

Fronthaul-Constrained Cloud Radio Access Networks: Insights and Challenges

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Abstract

As a promising paradigm for fifth generation (5G) wireless communication systems, cloud radio access networks (C-RANs) have been shown to reduce both capital and operating expenditures, as well as to provide high spectral efficiency (SE) and energy efficiency (EE). The fronthaul in such networks, defined as the transmission link between a baseband unit (BBU) and a remote radio head (RRH), requires high capacity, but is often constrained. This article comprehensively surveys recent advances in fronthaul-constrained C-RANs, including system architectures and key techniques. In particular, key techniques for alleviating the impact of constrained fronthaul on SE/EE and quality of service for users, including compression and quantization, large-scale coordinated processing and clustering, and resource allocation optimization, are discussed. Open issues in terms of software-defined networking, network function virtualization, and partial centralization are also identified.

Index Terms

Cloud radio access networks (C-RANs), fronthaul-constrained, cloud computing, large-scale coordinated processing

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I. INTRODUCTION

The mobile communication industry is currently developing the fifth generation (5G) system, with the objective of providing pervasive always-on, always-connected broadband packet services. It is widely agreed that compared to the fourth generation (4G) system, 5G should achieve system capacity growth by a factor of 1000, and spectral efficiency (SE), energy efficiency (EE) and data rate growth all by a factor of 10 [1]. To achieve these goals, radically new technologies need to be developed. Inspired by the green soft cloud/collaborative/clean access networks in [2], the cloud radio access network (C-RAN) has been proposed as a combination of emerging technologies from both the wireless and the information technology (IT) industries by incorporating cloud computing into radio access networks (RANs).

In C-RANs, the traditional base station (BS) functions are decoupled into two parts: the distributed installed remote radio heads (RRHs) and the baseband units (BBUs) clustered as a BBU pool in a centralized cloud server. RRHs support seamless coverage and provide high capacity in hot spots, while BBUs provide the large-scale processing and management of signals transmitted/received from diverse RRHs, where the cloud computing technology provides flexible spectrum management and advanced network coordination. Through the fronthaul between RRHs and BBUs, the cost-effective and power-efficient RRHs can operate as soft relays by compressing and forwarding the signals received from user equipments (UEs) to the centralized BBU pool, as depicted in Fig. 1. Further, the system can be developed using software radio technology to further enable all centralized processing to use platforms based on an open IT architecture, which makes upgrading to different RAN standards possible without hardware upgrades. Additional advantages of C-RANs include advanced technology facilitation, resource virtualization/cloudization, low energy consumption, and efficient interference mitigation through large-scale cooperative processing.

Since the C-RAN architecture was first proposed by China Mobile in 2011 [2], further research and development has been pursued. With the C-RAN architecture, mobile operators can quickly deploy RRHs to expand and make upgrades to their networks. Therefore, the C-RAN has been advocated by both operators (e.g., France Telecom/Orange, Telefonica, and China Mobile) and equipment vendors (e.g., Alcatel-Lucent LightRadio, and Nokia-Siemens LiquidRadio) as a means to achieve the significant performance gains required for 5G. At the same time, several

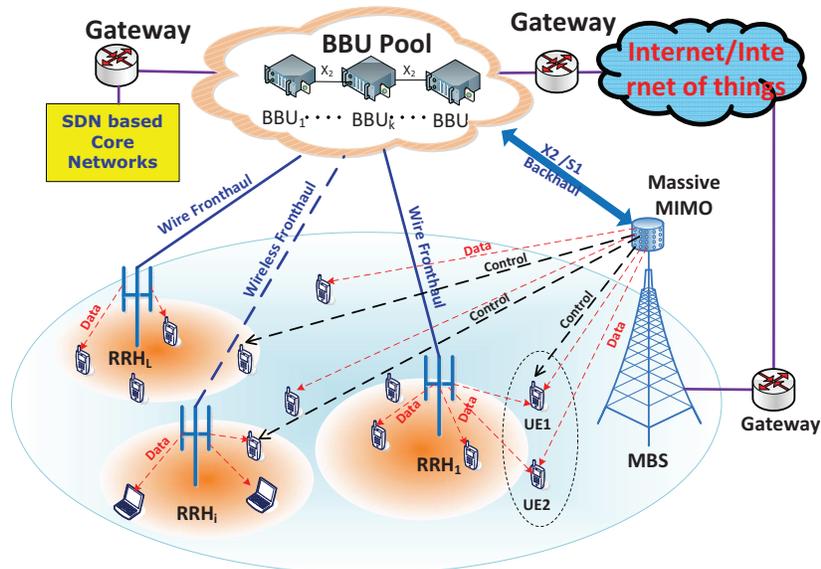


Fig. 1. The components and system architecture of C-RANs

C-RAN projects have been initiated in many organizations such as the Next Generation Mobile Networks (NGMN) project, the European Commission's Seventh Framework Programme, etc.

Despite their attractive advantages, C-RANs also come with their own challenges in connection with the fronthaul links created by this architecture. As presented in Fig. 1, a prerequisite requirement for the centralized processing in the BBU pool is an inter-connection fronthaul with high bandwidth and low latency. Unfortunately, practical fronthaul is technology capacity or time-delay constrained, which has a significant impact on SE and EE performance gains of C-RANs. To overcome the disadvantages of C-RANs imposed by the fronthaul constraints, compression and large-scale pre-coding/de-coding with low overhead are required. Additionally, radio resource allocation optimization taking the constrained fronthaul into account is also key to mitigating interference, guaranteeing the diverse quality of service (QoS) requirements for different UEs, and achieving significant SE and EE performance gains.

A number of studies of feasible designs and operations of C-RANs have been published recently. In [3], the heterogeneous cloud radio access network (H-CRAN) as a 5G paradigm toward green and soft themes is briefly presented to enhance C-RAN. To alleviate the capacity constraint on the fronthaul links, a multi-service small-cell wireless access architecture based on combining radio-over-fiber with optical wavelength division multiplexing (WDM) techniques is proposed in [4]. Unfortunately, until now the characteristics of fronthaul-constrained C-RANs

have not been highlighted, and a framework for improving SE/EE performance and guaranteeing diverse QoS requirements for different UEs with reference to the system architecture and key techniques has not been treated in depth. In this article, we present a comprehensive survey of technological features and core principles of fronthaul-constrained C-RANs. In particular, the system architecture of C-RANs is presented, and key techniques including large-scale coordinated processing and clustering, compression and quantization, and resource allocation optimization to improve SE/EE performance and guarantee diverse QoS requirements in fronthaul-constrained C-RANs are summarized. Challenging open issues related to fronthaul-constrained C-RANs, including software-defined networking (SDN), network function virtualization (NFV), and partial centralization, are discussed as well.

The remainder of this paper is organized as follows. C-RAN system architectures are introduced in Section II. Compression and quantization techniques to improve SE and EE performance for fronthaul-constrained C-RANs are presented in Section III. Large-scale coordinated processing and clustering techniques are introduced in Section IV. Resource allocation optimization techniques adaptive to diverse and time-varying packet services are discussed in Section V. Future challenges are highlighted in Section VI, followed by conclusions in Section VII.

II. C-RAN SYSTEM ARCHITECTURES

A C-RAN centralizes different baseband processing resources to form a single resource pool, such that the resource can be managed and dynamically allocated on demand. C-RANs have several advantages over traditional cellular architectures, such as increased resource utilization efficiency, low energy consumption, and light interference.

A. C-RAN Components

The general architecture of a C-RAN consists of three components, namely (i) a BBU pool consisting of a large number of BBUs with centralized processors, (ii) RRHs with antennas located at remote sites, and (iii) a fronthaul network that connects RRHs to BBUs with high capacity and low time latency.

1) *RRH*: RRHs are mainly used to provide high data rate for UEs with basic wireless signal coverage, by transmitting radio frequency (RF) signals to UEs in the downlink and forwarding the baseband signals from UEs to the BBU pool for centralized processing in the uplink. In general,

RRHs perform RF amplification, up/down conversion, filtering, analog-to-digital conversion, digital-to-analog conversion, and interface adaptation. By conducting most signal processing functions in the BBU pool, RRHs can be relatively simple, and can be distributed in a large-scale scenario with a cost-efficient manner.

2) *BBU Pool*: A BBU pool is located at a centralized site and consists of time-varying sets of software defined BBUs, which operate as virtual BSs to process baseband signals and optimize radio resource allocation. In the software defined BBU, the signal processing resources are dynamically allocated and the processing capability is adaptively reconfigured based on traffic-aware scheduling of UEs and time-varying radio channels. The radio resources of different BBUs can be fully shared, and thus a large-scale virtual multiple-input multiple-output (MIMO) system is formed from the BBU pool's perspective.

3) *Fronthaul*: Fronthaul is defined as the link between BBUs and RRHs, and its typical protocols include the common public radio interface (CPRI) and the open base station architecture initiative (OBSAI) [5]. Fronthaul can be realized via different technologies, such as optical fiber communication, cellular communication, and even millimeter wave communication. Generally, fronthaul falls into two categories: ideal without any constraints, and non-ideal with bandwidth, time latency and jitter constraints. Optical fiber communication without constraints is considered to be the ideal fronthaul for C-RANs because it can provide high transmission capacity at the expense of high cost and inflexible deployment. By contrast with optical fiber, wireless fronthauls employing cellular or microwave communication technologies with carrier frequencies between 5 and 40 Gigahertz (GHz) are cheaper and more flexible to deploy, at the expense of capacity and other constraints. Since wireless fronthaul or capacity-constrained optical fiber is cheap and flexible, these technologies are anticipated to be prominent in practical C-RANs, and thus this article will focus only on such non-ideal constrained fronthaul.

B. C-RAN System Structures

Although there are various possibilities for C-RAN structures, according to the constraints on fronthaul and the distribution of functions between BBUs and RRHs, three options are categorized as shown in Fig. 2.

Full centralization: This is also called a stacked BBU structure [2], where functions of the baseband (i.e., physical layer, Layer 1), the medium access control layer (MAC, Layer 2),

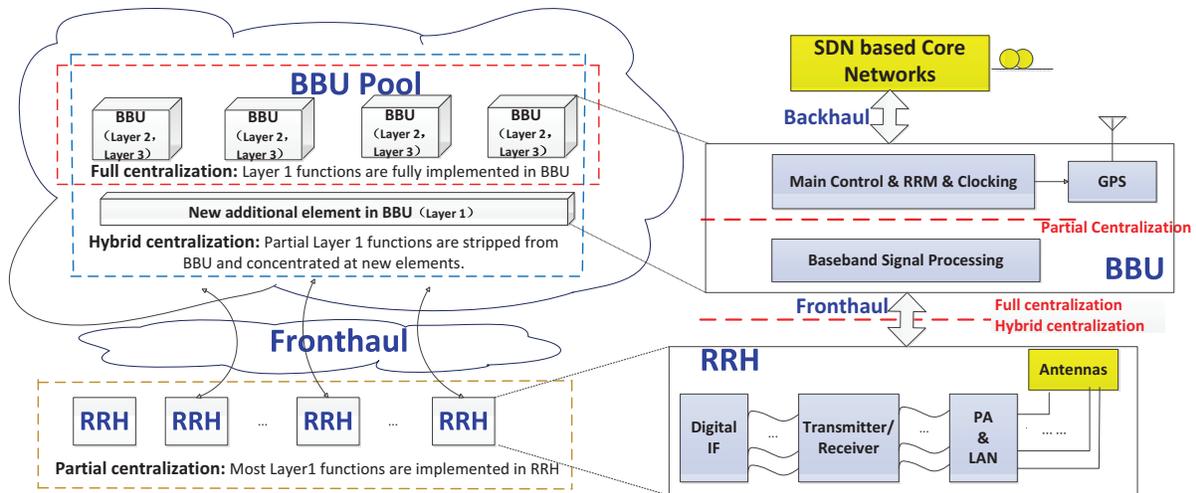


Fig. 2. Three options of C-RAN system structures

and the network layer (Layer 3) of the conventional BS are moved into the BBU. This option is the premier C-RAN configuration, which is clear and simple, but incurs a high burden on fronthaul. The BBU contains all processing and managing functions of the traditional BS. Since this structure has significant benefits in terms of operation and maintenance, significant attention has been devoted to developing techniques to alleviate the heavy burden on the fronthaul of this system.

Partial centralization: This is also called the standalone Layer 1 structure, in which the RRH integrates not only the RF functions but also some RF related baseband processing functions, while all other functions in Layer 1 and the upper layers are still located in the BBU. This option greatly reduces the RRH-BBU overhead and alleviates the constraints on fronthaul since Layer 1 bears the major computational burden of RANs. However, some advanced features such as coordinated multiple point transmission and reception (CoMP) and spatial cooperative processing for distributed massive MIMO cannot be efficiently supported. The interaction between Layer 2 and Layer 1 can also be complex, which increases the difficulty of interconnection between Layer 2 and Layer 1. In other words, this structure is still far from being practical.

Hybrid centralization: This is regarded as a special case of full centralization, in which partial functions in Layer 1 such as the user specific or cell specific signal processing functions are removed from BBUs, and assembled into a separate processing unit, which may be a part of the BBU pool. The benefit of this structure is its flexibility to support resource sharing and

the potential capability to reduce modifications and energy consumption in BBUs.

For the fully centralized structure, the performance of C-RANs is clearly constrained by the fronthaul link capacity. In the uplink, for instance, RRHs need to sample, quantize, and then forward the received RF signals to the BBU pool. With densely deployed RRHs, the fronthaul traffic generated from a single UE with several MHz bandwidth could be easily scaled up to multiple gigabits per second (Gbps). In practice, a commercial fiber link with tens of GHz capacity could thus be easily overwhelmed even under moderate mobile traffic. One approach to this problem is to utilize the partially centralization structure though substantial signal processing capabilities are required on RRHs; the other alternative is to adopt advanced techniques to optimize the performance under a fully centralized structure with constrained fronthaul. To simplify functions and capabilities of RRHs, the latter solution is the focus of this article, and the corresponding key techniques are surveyed.

III. SIGNAL COMPRESSION AND QUANTIZATION

A C-RAN can be regarded as a special case of a relay structure with a wireless first-hop link and a wireless/fiber second-hop link. Signal compression/quantization is critical to alleviating the impact of fronthaul constraints on SE and EE performance. From an information theoretic perspective, the effects of compression and quantization can be modeled via a test channel, with the uncompressed signals as the input and the compressed signals as the output. The test channel is often modeled as a Gaussian channel for simplicity of analysis, in which the output signal is generated from the input signal corrupted by an additive Gaussian compression noise. The design of a codebook for this channel is equivalent to setting the variance of the compression noise. An interesting result shows that by simply setting the quantization noise power proportional to the background noise level at each RRH, the quantize-and-forward scheme can achieve a capacity within a constant gap to a throughput performance upper (i.e., cutset) bound [6].

A. Compression and Quantization in the Uplink

In the uplink (UL), each RRH compresses its received signal and forwards the compressed data to the central BBU pool as a soft relay through the limited-capacity fronthaul link. The central BBU pool then performs joint decoding of all UEs based on all received compressed signals. Compared to conventional independent compression across RRHs, distributed source

coding strategies are generally beneficial since signals received at different RRHs are statistically correlated [7]. By leveraging signals received from other RRHs as side information, distributed source coding can reduce the rate of the compressed stream by introducing some uncertainty into the compressed signal that is resolvable and enables the quality of the compressed signal received from the desired RRH to be improved. The amount of rate reduction that is allowed without incurring decompression errors depends critically on the quality of the side information, which should be known to the encoder. When multiple RRHs compress and forward their received signals to the BBU pool, the compression design is transformed into the problem of setting the covariance matrix of the compression noises across different RRHs. In this setting, distributed Wyner-Ziv lossy compression can be used at RRHs to exploit the signal correlation. In particular, considering the fact that the observations of all coordinating RRHs are actually correlated because they are broadcast from the same source, distributed Wyner-Ziv compression can be applied to exploit this correlation and reduce the required fronthaul transmission rate.

However, the distributed compression techniques require each RRH to have information about the joint statistics of the received signals across all RRHs, and they are generally sensitive to uncertainties regarding the side information. Therefore, the implementation of distributed Wyner-Ziv compression is difficult mainly due to the high complexity of determining the optimal joint compression codebook and the joint decompressing/decoding at the BBU pool. Alternatively, for the independent compression method, the quantization codebook of an RRH is determined only by its local channel state information (CSI), and the decompression operation at the BBU pool is also on a per-RRH basis. Although independent quantization reduces the fronthaul complexity compared to joint compression design, the compression codebook generation is still based on information theoretic source coding techniques, which can be highly complex and impractical in a rapidly varying wireless environment. A robust compression scheme for a practical scenario with inaccurate statistical information about the correlation among the RRHs' signals was proposed in [7]. By using an additive error model with bounds on eigenvalues of the error matrix to model the inaccuracy, the problem is formulated and a corresponding solution is provided to achieve a stationary point for the problem by solving Karush-Kuhn-Tucker conditions. It is observed that, despite the imperfect statistical information, the proposed robust compression scheme can tolerate sizable errors with drastic performance degradation while maintaining the benefits of distributed source coding.

It is worth noting that a potential advantageous approach for C-RANs is when the decoder performs joint decompression and decoding. This approach was first studied in [8] for the scenario with multi-antenna BSs and multi-antenna UEs. The sum-rate maximization problem with joint decompression and decoding under the assumption of Gaussian test channels is shown to be an instance of non-convex optimization. To solve this problem, an iterative algorithm based on the majorization minimization (MM) approach was proposed to guarantee the convergence to a stationary point of the sum-rate maximization. As shown in Fig. 3, the advantage of the proposed joint decompression and decoding with MM has been demonstrated compared to the conventional approaches based on the separate decompression and decoding with exhaustive ordering or with greedy ordering. Further, the rates achieved by this approach are much closer to the cutset upper bound than those of separate decompression and decoding approaches.

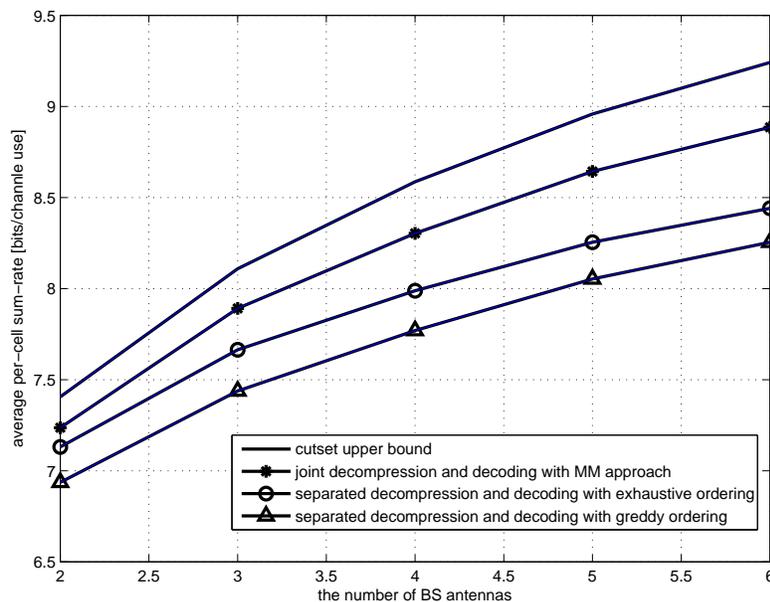


Fig. 3. Performance comparisons between the joint and separated decompression and decoding approaches, where the number of cells is assumed at 3, the UE transmission power is 20 dBm, the fronthaul capacity is constrained by 12 bit/c.u., and the inter-cell channel gain is assumed to be -10 dB [8].

B. Compression and Quantization in the Downlink

Similarly to the UL, the compression-and-forward strategy is also useful in the downlink (DL), where the BBU pool first pre-codes each message for UEs to allow for interference collaboration both across UEs and among data streams for the same UE, and then compresses the pre-coded signals for the distributed UEs via RRHs. As a counterpart of the distributed source coding strategy for the UL, the joint design of precoding and compression based on multivariate compression for finite-capacity DL fronthaul links was studied in [9]. Unlike conventional point-to-point compression, the effects of the additive quantization noises at UEs can be controlled through proper design of the correlation of the quantization noises across RRHs. The problem of maximizing the weighted sum-rate subject to the fronthaul constraints over the precoding matrix and the compression noise covariance for given weights can be formulated and solved. It is confirmed in [9] that the joint precoding and compression strategy outperforms conventional approaches based on the separate design of precoding and compression or independent compression across RRHs, especially when the transmit power or the inter-cell channel gain are large, or when the limitation imposed by the finite-capacity fronthaul links is significant. Notably, it is observed that multi-terminal compression strategies provide performance gains of more than 60% for both UL and DL in terms of the cell-edge throughput.

Instead of the aforementioned pure compression strategy with constrained fronthaul, a hybrid compression and message-sharing strategy for DL transmission is presented in [10]. In the proposed strategy, the BBU pool directly sends messages for some UEs to the RRH along with the compressed pre-coded signals of the remaining UEs. An overall algorithm to optimize the hybrid strategy involving the choice of beamforming vector, power, quantization noise levels, and more importantly the decision of which users should participate in the direct message transmission and which users in compression is presented. The numerical results show that the hybrid strategy can achieve a saving in fronthaul capacity of about 60% compared with the message-direct transmission scheme, and improve the rate of the 50th percentile user by about 10% at the same fronthaul capability compared with the pure compression scheme, which demonstrates that this approach outperforms the pure compression and the pure message-direct transmission schemes.

IV. COORDINATED SIGNAL PROCESSING AND CLUSTERING

Large-scale coordinated signal processing in the BBU pool is considered one of the most promising techniques to improve network capacity performance. It is necessary to exploit precoding and decoding coefficient design schemes that make special considerations for the capacity-constrained fronthaul. Full-scale coordination in a large-scale C-RAN requires the processing of very large channel matrices, leading to high computational complexity and channel estimation overhead. For example, when the optimal linear receiver is adopted, the computational complexity typically grows cubically with the precoding matrix size. This implies that the average computational complexity per RRH or per UE grows quadratically with the matrix size, which fundamentally limits the scale of RRH cooperation. One potential solution is to decompose the overall channel matrix into small sub-matrices, which results in adopting the user-centric clustering technique. According to the clustering technique, a sub-matrix can be formed and processed separately, although this would inevitably cause performance loss.

A. Precoding Techniques

There are two types of in-phase and quadrature (IQ)-data transfer methods in fronthaul: 1) **after-precoding**, with which a BBU transfers IQ-data after precoding data symbols with a beamforming matrix or vector, and 2) **before-precoding**, with which a BBU transfers beamforming weights for each data stream and data symbols separately before data symbols are precoded. The required bit-rate for after-precoding IQ-data transfer depends only on the number antennas used for transmission/reception at the RRH. With after-precoding, all the information for IQ-data should be exchanged for each symbol between the BBU and the RRH. In contrast, with before-precoding IQ-data transfer, data symbols for each user are exchanged for each symbol duration, but beamforming weights for each data stream are exchanged less frequently according to the channel coherence time.

In a C-RAN, only a small fraction of the overall entries in the channel matrix have reasonably large gains, since any given user is only close to a small number of RRHs in its neighborhood, and vice versa. Thus, ignoring the small entries in the channel matrix can significantly sparsify the matrix, which potentially leads to a great reduction in processing complexity and channel estimation overhead. Therefore, group sparsity is often required rather than individual sparsity in practical C-RANs. For example, the mixed l_1/l_p -norm is adopted in [11] to induce sparsity

in large-scale cooperative C-RANs. Two group sparse beamforming (GSBF) algorithms of different complexities are proposed: namely, a bi-section GSBF algorithm and an iterative GSBF algorithm. It is demonstrated that the GSBF framework is very effective in providing a near-optimal solution. The bi-section GSBF algorithm proves to be a better option for large scale C-RANs due to its low complexity. The iterative GSBF algorithm can be applied to provide better performance in a medium-size network. Note that all the precoding techniques mentioned in this section assume the availability of perfect CSI at the BBU. It is therefore apparent that the acquisition of perfect CSI is critical to optimal precoding design in C-RANs; however, obtaining perfect CSI is very challenging because many parameters are involved, leading to significant estimation errors, quantization errors and feedback delays.

B. Clustering Techniques

By controlling the number of RRHs in one cluster for a typical user, clustering techniques can limit the estimation overhead and computational complexity to a low level, which results in low capacity requirements on the fronthaul. However, this technique inevitably reduces the C-RAN large-scale cooperative processing gains and lowers the C-RAN capacity. By limiting the scale of coordinated RRHs within a small cluster, the centralized processing capability is not fully exploited.

There are two types of RRH clustering schemes: disjoint clustering and user-centric clustering. In disjoint clustering, the entire C-RAN is divided into non-overlapping clusters and RRHs in each cluster jointly serve all UEs within the coverage area. Although disjoint clustering has already shown its effectiveness in mitigating the inter-cell interference, those UEs at the cluster edge still suffer from considerable inter-cluster interference. Alternatively, in user-centric clustering, each UE is served by an individually selected subset of neighboring RRHs and different clusters for different UEs may overlap. The benefit of user-centric clustering is that there exists no explicit cluster edge. The user-centric clustering scheme can be further categorized into two different implementations depending on whether the RRH clustering is dynamic or static over different time slots. In dynamic user-centric clustering, the RRH cluster for each UE can change over time, allowing for more freedom to fully utilize the fronthaul resources. However, dynamic user-centric clustering also requires a large amount of signaling overhead as new UE associations need to be established continuously. In static user-centric clustering,

the UE association is fixed over time and may only need to be updated as the UE location changes. Dynamic clustering can significantly outperform the disjoint clustering strategy, while the heuristic static clustering schemes can achieve a substantial portion of the performance gain.

The cluster size is a critical system design parameter. Optimal dimensioning of the cluster size is necessitated by the facts that: 1) the cluster size determines the number of active RRHs at any given time. In turn the density of active RRHs shapes the co-channel interference experienced by a scheduled UE; 2) the radius of the cluster characterizes the number of concurrently scheduled UEs per unit area; and 3) the dimensions of a cluster determines the number of RRHs serving a scheduled UE. This in turn determines the diversity gain experienced due to spatially distributed RRHs.

In [12], an explicit expression for the successful access probability (SAP) for clustered RRHs is derived by applying stochastic geometry. By using the obtained theoretical result as a utility function, the clustering of RRHs is formulated as a coalitional formation game model, and a merge and split method is proposed as an efficient solution. Fig. 4 provides the average data rate of the proposed solution (named Algorithm 2), where the fronthaul constraint is considered. The maximum number of RRHs in each C-RAN cluster is set as $N_{th} = 3, 6, 9$, which means that the maximum cluster size per user is constrained. The average data rate increases as N_{th} increases. By allowing the formation of larger clusters, more interference can be removed, and thus the performance can be improved. Moreover, the average data rate approaches that of Algorithm 1 without fronthaul constraints when the threshold of cluster size is set as $N_{th} = 9$. Compared with Algorithm 1, the cluster size is restricted by the given threshold. The simulation results show that the distribution of Algorithm 2 is almost coincident with that of Algorithm 1 when the value of N_{th} is large enough.

V. RADIO RESOURCE ALLOCATION AND OPTIMIZATION

In fronthaul-constrained C-RANs, more advanced radio resource allocation and optimization (RRAO) techniques are required than in traditional cellular networks due to the densely distributed RRHs and the powerful centralized BBUs. Multi-dimensional joint resource optimization including precoding, resource block (RB) allocation, user scheduling, power allocation, and cell association can significantly enhance overall system performance and maintain satisfactory QoS for UEs in C-RANs. Due to the large-scale cooperative processing among RRHs and the

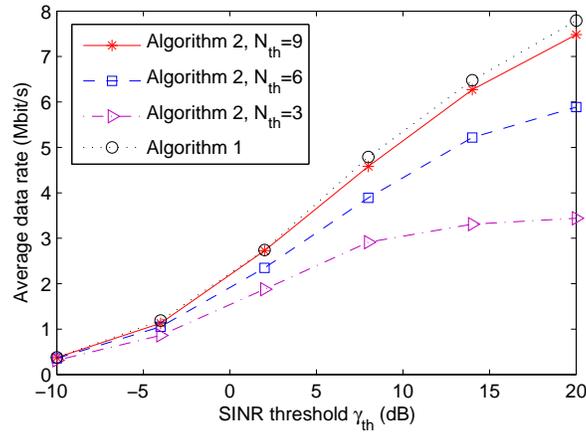


Fig. 4. Average data rate comparisons between the dynamical clustering solution (Algorithm 2) with limited fronthaul and Algorithm 1 with ideal fronthaul, where the frequency bandwidth is assumed to be 5 MHz, the radius of the effective region is set at 500 m, the transmit power is set at 23 dBm, the transmit power of interfering RRH nodes is set at 23 dBm, the noise power spectral density is set at -162 dBm/Hz, and the path loss exponent is set at 4.

delay-tolerant packet traffic arriving in an unpredictable and bursty fashion, RRAO comes with extraordinary challenges because the problem is largely intractable due to its non-convex nature.

To deal with the delay-aware RRAO problem, there are mainly three approaches, including equivalent rate constraint, Lyapunov optimization, and Markov decision processes (MDPs). The equivalent rate constraint approach is to convert the average time delay constraints into equivalent average rate constraints using queuing theory or large deviations theory. The Lyapunov optimization approach is to convert the average delay constraints into a minimization of the Lyapunov drift-plus-utility function. The MDP approach is a systematic approach to dealing with delay-aware RRAO by solving the derived Bellman equation in a stochastic learning or differential equation setting. Compared to the equivalent rate constraint approach and Lyapunov optimization approach, MDP can achieve the best performance at the expense of the highest complexity.

In [13], a hybrid coordinated multi-point transmission (H-CoMP) scheme is presented for downlink transmission in fronthaul constrained C-RANs, which fulfills the flexible tradeoff between large-scale cooperation processing gain and fronthaul consumption. H-CoMP splits the traffic payload into shared streams and private streams. By reconstructing the shared streams and private streams to optimize pre-coders and de-correlators, the shared streams and private

streams can be simultaneously transmitted to obtain the maximum achievable degrees of freedom (DoF) under the limited fronthaul constraints. To minimize the transmission delay of the delay-sensitive traffic under the average power and fronthaul consumption constraints in C-RANs, the queue-aware rate and power allocation problem is formulated as an infinite horizon average cost constrained partially observed Markov decision process (POMDP). The queue-aware H-CoMP (QAH-CoMP) solution adaptive to both the urgent queue state information (QSI) and the imperfect channel state information at transmitters (CSIT) in the downlink C-RANs is obtained by solving a per-stage optimization for the observed system state at each scheduling frame. Since QAH-CoMP requires centralized implementation and perfect knowledge of CSIT statistics, and has exponential complexity with respect to (w.r.t.) the number of UEs, the linear approximation of post-decision value functions involving POMDP is presented. Further, a stochastic gradient is proposed to allocate power and transmission rate dynamically with low computing complexity and high robustness against the variations and uncertainties caused by unpredictable random traffic arrivals and imperfect CSIT. Furthermore, online learning is used to estimate the per-queue post-decision value functions and update the Lagrange multipliers effectively.

To compare performance gains of QAH-CoMP, three baselines are considered in simulations: coordinated beamforming (CB)-CoMP, joint processing (JP)-CoMP, and channel-aware resource allocation with H-CoMP (CAH-CoMP). All these three baselines carry out rate and power allocation to maximize the average system throughput with the same fronthaul capacity and average power consumption constraints as the proposed QAH-CoMP. For the CB-CoMP baseline, the BBU pool calculates the coordinated beamformer for each RRH to eliminate the dominating intra-cluster interference among RRHs. For JP-CoMP, all RRHs are jointly coordinated to suppress the RRH-interference in the BBU pool. For the CAH-CoMP baseline, H-CoMP transmission is adopted, while the power allocation and rate allocation are only adaptive to CSIT. Fig. 5 compares the delay performance of these four solutions for different packet arrival rates. The average packet delay of all the schemes increases as the average packet arrival rate increases. Compared with CB-CoMP, JP-CoMP can provide better delay performance. It is noted that the delay performance gains of JP-CoMP diminish as the packet arrival rate increases, which is due to the fact that the fronthaul capacity becomes relatively limited with the increasing packet arrival rate. Both CAH-CoMP and QAH-CoMP can provide better performance than the traditional CB-CoMP and JP-CoMP due to the contribution of H-CoMP. Apparently, the performance gain of

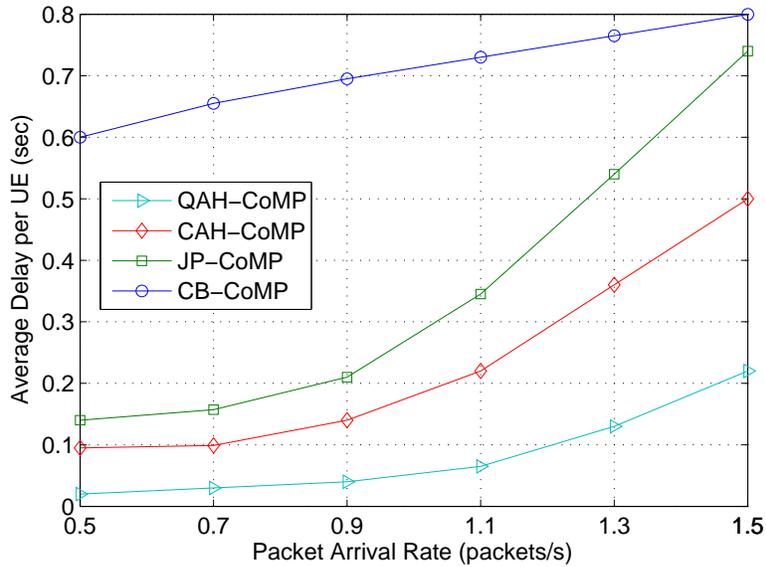


Fig. 5. Average packet delay vs. packet arrival rate, the maximum capacity fronthaul constraint is assumed to be 20 Mbit/s, the maximum transmit power is 10 dBm, the mean size of traffic packet is 4 Mbit/s, the maximum buffer size is 32 Mbits, the total frequency bandwidth is 20 MHz, and the scheduling frame duration is 10 ms.

QAH-CoMP compared with CAH-CoMP is contributed by power and rate allocation with the consideration of both urgent traffic flows and imperfect CSIT.

VI. CHALLENGING WORK AND OPEN ISSUES

Although there has been some progress on the above mentioned potential system architectures and advanced techniques for fronthaul constrained C-RANs, there are still many challenges ahead, including C-RANs with SDN, C-RANs with NFV, partially centralized C-RANs, standards development, field trials, etc. Since the C-RAN standards developments in 3GPP are still not open, and the corresponding field trials for 5G systems are far in the future, this section will discuss the aforementioned first three challenges.

A. C-RANs with SDN

SDN is an emerging architecture that decouples the network control and forwarding functions, which enables the network control to become directly programmable and the underlying infrastructure to be abstracted to adjust applications and network services dynamically. The

network intelligence is logically centralized in the SDN which maintains a global view of the network, which in turn enables network managers to configure, manage, secure, and optimize resources quickly via dynamic, automated SDN programs. As one key component in 5G, SDN will significantly influence the C-RAN interfaces to the core network.

SDN enables the separation of the control plane and the data plane, which can also be applied to C-RAN environments. However, currently envisioned C-RANs do not support the control and data decoupling functions. Rather, C-RANs have mainly been considered as means presented to provide data transmission with high bit rates. Due to high density RRHs, too much signaling overhead for the system control and broadcasting information will be necessitated, which will greatly degrade the C-RAN performance. Therefore, a new system architecture design for the control plane is needed to be compliant with the SDN architecture. Fortunately, heterogeneous cloud radio access networks (H-CRANs) have been proposed to efficiently support the control and data decoupling functions by incorporating macro base stations (MBSs) in C-RANs, where MBSs are used to deliver the control signaling and provide seamless coverage [3]. Therefore, how to design the interface between H-CRANs and the SDN based core network is an issue that should be investigated further. Since C-RANs allow the aggregation of traditional base station resources, and the SDN allows for load sharing, finding ways of combining them effectively is an important topic for future research.

B. C-RANs with NFV

NFV refers to the implementation of network functions in software running on general purpose computing/storage platforms. This approach allows the deployment of network functions in data centers and leveraging of traffic load through virtualization techniques. By contrast, the state of the art is to implement network functions on dedicated and application specific hardware. Hence, the main motivation for NFV is to exploit the economy of high volume hardware platforms, to reduce life and innovation cycles within telecommunication networks through software updates rather than hardware updates, and to exploit novel data center technologies. The C-RAN's core feature is resource cloudization, in which the centralized resources can be dynamically allocated to form a soft BBU entity. Given current vendors' proprietary and closed platforms, it is advantageous to develop an NFV based BBU platform for modern data centers, which consolidate many network equipment types onto industry standard high volume servers, switches

and storage, and which could be located in data centers, network nodes and in end user premises [14].

The virtualization of the BBU pool in C-RANs through NFV is still not straightforward. When incorporating NFV into C-RANs, the BBU pool should be deployed on multiple standard servers, in which there is an additional dedicated hardware accelerator for the computation-intensive physical layer function processes. Meanwhile, the additional hardware accelerator design should be required to meet the strict real-time requirements for wireless signal processing. The functionalities in upper layers as well as additional user applications, such as content distribution and web caching, could be implemented through a virtual machine. It is anticipated that by applying the NFV principles, most of the current radio signal processing and networking could be implemented in a general purpose computing environment, allowing new virtualized functions to be added to the network dynamically and intelligently.

C. C-RANs with Inter-Connected RRHs

To alleviate constraints of capacity and time latency on the fronthaul of C-RANs, distributed cooperation among inter-connected RRHs with the partial centralization structure is a promising alternative solution. In [15], fog computing is proposed to provide computing, storage, and networking services between end devices and traditional cloud computing data centers, typically, but not exclusively located at the edge of network, which can be used in C-RANs to alleviate the constraints of fronthaul and high computing capabilities in the BBU pool through transferring some cooperative processing into RRHs and even users from the centralized BBU pool. Therefore, interconnections between some RRHs are possible and the corresponding topology should be investigated. In [16], both mesh and tree-like backhaul network architectures are presented to decrease the negative influences of capacity-constrained backhaul links on CoMP. The trade-off between wireless cluster feasibility and the backhaul connectivity level are designed carefully. Particularly, compared to the mesh backhaul network architecture, the wireless cluster feasibility in the tree topology is about 50 percent lower with significant reduced network deployment and maintenance costs. Inspired by this backhaul clustering technique, the mesh and tree-like fronthaul clustering can be utilized to balance cluster feasibility and connectivity in partial centralization structure based C-RANs.

Based on the partial centralization structure of fog computing based C-RANs, the inter-RRH

interference can be suppressed in the centralized BBU pool with a high capacity constraint on fronthaul, or can be handled collaboratively between the distributed and adjacent RRHs without any constraints on fronthaul. Therefore, the topology should be adaptively configured to balance the constraints of fronthaul and the complexity of distribution cooperative processing. The advanced sparse beamforming and dynamic RRH clustering technique should be jointly optimized. In addition, the information asymmetry between the BBU pool and the connected RRH should be highlighted, and a contract based game model could be effective to optimize the radio resource allocation.

VII. CONCLUSIONS

This article has outlined and surveyed the state-of-the-art system architecture design, key techniques and future work for fronthaul constrained C-RANs. With the goal of understanding further intricacies of key techniques, we have broadly divided the body of knowledge into signal compression and quantization, coordinated signal processing and clustering, and radio resource allocation optimization. Within each of these aspects, we have summarized the diverse problems and the corresponding solutions that have been proposed. Nevertheless, given the relative infancy of the field, there are still quite a number of outstanding problems that need further investigation. Notably, it is concluded that greater attention should be focused on transforming the C-RAN paradigm into an SDN and NVF framework with fog computing.

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