Beamforming Optimization with Hybrid Association in C-RANs Under a Limited Backhaul

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***Abstract*—With the densification of heterogeneous networks in terms of both users and base stations (BS) being identified as an integral part of future communication systems, the problem of association needs to be reconsidered since conventional schemes which are simply based on the received signal strength lead to small cells being idle. Coordinated multipoint (CoMP) techniques show great potential in improving the network performance, however, the gain of such cooperative solutions is bottlenecked by the backhaul. We present an approach for determining the beamforming in the downlink (DL) for all users, while making use of a hybrid association strategy that depends on both power and distance. Moreover, we make use of CoMP transmission as a tool for interference management and performance improvement, this can be especially beneficial for cell edge users suffering from high interference which is common in heterogeneous networks. An optimization problem is formulated that provides flexibility in declaring individual transmit power and backhaul constraints per BS and maximizes the weighted minimum user rate in order to promote fairness. As the optimization problem is nonconvex we employ semi-definite-relaxation to obtain a sub-optimal solution. Using simulations we evaluate the performance of the proposed strategy and the gain achieved in comparison to conventional schemes. A suggestion is made for the optimal cooperation level based on multiple performance criteria.**

I. Introduction

Today's networks require major modifications to accommodate higher data rates and reliability to deliver the features and capabilities envisioned for future generations. With major network densification plans in place, it is predicted that within 10-15 years the number of base stations will outgrow the number of cell phones in order to meet service demands [1]. Suggestions of separating the baseband processing unit and radio frequency parts for a centralized, cloud radio access network (C-RAN), not only provides the opportunity to include cloud functionalities but also accommodates small cell deployment, whilst offering flexibility and improved processing resource utilization [2]. This development requires rethinking of key aspects such as association and interference management in order to facilitate the vast number of base stations and users. Cell association in traditional networks was typically defined to the strongest BS, however, in heterogeneous networks the optimal association requires a more sophisticated and dynamic selection process. Furthermore, any solution developed for heterogeneous networks needs to carefully consider the limited backhaul resources of the network, which is one of the bottlenecks in terms of performance and cost [3]. For the problem of association in heterogeneous networks, cell range expansion has recently attracted interest due to its ability to balance the load between nodes. With this approach a bias is added to the signal received from a small cell to attract more users, thus eliminating the problem of having overloaded macro-cells and under-utilized pico cells [3]–[5]. However, this causes the users in the expanded regions to suffer from interference. In [6] an interference mitigation technique is offered based on time-domain orthogonalization, which leaves certain sub-frames of the interfering BS blank and schedules the users in the expanded regions in the interference-protected sub-frames. Although this method improves the performance of users in the expanded region, it bottlenecks the performance of macro-cells which are paramount in offering good network coverage. A location aware scheme which uses a combination of cell range expansion and CoMP has been studied in [7]. However, the proposed solution considers a system without any backhaul restrictions and only targets users suffering interference from small cells and not the macro cells. Since the macro cells are the high power interfering node, it is imperative to consider the interference they cause to users in small cells. The works in [8] and [9] focus on transmit beamforming design for the purpose of enabling CoMP, however, none of the aforementioned works study the issue of association. As different CoMP transmission techniques demand different backhaul capacities, the authors in [10] and [11] considered a homogeneous case to optimize the tradeoff between CoMP joint transmission (JT) and CoMP coordinated beamforming (CB) usage. By adopting a rate splitting approach, the data is divided into private and shared parts; the private data is sent from the central processor to a single BS for CoMP-CB transmission, while on the other hand the shared data is sent to both BSs for CoMP-JT. However, they do not address the problem of association. Furthermore, the complexity of the former solution increases exponentially when the number of BSs is greater than two.

In our work we study a beamforming design and association problem while utilizing CoMP-JT to allow simultaneous transmission from multiple base stations for enhancing the throughput performance. Note that while joint transmission offers a better performance in comparison to other CoMP techniques, it requires accurate channel state information (CSI), synchronization and

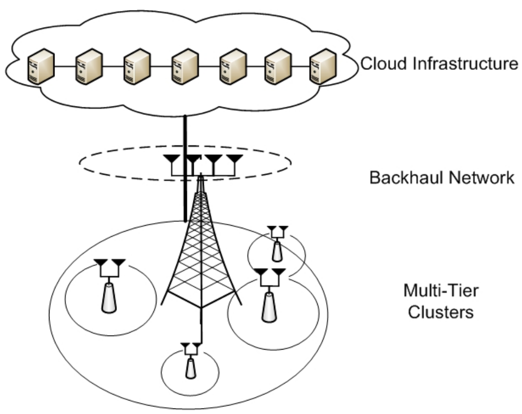

Fig. 1. Schematic of a heterogeneous network with cloud data center.

high backhaul capacity [12]. Hence, in this work we study the performance of such a system under a limited backhaul signifying a realistic C-RAN. To the best of our knowledge this is the first work that considers beamforming optimization with a hybrid association strategy for a network utilizing CoMP-JT under a limited backhaul.

Contribution: We provide a signal model of a DL user in a cooperative heterogeneous network serving multiple users. Our goal is to maximize the weighted minimum user rate subject to power, beamforming and backhaul constraints. This is done by obtaining the beamforming vectors and BS associations whilst enabling the use of CoMP-JT. A convex formulation is obtained by using a semi-definite-relaxation framework which allows us to find a sub-optimal solution for the transmit beamforming vectors. The system performance is then investigated with different cooperation levels and an optimal region of cooperation is suggested based on multiple criteria.

Paper Organization: The rest of the paper is organized as follows. The system model is defined in Section II, while Section III describes the optimization problem and its constraints. Section IV describes the deployed hybrid association scheme and provides a semidefinite relaxation of the optimization problem with an obtainable solution using the randomization technique. Section V includes the simulations setup, while also illustrating and discussing the performance gains of our solution in depth. Lastly, Section VI draws conclusions from our research results.

II. System Model

We consider a cooperative, heterogeneous cluster of B BSs, each equipped with N_j transmit antennas with maximum average transmit power P_j, where j is the index of the corresponding BS, while the set of BSs is given by $\mathbb{K}_{BS}$. Operating in DL, there are Q number of single antenna co-channel users, with the set of users given by $\mathbb{K}_{UE}$. The channel vector between the j-th BS and the i-th user is denoted by $\mathbf{h}_{ij}^H \in \mathbb{C}^{1\times N_j}$ and is assumed to adopt the uncorrelated block flat-fading model, where i indicates the index of the corresponding user. The global channel vector for user i is shown by $\mathbf{h}_i^H = [\mathbf{h}_{i1}^H, \cdots, \mathbf{h}_{iB}^H] \in \mathbb{C}^{1\times N_{Tot}}$, where $N_{Tot} = \sum_j N_j$. Similarly, $\mathbf{w}_{ij} \in \mathbb{C}^{N_j \times 1}$ is the individual beamforming vector at the j-th BS, intended for the i-th user, while the global precoding vector for user i is $\mathbf{w}_i = [\mathbf{w}_{i1}^H, \cdots, \mathbf{w}_{iB}^H]^H \in \mathbb{C}^{N_{Tot}\times 1}$. The association between users and BSs is defined by $\Psi_{ij} \in \{0, 1\}$, where a zero indicates no association and one represents an active association between the base station and user. The backhaul connects the large cell to small cells and allows sharing of user data and information. In this work, we assume perfect knowledge of CSI at all BSs and consider the traffic associated with CSI to be negligible in order to merely assess the impact of the user's data backhaul consumption especially when CoMP-JT is enabled. Figure 1 provides an illustration of a typical C-RAN architecture deploying cloud infrastructure.

The baseband signal model received at the i-th user in a cooperative network is mathematically represented as

$$y_i = \mathbf{h}_i^H \mathbf{w}_i x_i + \sum_{q\neq i}^{Q} \mathbf{h}_i^H \mathbf{w}_q x_q + z_i, \tag{1}$$

where x_i is the uncorrelated complex zero mean data symbol transmitted for the i-th user, such that $\mathbb{E}\{|x_i^2|\} = 1$, and z_i is the complex additive white Gaussian noise (AWGN) with zero mean and variance σ_i^2, such that $z_i \sim \mathcal{CN}(0, \sigma_i^2)$. The signal-to-noise-plus-interference-ratio (SINR) for the i-th user is given by

$$\gamma_i = \frac{|\mathbf{h}_i^H \mathbf{w}_i|^2}{\sum\limits_{q\neq i}^{Q} |\mathbf{h}_i^H \mathbf{w}_q|^2 + \sigma_i^2}, \quad i \in \mathbb{K}_{UE}. \tag{2}$$

III. Optimization Problem

In this section, we describe the mathematical optimization problem in which the aim is to find the beamformers and the associations, $\mathbf{w}_i$ and Ψ_{ij}, such that the minimum user rate in the network is maximized. The individual quality demand of each link can be represented by weights, $\eta_i \in \mathbb{R}^+$. An auxiliary variable, R_i, is defined as the rate delivered to the user, this is done in order to allow formulation of the backhaul constraint. Note that the corresponding rate of the i-th user is normalized by the DL transmission bandwidth. The optimization problem is then described as

$$\max_{\Psi_{ij}, \mathbf{w}_i, R_i} \quad \min_i (\frac{1}{\eta_i} R_i) \tag{3a}$$

$$\text{s.t.} \quad R_i \leq \log_2 (1 + \frac{\mathbf{h}_i^H \mathbf{w}_i \mathbf{w}_i^H \mathbf{h}_i}{\sum\limits_{q\neq i}^{Q} \mathbf{h}_i^H \mathbf{w}_q \mathbf{w}_q^H \mathbf{h}_i + \sigma_i^2}), \quad i \in \mathbb{K}_{UE}, \tag{3b}$$

$$\sum_{i=1}^{Q} \|\mathbf{w}_{ij}\|^2 \leq P_j, \quad j \in \mathbb{K}_{BS}, \tag{3c}$$

$$\sum_{i=1}^{Q} \Psi_{ij} R_i \leq C_j, \quad j \in \mathbb{K}_{BS}, \tag{3d}$$

$$\| \|\mathbf{w}_{ij}\|_2^2 \|_0 = \Psi_{ij}, \quad i \in \mathbb{K}_{UE}, j \in \mathbb{K}_{BS}, \tag{3e}$$

where (3a) is the minimum user rate which is to be maximized, while (3c) represents the power constraint with P_j denoting the maximum transmission power of the j-th BS. Equation (3d) displays the formulation of the backhaul constraint as a sum of the throughput provided to the associated users, while C_j is the backhaul capacity of the j-th BS. The relationship between the beamforming vectors and the associations are defined in (3e) using the ℓ_0 norm, which sets the power allocated, $\|\mathbf{w}_{ij}\|_2^2$, to the user to zero if there is no association. Note that the defined optimization problem has a non-convex structure and is computationally difficult to solve.

IV. Hybrid Association and Semi-definite-Relaxation (SDR)

A. Hybrid Association Strategy

In order to obtain a convex formulation of the original problem, to which SDR can be applied, the association problem is tackled using a hybrid strategy which selects associations based on BS power constraints and distance to the user. The motivation behind the proposed association strategy is to allow effective use of the data present in the BS backhaul links, which is one of the major performance bottlenecks of a C-RAN. This is especially the case in heterogeneous designs where a large cell can offer a better SNR compared to a small cell in the close vicinity of the users, hence overloading the large cell. This can be rectified by associating the users based on distance, thus, avoiding idle small cells. However, it is also important that the user is associated to a BS that has the potential of effectively using the data consuming its backhaul by transmitting with sufficiently good links, note that this will essentially depend on the individual power constraint of each BS.

In order to identify suitable BSs for transmission, the quality of each communication link is assessed and compared to others. Our quality indicator is defined as $\Phi_{ij} = \frac{P_j}{d_{ij}^{\alpha}}$, where d_{ij} denotes the distance between the user and the BS and α represents the path loss exponent. The decision to enable CoMP transmission between BSs is then made by comparing the quality of all links to the highest one, shown by Φ_{ij^*}. This may be formulated as $\beta_{ij} = \frac{\Phi_{ij}}{\Phi_{ij^*}}$, note that if two links can offer similar quality, the ratio will be closer to 1. On the other hand if there is a dominating link the ratio will be closer to 0. An active cooperation cluster is then formed by those BSs which satisfy $\beta_{ij} \geq \theta$, where $\theta \in [0, 1]$ is the cooperation threshold. By taking into consideration both resource and distance, we allow for a more distributed association of users, as it is no longer solely based on SNR and hence avoid overloading the large cell. Furthermore, having the individual power constraint of each BS integrated in the quality indicator, ensures that a BS is selected with more potential and hence, a good quality link is provided for transmitting the user's data from the backhaul. Another important feature of this strategy is that instead of a fixed size cooperation cluster, the size depends on θ, where a value of 1 will result in single association and 0 results in cooperation of all BSs. Note that θ can be individually defined per base station or even per user in order to adapt the network to the service and operation requirements, e.g., high mobility users can be given a low threshold, similarly BSs which have good synchronization capabilities for supporting CoMP-JT, may be given a low threshold in order to increase cooperation. Nonetheless, from our investigations and simulations, shown later in Section V, we are able to suggest a region for θ with good trade off between minimum rate and energy efficiency.

B. Zero-Forcing Beamforming for Interference Mitigation

Multiple-input multiple-output (MIMO) communication techniques are an effective method for achieving high capacities, interference management and increased diversity. A way of eliminating multi-user interference, experienced in the original problem, is to use zero-forcing spatial filters at the base stations [13]. This is implemented by employing block diagonalization (BD) which is a generalization of channel inversion and can be integrated into the beamforming design by enforcing the following constraint, i.e., $\mathbf{h}_i^H \mathbf{w}_q = 0, \forall q \neq i$. Note that although this approach requires the total number of transmit antennas to be larger than or equal to the number of receive antennas, it offers a relatively low computational cost [14]. This technique essentially favors lower transmit power in order to null the interference and by doing so also assists in keeping constraint (3b) tight. With the aforementioned hybrid strategy and the elimination of the interference terms the optimization problem is now carried out over $\mathbf{w}_i$ and R_i and can be written as

$$\begin{aligned}
\max_{\mathbf{w}_i, R_i} \quad & \min_i \left(\frac{1}{\eta_i} R_i\right) && \text{(4a)}\\
\text{s.t.} \quad & \text{(3c), (3d)} && \text{(4b)}\\
& R_i \leq \log_2\left(1 + \frac{\mathbf{h}_i^H \mathbf{w}_i \mathbf{w}_i^H \mathbf{h}_i}{\sigma_i^2}\right), \quad i \in \mathbb{K}_{UE}, && \text{(4c)}\\
& \|\mathbf{w}_{ij}\|^2 \leq \Psi_{ij} P_j, \quad i \in \mathbb{K}_{UE}, j \in \mathbb{K}_{BS}, && \text{(4d)}\\
& \mathbf{h}_i^H \mathbf{w}_q = 0, \quad \forall q \neq i, \quad i, q \in \mathbb{K}_{UE}. && \text{(4e)}
\end{aligned}$$

C. SDR for Minimum Rate Maximization

Using the semi-definite-relaxation framework [15], we achieve an equivalent formulation of the optimization problem by defining $\tilde{\mathbf{W}}_i = \mathbf{w}_i \mathbf{w}_i^H$ and imposing the constraint that $\tilde{\mathbf{W}}_i$ is a positive semidefinite matrix with rank one, this results in the following reformulation

$$\begin{aligned}
\max_{\tilde{\mathbf{W}}_i, R_i} \quad & \min_i \left(\frac{1}{\eta_i} R_i\right) && \text{(5a)}\\
\text{s.t.} \quad & R_i \leq \log_2\left(1 + \frac{\mathrm{tr}(\mathbf{h}_i \mathbf{h}_i^H \tilde{\mathbf{W}}_i)}{\sigma_i^2}\right), \quad i \in \mathbb{K}_{UE}, && \text{(5b)}\\
& \sum_{i=1}^{Q} \mathrm{tr}(\mathbf{\Pi}_j \tilde{\mathbf{W}}_i \mathbf{\Pi}_j) \leq P_j, \quad j \in \mathbb{K}_{BS}, && \text{(5c)}\\
& \sum_{i=1}^{Q} \Psi_{ij} R_i \leq C_j, \quad j \in \mathbb{K}_{BS}, && \text{(5d)}\\
& \mathrm{tr}(\mathbf{\Pi}_j \tilde{\mathbf{W}}_i \mathbf{\Pi}_j) \leq \Psi_{ij} P_j, \quad i \in \mathbb{K}_{UE}, j \in \mathbb{K}_{BS}, && \text{(5e)}\\
& \mathrm{tr}(\mathbf{h}_q \mathbf{h}_q^H \tilde{\mathbf{W}}_i) = 0, \quad \forall i \neq q, \quad i, q \in \mathbb{K}_{UE}, && \text{(5f)}\\
& \mathrm{rank}(\tilde{\mathbf{W}}_i) = 1, \quad i \in \mathbb{K}_{UE}, && \text{(5g)}\\
& \tilde{\mathbf{W}}_i \succeq 0, \quad i \in \mathbb{K}_{UE}, && \text{(5h)}
\end{aligned}$$

where $\mathbf{\Pi}_j$ is a binary selection matrix of size $N_{Tot} \times N_{Tot}$ which allows us to consider the elements in $\tilde{W}_i$ corresponding to the j-th BS. The above formulations do not yet hold a convex structure due to the rank one constraint and subsequently Equation (5g) is dropped in order to obtain a relaxed version of the problem which is convex and can be efficiently solved by numerical solvers, such as [16]. The well known randomization technique is then used to find a rank-1 approximation of the optimal general-rank matrices, that will satisfy all the constraints, whilst ensuring that (5b) is tight [15]. It should be noted that a general rank covariance matrix may be as well implemented via space-time-block coding schemes such as [17].

V. Simulation Results

In this section we illustrate the performance of our proposed solution via Monte-Carlo simulations. The setup parameters follow the 3GPP LTE specification [18] for a heterogeneous scenario and the system performance is averaged for 200 channel realizations. The channel gain between the i-th user and j-th BS is calculated by $\mathbf{h}_{ij} = \kappa_{ij}\mathbf{g}_{ij}$, where κ_{ij} denotes the large scale fading consisting of path loss and shadowing, while $\mathbf{g}_{ij} \in \mathbb{C}^{N_j \times 1}$ represents the small scale fading, between user i and BS j, following a complex Gaussian distribution with zero mean and unit variance. The probability of having a line-of-sight (LOS) between the large cell and users is given by

$$P_{los}(d) = \min(0.018/d, 1) \times (1 - \exp(-d/0.063)) + \exp(-d/0.063), \quad (6)$$

with d [km] denoting the distance between the BS and the user, whereas in the case of small cell the probability of LOS is expressed as

$$P_{los}(d) = 0.5 - \min(0.5, 5\exp(-0.156/d)) + \min(0.5, 5\exp(-d/0.03)). \quad (7)$$

In the simulated scenarios there exists a single large cell, at the center, capable of carrying out the baseband processing of the cluster in a centralized manner. The large cell is populated by two small cells, following a uniform random distribution. Four single antenna users, with $\eta_i = 1$, are distributed such that the probability of being located inside a small cell is $P_{hotspot} = \frac{2}{3}$. All the BSs are equipped with four antennas and a backhaul link capacity of 500Mbps. Table I summarizes the considered simulation parameters. The performance of the proposed solution is compared to common schemes in use, such as a fully cooperating network in which all BSs are transmitting to all the users, represented by "Full-CoMP". The "Dist.2-CoMP" scheme defines a fixed size cooperation cluster of BSs to serve users, as the closest two BSs. We also define a non-cooperative scheme, identified as "Dist.1", in which each user connects to the nearest cell. Note that in this scheme there will be no joint transmission, in order to provide a good reference for when CoMP-JT is enabled, however the single cell association is still able to perform ZF. The hybrid strategy is analyzed with three different values of the path loss exponent $\alpha = [2.5, 3, 3.5]$ in order to provide in depth studies, however it is important to note that the path loss exponent value which coincides best with our simulated scenario based on the 3GPP specification is $\alpha = 3$.

In Fig. 2 we study the minimum user rate performance of the schemes with different values of θ. It can be seen that full cooperation provides the best performance, due to its ability to support cell edge users. It can also be observed that "Dist.2-CoMP" offers a minimum rate performance similar to full cooperation, this indicates that cooperating with more BSs does not necessarily guarantee improvement, and hence, also reconfirms the need for developing a method for selecting suitable BSs for CoMP. It can be seen that with the hybrid methods the minimum user rate generally tends to decrease with less cooperation, which is understandable due to less support for cell edge users. It can also be extracted that with a lower α the association scheme becomes more power dependent, therefore, connecting to the high power large cell and offering a better rate. Although in the hybrid schemes the minimum user rate tends to decrease with less cooperation, it is important to note that this drop is not significant, for instance for the case of $\alpha = 3$ at $\theta = 0.5$, the drop compared to the "Full-CoMP" is less than 9%. The performance of "Dist.1" serves as a benchmark for a case where the value of α is high, which causes the distance component in the hybrid quality indicator to dominate and hence connect the user to the closest cell.

The sum throughput performance of the simulated schemes is illustrated in Fig. 3, where it is shown that full cooperation does not equate to offering the best performance. The reason for this lies in the backhaul restriction imposed; when the network operates in full cooperation mode the user's data will be present in BSs which are not necessarily capable of improving the performance by joint transmission, this is due to low power constraint or bad channel conditions. Schemes such as "Dist.2-CoMP" and the hybrid ($\alpha = 2.5, 3$) are able to outperform "Full-CoMP" by selecting a cooperation cluster which is actually capable of improving the user performance and leaving the backhaul of other cells free for other users. Similar to the minimum user rate it can be seen that a hybrid scheme with a higher α is more distance dependent and hence the drop in performance which can be compared to the extreme case of "Dist.1". It is paramount to point out that, similar to the minimum user rate performance, the drop in performance using the hybrid strategies is relatively small. For instance in the case of $\alpha = 3$ at $\theta = 0.5$, as before, the proposed hybrid strategy only experiences a 1.3% loss.

From Fig. 4 it can be seen that full cooperation results in the highest power consumption in the network. In comparison, "Dist.2-CoMP" demands a slightly less power consumption, resulted from connecting to the nearest two cells which may not be the high power large cell. As θ increases, the condition for cooperation becomes more stringent, resulting less power consumption. This is also evident in the hybrid strategy where the power consumption declines as the threshold for cooperation increases. However, a small raise in power consumption occurs when $\theta = 1$, due to the users tendency to connect to the large cell. With the objective of the optimization problem being to maximize the minimum rate, the large cell is able to invest more in transmission power as compared to small cells. This is less likely to happen if the scheme is more power dependent, such as $\alpha = 2.5$, because the large cell would more likely be the primary association. What can be most crucially taken from Fig. 4 is the significant reduction in power achieved. For example for $\alpha = 3$ at $\theta = 0.5$, the power consumption of the network is reduced by 39.7%.

In Fig. 5 the energy efficiency of the schemes are studied, in order to provide better insight on the gains of our proposed approach. As it can be seen due to the small decrease in the sum throughput relative to the drop in power consumption, the proposed hybrid strategies are able to perform better than the "Full-CoMP" and "Dist.2-CoMP" schemes. It is also observed that with a more distance dependent strategy, higher α, the energy efficiency increases with a performance cap of "Dist.1". This is due to a more aggressive use of small cells which consume less power. The decrease in the tail end of the hybrid schemes, where $\theta = 1$, is due to the raise in power consumption explained previously. The gain achieved using the hybrid strategy for $\alpha = 3$ at $\theta = 0.5$, relative to the full cooperation scheme is evaluated to be at an impressive 37.6%. The trade off between minimum user rate and energy efficiency is investigated in Fig. 6 for the hybrid $\alpha = 3$ scheme, which corresponds to our simulation setup. It can be observed that with increasing minimum rate there exists a region with the best energy efficiency performance at $\theta = 0.83$. Note that although the energy efficiency generally declines at higher rates, one can achieve a better tradeoff using the recommended value of θ, using our proposed approach, in comparison to single BS association. This can also serve to reconfirm that too much cooperation can result in little improvement at the expense of greater degradation in other performance metrics.

TABLE I
SIMULATION PARAMETERS

Parameter	**Settings**
Carrier Frequency	2GHz
Bandwidth	10MHz
Large Cell Radius	250m
Small Cell Radius	50m and 40m
Large Cell Transmission Power	40dBm
Small Cell Transmission Power	34dBm and 28dBm
Path Loss (dB) between large cell and users (d in km)	LOS: $103.4 + 24.2\log_{10} d$ NLOS: $131.1 + 42.8\log_{10} d$
Path Loss (dB) between small cells and users (d in km)	LOS: $103.8 + 20.9\log_{10} d$ NLOS: $145.4 + 37.5\log_{10} d$
Shadowing Standard Deviation	Between large cell and UE : 8dB Between small cells and UE: 10dB
Noise level	-134dBm/Hz

VI. CONCLUSION

In our work we presented a new approach to maximize the weighted minimum user rate in a heterogeneous C-RAN by determining the DL beamforming vectors under backhaul, power and zero-forcing interference constraints. Additionally we contributed a hybrid quality indicator which enables joint transmission only when it can be effective, whilst not dictating fixed size cooperation clusters as in conventional schemes. The solution displays significant gains achieved in terms of energy efficiency at the expense of small degradation in terms of throughput. From our simulations it is also possible to observe the cooperation threshold range for which the best trade off between minimum user rate and energy efficiency can be reached. Moreover, the flexibility provided in the model allows for individual BS power and backhaul capacity constraints to be declared, which is highly relevant to the case of heterogeneous networks operating under restricted backhauls. To the best of our knowledge this is the first work that considers beamforming optimization and hybrid association in a heterogeneous C-RAN whilst considering backhaul constraints.

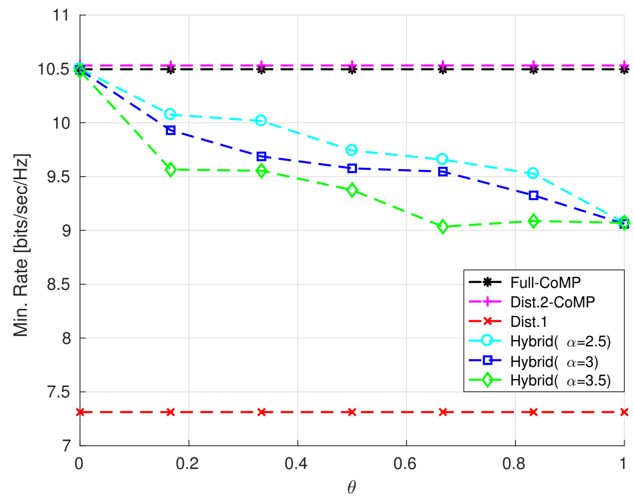

Fig. 2. Min. User Rate vs. Cooperation Threshold. Less cooperation reduces the minimum user rate performance, as cell edge users suffer.

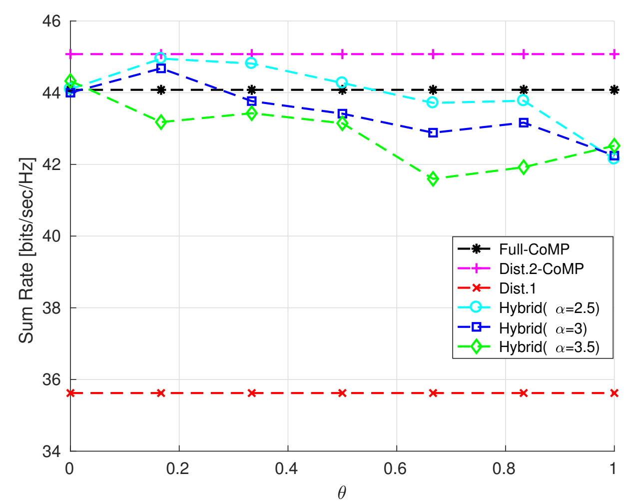

Fig. 3. Sum Throughput vs. Cooperation Threshold. The hybrid strategies do not experience a significant decline with higher threshold and are even able to outperform full cooperation due to better use of the limited backhaul resources.

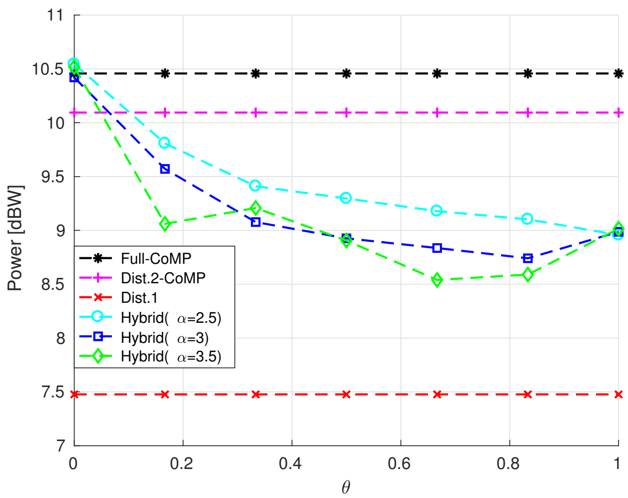

Fig. 4. Power Consumption vs. Cooperation Threshold. The power consumption generally reduces with less cooperation.

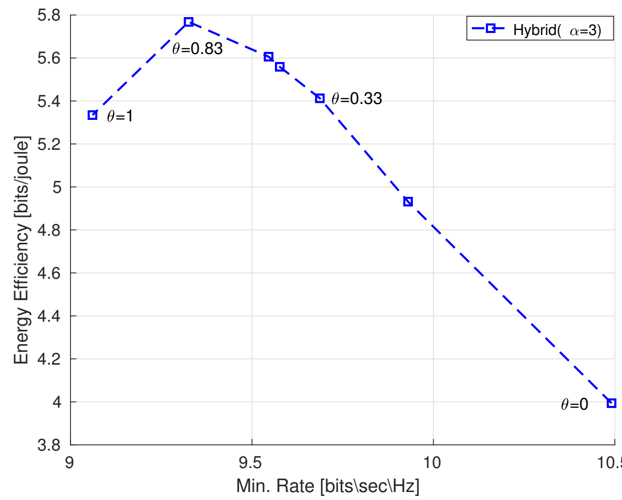

Fig. 6. Energy Efficiency vs. Min. User Rate, for case $\alpha = 3$. A good region of operation can be achieved based on two criteria when $\theta = 0.83$.

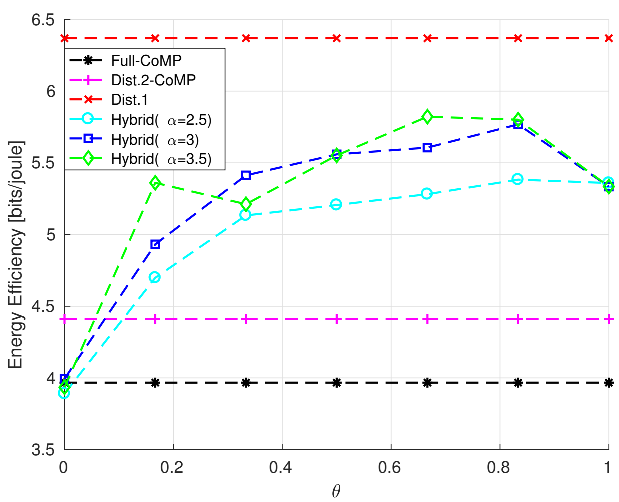

Fig. 5. Energy Efficiency vs. Cooperation Threshold. All the hybrid schemes are able to outperform full cooperation due to better quality associations.

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