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Base Station Cooperation in MIMO-Aided Multi-User Multi-Cell Systems Employing Distributed Probabilistic Data Association Based Soft Reception

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***Abstract*—Inter-cell co-channel interference (CCI) mitigation is investigated in the context of cellular systems relying on dense frequency reuse. A distributed Base Station (BS) cooperation aided soft reception scheme using the Probabilistic Data Association (PDA) algorithm and Soft Combining (SC) is proposed for the uplink of multi-user multi-cell MIMO systems. The realistic hexagonal cellular model relying on unity Frequency Reuse (FR) is considered, where both the BSs and the Mobile Stations (MSs) are equipped with multiple antennas. Local cooperation based message passing is used instead of a global message passing chain for the sake of reducing the backhaul traffic. The PDA algorithm is employed as a low complexity solution for producing soft information, which facilitates the employment of SC at the individual BSs in order to generate the final soft decision metric. Our simulations and analysis demonstrate that despite its low additional complexity and backhaul traffic, the proposed distributed PDA-aided reception scheme significantly outperforms the conventional non-cooperative bench markers.**

***Index Terms*—Distributed processing, base station cooperation, co-channel interference, soft combining, probabilistic data association.**

I. Introduction

SPECTRALLY efficient techniques, such as Multiple-Input Multiple-Output (MIMO) antennas and near-unity Frequency Reuse (FR) are expected to be employed in the next-generation cellular networks. In this context, the achievable performance gain of multi-user multi-cell MIMO systems is predominantly limited by the inter-cell Co-Channel Interference (CCI) [1]. Recently, advanced receiver techniques using Base Station (BS) cooperation for exploiting the potential capacity of cellular systems were investigated [2]-[4]. The simplest conceptual approach to BS cooperation is to assume that there is a Central Processing Unit (CPU), which coordinates the operation of all BSs [2]. However, the CPU constitutes a single point of potential failure, thus the entire network is vulnerable. Additionally, since the complexity of Multi-User Detection (MUD) is dominated by the number of users, having a CPU imposes a potentially excessive computational burden and huge backhaul traffic, thus may become less attractive.

A distributed implementation of the iterative interference cancellation framework used in [2] was then developed for single-antenna aided multi-user systems in [3]. Altough this scheme was shown to strike an attractive compromise, it has an exponentially increased computational complexity imposed by the computation of the soft information using the max-log Maximum *A Posteriori* (MAP) algorithm. Furthermore, the multiple rounds of iterative message exchange operations between the cooperative BSs may still impose a potentially excessive backhaul traffic. The Belief Propagation (BP) algorithm was also applied to the problem of distributed detection in the single-antenna aided two-dimensional Wyner model [4], which performs a chain-like message passing between all the BSs and provides a globally near-optimum solution. However, it relies on network-wide optimum information exchange, which unfortunately results in a potentially excessive backhaul traffic and latency, especially for a star-like architecture routinely used for interconnecting the BSs [3].

The Probabilistic Data Association (PDA) method, which was originally proposed for target tracking [5], may also be developed into a reduced-complexity design alternative for the MAP algorithm [6][7]. The PDA technique may be regarded as a promising detection technique owing to its attractive properties. Firstly, it may achieve a near-optimal MUD performance, especially in the context of Code Division Multiple Access (CDMA) systems [6]. Secondly, it has a polynomial complexity, increasing no faster than $O\left(L^3\right)$, where L is either the number of transmit antennas in MIMO systems or the number of users in CDMA [6]. Furthermore, the higher the number of transmit antennas or users, the better the attainable performance, provided that the channel is not rank-deficient [8].

In this paper we further develop the PDA algorithm into a distributed multi-user soft-reception scheme to support BS cooperation. A realistic 19-cell hexagonal cellular MIMO-aided network model relying on either perfect or imperfect channel estimation is considered. In this model, the entire channel consists of multiple *matrix sub-channels*, rather than of *scalar sub-channels*, as in [2]-[4]. A simple but effective Soft Combining (SC) technique is used at each BS to generate the final soft-decision information, which indicates that the fundamental philosophy of the proposed method is not “interference cancellation” but “knowledge sharing and data fusion”. Despite its significant performance gain over the conventional non-cooperative MUD schemes, the proposed approach imposes a low complexity and low backhaul traffic on BS cooperation, as a benefit of the PDA’s rapid convergence, because only the converged soft-information is exchanged for one round between the BSs of the specific cooperative BS-cluster considered.

II. Hexagonal Cellular Network Model

Consider a hexagonal cellular network model, where both the BSs and MSs are equipped with multiple antennas. Therefore, instead of having a point-to-point Channel Impulse

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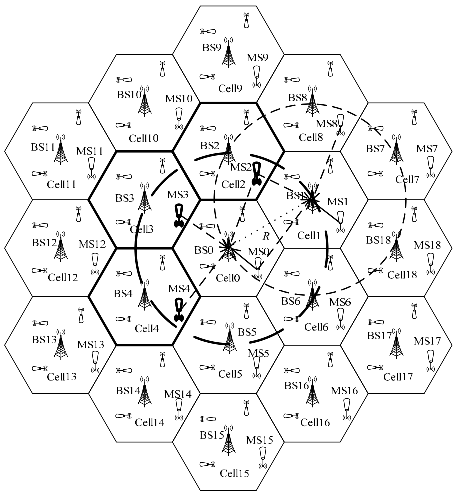

Fig. 1. Hexagonal cellular model with CCI and unity frequency reuse.

Response (CIR) between each BS and MS [3][4], we have a CIR matrix, where the interference imposed on each MS stems not only from other MSs, but also from their own multiple antennas. A unity FR is employed for all the cells and an orthogonal multiple access technique may be applied. Therefore, the intra-cell interference is assumed to be negligible, while the CCI imposed by MSs of the interfering cells is dominant.

Let us consider the topology shown in Fig. 1 as an example, which constitutes a *snapshot* of the dynamic network. Assume that there are N_b BSs and N_u MSs in this network (for the sake of comparability with classic cellular networks, N_b is set to 19 in Fig. 1), and K_i MSs in each cell, $i = 1, 2, \cdots, N_b$. For simplicity of analysis we assume that each BS and MS is equipped with M_b and M_u antennas, respectively. The position of each network entity is represented by its *dynamically updated polar coordinates* with respect to the specific *serving* BS. This dynamic coordinate system naturally lends itself to distributed processing. For example, if the central cell (Cell0) of Fig. 1 is considered, the point at BS0 may be defined as the origin and the BS in the upper-right adjacent cell of Cell0 may be described as BS1=$(R, \pi/6)$, where R is the distance between two immediate neighbor BSs.

For simplicity of conceptual illustration, we assume that the same frequency slot is assigned to the MSs situated at the same relative position in their corresponding home cell in Fig. 1. For example, MS0, MS1, MS2, $\cdots$, MS18 in the lower-right corner of each cell are all the co-channel users. When invoking dynamic frequency allocation, *not all* the co-channel users but only those located within the *Detectable Range (DR)* of a specific BS are considered to be interfering with the desired user. Hence the number of *effective* interferers with respect to each user may be different. For instance, when the signal of MS0 is expected to be detected by its home BS, namely by BS0, only MS2, MS3 and MS4, which are emphasized as bold, are the effective interferers. By contrast, the other co-channel users, such as MS1, MS5 and MS6 are not deemed to be effective interferers, since they are outside the disk centered at BS0 and having a radius of R. More explicitly, they are outside the DR of BS0. For MS7, MS10, and MS11, however, the number of interferers is two, one and zero, respectively, although they are all at the boundary of the network. On the other hand, the signal of MS0 may also be adequately received at BS1, BS5 and BS6, which therefore have the potential to act as the serving BSs of MS0. Similarly, the number of adjacent BSs supporting each MS may be different as well. We assume in general that for each served MS there are C_u such effective co-channel MSs and C_b adjacent serving BSs, respectively. Then the four-tuple (M_b, M_u, C_b, C_u) may be used to represent the cooperating BS-cluster, which is dynamically changing for the different served MSs.

III. Cooperative Distributed Soft Reception

A. Signal Model

Based on the hexagonal topology of Fig. 1, we consider an idealized synchronous uplink where the signal received at BSk is modeled as

$$\mathbf{y}^k = \mathbf{H}_k^k \mathbf{x}^k + \sum_{\alpha_i \neq k} \mathbf{H}_{\alpha_i}^k \mathbf{x}^{\alpha_i} + \mathbf{n}^k = \mathbf{H}_k^k \mathbf{x}^k + \mathbf{N}^k + \mathbf{n}^k, \quad (1)$$

where $\mathbf{x}^{\alpha_i}$ is the length-M_u vector of symbols transmitted from MSα_i in Cellα_i, and each symbol is from the constellation $\mathcal{A} = \{a_1, a_2, \cdots, a_M\}$. Still refering to Eq. (1), $\mathbf{H}_{\alpha_i}^k$ is the $(M_b \times M_u)$-element channel matrix between MSα_i and BSk, $i = 1, 2, \cdots, C_u$, $k = 1, 2, \cdots, N_b$, while $\mathbf{n}^k$ is the length-M_b complex-valued circular symmetric Gaussian noise vector with zero mean and covariance matrix $N_0 \mathbf{I}_{M_b}$ at BSk, where $\mathbf{I}_{M_b}$ is an $(M_b \times M_b)$-element identity matrix.

Let us now define the interference intensity as the channel gain ratio of the interfering users over that of the local desired user, namely as $\rho_{\alpha_i}^k = \left\|\mathbf{H}_{\alpha_i}^k\right\|_F / \left\|\mathbf{H}_k^k\right\|_F$, $0 \leq \rho_{\alpha_i}^k \leq 1$, where $\|\cdot\|_F$ represents the Frobenius norm of a matrix.

As opposed to conventional non-cooperative detection, the distributed detection of $\mathbf{x}^k$ carried out with the aid of BS cooperation detects the desired user's signal not only in the local cell, but rather jointly detects all the co-channel users' signals over-heard from the neighboring cells. More explicitly, the co-channel users' signals are no longer considered as detrimental interference, we rather consider these co-channel users' soft decision information as useful source of further information to be exploited by cooperative processing via message passing amongst the BSs. To this end, Eq. (1) may be reformulated as a distributed MIMO model, where the cooperating BSs may be viewed as MIMO elements, yielding

$$\mathbf{y}^k = \mathbf{G}^k \mathbf{s}^k + \mathbf{n}^k, \quad (2)$$

where we have $\mathbf{G}^k = \left[\mathbf{H}_k^k, \mathbf{H}_{\alpha_1}^k, \cdots, \mathbf{H}_{\alpha_{C_u}}^k\right]$, $\mathbf{s}^k = \left[(\mathbf{x}^k)^T, (\mathbf{x}^{\alpha_1})^T, \cdots, (\mathbf{x}^{\alpha_{C_u}})^T\right]^T$ and the elements of $\mathbf{s}^k$ are denoted as s_t^k, $t = 1, 2, \cdots, M_u\,(C_u + 1)$. For the sake of generality, the constraint of $M_u\,(C_u + 1) \leq M_b$ is not imposed here.

In the case of *imperfect* channel knowledge, the estimated channel matrix $\hat{\mathbf{H}}_k^k$ and $\hat{\mathbf{H}}_{\alpha_i}^k$ associated with the channel-estimation error matrices $\mathbf{E}_k$ and $\mathbf{E}_{\alpha_i}$ may be deemed to obey the Gaussian distribution of $\mathcal{CN}\,(0, 1,)$. They can be written as $\hat{\mathbf{H}}_k^k = \beta_k \mathbf{H}_k^k + \sqrt{1 - \beta_k^2}\mathbf{E}_k$ and $\hat{\mathbf{H}}_{\alpha_i}^k = \beta_{\alpha_i} \mathbf{H}_{\alpha_i}^k + \sqrt{1 - \beta_{\alpha_i}^2}\mathbf{E}_{\alpha_i}$, respectively [9], where β_k and β_{α_i} indicate the channel estimation quality and may be assumed to be close to 1, but not higher than 1. Thus the received signal models of Eq. (1) and Eq. (2) may be rewritten as $\mathbf{y}^k = \hat{\mathbf{H}}_k^k \mathbf{x}^k + \sum\limits_{\alpha_i \neq k} \hat{\mathbf{H}}_{\alpha_i}^k \mathbf{x}^{\alpha_i} + \mathbf{n}^k$ and $\mathbf{y}^k = \hat{\mathbf{G}}^k \mathbf{s}^k + \mathbf{n}^k$, respectively, where we have $\hat{\mathbf{G}}^k = \left[\hat{\mathbf{H}}_k^k, \hat{\mathbf{H}}_{\alpha_1}^k, \cdots, \hat{\mathbf{H}}_{\alpha_{C_u}}^k\right]$, or $\hat{\mathbf{G}}_k = \bar{\beta}_k \mathbf{G} + \sqrt{1-\bar{\beta}_k^2}\bar{\mathbf{E}}_k$ with $\bar{\beta}_k$ and $\bar{\mathbf{E}}_k$ being the composite-channel estimation error indicators. Note that when β_k=β_{α_i}=1, the signal model under imperfect CSI transforms into that of perfect CSI. Below we will continue by considering perfect channel estimation, while presenting the proposed soft reception algorithm. The case of imperfect channel knowledge may be readily considered by the substitution of the corresponding perfect channels with the estimated channels.

B. Parallel Detection Using the PDA Algorithm

The first action of the distributed soft reception scheme is that the BSs perform parallel detection employing the PDA algorithm as a low complexity solution, in order to estimate the *A Posteriori* Probability (APP) of each transmitted symbol without an exhaustive search in the space of all possible symbol combinations. Each BS jointly detects the signals of multiple users, including both the local user and other cells' users roaming close to this BS, which would be termed as interfering users in conventional non-cooperative systems. For ease of exposition, we consider detection at BS*k* as an example and omit the BS index k in our forthcoming exposition.

i) When we have $M_u\left(C_u+1\right) \leq M_b$, Eq. (2) may be further formulated as the decorrelated model

$$\tilde{\mathbf{y}} = \mathbf{s} + \tilde{\mathbf{n}} = s_t\mathbf{e}_t + \sum_{l\neq t} s_l\mathbf{e}_l + \tilde{\mathbf{n}} \triangleq s_t\mathbf{e}_t + \mathbf{v}_t, \quad (3)$$

where $\tilde{\mathbf{y}} = \left(\mathbf{G}^H\mathbf{G}\right)^{-1}\mathbf{G}^H\mathbf{y}$, $\tilde{\mathbf{n}}$ is a colored Gaussian noise with a zero mean and covariance of $N_0\left(\mathbf{G}^H\mathbf{G}\right)^{-1}$, $\mathbf{e}_l$ is a column vector with 1 in the l-th position and 0 elsewhere, and $\mathbf{v}_t$ denotes the interference plus noise term for symbol s_t, for t, $l = 1, 2, \cdots, M_u\left(C_u+1\right)$. For each symbol s_t, we have a probability vector $\mathbf{P}(t)$ whose m-th element $P_m(s_t|\mathbf{y})$ is the current estimate of the APP of having $s_t = a_m$, where $m = 1, 2, \cdots, M$, with a_m being the m-th element of the modulation constellation $\mathcal{A}$. The key philosophy of the PDA algorithm is to approximate $\mathbf{v}_t$ obeying the Gaussian mixture distribution as a single multivariate colored Gaussian distributed random vector with a mean of $\mathrm{E}\left(\mathbf{v}_t\right) = \sum_{l\neq t}\bar{s}_l\mathbf{e}_l$, covariance of $\mathrm{V}\left(\mathbf{v}_t\right) = \sum_{l\neq t}\mathrm{V}\left\{s_l\right\}\mathbf{e}_l\mathbf{e}_l^T + N_0\left(\mathbf{G}^H\mathbf{G}\right)^{-1}$, and pseudo-covariance of $\mathrm{U}\left(\mathbf{v}_t\right) = \sum_{l\neq t}\mathrm{U}\left\{s_l\right\}\mathbf{e}_l\mathbf{e}_l^T$, where

$$\bar{s}_l = \sum_{m=1}^{M} a_m P_m(s_l|\mathbf{y}), \quad (4)$$

$$\mathrm{V}\left\{s_l\right\} = \sum_{m=1}^{M} (a_m - \bar{s}_l)(a_m - \bar{s}_l)^* P_m(s_l|\mathbf{y}), \quad (5)$$

$$\mathrm{U}\left\{s_l\right\} = \sum_{m=1}^{M} (a_m - \bar{s}_l)(a_m - \bar{s}_l)^T P_m(s_l|\mathbf{y}). \quad (6)$$

Here $P_m(s_l|\mathbf{y})$ is initialized as a uniform distribution and will be replaced with an updated probability at each iteration of the PDA algorithm. Let $\mathbf{w}_m^{(t)} = \tilde{\mathbf{y}} - a_m^{(t)}\mathbf{e}_t - \sum_{l\neq t}\bar{s}_l\mathbf{e}_l$, and

$$\varphi_m(s_t) \triangleq \exp\left(-\left(\begin{array}{c}\Re(\mathbf{w}_m^{(t)})\\ \Im(\mathbf{w}_m^{(t)})\end{array}\right)^T \mathbf{\Lambda}_t^{-1}\left(\begin{array}{c}\Re(\mathbf{w}_m^{(t)})\\ \Im(\mathbf{w}_m^{(t)})\end{array}\right)\right), \quad (7)$$

where we have

$$\mathbf{\Lambda}_t \triangleq \left(\begin{array}{cc}\Re\left(\mathrm{V}\left(\mathbf{v}_t\right)+\mathrm{U}\left(\mathbf{v}_t\right)\right) & -\Im\left(\mathrm{V}\left(\mathbf{v}_t\right)-\mathrm{U}\left(\mathbf{v}_t\right)\right)\\ \Im\left(\mathrm{V}\left(\mathbf{v}_t\right)+\mathrm{U}\left(\mathbf{v}_t\right)\right) & \Re\left(\mathrm{V}\left(\mathbf{v}_t\right)-\mathrm{U}\left(\mathbf{v}_t\right)\right)\end{array}\right), \quad (8)$$

while $a_m^{(t)}$ indicates that a_m is assigned to s_t, and $\Re(\cdot)$ as well as $\Im(\cdot)$ represent the real and imaginary part of a complex variable, respectively.

Since it is assumed that the transmitted symbols have equal *a priori* probabilities, the APP of s_t is given as

$$P_m(s_t|\mathbf{y}) = \frac{p_m(\mathbf{y}|s_t)P(s_t = a_m)}{\sum_{m=1}^{M} p_m(\mathbf{y}|s_t)P(s_t = a_m)} \approx \frac{\varphi_m(s_t)}{\sum_{m=1}^{M}\varphi_m(s_t)}. \quad (9)$$

In summary, the algorithm proceeds as follows.

1) Initialization: set the initial values of the symbol probabilities $P_m(s_t|\mathbf{y})$ using a uniform distribution for $\forall t = 1, 2, \cdots, M_u\left(C_u+1\right)$, $\forall m = 1, 2, \cdots, M$, i.e. $P_m(s_t|\mathbf{y}) = 1/M$; set the iteration counter to $z = 1$.

2) Set the symbol index to $t = 1$.

3) Based on the current values of $\{\mathbf{P}(l)\}_{l\neq t}$, compute $P_m(s_t|\mathbf{y})$ via Eq. (4) $\sim$ Eq. (9), which will replace the corresponding elements of $\mathbf{P}(t)$.

4) If $t < M_u\left(C_u+1\right)$, let $t = t+1$ and go to step 3). Otherwise, go to step 5).

5) If $\mathbf{P}(t)$ has converged, $\forall t$, or the iteration index has reached its maximum, terminate the iteration. Otherwise, let $z = z+1$ and return to step 2).

ii) When we have $M_u\left(C_u+1\right) > M_b$, the appropriately modified version of the PDA method [10] may be applied to the current problem. Alternatively, the non-decorrelated signal model of [8] may be applied, yielding an equivalent performance to that of the decorrelated signal model based PDA [11]. In the case of the non-decorrelated model, Eq. (2) may be expanded as

$$\mathbf{y} = \mathbf{g}_t s_t + \sum_{l\neq t}\mathbf{g}_l s_l + \mathbf{n} \triangleq \mathbf{g}_t s_t + \mathbf{u}_t, \quad (10)$$

where $\mathbf{g}_l$ is the l-th column of $\mathbf{G}^k$. Then the PDA algorithm is obtained using a similar derivation to that of its counterpart in case (i), as outlined throughout Eq. (4) $\sim$ Eq. (9).

C. Parallel Message Exchange via UCS Mode

The effective neighboring BSs incorporated in the same cooperative BS-cluster will then exchange their soft decision information produced by the PDA algorithm in parallel, assuming the presence of an idealized optical fibre backbone. The impairments of a realistic optical fibre were quantified in [12]. It is emphasized that each BS plays the role of both client and server. In other words, each BS operates in a UCS mode. As a server, it helps detect the signals of all co-channel users at all the cooperating cells, and then the soft decision information is sent to each user's home BS. This message passing action substantially benefits the signal detection process in neighboring cells. As a client, each BS receives multiple copies of soft decision information for its own desired user's signal. The exchange of soft information is carried out with the aid of BS cooperation. For example, BS0 estimates the APP of its own user MS0, and additionally forwards the APPs of MS2, MS3 and MS4 to the corresponding sites of BS2, BS3 and BS4, respectively. On the other hand, in order to aid the detection of MS0, the surrounding BS0, BS1, BS5 and BS6 output $P_m\left(s_t^0|\mathbf{y}^0\right)$, $P_m\left(s_t^0|\mathbf{y}^1\right)$, $P_m\left(s_t^0|\mathbf{y}^5\right)$,

$P_m\left(s_t^0|\mathbf{y}^6\right)$, respectively, and all these probabilities will be forwarded to BS0, namely to the home BS of MS0. Therefore, BS0, BS1, BS5 and BS6 assist in the detection of MS0.

D. Soft Combining (SC) and Final Decision

Based on the aggregated soft decision information, each BS individually performs SC of all the copies of its own desired user's soft information according to

$$P_m(s_t|\mathbf{y}_{coop}) = P_m(s_t|\mathbf{y}^k)\prod_{j=1}^{C_b} P_m(s_t|\mathbf{y}^{\beta_j}), \qquad (11)$$

where $\mathbf{y}_{coop}$ stands for the received signal used for BS cooperation, i.e. $\mathbf{y}^k$ and $\mathbf{y}^{\beta_j}$, $j = 1, \cdots, C_b$. $P_m(s_t|\mathbf{y}_{coop})$ represents the composite soft decision information[1]. Again, let us consider the detection of MS0's signal as an example, where the composite soft decision information is $P_m\left(s_t^0|\mathbf{y}_{coop}\right) = P_m\left(s_t^0|\mathbf{y}^0\right) P_m\left(s_t^0|\mathbf{y}^1\right) P_m\left(s_t^0|\mathbf{y}^5\right) P_m\left(s_t^0|\mathbf{y}^6\right)$. Note that for the sake of numerical stability, the soft information should be further normalized as

$$P_m\left(s_t|\mathbf{y}_{coop}\right)_{norm} = \frac{P_m\left(s_t|\mathbf{y}_{coop}\right)}{\sum\limits_m P_m\left(s_t|\mathbf{y}_{coop}\right)}. \qquad (12)$$

Finally, make a decision for each transmitted symbol s_t, yielding $\hat{s}_t = a_{m'}$ at each corresponding BS, where

$$m' = \arg\max_{d=1,2,\cdots,M} \left\{P_d(s_t|\mathbf{y}_{coop})_{norm}\right\}. \qquad (13)$$

E. Complexity Analysis

The proposed distributed soft reception scheme has a worst-case complexity at each BS per iteration, which is on the order of $O\left[\left(M_u\left(C_u+1\right)\right)^3\right]$, provided that the Sherman-Morrison-Woodbury formula is applied for the computation of $\mathbf{\Lambda}_t^{-1}$ [6]. No exhaustive network-wide information exchange is applied, since this would impose an excessive complexity. As a reduced-complexity alternative, the converged APPs are exchanged among the adjacent BSs in the cooperative BS-cluster only once, namely after the PDA detection was completed at each of the participating BSs. Hence both the complexity and the backhaul traffic imposed by the associated message exchange and SC remains modest. More explicitly, in the entire reception process of a symbol vector, only $C_u M$ messages are passed from each cooperating BS to the others. Furthermore, the SC requires only a few simple arithmetic operations, as seen in Eq. (11).

IV. Simulation Results

In this section, we characterize the achievable performance of the proposed distributed soft reception scheme using Monte Carlo (MC) simulations in the hexagonal cellular network of Fig. 1. QPSK modulation is used and the knowledge of the average equivalent SNR per receive antenna formulated as $\mathrm{SNR} \triangleq 10\log_{10}\left(E\left\{\|\mathbf{Gs}\|^2\right\}\Big/E\left\{\|\mathbf{n}\|^2\right\}\right)$ is exploited at each BS. Flat Rayleigh fading channels are considered, i.e. the entries of each sub-channel matrix between an MS and a BS are chosen as independent and identically distributed (i.i.d.), zero mean, unit-variance complex-valued Gaussian random variables. A new realization of each channel matrix is drawn for each data burst consisting of 1000 transmitted symbol vectors. Each element of the noise vector $\mathbf{n}^k$ is i.i.d. $\mathcal{CN}(0, N_0)$, and we set $M_u = 2$ and $M_b = 8$. Since the PDA algorithm typically converges within $3 \sim 5$ iterations [6], we set the maximum number of iterations to $I = 5$.

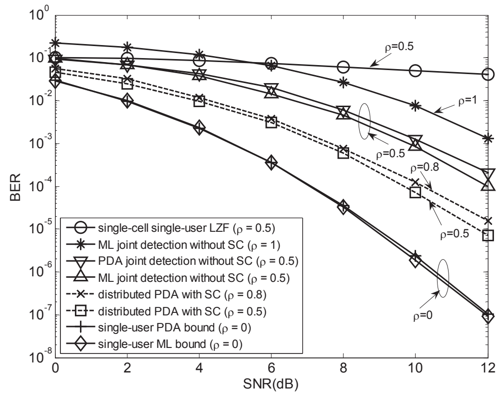

Fig. 2. Performance comparison of PDA and ML joint detection without SC, distributed PDA with SC, single-cell single-user LZF detector, single-user ML and PDA bounds, QPSK.

In the case of *perfect CSI*, Fig. 2 compares the Bit Error Ratio (BER) performance of eight different reception schemes, including the PDA and the ML single-user bounds recorded at BS0 for MS0. For simplicity, an identical interference intensity was assumed for the interfering MSs, where ρ represents $\rho_{\alpha_i}^k$. This is justified because all the MSs imposing interference on each of the desired MSs are situated in the neighboring cells and have similar distances from the desired MS's home BS.

The "single-cell single-user LZF" scenario refers to the Linear Zero Forcing (LZF) based SUD invoked at each BS, where the co-channel users' signals arriving from the other cells is simply treated as background noise. Naturally, this low-complexity SUD leads to a poor performance. The PDA and the ML joint detectors dispensing with SC refer to the joint detection of multiple co-channel MSs at each BS, where again, no SC is invoked and different ρ values are assumed in Eq. (2). The ML detector is implemented with the aid of a reduced-complexity sphere decoder [13], where the sphere radius is adaptively adjusted according to the prevalent SNR-level, in order to avoid a search failure. The PDA and the ML detectors do not share soft decision information with other cells, since no message exchange and no SC is used. Nonetheless, a substantial BER improvement is shown in comparison to the LZF SUD, especially when ρ is small.

The dashed curves represent the proposed distributed soft reception scheme operating under $\rho = 0.5$ and $\rho = 0.8$. We observe from Fig. 2 that a significant further BER improvement is achieved, which is attributed to the macro-diversity gain provided by joint cooperative BS processing. The PDA and the ML single-user bounds are obtained by setting $\rho = 0$, which implies that the CCI vanishes. This scenario is equivalent to a single-user (2×8)-element spatial multiplexing MIMO system. It is observed in Fig. 2 that the PDA bound is extremely close to the ML bound. The results recorded in Fig. 2 for different ρ values characterize the impact of ρ on the attainable reception performance. It may be concluded from Fig. 2 that the interference intensity ρ is the key factor limiting the achievable performance of cellular MIMO networks.

When considering the more practical *imperfect CSI* scenario, Fig. 3 evaluates the performance of the proposed dis-

[1]Equation (17) may also be interpreted as the sum of bit LLRs, where "multiplication" is converted to "addition" in the logarithmic domain.

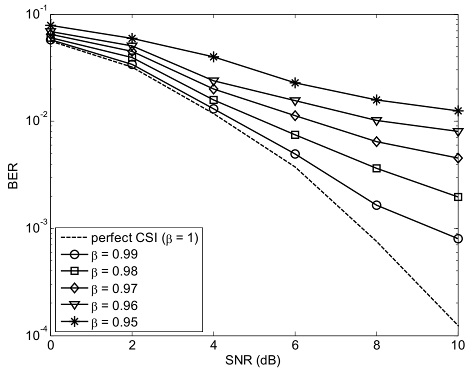

Fig. 3. Performance of distributed PDA in different levels of channel estimation quality, $\rho = 0.8$, QPSK.

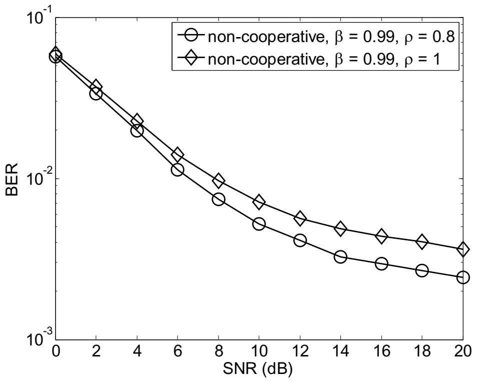

Fig. 4. Performance of non-cooperative PDA in different levels of interfering intensity and a given level of channel estimation quality $\beta = 0.99$, $M_b = 8, M_u = 2$, QPSK.

tributed soft reception scheme at different levels of channel estimation quality. Fig. 4 characterizes the performance of the non-cooperative PDA scheme, where the inter-cell CCI is regarded as noise at each BS under the assumption that we have $\beta = 0.99$ and an interference intensity of $\rho = 1$ or $\rho = 0.8$. It is observed in Fig. 4 that an error floor emerges in the high-SNR region, since the fixed level of interference plays a dominant role, when the SNR is high. Therefore, we observe by comparing the results of Fig. 3 and Fig. 4 that the distributed cooperative PDA is capable of mitigating the effects of the error floor imposed by imperfect CSI by exploiting that the interference becomes a useful source of increased signal energy as a benefit of the more sophisticated distributed PDA detector. Finally, in Fig. 5 we characterize the convergence performance of the proposed distributed PDA algorithm under imperfect CSI conditions. It may be observed in Fig. 5 that the distributed PDA converges in a few iterations, hence imposing a low complexity.

V. Conclusions

We proposed a distributed PDA based soft reception scheme for BS cooperation in the uplink of multi-user multi-cell MIMO systems. The realistic hexagonal cellular model relying on unity frequency reuse was considered. The distributed PDA based scheme was shown to converge in few iterations, hence it constitutes a low-complexity solution for jointly estimating the initial soft decision information at each BS. Each BS

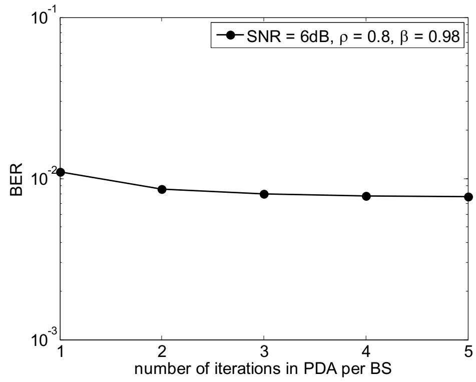

Fig. 5. Convergence property of distributed PDA with SC, SNR = 6dB, QPSK, $\beta = 0.98$, $\rho = 0.8$.

shares the MSs' soft information with the aid of their message exchange and generates the final soft decision information with the aid of SC. The simulation results as well as our complexity analysis demonstrate that the proposed scheme significantly outperforms the conventional non-cooperative schemes, while imposing a modest additional complexity and backhaul traffic. We also investigated the performance of the proposed distributed PDA in the more practical imperfect CSI scenario and demonstrated that the proposed soft reception scheme succeeds in mitigating the system's error floor.

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