1 Overview of C-RAN

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1.1 Introduction

In 2008, as the specification for long-term evolution (LTE) Release 8 was frozen in the Third Generation Partner Project (3GPP), operators began to shift the network deployment focus to 4G. In 2009, the world's first commercial LTE network was launched by TeliaSonera in Norway and Sweden. As of today, there are several hundred LTE networks in operation, providing unprecedented user experiences to customers. Consequently, we are witnessing the recent mobile traffic explosion in the telecom industry. It is expected that by 2020 consumer Internet traffic will increase by a factor of over one thousand [1].

As operators roll out and expand 4G networks, more and more challenges arise.

First, network deployment is becoming more and more difficult simply due to an insufficient number of equipment rooms. Traditional base stations (BSs) comprise either a co-located baseband unit (BBU) with a radio unit or a distributed BBU with a remote radio unit (RRU) connected via fiber. For either case, a separate equipment room with supporting facilities such as air conditioning is required in order for BS deployment. However, since the operating frequency of LTE is usually higher than that of 2G and 3G, the coverage of an LTE cell is smaller than that of a 2G or 3G cell. As a result, more LTE cells are needed to cover the same area, meaning that more equipment rooms are required. Unfortunately, this is increasingly difficult since available real estate is becoming scarcer and more expensive. Traditional deployment puts a lot of pressure on capital expenditure (CAPEX).

Second, in a society where people are promoting energy conservation and environment protection, power consumption has become a sensitive word and a major concern for operators. It is estimated that the carbon footprint of the ICT industry accounts for 2% of the global total, which is the same as that of the aviation industry. For the telecom industry, further analysis has shown that a large percentage of power consumption in mobile networks comes from radio access networks (RANs) [1, 2]. Take China Mobile's networks, for example. The largest mobile network in the world consumed over 14 billion kWh of energy in 2012 in its network of 1.1 million base stations. It can be seen that saving energy in RANs could directly lower the operating expense (OPEX) of the network.

Last, but not least, a concern comes from interference issues. Long-term evolution is expected to have much more interference owing to the increased number of cells, i.e., a shortened intercellular distance than with 2G or 3G. In addition, the interference issue will become increasingly urgent when heterogeneous networks with high densities of small cells are introduced. In order to mitigate interference, various cooperative algorithms such as coordinated multi-point (CoMP) [2] have been proposed. However, efficient CoMP algorithms such as Joint Transmission (JT) cannot achieve their maximum performance gain using traditional LTE architecture with X2 interfaces, owing to their high latency and low bandwidth [3, 4]. There is a need to facilitate information exchange in an efficient way to enable and maximize the effect of CoMP from an architecture perspective.

In order to address the aforementioned challenges, both industry and academia are proactively investigating and researching potential technologies, one of which is Centralized, Collaborative, Cloud, and Clean RAN or, in brief, Cloud RAN (C-RAN). In this chapter, we will provide an overview of C-RAN, including its basic concept, benefits, and challenges as well as the evolving C-RAN architecture based on a new fronthaul interface.

1.2 C-RAN Basic

In 2009, China Mobile (CMCC) proposed the concept of C-RAN for the first time. The “C” here has four meanings, “centralized, collaborative, cloud, and clean”. The basic idea of C-RAN starts from centralization, which is to aggregate different BBUs, which in traditional deployment are geographically separated, into the same location. It is clear to see that the base stations that C-RAN supports should be of the distributed type, i.e., the BBU and the RRU are separate and are connected via fiber.

The advantages of centralization are very straightforward. First, the number of equipment rooms for BS placement is greatly reduced, leading to CAPEX reduction. Furthermore, the facilities, especially the air conditioning, could be shared by BBUs in the same central office. Given that power consumption by air conditioning usually accounts for over half the total for operators, extensive facility sharing helps to save energy. According to the report in [2], such saving could be as high as 70% compared with the traditional deployment method in a 3G trial network. Therefore, the OPEX could be greatly reduced.

Further, centralization leads to C-RAN’s second namesake, “collaborative”. The idea behind it is that once the BBUs are aggregated in the same place, communication between them will become much easier, faster, and more effective. In fact, like in a data center, it is convenient to connect different BBUs together with switches of high bandwidth and low latency. In this way, the information exchange among BBUs can be completed in a timely manner, which facilitates the implementation of joint processing technologies. As a result, system performance is expected to be improved.

The ultimate goal of C-RAN is to realize the “cloud”feature, which is similar to the cloudification concept in data centers. The essence of cloudification is to soften baseband processing resources, which are of a "hard" nature in traditional BSs in the sense that they are developed on proprietary platforms. In these platforms the processing resources present hardware such as digital signal processing (DSP) and application specific integrated circuits (ASICs), making it difficult to achieve resource sharing. In C-RAN with cloudification, the processing resources are supposed to be "soft" and flexible enough that they can be dynamically managed with different operations on BBU such as instantiation, scale-in, and scale-out. In this sense, the BS in C-RAN could be called "soft" to distinguish it from the "hard" BS in traditional systems.

Figure 1.1 illustrates a C-RAN architecture based on a commercial off-the-shelf (COTS) platform. A C-RAN system centralizes different processing resources together to form a pool so that the resources can be managed and dynamically allocated on demand. The key enabler towards C-RAN is the virtualization technology widely used in modern data centers. With virtualization, standard IT servers are used as the general platform with computation and storage as the common resources. As shown in

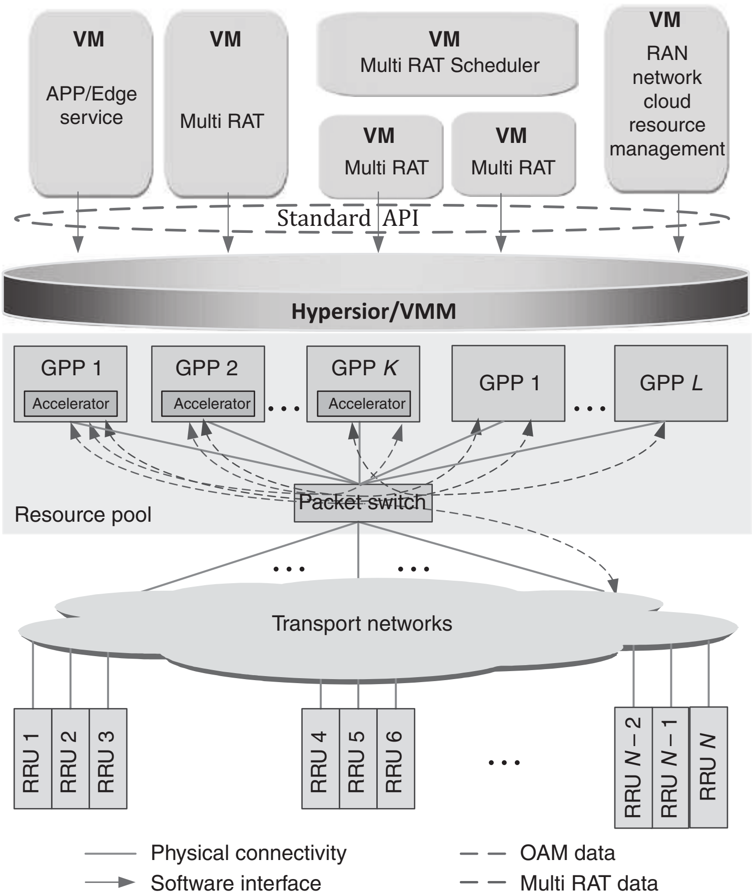

Figure 1.1 Illustration of the C-RAN architecture.

Fig. 1.1, on top of the servers different applications run in the form of virtual machines (VMs). The indispensible applications in C-RAN are those that realize different radio access technologies (RATs) including 2G, 3G, 4G, and future 5G. Additional user applications such as content delivery network (CDN) and Web Cache can also be deployed on the open virtualized platform. In addition, the C-RAN platform could provide a set of standard application program interfaces (APIs), which opens an opportunity for new service provision and deployment. In this way, C-RAN is no longer a single RAT processing entity but rather a platform for the coexistence of diverse services.

1.3 Challenges

Towards the realization of C-RAN lie two major challenges: the fronthaul (FH) issue and virtualization for cloudification.

A FH link is the link between the BBU and the RRU. Typical FH interfaces include the common public radio interface (CPRI) and the open base station architecture initiative (OBSAI). Since CPRI is the most widely used FH protocol in the industry, in this chapter, unless otherwise mentioned, we will use CPRI to represent FH in order to describe the issues. In C-RAN with centralization, fibers are used to connect the BBU pool with the remote RRUs. The larger the centralization scale, the more fibers are needed. In other words, centralization may consume a large number of fiber resources, which is unaffordable to most operators given fiber scarcity. The FH issue has been widely studied, with several proposed schemes including various compression techniques, wavelength division multiplexing (WDM), optical transport networks (OTNs), microwave transmission, and so on. Readers can find more information in [2, 5]. In Chapter 18 we will present field trial results to verify the feasibility of WDM FH solutions. In general, WDM-based FH solutions are mature enough to save fiber consumption effectively in support of C-RAN large-scale deployment. The major concern lies in the additional cost of the introduction of new WDM transport equipment in the networks.

The other challenge of C-RAN lies in how to realize the cloudification feature. It is strongly believed that a key to this goal is the virtualization technology which has been pervasive as a key cloud computing technology in data centers in the IT industry for many years. However, the use of virtualization in the telecom networks is far more complicated owing to the unique features of wireless communications, especially the baseband processing in RAN. Carrier-grade telecom functions usually have extremely strict requirements for real-time processing. For example, for TDD-LTE systems it is required that an ACK or NACK must be produced and sent back to the user equipment (UE) or eNodeB (eNB) within 3 ms after a frame is received [5]. Traditional data center virtualization technology cannot meet this requirement. Therefore, the virtualization technology and the COTS platforms need to be optimized and even customized in various aspects, from the in/out (I/O) interface, hypervisor, and the operating systems to the management systems, in order to be competent for real-time and computation-intensive baseband processing.

1.4 Evolved C-RAN with NGFI

As mentioned in the previous sections, the FH issue has been one of the key challenges for C-RAN. Several solutions including CPRI compression and WDM transport technologies have been proposed. In essence, the idea of all the solutions is to "accommodate" the FH without changing the FH interfaces themselves. It should be realized that the root cause for the FH challenge lies exactly at the FH interfaces themselves. Take the CPRI as an example: CPRI specification has defined several classes of line rates. For a TD-LTE carrier with 20 MHz and eight antennas, the CPRI rate could be as high as 9.8 Gb/s [6]. Moreover, the rate is constant regardless of the dynamically changing mobile traffic, which leads to low transmission efficiency. In addition, existing CPRI interfaces have other shortcomings, such as low scalability and flexibility, which impede C-RAN large-scale deployment. Therefore in [7–9], the authors proposed to redefine the CPRI and brought forward a new concept called next generation fronthaul interface (NGFI). This concept possesses the following desirable features [7, 8].

- Its data rate should be traffic-dependent and therefore support statistical multiplexing.
- The mapping between BBU and RRH should be one-to-many and flexible.
- It should be independent of the number of antennas.
- It should be packet-based, i.e. the FH data could be packetized and transported via packet-switched networks.

The key way to achieve NGFI is to repartition the function layout between the BBUs and the RRUs (see Fig. 1.2). Traditionally, all the baseband functions, including the physical layer (PHY), media access control (MAC), and the packet data convergence protocol (PDCP) are processed on the BBU side while the RRU mainly deals with the

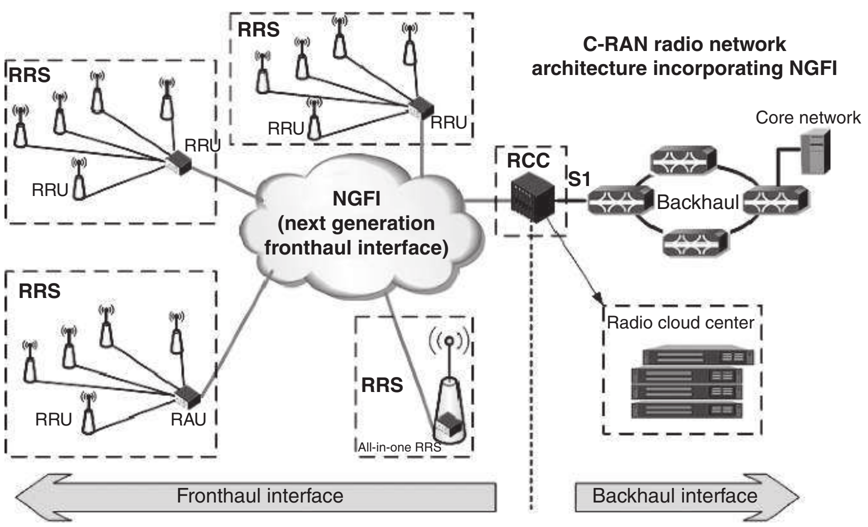

Figure 1.2 NGFI-based C-RAN architecture.

radio-related functions. The signal transmitted by the CPRI is the high-bandwidth I/Q sampling signal. From the effective-information perspective, any data between the baseband protocol stacks (e.g., between MAC and PHY) could be transported. The basic idea of function splitting is to move partial baseband functions to the RRU to reduce the bandwidth without losing any information.

There have been some related studies on this topic in the literature. To achieve NGFI in general, the function splitting should decouple the bandwidth from the antennas, which can be achieved by moving antenna-related functions (downlink antenna mapping, FFT, channel estimation, equalization, etc.) to the RRU. It is shown that the FH bandwidth of an LTE carrier may decrease to the order of 100 Mb/s no matter how many antennas are used [10]. In addition, it is suggested that the user equipment (UE) processing functions should be decoupled from cell-processing functions. In this way, the FH bandwidth will be lowered and, more importantly, load-dependent. The load-dependent feature gives an opportunity to exploit the statistical multiplexing gain when it comes to FH transport network design for C-RAN deployment. Thanks to statistical multiplexing, the bandwidth needed for the transport of a number of FH links in C-RAN can be reduced greatly, subsequently decreasing the cost.

The support of collaborative technologies is another key factor for the design of function splitting. The coordinated multi-point algorithm has been viewed as one of the key technologies in 4G and 5G to mitigate interference. It can be divided into two classes: MAC-layer coordination and physical-layer coordination. For example, collaborative schedule (CS) is an MAC-layer coordinated mechanism. Joint reception (JR) and joint transmission (JT) are physical-layer coordinated technologies. In [11] it was found that the performance gain of JR and JT decreases significantly as the number of antennas increases. Moreover, in [7] the authors found through field trial data that MAC-level collaborative technologies can bring comparable performance gains with lower complexity, easier implementation, and fewer constraints. On the basis of these observations, it is suggested that the function splitting for NGFI does not have to support PHY-layer coordination technology. Considerable performance gain is achieved by supporting MAC-layer coordinated technologies.

Function splitting is just the first step for NGFI. When it comes to the FH networks in the context of C-RAN, there is a radical change compared with original WDM or other existing FH solutions. Thanks to the packet-based features, it is expected that packet switching networks will be used to transport the NGFI packets. This is when the Ethernet can come into play. Thanks to its ubiquity, low cost, high flexibility, and scalability, it is proposed that the Ethernet should be adopted as the NGFI FH solution. There are several benefits. First, an Ethernet interface is the most common interface on standard IT servers and use of the Ethernet makes C-RAN virtualization easier and cheaper. Second, the Ethernet can make full use of the dynamic nature of NGFI to realize statistical multiplexing. Third, flexible routing capabilities could also be used to realize multiple paths between BBU pools and RRH [7].

The main challenges for the Ethernet as an FH solution lie with the high timing and synchronization requirements imposed by the NGFI interface. Although the exact NGFI has so far not been specified, it is possible that NGFI may keep some requirements of the CPRI, such as the synchronization requirements. The allowable radio frequency error for a CPRI link is 2 ppb and the timing alignment error must not exceed 65 ns in order to support multiple-input multiple-output (MIMO) and transmission diversity [12]. In order to meet the timing requirements, both the BBU and the RRUs should be perfectly synchronized, which therefore requires a very accurate clock distribution mechanism. Potential solutions may include any combination of the Global Positioning System (GPS), IEEE 1588, and synchronous Ethernet (Sync-E). Finally, the transport protocols on top of the Ethernet such as Multi-Protocol Label Switching (MPLS) and Packet Transport Network (PTN) that establish transport paths for FH traffic need to be defined.

As proposed by the authors in [7], the C-RAN architecture is also evolving as traditional FH interfaces change to NGFI. As shown in Fig. 1.2, the evolved C-RAN consists of three parts [7]:

- a radio aggregation unit (RAU) With function split, the moved partial BB functions form a new entity which is called the radio aggregation unit. This is a logical concept and its realization depends on implementation solutions. For example, the RAU could be integrated into the RRU to form a new type of RRU. Alternatively, it could be an independent hardware entity.
- remote radio systems (RRS) An RRS consists of an RAU and multiple RRUs. It is expected that collaboration could happen among different RRHs via the RAU within the same area coverage of an RRS. There could be multiple RRSs in a C-RAN network.
- a radio cloud center (RCC) The remaining BB functions together with high-layer functionalities constitute an RCC. The RCC is the place where all the processing resources are pooled into a cloud with virtualization technology.

1.5 Deployment Cases and Standardization Activities

Since its proposal in 2009, C-RAN has gradually become a hotter and hotter topic in both industry and academia. Centralization has been tested and deployed by many major operators. China Mobile, for example, as the originator of C-RAN, has been actively conducting C-RAN centralization field trials in more than ten cities across 2G, 3G, and 4G since 2010. The two biggest carriers in South Korea, SK Telecom and Korea Telecom, have adopted the C-RAN centralization method to deploy commercial LTE networks since 2011. In Japan, DoCoMo has successfully completed an outdoor-commercial-environment verification of its Advanced C-RAN, achieving a 240 Mbps downlink using 35 MHz bandwidth in February 2015. There are many other operators experimenting with C-RAN including Orange, China Telecom, and China Unicom.

At the same time, several C-RAN projects have been initiated in many organizations including Next Generation Mobile Networks (NGMN) and the European Commission's Seventh Framework Program (EU 7FP). In NGMN, a dedicated C-RAN project named

P-CRAN was founded in 2010 [13]. Led by China Mobile and receiving extensive support from both operators and vendors, including KT, SKT, Orange, Intel, ZTE, Huawei, and Alcatel-Lucent, this project aimed at promoting the concept of C-RAN, collecting requirements from operators, and helping build the ecosystem. The project was closed at the end of 2012, releasing four deliverables into the industry. Through the deliverables, the advantages of C-RAN in saving the total cost of ownership (TCO) and speeding up site construction are well understood. In 2013, NGMN extended the study on C-RAN into a C-RAN work stream under the project RAN Evolution. On the basis of previous C-RAN projects, this work stream aimed at a more detailed study on the key technologies critical to C-RAN implementation, including BBU pooling, RAN sharing, function splitting between the BBU and the RRU, and C-RAN virtualization. In addition, there are several C-RAN related projects under EU FP7. For example, the iJOIN project deals with the interworking and joint design of an open access and backhaul network architecture for small cells on cloud networks [14]. Another project, Mobile Cloud Networking (MCN), aims at exploiting cloud computing as the infrastructure for future mobile network deployment and operation and innovative value-added services [15].

There are also many efforts in the fronthaul area, especially for NGFI. In NGMN, schemes of BBU-RRH function splitting are being analyzed, aiming at reducing the FH bandwidth to facilitate C-RAN deployment [13]. Open Radio Interface (ORI) is studying the compression technologies with the aim of reducing the CPRI data rate. The CPRI forum has begun a discussion of “Radio over Ethernet”, whose idea is to use the Ethernet to transport CPRI streams. In the IEEE a task force called IEEE 1904.3 was founded, targeting the design of CPRI encapsulation on Ethernet packets [16]. There has also been heated discussion regarding FH in the IEEE 802.1 time-sensitive networking task group and the IEEE 1588 working group. In addition, IEEE is considering founding a dedicated NGFI working group to promote and study NGFI comprehensively. There are some EU-funded research projects including convergence of fixed and mobile broadband access/aggregation networks (COMBO) [17], intelligent converged network consolidating radio and optical access around user equipment (iCIRRUS) [18], and X-Fronthaul.

Among the projects, it is worth mentioning the IEEE 1904.3 task force that deals with the FH data encapsulation in the form of Ethernet packets. The IEEE 1904.3 Radio over Ethernet (RoE) project is an ongoing effort to standardize a versatile encapsulation solution for transporting radio samples with the associated control traffic over a switched Ethernet network. The RoE project concerns only transport-level encapsulation with a flow-level multiplexing capability and the required enablers for the time synchronization of transported radio and control data flows. This project is by design agnostic to the transport technologies and the functional splitting between the BBU and RRU, which implicitly allows its use for existing and future 5G radio technologies. For incremental deployments, RoE also offers mechanisms for transporting and mapping existing fronthaul solutions such as CPRI into its native transport service. Furthermore, RoE can be transported over any networking technology that carries Ethernet packets, assuming that the NGFI timing requirements can be met.

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2 Advanced C-RAN for Heterogeneous Networks

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2.1 Introduction

Motivated by the increase in user demand for high data rates and new service applications due to the fast market penetration of smartphones, a large number of mobile operators in the world are introducing long-term evolution (LTE) into their networks [1]. In accordance with the further growth of mobile data traffic, these operators are deploying, or plan to deploy, their LTE networks with multiple-frequency-band operation in order to provide satisfactory user experience to their customers. Therefore, from the viewpoint of mobile operators, technologies that achieve high capacity LTE networks deployed with multiple-frequency-band operation are essential.

In order to achieve high capacity by utilizing multiple LTE frequency bands, carrier aggregation (CA) was specified as one of the new features for LTE in 3GPP Release 10 (i.e., LTE-advanced) [2]. The CA feature will enable operators to provide improved user throughput in their LTE networks by simultaneously using multiple LTE carriers. It can support large bandwidths (up to 100 MHz) and the flexible use of a fragmented spectrum in different frequency bands, where multiple LTE carriers do not have to be contiguous in a frequency band and can even be located in different frequency bands. The increase in user throughput with CA is achieved by assigning available radio resources over multiple LTE carriers to a single user. However, in a high-load network condition due to a large number of connected users, the increase in user throughput would be limited as the radio resources that could be assigned to a single user would not be changed irrespectively of whether CA is employed. Therefore, the utilization of CA only will not contribute to an increase in network capacity.

One conventional way to increase network capacity is to increase the number of cell sites in a certain area (i.e., to employ a densification of cells). However, the densification way of using macro cell deployment is becoming less efficient especially in dense urban areas since it has become difficult to find sites (a building or tower) in which new macro base stations can be installed. To cope with this problem, the deployment of heterogeneous networks, in which multiple small cells are deployed over a macro-cell area, is considered to be a promising option. In this deployment, the frequency band of the small cells is the same as that of the macro cell. A small cell will support smaller coverage areas served by smaller-size equipment with reduced transmission power, e.g., 1 W, compared with that of conventional macro-cell base stations. Mobile operators can easily improve network capacity even in dense urban areas by using multiple small-cell