SINR Balancing with Coordinated Multi-cell Transmission

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Abstract—Coordinated multi-cell processing facilitates multi-user precoding techniques across distributed base station (BS) antenna heads. Hence, it can efficiently exploit the available spatial degrees of freedom in a multi-user multiple-input multiple-output (MIMO) channel. A generalised method for joint design of linear transceivers with coordinated multi-cell processing subject to per-BS/antenna power constraints is proposed. The system optimisation objective is to balance the weighted SINR across all the transmitted data streams. The method can accommodate a variety of scenarios from coherent multi-cell beamforming across a large virtual MIMO channel to single-cell beamforming with inter-cell interference coordination and beam allocation. The performance of different coherent/non-coherent and coordinated/non-coordinated multi-cell transmission methods with optimal and heuristic beam allocation algorithms is numerically compared in different scenarios with varying inter-cell interference. The coherent multi-cell beamforming greatly outperforms the non-coherent cases, especially at the cell edge and with a full spatial load. However, the coordinated single-cell transmission with interference avoidance and dynamic beam allocation performs considerably well with a partial spatial loading.

I. INTRODUCTION

The spectral efficiency of wireless networks needs to be greatly improved allowing for increased flexibility to serve an ever-increasing number of simultaneous users and future services. In conventional cellular systems, each base station (BS) processes the signals of in-cell users independently, treating other users as inter-cell interference. This leads to an interference limited behaviour where the interference, experienced especially by the cell-edge users, must be mitigated by sharing and reusing the degrees of freedom available to the network.

Coordinated multi-cell processing facilitates multi-user precoding techniques across several distributed antenna heads, which can be used to improve the utilisation of the physical resources by exploiting the available spatial degrees of freedom in a multi-user multiple-input multiple-output (MIMO) channel [1]–[4]. Assuming linear transceiver processing, a coordinated antenna system with $N$ antennas would ideally be able to accommodate up to $N$ streams/beams without becoming interference limited. Mutual interference between the streams can be controlled or even completely eliminated by a proper selection of transmit weight vectors. This is especially true in the coherent multi-cell MIMO case, where user data is conveyed from multiple BS antenna heads over a large virtual MIMO channel [3], [4].

The coherent multi-user multi-cell precoding techniques, however, have high requirements in terms of signalling and measurements. In addition to the complete channel knowledge of all jointly processed links, carrier phase synchronisation across the transmitting nodes and centralised entities performing scheduling and computation of joint precoding weights are required. A large amount of data needs to be exchanged between the network nodes. Thus, high speed links, such as optical fibres or dedicated radio links, are needed.

Another form of coordinated transmission is a dynamic multi-cell scheduling and interference avoidance, where the network nodes coordinate their transmissions (precoder design, scheduling) in order to minimise the inter-cell interference. The phase coherence between the transmit nodes is not required, since each data stream is transmitted from a single BS node. Thus, the non-coherent coordinated multi-cell transmission approaches have somewhat looser requirements on the coordination and the backhaul, but could potentially still need centralised resource management mechanisms. Also, full channel knowledge of all jointly processed links is still needed for the ideal interference avoidance.

In this paper, a generalised method for joint design of the linear transceivers with coordinated multi-cell processing subject to per-BS/antenna power constraints is proposed. The system optimisation objective in this paper is to provide an equal weighted SINR for the transmitted data streams, i.e., to maximise the minimum weighted SINR per stream. The optimisation problem is quasiconvex for receivers with a single antenna or with a fixed receive beamformers [5], [6]. Thus, the optimal solution can be found for those configurations.

The generalised method can accommodate two special cases previously available in the literature: coherent multi-cell beamforming with per BS power constraints, which requires a full phase synchronisation between all BSs [7]; and coordinated single-cell beamforming case, where all the transceivers are jointly optimised while considering the other-cell transmissions as inter-cell interference (see solution in [8] for the minimum power beamformer design). Furthermore, the model can handle any combination of the aforementioned cases, where the number of jointly transmitting nodes may vary between users.

In the coordinated single-cell beamforming case, each
stream is transmitted from a single BS. In such a case, a user is typically allocated to a cell with the smallest path loss. Near the cell edge, however, the optimal beam allocation strategy may also depend on the time varying properties of the channel. Thus, large gains from fast beam allocation (cell selection) algorithms are potentially available for the cell edge users. The optimal cell or BS assignment per beam is a difficult combinatorial problem and it requires an exhaustive search over all possible combinations of beam allocations. This is clearly computationally prohibitive for a large number of users and BSs. Therefore, a set of sub-optimal heuristic allocation algorithms is proposed.

The presented methods require a complete channel knowledge between all pairs of users and BSs, and hence, the solution represent an absolute upper bound for the less ideal solutions with an incomplete channel knowledge. The performance of coherent and non-coherent coordinated transmission with different beam allocation algorithms, as well as, non-coordinated transmission and inter-cell interference free scenario with time division multiple access (TDMA), is numerically compared in different operating scenarios with varying inter-cell interference. Even though the model is presented for the general case with multiple receive antennas per user, the numerical results are shown only for the single antenna receiver case for simplicity.

II. SYSTEM MODEL

The cellular system consists of $N_B$ BSs, each BS has $N_T$ transmit antennas and user $k$ is equipped with $N_{R_k}$ antennas. A set $U$ with size $K = |U|$ includes all users active at the given time instant, while a subset $U_b \subseteq U$ includes the users allocated to BS $b$, $k \in U_b$. Each user $k$ can be served by $M_k$ BS’s which define the joint processing set $B_k$ for the user $k$, and $B_k \subseteq B = \{1, \ldots, N_B\}$. The signal vector $y_k \in \mathbb{C}^{N_T \times K}$ received by the user $k$ consists of the desired signal, intra- and inter-cell interference, and it can be expressed as

$$y_k = \sum_{b \in B_k} a_{b,k} H_{b,k} x_{b,k} + \sum_{b \in B_k} a_{b,k} H_{b,k} \sum_{i \neq k} x_{b,i} + \sum_{b \in B \setminus B_k} a_{b,k} H_{b,k} x_{b} + n_k$$

where the vector $x_{b,k} \in \mathbb{C}^{N_T}$ is the transmitted signal from the $b$'th BS to user $k$, $x_b \in \mathbb{C}^{N_T}$ denotes the total transmitted signal vector from BS transmitter $b$, $n_k \sim \mathcal{CN}(0, N_0 I_{N_{R_k}})$ represents the additive noise sample vector with noise power density $N_0$, and $a_{b,k} H_{b,k} \in \mathbb{C}^{N_{R_k} \times N_T}$ is the channel matrix from BS $b$ to user $k$ with large-scale fading coefficient $a_{b,k}$. The entry $[H_{b,k}]_{r,t}$ represents the complex channel gain between TX antenna $r$ and RX antenna $r$. The elements of $H_{b,k}$ are normalised to have unitary variance, i.e., $E\{|[H_{b,k}]_{r,t}|^2\} = 1$. The total transmitted vector $x'_b$ from BS $b$ consists of transmissions to all the users in the user set $U_b$.

The transmitted vector for user $k$ is generated at BS $b$ as

$$x_{b,k} = M_{b,k} d_k$$

where $M_{b,k} \in \mathbb{C}^{N_T \times m_k}$ is the pre-coding matrix, $d_k = [d_{1,k}, \ldots, d_{m_k,k}]^T$ is the vector of normalised complex data symbols, and $m_k \leq \min(N_T M_B, N_{R_k})$ denotes the number of active data streams.

The total power transmitted by the BS $b$ is

$$\text{Tr} \left( E \left[ x'_b x'_b^H \right] \right) = \text{Tr} \left( \sum_{k \in U_b} M_{b,k} M_{b,k}^H \right).$$

Consequently, the power per transmit antenna is given as $\sum_{k \in U_b} M_{b,k} M_{b,k}^H \leq N_T$.

We focus on linear transmission schemes, where the $N_B$ BS transmitters send $S$ independent streams, $S \leq \min(N_B N_T, \sum_{b \in U} N_{R_b})$ per transmit dimension. For per stream processing is considered, where for each data stream $s$, $s = 1, \ldots, S$ the scheduler unit associates an intended user $k_s$ with the channel matrices $H_{b,k_s} \in \mathbb{C}^{N_T \times N_{R_k}}$, $b \in B_s$. Note that more than one stream can be assigned to one user, i.e. the cardinality of the set of scheduled users, $U = \{k_s | s = 1, \ldots, S\}$, is less than or equal to $S$.

Let $m_{s,b} \in \mathbb{C}^{N_T \times N_{R_k}}$ and $w_s \in \mathbb{C}^{N_{R_k}}$ be arbitrary transmit and receive beamformers for the stream $s$. The SINR of the data stream $s$ can be expressed as

$$\gamma_s = \frac{\left| \sum_{b \in U_b} a_{b,k_s} w_s^H H_{b,k_s} m_{b,s} e^{j\phi_b} \right|^2}{N_0 \| w_s \|^2 + \sum_{i=1,i \neq s}^S \left| \sum_{b \in U_b} a_{b,k_s} w_s^H H_{b,k_s} m_{b,s} e^{j\phi_b} \right|^2}$$

where $\phi_b$ represents the possible carrier phase uncertainty of base station $b$. If the BSs have unsynchronised local oscillators and independent phase locked loops, their phase uncertainties are different and continuously drifting.

III. GENERALISED SINR BALANCING WITH COORDINATED BS PROCESSING

In this section, a general method for solving SINR balancing problem with coordinated BS processing is presented. The generalised method can accommodate the following special cases:

- Coherent multi-cell beamforming ($B_s = B_k = B \forall k, s$) with per BS and/or per-antenna power constraints, which requires a full phase synchronism between all $b \in B$ [7].

- Coordinated single-cell beamforming case ($|B_s| = 1 \forall s$), where all the transceivers are jointly optimised while considering the other-cell transmission as inter-cell interference. (similar to solution in [8], [9] for the minimum power beamformer design).

- Any combination of above two, where $|B_s|$ and $|B_s|$ may be different for each user $k$ and/or stream $s$.

Note that the presented method requires a complete channel knowledge of $a_{b,k} H_{b,k}$ between all pairs of $k$ and $b$, and hence, the solution represents an absolute upper bound for the less ideal solutions with an incomplete channel knowledge.

1. Observe that in some special cases, $B_s$ can be a subset of $B_{b,s}$. For example, a user may receive data from several BSs, while each stream is transmitted from a single BS.
The system optimisation objective is to keep the SINR per data stream \( \gamma \) in fixed ratios in order to guarantee fairness between streams/users, i.e. \( \gamma_s/\beta_s = \gamma_o \), and \( \gamma_o \) has to be maximised subject to per BS power constraints. The weights, \( \beta_s > 0 \), \( s = 1, \ldots, S \), are used to prioritise the data streams of different users differently and they can be chosen based on different criteria, e.g. by the preference class or by the latency requirements of the particular service. The optimisation problem can be formulated as maximisation of the minimum weighted SINR per stream:

\[
\beta_s^{-1} \sum_{s=1}^{S} \frac{\sum_{b \in B_s} a_{b,k} w_{s}^H H_{b,k} m_{b,s}}{N_0 \left\| w_s \right\|^2 + \sum_{i=1, i \neq s}^{S} \sum_{b \in B_i} a_{b,k} w_{s}^H H_{b,k} m_{b,i}}^2 
\]

subject to:

\[
\sum_{s \in S_b} \left\| m_{b,s} \right\|^2 \leq P_b, \quad b = 1, \ldots, N_B \tag{5}
\]

where the optimisation variables are \( m_{b,s} \in \mathbb{C}^{N_s} \) and \( w_s \in \mathbb{C}^{N_s \times N_T} \), \( s = 1, \ldots, S \), and \( S_b \) includes all streams allocated to BS \( b \), i.e., \( S_b = \{ s \mid k_s \in B_b \} \). Problem (5) is not jointly convex in variables \( m_s \) and \( w_s \). However, for a fixed \( m_{b,s} \), \( s = 1, \ldots, S \), (5) has a unique solution given by the LMMSE receiver:

\[
w_s = \left( \sum_{b \in B_s} a_{b,k}^2 H_{b,k} m_{b,s} m_{b,s}^H H_{b,k}^H + N_0 I_{N_T} \right)^{-1} \sum_{b \in B_s} a_{b,k} H_{b,k} m_{b,s} \tag{6}
\]

which provides the maximum SINR for stream \( s \). Furthermore, for a single-antenna receiver or a fixed \( w_s \), (5) is quasiconvex in \( m_{b,s} \) [5], [6]. Thus, it can be solved with any accuracy \( \epsilon > 0 \) by the bisection method [10] presented in Algorithm 1.

**Algorithm 1**: SINR balancing for fixed receive beamformers

1. Initialise \( \gamma_{\min} = \text{SINR}_{\min} \) and \( \gamma_{\max} = \text{SINR}_{\max} \), where \( \text{SINR}_{\min} \) and \( \text{SINR}_{\max} \) define the range of relevant SINRs. Let \( \epsilon > 0 \) be the desired accuracy.

2. Set \( \gamma_0 = (\gamma_{\max} + \gamma_{\min})/2 \)

3. Solve the following feasibility problem

\[
\text{find } m_{b,s}, \quad s = 1, \ldots, S, \quad b \in B_s, \quad \text{s. t.} \quad \sum_{b \in B_s} a_{b,k} w_{s}^H H_{b,k} m_{b,s} \geq \beta_s \gamma_0,
\]

\[
N_0 \left\| w_s \right\|^2 + \sum_{i=1, i \neq s}^{S} \sum_{b \in B_i} a_{b,k} w_{s}^H H_{b,k} m_{b,i}^2 \geq \beta_s \gamma_0,
\]

\[
s = 1, \ldots, S, \quad \sum_{s \in S_b} \left\| m_{b,s} \right\|^2 \leq P_b, \quad b = 1, \ldots, N_B \tag{7}
\]

If the problem is feasible, then set \( \gamma_{\min} = \gamma_0 \). Otherwise, set \( \gamma_{\max} = \gamma_0 \).

4. If \( (\gamma_{\max} - \gamma_{\min}) < \epsilon \), then go to Step 2. Otherwise, return \( m_{b,s} = m_{b,s}, \quad s = 1, \ldots, S \), where \( m_{b,s} \) is the last feasible solution of (7) and STOP.

The constraints of problem (7) can be expressed as a generalised inequality with respect to the second-order cone [5], [10], and hence, it can be solved by using a second-order cone program (SOCP) solver [11]. By reformulating the approach presented in [6] to the case with generic coordinated BS processing, (7) can be presented as the following SOCP:

\[
\text{find } m_{b,s}, \quad s = 1, \ldots, S, \quad b \in B_s
\]

\[
\begin{bmatrix}
1 + \frac{\gamma_0}{\beta_s} \sum_{b \in B_s} a_{b,k} w_{b,k}^H H_{b,k} m_{b,s} \\
\sum_{b \in B_s} a_{b,k} w_{b,k}^H H_{b,k} m_{b,s} \\
\vdots \\
\sum_{b \in B_s} a_{b,k} w_{b,k}^H H_{b,k} m_{b,s} \\
\sqrt{N_0} w_s
\end{bmatrix} \succeq 0,
\]

subject to:

\[
s = 1, \ldots, S, \quad \| \text{vec}(M_b) \|_{\text{SOC}} \succeq 0, \quad b = 1, \ldots, N_B \tag{8}
\]

where the variables are \( m_{b,s} \). The inequality with respect to the second-order cone is denoted by \( \succeq \text{SOC} \), i.e., for any \( x \in \mathbb{R}^n \) and \( y \in \mathbb{C}^m \), \( x^T y \succeq 0 \) is equivalent to \( x \succeq \| y \|_{10}^2 [10] \).

Finally, a solution for problem (5) can be found by using a coordinate ascent method, i.e., alternating between (6) and Algorithm 1 until convergence for fixed \( m_{b,s} \) and \( w_s \), respectively. See [6, Algorithm 1] for more details. The block coordinate ascent method converges to the global optimum if the problems solved at each step have unique solutions [12].

The optimal objective value \( \gamma_o \) for fixed \( w_s \) (i.e., Algorithm 1) is indeed unique, but the resulting \( m_{b,s} \), \( s = 1, \ldots, S \) is not guaranteed to have a unique solution in general, due to the quasi-convexity of the original problem [5], [6]. Therefore, global optimality of the above method can only be guaranteed for the single-antenna receiver case.

IV. BEAM ALLOCATION ALGORITHMS

Assuming linear transceiver processing, a coordinated antenna system of \( N_B \) BSs each with \( N_T \) antennas may ideally accommodate up to \( S \leq \min(N_B N_T, \sum_{k \in \mathbb{C}} N_{R_k}) \) streams/beam without becoming interference limited. Mutual interference between \( S \) streams can be controlled or even completely eliminated by a proper selection of weight vectors. This is especially true in the coherent multi-cell MIMO transmission case, where the user data is conveyed from multiple BS antenna heads over a large virtual MIMO channel.

In the coordinated single-cell beamforming case \((|B_s| = 1 \forall s)\), each stream is transmitted from a single BS. In such a case, a user \( k_s \) is typically allocated to a cell \( b \) with the smallest path loss, \( \arg \max_{b\in B} a_{b,k} \). Near the cell edge, however, the optimal beam allocation strategy may also depend on the time varying properties of the channel \( H_{b,k} \). Thus, large gains from fast beam allocation (cell selection) algorithms are potentially available for the cell edge users. The optimal cell or BS assignment per beam is generally a difficult combinatorial problem and it requires an exhaustive search over all possible combinations of beam allocations, and
recomputing the algorithm for each allocation. This is clearly computationally prohibitive for a large $K$ and $N_T$. Therefore, sub-optimal allocation algorithms are needed in practice.

For simplicity, the allocation problems have often been addressed for systems with users having a single receive antenna. When the users are equipped with multiple receive antennas, receiver antenna coordination further enhances the data rates. The signal space of each user has multiple dimensions, allowing for multiple beams to be allocated per user. Therefore, the receiver signal space has to be considered when selecting the optimal sets of users, as well as the dimension and orientation of the signal subspace used by each selected user. This further complicates the allocation problem. Since the transmitter vectors, and thus, the corresponding receiver vectors at each user are affected by the set of selected users, it is impossible to know the actual receiver structure at the transmitter before the final beam allocation. An obvious candidate for an intelligent initial guess of the receiver matrix, the transmitter before the final beam allocation. An obvious users, it is impossible to know the actual receiver structure at

$$\text{min}(\Lambda_{b,k}, R_{b,k}) \text{ virtual single-antenna users (eigenbeams) with corresponding channel gains}$$

$$h_{b,k,l} = a_{b,k}u_{b,k,l}^Hb_{b,k,l} = a_{b,k,l}\lambda_{b,k,l}v_{b,k,l},$$

where $u_{b,k,l}, \lambda_{b,k,l}$ and $v_{b,k,l}$ correspond to $l$th column (or diagonal term) of $U_{b,k}, \Lambda_{b,k}$ and $V_{b,k}$, respectively. This type of approach has been taken, e.g., in [13], [14].

The aim of any beam-to-cell allocation algorithm is to select such BSs that the resulting beamformers mutually interfere as little as possible while providing large beamforming gains towards the intended users. A set of heuristic allocation algorithms for the coordinated single-cell beamforming case ($|B_s| = 1 \forall s$) are proposed in the following:

1) **Greedy selection:** The algorithm consecutively selects at most $\text{min}(\sum_b N_{R_b}, N_T)$ channels from the total set of $\sum_b \text{min}(N_{R_b}, N_T)$ channels. First, the strongest channel among all channels $\text{arg max}_{b,k,l} h_{b,k,l}$ is selected. Subsequently, on each step of the selection process, the channel with the largest component orthogonal to the previously selected set of beams is chosen. See similar beam allocation approaches, e.g., in [13], [14].

2) **Maximum eigenvalue selection:** The eigenvalues (norms) of the virtual channel vectors $h_{b,k,l}$ are simply sorted and at most $N_T$ streams are allocated per cell. Spatial compatibility with other channels is not considered.

3) **Eigenbeam selection using maxmin SINR criterion:** A simplified exhaustive search is carried out over all possible combinations of user-to-cell and streambeam-to-user allocations, $B_s$ and $S_s = \{ s \mid k_s \in U_b \}$, where the beamformer $\mathbf{m}_b, s$ for each stream $s$ is matched to the virtual channel vector $h_{b,k_s,l_s}$, i.e., $\mathbf{m}_b, s = v_{b,k_s,l_s} \sqrt{P_T / |S_s|}$. For each allocation, the receivers $\mathbf{w}_s$ and the corresponding SINR values $\gamma_s$, $s = 1, \ldots, S$

are calculated as in (6) and (4), respectively. Finally, the selection of the allocation is based on the maxmin SINR criterion, i.e., $\text{arg max}_{b,k,l} s=1, \ldots, S \gamma_s$.

4) **Eigenbeam selection using max rate criterion:** Same as above except that the selection is based on the maximum rate criterion, i.e., $\text{arg max}_{b,k,l} \sum_{s=1}^S \log_2(1 + \gamma_s)$.

Note that the usage of the greedy approach is rather limited since it can only be used when $S \leq N_T$. Thus, it cannot be applied to the interference limited scenarios, $S > N_T$.

V. **Numerical Results**

A flat fading multiuser MIMO system is considered, where $K = 2 - 4$ users are served simultaneously by 2 BSs. The number of antennas at BSs and terminals were $\{N_{R_b}, N_{T_s}\} = \{2 - 4, 1\}$. For simplicity, the BSs were assumed to have an equal maximum power limit $P_T$, i.e., $P_b = P_T \forall b$. The SNR for each user was based on the smallest pathloss among $N_B$ BSs and defined as $\text{SNR}_b = P_T \text{max}_{b \in B} \alpha_{b,k}^2 / N_0$. In the simulations, the elements of the channel matrices $H_{b,k}$ were modelled as i.i.d. Gaussian random variables. The simulation scenario is depicted in Fig. 1. For simplicity, we assume that the users are divided into $N_B$ groups where the users have identical large scale fading coefficients $a_{b,k}$. Furthermore, the distance between different user groups, as well as, SNR per user were kept at identical values. The distance is defined by a parameter $\alpha$ which fixes the ratio of path losses between the different user groups, as defined in Fig. 1. When the parameter $\alpha$ is fixed at 0 dB, all $K$ user are located exactly on the cell border. On the other hand, cells are completely isolated when $\alpha = \infty$.

We study the sum rate achievable using the maximisation of the minimum weighted SINR per data stream criterion with a per BS power constraint. Equal weighting of data streams $\beta_s = 1 \forall s$ is used in the SINR balancing algorithm. Since the optimal balanced SINR for each stream $s$ is identical $\gamma_s = \gamma_s \forall s$, the resulting sum rate can be expressed as $S \log_2(1 + \gamma_s)$. The following cases were compared by simulations:

1) Coherent multi-cell MIMO transmission ($B_s = B \forall s$) with per BS power constraints

2) Coordinated single-cell transmission ($|B_s| = 1 \forall s$)

- Exhaustive search over all possible combinations of beam allocations. The SINR balancing algorithm from Section III is recomputed for each allocation.
- Fixed allocation, i.e., user $k_a$ is always allocated to a cell $b$ with the smallest path loss, $\arg \max_{b \in B} a_{b,k_a}$.
- Eigenbeam selection both with max rate and maxim SINR allocation criteria.
- Greedy selection (can be applied when $S \leq N_T$).

3) Non-coordinated single-cell transmission ($|B_s| = 1 \forall s$), where the other-cell interference is assumed to be white Gaussian distributed

4) Single-cell transmission with time-division multiple access (TDMA), i.e., without inter-cell interference

Figs. 2(a) and 2(b) show the ergodic sum rate of $\{K, N_B, N_T, N_{R_k}\} = \{4, 2, 2, 1\}$ system for different TX processing methods as a function of the distance between different user sets, and for 0 and 20 dB single link SNR, respectively. It can be seen that coherent multi-cell beamforming greatly outperforms all other simulation cases when the distance between different user sets is finite. This is due to the fact that the coherent multi-cell beamforming can fully eliminate the inter-cell interference unlike the single-cell beamforming methods. The sum rates of non-coordinated and coordinated schemes become asymptotically equivalent as the distance approaches the infinity ($\alpha = \infty$), i.e., there is no gain from the coordinated multi-cell processing.

As the distance $\alpha$ approaches zero, the single-cell beamforming cases with four scheduled users becomes spatially overloaded, i.e., interference limited. For example, the achievable SINR $\gamma_s$ per data stream $s$ becomes sub-unitary at $\alpha = 0$ dB and the resulting maximum achievable rate is, 
$$4 \log_2(1 + \gamma_s) \leq 4$$

with a fixed beam allocation in the high SNR region, as seen from Fig. 2(b). Near the cell edge, the optimal beam allocation strategy depends on the properties of channel realisations $H_{b,k} \forall b, k$. Large gains from different beam allocation (cell selection) algorithms are available for the cell edge users. However, the channel dependent beam allocation is beneficial only within a $\sim$5 dB region around the cell edge. Otherwise, a beam should be allocated to a cell with the smallest path loss.

The heuristic eigenbeam based selection with maxim SINR criterion performs nearly the same as the optimal assignment per beam with an exhaustive search. Also, a simple maximum eigenvalue based selection largely outperforms the fixed allocation case. Note that there only eight allocation alternatives for the exhaustive search in the scenario of Figs. 2(a) and 2(b). However, the number of combinations increase very rapidly as the number of users and BSs increases, e.g., 90 alternatives for 3 BSs and 6 users.

The inter-cell interference is omitted in the precoder design both in the non-coordinated TX processing case and in the TDMA case, and thus the resulting beamformers are identical for both cases. All the coordinated TX processing techniques outperform the corresponding cases with non-coordinated single-cell TX processing. In the TDMA case, the transmission is time multiplexed between the BSs, and hence the reception is interference free. The TDMA case with an exhaustive search has better performance than non-coordinated TX processing with fixed allocation (Figs. 2(a)). As the distance between users sets approaches infinity the ergodic sum rate of both TDMA methods (exhaustive search and fixed) approaches 1 bits/s/Hz, which obviously is just half of the sum rate provided by the coherent and coordinated/non-coordinated TX processing methods.

The relative gain from the coherent multi-cell beamforming as compared to the coordinated single-cell transmission methods is greatly increased when the single link SNR is increased from 0 to 20 dB, as seen from the Fig. 2(b). At $\alpha = 0$, the ergodic sum rate is at least three times higher than that of coordinated single-cell beamforming with an exhaustive search of beam allocations. One can see that even the TDMA approach provides a higher sum rate than any coordinated single-cell TX processing method when $\alpha < 8$ dB. It is
noteworthy, however, that the coherent multi-cell processing does not increase significantly the sum rate (maxmin SINR) at high SNR as compared to the case where the cells are completely isolated ($\alpha = \infty$). Some other optimisation criterion such as sum rate maximisation used with coherent multi-cell beamforming would result in significantly larger increase in the sum rate as $\alpha$ approaches zero.

Let us now consider two cases where either $K$ is reduced to half $\{K, N_{B}, N_{T}, N_{R_k}\} = \{2, 2, 2, 1\}$ or $N_T$ is doubled $\{K, N_{B}, N_{T}, N_{R_k}\} = \{4, 2, 4, 1\}$, and both BSs serve only one or two users in the single cell transmission cases, respectively. Now, neither scenario is any longer interference limited in the coordinated single-cell beamforming case, i.e., $S \leq N_T$. Therefore, the performance of the coordinated single-cell beamforming case is greatly improved, as illustrated in Figs. 3 and 4 for 20 dB SNR. Furthermore, the common SINR value is greatly improved due to increased spatial degrees of freedom available in both scenarios.

VI. CONCLUSION

A generalised method for joint design of the linear transceivers with coordinated multi-cell processing subject to per-BS/antenna power constraints was proposed for the weighted SINR balancing optimisation objective. The method can accommodate a variety of scenarios from coherent multi-cell beamforming across a large virtual MIMO channel to a single-cell beamforming with inter-cell interference coordination and beam allocation. The performance of different coherent/non-coherent and coordinated/non-coordinated multi-cell transmission methods with optimal and heuristic beam allocation algorithms was numerically compared. The coherent multi-cell beamforming was shown to greatly outperform the non-coherent cases especially at the cell edge and with a full spatial load. However, the coordinated single-cell transmission with interference avoidance and dynamic beam allocation performed relatively well with a partial spatial loading.

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