An Overview of Cloud RAN: Architecture, Issues and Future Directions

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Abstract. Cloud radio access network (C-RAN) has been considered as one of the enabling network architectures towards the implementation of fifth generation (5G) wireless systems. Combining with advanced radio, wireless and computing techniques, C-RAN provides great potential to improve the network capacity, spectrum efficiency, energy efficiency and operational flexibility. Therefore, C-RAN has attracted considerable attention from both academia and industry. In this paper, we review the architecture and some of the key physical (PHY) layer signal processing issues of C-RAN. The functional split and limited-capacity fronthaul impose PHY layer issues and signal processing opportunities, e.g., channel state information acquisition, effective compress-and-forward methods and intelligent resource allocation schemes. Moreover, some emerging 5G techniques which can be supported by or integrated with C-RAN architecture, such as software-defined networking, heterogeneous networking, communication at millimeter wave frequencies and full-duplex radio are discussed. The challenges and future research directions are also presented, where mobile edge computing and caching, multi-dimensional resource management and PHY layer security and energy-efficient designs are highlighted.

Keywords: Cloud RAN · 5G networks · Fronthaul · HetNet · mmWave · Full-duplex · Mobile edge computing

1 Introduction

The volume of the wireless data traffic is increasing rapidly due to the unprecedented popularity of smartphones, tablets and machine-centric devices [1–3]. The explosive growth of wireless data traffic cannot be satisfied by traditional cellular system due to pretty high per-bit cost and scarce spectrum resources. Confronted with such unprecedented traffic growth, mobile operators are looking for new technologies to meet the diverse and increasing demands of users with guaranteed quality-of-service (QoS) and quality-of-experience (QoE) [4]. However, it is a challenging task to improve the key performance metrics of the network under limited resource and cost.

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The network throughput, service coverage, spectrum efficiency (SE) as well as energy efficiency (EE) should be jointly considered and optimized. Aiming to address these pertinent issues, dense deployment of access points (APs) or base stations (BSs) can be considered [5], which makes it proximal for any device to access the network. Such AP/BS densification compensates the path loss of the wireless channel and has the potential to improve the network throughput and EE. Meanwhile, full frequency reuse can be adopted to improve the SE with advanced physical (PHY) layer techniques, such as multiuser multiple-input multiple-output (MIMO) and massive MIMO [6, 7]. As the density of the AP/BS increases, co-channel interference may also increase [8], which calls the need for proper interference management to maintain high network throughput.

From a system's perspective, advances of the radio access network (RAN) itself may only contribute to a fraction of the performance gains to meet the requirement of ever-increasing data demands. Note that there have been heterogeneous networks (HetNets), which can be deployed with different available spectrum resources and service coverage capabilities [9]. However, cooperation among different HetNets is neither easy nor smooth under concurrent network architectures and protocol stacks. Such inefficiency in heterogeneous resource utilization also indicates inefficient usage of infrastructure. Therefore, integrating these heterogeneous network components, spectrum resources, APs/BSs to offer flexible and reliable on-demand services are of great practical and commercial interest. Such functional integration may require the evolution of the whole network, not only the RAN itself. Cloud computation techniques have been widely and successfully used in the area of computation/data networks [10]. Recently, the concepts of software-defined network (SDN) [11–13] and network function virtualization (NFV) [14] have been introduced to wireless communication networks. The basic idea behind these concepts is to abstract different physical resources, components and functional entities into a logic resource pool, then different resources can be centrally orchestrated to meet the specific demands according to flexible protocols [15]. Therefore, APs/BSs in RAN can be abstracted as antennas with different coverage abilities and signal processing abilities. Assuming centralized control and processing, the seemingly interfering APs/BSs can together form an MIMO network in RAN, where AP/BS densifications may be beneficial and interference-free. In the core network, signal processing and control can be done at the central unit (CU) and the heterogeneous resources can be flexibly scheduled and used without any barrier to meet the required demands. To this end, Cloud-RAN (C-RAN) architecture has attracted significant research attention from both academia and industry [2, 3, 6]. It has been regarded as a promising technology towards implementing the fifth generation (5G) wireless systems [16].

In this survey paper, we review the general architecture of C-RAN with special focus on PHY layer signal processing aspects. In particular, we first review the functional split solutions in C-RAN, which partially move the baseband signal processing from the conventional AP/BS to the cloud server. It is noted that the capacity of the fronthaul needs to be carefully considered, and some key PHY signal processing techniques are introduced, namely channel state information (CSI) acquisition, compression and transmission, and resource management. The possible integration of other promising 5G techniques such as HetNets, SDN, mmWave and full-duplex with

C-RAN infrastructure is also discussed. These techniques are expected to offer more physical spectrum resources, infrastructure resources, elastic networks and flexible protocols. Finally, we envision several challenges and future directions associated with C-RAN design.

The rest of this paper is organized as follows. In Sect. 2, C-RAN architecture in terms of key components and functional split is introduced. In Sect. 3 emerging PHY layer signal processing approaches for C-RAN are presented. In Sect. 4 we discuss some promising 5G techniques that can be supported and integrated with C-RAN. Some open research challenges and promising future directions are outlined in Sect. 5. Section 6 concludes this paper.

2 C-RAN Architecture

In this section, the architecture of C-RAN is presented with detailed explanations on the key components and the options of functional split. It is noted that the PHY layer and some upper layer functionalities are all located in the BS within the conventional RANs, which imposes high cost for network deployment and upgrading. Different from conventional RANs, C-RAN simplifies the BS by moving a significant part of its functionalities to the cloud server, namely the baseband unit (BBU). Therefore the deployment of a larger number of APs, namely the remote radio heads (RRHs), is possible and cost-effective. Such a new paradigm of network architecture is considered to be the foundation of the future wireless communication systems.

2.1 Key Components

Figure 1 shows the architecture of C-RAN, where the BBUs are in the cloud server, and the RRHs are geographically separated from BBUs. In addition, BBU and RRH are connected via a fronthaul link, while BBU and core network are connected via a backhaul link [17].

BBU: The BBU is enabled by cloud computing, which achieves flexible spectrum management and advanced network coordination [4]. Moreover, BBU can handle a significant part of baseband signal processing of the whole network, it also controls the signaling to RRHs. Compared to a traditional BS, the joint signal processing across a larger coverage area can be done at the BBU side in a centralized and soft way [18], which bears the potential to mitigate interference and improve the performance.

RRH: The RRH is mainly responsible for the radio frequency function and some simple signal processing. The deployment of RRH can provide seamless connection, especially in the hot spot areas. Moreover, densely deployed RRHs can offer stronger coverage with high data rate.

Fronthaul link: The fronthaul links can use wired or wireless medium based on the application scenarios, and they are capacity-limited in general. Within the two-hop C-RAN structure, the limits of fronthaul should be carefully considered for practical system designs.

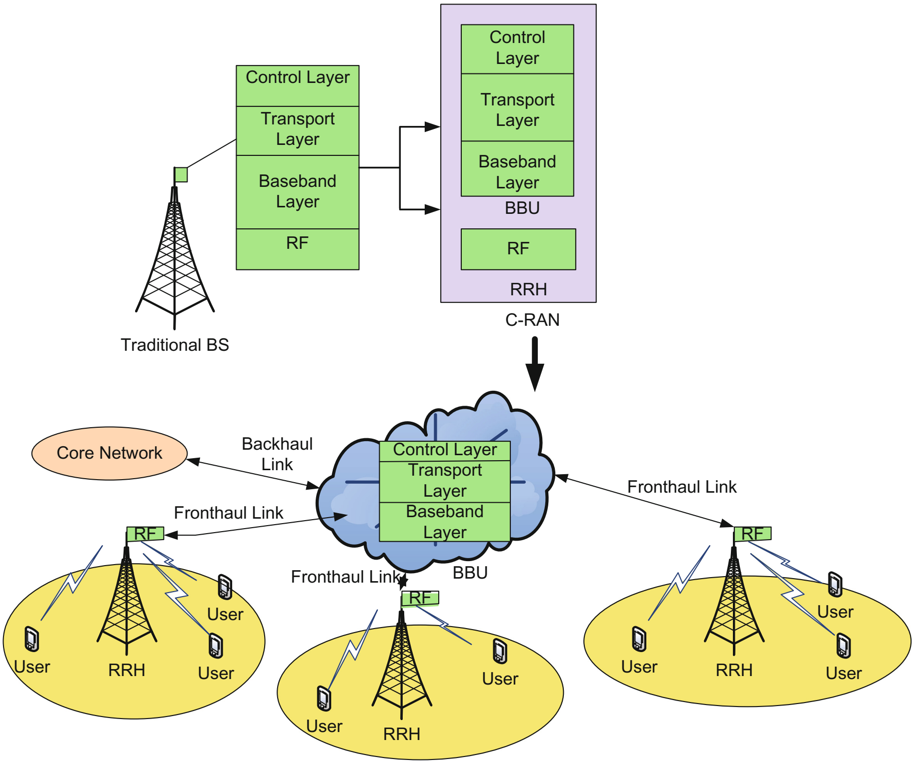


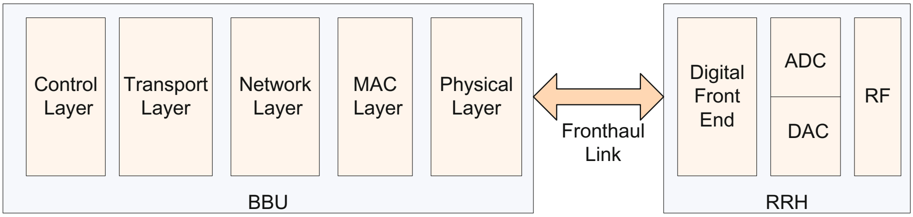
Fig. 1. C-RAN architecture.

It is worth pointing out that there are prominent advantages of the C-RAN architecture. For example, C-RAN can provide larger bandwidth by integrating heterogeneous spectrum resources, which increases the service coverage area of users. In addition, the centralized management of BBU can decrease the capital and operation expenditures. Potential gains of a large number of RRHs can be achieved by using the cooperative processing and advanced MIMO techniques.

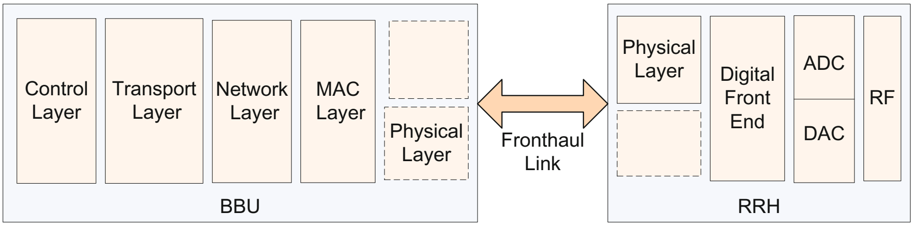
2.2 Functional Split

The centralization of the baseband signal processing in C-RAN architecture improves the flexibility of network coordination, which also enables high cooperative processing gains [19]. However, there exist tradeoffs among the split option, fronthaul capacity and signal processing complexities. In this subsection, we present three possible options of functional split between BBU and RRH, and briefly remark on the tradeoffs.

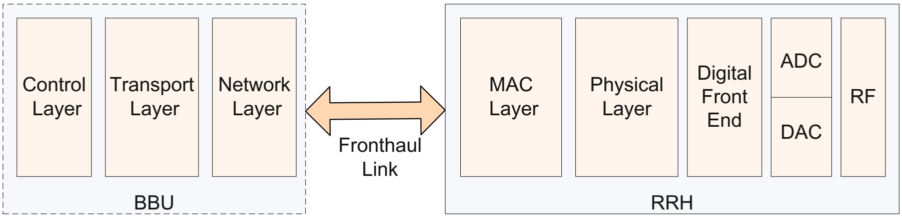
The first option is shown in Fig. 2(a), which is proposed for the initial C-RAN architecture [1]. Almost all PHY layer functionalities are moved to BBU. Meanwhile, RRH acts as a simple relay with RF, ADC/DAC and digital front-end. In this option, BBU and RRH are connected by the common public radio interface (CPRI) [2]. This centralized PHY architecture may achieve the highest cooperative processing gain. However, forwarding I/Q samples via fronthaul links requires very high transmission bandwidth. Aiming to limit the fronthaul bandwidth, I/Q samples should be compressed at BBU and RRH [19, 20]. The second option is shown in Fig. 2(b), where the baseband processing is partially centralized and some PHY layer processing is still reserved at RRH. This functional split can significantly reduce the transmission bandwidth within the fronthaul, and also achieves high cooperative processing gains.



a) Option 1



b) Option 2



c) Option 3

Fig. 2. Functional split between BBU and RRH.

However, the implementation of cooperative processing becomes complicated due to the distributed deployment of PHY functionalities [18]. This architecture aims to strike a balance between fronthaul capacity and signal processing complexity. The last option is shown in Fig. 2(c), where all functions of PHY layer are moved to the RRH.

In this architecture, the transmission bandwidth of fronthaul link is reduced to the maximum medium access control (MAC) layer throughput, which imposes the minimum fronthaul bandwidth requirement as compared to the previous two options. The price paid for this reduction is the increased scheduling delay in the fronthaul link, which may degrade system performance and network throughput [1], while the benefit of this architecture is the saving of power consumption at BBU and higher flexibility to support radio resource allocation towards users [17].

To sum up, dividing baseband signal processing between BBU and RRH gives several options to deploy the C-RAN with different fronthaul capacity limits. However, without suitable PHY layer signal processing, it is challenging to realize cost-effective deployment of C-RANs.

3 PHY Layer Signal Processing

In this section, we discuss signal processing approaches in the PHY layer, where CSI acquisition, data compression and transmission, and resource management are focused as shown in Fig. 3. It is noted that accurate CSI is the prerequisite of many advanced data transmission schemes, where both training-based and blind schemes can be used. In addition, the massive RRHs and the limited capacity of the fronthaul impose new challenges for CSI acquisition and data transmission. Therefore, advanced compression schemes are necessary to address these issues. Finally, radio resource allocation is discussed, which improves system performance.

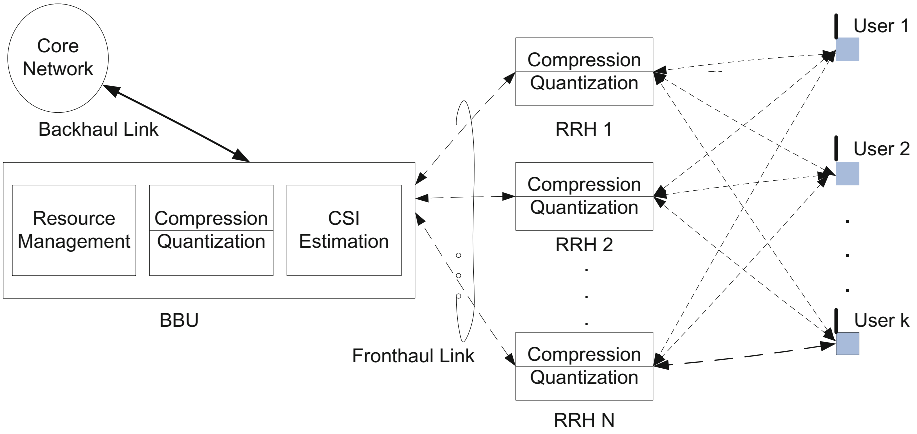


Fig. 3. PHY layer signal processing for uplink and downlink of C-RAN.

3.1 CSI Acquisition

CSI acquisition is the first step for data transmission in C-RAN. It is noted that C-RAN consists of two-hop links, namely the access links between RRHs and users and the fronthaul links between BBUs and RRHs. To this end, the channel estimation methods are similar to those of the relay channels while the constraints of the fronthaul and massive RRHs should be carefully considered. Saving overhead for CSI acquisition in C-RAN is necessary and important. Considering the limited capacity of fronthaul links, the transmission overhead of training sequences should not be very large, and the limited resources devoted to CSI estimation shall be fully utilized. For uplink transmission in C-RAN, the joint channel estimation and CSI compression transmission schemes have been proposed in the literature. The BSs compress the received data and training signals and transmit them to BBU, then BBU estimates the channel and decodes the data [22, 23]. These schemes can significantly reduce the transmit overhead of training sequences and relieve the severe burden of fronthaul links. Moreover, sparse channel estimation has been proposed in [24] based on the principle of compressed sensing, where the inherent sparse nature of C-RAN can be utilized to save system overhead. It is worth pointing out that as C-RAN evolves, more factors should be taken into account in the channel estimation, e.g., the increasing number of channel parameters, the heterogeneity of APs and the delay of fronthaul links. Therefore, fast, scalable and cost-effective channel estimation methods should be developed to meet the demands of C-RANs.

3.2 Compression and Transmission

A high amount of traffic including training sequences and data must be transmitted on the fronthaul links. However, the capacity of fronthaul link is in general limited, which serves as the main bottleneck to fully achieve large-scale cooperative processing gains in C-RANs. To this end, various compression and quantization methods for uplink and downlink transmission have been proposed in the literature [21, 24–26]. For uplink transmission, signals from users are quantized at the RRHs and sent to BBU for further signal processing. This is known as the compress-and-forward strategy in the literature [21]. BBU needs to extract the useful CSI from the quantized and compressed samples while performing detection and decoding. For downlink transmission, BBU performs joint compression and encoding, and then the compressed samples are forwarded to the RRHs using fronthaul links. Moreover, for multi-user transmission BBU can perform joint quantization of multiple sources, which is known as the multivariate quantization [24]. Compared to the conventional point-to-point quantization, multivariate quantization can reduce the negative impact of quantization errors, which distinctly improves the quality of signals transmitted to users. Table 1 compares various relevant compression methods for C-RAN, which has been considered in [2, 4, 21, 25].

3.3 Resource Management

Resource management is an important issue to fulfill the potential of C-RAN to achieve higher SE and EE. Although conventional resource allocation schemes can be borrowed to improve SE in C-RAN, EE-oriented optimization calls for new designs. Recently, there has been some works on the methods to improve EE in C-RAN [9, 27–29].

Table 1. Compression methods for C-RAN uplink and downlink transmission.

Name of the compression methods	Communication–Oriented Optimization	Complexity	Compression ratio	Number of RRH antennas
Compression using scheduling side information	No	Low	High compression ratio	Single antenna
Wyner-Ziv lossy compression	No	High	High compression ratio, support a larger number of antennas	Single antenna
Adaptive compression	Minimize the number of bits under the BLER constraint	Low	Adaptive compression ratio, exploit the cross-correlation of signals	Single antenna
Spatial compression	Maximize the minimum SINR by delicately designing the power allocation	Low	Significant gain over the conventional quantize-and-forward	Multiple antennas

For example, energy saving can be achieved by switching off a subset of RRHs when the network traffic load is not high. To this end, the rest RRHs should collaboratively serve all users including users in the BS sleeping area as shown in Fig. 4. Results show that the BS sleeping method [29] reduces the total power consumption. Although promising, the selection of the sleeping RRHs is a non-trivial task; the related optimization problem is complicated and requires network coordination. On the other hand, the radio resource in C-RAN is multi-dimensional. The RRH clustering, transmit beamforming, user association and power allocation can be jointly optimized to meet different objectives in terms of SE, EE and delay [28]. To this end, efficient resource allocation schemes should be developed; and the implementations of these algorithms are also influenced by the functional split of the underlying network architecture.

4 C-RAN and 5G Technologies

In this section, we discuss flexible network configuration of C-RAN, which can be combined with other candidate 5G technologies. As mentioned earlier, next generation of wireless communication networks call for significant innovation in both PHY layer techniques in the RAN as well as the entire network architecture. In order to exploit potential gains, C-RAN should cooperate with other advanced technologies, e.g., HetNets, SDN, mmWave and full-duplex radio, as illustrated in Fig. 5. Integrated with SDN framework, the BBU is placed at the control layer, while RRH is placed at the infrastructure layer. Infrastructure layer of SDN is often operated with HetNets, which includes low power nodes (LPNs) and high power nodes (HPNs). Furthermore, new resources such as mmWave spectrum can be used to further improve the network

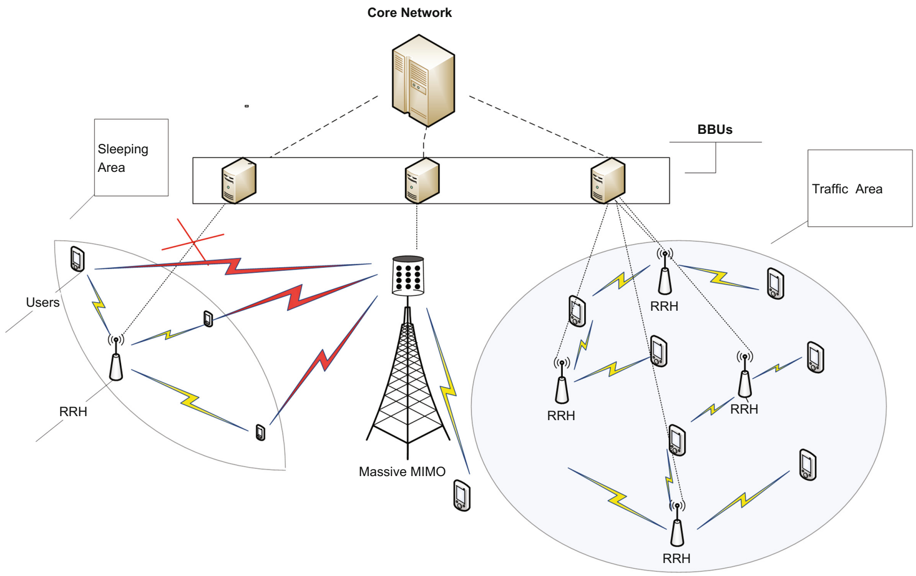


Fig. 4. Resource management in C-RAN.

throughput. Finally, full-duplex operation can be embedded into C-RAN architecture to further improve the system SE.

4.1 HetNets and C-RAN

In this subsection, we briefly show the advantages of implementing C-RAN into HetNets to enable more flexible utilization of heterogeneous resources. Low power nodes, such as pico BS, femto BS and small cell BS, are components to increase the capacity of cellular networks in the hot spot areas [30]. Low power nodes can cooperate with high power nodes, such as macro BSs or micro BSs. The prominent advantage of HetNets is to support high data rates in hotspot areas. However, the handover among different networks/APs/BSs may not be smooth, and the interference management is in general challenging. The 5G system is expected to solve this problem with the help of C-RAN. The combination of HetNet and C-RAN results in a new paradigm of RAN, namely the heterogeneous cloud radio access network (H-CRAN) [31], which is shown in Fig. 5. Such network architecture enjoys several advantages. Firstly, deploying C-RAN to support HetNet can achieve seamless connection. Moreover, compared to the traditional wireless cellular network, H-CRAN can provide significant SE and EE by using large-scale cooperative processing and resource management. Finally, the collaboration between HetNets and C-RAN facilitate effective mobility management to achieve a smooth handover.

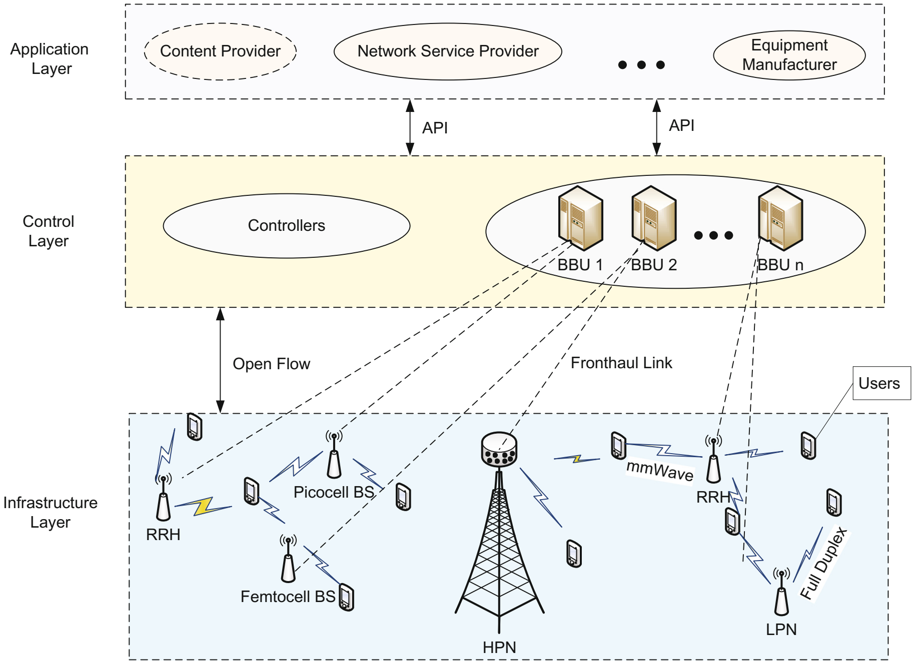


Fig. 5. C-RAN and some of the candidate 5G technologies.

4.2 SDN and C-RAN

SDN is a cost-effective, adaptable and manageable architecture, which decouples network control and forwarding functionality [17]. It is convenient for the operators to upgrade software separately from hardware via centralized controllers in the control layer. The first architecture of SDN was proposed only for wired communications. Unfortunately, the original conceptual SDN framework is not readily implementable in wireless communication networks. A solution of this problem is to combine SDN with C-RAN, i.e., SDN-CRAN [31]. SDN consists of an application layer, a control layer and an infrastructure layer. In SDN-CRAN architecture, the BBU is operated in the control layer and RHHs are in the infrastructure layer as shown in Fig. 5. The control layer is the core part of SDN architecture. The functions of data traffic offloading, caching, storage, mobility management are all controlled by BBU with the help of SDN.

4.3 mmWave and C-RAN

Millimeter wave (mmWave) is a strong candidate technology for 5G systems [32–35], and it can be used to empower C-RAN. First, the mmWave spectrum spans from 3 GHz to 300 GHz, which offers abundant spectrum resources to enable a huge transmission bandwidth. In C-RAN, mmWave can not only be utilized to improve the capacities of the access links between RRH and user, but also improve the wireless fronthaul capacity as well. Secondly, the propagation characteristics of mmWave [35] facilitate the dense deployment of RRHs and also simplify the interference management. The high attenuation of mmWave indicates its application in line-of-sight (LoS) environment, which matches well to the layout of C-RAN. The RRHs are deployed to be near to users, where LoS scenarios are predominant. Meanwhile, the strong path-loss of mmWave will cause less interference leakage; therefore, the location-aware and local interference managements may be useful in C-RAN, which in turn relieve the heavy burden of large-scale network coordination and fronthauling. Finally, mmWave can enable cost-efficient MIMO techniques to further improve the SE and EE in C-RAN [6]. Because the wave-length of mmWave frequencies is small, the technology also enables to build very compact and low-cost antenna arrays with large number of elements [32]. When RRHs are equipped with such antenna arrays, advanced directional beamforming can be dynamically designed to improve the SE and EE in C-RAN.

4.4 Full-Duplex and C-RAN

Full duplex communications can realize the simultaneous transmission and reception on the same frequency resource; therefore it is possible to achieve the goal of doubling the SE in future wireless systems [36]. In C-RAN, full-duplex radio technique can be implemented at the RRHs [37]. When employing full-duplex communications, the major challenge is to combat with the loopback interference (LI), which is leaked from the output to the input side of transceiver. There are several antenna domain, analog domain and digital domain approaches for suppressing the LI. In a full-duplex enabled C-RAN, LI can be naturally mitigated due to the path loss among the distributed RRHs [38, 39]. Moreover, to improve the transmit data rate and mitigate LI in a full duplex C-RAN, it is worthwhile to investigate schemes to properly design the RRH association and beamforming. The combination of full-duplex and other types of duplexing models in C-RAN also deserves further research attention.

5 Challenges and Future Directions

In this section, challenges and interesting future directions for C-RAN are briefly discussed. Specifically, mobile edge computing and caching, multi-dimensional resource management, and PHY layer security of C-RAN are highlighted.

5.1 Mobile Edge Computing and Caching

Aiming to offload the heavy burden of the fully centralized C-RAN, mobile edge computing (MEC) has been recently proposed to offer computing capabilities and resources to the edge devises in the RAN [47]. In particular, some new elements are deployed at the BS, RRH and users, which can perform local signal processing and storage functions. Employing mobile edge computing, some popular contents such as videos or social media can be locally cached and processed by the edge devices; the delivery and service latency towards the users can be significantly reduced, improving the QoE of users [39]. To this end, a possible evolution of C-RAN has been proposed, namely the fog radio access network (F-RAN) [40]. The main idea of F-RAN is to remove some signal processing functions from the central cloud to the geographically distributed RRHs. A convenient realization of F-RAN is to equip the RRHs with limited cache storage so these RRHs can pre-fetch the popular content videos during the off-peak hours. Compared to the conventional C-RAN, F-RAN can significantly relieve the serious traffic burden of fronthaul links to effectively avoid the network congestion and reduce the service delay. In this scenario, the major challenge is to effectively utilization the limited storage capacity and to increase the probability that the requirement of users can be satisfied locally to improve the QoS of users.

5.2 Multi-dimensional Resource Management

C-RAN encompasses multi-dimensional resources, including radio resources, computation resources, storage resources and power in general [41–43]. Noting the MEC and caching have been introduced as new functional elements of C-RAN, the resource management and allocation is more challenging and complicated to meet diverse requirements, objectives and constraints. For example, the radio resources should be jointly considered with the computational and storage capabilities to enable high quality video service with mobile edge computing, while the capacity constraints of the fronthaul and the delay constraints for the fetch-and-forward transmission should be carefully taken into account in C-RAN. Although the conceptual model of SDN and NFV suggests resource abstraction in a global view, the large-scale and fast resource slicing is still very challenging due to its inherent complexity, protocol barrier and stringent delay constraints. Moreover, the integration of multi-dimensional heterogeneous resources is challenging, such as the mobility management and cooperation among HetNets [43]. Aiming at large-scale and multi-dimensional resource management, the game theoretical approach [44] as well as distributed learning based schemes [45] may be useful in conjunction with mobile edge computing. Moreover, big data and advanced data mining techniques [46] can be introduced in C-RAN to model and predict the user's behavior, contents popularity and service diversities and so on, which will enable more intelligent and fast resource management.

5.3 PHY Layer Security of C-RAN

Due to the openness of the radio mode in C-RAN, exchanged information becomes more vulnerable to eavesdropping. The broadcast nature of the wireless transmission medium, the relay-like RRH functions and the cloud environment all make the secure information transmission challenging in C-RAN. Focusing on the PHY layer, recently PHY layer security has been proposed as a viable technique to secure wireless communications [48, 49] against eavesdropping and attacking. Different from the conventional cryptographic techniques in the higher layers, PHY layer security exploits the characteristics of the wireless channels to secure message transmission. In some network settings, such as the conventional signal-cell, multi-cell and HetNets, PHY layer security can improve secrecy rates [48, 49]. In C-RAN, one of the unique challenges to apply PHY layer security is the smart coordination of the ubiquitous interference. As the density of RRH increases, mutual interference may become stronger and the interplay among useful signal, interference signal and jamming signal becomes more complicated. To this end, advanced collaborative MIMO signal processing can be used, where RRHs can be clustered to jointly perform secrecy beamforming [50, 51] to combat eavesdropping and interference can be judiciously utilized to improve the secrecy performance [52].

6 Conclusion

In this paper, we discussed fundamental concepts, key techniques, and challenges of the C-RAN architecture in the context of emerging 5G wireless communication systems. We reviewed key components of C-RAN, functional split between the BBU and RRH as well as the signal processing approaches for uplink and downlink transmission. To effectively utilize the limited capacity of fronthaul links, compression and quantization methods for C-RAN uplink and downlink transmission were investigated. In addition, resource management schemes for energy saving were discussed to meet the requirements of green communications. To exploit potential performance gains, SDN, HetNets and mmWave and full-duplex communications can be combined with C-RAN to increase the SE, EE and network throughput. Finally, we presented some challenges and future directions, where mobile edge computing and caching, multi-dimensional resource management and wireless security are major concerns for further evolution of the C-RAN architecture.

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