

# A Comprehensive Survey on Resource Allocation for CRAN in 5G and Beyond Networks

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**Abstract**—The diverse service requirements coming with the advent of sophisticated applications as well as a large number of connected devices demand for revolutionary changes in the traditional distributed radio access network (RAN). To this end, Cloud-RAN (CRAN) is considered as an important paradigm to enhance the performance of the upcoming fifth generation (5G) and beyond wireless networks in terms of capacity, latency, and connectivity to a large number of devices. Out of several potential enablers, efficient resource allocation can mitigate various challenges related to user assignment, power allocation, and spectrum management in a CRAN, and is the focus of this paper. Herein, we provide a comprehensive review of resource allocation schemes in a CRAN along with a detailed optimization taxonomy on various aspects of resource allocation. More importantly, we identify and discuss the key elements for efficient resource allocation and management in CRAN, namely: user assignment, remote radio heads (RRH) selection, throughput maximization, spectrum management, network utility, and power allocation. Furthermore, we present emerging use-cases including heterogeneous CRAN, millimeter-wave CRAN, virtualized CRAN, Non-Orthogonal Multiple Access (NoMA)-based CRAN and full-duplex enabled CRAN to illustrate how their performance can be enhanced by adopting CRAN technology. **We then classify and discuss objectives and constraints involved in CRAN-based 5G and beyond networks.** Moreover, a detailed taxonomy of optimization methods and solution approaches with different objectives is presented and discussed. Finally, we conclude the paper with several open research issues and future directions.

**Index Terms**—Cloud RAN, optimization, resource allocation, 5G and beyond networks.

## I. INTRODUCTION

The tremendous growth in data transmission has a revolutionary impact on wireless networks. It is projected that the number of wireless devices continues to grow at a prodigious rate [1]. Therefore, mobile network operators (MNOs) are expected to face challenging conditions in order to increase network capacity. In addition, modern applications have a diverse range of service requirements including latency and energy consumption. In the last few years, researchers in the field have been predominantly concerned with devising

state-of-the-art, innovative, as well as disruptive concepts and technologies, pursuing leaps and strides beyond those of today's cellular systems and their known limitations [2], [3].

Several alternatives have been proposed to **increase network/system capacity** in an energy-efficient way. First, the spectrum efficiency can be improved by using advanced techniques such as massive multiple-input and multiple-output (MIMO) which uses a very high number of antennas to transmit messages of multiple devices utilizing the same time-frequency resource [4]–[7]. Second, a small cell heterogeneous network (HetNet) can be deployed in which traditional macro cells provide basic coverage for the devices while small cells yield high throughput and offloading [8], [9]. However, small cell HetNets produce more interference and increase the total cost of ownership (TCO) which consists of capital expenditure (CAPEX) and operating expenses (OPEX). Third, opportunistic spectrum access can be a solution to improve spectrum efficiency in which secondary users can exploit spectrum holes to transmit their data [10], [11]. However, reliability is a major concern in most of the critical scenarios. To meet user requirements, mobile operators are compelled to increase the TCO. In return, the average revenue per user (ARPU) cannot meet with the increasing expenses. These challenges have forced wireless network experts to design novel architectures to optimize CAPEX, OPEX, ARPU, and energy consumption.

In the current radio access network (RAN) architectures, the processing capacity of a base station (BS) can only be used by its own users. Network densification is one way to increase capacity in current RAN architecture at the cost of increased CAPEX and OPEX [12]. Furthermore, sophisticated technologies including coordinated multipoint (CoMP) can increase capacity and reduce interference. However, it puts tight delay constraint on timely coordination among the BSs [13]. Therefore, current RAN architectures are not scalable to efficiently support the ever-increasing number of wireless devices/users.

In the above context, Cloud-RAN (CRAN) is considered as a potential solution to address the challenges posed by the existing RAN architecture by using a central wireless cloud network for managing the involved resources. The idea of CRAN was initialized by IBM in 2010 [14] and later by China Mobile described it in detail [15]. Many other network operators and vendors including Alcatel-Lucent, Huawei, ZTE, Nokia Siemens Networks, Intel, and Texas Instruments are also investigating the potential of CRAN in mobile networks [16]. The key characteristics of CRAN include centralized processing, sharing of resources, real-time cloud computing, and energy-efficient infrastructure [17], [18]. The major advantages

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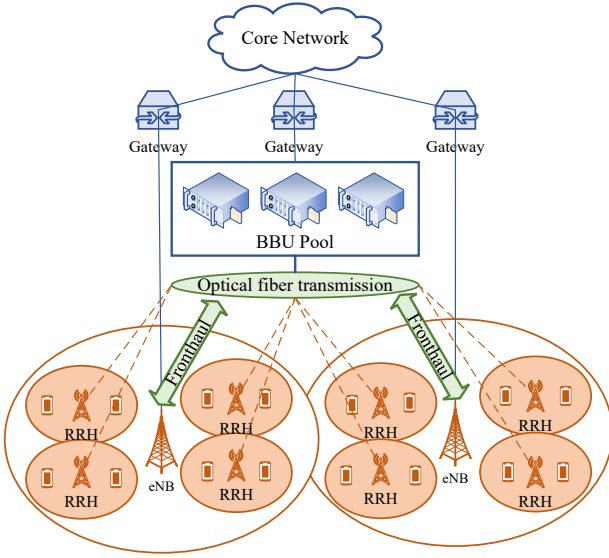


Fig. 1. CRAN architecture for 5G and beyond networks.

of shifting from the distributed RAN to CRAN are: i) saving OPEX cost because of centralized maintenance, reduced power requirements, and efficient energy consumption, ii) improved performance of network due to advanced coordinated signal processing techniques, iii) flexible software upgrade, iv) increase in ARPU, etc. Furthermore, CRAN is envisioned as an integral part of fifth generation (5G) and beyond wireless networks [19], [20].

Figure 1 depicts an overview of CRAN architecture, which mainly consists of base-band units (BBUs), optical fiber transmission, and remote radio heads (RRHs). The BBU pool is a centralized processing unit and is shared among all the cell sites. **The BBU is responsible for performing functions such as base-band processing and packet processing while the RRHs collect RF signals from users and transmit them to the cloud over the optical fiber transmission link. Also, RRHs can transmit data to users after receiving from the cloud.** The fronthaul of a CRAN architecture consists of RRHs to the BBU pool whereas the backhaul connects the BBU pool to the cloud/core network. It is relatively easy to add new BBU in this architecture which makes CRAN architecture scalable and easy to maintain. In a nutshell, CRAN performs complex computational processing in a centralized way and simple functions such as frequency conversion, amplification, analog to digital (A/D) and digital to analog (D/A) conversion are left for RRHs.

The CRAN architecture offers several benefits for 5G and beyond networks. First, the centralized BBU pool can efficiently utilize resources and thus reduce the CAPEX and OPEX. Approximately 15% CAPEX and 50% OPEX reduction are expected with CRAN in comparison with traditional cellular networks [15]. Second, it can efficiently incorporate advanced features of long-term evolution (LTE)-advanced such as CoMP and interference mitigation [19]. Third, it can minimize power consumption by switching off some BBUs in the pool without affecting the overall network coverage. ZTE

forecasted that CRAN can save 67-80% power when compared with traditional cellular networks depending on the number of cells a BBU can cover [21], [22]. Fourth, it is scalable and adaptable to non-uniform traffic [23]. **Additional RRHs can be added in the existing BBU pool to enhance coverage.** Similarly, existing cells can be divided or new RRHs can be installed in order to increase network capacity which in turn provides network flexibility. **Last but not least, CRAN provides relatively easy network maintenance and upgrades mainly because of nearby BBUs.** The transition from the traditional cellular architecture to the CRAN has to face many challenges. Particularly, many challenges that have been already addressed in the traditional cellular networks need to be revisited in a CRAN. Resource allocation is one such problem which includes user assignment, RRH selection, throughput maximization, spectrum assignment, network utility maximization and power allocation. Recent research works in CRAN show that efficient resource allocation schemes can significantly enhance the performance in terms of throughput and energy-efficiency [24]–[28].

#### A. Review of Survey and Comparison Articles on CRAN

Resource allocation in a CRAN has quite a wide scope and it requires expertise from multiple disciplines, mainly engineering and computer science. There are many resource allocation schemes recently proposed for a CRAN; however, the existing research in this area is scattered with the focus on a finite set of issues. There exist survey and comparison articles related to CRAN. For example, authors in [29] presented a survey on recent research in CRAN for 5G cellular systems. The authors focused on existing papers on throughput enhancement, interference management, energy efficiency, latency, security, cost reduction. On the other hand, a comprehensive tutorial on technologies, requirements, architectures, challenges, requirements, and solutions for the efficient CRAN fronthaul in 5G and beyond networks is presented in [30]. Fronthaul technologies such as mm-wave and wireless fidelity are considered and the main focus of this work is optical technologies. Another survey on comparison of RAN architectures (including CRAN, heterogeneous CRAN, and fog-RAN) is presented in [31]. The architectures are compared in terms of energy consumption, operations expenditures, resource allocation, spectrum efficiency, system architecture, and network performance.

In summary, existing CRAN works do not provide a comprehensive survey of resource allocation for CRAN. Unlike these works, we provide a comprehensive survey of resource allocation for CRAN in 5G and beyond networks from the optimization viewpoint.

#### B. Contributions of this paper

There exist a few survey papers in the area of CRAN in the literature [16], [32], [33]. A survey on recent advances in a CRAN has been presented in [32]. This includes system architecture, key technologies (the fronthaul compression, resource allocation and optimization and cooperative processing). However, only a section has been dedicated to resource

allocation, which does not sufficiently discuss the related works in the literature. Furthermore, authors in [16] presented a comprehensive survey on a CRAN and its implementation. More specifically, the paper encompasses the technological aspect of a CRAN and classifies its benefits in terms of energy efficiency and cost perspective. Once again the focus has not been given to resource allocation in a CRAN. Moreover, the authors in [33] presented the resource allocation mechanisms for heterogeneous entities in a CRAN. Various resource allocation mechanisms have been scratched to enhance spectral and energy efficiency, however, only advances and challenges have been highlighted without providing a comprehensive review of the state-of-the-art. Unlike the existing survey articles, this paper focuses on providing a broad range of resource allocation techniques and emerging use-cases for the CRAN along with a detailed classification of the involved objectives, constraints, optimization methods and solution types/algorithms.

In this paper, we provide a generalized framework to be utilized for research in resource allocation for CRAN systems. The objective is to provide a comprehensive survey of resource allocation schemes which can provide a holistic view of objectives, constraints, problem types, and solution strategies in a CRAN. We present several emerging use-cases for CRAN along with application-specific objectives. We also provide a discussion on challenges and open issues in a CRAN in the context of 5G and beyond networks. To the best of our knowledge, this paper is the most comprehensive survey targeting resource allocation in a CRAN for 5G and beyond networks. In the following, we highlight the main contributions of this paper.

- 1) We identify the key elements of resource allocation in a CRAN and then propose a generalized framework along with the involved objectives, constraints, optimization type, solutions/algorithms, which can be utilized for resource allocation and management for CRAN in 5G and beyond networks.
- 2) We discuss various emerging use-cases of CRAN including heterogeneous CRAN, millimeterwave (mmWave) CRAN, distributed antenna systems, Non-Orthogonal Multiple Access (NOMA) based CRAN, energy harvesting-based CRAN, virtualized CRAN, full-duplex enabled CRAN and cell-free massive MIMO.
- 3) We present a detailed classification of objective functions utilized in the CRAN optimization problems by categorizing them into four broad categories, namely, resource, throughput, energy and miscellaneous, and provide a detailed review of existing works dealing with these objective functions.
- 4) Also, we propose a detailed classification of the involved constraints in CRAN optimization problems by classifying them into five broad categories, namely, quality, power, throughput, resource, and miscellaneous along with a detailed review of the existing literature under each category.
- 5) Furthermore, a detailed taxonomy of optimization methods is presented based on the techniques utilized in the existing CRAN literature, and related works are

reviewed in detail.

- 6) Moreover, solution types/algorithms utilized in CRAN optimization are classified and reviewed in detail.
- 7) Finally, some open research issues and future recommendations are presented to stimulate future research activities in the related domains.

The rest of the paper is organized as follows. Section II presents a brief overview of resource allocation elements in CRAN and discusses various other parameters of resource allocation problems in CRAN. The emerging use-cases of CRAN are discussed in Section III. Section IV covers the classification of objectives and constraints for resource allocation problems in CRAN. Section V provides the taxonomy of resource allocation problem types and their solutions. Open research topics and future recommendations/directions are presented in Section VI. Finally, the conclusions are drawn in Section VII. To improve the flow of the paper, we present the definition of acronyms used in this paper in Table I.

## II. RESOURCE ALLOCATION IN CRAN

Figure 2 shows a generalized framework for resource allocation in a CRAN. Typically in a CRAN, the resource allocation tasks are performed at the centralized entity BBU and the RRHs are only used for transmission and reception of the signal. Since the BBU pool has complete information about the connected RRHs in the network, the resource allocation task can easily be executed there. **However, managing the resource allocation task with various conflicting objectives (resource, throughput and energy) and constraints (power, throughput, resource, quality, CPU, cloud, and memory) is a challenging task and it must be done while maintaining the quality of service (QoS) parameters of various network entities.** There are several different optimization solutions/algorithms proposed in the literature for resource allocation in a CRAN (See Section IV) for several emerging applications (See Section III).

### A. Resource Allocation Elements

Here, we will briefly discuss the basic elements for resource allocation in a CRAN.

1) *User Assignment*: Like in any wireless network, efficient user assignment is of vital importance in a CRAN [34]. User scheduling refers to the selection of a group of users in a particular time slot with the objective of enhancing the network throughput. Concerning the limited resources and interference constraints, intelligent scheduling of users is the key for enhance the throughput of the network, and for subsequently minimizing the impact of interference. On the other hand, evaluating the group of users for a particular time slot in a CRAN is a computationally intense task and is one of the active research areas nowadays.

2) *RRH Selection*: In a CRAN, the functionality of RRH is simply the transmission and reception of the signal. However, the RRH selection is a critical task and it has a direct impact on the spectral and energy efficiency of the network [35]. In addition, RRHs can cooperate with each other and perform the centralized beamforming task which can also have direct impact on the throughput enhancement of the wireless channels.

TABLE I  
DESCRIPTION OF THE ACRONYMS USED IN THIS PAPER.

Acronyms	Description
5G	Fifth generation
A/D	Analog to Digital
AP	Access point
ARPU	Average revenue per user
BBU	Base-band units
BCD	Block coordinate descent
BSs	Base stations
CAPEX	Capital expenditure
CoMP	Coordinated multipoint transmission
CPU	Central processing unit
CRAN	Cloud radio access network
CSI	Channel state information
D/A	Digital to Analog
D2D	Device-to-device
DC	Difference-of-convex
FD	Full-duplex
H-CRAN	Heterogeneous CRAN
HetNet	Heterogeneous networks
IDL	Infrastructure deployment and layout planning
ILP	Integer linear programming
INLP	Integer non-linear programming
JDD	Joint decompression and decoding
KKT	Karush-Kuhn-Tucker
LARAC	Lagrangian relaxation based aggregated cost
LTE	Long-term evolution
MCC	Mobile cloud computing
MIMO	Multiple-input and multiple-output
MINLP	Mixed integer non-linear programming
MM	Majorization minimization
mmWave	Millimeterwave
MNO	Mobile network operators
MSE	Mean-square-error
NFV	Network function virtualization
NOMA	Non-orthogonal multiple access
OPEX	Operating expenses
OFDMA	Orthogonal frequency division multiple access
PZs	Power zones
QoE	Quality of experience
QoS	Quality of service
RAN	Radio access network
RBs	Resource blocks
RPF	Regularized particle filter
RRHs	Remote radio heads
SI	Self-interference
SINR	Signal-to-interference-plus-noise ratio
SCA	Successive convex approximation
TCO	Total cost of ownership
UAV	Unmanned aerial vehicles

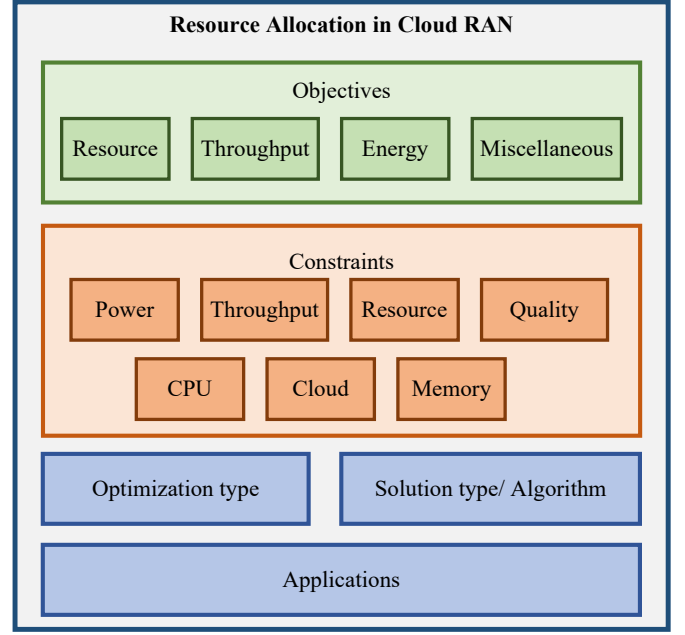


Fig. 2. Generalized framework for resource allocation in CRAN.

3) *Throughput*: To meet the ever-increasing throughput demand in 5G and beyond wireless networks, the CRAN framework can greatly complement the enhancement in the throughput. More specifically, many techniques can be adopted to enhance the throughput and meet the ever-growing demand including network coding, beamforming, and power management [36], [37].

4) *Spectrum*: Spectrum management is key for getting the real benefits of CRAN technology. Integration of licensed and unlicensed bands at the RRH is one of the active research areas nowadays. To achieve this, an optimized framework for the integration should be designed in such a way that the performance of legacy WiFi users should not be compromised [38]. On the other hand, mmWave band is also proposed as an important ingredient for 5G and beyond wireless networks [39], [40]. It is also suggested that mmWave is more appropriate for the backhaul link part. For the successful deployment of the mmWave band, spectrum management is a key research area for getting the real benefits from it.

5) *Network Utility*: Network utility is a general term and it encompasses various QoS parameters including throughput, delay, outage and blocking probabilities. The main concern in designing the network utility is to guarantee minimum QoS requirements of network entities [41].

6) *Power allocation*: Efficient power allocation is of vital importance in any wireless network. In a CRAN, it is more challenging because the RRHs are close apart in the 5G and beyond networks and this creates significant interference problems. In addition, efficient power allocation is also important because it has a direct impact on the energy and spectral efficiency [42].



## B. Resource Allocation Parameters

Towards designing suitable transmission strategies, parameters, and resource allocation methods in a CRAN, acquisition of Channel State Information (CSI) is an important and challenging research problem. In a CRAN, it is crucial to optimally utilize the resources at the cloud and to efficiently allocate the capacity of the fronthaul links which connect distributed RRHs with the BBUs.

Table II shows the typically involved resource allocation parameters in a CRAN. Virtualization enables efficient utilization of computing resources in a CRAN. In contrast to the traditional RANs, each cell in a CRAN is served by a virtualized BBU where the resources of the central BBU pool are dynamically shared among all the cells. Several works in the literature have addressed virtualization in a CRAN including [43], [47]–[49], [52], [53], [68], [75]–[77], [80], [87], [90]. The uplink design in a CRAN is relatively challenging as all the base-band processing is shifted to the BBU pool. Also, RRHs relay information to the cloud decoder for further processing which gives rise to the issues related to distributed compression and decoding specifically in multi-antenna systems. Problems related to the CRAN uplink have been vastly investigated in literature including [44]–[46], [52], [56]–[58], [61], [65], [68], [69], [71]–[73], [75], [84], [89], [90]. The downlink design in a CRAN is also important as the RRHs transmit the received signals from the BBUs to users. There are several challenging issues in the downlink for a CRAN such as scheduling coordination, energy minimization through user association, capacity enhancement through fractional frequency reuse and downlink-to-uplink interference cancellation. Plenty of research has been done to investigate downlink issues in a CRAN [43], [47], [49]–[52], [54], [55], [59], [60], [62]–[64], [66], [67], [69], [70], [74], [76]–[83], [85], [86], [88], [90]–[92].

Like any other optimization problems, optimization problems in a CRAN can be single objective addressing issues such as energy minimization, capacity maximization, etc. Many single objective optimization problems have been considered in literature [44]–[52], [54], [55], [57], [67]–[75], [77]–[79], [81]–[86], [88], [89]. Similarly, optimization problems can be multi-objective which can address multiple conflicting or non-conflicting objectives simultaneously. These multi-objective problems can be joint base station selection and distributed compression or joint optimization of radio and computational resources [43], [53], [56], [58]–[66], [80], [87], [90]–[92]. The use of heterogeneous macro base stations in a CRAN can make heterogeneous CRAN to improve energy efficiency, coverage, and spectrum efficiency. There has been a significant amount of research works done in the context of both the homogeneous [43], [45], [46], [48], [49], [54], [55], [59]–[61], [63], [64], [66], [67], [69], [73], [75], [76], [78], [79] and heterogeneous CRAN [44], [47], [50]–[53], [56], [62], [65], [68], [70]–[72], [74], [77], [82]–[85], [88]–[92]. Both fronthaul (connects RRHs to the BBU pool) [44], [61], [70], [77]–[80], [82]–[93] and backhaul (connects BBU pool to the cloud/core network) [45]–[47], [51], [53], [55]–[60], [62], [63], [65], [66], [69], [71]–[75], [81], [94] have been investigated in literature for

different objectives including capacity maximization, energy consumption reduction, resource allocation and user association.

## III. EMERGING USE-CASES WITH THE CRAN ARCHITECTURE

In this section, we discuss several emerging use-cases and Radio Access Technologies (RATs) in 5G and beyond wireless networks, which can be supported by the CRAN architecture presented in Fig. 2. Also, in Fig. 3, we highlight these emerging use-cases and RATs, where the CRAN architecture could be utilized <sup>1</sup>.

### A. Heterogeneous CRAN (H-CRAN)

Beyond 5G wireless networks are envisioned to be highly heterogeneous in terms of access technologies and device capabilities, and highly dense due to the deployment of small/femto/pico cells to enhance the cellular capacity and coverage, leading to huge prevalence of HetNet. The ever-increasing cellular densification will enable the paradigm shift of the existing networks with the features of offloading, coverage expansion, capacity enhancement, and user quality of experience (QoE) improvement. On the other hand, CRAN can be a promising platform to manage the ultra-dense HetNets including macro and small/pico/femto BSs, thus resulting in the concept of H-CRAN [95]. In the H-CRANs, macro BSs are usually connected to the BBU pool over the backhaul via X2/S1 interfaces and the BBU pool is connected to RRHs/small BSs over the wireless/wired fronthaul. In contrast to the conventional CRAN (with a centralized processing unit and a large number of geographically separated small cells), H-CRAN also involves macro cells and allow the option of decoupling user-plane and control plane. With this functionality splitting approach, small cells may deal with the user traffic while macro cells may handle the signaling traffic, i.e., control signaling to maintain connectivity within a large area [96]. Such a splitting helps in reducing signaling traffic over the fronthaul and also to enhance the resource-usage efficiency, energy efficiency, and overall QoE.

Furthermore, the combination of H-CRAN with CoMP transmission is considered a promising paradigm to address the issues of limited fronthaul capacity and excessive interference in ultra-dense heterogeneous cellular networks. However, several works in literature have assumed the lossless fronthaul links with infinite capacity, which is unrealistic for the practical capacity limited fronthaul links. One potential approach to enable the transmission over capacity limited fronthaul links is to employ distributed compression techniques such as distributed Wyner-Ziv compression [97] in which each coordinating small BS can compress its own received signal and the processing center exploits the correlation among the receptions from all the coordinating small BSs in order to reconstruct their observations and subsequently the decoding of the user message. To this end, authors in [96] compared the

<sup>1</sup>Herein, our objective is to present different use-cases and RATs supported with the CRAN rather than the classification of the CRAN architecture.

TABLE II  
RESOURCE ALLOCATION PARAMETERS IN CRAN.

	Virtualization	Uplink/ Downlink	Single/ Multi- objective	Hom/Hetnet	Backhaul /Fronthaul
Ref.	Y/N	U/D	S/M	Hm/Ht	B/F
[43]	Y	D	M	Hm	
[44]		U	S	Ht	
[45]		U	S	Hm	B
[46]		U	S	Hm	B
[47]	Y	D	S	Ht	B
[48]	Y		S	Hm	
[49]	Y	D	S	Hm	F
[50]		D	S	Ht	
[51]		D	S	Ht	B
[52]	Y	D and U	S	Ht	
[53]	Y		M	Ht	B
[54]		D	S	Hm	
[55]		D	S	Hm	B
[56]		U	M	Ht	B
[57]		U	S		B
[58]		U	M		B
[59]		D	M	Hm	B
[60]		D	M	Hm	B
[61]		U	M	Hm	F
[62]		D	M	Ht	B
[63]		D	M	Hm	B
[64]		D	M	Hm	
[65]		U	M	Ht	B
[66]		D	M	Hm	B
[67]		D	S	Hm	
[68]	Y	U	S	Ht	B
[69]		D and U	S	Hm	B
[70]		D	S	Ht	F
[71]		U	S	Ht	B
[72]		U	S	Ht	B
[73]		U	S	Hm	B
[74]		D	S	Ht	B
[75]	Y	U	S	Hm	B
[76]	Y	D	S	Hm	
[77]	Y	D	S	Het	F
[78]		D	S	Hm	F
[79]		D	S	Hm	F
[80]	Y	D	M		F
[81]		D	S		B
[82]		D	S	Het	F
[83]		D	S	Het	F
[84]		U	S	Het	F
[85]		D	S	Het	F
[86]		D	S		F
[87]	Y		M		F
[88]		D	S	Het	F
[89]		U	S	Het	F
[90]	Y	U & D	M	Het	F
[91]		D	M	Het	F
[92]		D	M	Het	F

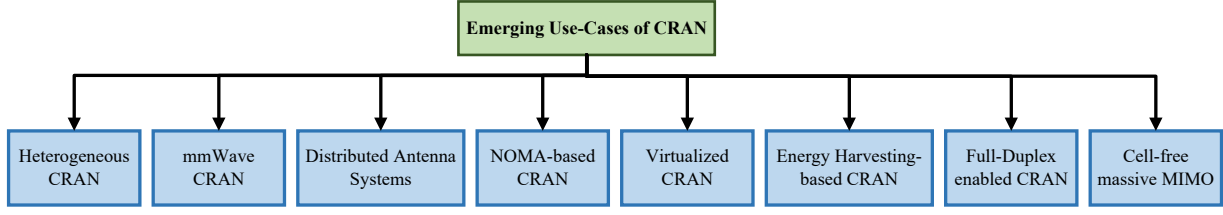


Fig. 3. Emerging use-cases and RATs in 5G and Beyond Networks supported by the CRAN architecture.

performance of distributed compression with the conventional quantization-only scheme via numerical results and showed that distributed compression can significantly reduce the required fronthaul rate for a given target user rate, and joint decompression and decoding (JDD) can further improve the performance.

Optimization of power consumption in the deployment of an H-CRAN architecture is one of the crucial issues. Although there are several BSs switching policies proposed in the literature to minimize the cellular power consumption, ping-pong issue, i.e., the oscillations of small BSs between active and sleep modes, becomes a critical challenge towards minimizing the overall power consumption and to maintain the network stability. To this end, authors in [98] proposed a handover margin-based genetic algorithm to minimize the power consumption as well as to reduce the frequent switching mode of small BSs. It is shown that a significant reduction in power consumption and improvement in the network stability are obtained with the optimum switching decision level and the handover margin obtained from the proposed algorithms. In addition, one of the major bottlenecks in H-CRANs is the limited fronthaul capacity due to the ever-increasing demand for high data-rate services and the number of users. Although the wireless medium is an economic choice over optical fiber, spectrum scarcity is a major issue. To this end, sharing of the spectrum resources between the fronthauls and RANs could be promising [99]. Also, another potential approach is to employ compress and forward strategies to reduce the communication load between the RRHs and BBU pool [100]. Authors in [101] considered both of these techniques (spectrum sharing and compress-and-forward approach) and studied the joint optimization of bandwidth allocation and compression noise with the objective of maximizing the achievable ergodic sum-rate. Moreover, other issues in H-CRANs include power allocation, user association, and admission control. To this end, the article [102] formulated a joint problem incorporating all these aspects including user association, power allocation, and admission control with the objective of maximizing the overall network throughput. This joint problem falls under the category of mixed-integer nonlinear problems (MINLP) which are usually **non-deterministic polynomial-time hard (NP-hard)**. To solve this, a linear programming-based outer approximation method is employed and the effectiveness of the proposed method was verified via numerical results.

### B. Millimeter wave (mmWave) CRAN

Cellular network densification and mmWave communications are considered promising enablers to meet the data rate requirements of future beyond 5G networks by utilizing highly dense BSs/access points (APs) and huge bandwidth available in the higher frequency bands, respectively. Also, CRAN can enable the network densification in a cost-efficient manner for enhancing the spectral efficiency and energy efficiency of the next-generation wireless networks. By integrating CRAN architecture with the mmWave communications, both the objectives of huge bandwidth and network densification can be achieved, thus leading to the concept of mmWave CRAN [40]. Furthermore, in contrast to the communications in low-frequency bands, mmWave communications is more susceptible to blockages including shadowing and building walls and is also affected by atmospheric conditions.

On one hand, it has been suggested that mmWave propagation is more suitable for dense deployments scenarios [103] and on the other hand, CRAN can enable the deployment of denser cellular networks, leading to the mmWave CRAN [104]. Nevertheless, the main issue in mmWave CRAN is the saturation of digital fronthaul links caused by a huge amount of quantized/compressed baseband signals. To address this, it is important to investigate cost-effective techniques which can reduce the transmission rate at the fronthaul link of mmWave CRANs. Also, due to cost and complexity issues, conventional compression and channel estimation techniques investigated in the context of CRANs with narrow bandwidth considerations may not be suitable for mmWave CRANs. To this end, authors in [40] proposed a new mmWave based architecture for CRANs with the RRHs equipped with advanced lens antenna arrays, which transforms the angular domain sparsity of mmWave channels into the spatial domain. The utilization of lens array antennas can significantly reduce the fronthaul rate requirements as well as the interference among the users to perform joint decoding of uplink transmissions at the centralized unit. In addition, authors in [104] carried out the performance analysis of mmWave CRANs by using stochastic geometry in terms of average latency, outage probability, and throughput while considering various factors of mmWave CRAN systems such as the density of RRHs, blockages, and path loss. The closed-form expressions for outage probability in the noise-limited scenario and its lower and upper bounds in the interference-limited scenario are derived while considering different mobile users association strategies.

### C. Distributed Antenna Systems

Compared to the existing cellular networks, the entire baseband processing is transferred to the BBUs in the cloud in full-phase CRAN implementation. Only the radio transmission part is carried out at the RRHs. The transition to such full-phase CRAN with fully virtualized BBUs at the cloud may add significant overhead to the MNOs in terms of infrastructure replacement and cost. To address this issue, authors in [105] proposed a transition architecture in which baseband processing is still carried out at the macro BSs, however, macro BSs are connected to the RRHs over a reconfigurable fronthaul links and the RRHs are dynamically connected to the BBUs based on the user demand. Such dynamic distributed antenna system can enable the macro BSs to form a basic coverage layer over the control plane at the lower carrier frequencies and densely distributed RRHs to provide on-demand capacity at the mmWave frequencies over the user plane.

### D. NOMA-based CRAN

NOMA has been considered as a promising multiple access technology for future wireless networks and it has been already included in the 3GPP LTE-A standard for improving the spectral efficiency and energy efficiency [106]. The combination of NOMA with CRAN can be a potential solution for the IoT-enabled resource-constrained wireless networks. In this regard, authors in [86] investigated a NOMA-based CRAN systems by considering mmWave and sub-6GHz bands for access and fronthaul links, respectively. An optimization problem to maximize the energy efficiency was formulated under the constraints of transmit powers at the central unit and RRHs as well as devices' QoS. The objective function is transformed to the parameter-based objective function by employing fractional programming and then a two-loop iterative algorithm is employed to overcome the issue of nonconvexity. With the help of numerical results, performance of the proposed NOMA-based CRAN is shown to be better than the conventional NOMA scheme in terms of energy efficiency and throughput.

Furthermore, authors in [107] studied a NOMA-enabled CRAN framework by considering the NOMA based scheduling of two users in the same resources in combination with coordinated beamforming to enhance the performance of cell-edge users. The analytical expressions for outage probability have been derived for both the nearby and cell-edge users. It has been shown that the proposed NOMA-enabled RAN framework can enhance the performance of cell-edge users. In the context of NOMA-enabled H-CRANs, the authors in [108] discussed various aspects of energy efficiency and highlighted the main technologies and issues for employing NOMA in H-CRANs. The key technologies identified for NOMA-enabled H-CRANs include massive MIMO, cognitive radio, mmWave communications, wireless charging, cooperative transmission, and device-to-device (D2D) communications.

### E. Energy harvesting-based CRAN

One of the crucial issues of an H-CRAN system is how to reduce the total system power consumption. One of the

potential techniques to address this issue is to employ energy harvesting techniques by which energy can be harvested from either RF energy or ambient energy sources including solar and wind [109]. To this end, authors in [83] analyzed the energy efficiency of H-CRAN with several green RRHs equipped with the energy harvesting modules. A joint optimization problem is formulated by considering various aspects such as power allocation, user association, admission control, and energy harvesting with the objective of maximizing energy efficiency. Thus formulated fractional mixed integer nonlinear programming problem is solved by utilizing a mesh adaptive direct search algorithm.

### F. Virtualized CRAN

Another emerging CRAN architecture is a virtualized CRAN which can be enabled with the virtualization and software defined networking paradigms. **The network function virtualization (NFV) enables sharing of various resources such as licensed spectrum, backhaul, core and access network, power and network infrastructure among MNOs for better resource utilization efficiency and energy efficiency.** Furthermore, the combination of CRAN and virtualization paradigm helps to mitigate the issues of existing LTE-based networks including dynamic traffic management and information exchange among cells in dense cellular networks. To this end, authors in [110] investigated the requirements and potential gains from the integration of CRAN and network virtualization, and also proposed network virtualization techniques for CRAN with the objectives of maximizing total system throughput and minimizing the delay. A resource allocation problem has been formulated for the considered joint CRAN network virtualization architecture and both the optimal and low-complexity sub-optimal solutions have been obtained. Via numerical results, it has been shown that joint CRAN and network virtualization architecture can be highly effective in handling unbalanced loads among the MNOs and can significantly enhance the network performance. Similarly, the article [111] proposed a virtualized CRAN for the 5G network by utilizing the concept of virtualized BSs which can be formed either on per-user basis or per-cell basis by assigning on-demand virtualized resources. For the effective resource allocation in a virtualized CRAN, it is essential to utilize a cross-layer optimization framework, which can optimally manage various resources including digital unit processing resources, fronthaul capacity and radio resources for end users while considering the underlying system constraints.

To achieve the efficient splitting of functionalities between BBU and RRHs in CRANs, the baseband processing chain can be considered as a combination of virtual network functions and BBU processing can be carried out at different points instead of offloading all the BBU processing to the cloud. Such a partially centralized framework can relax the latency and bandwidth requirements and also reduce the fronthaul cost. Nevertheless, MNOs need to deal with the multi-dimensional trade-off among various conflicting objectives. For example, bandwidth requirements can be decreased by performing some level of processing at the BSs, however, this will reduce the



opportunity of having coordinated signal processing and multiplexing gain. In this regard, authors in [112] proposed a user-centric CRAN architecture to optimize the placement of BBU processing functions while taking into account the capabilities of cloud infrastructure and the throughput requirements.

#### G. Full-Duplex enabled CRAN

With the recent advances in self-interference (SI) mitigation techniques including analog cancellation, digital cancellation and antenna cancellation, full-duplex (FD) technology has emerged as a promising technique to enhance the spectral efficiency in 5G and beyond wireless networks [113]. However, the main challenge for implementing FD-enabled cellular system is the mutual interference between uplink and downlink transmissions. One of the solutions to mitigate this issue could be to utilize cooperative communications enabled by the CRAN architecture. The CRAN architecture has been shown to be significantly beneficial to support FD-enabled BSs assuming that the sufficient fronthaul capacity is available and suitable user scheduling or interference cancellation method at the mobile stations is employed [114]. To design an FD-enabled CRAN with RRHs operating in FD mode for concurrent transmission and reception of data streams, inter-RRH interference and CSI need to be taken into account. Also, downlink mobile users get interfered by the transmissions from uplink mobile users. Although various multi-user detection/decoding techniques have been suggested for interference mitigation in FD-enabled CRAN [114], their implementation is complex from a practical perspective.

To overcome the aforementioned issue, authors in [115] studied a joint problem of multi-cell beamforming and power control with a single-user detection at the BBU and downlink mobile stations. An optimization problem to optimize the beamformers of FD-enabled RRHs and power control of uplink mobile stations is formulated with the objective of the sum power of CRAN with the QoS constraints at both the uplink and downlink mobile stations. Thus formulated non-convex problem is solved by utilizing second-order cone-programming based alternating optimization. In addition, authors in [116] carried out the stochastic analysis of FD-enabled CRAN while considering user-centric cooperative clusters, non-isotropic channel fading conditions and fronthaul capacity limitations. The analytical expressions for the uplink and downlink spectral efficiencies of an FD-enabled CRAN are derived and significant performance gain of FD CRAN is shown over the half-duplex CRAN through numerical results.

#### H. Cell-free massive MIMO

The massive antenna array utilized in massive MIMO-enabled BSs can be deployed either in collocated or distributed set-ups. As compared to the collocated massive MIMO which has the benefits of low backhaul bandwidth requirements, the distributed massive MIMO systems can provide much higher probability coverage at the cost of increased backhaul bandwidth by exploiting the diversity against shadow fading [117]. In the distributed multi-antenna setting, the recently emerging concept of cell-free massive MIMO comprises of a

huge number of distributed BSs/APs which concurrently serve a much smaller number of users distributed over a wide area [118]. In such a distributed system set-up, all the BSs/APs connected to a centralized unit cooperate phase-coherently over a backhaul to serve all users with the same frequency-time resources and there are no boundaries or cells, thus referred as “cell-free massive MIMO” [119]. Similar to the benefits highlighted earlier for the case of mmWave-based CRAN, mmWave technology can be utilized in combination with cell-free massive MIMO systems to exploit the high bandwidth at the mmWave frequencies. Due to high-power consumption levels and production costs at the mmWave frequencies, fully digital implementation of massive MIMO systems is challenging and to address this, hybrid transceiver architectures with both the analog and digital processing and hybrid beamforming/precoding techniques seem promising [120]. To this end, authors in [119] analyzed the performance of both the downlink and uplink of cell-free mmWave massive MIMO systems with hybrid beamforming with the main focus on per-user rate by considering various practical constraints including imperfect channel estimation, fronthaul capacity limitations, and the non-orthogonality of pilot sequences.

Although the same transceiver processing becomes applicable to the conventional cellular massive MIMO and cell-free massive MIMO, the resource allocation problem becomes significantly different in cell-free massive MIMO system. Also, several tasks including random access, power control, user scheduling and the broadcasting of information should be implemented in a distributed manner without dividing these tasks into per-cell tasks [121]. Also, the favorable propagation and channel hardening principles applied for the cellular massive MIMO may not be applicable in the same way. To this end, authors in [121] have studied the system information broadcast problem in a cell-free massive MIMO system by quantifying the coverage area in terms of coverage probability and outage rate without considering the knowledge of CSI at both the APs and users.

### IV. CLASSIFICATION OF CRAN OBJECTIVES AND CONSTRAINTS

Resource allocation in CRAN can be done with various different objectives and constraints. In this section, we focus on different objectives and constraints considered in the literature for resource allocation in CRAN.

#### A. Objectives

We classify objectives in CRAN into four broad categories as shown in Fig. 4. These include resources, throughput, energy, and miscellaneous.

1) *Resources*: The research focused on resources as an objective consists of user assignment, maximization of the number of users in the network, and scheduling of RRH selection. A coordinated user assignment scheduling scheme across available resource blocks (RBs) and connected RRHs has been proposed in [122] to address the high capacity requirement for backhaul links in a CRAN. The scheduling problem is solved using graph theory and maximum weight

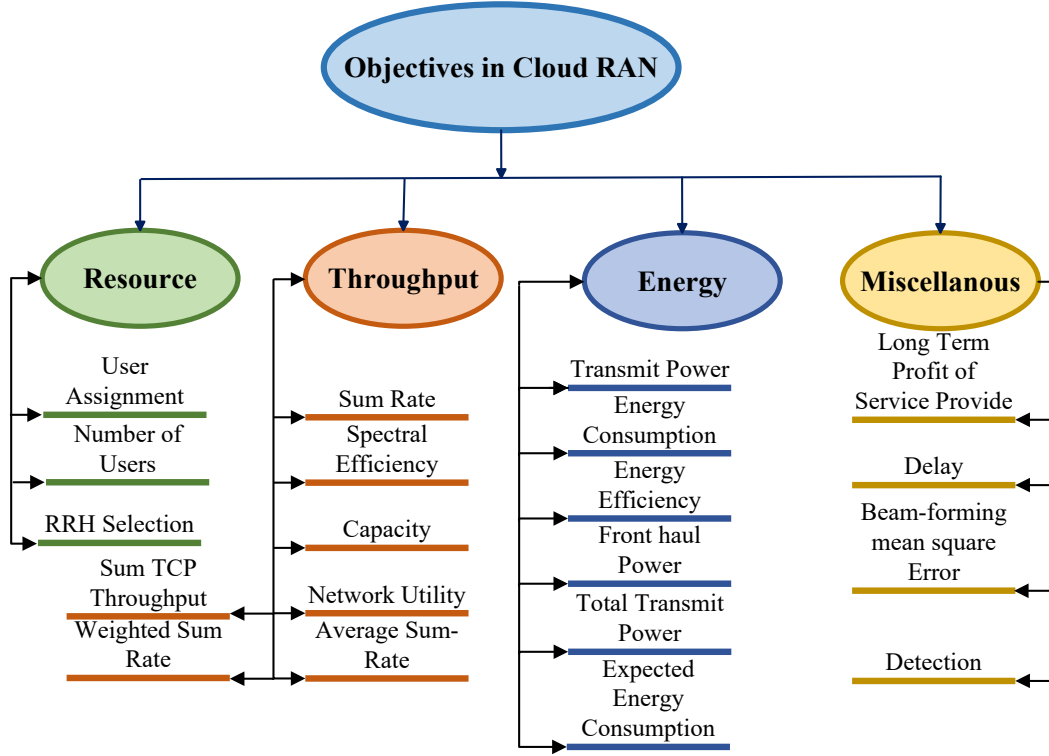


Fig. 4. Classification of objectives in CRAN.

clique, where the association of users, RBs and RRHs represent the vertices of the graph and benefit of association of each vertex is represented by its assigned weight. The problem of maximizing the number of scheduled users in H-CRAN has been addressed in [123] by using outer approximation algorithm. The number of users sharing a channel has been maximized to improve the spectral efficiency of cloud-based cognitive RAN in [124]. Also, a resource balancing algorithm has been used to solve the channel and power assignment problem. In [125], joint pilot allocation and beamforming design is considered to maximize number of admitted users for ultra-dense TDD C-RAN. A novel pilot allocation algorithm is proposed by considering the multi-user pilot interference.

Although RRHs consume less power compared to the conventional BSs, the deployment of a large number of RRHs in CRAN results in a significant increase in overall power consumption. The scheduling of RRHs can play a key role while exploiting the sparsity of users in the network. The inactive RRHs can be switched off to minimize the network power consumption. A greedy selection algorithm has been used in [53] to select a set of RRHs to switch off. Similarly, authors in [35] jointly optimized sub-channel assignment, power allocation, and RRH assignment. A three-step algorithm has been proposed to solve the problem iteratively. Authors in [126] proposed a joint RRH activation and outage constrained coordinated beamforming algorithm for CRAN. A low complexity algorithm has been proposed to solve the joint optimization problem using the group-sparse beamforming strategy. BS selection and distributed compression have been jointly optimized in [71] as well to compensate

for the performance loss in the uplink CRAN due to the imperfect statistics regarding the received signal across BSs. The problem has been formulated using deterministic worst-case approach and Karush-Kuhn-Tucker (KKT) conditions are used to determine optimality. Most of the existing works on CRAN consider a single cloud environment. A more practical network deployment scenario could be the one with multiple clouds and inter-cloud interference. In [54], the user to cloud assignment problem has been addressed for a multi-CRAN scenario and a distributed auction based iterative algorithm has been proposed for cloud association which maximizes the network-wide utility.

2) *Throughput*: Sum-rate is an important network performance metric as it considers non-symmetric source rates. The sum-rate is maximized under the practical network constraints in coordinated scheduling problem in CRAN by using exhaustive search. To this end, an RRH clustering solution has been proposed in [127] to maximize the sum throughput of CRAN while minimizing the inter-cell cooperation processing cost in terms of energy consumption using Pascoletti and Serafini scalarization method [128]. Ergodic sum-rate for uplink in H-CRAN has been maximized by optimizing bandwidth allocation and fronthaul compression at radio access links in [89]. A distributed compression scheme has been proposed to maximize the achievable rate of the CRAN system in [129]. It employs distributed Wyner-Ziv compression and optimizes the compression rate at each BS. Furthermore, ergodic sum-rate has been maximized by selecting the optimal transmission strategy in [130]. Beamforming and data transfer methods have been jointly selected to optimize wireless sum-rate for a given

link capacity and user environment. Sum-rate problem has also been addressed in [131], where the optimal IQ-data transfer method and beamforming technique have been selected for cloud massive MIMO operation in order to improve the CRAN system capacity. The sum-rate has been maximized by selecting the best relay and optimization of physical layer network coding in [44]. Similarly, sum-rate of compute and forward cloud network has been maximized under the minimum rate constraint using the Pareto frontier. Sum-rate maximization in CRAN is also studied in [56] while jointly optimizing BS selection and distributed compression for the multi-antenna uplink system using iterative block-coordinate ascent algorithm. In addition, sum-rate maximization under backhaul capacity constraint for CRAN with multihop backhaul topology has been investigated in [65], where a backhaul compression scheme based on linear in network processing has been proposed for the uplink. **In [132], non-coherent transmission design is studied to maximize sum-rate, where each RRH can transmit different symbols and the strict phase synchronization is not required..**

Spectral efficiency maximization is one of the most important objectives for the success of CRAN. In this regard, a probability-weighted based resource allocation algorithm has been proposed with an objective to maximize the spectral efficiency of CRAN in [133]. The algorithm optimizes QoS for both macro and small cell users by minimizing the cardinality of the set of interfering nodes in the network. In [134], a MIMO system design under the mixed power constraint has been investigated for CRAN to enhance the network capacity. It derives optimal solution for RRH transceiver design using iterative logic and a non-iterative matrix version water-filling scheme. Furthermore, resource allocation in a multi-CRAN has been investigated with an objective to maximize network utility by formulating and solving the conflict graph in [55]. It maximizes the network utility by formulating and solving the conflict graphs. In [135], overall network utilization of multi-cloud CRAN has been maximized by solving the constraint resource allocation problem using the heuristic algorithm. Additionally, resource allocation for delay sensitive applications in energy harvesting CRAN has been addressed in [78], where the presented solution maximizes the utility of user equipment using a Lyapunov optimization technique.

In a CRAN, instantaneous backhaul capacity affects the overall network performance since the computing resources for baseband processing are located at the central unit. In [57], the uplink sum-rate has been maximized for CRAN under the time-averaged backhaul constraint. The proposed distributed stochastic algorithm optimizes the uplink compression rate of each RRH by using a quantize and forward scheme. Furthermore, in [90], a multi-objective resource allocation scheme has been proposed for software-defined CRAN which guarantees minimum sum-rate for all users. Topology configuration and rate allocation problem for CRAN have been studied in [45], [46]. Similarly, a decision-theoretic approach to improve the sum throughput of the mobile cloud computing (MCC) user has been employed in [45]. In addition, a decision-theoretic approach has been employed to address the imperfect and delayed CSI concern in a CRAN in [46] to maximize the sum

end-to-end throughput of the MCC users.

Moreover, antenna selection in a large distributed MIMO CRAN has been investigated in [59] to maximize the average weighted sum-rate for each antenna. The selection of antennas to serve a particular set of users is done based on the regularized zero-forcing precoding. To avoid excessive CSI acquisition and processing overhead, another downlink antenna selection scheme for large MIMO networks has been proposed in [60] to maximize the average weighted sum-rate by optimizing the antenna selection and power allocation per antenna. Also, a weighted sum-rate maximization problem for given backhaul and power constraints has been studied in [62] by joint precoding and compression strategy for the CRAN. The maximization of weighted sum-rate on the uplink of CRAN under the overall backhaul capacity constraint has been studied in [68]. It has been established that the optimal results for the weighted sum-rate maximization problem can be achieved by setting the quantization noise levels proportional to the noise in high signal to quantization noise ratio regime. The network-wide weighted sum-rate maximization problem has been studied in [136] by joint user scheduling and beamforming at the RRH, and a graph theoretical approach has been proposed to solve the joint optimization problem. In addition, the downlink weighted sum-rate of H-CRAN system is maximized in [91] by optimizing the bandwidth and power allocation in each RRH cluster that minimizes the inter-tier interference.

Regarding spectrum sharing, dynamic spectrum access for the CRAN has been investigated in [47], where the overall network resource efficiency (in terms of transmitted bits per unit resource cost) has been maximized for the available spectrum and antenna resources in a massive distributed MIMO system. Furthermore, in [61], overall network throughput has been maximized by optimizing the power and fronthaul rate allocation in orthogonal frequency division multiple access (OFDMA)-based CRAN system. In [77], overall system throughput has been maximized for the CRAN with wireless network virtualization by using the heuristic technique. Total network throughput has been maximized for the H-CRAN while considering the user QoS requirements and fronthaul capacity constraints by using the game-based algorithm in [85]. The overall network throughput has been maximized for the H-CRAN by using branch and bound outer approximation approach in [123]. Joint scheduling of users to maximize the total throughput of CRAN has been considered in [137]. Similarly, in [138], CRAN throughput has been maximized subject to channel state by using a branch and bound method. In [139], a harvest-and-forward scheme has been proposed to maximize the achievable rate of the relay channel by jointly optimizing the antenna selection and power splitting ratio in the network.

3) *Energy*: In addition, energy consumption is one of the key objectives for CRAN. To this end, authors in [67] studied the overall transmit power minimization for the CRAN by using a stochastic coordinated beamforming framework. The optimal transmission strategy has been achieved under the CSI uncertainty while guaranteeing the QoS requirements of users. Furthermore, power consumption of the BBU pool has been

minimized through a proposed BBU virtualization scheme in [43]. All cells dynamically share the computing resources of BBUs based on a heuristic simulated annealing algorithm. In [73], the overall transmission power has been minimized under the backhaul capacity constraint. Also, a layered transmission and compression strategy has been proposed by using the competitive optimality criterion which guarantees that a given fraction of the maximum transmission rate can be achieved even with the imperfect CSI. In [140], imperfect CSI is considered, where the large-scale fading (such as path-loss and shadowing) is assumed to be known for the unavailable CSI associated with distant RRHs. The objective is to minimize energy and user selection for multi-channel C-RAN. The lower bound of UEs' rate expression is derived, based on which low-complexity algorithms are proposed. Moreover, in [141], transmit power consumption has been minimized by finding optimal precoding matrix that satisfies the computational and latency constraints. Joint optimization of communication and computation resources in the CRAN has been explored under the strict latency and power constraints. In [142], the authors jointly optimize the precoding matrices and the set of active RRHs to minimize the network power consumption for a user-centric C-RAN, where both the RRHs and users have multiple antennas. A low-complexity user selection algorithm is proposed along with a low-complexity network power minimization algorithm.

Moreover, authors in [48] studied the energy consumption minimization problem for the mobile device while satisfying the time constraint by offloading tasks to the cloud. The collaborative task execution at the cloud has been modeled as a constrained stochastic shortest path problem and an energy efficient scheduling policy based on Lagrangian relaxation based aggregated cost (LARAC) algorithm has been proposed. Also, in [143], the overall system power consumption in both the BBUs and RRHs has been minimized under the QoS constraints and a bisection search algorithm has been proposed for the selection of active RRHs in the CRAN cluster. Similarly, in [52], authors studied the weighted sum-power minimization problem for the CRAN, where interference has been coordinated by joint user association and beamforming solution. Authors proposed algorithms based on group-sparse optimization and relaxed-integer programming techniques for the joint downlink and uplink optimization of user association and beamforming design, respectively.

Regarding the energy conservation of resource-constrained mobile devices, authors in [144] proposed an energy-efficient application execution policy for CRAN for mobile users under stochastic channel conditions. The scheduling problem has been modeled as a constrained optimization problem and a closed form solution has been obtained that minimizes the total power consumption by dynamically adapting the clock rate of the mobile device and by optimally adjusting the data transmission rate to the cloud. In [145], the overall power consumption has been minimized subject to the latency constraint by adapting precoding matrices of the mobile devices and cloud computational resources allocated to the users. Also, the overall power consumption has been minimized by joint optimization of radio and computational resources of multicell

MIMO CRAN. Similarly, the overall power consumption at the mobile device has been minimized under the power budget and latency constraints through computational offloading in [58]. The local optimal solution was obtained for multi-cell multi-user scenario using the proposed centralized and distributed iterative algorithms.

In addition, a framework for minimization of both system power and bandwidth consumption of hybrid CRAN subject to end-to-end delay constraint from central cloud to the end user has been presented in [87], [146]. The interplay of energy and bandwidth consumption has been analyzed when the baseband function is centralized at edge cloud compared to the central cloud. In [80], the effect of variation in delay requirements of users on the energy consumption of hybrid CRAN has been investigated. This delay model has been incorporated in the proposed framework for minimizing the energy consumption of hybrid CRAN. Furthermore, energy harvesting H-CRAN has been considered in [147] and a solution has been presented to maximize the use of green power harvested at the RRHs thus reducing the grid energy consumption.

Additionally, the energy efficiency of the distributed large-scale MIMO CRAN has been studied in [148]. Authors applied large random matrix theory to propose an energy efficient power allocation scheme based on the regularized zero-forcing precoding. The proposed scheme allocates power for each user according to its QoS requirement in the presence of imperfect CSI and interference. The effect of RRH user association on the energy efficiency of H-CRAN has been investigated in [149], where a resource allocation scheme has been proposed based on the Lagrange dual decomposition method to jointly optimize the allocation of RB and transmit power subject to the inter-tier interference and user association. The effect of control data separation architecture on the energy efficiency of H-CRAN has been studied in [82], in which a closed-form optimal solution has been presented for resource and power allocation under fronthaul capacity constraint by using the Lagrange dual decomposition method. Also, the energy efficiency of H-CRAN has been investigated in [83], where an energy harvesting solution has been presented that minimizes the grid power consumption. In [84], the energy efficiency of H-CRAN has been improved by switching off underutilized BBUs and offloading traffic to low power femtocell APs. Joint access and fronthaul resource allocation in H-CRAN with dual connectivity in millimeter wave and microwave bands has been investigated to maximize the energy efficiency of the system in [88]. The energy efficiency of NOMA-based CRAN has been explored in [86], where the transmit power at the RRH and a central processor at the cloud were optimized subject to the QoS constraint of devices.

Moreover, authors in [150] studied fronthaul capacity and power consumption for the downlink CRAN design. Particularly, two closely related optimization problems were studied, namely pricing-based total power and fronthaul capacity trade-off and fronthaul-constrained power minimization. A solution based on concave approximation and gradient search methods has been presented for power and fronthaul capacity tradeoff problem which gives the optimal set of active RRHs and precoding matrices such that the total transmission power is mini-



mized for a given fronthaul capacity. For fronthaul-constrained power minimization problem, an iterative algorithm has been proposed that uses a gradient method to determine optimum total transmission power for the constrained fronthaul capacity.

Authors in [49] studied the total transmission power minimization problem subject to the user QoS constraint. The exhaustive search method has been employed to determine the optimal solution for minimizing the total transmission power of CRAN under the power budget, fronthaul capacity, and user QoS constraints. Two low complexity algorithms, namely Pareto optimum and fast matching Hungarian algorithms were also presented to determine the optimum user association. In [50], a stochastic beamforming framework has been presented based on the chance-constrained programming to minimize the total transmit power of CRAN. The proposed solution utilizes mixed CSI and ensures QoS requirement in terms of system outage probability. Furthermore, a green CRAN framework has been presented in [151] to minimize the overall network power consumption, where authors formulated a joint RRH selection and power minimization beamforming problem, and solution has been proposed based on the branch and bound method. In [152], the total transmission power of a fronthaul constrained CRAN has been minimized by selecting an optimal set of active RRHs and their respective beamforming vectors, and an iterative fast greedy algorithm has been proposed for the admission control based on single stage semi-definite program. In addition, in [81], total transmit power of multi-cloud CRAN has been minimized subject to backhaul capacity and QoS constraints. The proposed solution considers the downlink of multi-cloud CRAN and attempts to limit the inter-cloud and intra-cloud interference with imperfect CSI. Similarly, the total transmit power of ultra-dense CRAN has been minimized by optimizing the beamforming vector subject to user rate requirement and fronthaul capacity constraint in [153].

4) *Miscellaneous*: Authors in [79] studied a problem of guaranteeing the QoE for mobile users in CRAN through the use of cache-enabled unmanned aerial vehicles (UAVs) while minimizing the overall power consumption of UAVs. In [66], a multivariate joint compression scheme has been proposed for downlink CRAN to minimize the additive quantization noise at the user. An iterative algorithm has been employed to maximize the weighted sum-rate of BSs under the power and backhaul capacity constraints. Long term profitability of CRAN service provider has been studied in [154], where a solution has been proposed based on the joint optimization of scheduling and pricing decisions. The proposed dynamic scheduling and pricing algorithm is based on Lyapunov optimization technique and provides close to optimal results in terms of long term profit and queuing delay even in the random environment. In [155], robust beamforming for H-CRAN is investigated to minimize mean square error of all channel estimates. Also, spectral efficiency of the network is maximized by optimizing beam vector. An optimal resource allocation problem in H-CRAN has been studied in [92], where traffic offloading between operators has been proposed to maximize the overall profit of the network operator and system energy efficiency subject to network uncertainties. Similarly, in [70],

a hybrid CoMP scheme has been proposed to minimize delay under the average power and fronthaul consumption constraint for delay sensitive traffic in the downlink CRAN. It has been concluded that the performance gain of the hybrid CoMP solution largely depends on the cooperation level under the limited fronthaul capacity.

The relay nodes can be deployed to increase the coverage of CRAN. In this direction, authors in [63] investigated the linear minimum mean-square-error (MSE) beamforming design where the beamforming matrices at the RRHs and relay nodes have been jointly optimized. The proposed distributed beamforming algorithm minimizes MSE under per-antenna power constraint. A precoding design based on linear MSE for distributed antenna systems in CRAN has also been proposed in [64], where optimal condition decomposition method has been used to decompose the average MSE minimization problem and to solve the subproblems in parallel under per-antenna power constraint at the RRHs. In [156], a robust transceiver design for distributed antenna systems in CRAN has been studied and a low complexity algorithm has been proposed based on alternating direction method of multipliers. The proposed minimum MSE precoding algorithm takes into account the channel estimation errors and minimizes average MSE under the RRH per-antenna-power constraint. In [51], CRAN with delay aware cooperative beamforming has been studied for delay sensitive traffic under the limited backhaul consumption. A threshold based user centric clustering scheme has been proposed using an infinite horizon average cost Markov decision process approach. Infrastructure deployment and layout planning (IDL) problem for CRAN has been addressed in [63] by modeling as generic integer linear programming (ILP) problem. The proposed solution minimizes the overall network deployment cost by jointly optimizing the RRH placement, user association, and network resource utilization while satisfying the coverage requirement.

## B. Constraints

Figure 5 categorizes the constraints related to the CRAN in the literature into five broad categories, namely, quality, power, throughput, resource, and miscellaneous.

1) *Quality*: Densely deployed RRHs in a CRAN can induce large interference to each other due to the close proximity that can degrade the overall network performance and QoS. The service offered to the user is usually guaranteed by including the constraint on signal-to-interference-plus-noise ratio (SINR) performance of the user while designing cooperative transmission for CRAN in [49]. In [52], the energy efficiency of CRAN has been improved through access control and beamforming under the downlink SINR constraint. In the similar setting, authors in [53] considered the constraint on the target SINR while minimizing the network power consumption. Similarly, in [152], user SINR constraint has been considered to minimize the total transmission power of CRAN while optimizing the set of serving multi-antenna RRHs and the beamforming vectors. The IDLP problem of CRAN is addressed in [93] for the threshold SNR requirement of the user. In [133], the H-CRAN is investigated, where the number of small cells sharing

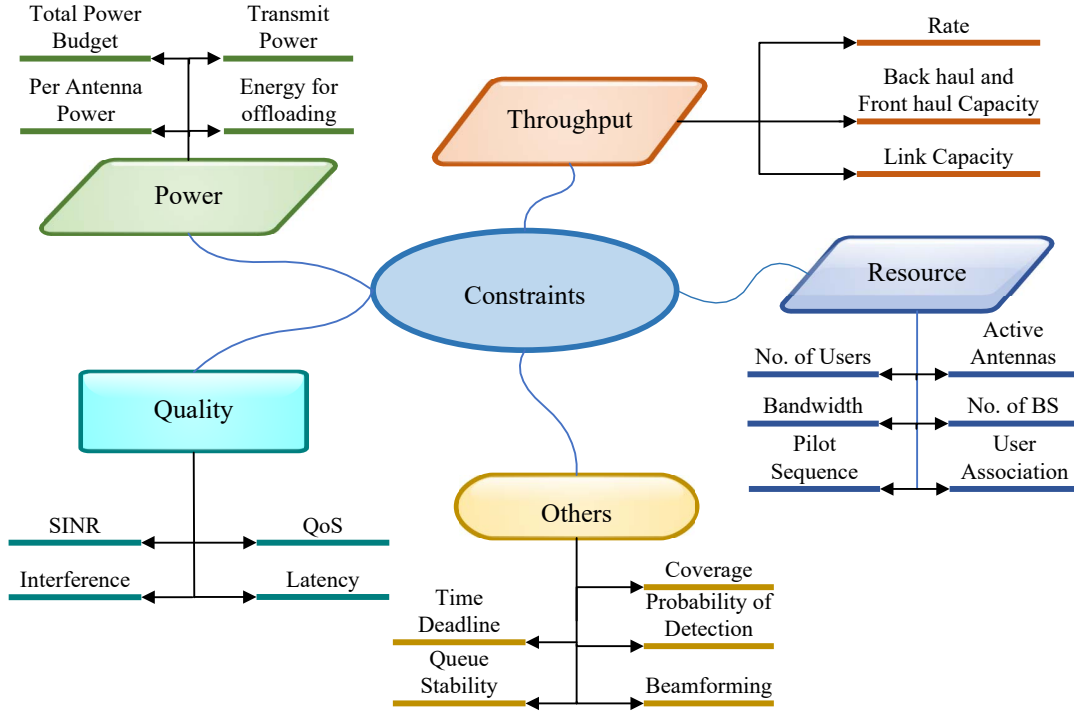


Fig. 5. Classification of constraints in CRAN.

the spectrum with the macro cell has been maximized such that the SINR requirements of the macro and small cell users can be satisfied.

For the H-CRAN scenario considered in [149], exclusive RBs have been assigned to the UE considering its rate-constraint QoS requirement, and joint optimization of resource and power allocations in H-CRAN subject to a constraint on the inter-tier interference is presented. In [150], an energy efficient design for the downlink CRAN has been presented subject to the QoS constraint of the user represented by the target SINR. In [50], a stochastic beamforming framework for CRAN has been proposed to minimize the overall transmit power while ensuring the system QoS requirement of tolerable outage probability. The overall power consumption of CRAN has been minimized while ensuring the cross-layer QoS in terms of the system expected delay [143]. Similarly, user demand rate constraint has been investigated in [151] for the design of green CRAN where the network power consumption has been minimized. The probabilistic QoS requirement of the user in terms of system outage has been considered in [67] for the design of coordinated beamforming that minimizes the total transmit power of CRAN. The QoS constraint in terms of achievable data rate is investigated in [81] for total transmit power minimization of multi-cloud CRAN by limiting interference in the system. The QoS in terms of user rate requirement is studied in [85] while maximizing the total network throughput of H-CRAN. Similarly, the user scheduling problem in H-CRAN has been addressed in [123] subject to QoS constraint that guarantees a minimum rate to the users. In [92], traffic offloading between network operators in H-CRAN has been studied under the QoS constraint of the users that

defines their minimum rate requirement. In addition, user QoS in terms of throughput and fairness is studied as constraints for user throughput maximization in H-CRAN [138].

Delay in the cloud services due to the processing and transmission between the CRAN entities is a critical issue. To this end, the constraint on per-user response latency has been investigated in [45] while maximizing the throughput over CRAN. The response latency experienced by each MCC user has been studied as a constraint in [46] to address topology configuration and rate allocation problem in the CRAN. Latency in accessing the cloud through a wide area network has been considered as a constraint in [141] for the joint optimization of the computation and communication resources to address the computation offloading problem. Similarly, latency constraint has been investigated in [144] to minimize the overall energy consumption of the user in a MCC framework. Energy efficient optimal cloud computing framework has been presented in [144] subject to the delay constraint on application completion deadline. The optimization of user energy consumption has been investigated for multi-cell mobile edge computing while meeting the latency constraint on accessing the cloud through wide area network in [58]. Resource allocation for delay sensitive applications in energy harvesting CRAN has been studied in [78] subject to maximum allowed delay bounds. The constraint on end-to-end delay has been considered in [146] for the joint optimization of system power and bandwidth consumption of hybrid CRAN. In [80], the energy consumption of a hybrid CRAN has been studied subject to the delay requirements of users.

2) *Power*: The power budget constraint has been investigated in [141] for the optimal allocation of computation and

communication resources. In [59], sum power constraint has been studied for the sum-rate maximization whereby on the downlink an optimal antenna selection is made for the large distributed MIMO based CRAN. Average power constraint has been included in resource allocation aiming to minimize transmission delay in CRAN with limited fronthaul capacity [70]. Similarly, in [134], transceiver design has been investigated under the mixed power constraint for MIMO based CRAN system.

Since each antenna has its own amplifier, it is important to consider the per-antenna power constraint. To this end, the per-antenna power constraint has been considered in [128] for mitigating the interference among RRHs by using a dynamic clustering algorithm. On the other hand, in [59], [60], the average weighted sum-rate has been maximized under the per-antenna power constraint based on large scale fading. Relay-assisted CRAN has been investigated in [63] under the per-antenna power constraints at both RRHs and relay nodes. The per-antenna power constraint has been included to design a robust precoding solution for CRAN in [64]. A robust transceiver design has been presented while considering the per-antenna power constraint for multi-cell distributed antenna systems in [156]. In [91], per-RRH power constraint has been considered to maximize the downlink weighted sum-rate of massive MIMO CRAN by coordinating interference within the system.

Although the majority of research in the literature considers sum power constraint, it is more practical to consider the per BS transmit power constraint. In this regard, authors in [157] investigated the optimization of backhaul quantization under the transmit power constraint for cloud radio multistatic radar. Joint user association and beamforming design has been investigated under the transmit power constraint for both the uplink and downlink in CRAN [52]. The problem of coordinated transmission has been addressed by considering the transmission power constraint for downlink in the CRAN [150]. The constraint on the maximum transmit power of each RRH has been considered to investigate the resource management problem in a distributed MIMO based CRAN [148]. The energy efficiency of CRAN has been investigated under the total transmit power constraint of RRHs in [149]. In [124], a cloud-based cognitive RAN has been investigated under the transmit power constraint to minimize interference. Coordinated beamforming and admission control design have been examined under the maximum RRH transmission power constraint for CRAN with limited fronthaul capacity in [152]. Throughput maximization of OFDMA-based CRAN has been investigated under the transmit power constraint in [61]. Antenna selection in energy harvesting relay channels has been explored under the total transmit power constraint in [139]. Per-BS transmit power constraint has been included in the design of joint precoding and compression scheme for the downlink of CRAN in [62]. In [66], the per-BS power constraint has been considered for the design of multivariate backhaul compression on the downlink of CRAN. The per-BS power constraint has also been considered to study the multi-terminal backhaul compression for CRAN in [69]. Sparse beamforming and clustering solution has been proposed in

[74] under the weighted per-BS power constraint to maximize the weighted sum-rate in downlink CRAN system. Maximum transmit power constraint has been considered for UAV-based CRAN to improve QoE of mobile users in [79].

Similarly, the maximum power constraint on MBS and RRHs has been evaluated for the energy efficiency of energy harvested H-CRAN in [83]. The limitations of overall transmit power of energy harvested RRHs has been examined to maximize green energy in an energy harvested CRAN in [147]. An energy efficient solution for NOMA-based CRAN has been proposed in [86] under the transmit power constraint on RRHs and the central processor. In [88], power limitation on each BS has been considered to optimize the energy efficiency of H-CRAN with dual connectivity in the access and fronthaul. Joint user scheduling and beamforming at RRH has been studied in [136] subject to the maximum power constraint per RRH. The uplink and downlink power constraint of users and RRHs were considered for the maximization of network throughput of H-CRAN in [123]. In [81], BS power constraint has been evaluated to minimize the total transmit power of a multi-cloud CRAN.

The frames transmitted by the BS comprise of multiple time-frequency blocks called power zones (PZs) that have a fixed transmit power. Since a user can be served by more than one PZ within a frame, it is important to study its effect on the fixed power transmission. To this end, in [122], coordinating scheduling problem of assigning users to the PZs has been studied under the fixed transmission power constraint such that the overall network utility is maximized. On the other hand, in [53], joint selection of active RRHs and coordinated beamforming has been investigated to improve the energy efficiency of CRAN under the constraint on the overall network power consumption. Similarly, the task scheduling problem has been investigated as a constrained shortest path problem under the constraint on the total energy consumption of the mobile device in [48].

3) *Throughput*: The minimum rate constraint has been considered while maximizing the overall throughput of the cloud network in a relay cooperated CRAN in [44]. In [157], the total transmission rate constraint has been studied for communication between multiple receiving antennas for backhaul in CRAN. Energy efficiency maximization problem under the per-user data rate requirement constraint has been examined in [148]. Minimum data rate requirement per user has been considered in [82] while optimizing the energy efficiency of H-CRAN. In [83], minimum data rate to the users has been ensured for user association to maximize energy efficiency in energy harvested CRAN. Similarly, in [147], minimum data rate requirement of each user has been satisfied to maximize utilization of green energy harvested by RRHs in H-CRAN. Minimum rate requirement per user has been considered for the joint access and fronthaul resource allocation in [88] for an H-CRAN with the dual connectivity. Furthermore, the user rate requirement has been ensured to minimize the total transmit power for optimal beamforming vector for ultra-dense CRAN [153]. The QoS requirement of users in an H-CRAN has been ensured in [84] in terms of minimum reserved rate while studying an energy efficient resource allocation problem.

Fronthaul capacity and cloud processing constraints are considered important to study the cooperative transmission in CRAN such that the total transmission power of the network can be minimized [49]. Authors in [150] considered the fronthaul capacity constraint for the energy efficient design of coordinated downlink transmission in a CRAN. Besides, joint BS selection and distributed compression has been studied for capacity-constrained backhaul links for the uplink of CRAN in [56]. An iterative algorithm has been proposed based on block coordinate ascent for the selection of the optimal set of BSs. In [152], joint coordinated beamforming and admission control design for CRAN has been presented that takes into account the limited fronthaul link capacity. The JDD on the uplink of CRAN has been studied for the capacity-constrained backhaul link in [158]. In [61], an optimal power control policy has been proposed under fronthaul capacity constraint that maximizes the overall throughput of CRAN. Backhaul capacity constraint has been studied in [62] for weighted sum-rate maximization of CRAN. Backhaul capacity constraint has been studied for sum-rate maximization [65], where a compression scheme has been proposed for the uplink of CRAN. In [66], backhaul capacity constraint has been included in the design of sum-rate maximization and compression strategy. Sum backhaul capacity constraint has been considered for the sum-rate maximization [68]. Multiterminal backhaul compression techniques have been investigated for CRAN under the backhaul capacity constraint in [69]. In [70], fronthaul consumption constraint has been considered to study the performance of delay-sensitive traffic in stochastic CRAN. The capacity constrained backhaul links have also been considered to study distributed compression on the uplink of CRAN having multi-antenna BSs in [71] and [72]. In [73], backhaul capacity restrictions have been considered while minimizing the overall transmission power of CRAN with imperfect CSI.

Network utility maximization problem has been addressed in [74] while taking into account the per-BS backhaul capacity constraint. The sum backhaul constraint is studied to maximize overall sum-rate for uplink multi-cell processing in [75]. The constraint on overall fronthaul capacity has been considered in [82] to study the resource allocation problem in the H-CRAN such that the energy efficiency is maximized. In [85], the capacity constraint on fronthaul links has been ensured to maximize the network throughput to address user association in an H-CRAN. The energy efficiency of NOMA based CRAN has been studied in [86] subject to fronthaul capacity constraint. System energy efficiency of H-CRAN has been optimized in [88] such that the achievable rate per BS is limited by the capacity of fronthaul links. Limited fronthaul capacity has also been considered in [89] and bandwidth allocation and compression problem on the uplink of H-CRAN has been addressed to maximize the ergodic sum-rate. Similarly, fronthaul capacity has been ensured to maximize the downlink weighted sum-rate for massive MIMO CRAN in [91]. Limited capacity on fronthaul links between RRH and BBU pool has been considered to maximize the network operator profit for H-CRAN in [92]. Fronthaul capacity constraint has also been observed in [153] to study the power minimization problem in ultra-dense CRAN and an optimal beamforming solution is

presented. In [154], online scheduling and pricing algorithm has been studied under the link capacity constraint. Fronthaul capacity constraint has been considered in [150] to study the energy efficient coordinated transmission design for the downlink in a CRAN.

4) *Resource*: Authors in [130] examined the constraint on the number of served users while maximizing sum-rate for a massive MIMO based CRAN. The constraint on the number of concurrently served users has also been evaluated in [131] for the design of optimal data transfer and beamforming solution for a MIMO based CRAN. In [127], the constraint that a user can at most connect to one BS, however, can occupy multiple RBs has been considered for a coordinated scheduling problem in a CRAN. The constraint on the set of UEs connected to the RRH has been examined in [77] to maximize overall system throughput in CRAN. In [84], the constraint that each user can associate with only one AP and each subcarrier on an AP can be assigned to only one user has been considered for the energy-efficient resource allocation in a H-CRAN. Joint user scheduling and beamforming at RRH has been studied in [136] under the constraint that each user can be served at most by one BS but possibly multiple RRHs. The user scheduling problem in H-CRAN has been addressed in [123] subject to the constraint that the set of users connected to macro BS and RRH are mutually exclusive. The constraint that a user can be serviced by multiple BSs within a cloud, however, it must not occupy the same RB across different BSs is evaluated to maximize overall network utilization of multicloud CRAN in [135]. In [137], the constraint that each user must connect to the maximum of one RRH has been examined to maximize the total throughput of CRAN by considering the mixed flow of multiple users in each RB.

The baseband processing procedures for each BS are divided into tasks that can be processed by several BBUs. To this end, in [43], the constraint on the task requirement of each BS has been considered to optimize the power consumption of CRAN through a BBU virtualization scheme. In a multi-cell network, system capacity is affected by the pilot contamination. In [130], [131], the constraint on pilot contamination on the ergodic sum-rate of cloud MIMO network has been investigated. Sum-rate typically increases with the increase in the number of active antennas in a MIMO system. However, the number of active antennas in practice is constrained by the degree of freedom in the spatial domain. In this regard, wireless capacity maximization problem for MIMO based CRAN has been addressed by considering the number of active antennas used to transmit in [130], [131]. Resource utilization cost of CRAN has been studied in [47] to select an optimal set of antenna resources, and also network efficiency has been evaluated under the constraint on the total number of active transmit antennas. In [139], the constraint on the number of antennas engaged in the information exchange has been evaluated to maximize the achievable rate of multiple antenna energy harvesting relay channels. The constraint on the number of BSs a user can simultaneously connect has been considered in [122]. Similarly, network utility maximization problem has been addressed for the CRAN such that a UE can only connect with one BS at most but multiple PZs of



that BS.

Furthermore, in [54], resource connectivity constraint to ensure high multiplexing gain has been considered to maximize the network-wide utility function for multi-CRAN. It restricts that a user cannot be connected to more than one cloud at a time and the number of users per cloud is limited to the number of connected RRH antennas. To this end, for a multi-CRAN scenario in [55], the resource connectivity constraint has been examined to maximize the overall network utility in a scheduling optimization problem. It constraints that each user can only connect to one cloud at a time, however, each user can associate with multiple BSs. In a CRAN, RRHs can dynamically share computing resources of multiple BBUs to improve the overall resource utilization. In this regard, power consumption of BBUs has been optimized subject to the constraint on the additional computing resources needed by the BBUs for inter-BBU communication in [43].

5) *Miscellaneous*: The achievable rate of multiple relay channel has been investigated for CoMP operation in a CRAN that is constrained by the noise introduced by the Wyner-Ziv compression at the node [129]. In [93], CRAN deployment and infrastructure requirements have been investigated under the mobile coverage ratio requirement such that the overall cost of the network is minimized. Furthermore, in [51], constrained beamforming vector that is adaptive to the queue state information and the CSI has been considered to study cooperative beamforming for delay sensitive traffic in CRAN with the limited backhaul. Also, authors in [48] examined the collaborative task execution in CRAN mobile device under the probabilistic time deadline constraint such that the application can be executed on the device itself or offloaded to the cloud for processing. In [57], queue stability and backlog size have been considered in the selection of compression rates for uplink data transmission in CRAN. Also, a network model has been proposed in which the compression rate can exceed the instantaneous backhaul capacity as long as the queue is stable.

## V. TAXONOMY OF CRAN OPTIMIZATION AND SOLUTIONS

In this section, we will provide optimization taxonomy in a CRAN and various solution types as well as algorithms proposed in the literature for optimization in a CRAN.

### A. Optimization Taxonomy

Figure 6 shows that the optimization taxonomy in a CRAN can be broadly categorized into deterministic and non-deterministic categories. In the following, we discuss sub-categories of these categories along with various underlying optimization types.

1) *Deterministic Solutions*: The deterministic CRAN optimization solutions can be of continuous and discrete types, which are discussed below with regard to the CRAN system optimization. Depending on the convexity property of the optimization problem, there exist three different types of continuous solutions, namely, non-convex, convex and difference-of-convex (DC), which, in the context of CRAN system optimization, are discussed below.

**Non-convex**: Out of the continuous solutions investigated in the CRAN literature, the most commonly investigated solutions are non-convex [51], [58], [60], [61], [63], [64], [66], [73]–[75], [128], [148], [149], [156], which are briefly discussed in the following.

One major issue in CRAN systems is the lack of CSI relative to the received signals at the BSs of other cells for designing transmission strategies at the mobile stations and compression strategies at the BSs. To address this issue, authors in [73] formulated a non-convex quadratically constrained quadratic program to minimize the transmit power under the backhaul capacity constraint. The layered transmission and compression strategies are proposed to provide more beneficial channel conditions to the neighboring BSs. Authors in [60] formulated a joint optimization problem of antenna selection, power allocation, and regularization factor to maximize the average weighted sum-rate. The formulated problem is a mixed combinatorial and non-convex problem. Similarly, a multi-objective non-convex optimization problem is formulated in [128] with an objective to maximize the throughput contribution of RRH and minimizing its total power consumption while guaranteeing its energy efficiency. The formulated multi-objective problem is transformed into a single-objective optimization problem by utilizing the Pascoletti and Serafini scalarization method.

To solve the non-convex problem of delay-aware cooperative beamforming control in CRAN, authors in [51] formulated the problem as an infinite horizon average cost Markov decision process and derived its conservative formulation. Another article [74] proposed a joint dynamic clustering, user scheduling and beamforming design strategy for the downlink of CRAN with the objective of maximizing the network utility. The formulated problem is non-convex and obtaining its global optimal solution is challenging. Therefore, the authors utilized heuristic algorithms to approach a local optimal solution. Designing a robust transceiver in multi-cell distributed antenna systems is another crucial issue in CRAN. To this end, authors in [156] proposed a robust transceiver design algorithm by utilizing the Bayesian philosophy with the Gaussian distributed channel error while aiming to reduce the negative impacts of channel estimation errors. A non-convex optimization problem of minimizing average MSE under the per-antenna power constraints at the RRHs is formulated while taking into account channel estimation errors. Subsequently, an alternating direction method of multipliers algorithm was employed to decouple the complex relationship between the optimization objective and per-antenna power constraint by introducing an auxiliary variable. Furthermore, the authors in [75] formulated the overall sum-rate maximization problem under the sum backhaul capacity constraint, which is a non-convex problem and finding an optimal solution becomes challenging. To address this, the Lagrangian method was applied by utilizing the KKT conditions necessary for the optimality.

In addition, in [66], a non-convex optimization problem has been formulated to maximize the weighted sum-rate under the backhaul constraints to find the precoding matrix and compressive co-variance matrix in a compression-enabled

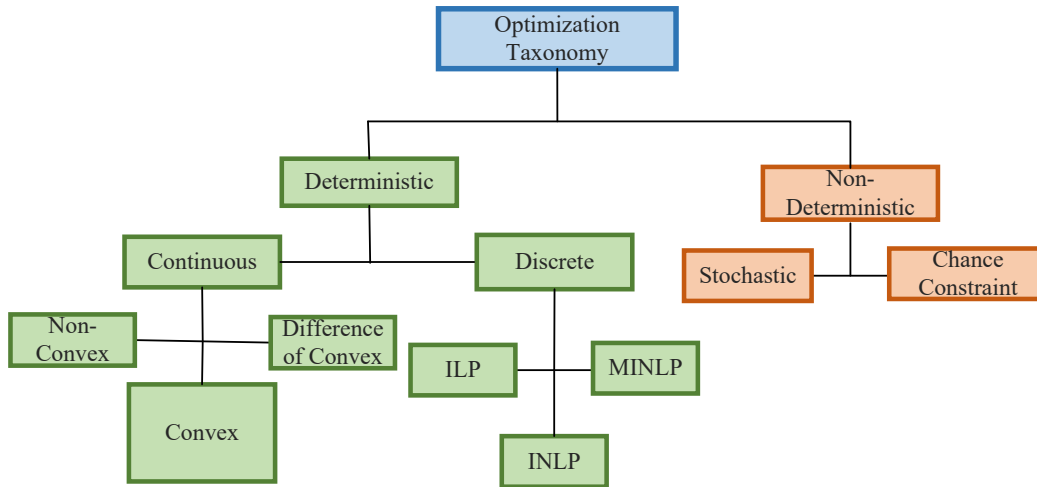


Fig. 6. Optimization taxonomy in a CRAN.

CRAN. In contrast to other works dealing with independent compression of signals intended for different BSs, the work proposed multivariate compression to better control the impact of additive quantization noises at the mobile stations. Similarly, the authors extended the work to [62], where the joint precoding and multivariate backhaul compression problem has been studied subject to power and backhaul capacity constraints and an iterative algorithm was employed to solve the underlying non-convex problem. Moreover, the work in [64] investigated a distributed linear MMSE precoding design problem in a CRAN, in which the non-convex precoder design optimization problem has been decomposed into several sub-problems by employing a low-complexity decomposition algorithm. Subsequently, sub-problems have been solved by using the Lagrange multiplier method and it was shown that the operations of sub-problems can be performed in parallel with only limited information exchange.

In the context of a distributed large-scale MIMO CRAN consisting of a number of spatially distributed RRHs, authors in [148] proposed a regularized zero-forcing precoding for the resource management problem. A non-convex optimization problem was formulated to maximize the network energy efficiency (defined as the ratio of the average total data rate to the total transmit energy consumption) via power allocation under the constraints of the maximum transmit power of each RRH and the UE's data-rate requirement. The problem was decomposed into outer and inner loop problems, which were then transformed by employing fractional programming and geometric programming, respectively. In addition, [149] studied the energy efficiency maximization problem for RB and power allocation with constraints on required QoS, inter-tier interference and allowable maximum transmit power in a H-CRAN. The formulated problem is non-convex in nature and an equivalent convex feasibility problem was reformulated and the corresponding closed-form expressions are derived by employing the Lagrange dual decomposition method. Another paper [58] studied the problem of optimizing both the radio (transmit precoding matrices of the mobile users) and com-

putational (CPU cycles/second assigned by the cloud to each mobile user) resources with the objective to minimize overall users' energy consumption under the latency constraints. The formulated optimization problem has been found to be non-convex in both the objective function and constraints and was solved by using a successive convex approximation (SCA) technique based iterative algorithm.

Additionally, authors in [61] considered a joint power control and fronthaul quantization design in CRAN with the objective of maximizing the overall system throughput subject to the constraint on each RRH's fronthaul link capacity. The formulated problem is non-convex because of the non-convex objective function over the evaluated variables, i.e., power and rate. In [63], authors considered the problem of designing linear minimum MSE beamforming in a relay-assisted CRAN consisting of relay nodes to enhance the network coverage. A leakage-based minimum MSE minimization problem was formulated for the joint optimization of beamforming matrices at both the RRHs and relay nodes subject to the per-antenna power constraints. Thus formulated optimization problem was shown to be non-convex and multiple-variable optimization problem.

**Convex:** As compared to the non-convex problems, only a few problems have been noted as convex in the context of CRAN optimization in the existing literature. The CSI overhead is considered as one of the major factors in consuming the radio resources in CRAN systems. To this end, authors in [50] considered the problem of CSI overhead reduction and downlink coordinated beamforming in a unified framework. Mainly, a stochastic beamforming framework has been proposed with the objective to maximize the total transmit power while satisfying the QoS requirements with the mixed CSI. The optimization problem has been formulated as a second-order conic programming problem, which is a convex problem and can be efficiently solved by using interior-point methods. Furthermore, the article [144] studied the energy consumption optimization of an MCC system under the stochastic wireless channel. The objective was to develop optimal scheduling

policies to minimize the energy consumption by the device either by offloading the mobile applications to the cloud or by performing optimal execution of the applications in the mobile devices. Both scheduling problems were formulated as constrained convex optimization problems with the application completion time constraint, and the corresponding closed-form solutions were obtained, which can provide optimal scheduling policies.

As the RRHs are connected to the BBU pool via the optical transport links, it becomes crucial to minimize power consumption in the transport network. In this regard, authors in [53] formulated a problem of joint RRH selection and power minimization beamforming towards designing green CRAN. With the help of group-sparse beamforming, the original combinatorial problem was relaxed to a convex problem by utilizing the group-sparsity inducing norm. However, the quantification of the performance gap due to convex relaxation normally requires the knowledge of specific prior information. Moreover, the article [68] employed a compress and forward scheme in the BSs, which sends the quantized version of the received signals to the cloud-computing based central processor by utilizing either a single-user compression or the distributed Wyner-Ziv coding. Under this framework, quantization noise level optimization problem for the weighted sum-rate maximization was considered subject to a constraint on a sum backhaul capacity. To solve this problem, an alternating convex optimization method has been employed to find the local optimum solution.

**Difference-of-Convex (DC):** In addition to convex and non-convex problems, some DC problems have appeared in the CRAN literature. For example, at the uplink of multi-antenna CRAN, the article [157] studied the problem of maximizing achievable sum-rate with the JDD which is shown to be an instance of a class of DC problems. Furthermore, authors in [65] addressed the problem of performance degradation of a multiplex-and-forward scheme in CRAN having a dense deployment of radio units. In this scenario, the formulated sum-rate maximization problem under the backhaul capacity constraint is a DC problem. To solve this problem, the algorithm named DC programming (which is based on an iterative procedure and is known to converge to a stationary point) has been utilized. Moreover, in the context of multi-terminal backhaul compression problem, authors in [69] considered the design of power control parameters and the compression noise powers. The formulated optimization problem has been shown to belong to the class of DC problems. In addition, authors in [158] considered the problem of maximizing the sum-rate of a CRAN, consisting of a set of multi-antenna mobile stations and a set of multi-antenna BSs, with the JDD. Thus formulated optimization problem has been shown to be a DC, and a majorization minimization (MM) method has been employed to achieve guaranteed convergence to a stationary point.

As depicted in Fig. 6, another class of deterministic optimization involves discrete solutions. For example, [159] investigated such a discrete solution for an optimization problem. Authors studied the problem of scheduling users to the time/frequency blocks of a transmission frame and also finding their power levels with the objective of maximizing

the weighted sum-rate in a CRAN. The formulated network-wide optimization problem is mixed discrete and continuous optimization problem which involves the search over all possible assignments of the users to frequency/time blocks and determination of power-levels for every possible assignment. Such a problem becomes infeasible for an arbitrary-sized network. The optimization problem has been solved by utilizing a graph theoretical method with a joint scheduling and power control graph composed of several clusters, where each cluster represents the possible association among the users, BSs, and power levels for specific time/frequency block.

The discrete type of deterministic optimization problems can be further divided into ILP, integer non-linear programming (INLP) and MINLP as depicted in Fig. 6. Some of the existing CRAN works related to these optimization solutions are briefly discussed below.

**Integer Linear Programming (ILP):** Only limited research work considers ILP optimization problems in the CRAN context. For example, authors in [93] studied the problem of IDLP in a CRAN architecture by formulating the problem in terms of generic ILP model. The main objective of the considered optimization problem was to minimize the overall infrastructure deployment cost of a CRAN while optimally finding the locations of RRHs and wavelength division multiplexers, exploring the association between the RRHs and wavelength division multiplexers, and considering the coverage requirement of mobile users for accessing via the RRHs.

**Mixed Integer Non-Linear Programming (MINLP):** Authors in [49] proposed a joint optimization of transmission strategy and the allocation of the CRAN resources including fronthaul capacity and processing power. A cooperative transmission design scheme has been investigated in which the precoding vectors and baseband signals are processed and computed at the cloud. The joint optimization problem is a MINLP quadratic program, which is an NP-hard problem. Authors employed an optimal exhaustive search method and also low-complexity algorithms to solve the problem. For the precoding design problem, the original problem was relaxed by removing the rank-one constraint, which was then converted to a semi-definite program convex problem and solved by standard tools such as CVX solver. For the allocation of BBU resources, a standard binary integer programming algorithm has been suggested. Furthermore, the research work in [143] investigated a cross-layer based resource allocation mechanism with the objective of minimizing the total system power consumption in both the RRHs and the BBU pool. The problem has been characterized as an MINLP problem, which is NP-hard in nature. To solve this problem, the authors relaxed the original MINLP problem to a quasi-weighted sum-rate maximization problem, which has been then solved by employing a branch and bound method.

2) *Non-deterministic Solutions:* Non-deterministic solutions can be stochastic or chance-constrained as depicted in Fig. 6. In the following, we briefly discuss the existing works under these categories.

**Stochastic:** Towards optimizing the end-to-end performance of MCC users, authors in [45] studied the problem of topology configuration and rate allocation in CRAN. An optimization

problem has been formulated to maximize the sum transport control protocol with the constraint on the response latency, which is a constrained stochastic optimization problem. To solve this problem, a greedy policy has been employed to maximize the expected objective function value to be obtained in the current time-slot, which is found to be optimal while considering multiple horizons. Furthermore, such a stochastic optimization problem with the greedy policy can be converted to a deterministic optimization problem, which becomes an integer programming problem with discrete actions. Subsequently, to solve the integer programming problem, branch and bound method can be employed for the medium-sized problems and heuristics including Genetic algorithm can be applied for the very large-sized problems. Furthermore, authors extended the work in [45] to [160], where the dynamic operation of CRAN to enhance the end-to-end performance of MCC users was studied by holistically combining the CRAN and MCC platforms in the presence of delayed CSI. The main problem in this MCC combined CRAN system is the timely acquisition of CSI since only sub-optimal operations can be employed with deterministic optimization methods in the presence of the delayed CSI. In this regard, a stochastic optimization framework with the delayed CSI has been employed for the topology configuration and rate-allocation problem with the objective of maximizing the sum-throughput of MCC services.

**Chance Constrained:** Authors in [67] formulated a generic stochastic coordinated beamforming framework which can provide optimal transmission strategies with a generic stochastic model for modeling the CSI uncertainty. The stochastic coordinated beamforming problem formulation has been found to be a joint chance constrained program which is very intractable. To solve this intractable problem, a novel stochastic DC algorithm has been employed by formulating the intractable probability constraint.

### B. Solution Type/Algorithm

Figure 7 shows solution types/algorithms considered in the literature for a diverse range of objectives and constraints for the CRAN identified in Section IV.

**Iterative:** Iterative algorithms compute a sequence of points for an optimal solution starting from an initial guess. In [129], an iterative method was used to solve rate optimization problem while reducing the distributed compression noise. Fronthaul-constrained power minimization problem was addressed using an iterative algorithm in [150], where the power and fronthaul capacity trade-off is solved by adaptively adjusting pricing coefficients. Also, an iterative algorithm has been proposed for joint compression and BS selection for the uplink of CRAN [56]. In [158], an iterative algorithm based on the MM approach was proposed to maximize achievable sum-rate through joint decompression of BS signals and decoding of user messages. Similarly, in [58], an iterative algorithm has been proposed for computation offloading from mobile users to the cloud server that minimizes the overall energy consumption of users under the latency constraint. In [62], [66], iterative algorithms were employed to maximize the

weighted sum-rate of the BSs under the power and backhaul constraints.

Furthermore, algorithms based on the iterative solution have been proposed for locally optimal transmission and compression in [73]. Precoding vector of transmit antenna has been iteratively updated in the algorithm proposed for beamforming [63], [156]. The objective was to minimize MSE under the per-antenna power constraint. In [134], an iterative solution has been proposed for MIMO systems in a CRAN under the mixed power constraint. To optimize the quantization noise, a fixed point iterative solution was proposed in [75] that maximizes the overall sum-rate of BSs under the sum backhaul constraint. In [86], an iterative scheme has been proposed to maximize the energy efficiency of the NOMA based CRAN subject to fronthaul capacity and power constraints. A two-loop iterative algorithm has been proposed in [91] to maximize downlink sum-rate in the H-CRAN subject to per RRH power and fronthaul capacity constraints.

**Heuristic:** Heuristic techniques offer near-optimal solution more quickly and with lower computational requirements compared to the other optimization methods. In [43], an algorithm based on heuristic approach has been developed for BBU virtualization to improve power efficiency. Similarly, in [54], a centralized heuristic solution has been proposed for user assignment problem in a multi-cloud environment. In [61], heuristic algorithms were proposed for power and rate allocation in CRAN. BS clustering solutions based on the heuristic scheme were proposed in [74] that maximize network utility under per-BS backhaul constraint for downlink CRAN. Besides, coordinated scheduling problem for downlink CRAN has been addressed in [127] and a heuristic solution has been proposed to maximize overall network utilization. Resource allocation problem in a multi-cloud CRAN has been investigated in [135] and a solution based on the heuristic algorithm has been proposed that maximizes the network-wide utilization. CRAN with network virtualization has been studied in [77] and a heuristic scheme has been proposed to address the resource allocation problem that maximizes aggregate throughput and delay performance of the network.

**Exhaustive Search:** Exhaustive search methods determine the optimal solution by computing values at equally spaced points within the search space. The exhaustive search algorithm has been used for optimal data transmission and beamforming schemes for MIMO CRAN [130], [131]. Exhaustive search methods were also used for the implementation of spectrum sharing in a CRAN [47]. Also, the resource allocation problem has been addressed for CRAN by using exhaustive search algorithm [49]. In [59], bisection method combined with exhaustive search has been used for antenna selection in a large distributed MIMO network.

**Block coordinate descent (BCD)-MM:** BCD methods partition the variable space into blocks and optimize the objective function against each block iteratively, reducing the overall computational requirement. To this end, the issue of quantization noise has been addressed for backhaul constrained CRAN by using BCD algorithm combined with MM (BCD-MM) in [157]. The proposed solution jointly optimizes the code vector and quantization noise of the transmitting antennas.



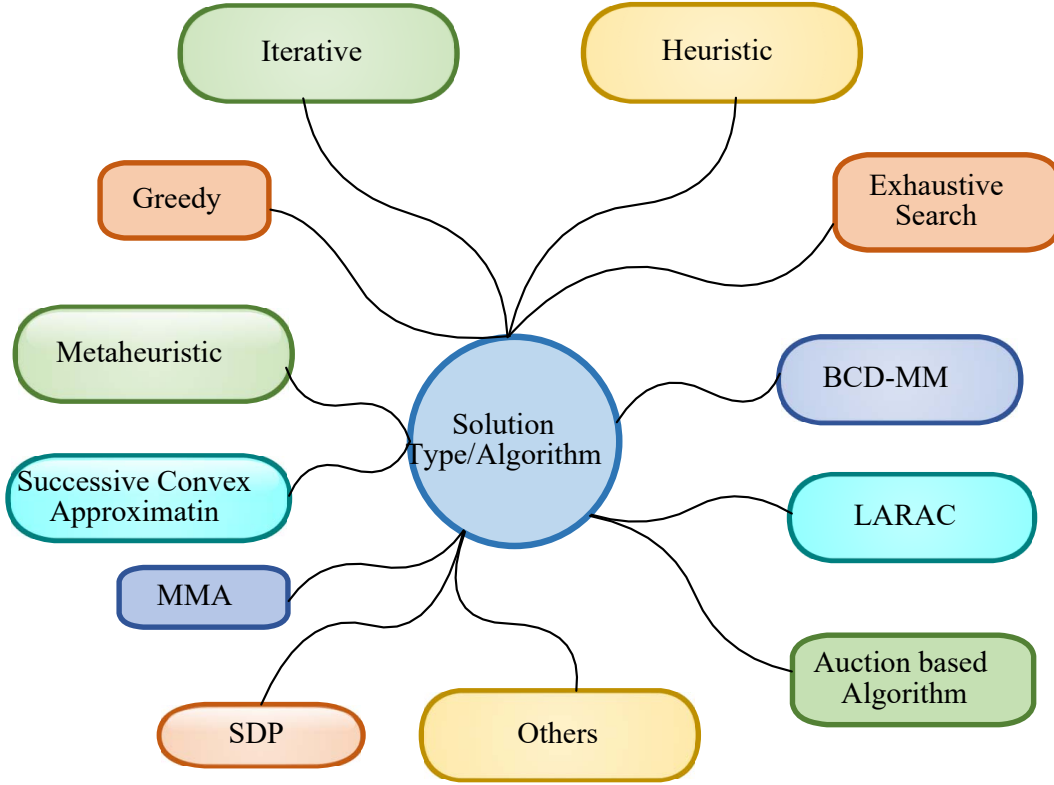


Fig. 7. Solutions types/algorithms for optimization in CRAN.

**LARAC and Lagrange Dual Decomposition:** A scheduling solution has been proposed by using LARAC algorithm presented in [48]. The proposed scheme minimizes power consumption at the mobile device by employing collaborative task execution under the time constraint. With Lagrange relaxation technique, the problem has been decomposed into simpler components that are solved independently and finally combined to arrive at the global solution. A solution based on Lagrange dual decomposition combined with the iterative scheme has been proposed in [64] for the precoding design of a distributed antenna system in a CRAN. The proposed solution minimizes the MSE under per-antenna power constraint at RRH. In [149], inter-tier interference in H-CRAN has been addressed by using the Lagrange dual decomposition method by jointly allocating RBs and transmit power to RRHs. The Lagrange dual method has also been considered for resource management problem in a distributed MIMO CRAN [144]. Fractional programming method combined with Lagrangian dual decomposition has been used in [82] to optimize the network energy efficiency of downlink H-CRAN. In [147], energy harvesting CRAN has been investigated and an algorithm based on Lagrange dual decomposition has been proposed to maximize the utilization of green energy harvested by the RRHs. A resource allocation scheme based on Lagrange dual decomposition algorithm for density-aware software defined CRAN has been presented in [90].

**Auction based Algorithm:** Auction algorithms are often used to solve assignment problems where the competitors bid for assignment. A multi-cloud association problem has

been addressed by using an auction based algorithm in [54]. The proposed distributed solution maximized network utility under the user assignment constraint that a user cannot be simultaneously connected to more than one cloud.

**Greedy:** Greedy algorithms obtain a globally optimum solution by selecting a locally optimal solution at each step. In [128], a greedy algorithm has been used to solve the multi-objective optimization problem for clustering in a CRAN. The proposed solution maximizes system throughput while minimizing total power consumption. A greedy algorithm has been used to jointly study the rate allocation and topology configuration problem in a CRAN such that the network throughput is maximized under response latency constraint in [45], [46]. In [53], the energy efficiency of CRAN has been addressed by using a greedy algorithm that selects a set of active RRHs along with coordinated beamforming. A greedy antenna selection and power splitting scheme has been presented to maximize the achievable rate in relay channels in [139]. In [71], [72], distributed compression schemes based on a greedy algorithm were presented for uplink CRAN that maximize the sum-rate.

**Successive Convex Approximation (SCA):** In SCA, a locally tight approximate of the original problem has been solved at each iteration subject to the tight constraints set. Computation offloading has been investigated by using the SCA technique in [145] such that the overall energy consumption of the user is improved under the latency constraint. Also, in [68], SCA technique has been used to maximize uplink CRAN sum-rate by optimizing the quantization noise under the backhaul

capacity constraint. Traffic offloading from CRAN to low power femtocells has been investigated in [84] and a two-step iterative algorithm based on SCA has been proposed to improve the energy efficiency of the network. In [88], an SCA based iterative scheme has been employed for solving the joint access and fronthaul resource allocation problem in H-CRAN. In addition, the optimization of beamforming vector in ultra-dense CRAN has been addressed in [153] by using an iterative SCA approach and a solution has been proposed that minimizes the total transmit power.

**Semidefinite Programming:** In semidefinite programming, the objective function is optimized subject to a semidefinite constraint on variables. For example, in [152], coordinated beamforming and admission control problem for multi-antenna RRHs in downlink CRAN has been formulated as a single stage semidefinite program. The proposed algorithm optimizes the total transmission power under the QoS and fronthaul capacity constraints.

**Others:** Several other optimization methods have also been considered in the literature. For example, in [44], Pareto frontier was used to find an optimal solution that maximizes the sum-rate of the users. A graph theoretical approach was used for the CRAN user scheduling problem in [122], [136], [137]. Furthermore, a bisection search algorithm was used for the RRH selection problem that improves the overall energy efficiency in [143]. In [60], a bisection search method was employed for joint antenna and power selection on downlink CRAN that maximizes the weighted average sum-rate. In [50], a tractable approximation method for stochastic beamforming was employed to minimize the total transmit power. Group-sparse optimization and relaxed-integer programming based algorithms were proposed for interference coordination in a CRAN in [52]. In [154], a dynamic pricing and scheduling solution was proposed based on the look-ahead algorithm that maximizes the operator's profit. In [151], a branch and bound method was employed to optimize network power consumption.

Moreover, a graph theoretical approach has been used for user scheduling in a multi-cloud environment to maximize the network utility in [55], [122]. Drift plus-penalty policy has been considered to maximize the average sum-rate in [57]. In [65], [69], iterative MM algorithms were employed to study the efficient routing and compression scheme for uplink CRAN. A stochastic programming algorithm was proposed in [67] for coordinated beamforming under CSI uncertainty. In [133], a probability-weighted algorithm was considered for resource allocation and interference management in a CRAN. An online stochastic gradient algorithm was proposed for rate and power allocation in a CRAN for delay sensitive traffic in [70]. Similarly, a scalable online algorithm was proposed in [78] by using the Lyapunov stochastic network optimization technique for resource allocation in energy harvesting CRAN. Grid energy consumption in energy harvesting CRAN was minimized in [83] by using a mesh adaptive direct search algorithm. An algorithm based on machine learning framework was proposed in [79] to improve QoE of devices in CRAN. A game based user association algorithm was presented in [85] for capacity constrained fronthaul in H-CRAN. Ergodic sum-

rate is maximized in [89] for H-CRAN by jointly optimizing the bandwidth allocation and compression using Dinkelbach's algorithm. In addition, outer approximation approach was used in [123] to maximize the overall throughput in the H-CRAN. The stochastic programming model was considered in [92] for resource allocation optimization in the H-CRAN by considering network uncertainties. In [138], a regularized particle filter (RPF) scheme was considered for optimal resource allocation in the H-CRAN.

## VI. OPEN RESEARCH TOPICS AND FUTURE RECOMMENDATIONS

Despite extensive research in resource allocation for CRAN, there are still areas that need more investigation. Here, we briefly discuss some open issues that pertain to the success of CRAN.

### A. Joint Resource Allocation over Constrained Fronthaul/Backhaul

Advanced and sophisticated resource allocation schemes are required in the CRAN, mainly because of need of additional computing resources. One of the key challenges is to design efficient compression algorithms for fronthaul links in a CRAN that connect radio units to the control units [161]. To this end, it is important to investigate the effect of latency of the fronthaul on the performance of the upper layers. In addition, optimal resource allocation with over-constrained fronthaul needs further investigation. The effect of imperfect fronthaul link with packet loss could also be another interesting topic. Also, the fronthaul network is expected to be highly heterogeneous with different link capacities and latency, thus requiring the need of re-configurable fronthaul which can be adapted based on the network topology and the traffic load [162].

In a CRAN, sum-rate performance gain can be improved by using adaptive after/before-precoding methods. In this regard, it is important to investigate the problem of precoding that uses the minimum backhaul [130]. Also, the accurate profiling of users is an essential milestone to determine appropriate strategies for the design of re-configurable backhaul in a CRAN [163]. In addition, efficient algorithms should be designed to maximize the system performance based on user profiles and traffic load to determine the optimal backhaul. Furthermore, investigating the performance of BS cooperation with clustering (particularly with large size clusters) while considering the reconfigurable backhaul in the ultra-dense deployment of BSs could be a promising future research direction. Moreover, future research in this direction should focus on investigating efficient resource optimization techniques while considering the constraints of both the fronthaul and backhaul links as well as the demands from the user-side.

### B. Latency Minimization

The amount of transmission delay may increase with the increase in number of BSs. It is important to investigate the impact of transmission and scheduling delays as these can

significantly contribute for real-time processing capability of proposed schemes. In this direction, the theoretical analysis of delay-sensitive traffic for hybrid CoMP in a CRAN needs detailed investigation [70]. It is also important to study the trade-off between performance and delay caused by coding over multiple-fading blocks [73]. One promising solution to minimize the network latency in a CRAN system is to offload the tasks and contents to the edge of the network by employing suitable edge computing [164] and proactive caching [165] solutions, respectively. Moreover, collaborative edge-cloud processing [166] can benefit from the advantages of both the cloud-processing and edge-processing, and can enable the real-time operation of delay-sensitive applications while also handling the massive amount of data at the cloud-server.

### C. Energy Efficiency

Energy consumption of mobile applications in a CRAN can be reduced by using collaborative task execution methods [48]. Towards this direction, it is important to investigate the trade-off between energy consumption and performance of the application while introducing power saving mode and power allocation on mobile devices. Joint MIMO and discontinuous transmission have been investigated to improve energy efficiency in [167]. However, a coordinated BS scheme is required in which BSs share MIMO transmissions and discontinuous transmission cycles to further enhance energy efficiency and reduce inter-cell interference. Although joint RRH selection and power minimization beamforming have been shown to be beneficial in improving the energy efficiency of a CRAN [53], analyzing the efficiency of beamforming algorithms for very large-scale CRANs needs further attention. Also, on-demand scheduling of baseband computing resources for multiple radio access technologies using NFV can reduce energy consumption [162].

The application of energy harvesting from the renewable energy sources should be further investigated to enhance the performance of ultra-dense CRANs in terms of energy efficiency. During the low traffic time, a large number of RRHs may be under-utilized by serving low traffic while consuming substantial energy [84]. To this end, it is important to investigate effective RRH switching-off schemes to reduce energy consumption under low traffic situations.

### D. Learning-assisted Optimization

Optimizing the operation of cellular networks including CRANs has been challenging over the generations due to the rapidly increasing number of configurable parameters [168]. Also, the application of the conventional optimization techniques in emerging ultra-dense networks becomes computationally complex and it is usually difficult to come across optimal solutions with low complexity in many scenarios. To this end, emerging Machine Learning (ML) techniques can be promising to speed up the optimization process as well as to find heuristic solutions in an iterative manner in the scenarios where it becomes complex to come across an optimal solution. To this end, investigating the applications of ML techniques

for the effective operation and management of CRAN-based Beyond 5G systems is a promising future research direction. Besides the conventional supervised, unsupervised and reinforcement learning techniques, some of the emerging ML techniques applicable in this direction include collaborative learning, distributed learning, active learning, hybrid learning (data-driven and model-based), federated learning [169] and Quantum ML [170].

### E. Network Scalability

The CSI is often required to improve the performance of a CRAN [50]. Although stochastic beamforming approach is used in the literature to reduce the overhead of CSI acquisition, there arises the need of more efficient algorithms for large-scale practical networks. Also, it would be interesting to investigate uplink CRAN for a scenario where the number of radio units is greater than the number of mobile devices [57]. Furthermore, the compression strategies for the uplink in a CRAN can be optimized to maximize the sum-rate capacity [158]. However, the complexity of algorithms is an important concern for the large-scale deployment of CRANs. Also, heuristic algorithms should be investigated for the efficient IDLP of large-scale CRANs [93]. In addition, time-efficient heuristic algorithms need further attention to address the issues of network scalability for reducing the complexity in large-scale hybrid CRANs.

### F. Mobility Management

Providing robust and continuous connectivity through multiple wireless communication technologies is a key for the vehicles on the move. In this direction, it is important to investigate the design of optimized algorithms and utility functions with less complexity based on the user-centric requirements or requirements of network operators. Since the correlation of mobile call patterns becomes high with the co-location patterns in the coverage area of the same BS at the same time [171], it is highly important to incorporate user mobility data in the optimization of CRAN for enhancing its performance in the presence of large-scale user mobility. Furthermore, investigating suitable mobility models for different types of traffics (human, machine) and designing mobility-aware adaptive techniques [172] for the effective optimization of CRAN system parameters is an interesting future research direction.

### G. Service Management

Blocking probability and call wait time can be improved by employing efficient admission control schemes in a CRAN while ensuring various QoS requirements [173]. To this end, Fuzzy logic approach can be applied for admission control in HetNets with different QoS requirements. In addition, ML and artificial intelligence algorithms can be effective for the efficient management of heterogeneous services/applications in the CRAN systems including the design of effective admission control schemes. Also, ML techniques can be significantly helpful to handle self-configuration, self-optimization and self-healing operations in the CRANs [168]. Furthermore, it is

important to measure the network parameters such as sparsity in the network topology [174] and the traffic conditions so that the signaling architecture can be adapted accordingly for the performance enhancement of a CRAN system.

#### H. Network Virtualization

Wireless network virtualization should be investigated to optimize the end-to-end performance of a CRAN system [45]. A virtual cell can be configured with a mobile user located in the center surrounded by the serving RRHs in a circular area. A single-user transmission in a virtual cell is not an optimal strategy presented in [76]. This will cause interference when users come nearby to each other. Therefore, taking into account the benefits of multiuser cooperative transmission in reducing the interference, it is important to investigate suitable virtualization techniques to enable cooperative multiuser transmissions in CRANs. Also, emerging network slicing techniques [175] can be investigated on the top of the virtualized CRAN to support heterogeneous 5G services including enhanced mobile broadband, massive machine-type communications and ultra-reliable and low-latency communications.

#### I. Field Trials

It is important to implement and make the field testing of the proposed schemes in the literature to determine their suitability in practical scenarios. For example, the network selection scheme in [176] can be implemented by using a database and mobile devices. Also, the actual performance gain which a user can achieve by using CoMP transmission based on CRAN [177] can be analyzed through the field tests. Although the theoretical framework of energy-optimal MCC for the stochastic wireless channel is presented in the literature [144], its realistic performance in real-world applications can be known after the field trials. Moreover, aggregation approaches and ML techniques for online learning based policies could be investigated for the realistic scenarios where the network parameters are unknown and vary over the time [94]. In addition, the queue-aware resource allocation policy with hybrid CoMP [70] should be demonstrated through real experiments to determine its performance in fronthaul-constrained CRANs. Based on the above, it can be concluded that most of the theoretical studies in the literature need to be verified via field-trials, thus requiring the need of more future research in developing experimental prototypes and real-world measurement-based analysis.

### VII. CONCLUSIONS

5G and beyond networks are expected to support diverse service requirements of numerous emerging applications. The scalability and cost efficiency of CRAN makes it a potential candidate to manage the expanding network infrastructure and resources for diverse service requirements. In this regard, this paper presented a comprehensive survey of resource allocation in a CRAN along with its objectives, constraints, optimization taxonomy, solutions, and applications with the aim of providing readers with a holistic view of different aspects of resource

allocation in CRAN. The basic elements of resource allocation in CRAN have been discussed including user assignment, RRH selection, throughput, spectrum, network utility, and power allocation. Also, we presented several emerging use-cases in order to show the importance of CRAN in scenarios where users have diverse service requirements. We then classified the objectives in CRAN into broad categories: resources, throughput, energy, and miscellaneous. Furthermore, we categorized constraints related to the classified objectives in the CRAN including power, throughput, resources, quality, and miscellaneous. We also presented a taxonomy of CRAN optimization where we broadly divided it into deterministic and non-deterministic approaches. Several algorithms/solution approaches including iterative, heuristic, meta-heuristic, SCA and exhaustive search utilized for solving CRAN optimization problems were discussed. Finally, several open issues were identified and future research directions were suggested. In a nutshell, efficient resource allocation schemes for the CRAN can improve the performance of the upcoming 5G and beyond wireless networks, which need to deal with diverse use-cases and service requirements.

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