Joint User Association and Robust Beamforming Optimization for C-RANs with Wireless Fronthauls

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***Abstract*—Future networks are expected to accommodate an ultra-dense distribution of users and infrastructure, whilst satisfying high quality of service (QoS) demands. In such interference limited scenarios, coordinated multi-point joint transmission (CoMP-JT) schemes are known to achieve considerable gains by making use of the interference signals. Unfortunately, the widespread implementation of such solutions face various challenges, such as imperfect channel state information (CSI) availability, limited capacity fronthaul links as well as the high cost of fiber. In this work, we address these challenges in a multi-user downlink C-RAN with wireless fronthaul links. Our goal is to minimize the overall network power consumption, by obtaining the optimal user associations, remote radio heads (RRHs) states, robust beamforming designs and the power allocated to the wireless fronthaul. The optimization is formulated as a mixed integer-second order cone (MI-SoCP), which uses second order CSI statistics. We investigate the performance of our solution via numerical evaluations, which indicate significant improvements in terms of power consumption and user rate.**

***Index Terms*—Array signal processing, mixed-integer programming, coordinated multipoint transmission, network optimization, green communications, limited CSI, robust beamforming**

I. Introduction

The predicted explosive growth in the number of users and their data demand will transform the shape of conventional networks to one which is ultra-dense and interference limited. This spurs the need for more energy efficient resource allocation and interference management techniques, which also take into account practical restrictions of the network. The emergence of C-RAN as a key technology for future generation networks has been justified by lower operation expenditure and superior support for computationally heavy technologies and algorithms [1]. Integration of virtualization in C-RAN has also provided the opportunity for better allocation of the computational resources themselves, as shown in [2]. Furthermore, developments in wireless fronthaul technologies, such as mm-waves and massive MIMO [3], incur negligible impact on the radio access network, thus encouraging the dense deployment of RRHs. Coordinated transmission techniques, such as CoMP-JT, have continued to gain attention due to their performance gains in dense, interference limited networks. Unfortunately however, the performance of these schemes is highly dependent on parameters such as CSI availability, fronthaul capacity and latency.

While the problem of robust beamforming with inaccurate CSI has attracted much research, e.g., [4], [5], it is often assumed that the user associations are given (using distance or achievable SINR). However, in cooperative networks the fronthaul load incurred by the users association to the access nodes is critical and yet there are no studies addressing joint user association and robust beamforming optimization. Note that by jointly optimizing the two parameters, we exploit the relation between user associations and beamforming, in order to attain a superior performance. Due to the combinatorial nature of the joint association and beamforming optimization, existing works such as [6]–[8], often assume impractical simplifications or offer non-robust sub-optimal solutions. Other works such as [9]–[13] provide non-robust heuristic solutions to the joint optimization problem.

Paper Contribution: We propose a novel robust MI-SoCP for power minimization. The model uses second order CSI error statistics and jointly determines the user associations, RRH states, robust beamforming vectors and the allocated powers for wireless fronthaul links. To the best of our knowledge, there are no works in the literature which study a joint robust optimization problem. The numerical evaluations demonstrate the achievable gains and emphasize the importance of unifying user association and robust beamforming design via a joint optimization framework.

Paper Organization: In Section II we describe the system model under consideration, while the robust joint optimization framework is presented in Section III. The performance of the proposed method is evaluated via simulations in Section IV. Lastly, we provide a summary and draw conclusion to our work in Section V.

II. System Model

We consider a single cooperative cluster, where the RRHs are connected wirelessly to a central unit (CU) as depicted in Fig. 1. We refer the reader to works such as [14] on how to obtain such cooperative clusters with negligible inter-cluster interference, and instead focus on solving the joint optimization

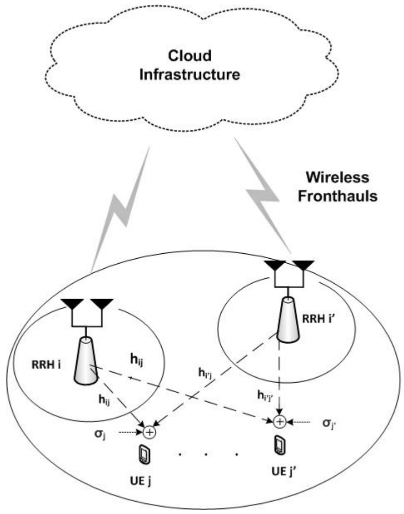


Fig. 1: A typical heterogeneous C-RAN architecture.

problem. We assume the RRHs perform channel estimation and pass the user CSI and the error statistics onto the CU. The CU, often equipped with cloud computing, designs the robust beamforming vectors with the CSI knowledge using the proposed optimization framework. The designed beamforming vectors are then reported to the RRHs, which have the capability to decode and jointly coordinate their transmission.

A. Multi-user Downlink

A cooperative cluster is assumed to include M_{RRH} RRHs, each with N_i antennas and a maximum transmission power of P_i^{max}, we use i as the index of RRHs. Each RRH may operate in either an idle state or an active state, with P_i^{idle} and P_i^{active} representing the corresponding static power consumption. We use $\beta_i \in \{0,1\}$ to describe the state of the RRH, where zero and one indicate idle and active states, respectively. The power consumption model of the RRHs is discussed in more detail in Section II-D. The cluster is populated by M_{UE} co-channel single antenna downlink users. The minimum received SINR of each individual user, which serves as a QoS measure is assumed to be given and is denoted by γ_j, where j is the index of the user. We use the variable $\alpha_{ij} \in \{0,1\}$ to describe the association between the i-th RRH and the j-th user, where a one denotes an active association. Note that active association will incur a load on the fronthaul of the RRH, corresponding to the users' demand. The channel between the i-th RRH and the j-th user are represented by $\mathbf{h}_{ij} \in \mathbb{C}^{N_i}$ and modelled as flat fast fading channels following a Rayleigh distribution. The global channel vector of the j-th user is the concatenation of the individual channels and is denoted by $\mathbf{h}_j \in \mathbb{C}^{N_{Tot}}$, where $N_{Tot} = \sum_i N_i$. Similarly, the concatenation of the individual beamforming vectors, $\mathbf{w}_{ij} \in \mathbb{C}^{N_i}$, describes the global beamforming vector of the j-th user, as $\mathbf{w}_j \in \mathbb{C}^{N_{Tot}}$. The uncorrelated data symbol for the j-th user is presented by $s_j \sim \mathcal{CN}(0,1)$. We let n_j represent the complex additive white Gaussian noise, where $n_j \sim \mathcal{CN}(0,\sigma_j^2)$. For the described system, the signal model received by the j-th user is given below

$$y_j = \mathbf{h}_j^H \mathbf{w}_j s_j + \sum_{q \neq j} \mathbf{h}_j^H \mathbf{w}_q s_q + n_j, \quad \forall j. \tag{1}$$

B. Inaccurate CSI Availability

The channel estimates are considered to be comprised of the true channel and an error as presented below

$$\tilde{\mathbf{h}}_j = \mathbf{h}_j + \boldsymbol{\delta}_j, \quad (\boldsymbol{\delta}_j \perp \tilde{\mathbf{h}}_j \perp s_j \perp n_j), \quad \forall j, \tag{2}$$

where $\boldsymbol{\delta}_j \sim \mathcal{CN}(\mathbf{0}, \mathbf{C}_j)$ is the error caused by inaccuracies in the channel estimation and is assumed to be statistically independent of the data symbols and noise. In slow fading channels, it can be assumed that the instantaneous CSI is accurately estimated and sent to the RRH by the users. However, since fast fading channels are considered here, instantaneous CSI is not available. Instead, we assume that statistical CSI knowledge is available, i.e., mean and covariance [15]. The statistical knowledge regarding the CSI error may be incorporated into the SINR formulation as shown below

$$\gamma_j = \frac{\mathbb{E}\{|\tilde{\mathbf{h}}_j^H \mathbf{w}_j s_j|^2\}}{\sum\limits_{q \neq j} \mathbb{E}\{|\tilde{\mathbf{h}}_j^H \mathbf{w}_q s_q|^2\} + \sum\limits_{q} \mathbb{E}\{|\boldsymbol{\delta}_j^H \mathbf{w}_q s_q|^2\} + \mathbb{E}\{|n_j|^2\}}, \tag{3}$$

where γ_j denotes the SINR of j-th user and $j, q \in \mathbb{K}_{UE}$. The first term in the denominator represents the interference caused on the estimated part of the channel, while the second is the interference on the error part of the channel. Where the first and second terms are separated using the statistical independence presented in (2). By combining equations (2) and (3), the average SINR may be reformulated to

$$\gamma_j = \frac{|\tilde{\mathbf{h}}_j^H \mathbf{w}_j|^2}{\sum\limits_{q \neq j} |\tilde{\mathbf{h}}_j^H \mathbf{w}_q|^2 + \sum\limits_{q} (\mathbf{w}_q^H \mathbf{C}_j \mathbf{w}_q) + \sigma_j^2}, \quad \forall j. \tag{4}$$

Note that as the position of RRHs and the CU are always fixed, it is not necessary to extend the robust design to the wireless fronthaul links.

C. Wireless Fronthaul Links

The real world implementation of wired fronthaul comes with drawbacks such as high capital expenditure (CAPEX), limited capacity and scalability. Substituting wireless fronthaul solutions, is a feasible approach that not only reduces the costs but also improves the utilization of the fronthaul links. As the focus of this work is joint user association and beamforming optimization, a point to point communication link, with negligible interference on the access network is sufficient for modelling the fronthaul links. This is justified by recent developments in wireless fronthaul technologies, which use mm-waves and massive MIMO to achieve out-of-band wireless links or create directive narrow beams, respectively. Note that the design of the interference free fronthaul lies outside the scope of this work

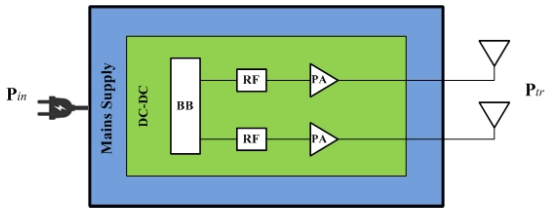


Fig. 2: Block diagram of RRH.

as it is an independent task that has been addressed in literature [3], [16]. We model the channel gain between the CU and the i-th RRH by the coefficient ν_i^{CU}. The power required to satisfy the fronthaul capacity requirement between a CU and RRH is of interest here. Note that with this notion, the capacity of the fronthaul link is no longer permanently fixed (as in the wired case), but instead depends on the noise, the channel quality and the allocated power, denoted by P_i^{CU}. The achievable capacity of the fronthaul links can be presented as below

$$C_i = B_i \log_2 \left(1 + \frac{P_i^{CU} \nu_i^{CU}}{\sigma_i^2}\right), \quad \forall i. \tag{5}$$

where B_i is the bandwidth of the communication link between the CU and the i-th RRH.

D. RRH Power Consumption Model

The RRH power consumption model used here follows the load-dependent power model developed in [17] and [18]. The main components of the RRH considered are the power amplifier (PA), the small-signal RF transceiver (RF-TRX), the baseband (BB) interface, DC-DC power supply and mains supply as depicted in Figure 2. We denote the power consumption related to the RF-TRX and the BB interface by P_{RF} and P_{BB}, respectively. μ_{DC}, μ_{MS} and η_{PA} represent the DC power supply loss, the mains supply loss and the PA efficiency, respectively. Note that in contrast to a traditional base station, an RRH requires no cooling power and also experiences negligible feeder losses as the PA is placed close to the transmit antenna. The implementation of idle state, enabled by the rapid deactivation of certain components, is known to be a key solution for reducing the power consumption. The power consumption of the RRH during the active state consists of a static and a linear load dependent part. The relationship between the RF transmit power and the total power consumption of the i-th RRH, denoted by P_i^{RRH} is provided below

$$P_i^{RRH} = \begin{cases} N_i . P_i^{idle} & \text{if } \beta_i = 0 \\ N_i . (P_i^{active}) + \Delta \|\mathbf{w}_i\|_2^2 & \text{if } \beta_i = 1 \end{cases} \tag{6}$$

where Δ is the linear load dependent power gradient, which is multiplied by the transmit power of the i-th RRH. Note that the vector $\mathbf{w}_i$ is the concatenation of the elements of all users individual beamforming vectors, $\mathbf{w}_{ij}$, which correspond to the i-th RRH. The static P_i^{active} is calculated at minimum load $P_{min} = P_i^{max} \times 0.1\%$ as shown below

$$P_i^{active} = \frac{\frac{P_{min}}{\eta_{PA}} + P_{RF} + P_{BB}}{(1-\mu_{DC})(1-\mu_{MS})}, \quad \forall i. \tag{7}$$

Using the above power consumption model for the RRHs and the power allocated to the fronthaul links, the total power expenditure, considered in this work, is expressed as

$$P_{Tot} = \sum_i P_i^{RRH} + \sum_i P_i^{CU} \tag{8}$$

III. Optimization Model

The objective of the proposed optimization framework is to minimize the total power consumption of the network, while satisfying users' QoS demands. The optimization framework, presented below, jointly determines the user to RRH associations, state of the RRHs and the robust beamforming design, as well as the power allocated to the fronthaul links.

$$\min_{\alpha_{ij}, \beta_i, \mathbf{w}_j, P_i^{RRH}, P_i^{CU}} \quad \sum_i P_i^{RRH} + \sum_i P_i^{CU} \tag{9a}$$

$$\text{s.t.} \quad N_i((1-\beta_i)P_i^{idle} + \beta_i P_i^{active}) \tag{9b}$$

$$+ \Delta \|\mathbf{w}_i\|^2 \leq P_i^{RRH}, \quad \forall i,$$

$$\|\mathbf{w}_i\| \leq \sqrt{P_i^{max}}, \quad \forall i, \tag{9c}$$

$$\|\mathbf{w}_{ij}\| \leq \alpha_{ij} \sqrt{P_i^{max}}, \quad \forall i, \forall j, \tag{9d}$$

$$\left\| \begin{array}{c} \text{vec}\{\mathbf{F}_j^H \mathbf{W}\} \\ \sigma_j \end{array} \right\| \leq \sqrt{1 + \frac{1}{\gamma_j}} \tilde{\mathbf{h}}_j^H \mathbf{w}_j, \quad \forall j, \tag{9e}$$

$$\Im\{\tilde{\mathbf{h}}_j^H \mathbf{w}_j\} = 0, \quad \forall j, \tag{9f}$$

$$\sum_j \alpha_{ij} B_{ij} \log_2 (1 + \gamma_j) \leq \tag{9g}$$

$$B_i \log_2 \left(1 + \frac{P_i^{CU} \nu_i^{CU}}{\sigma_i^2}\right), \quad \forall i,$$

$$\sum_i P_i^{CU} \leq P_{CU}^{Tot}, \tag{9h}$$

$$\alpha_{ij} \leq \beta_i, \quad \forall i, \forall j, \tag{9i}$$

$$\alpha_{ij}, \beta_i \in \{0, 1\}, \quad \forall i, \forall j. \tag{9j}$$

where the objective is the sum of all RRHs' total power consumption and the wireless fronthaul power. Constraint (9b) describes the load dependent power consumption of an RRH, while (9c) is the maximum transmit power constraint of each RRH. We make use of (9d) to enforce the impact of the association variable on the beamforming vectors. For incorporating the statistical CSI error knowledge into our design, we decompose $\tilde{\mathbf{h}}_j \tilde{\mathbf{h}}_j^H + \mathbf{C}_j = \mathbf{F}_j \mathbf{F}_j^H$ (using singular value decomposition) and obtain the matrix $\mathbf{F}_j$. The SINR demand of each user is then formulated as an SoC (9e), with $\mathbf{W}$ defined as the concatenation of the beamforming vectors $\mathbf{w}_j$ of all users. This formulation is possible as an arbitrary phase rotation may be added to the beamforming vectors without affecting the SINR. Therefore, $\tilde{\mathbf{h}}_j^H \mathbf{w}_j$ can be assumed to be real without loss of generality, as indicated in constraint (9f). For further details on this topic, we refer the reader to the original work in [19]. Since power minimization subject to given SINR requirements is considered, the SINR constraint (9e) is expected to be satisfied with equality, therefore it can be argued that the corresponding rate demands of the users are also known. This is useful for the formulation of the wireless fronthaul capacity, as shown by (9g), where B_{ij} denotes the bandwidth of the communication link between the i-th RRH and j-th user. Lastly, constraint (9h) describes the transmit power limit of the CU, while (9i) ensures an RRH is only active when there is a connected user. It is worth highlighting that the presented optimization problem is of the class of MI-SoCP and can be solved optimally via well known off-the-shelf numerical solvers such as Gurobi or MOSEK.

IV. Simulation Results & Discussion

The performance of the proposed framework is studied via Monte Carlo simulation. The used parameters and simulation setup follow the common standards and are summarized in Table I. Three RRHs, each equipped with two antennas, are distributed uniformly within the cluster. Five co-channel users populate the cluster, also following a uniform random distribution. The channels between the users and the RRH antennas consist of large scale and small scale fading following the Rayleigh fading model. Based on prior arguments regarding the wireless fronthaul, in section Section II-C, the channel between the CU and each RRH is modeled as an LOS link. The simulation results are averaged over 500 feasible channel realizations and only those with a feasibility of over 80% are displayed. Lastly, it is worth mentioning that without loss of generality all rates are normalized to the bandwidth.

TABLE I: Simulation Parameters

Parameter	Settings
Carrier Frequency	2GHz
Bandwidth	10MHz
Cluster Radius	250m
RRH Max. Transmission Power	43dBm
Path Loss (dB), d[km]	LOS: $103.4 + 24.2 \log_{10} d$ NLOS: $131.1 + 42.8 \log_{10} d$
LOS Probability, d[km]	$\min(\frac{0.018}{d}, 1)(1 - \exp(-\frac{d}{0.063}))$ $+ \exp(-\frac{d}{0.063})$
Shadowing	8dB
Noise level	-164dBm/Hz

We compare the performance of the proposed optimization, shown as "Proposed", framework to several methods. "Single Association" is a joint optimization framework where each user can connect to only one RRH. "FCoMP" is a fully cooperative network and focuses on the beamforming optimization, with all users are associated to all RRHs. Note that the two aforementioned schemes represent the extremes in terms of user association and utilization of coordinated joint transmission. "Hybrid 1" and "Hybrid 2" are beamforming design techniques, which rely on semidefinite programming and SoCP respectively, with given associations from heuristic schemes. The heuristic used here is hybrid association, which compares the hybrid quality of all links (a metric based on a ratio of distance and power) and associates to a subset of all RRHs depending on a cooperation threshold. We set the cooperation threshold to 0.5 and refer the reader to the original papers, [7], [9], for further details. It is worth mentioning that other low complexity heuristic methods, e.g., nearest cell association and MRT beamforming were also considered, however they were omitted as they resulted in a large number of infeasible solutions for the range of SINR and the node density of interest here.

The power consumption performance is first evaluated under perfect CSI availability in Figure 3 (a). It is evident that the proposed joint optimization method achieves significant power reductions (more than 30% at low SINRs), whilst also supporting high SINR demands. It can also be deduced that even where joint transmission is not possible (as in Single Association), it is still beneficial to have the user associations as a design parameter. Figure 3 (b) shows that the proposed framework also results in a lower fronthaul consumption in comparison to full cooperation even at high SINR demands. These results suggest that even when the users' SINR demands are high, the optimal association is not to cooperate with all access nodes but instead with a select few. Figure 3 (c) illustrates how the power consumption varies with increasing noise, where it can be observed that the proposed method offers a superior performance in comparison to other methods.

Table II. provides a run time comparison of the proposed framework to lower complexity decoupled methods which only perform beamforming with heuristic associations.

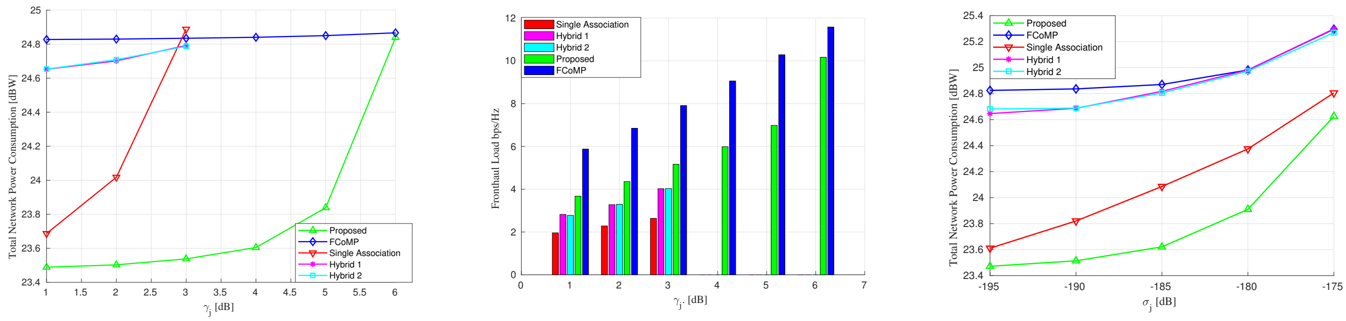
TABLE II: Run time vs. complexity

	Average Run Time [s]		
Complexity	**Proposed MI-SoCP**	**Hybrid SoCP**	**Hybrid SDP**
$M_{UE} = 3, N_i = 2$	0.8049	0.8408	0.6793
$M_{UE} = 3, N_i = 4$	1.1147	0.8783	1.0630
$M_{UE} = 4, N_i = 2$	1.4084	0.9539	0.7654

For studying the impact of imperfect CSI knowledge on our robust framework, we construct a correlated error covariance matrix as a random positive semi-definite matrix. Such an error covariance represents a scenario in which the CSI errors are different in various directions. This is practically relevant when the CSI estimation error is dominated by inter-cell interference and payload contamination. The CSI error is controlled by the scalar z, where $\mathrm{tr}(\mathbf{C}_j) = z$. Figure 4. offers a performance overview of the proposed method under various CSI errors. Robust designs are shown to better support high user rates, especially as the CSI error grows larger (23% gain in minimum user rate for $z = 5$).

V. Conclusion

With the trend of ultra-dense, interference limited networks, the design of practical power efficient solutions has become a valuable endeavor. Although coordinated techniques present a viable strategy with considerable gains, their performance is volatile to CSI availability. Moreover, the limited capacity and high cost of wired fronthaul links are also major concerns. To address these issues, a joint user association and robust beamforming optimization framework is proposed. The aim is to minimize the load dependent power consumption of the network



(a) Total power consumption vs. min. SINR.

(b) Fronthaul load vs. min. SINR

(c) Total power consumption vs. noise.

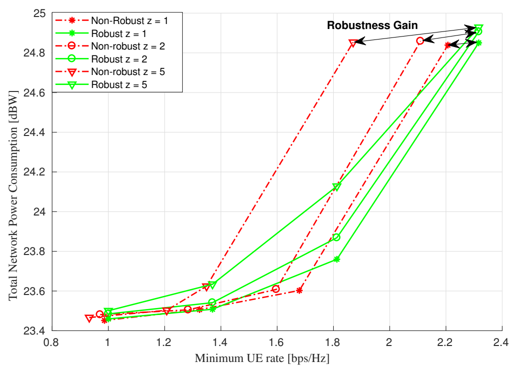


Fig. 4: Total power consumption vs. min. user rate under different CSI errors for our proposed framework.

through joint optimization of the user associations, robust beamforming designs, RRH states as well as the powers for the fronthaul links. Simulation results indicate that significant power savings are possible by having the user association as a design variable, rather than having predefined associations as in conventional methods. While the robust designs show promising results for supporting higher user rates with imperfect CSI.

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