DJP: Dynamic Joint Processing for Interference Cancellation in Cloud Radio Access Networks

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***Abstract*—Coordinated Multi-Point (CoMP) processing is one of the promising methods to mitigate the intra-cluster interference in cellular systems, to improve the average Signal-to-Interference-plus-Noise Ratio (SINR), and to increase the overall spectral efficiency. Such method, however, does not take any action to mitigate the inter-cluster interference, which leads to poor performance for cluster-edge Mobile Stations (MSs) and, consequently, to unfairness in service provision. In the context of Cloud Radio Access Network (C-RAN) – a new centralized paradigm for wireless cellular networks in which Base Stations (BSs) are physically unbundled into Virtual Base Stations (VBSs) and Remote Radio Heads (RRHs) – an innovative solution, called Dynamic Joint Processing (DJP), is proposed to mitigate *both* intra- *and* inter-cluster interference so to improve performance of cluster-edge MSs. A dynamic clustering approach is presented in which, for each subcarrier, a *virtual cluster* is defined, and its size is dynamically changed based on the position of the MSs. Simulation results confirm the validity of our approach.**

***Index Terms*—Cloud Radio Access Network, Interference Management, Coordinated Multi-Point Processing, Virtualization.**

I. Introduction

The Coordinated Multi-Point (CoMP) transmission and reception technique, which is based on cooperative Multiple Input Multiple Output (MIMO), is one of the promising methods to mitigate the average interference in cellular systems and to increase the overall spectral efficiency at the cost, however, of a higher receiver complexity [1], [2]. In CoMP, a set of neighboring cells are divided into *clusters*; within each cluster, Base Stations (BSs) are connected to each other via the Back-haul Processing Unit (BPU) and exchange Channel State Information (CSI) as well as Mobile Station (MS) signals. Coordination of the BSs within a cluster can improve the overall Signal-to-Interference-plus-Noise Ratio (SINR). In the uplink, each BS receives a combination of MS signals from its own and from the other neighboring cells. By combining the CSI from different cells and sharing the received signals at the BPU, CoMP is able to cancel the *intra-cluster interference*.

CoMP cannot, however, mitigate the inter-cluster interference, which affects poorly the performance of cluster-edge MSs, which greatly suffer from such interference. Hence, in a cellular network with a frequency reuse factor equal to 1, the achieved system capacity is still significantly far from the interference-free capacity upper bound. Furthermore, one of the main requisites of Long-Term Evolution (LTE) systems is the very low latency: *the additional processing required for multiple-site reception/transmission and CSI acquisition as well as the communication overhead incurring among different BSs add significant delay and limit the cluster size (especially for massive MIMO)*. Moreover, BS clocks need to be in phase in order to enable proper operation of CoMP, which requires a highly accurate phase or time-of-day synchronization. To overcome these challenges, the BSs should form a type of centralized Radio Access Network (RAN).

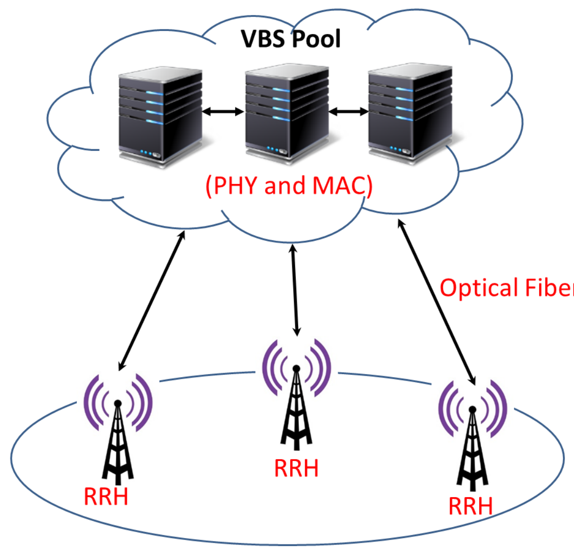


Fig. 1: Cloud Radio Access Network (C-RAN) architecture, where the Base Stations (BSs) are physically unbundled into Virtual Base Stations (VBSs) and Remote Radio Heads (RRHs). VBSs are housed in centralized processing pools and can communicate with each other at Gbps speeds.

Cloud Radio Access Network (C-RAN) [1], [3] is a new architecture for wireless cellular networks that addresses efficiently the fluctuation in capacity demand while keeping the cost of delivering services to the users low. It also provides a higher degree of cooperation and communication among BSs. *C-RAN represents a clean-slate design and allows for dynamic reconfiguration of computing and spectrum resources*. Characteristics of C-RAN are: i) centralized management of computing resources, ii) collaborative communications, and iii) real-time cloud computing on generic platforms. As shown in Fig. 1, C-RAN is composed of Remote Radio Heads (RRHs) distributed over a wide geographic region controlled by remote Virtual Base Stations (VBSs) housed in centralized processing pools. VBSs and their corresponding RRHs should be connected by high-bandwidth low-latency media (e.g., the use of optical fibers allows for a maximum distance of separation of 40 km between the RRU and its VBS) [3]. The communication functionalities of the VBSs are implemented on Virtual Machines (VMs) hosted over general-purpose computing platforms, which are housed in one or more racks of a small cloud datacenter. In a centralized VBS pool, since all the information from the BSs is resident in a common place, the BSs can exchange control data at Gbps. This can provide a high degree of freedom to be used to make optimized, real-time decisions and to improve the overall system performance.

Centralized management of computing resources, i.e., BS pooling, renders BS information global and, hence, enables cooperative communication techniques at the MAC and PHY layers that were previously not implementable due to strict inter-BS coordination requirements (in terms of throughput and latency). Examples of MAC- and PHY-layer enhancements include joint flow scheduling and load balancing [4], collaborative spatial multiplexing [5], interference alignment and cancelation [6], and advanced mobility management [7]. Even though work has been done on the aforementioned cooperative communication techniques, which can all benefit from the C-RAN characteristics, research on enabling technologies for C-RAN itself is still at a nascent stage.

In this paper, we propose a novel solution, called *Dynamic Joint Processing (DJP)*, which decreases *both* the intra- and inter-cluster interference without increasing the size of clusters. To achieve this goal, we introduce the idea of *"VBS-Cluster"* and present a dynamic clustering approach to avoid having users at the edge of a virtual cluster. Specifically, we define *virtual clusters* per subcarrier[1]: unlike in the traditional CoMP where the clusters are *"omni-subcarrier"* (i.e., in each cluster *all* subcarriers are used), in our approach the clusters are *"uni-subcarrier"* (i.e., each cluster generally only deals with *one* subcarrier). Moreover, the cluster size of the coordinated cells is not fixed and can be changed dynamically based on the MSs' positions. In fact, we dynamically optimize the size of virtual clusters in such a way as to decrease the inter-cluster interference and to increase the throughput of cluster-edge MSs, thus achieving fairness in service provisioning.

The rest of the paper is organized as follow. In Sect. II, we present the system model, discuss about our proposed solution, and explain how we are able to decrease the average interference with respect to (w.r.t.) current static solutions. In Sect. III, we validate our statements through Monte Carlo simulations and show the potential of our solution. Finally, in Sect. IV, we draw the main conclusions.

II. Proposed Solution

To understand our solution, here below we formulate the problem, detail issues with CoMP, and explain why CoMP is unable to overcome current cellular network challenges.

[1]In Orthogonal Frequency Division Multiple Access (OFDMA), the spectrum is divided into a fixed number of subcarriers and a high data rate is split into lower-rate streams that are transmitted over some of these subcarriers.

A. System Model

In CoMP, a set of neighboring cells is divided into clusters, and in each cluster the BSs coordinate with each other in order to improve the average SINR. Since in each cluster the BSs receive a combination of *internal* and *external* MS signals[2], the goal of CoMP is to cancel the intra-cluster interference. We assume that in the cluster there are M single-antenna BSs and $N \leq M$ single-antenna MSs (using the same subcarrier). Under these assumptions, the relationship between the received signals by internal BSs and the transmitted MS signals at different time instants can be expressed through the following linear noisy model,

$$\mathbf{y}(k) = \sum_{j=1}^{N} s_j^{in}(k)\mathbf{h}_j^{in}(k) + \mathbf{n}(k) = \mathbf{H}_{in}(k)\mathbf{s}_{in}(k) + \mathbf{n}(k), \tag{1}$$

where, for clarity, the time variable t is omitted; here, $\mathbf{s}_{in}(k) = [s_1^{in}(k), \ldots, s_N^{in}(k)]^T$ is the $N \times 1$ vector of internal MS signals, $\mathbf{y}(k) = [y_1(k), \ldots, y_M(k)]^T$ is the $M \times 1$ vector of signals received by the internal BSs over the k^{th} subcarrier, $\mathbf{H}_{in}(k)$ is the $M \times N$ channel coefficients between the MSs and BSs ($\mathbf{h}_j^{in}(k)$ being its j^{th} column), and $\mathbf{n}(k) = [n_1(k), \ldots, n_M(k)]^T$ is the $M \times 1$ background noise vector with independent and identically-distributed (i.i.d.) components. Note that in (1) we have included the inter-cluster interference as part of the background noise, i.e.,

$$\mathbf{n}(k) = \mathbf{H}_{ex}(k)\mathbf{s}_{ex}(k) + \mathbf{w}(k), \tag{2}$$

where $\mathbf{s}_{ex}(k) = [s_1^{ex}(k), \ldots, s_L^{ex}(k)]^T$ is the $L \times 1$ vector of the external MS signals (causing inter-cluster interference), $\mathbf{H}_{ex}(k)$ is the $M \times L$ channel coefficients between the external MSs and internal BSs, and $\mathbf{w}(k) = [w_1(k), \ldots, w_M(k)]^T$ is the $M \times 1$ vector of Additive White Gaussian Noise (AWGN).

A simple form of coordination is achieved by employing a Zero-Forcing (ZF) receiver. In the ZF receiver (for the uplink), since the CSI from all the internal BSs in a cluster is available, we can form the equalizer as,

$$\mathbf{G}_{ZF} = \left(\mathbf{H}_{in}^{\dagger}\mathbf{H}_{in}\right)^{-1}\mathbf{H}_{in}^{\dagger}, \tag{3}$$

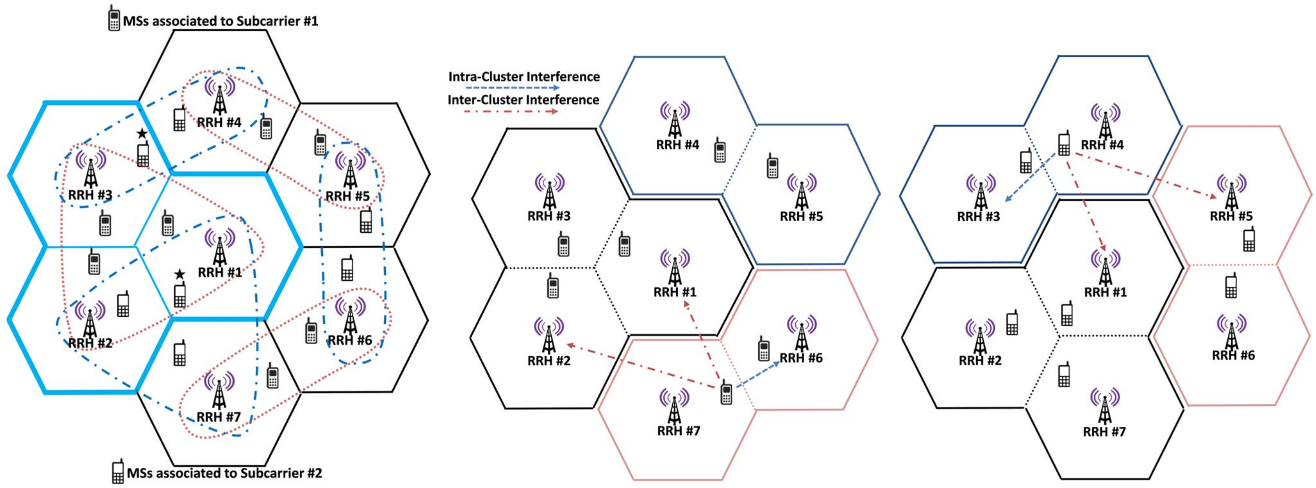
where the output of the ZF receiver is given by,

$$\hat{\mathbf{s}}_{in}(k) = \mathbf{G}_{ZF}(k)\mathbf{y}(k) = \mathbf{s}_{in}(k) + \mathbf{G}_{ZF}(k)\mathbf{n}(k). \tag{4}$$

Here, $\hat{\mathbf{s}}_{in}(k) = [\hat{s}_1^{in}(k), \ldots, \hat{s}_N^{in}(k)]^T$ is the $N \times 1$ vector of estimated internal MS signals, each of which is associated with a combination of the background noises at all the receivers. *From* (2) *and* (4)*, it is clear that CoMP is able to cancel the intra-cluster interference, but does not take any action to decrease the inter-cluster interference affecting cluster-edge MSs (which is incorporated in the background noise)*, i.e.,

$$\hat{\mathbf{s}}_{in}(k) = \mathbf{s}_{in}(k) + \mathbf{G}_{ZF}(k)\mathbf{H}_{ex}(k)\mathbf{s}_{ex}(k) + \mathbf{G}_{ZF}(k)\mathbf{w}(k). \tag{5}$$

[2]We name a MS (or BS) inside the cluster as *internal* MS (or BS) and outside as *external* MS (or BS), and use subscripts "$_{in}$" and "$_{ex}$," respectively.



(a) Conventional CoMP (b) Virtual clusters for subcarrier #1 (c) Virtual clusters for subcarrier #2

Fig. 2: (a) Conventional CoMP, where the cluster (consisting of cells #1, #2, and #3) is omni-subcarrier and starred MSs have an intense inter-cluster interference on the neighboring cells; (b), (c) The clusters are virtual uni-subcarrier and there is no cluster-edge MS as cell clustering is based on the MSs' and RRHs' positions.

B. Dynamic Joint Processing (DJP)

If we assume that the background noise at the l^{th} receiver has a variance of σ_l^2, then the noise in the i^{th} estimated MS signal has a variance of $g_{i1}^2\sigma_1^2 + \cdots + g_{iM}^2\sigma_M^2$, where g_{ij} is the $(i,j)^{th}$ component of the equalizer matrix $\mathbf{G}_{ZF}$. It is clear from (5) that *the interference generated by the external cluster-edge MSs dramatically decreases the SINR and has a severe destructive impact on the performance of the serving cluster*. In traditional CoMP, since only a group of BSs are connected to each other and can exchange data, the cluster boundaries are set and cannot be changed dynamically as needed. Hence, CoMP only changes the boundaries of interference from cell to cluster. On the other hand, increasing the cluster size would lead to an increase in complexity to run the CoMP algorithms and also to an increase in the delay to exchange the CSIs between MSs and BSs, which is in conflict with the low-latency requirement of LTE systems.

Conversely, in the C-RAN architecture, all the VBSs of a large region are centralized in a common datacenter. This centralized characteristic along with real-time virtualization technology provides an extra degree of freedom that is useful to mitigate *both* the intra-cluster as well as inter-cluster interference. In addition, the VBSs can communicate and exchange data with each other at Gbps speeds. Unlike in traditional CoMP where each cell is associated *statically* with a certain cluster, in C-RAN we are able to associate each cell with different clusters dynamically and add/remove cells to/from a certain cluster. This means that we can cluster VBSs into *VBS-Clusters* while the associated RRHs in each cluster act as a *single coherent antenna array* distributed over the cluster region. We leverage these properties to form *virtual clusters* so to mitigate the intra- as well as inter-cluster interference and consequently boost the overall system spectral efficiency.

In our DJP solution, *for each subcarrier* we divide the neighboring cells into *virtual clusters* based on the position of the associated MSs and on their distances from the neighboring RRHs; the virtual clusters are defined per subcarrier such that the detrimental impact of inter-cluster interference is minimal. Unlike in CoMP in which the clusters are *"omni-subcarrier"* (i.e., in each cluster all subcarriers are used), in our solution the virtual clusters are *"uni-subcarrier"* (i.e., each cluster only deals with one subcarrier). Consequently, each cell may be part of different virtual clusters for different subcarriers.

To clarify the motivation for this design choice, we use the network of 7-cell sites (as shown in Fig. 2) with two operating subcarriers; we also use different icons for the MSs operating on different subcarriers. In Fig. 2(a), we assume that this network works under traditional CoMP and cells #1, #2, and #3 form a omni-subcarrier cluster (cluster boundaries are shown with thick lines and different color). In this case, the internal MSs associated with subcarrier #2 and located in cluster-edge regions (which are distinguished by star) have a destructive inter-cluster interference on the neighboring external RRHs (#4 and #7). To address this problem, we propose to form *virtual uni-subcarrier clusters* based on the position of MSs and RRHs. Virtual clustering must be done is such a way that the internal MSs have minimal inter-cluster interference on the neighboring virtual clusters. *To do this, we need to measure the received power from each MS to the internal and external RRHs, and decide to change the serving cluster if the interference on external RRH is greater than the interference on internal RRHs.* In Fig. 2(a), dotted and dot-dash lines show uni-subcarrier clustering of cell sites associated with subcarriers #1 and #2, respectively. Figures 2(b) and (c) also show the uni-subcarrier clusters for subcarriers #1 and #2, respectively. For example, cells #1, #2, and #3 form a uni-subcarrier cluster for subcarrier #1 (Fig. 2(b)) and cells #1, #2, and #7 form a uni-subcarrier cluster for subcarrier #2

(Fig. 2(c)). Note that each cell is associated with two uni-subcarrier clusters, while in traditional CoMP each cell is *only* associated with one omni-subcarrier cluster. The clustering is done is such a way that there is no cluster-edge MSs and the received power from MSs to external RRHs is very low. This is because with uni-subcarrier clustering all the internal MSs are as far as possible from external RRHs and situated in the center of the cluster.

Moreover, in DJP, the size of virtual clusters is not fixed, and can be changed based on the MSs' positions: if a MS in a certain cluster moves and becomes a cluster-edge MS, thus potentially generating high inter-cluster interference, we remove its serving cell from the serving virtual cluster and add it to a neighboring virtual cluster in such a way that that MS would cause less inter-cluster interference.

In order to formulate our solution, we consider that the frequency band has a set of subcarriers $\mathcal{F} = \{f_1, \ldots, f_K\}$, where K is the total number of subcarriers, and that, for each subcarrier, the network has a set of virtual uni-subcarrier clusters $\mathcal{J}_{LM}^k = \left\{1, \ldots, J^k\right\}$ $(1 \leq k \leq K)$; each virtual cluster consists of a set of RRHs $\mathcal{M}_j^k = \left\{1, \ldots, M_j^k\right\}$ $\left(1 \leq j \leq J^k\right)$, and in each virtual cluster there is a set of active MSs $\mathcal{N}_j^k = \left\{1, \ldots, N_j^k\right\}$ $\left(1 \leq j \leq J^k\right)$. Note that all the subcarriers are used by each cell and the frequency reuse factor is equal to 1. We measure the received power (in dB) from the MS $n_i^k \in \mathcal{N}_i^k$ by the RRH $m_l^k \in \mathcal{M}_l^k$ at time t as,

$$P_{rx}\left(n_i^k, m_l^k, t\right) = P_{tx}\left(n_i^k, t\right) - PL(n_i^k, m_l^k, t) - P_{\text{fad}}(n_i^k, m_l^k, t), \tag{6}$$

where $PL(n_i^k, m_l^k, t)$ is the large-scale path loss between the MS n_i^k and the RRH m_l^k at time t, $P_{tx}\left(n_i^k\right)$ is the transmitted power of the MS n_i^k, and $P_{\text{fad}}(n_i^k, m_l^k, t)$ is the time-varying shadowing fading loss.

As CoMP takes care of the intra-cluster interference, our goal is to minimize the inter-cluster one. To do this, we measure the summation of received inter- and intra-cluster interference power from the MS n_i^k to the neighboring and serving clusters as,

$$\begin{aligned} P_{ex}\left(n_i^k, j, t\right) &= \sum_{\forall m_j^k \in \mathcal{M}_j^k} P_{rx}\left(n_i^k, m_j^k, t\right), \\ P_{in}\left(n_i^k, i, t\right) &= \sum_{\forall m_i^k \in \mathcal{M}_i^k, m_i^k \neq n_i^k} P_{rx}\left(n_i^k, m_i^k, t\right), \end{aligned} \tag{7}$$

where $P_{ex}\left(n_i^k, j, t\right)$ is the received inter-cluster interference from MS n_i^k by the j^{th} virtual cluster and $P_{in}\left(n_i^k, i, t\right)$ is the received intra-cluster interference from MS n_i^k by its serving virtual cluster (i^{th} cluster). Then, we find the cluster that receives maximum inter-cluster interference from MS n_i^k and select it as the *nominated* cluster,

$$P_{j_{max}}\left(n_i^k, t\right) = \max_{1 \leq j \leq J^k, j \neq i} P_{ex}\left(n_i^k, j, t\right), \tag{8}$$

where $P_{j_{max}}\left(n_i^k, t\right)$ is the maximum inter-cluster interference from MS n_i^k and j_{max} is the index of the nominated cluster to be added to the serving cell in the k^{th} subcarrier at time t. In each iteration, we remove the serving cell from the serving cluster and add it to the nominated cluster if $P_{j_{max}}\left(n_i^k, t\right)$ exceeds $P_{in}\left(n_i^k, i, t\right)$ using an hysteresis threshold thr to avoid fluctuations that may lead to instability (Algorithm 1).

Algorithm 1 Dynamic Joint Processing (DJP)

Input: $\mathcal{F}_r$ = Set of associated subcarriers to the MS, $K_r = |F_r|$ = Number of associated subcarriers to the MS, thr = Hysteresis threshold, T = Time between two iteration

Description:

1: **for** $k = 1$; $k \leq K_r$; $k++$ **do**
2: i = index of serving virtual uni-subcarrier cluster
3: Calculate $P_{in}\left(n_i^k, i, t\right)$
4: **for** $j = 1$; $j \leq J^k$; $j++$ **do**
5: Calculate $P_{ex}\left(n_i^k, j, t\right)$
6: **end for**
7: Calculate $P_{j_{max}}\left(n_i^k, t\right)$
8: **if** $P_{j_{max}}\left(n_i^k, t\right) - P_{in}\left(n_i^k, i, t\right) > thr$ **then**
9: Remove the serving cell from the i^{th} cluster and add it to the j_{max}^{th} cluster
10: **end if**
11: **end for**
12: After T seconds repeat the DJP Algorithm (go to line 1)

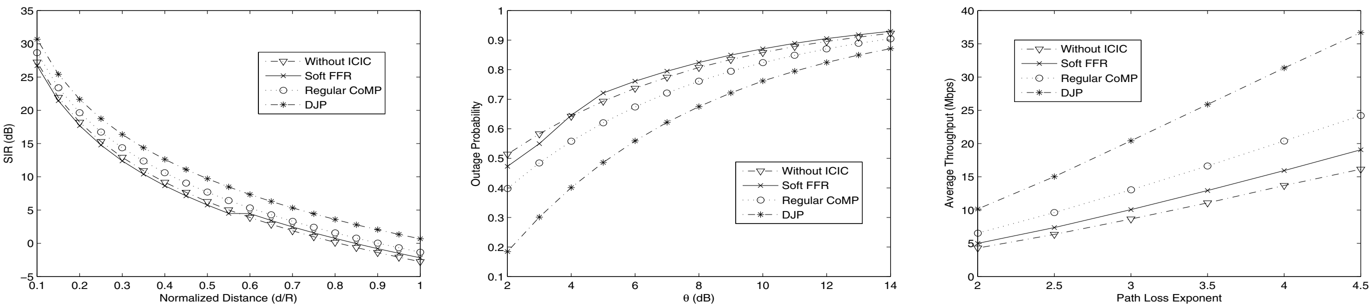
III. Performance Evaluation

We performed a wide range of Monte Carlo simulations to evaluate the performance of our solution and obtain statistically-relevant results. Table I lists the parameters used in our experiments. To implement CoMP, we considered omni-subcarrier clusters of size 3. For a fair comparison of our DJP against CoMP, we considered virtual uni-subcarrier clusters of size ranging from 2 to 4, where the average virtual cluster size is equal to the (fixed) CoMP cluster size of 3. We analyzed different performance metrics – including Signal to Interference Ratio (SIR), outage probability, average throughput, and Average System Spectral Efficiency (ASSE) – to compare DJP with Regular CoMP, Soft FFR [8], and traditional cellular network (without Inter-Cell Interference Coordination (ICIC)).

We compared the SIR in terms of the Normalized Distance d/R, where d is the distance between the MS and the center of its serving cell of radius R. As shown in Fig. 3(a), compared with the traditional network, Soft FFR, and Regular CoMP, our DJP solution provides a significant gain. For instance, for cell-edge MSs (e.g., $d/R = 0.85$) we have a 256% improvement in SIR (dB) compared to Regular CoMP. Also, we examined the performance of our solution in terms of outage probability Pr_{out}, i.e., the probability that a MS's instantaneous SIR falls below a threshold θ [dB], which is defined as,

$$\text{Pr}_{\text{out}} = \text{Pr}\{\text{SIR} < \theta\} = 1 - \text{Pr}\{\text{SIR} > \theta\}. \tag{9}$$

Figure 3(b) shows the variations of outage probability in terms of different SIR thresholds. Note that for $\theta = 3$ dB, the outage probability for DJP is 0.29 (which, using an ergodic interpretation, means that only 29% of the users have a SIR lower than 3 dB) while the outage probability for CoMP and Soft FFR is 0.48 and 0.54, respectively.



(a) (b) (c)

Fig. 3: (a) Signal to Interference Ratio (SIR) for different Normalized Distances; (b) Outage probability for different thresholds; (c) Average Throughput for different Pass Loss Exponent.

TABLE I: Simulation Parameters.

Parameters	Mode/Value
Cellular Layout	Hexagonal grid
Channel Model	Pass Loss and Shadowing
Frequency Reuse Factor	1
Cell Radius	500 m
Channel Bandwidth	10 MHz
Subcarrier Spacing	15 kHz
No. of Subcarriers	1024
Transmission Bandwidth	9 MHz
Interior Radius in Soft FFR	$0.6R$
Distance Dependent Path Loss	$91.66 + 32\log(d)$ dB
Carrier Frequency	914 MHz
No. of Antennae (N_{TX}, N_{RX})	$(1, 1)$
MS Transmit Power	21 dBm
Hysteresis Threshold (thr)	6.2 dB
MS Antenna	Omni-directional
Receiver Processing	Zero Forcing
Modulation Scheme	OFDMA

As the interference highly depends on the path-loss exponent, we explored the variation of the average throughput versus this exponent for different schemes. As shown in Fig. 3(c), for an urban area where the average pass-loss exponent is 3.1, DJP achieves an average throughput of 20.42 Mbps, whereas for Regular CoMP such throughput is equal to 13.04.

Last, but not least, we explored the performance of our solution for different Signal to Noise Ratios (SNRs). As shown in Fig. 4, in the low SNR regime (i.e., SNR<5 dB), the ASSE values for all schemes are very close to each other; however, when the SNR increases, our proposed solution outperforms the other schemes. For instance, for an SNR$=20$ dB, DJP achieves an ASSE of 1.99, while CoMP's is 1.4.

IV. Conclusion

We presented a novel solution, named Dynamic Joint Processing (DJP), that leverages the centralized characteristic of Cloud Radio Access Networks (C-RANs) in order to decrease the inter-cluster interference in CoMP methods. We introduced the idea of virtual clustering and defined uni-subcarrier clusters where the size of virtual clusters can be changed based

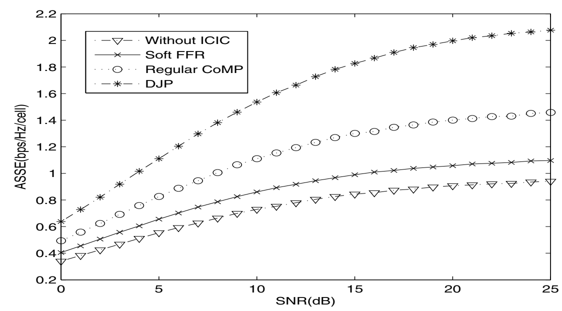


Fig. 4: Average System Spectral Efficiency (ASSE) as a function of Signal-to-Noise Ratio (SNR).

on the position of mobile stations. We proposed to change dynamically the serving cluster if the inter-cluster interference is greater than the intra-cluster interference.

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