thus huge link capacity.	Techniques such as data compression, aggregation, and redundancy removal should be considered.
	Latency reduction and synchronization	Mobile communications require synchronization and the lowest possible latency in order to ensure high quality of service.	Mobile communications require synchronization and lowest possible latency in order to ensure high quality of service.
	Overhead analysis	CPRI has standard control signaling information.	The trade-off between control overhead and bandwidth efficiency must be analyzed. It can also be dynamically adjusted depending on the link and network states.
	Novel standards	CPRI is not the optimal fronthaul standard for the C-RAN.	Novel standards such as ORI should be researched.

is an important benefit of conventional SDN. By integrating cognitive radio, physical layer intelligence can be obtained, resulting in better control of the overall network.

Mobility management: Mobility management ensures successful data delivery and ensures no disruption in communications while the users are moving. Future mobile networks are expected to provide high-speed connectivity to extremely mobile applications (e.g., high-speed trains), complicating mobility management [65].

3.3.2 Network and function virtualization

Despite attracting wide attention by both industry and academia, the NFV concept still remains in early stages. BBUs are shifted from physical machines to virtual machines. As VMs use the same physical resources, the following challenges aim to minimize overhead and ensure high performance:

Performance optimization: As network functions are executed on top of a hypervisor (e.g., KVM and Xen), additional overhead is introduced, leading to network performance degradation. Optimization of legacy hypervisors and the introduction of new virtualization technologies (e.g., Docker) are plausible solutions towards minimizing overhead and latency.

Network isolation: Network isolation enables abstraction and sharing of resources among different operators. Any configuration, customization, and topology change of any virtual network should not affect and interfere other coexisting operators. Isolation is challenging in wireless networks due to the broadcast nature of wireless communications. For example, a change in a cell configuration may introduce high interference to neighbor cells.

Resource allocation: Resource allocation is another significant challenge of wireless network virtualization. Unlike wired networks, resource allocation is more complicated on wireless networks due to the availability of spectrum, device mobility, and the differentiation of uplink and downlink channels.

Slice management: Slice management and efficient allocation of slice resources are interesting problems to be addressed [66]. Network slices should be created and scaled dynamically based on service requirements. The resource allocation algorithms may adopt different strategies depending on the slice size and service requirements. The dynamic characteristics of 5G mobile networks must be taken into account while designing and implementing those algorithms.

3.3.3 Fronthaul

Fronthaul has great impact on the performance of C-RAN [67]. To guarantee high network performance, links with high data rate and bandwidth, as well as low latency and jitter, are required. Legacy fronthaul [68] has been widely adopted in current network deployments, but it will face serious challenges in the upcoming generation of mobile networks. The underlying focus of the following challenges is to achieve the lowest possible overhead and latency:

Data reduction: CPRI transports raw I/Q samples. An 8 × 8 Multiple Input-Multiple Output (MIMO) system with a 100-MHz channel (as it is envisioned in 5G) will require approximately 160 GB/s capacity. Data reduction techniques, such as data compression, aggregation, and removal of redundancy should be implemented [69].

Latency reduction and synchronization: Before being processed, subframes need to be transported from RRHs to BBUs. To ensure high quality of service, the time required for the transportation should be extremely low. Synchronization information must be transmitted from BBUs to RRHs. Synchronization will be crucial in 5G mobile networks since access nodes are able to cooperate with each other. For example, a frequency offset between cooperating nodes will result in signal overlap, beamforming distortion, and degraded performance [70].

Overhead analysis: Overhead should be quantified and analyzed in order to identify design trade-offs. For example, smaller overhead may lead to reduced control information but increased bandwidth efficiency.

Novel standards: CPRI is not an open standard while it was originally designed as a BS internal interface. Currently, it may not be the optimal interface, mainly because of the high data rates required. Therefore, the European Telecommunications Standards Institute (ETSI) has initiated a new Industry Specification Group (ISG) called Open Radio Interface (ORI). The ORI goal is to develop an interface specification envisioning interoperability between parts of BSs of cellular mobile network equipment. The interface defined by the ORI ISG is built on top of the CPRI with the removal and addition of some options and functions in order to reach full interoperability.

3.4 Trends and advances

3.4.1 SDN and NFV

Transport SDN [71]: The provisioning of infrastructure to transport large data traffic between large geographical areas is too expensive for network operators. The multitude advantages of SDN, i.e., cost reduction, urge network operators to extend SDN utilization from data centers to large-scale geographic networks. SDN was originally designed to operate at layers 2 and 3 of packet-switched networks. Transport SDN (T-SDN) extends the SDN operation to the transport layer of circuit-switched networks. T-SDN is in an initial stage with many challenges and open issues. Due to its demand, T-SDN is gaining large attention from the industry and academia.

Edge computing [72]: The proliferation of Internet of Things (IoT) devices introduces a substantial amount of data traffic in the mobile network. Instead of routing IoT data to data centers for further processing, they are locally processed. As a result, the local process leads to network traffic reduction. Edge computing is an emerging trend which aims at bringing the computational resources close to the end devices. This shift of resources creates new complexities and challenges.

Industrial Internet of Things: IoT is an indispensable segment of 5G mobile networks and a prerequisite for Industry 4.0 [73]. The Industrial IoT (IIoT) paradigm [74] is envisioned to continuously obtain data from various sensors, transfer the data to cloud-based data centers for further processing, and update related configurations in the industrial systems based on those data. This feedback-based system will significantly raise the industry efficiency. As Wireless Sensor Networks (WSNs) are the basis of IIoT, research efforts are focused on the WSN virtualization. A virtual WSN is formed by supporting logical connectivity among collaborating sensors, based on either the information they track or the task they perform (e.g., traffic control and environmental monitoring).

3.4.2 Other transport technologies for fronthaul

Using point-to-point fiber, the number of links required linearly increases with the number of RRHs deployed, leading to capacity degradation, high cost, and increased network complexity. Authors in [75] discuss the urgency of incorporating other transport technologies in order to address the aforementioned issues. They also evaluate the capacity performance of fronthaul millimeter wave (mmWave) and provide a comparison of other potential fronthaul candidates. Table 3 provides a list of alternative transport technologies along with the advantages and issues of each one. In the following, the alternative transport technologies are discussed in detail.

Optical networks: Optical networks constitute a promising alternative solution for realizing the fronthaul of the C-RAN since they provide high-capacity and low-latency links [76]. Moreover, they can accommodate multiple CPRI links in a single fiber by using techniques such as wavelength-division multiplexing (WDM), in which each link is associated with different wavelengths (channel). This reduces the number of fiber resources required. Nonetheless, the network extensibility is still challenging as it requires new fiber installation, if that is not already in place, while the most optical devices come with a high cost.

CPRI over Ethernet: The use of Ethernet for transport in the fronthaul seems beneficial due to the maturity of the technology and its wide adoption. Statistical multiplexing and packet-based transport make CPRI over Ethernet (CoE) [77] efficient and cost effective. However, there are implementation challenges as packetization which introduces overhead and delay to the, already strict, latency budget. Furthermore, Ethernet communication is asynchronous, while fronthaul is characterized by strict synchronization requirements.

Millimeter-wave frequencies: Traditionally, mmWave had been used for long-distance point-to-point communications in satellite communications. Driven by its latest developments, mmWave is emerged as a promising technology in next-generation mobile networks. Signal propagation and channel characteristics have been extensively studied in the past. Nevertheless, [78] was one of the pioneer works that investigated mmWave's feasibility for next-generation mobile networks and demonstrated an early architecture. The authors in [79] conducted extensive signal and channel measurements, ultimately concluding that mmWave will be a key communication technology in next-generation mobile networks. To that end, many research studies (e.g., [80–82]) were developed in order to measure and compare mmWave's performance against conventional mobile technologies. The authors in [83] carried out a survey of existing solutions regarding standardization activities and discussed potential mmWave applications as well as open research issues. An extensive survey of recent channel measurement and channel modeling results was presented in [84]. The authors also reviewed several technical challenges, namely severe pathloss and penetration loss, high power consumption, inconsistent main-lobe gain and non-zero side-lobe radiation, and hardware impairments. Rappaport et al. [85] emphasized the importance of developing accurate propagation models for long-term development of future mmWave systems and provided a comprehensive compilation of mmWave propagation models.

mmWave bands hold much potential for use as wireless fronthaul, mainly because of the high spectrum availability [83]. The small wavelength enables placement of large arrays of antennas in a single transceiver, which encourages the implementation of MIMO techniques, providing better SINR and improved spectrum efficiency. mmWave also enables point-to-multipoint links [86], further reducing the deployment cost. Rebato et al. [87] studied how the

Table 3 Transport technologies for fronthaul

Transport technology	Advantages	Issues
Optical networks	High-capacity	Expensive optical devices
	Reduced fiber resources	Requires previous infrastructure
	Passive (in the case of passive optical networking)	Challenging network extensibility
CPRI-over-Ethernet	Efficient	Packetization introduces overhead and latency
	Cost-effective	Ethernet is an asynchronous protocol, while fronthaul has strict synchronization requirements.
	Universal availability of interfaces	
Millimeter-wave frequencies	High scalability and capacity	High path loss
	High frequency reuse	Low penetration
	Small form factor	Line-of-sight requirement
	Underutilized spectrum	
	Point-to-multipoint links	

path loss affects the mobile network deployment in terms of small-cell density and transmission power.

In [88], the authors studied the path selection and the link scheduling problem for mmWave transport network as a mathematical optimization problem. Using mixed-integer linear programming, they proposed a joint optimization for those objectives.

The authors in [89] proposed a converged radio-over-fiber solution and demonstrated two architectures. In the first architecture, the BBus are connected via fiber with the mmWave RRHs, and those mmWave RRHs are connected using mmWave links to small cells. Mobile users are connected to those small cells using traditional frequency bands. In the second architecture, the mmWave RRHs are directly connected to mobile users using mmWave links. Moreover, Sung et al. [90] implemented a fronthaul communication system based on mmWave and assessed its performance. They also demonstrated a real-time operation of a 28-GHz mmWave-based 5G prototype in order to confirm its technical feasibility.

3.4.3 Advanced C-RAN architectures

In Section 3.1, we described a primitive C-RAN architecture. As C-RAN is still in the early stages of research and deployment, this architecture can be used as a precursor for more advanced architectures, as the ones presented below.

Hybrid-RAN (H-RAN) [91] is the combination of heterogeneous network architecture with the C-RAN concept, aiming at further enhancing the performance of the mobile network. Heterogeneous network architecture involves the deployment of small cells (e.g., micro-, pico-, and femto-cells) and the utilization of multiple radio access technologies. This improves the network efficiency and coverage by deploying small cells in areas with increased capacity demands or areas with bare coverage.

Aiming to offload C-RAN burden, the Fog Radio Access Network (F-RAN) [92] is proposed as a possible evolution of C-RAN. Compared to C-RAN, collaborative radio signal processing and cooperative radio resource management procedures in F-RANs are adaptively implemented at the edge devices, which are closer to the end users. For example, by equipping RRHs with limited cache storage, it is possible to pre-fetch popular content, avoiding thus congestion and delays during peak hours. This technique is called edge caching [93] and is a key component in improving F-RAN's performance. Authors in [94] present a F-RAN architecture using non-orthogonal multiple access (NOMA) [95], which can effectively leverage C-RAN's advantages. They optimize the power allocation problem under a non-cooperation framework and the subchannel allocation problem using a many-to-many two-side matching game algorithm. Zhang et al. [96] discuss how the F-RAN attributes can assist in network load relief. For handover management and procedure, the authors propose a technique using edge caching. They also introduce an interference-aware price for edge caching in order to effectively manage resource allocation. Finally, they model the subchannel and power allocation problem as a non-cooperative game.

In Phantom Cell [97] architecture, small cells are overlaid on a macro cell. The macro cell uses lower frequencies and aims at ensuring wide coverage and high mobility, while small cells use higher frequencies for providing high data rates and capacity.

The authors in [98] discuss on the load balancing, handover, and interference issues that exist in conventional cell architectures. As cell size is shrinking, user movement lead to very frequent handovers which brings additional overhead and latency. A cell-less architecture was presented, in order to cope with the aforementioned issues and offer additional advantages such as superior traffic management, improvement of coverage, and avoidance of frequent handovers.

4 Conclusions

The upcoming arrival of 5G mobile networks introduces extensive modifications to current RAN architectures. In this paper, we investigated the C-RAN concept, the enabling technologies, and their key challenges. We also presented C-RAN implementations and discussed future trends and advances.

RAN is continuously evolving to provide higher data rates and capacity, efficient spectrum utilization, and massive and ubiquitous connectivity. Concepts such as SDN and NFV as well as advancements in optical and wireless technologies are shaping the way mobile networks are designed and deployed, ultimately enabling operators to provide more diverse, flexible, and cost-effective services to users.

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