Robust Multicell Cooperation in MIMO-OFDMA Networks

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Abstract: In future communication systems, the constraint of resource allocation is a challenging topic. The cell edge users in wireless systems experience low Signal to Interference and Noise Ratio (SINR) due to the high Inter-Cell Interference (ICI) and cannot fully benefit from Multiple-Input Multiple-Output (MIMO) multi-stream transmission capability. In this project, a practical approach to the multicell cooperation using joint user scheduling and rank coordination is proposed. In this, the cells coordinate among themselves using the transmission ranks (the number of transmitted streams) to maximize a network utility function, i.e., the throughput. Without going for the heavy machinery of an iterative scheduler, we aim for a simpler and practical method that directly tackles user scheduling and rank coordination. The dynamic coordination of the transmission ranks among cells helps cell edge users to benefit from higher rank transmissions. A distributed coordinated scheduler based on master-slave architecture is also studied and significant cell-edge performance gain is obtained using this approach.

Index Terms: Multi-user Multiple input Multiple output (MU-MIMO), distributed scheduler, downlink coordinated Multipoint (DL-CoMP).

I. INTRODUCTION

Communications through a wireless channel has many very challenges due to the complex propagation medium. The major difficulties faced in a wireless channel are fading and co-channel interference. When a signal is sent in the wireless environment, then due to the ground irregularities and typical wave propagation phenomena such as diffraction, scattering, and reflection, it may arrive at the receiver along a number of distinct paths, and this is referred to as a multi-path signal. Each one of these paths will have distinct and time-varying amplitude, angle of arrival and phase. These multi-paths can add up constructively or destructively at the receiver. Thus, the received signal parameters vary over frequency, time, and space. These differences are collectively referred to as fading and deteriorate link quality. Additionally, in the cellular systems, to increase the spectral efficiency and serve more number of users while maintaining minimum quality of service, frequencies are being reused in different cells that are adequately far apart. Therefore, one user's signal can be degraded by the interference from other users operating in the same frequency. Reduction in multi-user and co-channel interference has been an objective in the evolution of wireless cellular systems. The latest approach is to implement antenna arrays in the system. This coordinates the transmissions of a base stations' cluster and builds a distributed multiple-input multiple-output (MIMO) channel that allows for serving various users simultaneously and avoid interference among them altogether. . Antenna arrays can be setup at the transmitter, or receiver, or both ends. When the antenna array is at the receiver, fading can be decreased by using diversity techniques, i.e., combine the independently faded signals on the different antennas that are adequately separated. If the antennas receive independently faded signals, it is very unlikely that all signals undergo the same deep fades; hence, at least one good signal can be recovered. To satisfy the requirement of very high data rates for wireless Internet and multimedia services, multiple antennas set at both the transmitter and receiver have been proposed for fourth generation broadband wireless systems. This method is known as Coordinated Multi-Point (CoMP) or Network MIMO and is currently being incorporated into the LTE-Advanced standard.

There are two main types in CoMP techniques in 3GPP LTE-A, joint processing (data sharing among the cells) and the other is coordinated scheduling/beam forming (requires no data sharing among the cells). In this work, focuses on the second category requiring no data sharing. Three techniques of multi-cell cooperation in this category, coordinated beam forming, coordinated scheduling and coordinated power control, are typically investigated which can be performed independently or be combined. Although these methods have many merits in ideal environment, may vanish quickly in more practical scenarios due for instance to the fast varying nature of the inter-cell interference and inaccurate link adaptation, their sensitivity to Channel State Information (CSI) measurement, the quantized CSI feedback at the sub band level, the limited payload size of the uplink control channels and the latency of the backhaul and the feedback.

In recent research, clustering has been shown to decrease the feedback overhead and also to reduce the scheduler complexity and the number of cooperating cells without comprising the performance much. In another approach, the transmit beam former was developed to compensate for the imperfect CSI, by modeling as noisy channel estimates. Also, another non-ideal assumption was considered, i.e. limited feedback and the feedback bits were allocated among cells so as to reduce the performance degradation caused by quantization error. Then iterative algorithm was developed to optimize the downlink beam forming and the power allocation in time-division duplex (TDD) systems under limited backhaul consumption.

In this work, we propose a practical approach to the multicell cooperation using joint user scheduling and rank coordination in which the cells coordinate themselves the transmission ranks (the number of transmitted streams) to maximize a network utility function, in this case the throughput. Without going for the heavy machinery of an iterative scheduler, we aim for a simpler and practical method that directly tackles user scheduling and rank coordination. This scheme accounts for the impairments due to both the terminal and the network constraints, thus being more practical at the system level.The performances of conventional cooperation schemes designed under ideal conditions were reduced severely once simulated under more realistic conditions. However, this proposed rank coordination can outperform, with a much smaller feedback overhead (only two extra feedback bits) and lower scheduler complexity. Rank coordination decreases the coordination burden at the network side by bringing the contribution of the receivers into the multi-cell coordination, thereby balancing the overall effort of multi-cell coordination between the receivers and the network. This is particularly helpful in cases where we have to design multi-cell coordination schemes for non-ideal setup (when the network does not have enough information to make accurate decisions). In the normal centralized scheduler architecture, extensive interactions between the users and the BSs significantly increase the complexity and the overhead in the network making it not practical. But a distributed coordinated scheduler based on Master-slave architecture relies only on some low-overhead inter-cell message exchange.

II. DESIGN AND IMPLEMENTATION

In this work, we consider a downlink multicell MIMO-OFDMA network for the performance analysis of this scheme. There is assumed to be K users in N_c cells, K_i users in each cell i, T subcarriers, N_t transmit antennas at every base station and N_r receive antennas at every user end. The MIMO channel between a cell i and user q on subcarrier k is written as $\alpha_{q,i}^{1/2} H_{k,q,i}$, where $H_{k,q,i}$ is the small scale fading process of the channel and $\alpha_{q,i}$ refers to the large scale fading (path loss and shadowing),which is independent of the subcarrier. Serving cell is defined as the cell transmitting the downlink control information. Served user set of a cell i, denoted as K_i, is the set of users who have cell I as serving cell. Scheduled user set of cell i on subcarrier k, denoted as $K_{k,i} \subset K_i$, is the subset of users $\in K_i$ who are actually scheduled on subcarrier k at a certain time instant. CoMP measurement set of a user $q \in K_i$, whose serving cell is i, is the set of cells about which channel state/statistical information related to their link to the user is reported to the BS and is expressed based on long term channel properties as

$$M_q = \left\{ j \middle| \frac{\alpha_{q,i}}{\alpha_{q,j}} < \delta, \forall j \neq i \right\} \qquad (1)$$

The larger δ is, the larger will the CoMP measurement set be and the higher the feedback overhead. The CoMP measurement set does not include the serving cell i. Hence for multi-cell cooperation, a user feeds back its serving cell CSI and the CoMP measurement set CSI. A CoMP user is a user whose CoMP measurement set is not empty, $P_i = \{ q \in K_i \mid M_q \neq \emptyset \}$. The CoMP-requested user set of cell i is defined as the set of users that have cell i in their CoMP measurement set, i.e. $R_i = \{l \mid i \in M_l, \forall l\}$.The CoMP-requested user set can also be viewed as the victim user set of cell i as it is the set of users who could be impacted by cell i interference.

A. System model

Assume single user transmissions (a single user is allocated on a given time and frequency resource), on the subcarrier k, the cell i serves the user belonging to the $\mathbf{K}_{k,i}$ with $L_{k,i}$ data streams ($1 \leq L_{k,i} \leq N_t$). The transmit symbol vector $x_{k,i}$ made of $L_{k,i}$ symbols is power controlled by $S_{k,i}$ and precoded by the transmit precoder, $F_{k,i}$ such that the transmit precoded symbol vector is written as $\tilde{x}_{k,i} = F_{k,i} S_{k,i}^{1/2} x_{k,i}$. $F_{k,i}$is made of $L_{k,i}$columns denoted as $f_{k,i,m}$, m = 1,…., $L_{k,i}$. $F_{k,i}$can refer to either a closed-loop precoder designed based on the CSI feedback or an open loop precoder pre-defined per transmission rank $L_{k,i}$(e.g. space-time/frequency code or open-loop Single-User spatial multiplexing). Then for the user $q \in \mathbf{K}_{k,i}$ scheduled in cell i on subcarrier k, the received signal $\tilde{y}_{k,q}$ is shaped by $G_{k,q}$and the filtered received signal $y_{k,q}$ is written as,

$$y_{k,q} = G_{k,q} \tilde{y}_{k,q} = \sum_{j=1}^{n_c} \alpha_{q,j}^{1/2} G_{k,q} H_{k,q,j} F_{k,j} S_{k,j}^{1/2} x_{k,j} + n_{k,q} \qquad (2)$$

where $n_{k,q} = G_{k,q} \tilde{n}_{k,q}$and $\tilde{n}_{k,q}$ is a complex Gaussian noise. The receive filter $G_{k,q}$ is made of $L_{k,I}$ rows denoted as $g_{k,q,m}$, m = 1, ...,$L_{k,i}$. The strategy to compute $G_{k,q}$ is assumed to be only known by the receiver and not by the transmitter (similarly to practical systems). Also as in practical systems as LTE-A, we will assume uniform power allocation among streams, i.e. $S_{k,i} = E_{s,i}/L_{k,i}$ where $E_{s,i}$ is the total transmit power at base station i.

B. Resource Allocation Problem

A cooperative scheme relying on rank coordination coordinates dynamically the users in all cells and frequency resources such that the transmission rank of a given cell and frequency resource is favorable to the performance of that cell's users and of the adjacent cells' victim users scheduled on the same frequency resource. To relax the optimization problem by dealing with real rather than integer transmission ranks, we assume the transmission rank $L_{k,j}$ ∀j is a real variable and the throughput $T_{k,q,i}$ of user q in cell i on subcarrier k is a continuous function of $\{L_{k,j}\}_{\forall j}$. The beam forming directions $F_{k,j}$are fixed and predefined for every transmission rank $L_{k,j}$, ∀j. The weighted rate of cell i on subcarrier k is defined as $T_{k,i}= w_q T_{k,q,i}$ where $q \in \mathbf{K}_{k,i}$. The weights w_q account for fairness among users (and may be related for instance to the QoS of each user) and $T_{k,q,i}$ refers to the rate of scheduled user q in cell i on subcarrier k.

Our aim will be to maximize the network weighted sum-rate accounting for fairness among users and cells and design a coordinated scheduler that decides which frequency resource to allocate to which user in every cell with the appropriate transmission rank. This can be mathematically represented as,

$$\{K^{*}L^{*}\} = \arg\max_{\mathbf{K}CK,\mathbf{L}} \sum_{j=1}^{n_c} \sum_{k=0,q\epsilon \mathbf{K_{k,j}}}^{T-1} w_q T_{k,q,j}. \quad (3)$$

The above stated problem is to be maximized over transmission ranks and user schedule only, thus making it a combinatorial problem. Since the transmission ranks were taken as integers and not real, we can use a practical and distributed scheduler architecture instead of the centralized architecture that is not desirable. Therefore, the transmission ranks **L**are real and subject to the constraints $L_{k,j} \geq L_{min,j}$ and $L_{k,j} \leq L_{max,j}$. $L_{min,j}$ and $L_{max,j}$ refer to the minimum and maximum transmission rank in cell j, respectively and could be configured by the network (typically, $L_{min,j} = 1$ and $L_{max,j} = N_t$).

We define $I^{*}_{k,s,i}$as the transmission rank in cell ithat maximizes the throughput $T_{k,s,m}$of user sin cell m,

$$I^{*}_{k,s,i} = \arg\max_{L_{min,i} \leq L_{k,i} \leq L_{max,i}} T_{k,s,m}\left(L_{k,i}\{L_{k,j}\}_{j\neq i}\right). \quad (4)$$

And, if the network configures $L_{min,i} = 0$, all users choose their preferred interference rank as being equal to 0, so as not to experience any interference. Thus, the earlier mentioned problem can be simplified as a cell i on subcarrier k trying to maximize the following function

$$\Upsilon_{k,i} = T_{k,i} - \Pi_{k,i}, \qquad (5)$$

where,

$$\Pi_{k,i} = \sum_{m\neq i} \sum_{s\in K_{k,m}} \left(L_{k,i} - I^{*}_{k,s,i}\right) w_s \pi_{k,s,m,i} \qquad (6)$$

$$\text{and,} \pi_{k,s,m,i} = \frac{\partial T_{k,s,m}}{\partial L_{k,i}}. \qquad (7)$$

$\Upsilon_{k,i}$is the weighted sum-rate in cell iminus the payment $\Pi_{k,i}$ due to the interference created to the victim users scheduled in the neighboring cells. The payment $\Pi_{k,i}$ accounts for the weighted sum of all prices $\pi_{k,s,m,i}$over all scheduled users s in the network. The price $\pi_{k,s,m,i}$refers to how much the throughput of user s in cell m is sensitive to any change of the transmission rank of cell i. The quantity $\widetilde{w}_{k,s,i}= w_s \pi_{k,s,m,i}$can be thought of as the overall sensitivity of user s to any deviation of the transmission rank in cell i from its optimal $I^{*}_{k,s,i}$. The weight of a given user is proportional to its QoS and the deviation of the actual transmission rank in cell i with respect to the transmission rank in cell i that would maximize the victim user s throughput in cell m. If such a deviation is null for a certain user s, cell i is not fined for the interference created to user s.

Thus from (5), the cell i can decide upon the set of co-scheduled users and the transmission rank on subcarrier k as follows,

$$\{K^{*}L^{*}\} = \arg\max_{K_{k,i},L_{k,i}} \Upsilon_{k,i} \qquad (8)$$

C. Guidelines for the Rank Recommendation-based Coordination

From equation (3.5), we can see that the coordinated scheduler in cell i has to rely on the report of some local CSI from terminals belonging to $K_i$to perform single-cell processing at the BS and compute the term $T_{k,i} = w_q T_{k,q,i}$, $q \in \mathbf{K}_{k,i}$. It also relies on some message exchanges between cells, namely the reception by cell i of the price information $w_s \pi_{k,s,m,i}$ and $I^{*}_{k,s,i}$for all $s \in R_i$and the transfer from cell i of the price information $w_q \pi_{k,q,i,j}$ and $I^{*}_{k,q,j,}$for all $q \in P_i$ and $j \in M_q$. The accurate computations of $T_{k,q,i}$, $I^{*}_{k,q,j}$, $I^{*}_{k,s,i}$and $\pi_{k,q,i,j}$ are very challenging at the BS side as they are a function of many parameters specific to the receiver implementation and are highly sensitive to the accuracy of the channel measurement and feedback.

1) In order to bring the contribution of the receiver in the design of the coordinated scheduler, it is preferable that the user terminals q and s estimates, computes and reports the above quantities by accounting for the transmission ranks in the interfering cells, its receiver interference rejection capability and the measured channels as perceived at the receiver sides. Thus, the terminals $q \in \mathbf{K}_{k,i}$ and $s \in R_i$and cell i scheduler cooperate together with the aim of maximizing $\Upsilon_{k,i}$in equation (5) and minimizing $\Pi_{k,i}$ in equation (6).

2) Any user $q \in K_i$ served by cell i reports an estimate of $T_{k,q,i}$ and any user $s \in R_i$ belonging to a cell m, which is a victim of cell i interference, recommends cell i to choose $L_{k,i} = I^{*}_{k,s,i}$. User s reports that are sent to the cell I, contain$I^{*}_{k,s,i}$and an estimate of the user throughput loss $\Delta T_{k,s,i}$ achievable if the recommendation is not accounted for in cell i decisions on the transmission ranks. The cell i computes the price as,

$$\pi_{k,s,m,i} \approx \frac{-\Delta T_{k,s,i}}{L_{k,i} - I^{*}_{k,s,i}} (9)$$

where the user throughput loss, is defined as,

$$\Delta T_{k,s,i}= T_{k,s,m}(L_{k,i}, \{L_{k,j}\}_{j\neq i}) - T_{k,s,m}(I^{*}_{k,s,i}, \{L_{k,j}\}_{j\neq i}), (10)$$

for some predefined $\{L_{k,j}\}_{j\neq i}$. The quantity $(L_{k,i} - I^{*}_{k,s,i})\,\pi_{k,s,m,i}$ expresses the variation in user s throughput due to transmission rank $L_{k,i}$ rather than $I^{*}_{k,s,i}$. On the network side, the scheduler in cell i tries to achieve as much as possible the recommendation of the CoMP users and guarantee $L_{k,i} - I^{*}_{k,s,i} = 0$ on subcarriers where the victim user $s \in \mathbf{K}_{k,m}$ of cell i is scheduled.

3) Whenever the scheduler of a given cell i accepts the request of a recommended interference rank $I^{*}_{k,s,i}$ at time instant t and over frequency resource k, the victim users in the neighboring cell m who reported the recommended interference rank $I^{*}_{k,s,i}$ to cell i has to be scheduled at the same time instant t and on the same frequency resource k.

III. SCHEDULER IMPLEMENTATION

Based on the principles defined in earlier section, we can outline the practical implementation of the rank recommendation based coordinated scheduler. For practical scenarios, we drop the earlier assumption that beam forming directions were fixed and consider variable gains.

A. Wideband Rank Recommendation

The current systems use rank indicator (RI), CQI and Precoding Matrix Indicator (PMI) reports. RI is the preferred serving cell transmission rank and is a wideband and potentially long term information as it changes relatively slowly in the frequency and time domains. RI report therefore incurs a very small feedback overhead.

1) For a CoMP user q associated with the serving cell i ($q \in K_i$) and victim of a cell $j \in M_q$, this terminal reports its preferred serving cell wideband RI R^{*}_{q}, i.e. the user makes the hypothesis that $L_{k,i} = R^{*}_{q} \forall$ k at the time of report and that R^{*}_{q} maximizes user q throughput.

2) The same user q also transmits to the serving cell i the transmission rank of the interfering cell $j \in M_q$, denoted as the preferred interference RII$^{*}_{q,j}$, which maximizes its performance. The user recommends the interfering cell j to transmit a number of streams corresponding to $I^{*}_{q,j}$, i.e. $L_{k,j} = I^{*}_{q,j}$, $\forall$k.

B. Calculation of the preferred interference rank

At the time of CQI, R^{*}_{q} and $I^{*}_{q,\, j\in M_q}$ reports, the user $q \in$ Ki does not know the precoder in the interfering cell j. So the terminal computes the required information by averaging the throughput over the possible realizations of the transmit precoder $\mathbf{F}_{k,j}$ in the interfering cells $j \in M_q$, given the current realization of the channel matrices (measured at the terminal). Those precoders can be assumed to be selected in the limited feedback codebook C (defined for each rank and assumed the same in all cells).

1) The throughput average can be computed for each set of serving cell rank $L_{k,i}$, precoder $\mathbf{F}_{k,i}$ and interference rank $\{L_{k,j}\}_{j\in Mq}$. Thus the throughput average can be calculated from[1],

$$\widetilde{T}_{k,q,i}\left(F_{k,i},\ L_{k,i},\ \{L_{k,j}\}_{j\in M_q}\right) \approx \varepsilon_{\{F_{k,j}\in C\}_{j\in M_q}}\{T_{k,q,i}\} \quad (11)$$

where, $T_{k,q,i} = \sum_{m=1}^{L_{k,i}} \log_2\left(1 + \rho_{k,q,m}\right) \quad (12)$

$$\rho_{k,q,m} = \frac{\alpha_{q,i}\,|g_{k,q,m}H_{k,q,i}f_{k,i,m}|^{2}E_{s,i}/L_{k,i}}{\sum_{j\in M_q}\alpha_{q,j}\,||g_{k,q,m}H_{k,q,i}F_{k,j}||^{2}E_{s,i}/L_{k,j} + \sigma^{2}_{n,k,q}} \quad (13)$$

2) From equation (4), the user q in cell i can jointly compute the best set of preferred serving cell RI that is R^{*}_{q} and preferred recommended interference RI that is $I^{*}_{q,j}$, as follows[1],

$$\left\{R^{*}_{q}, \{I^{*}_{q,j}\}_{j\in M_q}\right\} = \arg\max_{L_{k,i}\{L_{k,j}\}_{j\in M_q}} \varepsilon_{k}\left\{\max_{F_{k,i\in C}} \widetilde{T}_{k,q,i}\right\}, \quad (14)$$

where the averaging is done over all subcarriers due to the wideband report of the RIs and the maximization is done over a restricted set of integers $L_{k,j} \in \{L_{min,j},\ldots,L_{max,j}\}\forall j$.

3) The best precoder (for closed-loop operations) for user q in cell i on subcarrier k for a given set of transmission ranks $L'_{k,i}$, $\{ L'_{k,j}\}_{j\in Mq}$ is selected as[1],

$$F^{*}_{k,i}\left(L'_{k,i}, \{L'_{k,j}\}_{j\in M_q}\right) = \arg\max_{F_{k,i}\in C} T_{k,q,i}\left(F_{k,i}, L'_{k,i}, \{L'_{k,j}\}_{j\in M_q}\right). \quad (15)$$

4) Once R^{*}_{q} and $I^{*}_{q,j} \in M_q$ are selected, user q computes the throughput estimate of q and the throughput loss estimate to be reported to the network using the following[1],

$$\widetilde{T}^{*}_{k,q,i} = \widetilde{T}_{k,q,i}\left(F^{*}_{k,i}\left(R^{*}_{q}, \{I^{*}_{q,j}\}_{j\in M_q}\right), R^{*}_{q}, \{I^{*}_{q,j}\}_{j\in M_q}\right) \quad (16)$$

$$\Delta\widetilde{T}_{k,q,i} = \widetilde{T}_{k,q,i}\left(F^{*}_{k,i}\left(L_{k,i}, \{L_{k,j}\}_{j\in M_q}\right), L^{*}_{k,i}, \{L^{*}_{k,j}\}_{j\neq i}\right) - \widetilde{T}^{*}_{k,q,i}\,, \quad (17)$$

$$\forall\ \left\{L_{k,i}, \{L_{k,j}\}_{j\in M_q}\right\} \neq \left\{R^{*}_{q}, \{I^{*}_{q,j}\}_{j\in M_q}\right\}.$$

Using the values ofR^{*}_{q}, $\{I^{*}_{q,j}\}_{j\in M_q}$, $\widetilde{T}_{k,q,i}$, $\{\Delta\widetilde{T}_{k,q,i}\}$, and $F^{*}_{k,i}\left(R^{*}_{q}, \{I^{*}_{q,j}\}_{j\in M_q}\right)$ (in case of closed loop operations), the coordinated scheduler can estimate the surplus function in equation(5) to solve equation (8). In practical systems, $\widetilde{T}^{*}_{k,q,i}$ and $\Delta\widetilde{T}_{k,q,i}$ would be obtained using a CQI and a differential (or delta) CQI.

C. Master-Slave Scheduler Architecture

The coordinated scheduler relies on anasynchronous Master-Slave architecture motivated by the principle 3 in section II.

At each time instant, only one BS acts as the Master (denoted as M) and the other BSs are the slave (denoted as S).

a) The Master BS, based on the reports of the preferred interference rank, decides a certain transmission rank $L_{k,M}$ constant ∀k, i.e. $L_{k,M} = L_M$, and schedules its users such that the transmission ranks of all scheduled users are as much as possible equal to L_M.

b) The Slave BSs, knowing that the Master BS will accept some recommended interference rank, will schedule with highest priority, their CoMP users who requested rank coordination to the Master BS.

IV. SCHEDULER OPERATION

Consider a 3 cell cluster (e.g. as in intra-site deployments) for ease of presentation and without loss of generality. For a given time instant, there are one Master BS (denoted as M) and two slave BSs (denoted as S1 and S2).

A. Calculation of transmission rank by Master BS

1) The users l in S_1 and S_2 recommend interference ranks $I^*_{l,M}$ to interfering cell M. The Master BS, upon reception of all information $I^*_{l,M}$and all the effective QoS $\tilde{w}_{k,l,M}$ of victim users l, with l ∈ $\{K_{S1},K_{S2}\}$, sorts those interference ranks by order of priority. In a given cell i, the vector $I_1^{(i)}$, $I_2^{(i)}$, $I_3^{(i)}$, ..., $I_N^{(i)}$denotes the priority of the interference ranks. For instance, $[I_1^{(1)},I_2^{(1)},I_3^{(1)},I_4^{(1)}]=[2,1,3,4]$ indicates that a recommended interference rank equal to 2 is the most prioritized in cell 1.

2) Master BS M decides upon the transmission rank L_M and allocates one transmission rank for each subframe where the BS acts as a Master BS. By doing so the each Master BS defines a cycling pattern of the transmission ranks with the objective of guaranteeing sometime-domain fairness. The priority and allocation of the transmission ranks accounts for the relative number of rank recommendation requests per rank.

B. Master BS scheduling operation

In cell M, we divide users into two subgroups:

1) $\mathcal{U}_{M,1} = \{q \in K_M \mid R^*_q = L_M\}$, i.e., the set of users in cell M whose preferred rank indicator is equal to the transmission rank L_M.

2) $\mathcal{U}_{M,2} = K_M \backslash \mathcal{U}_{M,1} = \{q \in K_M \mid q \notin \mathcal{U}_{M,1}\}$, i.e. the other users.

The scheduling in cell M is based on proportional fairness (PF) in the frequency domain till all frequency resources are occupied:

a) If $\mathcal{U}_{M,1} \neq \emptyset$, BS M schedules only users belonging to$\mathcal{U}_{M,1}$.

b) If $\mathcal{U}_{M,1} = \emptyset$, BS M schedules only users belonging to $\mathcal{U}_{M,2}$.

C. Slave BS scheduling operation

In cell S_i, i = 1, 2, the users are divided into three subgroups:

1) The set of CoMP users ∈ Si who recommend cell M and whose preferred interference rank is equal to the transmission rank L_M, i.e., $\mathcal{U}_{S_i,1} = \{q \in P_{S_i} \mid M \in M_q, I^*_{q,M} = L_M\}$.

2) The set of all other CoMP users ∈ Si, i.e. who either do not recommend cell M or recommend cell M but whose preferred interference rank is not equal to the transmission rank, i.e. $\mathcal{U}_{S_i,2} = \{q \in P_{S_i} | M \notin M_q\} \cup \{q \in P_{S_i} | M \in M_q, I^*_{q,M} \neq L_M\}$.

3) The set of non-CoMP users in Si, i.e. $\mathcal{U}_{S_i,3} = K_{S_i} \backslash P_{M,1}$.

Scheduling in cell Si is performed as follows:

a) If $\mathcal{U}_{M,1} \neq \emptyset$, S_i schedules users in the following order of priority:$\mathcal{U}_{S_i,1}$, $\mathcal{U}_{S_i,3}$and $\mathcal{U}_{S_i,2}$.

b) If $\mathcal{U}_{M,1} = \emptyset$, S_i schedules all users without any priority (i.e. only based on PF constraint).

V. PERFORMANCE ANALYSIS

In this work for simulation the cluster is assumed to be made of 3 cells. For a given time instant, there are one Master BS (denoted as M) and two slave BSs (denoted as S_1 and S_2).As shown in the table, the value of L_M in a given cell i changes with time (sub frame) according to the cycling pattern $I_1^{(i)}$,$I_2^{(i)}$, $I_1^{(i)}$, $I_2^{(i)}$, $I_3^{(i)}$indicating that whenever cell 1 is the Master BS, BS 1 transmits with rank $L_M = I_1^{(1)} = 2$, $L_M = I_2^{(1)} = 1$, $L_M = I_1^{(1)} = 2$, $L_M = I_2^{(1)} = 1$, $L_M = I_3^{(1)} = 3$ in sub frames 1,4,7,10,13 (only 9 sub frames shown in table).The assumptions which are considered for the system simulation are given in table2.The large scale fading factor needed for the triggering threshold are taken are 0.1 and 0.01. The shadowing loss factor is taken as 8. The LOS path loss and NLOS path loss are calculated as LOS=103.4+24.2*$\log_{10}$(d) and NLOS=131.1+42.8*$\log_{10}$(d). The cell edge users are taken as those users who are above a distance of 0.7 from cell centre (the distance between cell centre and edge being calculated from 0 to 1). The channel noise considered is standard gaussian noise with zero means and unit variance.

Table 1. Table depicting the scheduler operation cycle in a 3 cell cluster

Time	1	2	3	4	5	6	7	8	9
BS_1	$M,L_M=2$	S_1	S_1	$M,L_M=1$	S_1	S_1	$M,L_M=2$	S_1	S_1
BS_2	S_1	$M,L_M=1$	S_2	S_1	$M,L_M=2$	S_2	S_1	$M,L_M=1$	S_2
BS_3	S_2	S_2	$M,L_M=2$	S_2	S_2	$M,L_M=1$	S_2	S_2	$M,L_M=3$

Table 2. System level assumptions for simulation

Macro cell layout	Hexagonal grid, 3-sector site
System bandwidth	10 MHz (downlink only)
Carrier frequency	2 GHz
Inter-site distance	500 m
Base station power	45dB
Subband size	6 RB (subband)
Antenna configuration	4 × 4 uniform linear array
Scheduling	Proportional fair in time/frequency domains (for ease taken as number of recommendation requests)
Resource allocation	RB-level indication
Transmission mode	Single-user MIMO with and without rank coordination Triggering threshold δ : 10dB Inter-site clustering: 3 cells (sectors) per cluster
Feedback	Recommended interference rank (wideband): 2 bit No feedback errors
Channel estimation	ideal and non-ideal

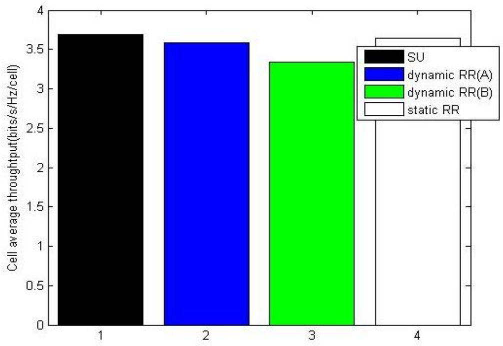

Figure 1(a). Cell average performance of the single-cell scheduler with baseline SU-MIMO report and rank recommendation-based report in a $n_t \times n_r= 4\times 4$

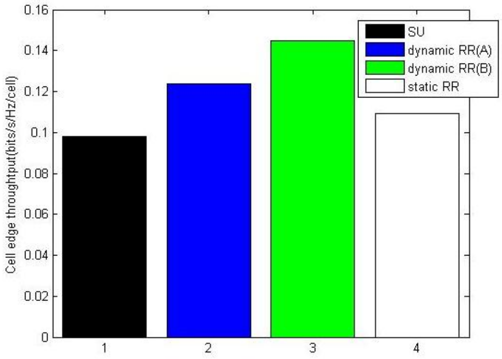

Figure 1(b). Cell edge performance of the single-cell scheduler with baseline SU-MIMO report and rank recommendation-based report in a $n_t \times n_r= 4\times 4$

With the dynamic cycling pattern $I_1^{(i)},I_2^{(i)},I_1^{(i)},I_2^{(i)}, I_3^{(i)}$ denoted as (A) in Figure 4.1, a gain of 20.7% is achieved at the cell edge by the proposed rank recommendation-based Master-Slave coordinated scheduling scheme over the baseline (without coordination) system with only 2 extra feedback bits. A second dynamic cycling pattern $I_1^{(i)},I_2^{(i)},I_1^{(i)},I_2^{(i)}, I_1^{(i)}$, denoted as (B), is also considered where more stress is given to cell edge users as the last entry of the pattern has been switched to I_1. Contrary to the first pattern, the second pattern has a non-negligible cell average throughput loss because $I_1^{(i)},I_2^{(i)}$are most of the time equal to 1 and 2 ∀i, and, therefore, users in the Master cell with the preferred RI equal to 3 and 4 have less chance to be scheduled.

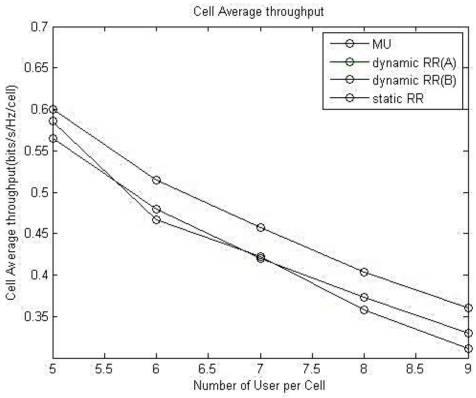

Figure 2(a). Cell average performance of the multi-cell scheduler with baseline SU-MIMO report and rank recommendation-based report in a $n_t \times n_r= 4\times 4$

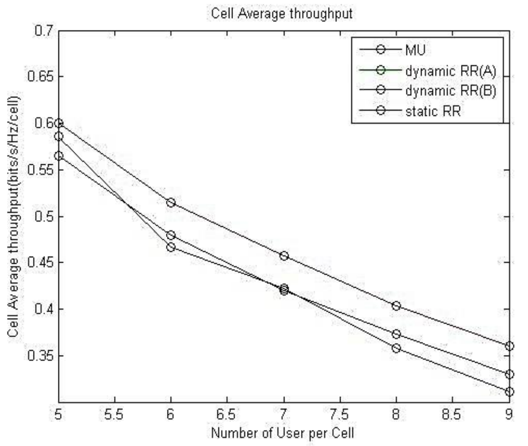

Figure 2(b). Cell edge performance of the multi-cell scheduler with baseline SU-MIMO report and rank recommendation-based report in a $n_t \times n_r = 4 \times 4$

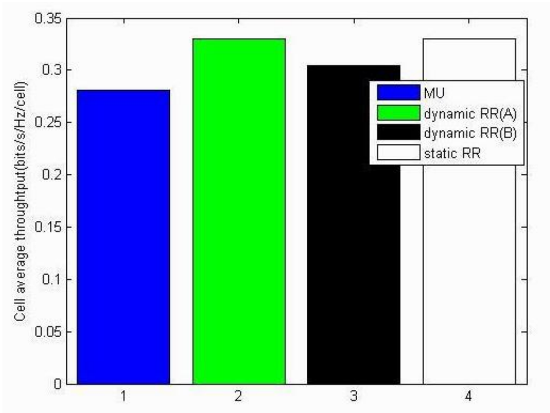

Figure 3(a). Cell average performance of the multi-cell scheduler with baseline SU-MIMO report and rank recommendation-based report in a $n_t \times n_r = 4 \times 4$

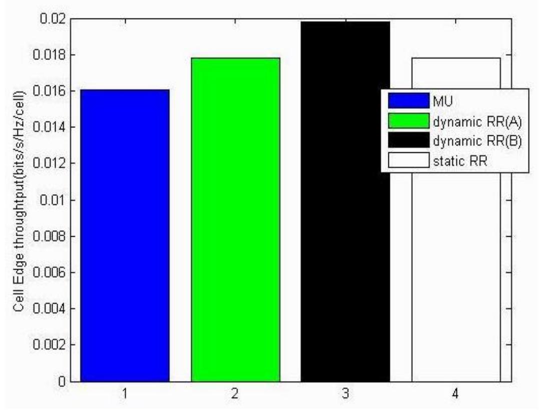

Figure 3(b). Cell edge performance of the multi-cell scheduler with baseline SU-MIMO report and rank recommendation-based report in a $n_t \times n_r = 4 \times 4$

It helps cell edge users because they have better chance to be scheduled and benefit from the rank recommendation, because if $\mathcal{U}_{M,1} \neq \emptyset$, BS M schedules only users belonging to $\mathcal{U}_{M,1}$.The cycling pattern $I_1^{(i)}, I_2^{(i)}, I_1^{(i)}, I_2^{(i)}, I_3^{(i)}$ outperforms $I_1^{(i)}, I_2^{(i)}, I_1^{(i)}, I_2^{(i)}, I_1^{(i)}$ in terms of cell average throughput because $\mathcal{U}_{M,1}$ is often empty in the subframe whose transmission rank is fixed to $I_3^{(i)}$, therefore allowing Master BS to schedule rank 3 and 4 users frequently

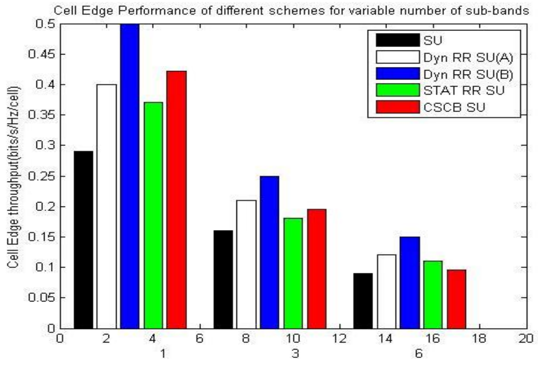

Figure 4 (a). Cell edge performance of the single-cell scheduler with baseline SU-MIMO report and rank recommendation-based report in a $n_t \times n_r = 4 \times 4$

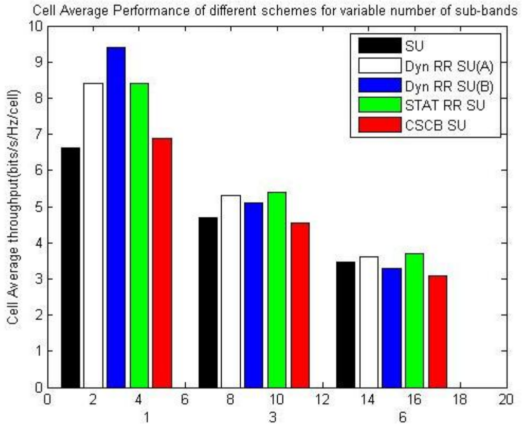

Figure 4(b). Cell average performance of the single-cell scheduler with baseline SU-MIMO report and rank recommendation-based report in a $n_t \times n_r = 4 \times 4$

The performance of a state-of-the-art iterative coordinated scheduling and beam forming (iterative CSCB) scheme has been compared with the proposed architecture, as a function of the sub band size. The rank coordination shows better performance than the iterative CSCB as shown in figure 4, with a lower feedback overhead and scheduler complexity.

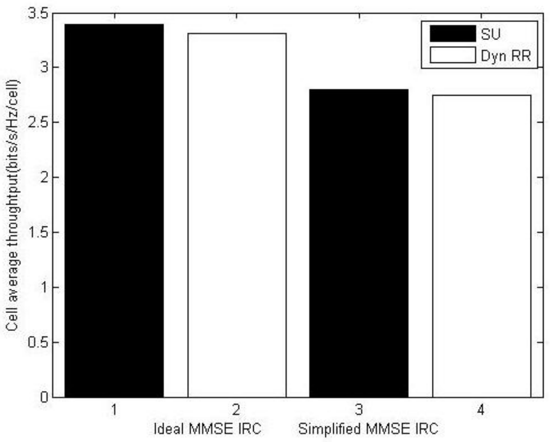

Figure 5(a). Cell average performance of the rank recommendation over single-cell SU-MIMO with ideal and simplified MMSE IRC

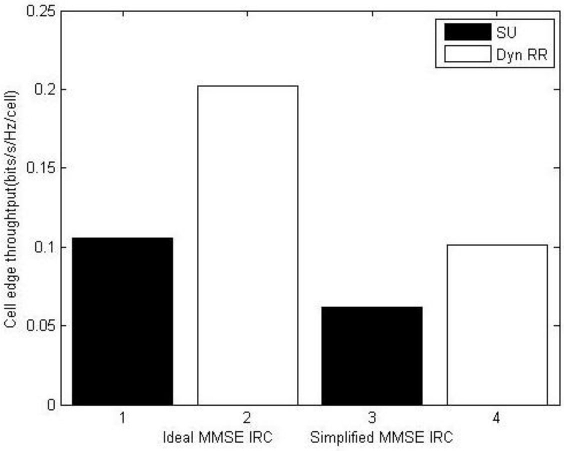

Figure.5(b). Cell edge performance of the rank recommendation over single-cell SU-MIMO with ideal and simplified MMSE IRC

The proposed coordination scheme provides significant gains also with other types of receivers; the one used here is a MMSE receiver with a simplified ICI rejection capability. It computes the receiver filter using an estimate of the covariance matrix of the interference by assuming the precoder in the interference cells as a identity matrix. A significant gain of roughly 17% at the cell edge is observed with the proposed rank recommendation-based Master-Slave coordinated scheduling scheme over the baseline (without coordination) system.

VI. CONCLUSION

A robust and practical interference mitigation technique has been introduced. This method relies on a dynamic coordination of the transmission ranks among cells in order to help cell edge users to benefit from higher rank transmissions. The coordination requires the report from the users of a recommended rank to the interfering cells. Upon reception of those information, the interfering cells coordinate with each other to take informed decisions on the transmission ranks that would be helpful to the victim users in neighboring cells and maximize a network utility function (in this throughput). This provides significant cell-edge performance gain over uncoordinated LTE-A system under a very limited feedback and backhaul overhead. It enables efficient link adaptation and is robust to channel measurement errors. Because of the user recommendation, the Master-Slave scheduler architecture does not experience the convergence and complexity issues of the iterative scheduler.

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