Distributed multicell-MISO precoding using the layered virtual SINR framework

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***Abstract*—In this letter, we address the problem of distributed multi-antenna cooperative transmission in a cellular system. Most research in this area has so far assumed that base stations not only have the data dedicated to all the users but also share the full channel state information (CSI). In what follows, we assume that each base station (BS) only has local CSI knowledge. We propose a suboptimal, yet efficient, way in which the multicell MISO precoders may be designed at each BS in a distributed manner, as a superposition of so-called *virtual SINR* maximizations: a virtual SINR maximizing transmission scheme yields Pareto optimal rates for the MISO Interference Channel (IC); its extension to the multicell MISO channel is shown to provide a distributed precoding scheme achieving a certain fairness optimality for the two link case. We illustrate the performance of our algorithm through Monte Carlo simulations.**

I. Introduction

MIMO cooperation in cellular networks is receiving a lot of attention in the research community due to the ability of this technique to effectively *exploit* inter-cell interference in reuse-one wireless networks, yielding gains both in terms of average system capacity, and quality of service fairness for cell-edge users (see for example [1]). From the point of view of their impact on overall wireless network design, multicell MISO schemes can be categorized according to how much feedback and inter-cell signaling is required for their implementation. For instance, in the full multicell MIMO implementation, sharing of the user data symbols is needed across the bases engaged in downlink cooperation (an assumption akin to soft-handoff in CDMA networks for instance). Moreover feedback is needed to carry channel state information (CSI) from the receivers to the transmitters, while so-called backhaul signaling is necessary for base stations to share the CSI needed to derive the downlink precoding vectors.

The ability of deriving schemes that can cope with local CSI only has a profound impact on the scalability and the spectrum efficiency of cooperative schemes. In the most optimistic case, data *and* CSI of all users in a system can be shared by all transmitters and these can transmit jointly to serve the users thereby forming, assuming no synchronization issues arise, a giant MIMO broadcast channel (BC): the only difference to a traditional MIMO BC is the individual power constraints at each BS [2], [3]. In a more realistic setup, it remains to be seen how backhaul signaling can be reduced while still reaping multicell MIMO benefits.

The issue of user data sharing amongst the transmitters was addressed in a few recent publications. For example, in [4] an iterative message passing procedure is suggested so that the final transmitted signal is obtained by having neighboring transmitters exchange information. A more information theoretical approach was taken in [5] for example, which considers, for a given model of the network (Wyner-based model) the impact of having finite backhaul links between a central processor and the different base stations in the system. However there is still a need to develop concrete precoding schemes suited to the problem of multicell MIMO precoding with limited exchange of CSI among base stations.

In the present work, we assume a downlink multicell MISO system where the bases share the data symbols but unlike most previous work on the subject we investigate the possibility of a drastic reduction in the sharing of CSI, so as to derive a *distributed precoding approach*. More precisely, we assume each transmitter has only local knowledge, in the form of the channel coefficients between itself and each of the users in its neighborhood. This could for example correspond to a TDD system, where CSI is obtained from uplink training.

In order to derive the distributed precoder we build upon work previously done for the case of the MISO interference channel (IC) [6], ie. where each of the interfering bases serve their home user only (unlike the multicell MISO case). In that work, a distributed beamforming coordination scheme for the MISO IC was presented based on the concept of so-called *virtual SINR*: the idea of maximizing such ratios appears in the context of the MIMO broadcast channel in [7], [8] for example, and in that of MISO interference channels in [9], [10] among others. However, the originality of [6] lies in the claim (and proof) that such an approach is Pareto optimal in general and sum rate optimal in some cases of interest.

We derive a novel approach suited to the multi-base MISO channel based on *layering* multiple precoders each solving a different IC rate maximization problem. Our intuition for doing this is that the channel under consideration may be viewed as the superposition of a set of IC channels, where assuming there are as many users being served as there are transmitters, the transmitter-receiver matching in each IC is a different permutation of the possible matchings. A power allocation problem across the layers is also presented. For ease

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of exposition, we restrict our presentation to the representative two-cell MISO case, but the ideas can be extended to $N > 2$ cells in a straightforward fashion.

The rest of the paper is organized as follows. Section II defines the system model and performance measures considered. Section III introduces the layered virtual SINR framework and gives the proposed power allocation heuristic. Simulations in Section IV illustrate the performance of the proposed algorithm via Monte Carlo simulations.

Notation In what follows we use the following notation. $\mathbb{E}$ denotes statistical expectation. $\mathbb{C}$ is the complex number field. Boldface lowercase letters represent vectors, and boldface uppercase matrices. $\mathcal{CN}(m, \sigma^2)$ is the probability distribution of a circularly symmetric complex Gaussian random variable of mean m and variance σ^2. $\mathbf{I}_{N_t}$ denotes the identity matrix of dimension N_t.

II. System Model

Our basic setup consists of two transmitters (e.g. base stations in a cellular system), denoted BS_1 and BS_2, with $N_t \geq 2$ antennas each, communicating with two single-antenna receivers (mobile terminals), denoted MS_1 and MS_2. This is illustrated in Figure 1, and could be generalized to the $N > 2$ cell case.

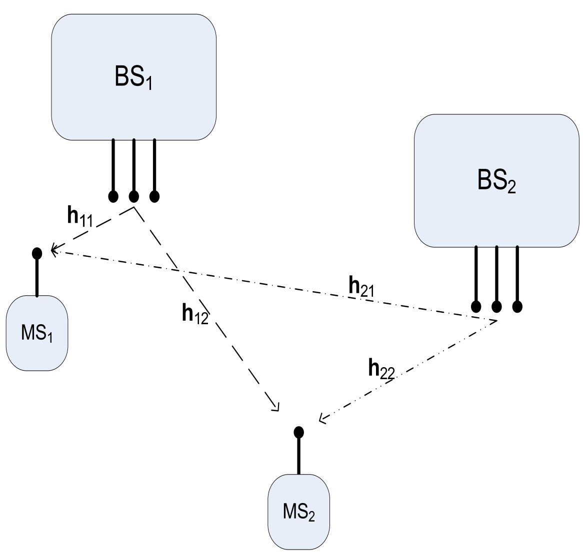

Fig. 1. CSI scenario considered for two transmitters. $\mathbf{h}_{11}, \mathbf{h}_{12}$ are known at BS_1, $\mathbf{h}_{21}, \mathbf{h}_{22}$ at BS_2.

Unlike in the MISO IC channel, we assume that data symbols for the two users are available at both transmitters, thus joint multibase precoding is possible.

We adopt a narrow-band channel model with frequency-flat block fading. Under linear precoding at each transmitter, the signal transmitted by BS_j, $\mathbf{x}_j$, is given by:

$$\mathbf{x}_j = \sum_{k=1}^{2} \sqrt{p_{jk}} \mathbf{w}_{jk} s_k \tag{1}$$

where $s_k \sim \mathcal{CN}(0, 1)$ is the symbol being transmitted intended for MS_k, $\mathbf{w}_{jk}$ is a unit-norm precoding vector used to carry this symbol from BS_j, i.e. $\|\mathbf{w}_{jk}\| = 1$, and p_{jk} is the corresponding transmit power used. Each BS is subject to an average transmit power constraint of P, in other words: $\mathbb{E}\left\{\mathrm{tr}\left(\mathbf{x}_j^H \mathbf{x}_j\right)\right\} = \sum_{k=1}^{2} p_{jk} \leq P$.

The signal received at user k is given by:

$$y_k = \sum_{j=1}^{2} \mathbf{h}_{jk} \mathbf{x}_j + n_k \tag{2}$$

where $\mathbf{h}_{jk}$ is the channel between MS_k and BS_j, $n_k \sim \mathcal{CN}(0, \sigma^2)$ is the noise at the considered receiver.

We assume that receivers have full CSI (CSIR) and do not attempt to decode the interfering signals. For notational convenience, we define $\bar{j}$ as the user not being j (in mathematical terms, $\bar{j} = \mod(j, 2) + 1$, for $j \in \{1, 2\}$). The rate achieved at user k is given by:

$$R_k = \log_2(1 + \gamma_k), \tag{3}$$

where the SINR γ_k is equal to:

$$\gamma_k = \frac{|\sum_{j=1}^{2} \sqrt{p_{jk}} \mathbf{h}_{jk} \mathbf{w}_{jk}|^2}{\sigma^2 + |\sum_{j=1}^{2} \sqrt{p_{j\bar{k}}} \mathbf{h}_{jk} \mathbf{w}_{j\bar{k}}|^2}. \tag{4}$$

A. Channel model

Channels are assumed to be Rayleigh fading, so that $\mathbf{h}_{jk} \sim \mathcal{CN}(\mathbf{0}, \sigma_{jk}^2 \mathbf{I}_{N_t})$. σ_{jk}^2 can account for path loss and shadowing, which vary on a larger time-scale relative to the fast fading.

B. Distributed CSIT Assumptions

Partial instantaneous CSI is assumed at each BS, which can be assumed to be obtainable locally: this corresponds to the channel coefficients between a BS and each of the users, i.e. BS_j knows $\mathbf{h}_{jk}, k = 1, 2$. This model of CSI is consistent with that used in a number of works such as [11], [12].

C. Optimization under Distributed CSIT knowledge

Under full CSIT at both transmitters, a joint transmission scheme which takes into consideration the individual power constraints at each BS can be implemented (for example [2], [3]): in fact sharing the CSIT reduces the setup to a MIMO broadcast channel. The case is more complicated for the distributed CSIT case considered here. Assuming the transmitters had statistical knowledge of the links they do not know locally, maximizing the expected sum rate under the above distributed CSIT assumptions would lead to an intractable functional optimization problem. We thus propose to instead make use of this distributed information in a simple but as will be shown in our simulation results effective way, by generalizing the virtual SINR framework applied to the IC in [6] to the joint precoding scenario.

III. Joint precoding with local CSIT: Virtual SINR approach

A. Virtual SINR Revisited for the MISO IC

In [6], the MISO IC was considered and the following algorithm was introduced to design for the beamforming vector to use at BS_k, denoted $\mathbf{w}_k$, to serve user k:

$$\mathbf{w}_k = \arg \max_{\|\mathbf{w}\|^2 = 1} \frac{|\mathbf{h}_{kk} \mathbf{w}|^2}{\frac{\sigma^2}{P} + \sum_{j \neq k} |\mathbf{h}_{kj} \mathbf{w}|^2}, \tag{5}$$

and full power was used. Note that a single index is used for the beamforming vector as each base serves a single user. This algorithm effectively consists of each transmitter maximizing a 'virtual SINR' defined as the ratio of the useful signal power at one's own user and the sum of noise plus interference power generated at the other users.

One of the main results of that paper is Theorem 1 restated for convenience below. It was also shown that both at low and high SNR, SNR $= \frac{P}{\sigma^2}$, the above beamforming vectors tend to the sum rate maximizing schemes of maximum ratio transmission and zero-forcing, respectively.

Theorem 1. *The rate pair obtained by beamforming using* $\mathbf{w}_k$*, as in* (5)*, lies on the Pareto boundary of the two-link rate region.*

Proof: The details are provided in [6]. ■

We now turn to the key problem addressed in this paper which is no longer the IC but a multi-base MISO channel, i.e. where the transmitters are both given the data symbols intended to all users.

B. Multicell MISO: Layered Virtual SINR

Given the local channel knowledge assumption, it is not possible for base stations to jointly design the whole beamforming matrix to carry symbols s_k, $k = 1, 2$ (cf. (1)). They can however still cooperate to transmit to the users in the system, as they have access to their data. One way to think of the thus defined channel is as a superposition of two interference channels: a first in which BS_1 serves MS_1 and BS_2 serves MS_2 and a second where BS_2 serves MS_1 and BS_1 serves MS_2; the difference from a regular superposition of ICs is that the data being transmitted to each user is effectively the same.

Guided by this view of the channel, we propose to use the concept of virtual SINR maximization introduced in the previous section to design the beamforming vectors at each base. What this means is that BS_j will design a virtual SINR beamformer to target MS_1 and another one to target MS_2, i.e. it applies the above algorithm (5) twice, thereby obtaining $\mathbf{w}_{jk}$, $j, k \in \{1, 2\}$ defined in (1) as:

Layered Virtual SINR maximizing beamforming solution:

$$\mathbf{w}_{jk} = \arg \max_{\|\mathbf{w}\|^2=1} \frac{|\mathbf{h}_{jk}\mathbf{w}|^2}{\frac{\sigma^2}{p_{jk}} + |\mathbf{h}_{j\bar{k}}\mathbf{w}|^2}. \tag{6}$$

Note that we replace P in (5) by p_{jk} in the above equation, where, as specified in section II, p_{jk} refers to the power allocated to MS_k's at BS_j. A heuristic method for how to determine the p_{jk} follows in the next subsection. We first give some intuitions to justify our approach.

Maximizing a virtual SINR effectively balances between the useful signal at the target user and the interference power generated at others. Moreover, one can do so while ensuring that, assuming synchronization in the system as we do here, the useful signal arriving at a given user from the different base stations does so constructively. In fact, one can show that the above virtual SINR maximization (6) yields a solution that may be written as [6]:

$$\mathbf{w}_{jk} = \sqrt{\zeta_{jk}} \frac{\Pi_{j\bar{k}}\mathbf{h}_{jk}^H}{\|\Pi_{j\bar{k}}\mathbf{h}_{jk}^H\|} + \sqrt{1-\zeta_{jk}} \frac{\Pi_{j\bar{k}}^{\perp}\mathbf{h}_{jk}^H}{\|\Pi_{j\bar{k}}^{\perp}\mathbf{h}_{jk}^H\|} \tag{7}$$

where $0 \leq \zeta_{jk} \leq 1, i, j = 1, 2$, $\Pi_{j\bar{k}}$ denotes the projection matrix onto $h_{j\bar{k}}$'s range, and $\Pi_{j\bar{k}}^{\perp}$ the projection matrix onto its null space. Thus, $\Pi_{j\bar{k}} = \frac{h_{j\bar{k}}^H h_{j\bar{k}}}{\|h_{j\bar{k}}\|^2}$, and $\Pi_{j\bar{k}}^{\perp} = \mathbf{I}_{N_t} - \frac{h_{j\bar{k}}^H h_{j\bar{k}}}{\|h_{j\bar{k}}\|^2}$. It is easy to verify that the product $\mathbf{h}_{jk}\mathbf{w}_{jk}$ will be a positive real value.

The formulation in (7) splits each transmit vector into a fully interfering and a non-interfering term. The splitting factor, ζ_{jk} is given by:

$$\zeta_{jk} = \frac{\|\Pi_{j\bar{k}}\mathbf{h}_{jk}\|^2}{\|\Pi_{j\bar{k}}\mathbf{h}_{jk}\|^2 + \|\Pi_{j\bar{k}}^{\perp}\mathbf{h}_{jk}\|^2 \left(1 + \frac{p_{jk}}{\sigma^2}\|\mathbf{h}_{j\bar{k}}\|^2\right)^2}, \tag{8}$$

which shows that as $\frac{p_{jk}}{\sigma^2}$ increases, more emphasis will be placed on the non-interfering component, whereas for low $\frac{p_{jk}}{\sigma^2}$, the solution reduces to maximum ratio transmission.

C. Power Allocation

Here we address the question of how to allocate the power between the two data streams at each BS. To find an answer, we first note the following:

Proposition 1. *Given the layered virtual SINR scheme, full power at each transmitter should always be used, i.e.:*

$$\sum_{k=1}^{2} p_{jk} = P, \quad \textit{for } j = 1, 2 \tag{9}$$

Proof: The proof is quite similar to that in the MISO IC case (see the proof of Proposition 1 in [13]) and relies on the fact that given that $N_t \geq 2$, it is always possible to increase the rates of one user by focusing more power orthogonally to the other user's channel. ■

Given Proposition 1, the power allocation problem is thus reduced to determining a single splitting parameter $0 \leq \lambda_j \leq 1$ at BS_j, $j = 1, 2$, whereby:

$$p_{j1} = P\lambda_j \text{ and } p_{j2} = P(1 - \lambda_j). \tag{10}$$

One would theoretically like to determine $\lambda_j, j = 1, 2$ so as to maximize some expected performance metric, the sum rate for example, given the channel knowledge at each user and the adopted layered virtual SINR transmission scheme. Maximizing the expected sum rate for the adopted beamforming structure requires finding optimal distributed power allocation strategies: for a given base station, these will be functions of its instantaneous local channel knowledge, but also need to take into account the statistics of the knowledge and of the strategy at the other transmitter. Similar to the more general optimal distributed precoding scheme design, determining such optimal power allocation strategies is an intractable functional optimization problem. We thus instead resort to heuristics which, though suboptimal, have the added benefit of not requiring the statistical knowledge of the links between the other transmitter and the users.

1) *Statistical power splitting:*
An intuitive approach is to split the power according to the following rule:

$$\lambda_j = \frac{\sigma_{j1}^2}{\sum_{k=1}^{2} \sigma_{jk}^2} \tag{11}$$

The intuition behind this is that a transmitter should allocate more power to the users that will benefit more from it, i.e. that it has stronger links to. Thus if the strength of the link to a user is quite low, there will be little use of allocating it any power.

2) *Channel aware power splitting:*
Pushing further the idea proposed in (11), another approach would be to split the power according to the instantaneous channel strength, as these are available locally, i.e.:

$$\lambda_j = \frac{\|\mathbf{h}_{j1}\|^2}{\sum_{k=1}^{2} \|\mathbf{h}_{jk}\|^2} \tag{12}$$

Complexity-wise, using (11) implies power splitting to be recomputed when the channel statistics change which would normally occur at much slower rate than the instanteneous change in the channel, which (12) follows.

1) Interference fairness: Although the power splitting above is not designed to maximize any fairness criterion, it turns out interestingly that it coincidentally provides an interference fair solution, where interference fairness is defined as a measure of the difference between the interference powers incurred at each user: in fact, the interference power at both users is the same, which leads us to the following lemma.

Lemma 1. *The power splitting* (12) *is strictly interference fair.*

Proof: The interference power at user k is equal to (cf. the SINR expression in (4)):

$$I_k = \left| \sum_{j=1}^{2} \sqrt{p_{j\bar{k}}} \mathbf{h}_{jk} \mathbf{w}_{j\bar{k}} \right|^2 . \tag{13}$$

Using the power allocation in (12) and the corresponding layered virtual SINR beamforming vectors as expressed in equations (7) and (8), the terms in the above summation may be written as:

$$\sqrt{p_{j\bar{k}}} \mathbf{h}_{jk} \mathbf{w}_{j\bar{k}} = \frac{\sqrt{P\beta_j} \cos\theta_j e^{\sqrt{-1}\angle \mathbf{h}_{jk}\mathbf{h}_{j\bar{k}}^H}}{\sqrt{1 + \frac{P\beta_j}{\sigma^2} \sin^2\theta_j \left(2 + \frac{P\beta_j}{\sigma^2}\right)}}, \quad k = 1, 2, \tag{14}$$

where $\cos^2\theta_j = \frac{|\mathbf{h}_{jk}\mathbf{h}_{j\bar{k}}^H|^2}{\|\mathbf{h}_{jk}^H\|^2 \|\mathbf{h}_{j\bar{k}}^H\|^2}$ and $\beta_j = \frac{\|\mathbf{h}_{jk}^H\|^2 \|\mathbf{h}_{j\bar{k}}^H\|^2}{\sum_{l=1} \|\mathbf{h}_{jl}^H\|^2}$. Thus

$$\sqrt{p_{j\bar{k}}} \mathbf{h}_{jk} \mathbf{w}_{j\bar{k}} = \sqrt{p_{jk}} \mathbf{h}_{j\bar{k}} \mathbf{w}_{jk} e^{\sqrt{-1}\pi} \tag{15}$$

and, as a result,

$$\begin{aligned} I_k &= \left| \sum_{j=1}^{2} \sqrt{p_{j\bar{k}}} \mathbf{h}_{jk} \mathbf{w}_{j\bar{k}} \right|^2 = \left| \sum_{j=1}^{2} \sqrt{p_{jk}} \mathbf{h}_{j\bar{k}} \mathbf{w}_{jk} e^{\sqrt{-1}\pi} \right|^2 \\ &= \left| \sum_{j=1}^{2} \sqrt{p_{jk}} \mathbf{h}_{j\bar{k}} \mathbf{w}_{jk} \right|^2 = I_{\bar{k}} \end{aligned} \tag{16}$$

■

From (14), one can also show that the interference power scales (provided $\mathbf{h}_{j1}$ and $\mathbf{h}_{j2}$ are not fully aligned, which occurs with probability 0) as $1/P$.

IV. Numerical Results

We compare the performance of our layered virtual SINR approach (LVSINR in the figures) to a fully centralized scheme, namely joint zero-forcing (i.e. both base stations pool their antennas together and do downlink zero-forcing) with optimal power allocation (JZF-PA in the figures): note that this is discussed under per-antenna power constraints in [14], among others; one can show that in the case considered here as well, this is a convex optimization problem which is relatively easy to solve. We further compare our results to a fully distributed case, where no data is shared among the transmitters, which uses the VSINR-based algorithm introduced in [6].

The results below are obtained by averaging over 10000 channel realizations, generated according to the specified distributions.

Figure 2 illustrates performance in terms of average sum rate for a symmetric channel: we define a symmetric channel as one where the variances of the channel coefficients of the links between MS_k and BS_k, $k = 1, 2$ (direct links) are equal and fixed at 1, whereas the variances of the channel coefficients of the links between MS_k and $BS_{\bar{k}}$, for $k = 1, 2$ (cross-links) are also equal and their value β is varied. The results are shown for $N_t = 2$ and for two power values: 0 and 10 dB. We note that at lower SNR, our distributed scheme performs as well as or even better, depending on the power allocation scheme used than zero-forcing even with power allocation (for the number of antennas considered): this is because at low SNR, the system is noise rather than interference-limited and the benefit of no inter-user interference by joint zero-forcing comes at too high a cost in terms of reduction in the useful signal power at the users. This is no longer the case at higher SNR. Moreover, at low SNR, the instantaneous heuristic (PA 2 in the figures) performs significantly better than the statistics-based heuristic (PA 1 in the figures) whereas the performances of both are comparable at higher SNR. More importantly, for any SNR regime, the higher the β, the stronger the cross-link and the more beneficial the cooperation. In fact, using the VSINR algorithm leads to lower sum rate for higher β, as in the absence of cooperation more interference is generated, whereas the opposite occurs for LVSINR and JZF-PA.

Figure 3 shows the performance comparison for a given arbitrary set of variances of the different links. Here too, one can see that as long as the "cross-links" are relatively strong there are rate gains to be obtained by sharing the data. Moreover, as the number of antennas increases the gap between our scheme and the JZF-PA scheme decreases. This is because we are increasing the number of antennas but only one user per base station is scheduled. Thus the dimensions of the null space of an interfered user's channel is increasing.

One can extend the LVSINR approach to $N > 2$ cells. This is illustrated for $K = 4$ users served by $N = 3$ base stations with $N_t = 4$, such that σ_{jk}^2, $j = 1, \ldots, 3, k = 1, \ldots, 4$, is given by the jth entry in the kth column in the following matrix

$$\begin{bmatrix} 1 & .5 & .05 \\ .2 & 1 & .2 \\ .05 & .5 & 1 \\ .3 & .3 & .08 \end{bmatrix}. \tag{17}$$

As there are fewer users to serve than there are base stations, comparing to a MISO IC (and applying the VSINR scheme) is no longer possible.

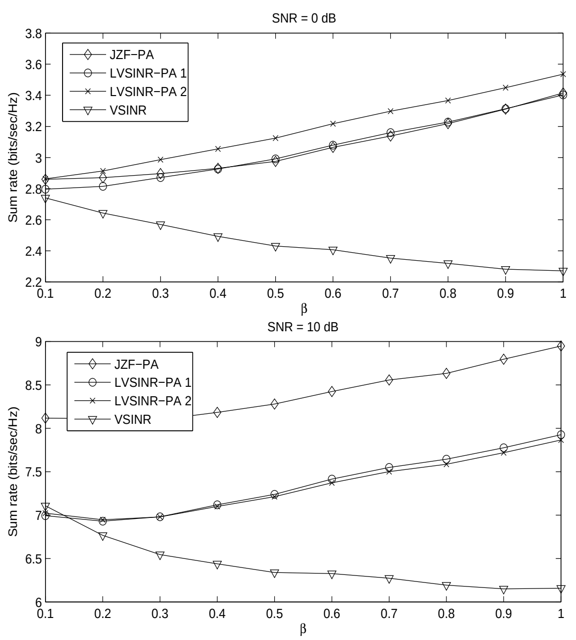

Fig. 2. Performance comparison for symmetric case for different SNR values: $\sigma_{11}^2 = \sigma_{22}^2 = 1$, $\sigma_{12}^2 = \sigma_{21}^2 = \beta$.

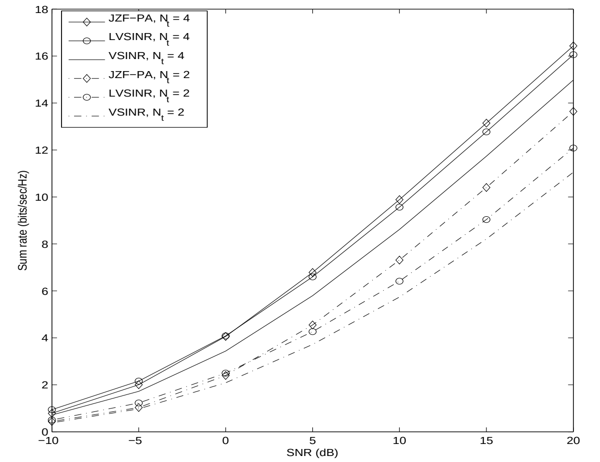

Fig. 3. Performance comparison for asymmetric case: $\sigma_{11}^2 = .5, \sigma_{12}^2 = .3, \sigma_{21}^2 = .3, \sigma_{22}^2 = 1$, for different number of antennas.

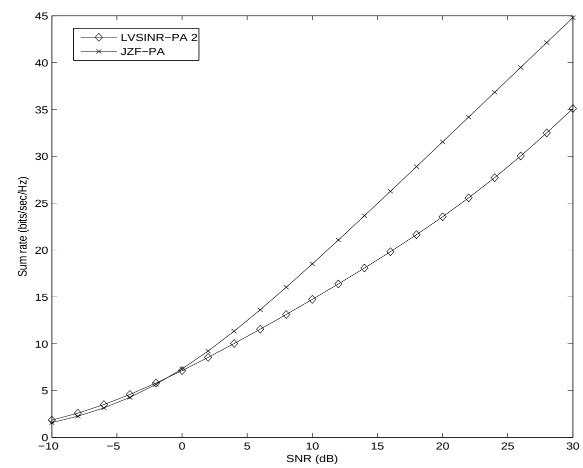

Fig. 4. Sample performance comparison for 3 cells, $N_t = 4$ and $K = 4$.

V. Conclusion

In this paper, a layered virtual SINR maximization approach was proposed for cooperatively serving users in a multicell MISO environment, where data is shared by the transmitters but only local knowledge of CSI is available. Monte Carlo simulations illustrate the benefit of such an approach.

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