Base Station Cooperation for Multiuser MIMO: Joint Transmission and BS Selection

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***Abstract*—The predicted enormous capacity gain of multiple-input multiple-output (MIMO) systems is significantly limited by co-channel interference (CCI), or by realistic outdoor propagation environments. In this paper, a common framework is proposed for the study of cooperative base stations (BS), to address those problems encountered on downlink of multicell multiuser MIMO systems. Specifically, both joint transmission (JT) and BS selection among cooperative base stations are analyzed and compared with each other. Some other advantages of BS cooperation are also explored including the power gain, channel rank/conditioning advantage, and macro-diversity.**

Keywords – MIMO, co-channel interference, BS cooperation

I. INTRODUCTION

MIMO techniques are anticipated to be widely employed in future wireless communications to address the ever-increasing capacity demands. However, achieving the predicted enormous capacity gains in realistic cellular multiuser MIMO networks could be problematic. First, the sharing of common system resources by multiple users and the frequency reuse among adjacent cells will bring in co-channel interference, which may greatly diminish the advantages of MIMO systems. The second problem is the rank deficiency and ill-conditionness of the MIMO channel matrix, mainly caused by the spatial correlation. Finally, the effect of the macroscopic fading, may also induce negative impact on the anticipated system capacity.

The study on the performance of interference-limited multicell multiuser MIMO attracted research attention only recently [2][3]. The advanced receiver techniques proposed in [5] improve the system performance at the cost of increased receiver complexity, and the achieved system capacity is still significantly away from the interference-free capacity upper bound, especially in environments with strong CCI. For environments with low mobility or slow fading, the idea naturally arises to move the CCI mitigation to the transmitter (BS) side on the downlink, where complex structure and advanced processing can be more easily accommodated, if channel state information (CSI) can be obtained at the transmitter side either through uplink estimation or through a feedback channel. Moreover, as multiple users in multiple cells are involved, cooperative processing at relevant base stations can be exploited. In this scenario, cooperative processing among relevant radio ports transforms the obstructive interference into constructive signals, which should offer large performance improvement. BS cooperation approach is feasible, as in the current infrastructure that is common to both cellular communications and indoor wireless internet access, the base stations and access points in the system are connected by a high-speed wired backbone that allows information to be reliably exchanged among them. This approach is also reasonable, as in environments with strong interference a mobile usually experiences several *comparable* and *weak* links from surrounding radio ports, where soft handoff typically takes place in current cellular CDMA networks. Some pioneering works on the joint transmission among cooperative BS's can be found in [6]~[9], which pay more attention on the capacity achieving dirty-paper coding (DPC) schemes. In this paper, from both information-theoretic and practical signal-processing standpoints, a common framework is proposed for the study of both joint transmissions (JT) and BS selections among cooperative base stations for downlink multicell multiuser MIMO networks. The proposed schemes are shown to significantly outperform the advanced receiver techniques in [5] and conventional non-cooperative signaling schemes. Although JT schemes can achieve great performance improvements, some of them may introduce BS synchronization, system complexity and unbalanced power allocation problems under certain adverse circumstances, in which the more practical BS selection schemes may partly maintain the good performance of JT schemes without such concerns. Meanwhile, some other advantages of BS cooperation, including the power gain, channel rank/conditioning improvement, and macrodiversity protection are also addressed and verified with more realistic channel models.

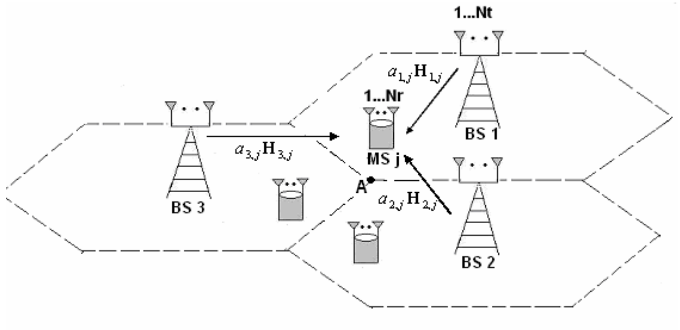

Figure 1. A multicell multiuser MIMO system with $N_b = 3,\ K = 3$

II. SYSTEM MODEL AND SINGLE CELL SIGNALING SCHEMES

In the downlink multicell system, we can dynamically assign different sets of frequency bands to users close to the BS and users around the cell border (e.g. around point **A** in Figure 1), in which strong CCI is involved. Therefore, we can simply consider these far users who have comparable distances to the in-cell and adjacent interfering BS's. Suppose in general that there are K such co-channel mobile users distributed around the cell border, with N_r the number of receive antennas at each mobile station (MS), and N_t the number of transmit antennas at each BS, respectively. Suppose that N_b is the total number of adjacent base stations in the system, so (N_t, N_r, N_b, K) can be used to represent the overall system, as in Figure 1 for a case with $N_b = K = 3$. With non-dispersive flat fading assumption, let $\{\mathbf{H}_{b,j}\}_{b=1,}^{N_b}{}_{j=1}^{K}$ be the small-scale fading channel matrix from BS b to MS j; and let $\{a_{b,j}\}$ be the corresponding large-scale fading coefficients with $a_{b,j}^2 = PL_{b,j}S_{b,j}$, where $PL_{b,j}$ represents the path loss, and $S_{b,j}$ denotes the shadow fading, typically modeled as a lognormal random variable with standard deviation σ. Note that on the downlink, if MS *j* is in cell *b*, $a_{b,j}\mathbf{H}_{b,j}$ represents an in-cell channel, otherwise it is an inter-cell channel.

For the traditional non-cooperative scenario with single-cell signaling, a mobile station (MS) only communicates with its own base station. Let b_j ($b_j \in \{1,.....,N_b\}$) represent the associated base station of user *j*, the equivalent discrete-time received signal of user *j* after matched filtering and sampling can then be expressed as:

$$\mathbf{y}_j = a_{b_j,j}\mathbf{H}_{b_j,j}\mathbf{x}_j + \sum_{k\neq j} a_{b_k,j}\mathbf{H}_{b_k,j}\mathbf{x}'_{k\_j} + \mathbf{n}_j \ , \quad j = 1,2,...,K \ , \tag{1}$$

where $\mathbf{x}_j$ is the transmitted signal intended for user *j*, and $\mathbf{n}_j$ is the background noise. The interference signal $a_{b_k,j}\mathbf{H}_{b_k,j}\mathbf{x}'_{k\_j}$ can come from any base station including b_j (when $b_k = b_j$). We assume that the matched filter at MS *j* can synchronize with the signature waveform of its desired signal, but not with the waveforms of the signals intended for other users. So we use $\mathbf{x}'_{k\_j}$ to represent the equivalent discrete-time transmitted signal intended for user *k* and asynchronously received at MS *j* after matched filtering and sampling, which is a certain linear combination of two temporally consecutive symbols of $\mathbf{x}_k$. In general, a pre-processing $N_t \times L_j$ matrix $\mathbf{T}_j$ is applied to the transmitted data for user *j* as $\mathbf{x}_j = \mathbf{T}_j\mathbf{s}_j$, where the $L_j \times 1$ vector $\mathbf{s}_j$ represents the actual data intended for user *j*, assumed to have i.i.d. complex Gaussian entries with zero mean and unit variance ($E(\mathbf{s}_j\mathbf{s}_j^H) = \mathbf{I}$). The signal intended for user *j* is transmitted with a power of $E[\mathrm{Tr}(\mathbf{x}_j\mathbf{x}_j^H)] = \mathrm{Tr}(\mathbf{T}_j\mathbf{T}_j^H) = P_{U\_j}$. If CSI is available at the transmitter, to maximize the capacity, L_j is chosen to be the number of the effective eigen-modes of the corresponding channel matrix $a_{b_j,j}\mathbf{H}_{b_j,j}$, and $\mathbf{T}_j$ is designed to perform eigen-beamforming based on the singular value decomposition (SVD) of the channel matrix; otherwise L_j simply equals to N_t and $\mathbf{T}_j = \sqrt{(P_{U\_j} / N_t)}\mathbf{I}$.

A lower bound for traditional single-cell signaling schemes can be derived with the conventional single user detector, which simply treats CCI as additive white Gaussian noise at MS *j*. The spectral efficiency for user *j* with this conventional single user detector is then approximately given by [5]:

$$R_{j\_conv} = \log\left|\mathbf{I} + \frac{a_{b_j,j}^2}{(N_0 + \sum_{k\neq j} P_{U\_k}a_{b_k,j}^2)}\mathbf{H}_{b_j,j}\mathbf{T}_j\mathbf{T}_j^H\mathbf{H}_{bj,j}^H\right|, \tag{2}$$

where $\mathbf{T}_j$ can be designed as discussed above. On the other hand, the single-cell signaling interference-free upper bound unrealistically assumes no interference at the receiver of MS *j*:

$$R_{j\_\text{single cell}} = \log\left|\mathbf{I} + \frac{a_{b_j,j}^2}{N_0}\mathbf{H}_{b_j,j}\mathbf{T}_j\mathbf{T}_j^H\mathbf{H}_{b_j,j}^H\right| = \sum_{l=1}^{L_j}\log(1 + \frac{P_l}{N_0}\lambda_l^2) \ , \tag{3}$$

where the second equality follows from the SVD of $a_{b_j,j}\mathbf{H}_{b_j,j}$. The receiver multiuser detection (MUD) schemes proposed in [5] can improve the performance of MIMO systems in a multicell structure. However, they require MS *j* to know not only its desired channel, but also the interfering channels, and some schemes may need to detect both the desired and interfering signals. They can be readily implemented at BS for CCI mitigation on the uplink, but may still be impractical for current MS on the downlink because of their complexity. Furthermore, it is found that the performances of the multiuser receivers are far from the interference-free upper bound (3), especially in environments with strong interference, which indicates a need to exploit more system resources for throughput enhancement.

III. JOINT TRANSMISSION WITH BS COOPERATION

For the joint transmission among cooperative BS's, we assume that CSI is available at the transmitter, and the transmit signal for each user is spread over all N_b base stations. Then $\mathbf{x}_j = [\mathbf{x}_j^{[1]T}, \mathbf{x}_j^{[2]T}, ..., \mathbf{x}_j^{[N_b]T}]^T$, where $\mathbf{x}_j^{[b]}$ is the transmitted signal intended for user *j* from BS *b*. With the assumption that the joint transmitter knows the propagation delay for each BS-MS pair, $\mathbf{x}_j$ can be pre-compensated at the joint transmitter for the different delays from different base stations to MS *j*. So MS *j* can still receive a synchronized $\mathbf{x}_j$:

$$\mathbf{y}_j = \mathbf{H}_{Ej}\mathbf{x}_j + \sum_{k\neq j}\mathbf{H}_{Ej}\mathbf{x}'_{k\_j} + \mathbf{n}_j \ , \tag{4}$$

where $\mathbf{H}_{Ej} = [a_{1,j}\mathbf{H}_{1,j},\ a_{2,j}\mathbf{H}_{2,j},\ ....,\ a_{N_b,j}\mathbf{H}_{N_b,j}]_{N_r \times N_t N_b}$, (5)

and in $\mathbf{x}'_{k\_j} = [\mathbf{x}_{k\_j}^{[1]'\,T}, \mathbf{x}_{k\_j}^{[2]'\,T}, ..., \mathbf{x}_{k\_j}^{[N_b]'T}]^T$, $\mathbf{x}_{k\_j}^{[b]'}$ represents asynchronous reception of $\mathbf{x}_k^{[b]}$ at MS *j*, given that $\mathbf{x}_k$ cannot be pre-compensated for MS *j* during joint transmission. Note that in this scenario, the transmit matrix $\{\mathbf{T}_j\}$ are of the dimension $N_t N_b \times L_j$, and $\{\mathbf{T}_j\}_{j=1}^K$ are designed only based on the characteristics of $\{\mathbf{H}_{Ej}\}_{j=1}^K$, which are assumed to be constant over a much longer period than the largest delay among all BS-MS pairs in the system, with the quasi-static fading channel assumption. So $\{\mathbf{T}_j\}$ are constant during this time period and we have $\mathbf{x}'_{k\_j} = \mathbf{T}_k\mathbf{s}'_{k\_j}$, where $\mathbf{s}'_{k\_j} = [\mathbf{s}_{k\_j}^{[1]'\,T}, \mathbf{s}_{k\_j}^{[2]'\,T}, ..., \mathbf{s}_{k\_j}^{[N_b]'T}]^T$, and $\mathbf{s}_{k\_j}^{[b]'}$ is the corresponding asynchronous reception of the sub-streams in $\mathbf{s}_k$ transmitted from BS *b*, as discussed above. Therefore, (4) can be re-written as

$$\mathbf{y}_j = \mathbf{H}_{Ej}\mathbf{T}\mathbf{s}_{[j]} + \mathbf{n}_j \ , \tag{6}$$

where $\mathbf{T} = [\mathbf{T}_1,\ \mathbf{T}_2,\ ....,\ \mathbf{T}_K]_{N_t N_b \times \sum_k L_k}$, and

$\mathbf{s}_{[j]}^T = [\mathbf{s}'_{1\_j}{}^T, ..., \mathbf{s}'_{j-1\_j}{}^T, \mathbf{s}_j^T, \mathbf{s}'_{j+1\_j}{}^T, ..., \mathbf{s}'_{K\_j}{}^T]_{\sum_k L_k \times 1}$. For simplicity, we still assume that $\{\mathbf{s}'_{k\_j}\}$ have i.i.d. complex Gaussian entries with zero mean and unit variance. The key problem of joint transmit processing among cooperative base stations is to jointly design a transmit matrix $\mathbf{T}$ to mitigate co-channel interference and enhance the system spectral efficiency with either a pooled power constraint:

$$\mathrm{E}[\sum_{\mathrm{k}=1}^{K}\mathrm{Tr}(\mathbf{x}_k\mathbf{x}_k^H)] = \mathrm{Tr}(\sum_{k=1}^{K}\mathbf{T}_k\mathbf{T}_k^H) \leq P_t \ , \tag{7}$$

or more practical per-base power constraints:

$$\mathrm{E}[\sum_{\mathrm{k}=1}^{K}\mathrm{Tr}(\mathbf{x}_k^{[b]}\mathbf{x}_k^{[b]\mathrm{H}})] = \mathrm{Tr}(\mathbf{T}^{[b]}\mathbf{T}^{[b]H}) = \mathrm{Tr}(\sum_{k=1}^{K}\mathbf{T}_k^{[b]}\mathbf{T}_k^{[b]H}) \leq P_{B\_b} \ , \tag{8}$$

for $b = 1,\ 2,\ ....,\ N_b$, where $\mathbf{T}^{[b]}$ and $\mathbf{T}_k^{[b]}$ are the rows in $\mathbf{T}$ and $\mathbf{T}_k$ corresponding to the transmit antennas at BS *b*, respectively. In our study, since MS *j* is not interested in correctly detecting $\mathbf{s}_k$, for $k \neq j$, the design of the joint transmit matrix $\mathbf{T}$ is actually not affected by the asynchronous receptions of interfering signals and $\{\mathbf{s}'_{k\_j}\}$ can be simply viewed as the data of some *virtual synchronous interfering users*.

As seen in Figure 1, by cooperating the N_b adjacent base stations, the downlink of a (N_t, N_r, N_b, K) multicell multiuser MIMO system forms a vector broadcast channel (BC), in which the $NT = N_t \times N_b$ transmit antennas are distributed among the N_b radio ports (or base stations) separated far apart from each other. Unlike traditional BC with co-located MIMO channels, the channel gains from any two antenna elements at different BS are guaranteed to be independent. With base station cooperation, the system resources can be pooled together for more efficient use. In particular, the severe CCI problem can be effectively controlled and significant performance improvement can be achieved. Meanwhile, the complexity at MS can be significantly reduced.

For a system with perfect data and power cooperation among N_b base stations, we can implement the throughput-achieving dirty paper coding [4][6], at the vector broadcast channel formed by cooperative BS's (we name it as JT-DPC), to obtain a system performance upper bound. Note that with the asynchronous vector BC model (4), we apply DPC in a slightly different way, where the encoder for the "current" user needs to non-causally know not only the encoding of "previous" users and associated CSI, but also the corresponding propagation delays, to pre-cancel the interference from "previous" users. Although the DPC scheme with a pooled power constraint gives us a simple performance upper bound for BS cooperation, it is more practical to use the per-base power constraints. Complex iterative multistage numerical methods for cooperative DPC with constraints (8) are proposed in [6][7][8].

For a better understanding of the achievable performance gains of JT schemes, we further consider some more practical linear joint transmitters. In general, the following expression holds true for the spectral efficiencies of user *j* with these joint linear transmission schemes:

$$R_{j\_subopt}(\mathbf{T}) = \log\left|\mathbf{I} + [N_0\mathbf{I} + \mathbf{H}_{Ej}(\textstyle\sum_{i\neq j}\mathbf{T}_i\mathbf{T}_i^H)\mathbf{H}_{Ej}^H]^{-1}\mathbf{H}_{Ej}\mathbf{T}_j\mathbf{T}_j^H\mathbf{H}_{Ej}^H\right|, \qquad (9)$$

where different schemes correspond to different choices of transmission matrices $\{\mathbf{T}_j\}$ or $\mathbf{T}$ with the constraints in (8). Compared with DPC, (9) may induce more transmit power inefficiency, as $\mathbf{T}$ is responsible for the mitigation of interference from both "previous" and "subsequent" users, and per-base power constraints are implemented instead of a pooled power constraint. Before discussing the designs of these linear JT schemes in detail, we first propose a simple algorithm for designing $\mathbf{T}$ with per-base power constraints. Let $L_T = \sum_{k=1}^{K} L_k$ be the overall number of data streams of *K* users. Suppose that a preliminary joint linear transmit matrix $\mathbf{G}_{N_bN_t\times L_T}$ is given, whose designs will be introduced in the sequel. Our design of $\mathbf{T}$ with per-base power constraints (8) is given by

$$\mathbf{T} = \mathbf{G}\mathbf{\Omega} = [\mathbf{G}_1,\ \mathbf{G}_2,\ ....,\ \mathbf{G}_K].\mathbf{\Omega}, \qquad (10)$$

where $\mathbf{\Omega}$ is an $L_T \times L_T$ diagonal matrix with diagonals $\{\mu_l\}_{l=1}^{L_T}$ each representing the allocated power for the corresponding original data stream, and $\mathbf{G}_j$ is the corresponding preliminary transmission matrix for user *j*. Since typically $L_T >> N_b$ and there are only N_b per-base power constraints in (8), we can further divide $\{\mu_l\}_{l=1}^{L_T}$ into N_b groups each with L_T / N_b elements having the same value:

$$\mathbf{\Omega} = blockdiag(\mu_1\mathbf{I}, \mu_2\mathbf{I}, ..., \mu_{N_b}\mathbf{I}\}\cdot \qquad (11)$$

Further define

$$\mathbf{Q}_{N_b\times N_b} = \begin{bmatrix} \left\|\mathbf{G}_1^{[1]}\right\|_F^2 & \left\|\mathbf{G}_2^{[1]}\right\|_F^2 & ..... & \left\|\mathbf{G}_{N_b}^{[1]}\right\|_F^2 \\ \left\|\mathbf{G}_1^{[2]}\right\|_F^2 & \left\|\mathbf{G}_2^{[2]}\right\|_F^2 & ..... & \left\|\mathbf{G}_{N_b}^{[2]}\right\|_F^2 \\ : & : & : & : \\ \left\|\mathbf{G}_1^{[N_b]}\right\|_F^2 & \left\|\mathbf{G}_2^{[N_b]}\right\|_F^2 & ..... & \left\|\mathbf{G}_{N_b}^{[N_b]}\right\|_F^2 \end{bmatrix}, \qquad (12)$$

where $\mathbf{G}_j^{[b]}$ is an $N_t \times L_T / N_b$ submatrix in **G**, corresponding to the transmit weights at BS *b* for the *jth* user as defined above. Let $\mathbf{P} = [P_{B\_1}, P_{B\_2}, ..., P_{B\_N_b}]^T$ be the per-base power constraint vector, then we can calculate $\mathbf{\Omega}$ by solving the linear system equation:

$$\boldsymbol{\mu} = [\mu_1^2, \mu_2^2, ..., \mu_{N_b}^2]^T = \mathbf{Q}^{-1}\mathbf{P}\,. \qquad (13)$$

When an infeasible solution ($\boldsymbol{\mu}$ does not have all positive entries) is obtained, we can simply refine it as:

$$\mathbf{\Omega} = \mu\mathbf{I}\,,\ \mu = \min_{b=1,2,...,N_b}\left(\frac{P_{B\_b}}{\left\|\mathbf{G}^{[b]}\right\|_F^2}\right), \qquad (14)$$

where $\mathbf{G}^{[b]}$ is the rows of **G** corresponding to transmit antennas at BS *b*. Note that (13) can utilize the full power at each BS, while in (14) only the BS satisfying the minimum value can transmit with full power and any other BS transmits with a power less than its power constraint. Furthermore, as will be shown in the next section, (14) requires the channel matrices associated with different BS's to be 'symmetric' enough, otherwise, too much power will be wasted by this simplified algorithm.

The design of **G** is straight forward. For example, for *zero forcing joint transmitter (JT-ZF),* $\mathbf{G} = \mathbf{H}_T^H(\mathbf{H}_T\mathbf{H}_T^H)^{-1}$ is the pseudo-inverse of the joint matrix

$$\mathbf{H}_T = [\mathbf{H}_{E1}^T,\ \mathbf{H}_{E2}^T,\ ...\ ,\ \mathbf{H}_{EK}^T]^T \qquad (15)$$

Here, we are more interested in a scheme called *joint transmitter with null-space decomposition (JT-Decomp),* in which

$$\mathbf{G}_j = \overline{\mathbf{V}}_j\mathbf{V}_j^{'}\ , \qquad (16)$$

where $\overline{\mathbf{V}}_j$ includes the right singular vectors corresponding to the null space (zero singular values) of the composed matrix $\overline{\mathbf{H}}_{T\_j} = [\mathbf{H}_{E1}^T, ..., \mathbf{H}_{Ej-1}^T, \mathbf{H}_{Ej+1}^T, ..., \mathbf{H}_{EK}^T]^T$, and $\mathbf{V}_j^{'}$ includes the first L_j right singular vectors of the virtual channel $\mathbf{H}_{Ej\_para} = \mathbf{H}_{Ej}\overline{\mathbf{V}}_j$. If $\overline{\mathbf{H}}_{T\_j}$ has a non-zero null space, $\mathbf{H}_{Ei}\overline{\mathbf{V}}_j = \mathbf{0}$, $i \neq j$ can be guaranteed. Interference from all other users is cancelled, and we obtain a set of equivalent parallel interference-free subchannels $\{\mathbf{H}_{Ej\_para}\}$.

Another basic advantage of JT schemes comes from the power gain or array gain, because, with joint transmission, the per-user channel matrix changes from a $N_r \times N_t$ matrix $a_{b_j,j}\mathbf{H}_{b_j,j}$ to an $N_r \times N_tN_b$ matrix $\mathbf{H}_{Ej}$. In (3), given that $\sum_i \lambda_i^2 = \|\mathbf{H}\|_F^2$, it is easily seen that with the same channel rank, power constraint, and power allocation algorithm, the higher the channel power, the larger the spectral efficiency. The power gain is significant if MS *j* has comparable links to adjacent base stations, which represents a strong CCI case. In general, for joint transmission schemes, transmit matrix **T** uses a portion of the total power for interference mitigation, and the per-base power constraint (8) may also reduce the available power. Such transmit power inefficiency may compromise the power gain. This effect is sometimes eminent for linear JT schemes, as will be seen in the simulations below.

To numerically show the achieved throughput improvement of these JT schemes, we use an ideal (2,2,3,3) symmetric scenario, which is similar to the Wyner's model used in [11][9]. Three co-channel users are located in three different cells (Figure 1), which may represent TDMA, FDMA, or orthogonal CDMA. We also assume that $a_{b,j}^2 = 0.5$ (no shadowing), $\forall b \neq b_j$, normalized with respect to the in-cell large-scale fading $\{a_{b_j,j}^2\}_{j=1}^3 = 1$, which represents a strong CCI scenario. For single-cell signaling schemes, data for each user is transmitted with an identical power $\{P_{U\_j}\}_{j=1}^K = P$. Pooled power constraint is imposed for DPC with $P_t = 3P$, while per-base constraints are enforced for JT-Decomp with $P_{B\_b} = P$. Also, the bounds of single-cell approaches, (2) and (3), and the spectral efficiency of the optimal multiuser receiver from [5] are given for reference. From Figure 2, we see that the performance of the optimal multiuser receiver is still significantly away from the single-cell upper bound. On the other hand, the DPC with BS cooperation results in a significant performance gain over the multiuser receivers, and they even outperform the single-cell interference-free upper bound. The linear JT scheme reduce interference at the expense of transmitter power inefficiency, which may compromise the power gain and may result in a performance worse than the single-cell interference-free upper bound. Nonetheless, it still significantly outperforms the multiuser receivers.

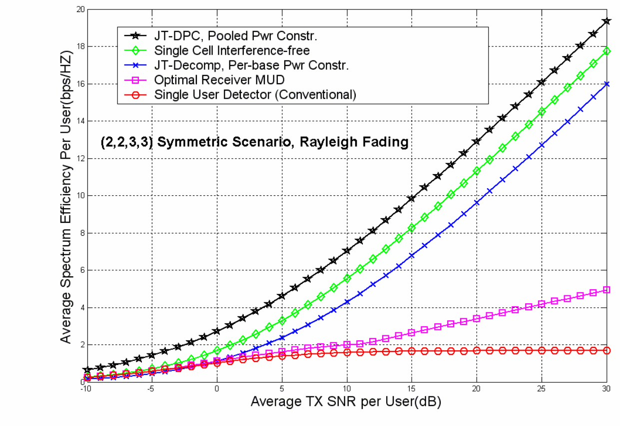

Figure 2. Spectral Efficiencies for Rayleigh Fading Channels

Besides its potential in CCI cancellation and its power gain, JT schemes assume other advantages. The first one is its advantage in channel rank and conditioning. In some extreme environments (e.g., the keyhole problem), a MIMO system will lose its capacity advantage (spatial multiplexing gain), even though other advantages like diversity and array gains may still preserve. Another important factor influencing the MIMO capacity is the channel condition number. In realistic environments, the channel may get ill-conditioned due to fading correlation, resulting from the existence of few dominant scatterers, small angle spread, and insufficient antenna spacing. For JT schemes, the overall transmit array is distributed among cooperative base stations, so in the equivalent channel for user j $\mathbf{H}_{Ej}$, $\{\mathbf{H}_{b,j}\}_{b=1}^{N_b}$ are independent with each other. The overall number of independent links is then given by $\sum_{b=1}^{N_b} rank(\mathbf{H}_{b,j})$, which is guaranteed to be at least equal to N_b. If $N_b \geq N_r$, $\mathbf{H}_{Ej}$ will always have a full rank. Furthermore, the channel conditioning will not be greatly degraded even if transmit fading correlation happens at each base station, as the fading between different transmit antennas at different base stations are still uncorrelated. To show this advantage, we simulate the same symmetric scenario as in Figure 2 except that $\{\mathbf{H}_{b,j}\}$ are of rank one. From Figure 3, we can see that the spectral efficiencies of single-cell signaling schemes and the single-cell upper bound degrade (cf. Figure 2) because of the reduced channel rank. There is a 2 more bits/s/Hz spectral efficiency gain for every 3dB transmit SNR increase for JT schemes at high SNR, while there is only a 1 bits/s/Hz gain with the same transmit SNR increase for the single-cell upper bound. That is why JT-Decomp can even outperform the single-cell upper bound at high SNR, as the spatial multiplexing gain compensates the power inefficiency. Thanks to channel rank and conditioning advantages with BS cooperation, performances of all joint transmission schemes don't deteriorate significantly in this deficient channel (cf. Figure 2).

Shadowing in wireless channels is a position sensitive factor, which means that signals from transmit antennas co-located at the same base station are generally subject to the same shadowing, while those from different base stations subject to independent shadowing. Under severe shadowing, the capacity of a single cell MIMO with co-located antennas will degrade significantly. On the other hand, JT schemes can provide the macrodiversity protection for shadowing impairment, because of their independency. Intuitively, the probability that all sub-channels of $\mathbf{H}_{Ej}$ are under deep shadow fading is much lower than a co-located MIMO channel. Macrodiversity cannot increase the mean of the received SNR, but will greatly reduce its variance. To demonstrate this, in the symmetric scenario of Figure 2 (Rayleigh fading), we consider the shadowing effect for $\{a_{b,j}\}$, which are independent for different base stations. In Figure 4, we compare the 10% outage spectral efficiency of the single-cell interference-free upper bound (3), with that of JT-Decomp, with the shadowing standard deviation σ ranging from 6dB to 15dB. Because of the macrodiversity protection, we can see that the outage spectral efficiency of JT-Decomp is much more robust than that of the single-cell upper bound when subject to shadow fading, outperforming it at severe shadowing scenarios.

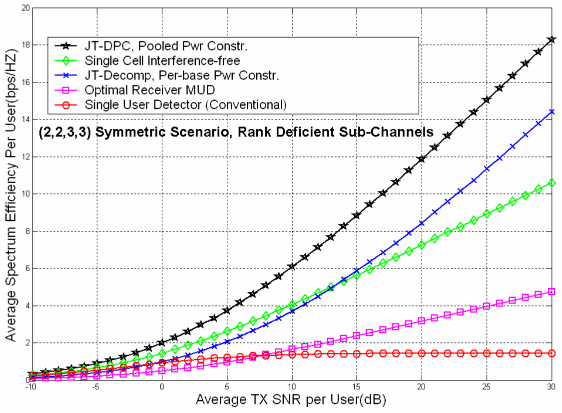

Figure 3. Spectral Efficiencies for Rank Deficient Channels

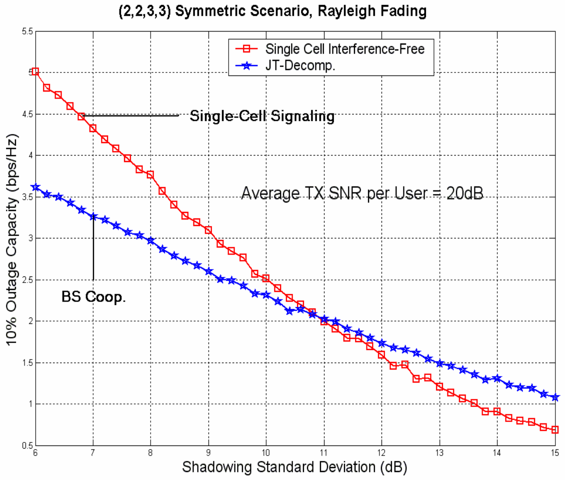

Figure 4. 10% Outage Spectral Efficiencies for Rayleigh Fading Channels with Shadowing

IV. BS SELECTION

Note that almost all the previous studies on JT schemes, such as those in [6][9], ignored the issues of asynchronous receptions for the purpose of tractable analysis. In our study, we assume that the cooperative base stations can pre-compensate different delays in $\mathbf{x}_j$, which results in its synchronous reception at MS *j*. The synchronization among different base stations is possible through, e.g., GPS devices. However, for some scenarios involving fast fading and/or high mobility, the pre-compensation may require too much system resource. On the other hand, the per-base power constraint issue for JT schemes may also induce some problems. As discussed above, the iterative multistage numerical power allocation methods proposed in [6][7][8] are quite complex and impractical. Furthermore, a good performance of our proposed suboptimal power allocation algorithm requires that the values of $\left\|\mathbf{G}^{[b]}\right\|_F$ in (14) are 'symmetric' enough for different base stations, otherwise, too much power will be discarded for the base stations other than the BS with the minimum value in (14). In reality, the randomness of MS positions (the path loss) and shadow fading may result in unbalanced values in $\left\|\mathbf{G}^{[b]}\right\|_F$ for different BS's, so the performance of JT schemes involving the per-base power constraint may be degraded in some adverse environments.

If we select only one BS to transmit all the signals of the co-channel MS's located around the cell borders, both the synchronization problem and the per-base power constraint problem encountered in JT schemes will disappear. Besides, in a point-to-point MIMO scenario, transmit antenna selection schemes can be used to replace the joint transmission among all the candidate transmit antennas [12], and some of the advantages of joint processing can be preserved, such as the diversity, with a reasonable performance penalty. Similarly, in our scenario, the advantages achieved by JT schemes among cooperative BS's, can be partly preserved in BS selection schemes. Specifically, since the signals for all the MS's are transmitted from one BS, the interference can be actively controlled by the pre-processing in the selected BS; secondly, the BS selection for sum capacity maximization tends to select a BS whose associated channel matrices have good rank and conditioning properties; for the same reason, macrodiversity is automatically achieved by the selection, which is obvious at low SNR; finally, the channel power gain in JT schemes becomes the selection gain (also obvious at low SNR), which is similar to the coding gain achieved by antenna selection. However, compared with JT schemes, the price paid for BS selection is the reduction of the total transmit power, to the power constraint of the single selected BS. Therefore, the performance of BS selection scheme is a joint effect of the above factors. Also, some system resource is dedicated for implementing the BS selection algorithm, just as antenna selection problems.

For simplicity, in this paper we only consider the optimal BS selection algorithm, which selects one BS with the largest sum capacity, when it transmits the signals for all the co-channel users using DPC. Other suboptimal selection rules with simpler transmitters (e.g. linear pre-coding schemes), which may find their counterparts in the antenna selection literature, is of our interest for future work. Therefore, the performance presented in this paper represents an upper bound of practical schemes.

To compare the performance of BS selection with JT scheme and with single cell signaling schemes, we simulate the same (2,2,3,3) scenario as in Section III, except that the symmetric assumption is replaced by realistic path loss and shadow fading models. Specifically, suppose in Figure 1, the radius of each cell is 1000m, and all the three MS's are randomly located within 200m around the point A (far users with strong CCI). In (1), the large scale fading factor is $a_{b,j}^2 = PL_{b,j}S_{b,j}$, which is composed of path loss $PL_{b,j}$ with an propagation exponential of 3.7, and of the shadow fading $S_{b,j}$ with a standard deviation of $\sigma = 8dB$. Also, a more practical small-scale fading channel model with transmit fading correlation is considered, because in a typical outdoor urban scenario, antenna arrays at the base stations are elevated above urban clusters and far away from local scattering, while mobile terminals are surrounded by rich scatterers, and the number of independent paths is limited by few far-field reflectors. Therefore, the downlink small-scale fading channel matrix for one BS-MS pair with co-located transmit array can be modeled as

$$\mathbf{H} = c\mathbf{H}_w\mathbf{A}_t^H, \tag{17}$$

where $\mathbf{A}_t$ collects the dominant transmit array response vectors, $\mathbf{H}_w$ is a normalized white Gaussian matrix, and *c* is the normalization factor. In this case, the channel matrix may be both rank-deficient and ill-conditioned, determined by the propagation and system parameters. In the simulation, we assume that there are 10 major paths from each BS to far-field reflectors, with angles of departure uniformly distributed in the range of $(0^o, 30^0)$. Again, per-base power constraint is used for JT-Decomp. with $P_{B\_b} = P$, and the power constrain on the selected BS is also *P*.

The results are shown in Figure 5. We can see that the single-cell signaling schemes will degrade significantly (cf. Figure 2) because of the newly introduced path loss, shadow fading model, and the poor channel conditioning. JT-Decomp. is also degraded, which is mainly caused by the unbalanced power allocation on different base stations, as discussed above. The proposed BS selection scheme achieves relatively good performance. Over a wide range (from low to intermediate) of SNR, it even outperforms the single cell interference-free upper bound, because of the macrodiversity and power gain achieved by the selection. At high SNR, although it is worse than the interference-free upper bound, the BS selection scheme still achieves good performance compared with JT-Decomp. and optimal receiver MUD. Note that JT-Decomp. outperforms the BS selection only at very high SNR, which is out of the scope under our considerations. More importantly, as discussed above, the good performance of BS selection in this realistic scenario is achieved without the penalty on synchronization and per-base power constraint problems.

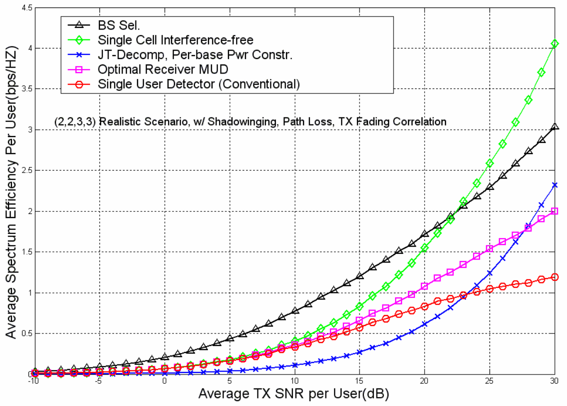

Figure 5. Spectral Efficiencies for a Realistic Scenario

V. CONCLUSIONS

In this paper, cooperative processing schemes, including joint transmission and BS selection, at multicell base stations, are introduced to address problems inherent on the downlink of cellular multiuser MIMO communications. In particular, the capability for co-channel interference cancellation, power gain, channel rank/conditioning advantage, and macro-diversity protection of BS cooperation are illustrated and verified. Although these advantages may not be achieved simultaneously and may compete with each other, there is still an optimistic prediction on overall system performance improvement, which reveals the great potential of base station cooperative processing on meeting the ever-increasing capacity demands for wireless communications. Although great performance improvements can be achieved by JT schemes, in certain adverse environments they also encounter some problems, including synchronization and unbalanced per-base power allocations, which can be solved by BS selection.

To summarize, our analysis in general provides an upper bound for the achievable performance with BS cooperation, which defines a common benchmark to gauge the efficiency of any practical schemes. Clearly the system performance is improved at the cost of significant system overhead related to CSI feedback and information exchange, which should be carefully justified in specific scenarios.

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