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Coordination in a Multi-Cell Multi-Antenna Multi-User W-CDMA System: A Beamforming Approach

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***Abstract*—The problem of designing Joint Power Control and Optimal Beamforming (JPCOB) algorithms for the downlink of a coordinated multi-cell W-CDMA system is considered throughout this paper. In this case, the JPCOB design is formulated as the problem of minimizing the total transmitted power in the coordinated multi-cell system, subject to a certain quality of service requirement for each user. In this paper, the performance of two JPCOB algorithms based on different beamforming approaches is compared over the coordinated multi-cell system. The first one, obtains local beamformers by means of the well-known virtual uplink-downlink duality. In contrast, the second algorithm implements multi-base beamformers, taking into account match filter equalizers at the receivers. Moreover, realistic system parameters, such as per-base station power constraints or the asynchronous nature of the signals arriving at the receivers, are taken into account. Simulation results show that the algorithm based on multi-base beamforming presents attractive properties, such as an inherent multi-base scheduling technique or a decreasing total transmitted power as the degree of coordination between base stations is increased.**

***Index Terms*—Coordinated multi-cell system, downlink multi-base beamforming, multi-base scheduling techniques, joint power control and optimal beamforming algorithms.**

I. INTRODUCTION

COOPERATIVE schemes have recently been proposed as an effective solution to improve the performance of interference-limited wireless systems. Such cooperative schemes typically include the conventional relaying between user terminals, but may be extended to the downlink of multi-cell wireless networks, where different base stations (BSs) cooperate by means of joint resource allocation schemes [1].

Assuming that the BSs are connected via a high-speed backbone, a more advanced form of cooperation based on signal processing techniques is possible. Generally speaking, the antennas from different BSs can transmit coordinately and each user can receive useful signals from several BSs. Herein, this form of cooperation is referred in this paper as coordinated multi-cell system, but it has also been reported in the existing literature as: *joint transmission* [2], *network coordination* [3], *distributed antenna systems* [4] or *cooperative spatial multiplexing* [5]. From a different point of view, the downlink of a coordinated multi-cell system can be formulated as a spatially distributed multiple-input multiple-output (MIMO) downlink problem.

To the best of our knowledge, the earliest studies of the coordinated multi-cell systems are [6]–[8]. In [6], a scheme combining a LQ-decomposition of the channel matrix with dirty-paper coding (DPC) is applied under a sum power constraint, i.e., BSs are subject to an average system power constraint. In [7] and [8], more realistic per-base station power constraints are considered when implementing the DPC technique and therefore, complex iterative multistage methods are derived.

One of the main contributions to the performance analysis of coordinated multi-cell systems can be found in [2]. In this paper, both DPC with a sum power constraint and sub-optimal algorithms for designing multi-base beamformers with per-base station power constraints are analyzed. Moreover, other advantages of the coordinated transmission, such as channel rank improvement, are also addressed.

Some recent works focus on the design and performance analysis of several multi-base beamforming schemes [9]–[11]. From a fairness point of view, the LQ-DPC scheme of [6] is applied in [3] to the problem of maximizing the minimum rate achieved by the users, subject to per-base station power constraints. Finally, results for transmitter optimization with per-antenna power constraints, can also be extended to coordinated multi-cell systems with per-base station power constraints [12], [13].

Perfect channel knowledge at the BSs and the need for a high-speed backbone are some of the practical concerns dealing with coordinated multi-cell systems. Regarding the high-speed backbone, in a realistic setting it is possible to have a constraint in the amount of information that BSs can exchange through the backbone, and the performance of the system may degrade significantly [14].

In a coordinated multi-cell system, each user receives its desired and interference signals from the multiple BSs in an asynchronous manner. The references previously mentioned do not make any assumption about this topic. Only [2] assumes that BSs can compensate the signals prior to transmission with their respective delays and therefore, each user receives a coherent sum of its desired signals, whereas the interference terms remain asynchronous.

In this paper, the downlink of a coordinated multi-cell multi-user and multi-antenna wideband code division multiple access (W-CDMA) system is considered. Since this is an

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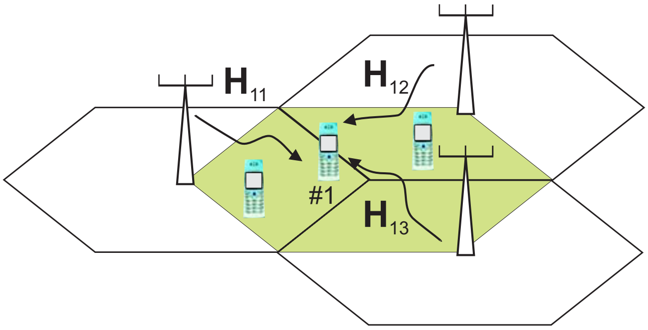

Fig. 1. Example of a three-cell coordinated multi-cell system.

interference-limited scenario, we are interested in the problem of designing Joint Power Control and Optimal Beamforming (JPCOB) algorithms. These algorithms may help the coordinated multi-cell system to overcome the interference and improve its performance in terms of capacity (the capacity is here represented as the number of admitted co-channel users).

The system model proposed in Section II is based on the one presented in [15] for MIMO systems. Within this linear framework, the JPCOB design is formulated as the problem of minimizing the total transmitted power in the coordinated multi-cell system subject to a certain quality of service (QoS) constraint for each user. In Section III, two iterative algorithms with per-base station power constraints are presented: a virtual uplink-based algorithm [16] and an alternative proposal that can be defined as a fully downlink algorithm, since it does not rely on the uplink-downlink duality. These algorithms share a common structure that reduces to a two-step iteration algorithm: first, beamformer optimization is performed and second, power updating is computed from a linear system of equations. The beamformer design step (local or multi-base) establishes the differences between the proposed algorithms.

Throughout the paper, we assume that perfect channel state information is available at the BSs. However, the BSs do not compensate the signals prior to transmission and due to the different propagation delays, each user in the system receives the desired and interference signals from the multiple BSs in an asynchronous manner.

The following notation is used: boldface upper-case letters denote matrices, boldface lower-case letters denote vectors and italics denote scalars. Superscripts $(\cdot)^T$, $(\cdot)^*$, $(\cdot)^H$ and $(\cdot)^\dagger$ denote the transpose, the conjugate, the conjugate transpose and the pseudo-inverse operations, respectively. By $\mathrm{diag}\{\mathbf{X}_k\}$ we indicate a block-diagonal matrix with blocks given by the set $\{\mathbf{X}_k\}$, whereas $\mathrm{vec}\{\cdot\}$ stands for the stacking vectorization operator. The Frobenius norm of a matrix is denoted by $\|\cdot\|_F$. $[\mathbf{X}]_{i,j}$ refers to the $(i,j)th$ element of $\mathbf{X}$ whereas $[\mathbf{x}]_k$ stands for the kth element of the vector $\mathbf{x}$. $\mathbf{e}_i$ denotes a zeros column vector with a one at the ith element, $\mathbf{1}_q$ denotes a $[q \times 1]$ all ones column vector and $\mathbf{I}_q$ represents the $[q \times q]$ identity matrix. Finally, $\otimes$ stands for the Kronecker product.

II. System Model

Consider a system with K multi-antenna BSs, equipped each one with N_t antennas, and M co-channel single-antenna users. In the coordinated scenario, users may receive their information signals from several BSs simultaneously (see Fig. 1).

Fig. 2 shows the block diagram of the described system. Let $\mathbf{a}$ be the $[M \times 1]$ vector containing the uncorrelated and normalized to unit power symbols, one per user, modulated and transmitted over the channels. Assuming linear receivers, and denoting by y_m the output of the mth receiver, for $m = 1, \ldots, M$, it can be stated that:

$$\underbrace{\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_M \end{bmatrix}}_{\mathbf{y}} = \mathbf{V}^H \mathbf{H}_{\mathrm{Rx}} \mathbf{H}_{\mathrm{Ch}} \mathbf{P} \mathbf{H}_{\mathrm{Tx}} \underbrace{\begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_M \end{bmatrix}}_{\mathbf{a}} + \mathbf{V}^H \mathbf{n}^0, \qquad (1)$$

where $\mathbf{H}_{\mathrm{Tx}}$ is a $[MKN_t \times M]$ block-diagonal matrix that includes the transmit beamformers $\mathbf{h}_{\mathrm{Tx}m}$, $\mathbf{P}$ is a $[MKN_t \times MKN_t]$ block-diagonal matrix that performs the power control, and $\mathbf{H}_{\mathrm{Ch}}$ is a $[M^2L \times MKN_t]$ matrix that contains the multi-path channels. Regarding reception, $\mathbf{H}_{\mathrm{Rx}}$ is a $[MQ \times M^2L]$ matrix that represents the filtering process over the received signals when a bank of Q correlators is used in each user receiver. After the correlation process, noise is added to the model, in such a way that $\mathbf{n}^0$ is the $[MQ \times 1]$ column vector denoting the concatenation of noise samples obtained at the correlator outputs (vectors $\mathbf{n}_m$ in Fig. 2). Finally, $[MQ \times M]$ matrix $\mathbf{V}$ includes all the equalizer taps applied at the correlator outputs.

Matrices $\mathbf{H}_{\mathrm{Tx}}$, $\mathbf{P}$, $\mathbf{H}_{\mathrm{Ch}}$, $\mathbf{H}_{\mathrm{Rx}}$ and $\mathbf{V}$ are split into M independent blocks closely related with each user. The inner structure is defined as (see Fig. 2):

$$\begin{aligned} \mathbf{H}_{\mathrm{Tx}} &= \mathrm{diag}\{[\mathbf{h}_{\mathrm{Tx}1}\mathbf{h}_{\mathrm{Tx}2}\ldots\mathbf{h}_{\mathrm{Tx}M}]\}, && (2)\\ \mathbf{P} &= \mathrm{diag}\{[\mathbf{P}_1\mathbf{P}_2\ldots\mathbf{P}_M]\}, && (3)\\ \mathbf{H}_{\mathrm{Ch}} &= [\mathbf{H}_{\mathrm{Ch}1}^T\mathbf{H}_{\mathrm{Ch}2}^T\ldots\mathbf{H}_{\mathrm{Ch}M}^T]^T, && (4)\\ \mathbf{H}_{\mathrm{Rx}} &= \mathrm{diag}\{[\mathbf{H}_{\mathrm{Rx}1}\mathbf{H}_{\mathrm{Rx}2}\ldots\mathbf{H}_{\mathrm{Rx}M}]\}, && (5)\\ \mathbf{V} &= \mathrm{diag}\{[\mathbf{v}_1\mathbf{v}_2\ldots\mathbf{v}_M]\}, && (6) \end{aligned}$$

where $\mathbf{P}_m$, $\mathbf{H}_{\mathrm{Ch}m}$, and $\mathbf{H}_{\mathrm{Rx}m}$ are, respectively, $[KN_t \times KN_t]$, $[ML \times MKN_t]$ and $[Q \times ML]$ matrices, whereas $\mathbf{h}_{\mathrm{Tx}m}$ and $\mathbf{v}_m$ are $[KN_t \times 1]$ and $[Q \times 1]$ vectors. It should be noted that $\mathbf{H}_{\mathrm{Ch}}$ is simply the stacking operation of sub-matrices $\mathbf{H}_{\mathrm{Ch}m}$.

Let us define the structure of the above sub-matrices and vectors. At the transmitter side, vector $\mathbf{h}_{\mathrm{Tx}m}$ contains the beamformers between each base station and a given user m:

$$\mathbf{h}_{\mathrm{Tx}m} = \mathrm{vec}\{[\underbrace{\mathbf{w}_{m1}}_{\mathrm{BS}_1}\ldots\underbrace{\mathbf{w}_{mK}}_{\mathrm{BS}_K}]\}, \qquad (7)$$

where $\mathbf{w}_{mk}$ is the $[N_t \times 1]$ transmit beamformer for the mth user and kth base station pair. Matrix $\mathbf{P}_m$ is a diagonal matrix with the per-base station root-squared transmit powers allocated to user m:

$$\mathbf{P}_m = \mathrm{diag}\left\{[\sqrt{p_{m1}}\ldots\sqrt{p_{mK}}]^T \otimes \mathbf{1}_{N_t}\right\}. \qquad (8)$$

The signal received by a given user m is the weighted sum (matrices $\mathbf{H}_{\mathrm{Tx}}$ and $\mathbf{P}$) of the vector symbol transmitted over the channel $\mathbf{H}_{\mathrm{Ch}_m}$:

$$\mathbf{H}_{\mathrm{Ch}m} = \mathbf{I}_M \otimes \mathbf{H}_{\mathrm{UE}_m}. \qquad (9)$$

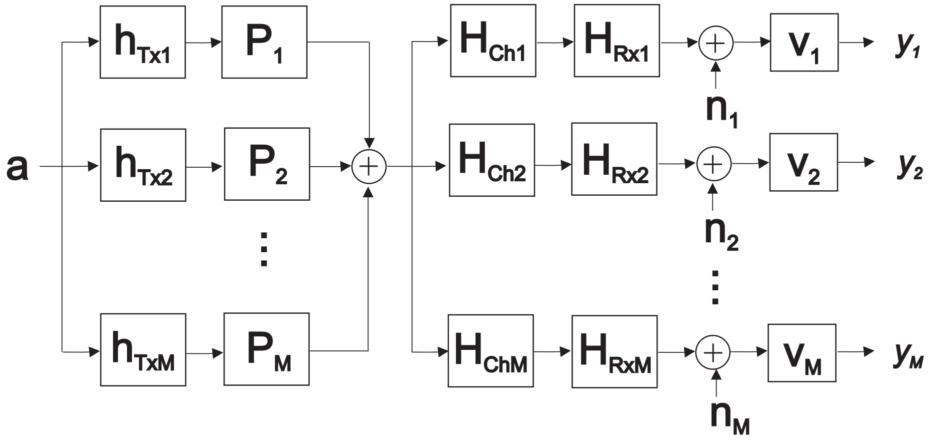

Fig. 2. Multi-Cell Multi-Antenna Multi-User downlink model for W-CDMA systems.

The $[L \times N_t]$ propagation channel for each base station-user pair, $\mathbf{H}_{mk}$, is modeled with a multi-path fading channel. Denoting by $L \cdot T_c$ the maximum propagation delay across the $K \cdot M \cdot N_t$ multi-path channels in the system, where T_c is the chip duration, and assuming that the symbol duration is longer than $L \cdot T_c$, inter-symbol interference can be ignored. Matrix $\mathbf{H}_{\mathrm{UE}m}$, with $[L \times KN_t]$ dimensions, contains the multi-path channels between the K BSs and the mth user, as depicted in Fig. 1:

$$\mathbf{H}_{\mathrm{UE}m} = [\mathbf{H}_{m1} \ldots \mathbf{H}_{mK}]. \tag{10}$$

The rows of matrices $\mathbf{H}_{mk}$, $k = 1, \ldots, K$, are defined by the different power delay profiles of each of the K multi-path channels received by user m.

Matrix $\mathbf{H}_{\mathrm{Rx}m}$ characterizes the processing carried out by the bank of correlators at the mth user receiver. For a given user m, desired and interference terms from the K BSs arrive in an asynchronous manner. Moreover, in W-CDMA multi-path channels cause the loss of orthogonality of the time-shifted versions of the spreading sequences. Therefore, matrix $\mathbf{H}_{\mathrm{Rx}m}$ includes the autocorrelation and cross-correlation values of the code set used in the system, as shown in [17], and its structure is defined as:

$$\mathbf{H}_{\mathrm{Rx}m} = [\mathbf{H}_{\mathrm{Rx}m1} \ldots \mathbf{H}_{\mathrm{Rx}mM}],$$

where the (q,l)th element of the $[Q \times L]$ matrix $\mathbf{H}_{\mathrm{Rx}mi}$, $i = 1, \ldots, M$, is defined as:

$$[\mathbf{H}_{\mathrm{Rx}mi}]_{q,l} = \frac{1}{N} \sum_{n=0}^{N-1} c_m^*(n) c_i(n-(q-l)). \tag{11}$$

N is defined as the number of chips of the code with maximum length among the M users active in the system. In the case of co-channel users, then $m = i$ in (11).

Finally, the output signal of the mth user can be expressed in matrix form as:

$$y_m = \mathbf{v}_m^H \mathbf{H}_{\mathrm{Rx}m} \mathbf{H}_{\mathrm{Ch}m} \mathbf{P} \mathbf{H}_{\mathrm{Tx}} \, \mathbf{a} + \mathbf{v}_m^H \mathbf{n}_m, \tag{12}$$

where vector $\mathbf{v}_m^H$ includes the equalizer taps belonging to user m.

III. ALGORITHMIC SOLUTIONS FOR MMSE BEAMFORMING

The JPCOB design is formulated as the problem of minimizing the total transmitted power in the coordinated multi-cell system subject to QoS constraints for each user. The QoS constraint is represented in this case by individual signal to interference plus noise ratio (SINR) constraints γ_m:

$$\begin{aligned} \min_{\mathbf{P}, \mathbf{H}_{\mathrm{Tx}}} \quad & \sum_{m=1}^{M} ||\mathbf{P}_m \mathbf{h}_{\mathrm{Tx}m}||^2, \\ \text{s.t.} \quad & \mathrm{SINR}_m(\mathbf{P}, \mathbf{H}_{\mathrm{Tx}}) \geq \gamma_m, \; m = 1, \ldots, M. \end{aligned} \tag{13}$$

This optimization problem has previously been solved for conventional non-coordinated multi-cell systems, where [18]–[20] are seen as the seminal references dealing with this topic. Other interesting extensions of these proposals can be found in [13], [15], [21], [22].

The JPCOB algorithm in [18] introduces the concept of virtual uplink in the transmit beamforming context. This virtual uplink allows to obtain local transmit beamformers for each base station from a simpler virtual uplink formulation. The proposed solution involves a two-step iteration: in a first step, the receive beamformers are obtained in the virtual uplink scenario, and in a second step, these vectors are used as transmit beamformers in order to update both virtual uplink and downlink powers.

In previous works, a extension of [18] is proposed for coordinated multi-cell systems [16]. This extension can be regarded as sub-optimal, since it follows the original local beamforming approach and BSs are only allowed to cooperate in the power updating step. On the other hand, it has been shown that in a coordinated scenario with perfect channel knowledge at the BSs, the application of multi-base beamforming schemes is a powerful tool for enhancing the system performance [9]–[11].

In this paper, an alternative solution to [16] is proposed by introducing a multi-base beamforming design. The downlink multi-base beamformer design is based on the MMSE criterion proposed in [23] for W-CDMA systems, where the multiuser interference is minimized using only spatial processing. This MMSE beamformer can be seen as the best choice for extending the local MMSE beamformer used in [16] to the multi-base case. In the text, this proposal is referred as a fully downlink algorithm, since the beamformer design does not rely on the uplink-downlink duality.

A. Virtual Uplink MMSE Beamformer (JPCOB-VUL)

In the virtual uplink-based algorithm, sub-optimal transmit beamformers are designed locally in each base station. For the mth user and kth base station pair, $\mathbf{w}_{mk}$ is designed to maximize the average virtual SINR received at the base station k from the user m, when the virtual uplink powers are fixed and a unit-variance noise is assumed in reception [16]:

$$\mathbf{w}_{mk} = \max_{\mathbf{H}_{\text{Tx}}} \text{SINR}_m^{\text{vu}}. \tag{14}$$

In W-CDMA systems, the duality between the virtual uplink and the downlink does not hold when the inter-finger interference is considered, unless some approximations are assumed [24], [25]. As a result, transmit beamforming design is here modified in such a way that only the paths with highest gains from each multi-path channel are included in (14). This way, the virtual uplink approach is still possible. See [16] for further details.

B. Downlink Multi-base MMSE Beamformer (JPCOB-DL)

Following [23], multi-base transmit beamformers can be obtained by minimizing a MMSE criterion as follows, see (1):

$$\begin{aligned}\mathbf{H}_{\text{Tx}}^{\text{MMSE}} &= \arg\min_{\mathbf{H}_{\text{Tx}}} E[\| \mathbf{a} - \mathbf{y} \|^2] \\ &= \arg\min_{\mathbf{H}_{\text{Tx}}} \| \mathbf{I}_M - \mathbf{H}\mathbf{H}_{\text{Tx}} \|_F^2,\end{aligned} \tag{15}$$

where $\mathbf{H} = \mathbf{V}^H \mathbf{H}_{\text{Rx}} \mathbf{H}_{\text{Ch}} \mathbf{P}$.

In this approach, a maximum ratio combining (MRC) equalizer is assumed at the receivers, in order to deal with the asynchronous reception of desired and interference terms. Without loss of generality, each of the Q correlators of the mth user is assumed to be synchronized with the highest gain path of each of the K multi-path channels ($Q \geq K$) (10). Vector $\mathbf{v}_m$ (6) stands for the MRC weights:

$$[\mathbf{v}_m]_q = [\mathbf{H}_{mk_q}]_{l_q,:} \mathbf{w}_{mk_q}, \ q = 1, \ldots, Q,$$

where k_q is the base station synchronized to the qth correlator, and $[\mathbf{H}_{mk_q}]_{l_q,:}$ stands for l_qth row of matrix $\mathbf{H}_{mk_q}$.

Applying the vec$\{\cdot\}$ operator to (15) and considering the general matrix equality $\text{vec}(\mathbf{ABC}) = (\mathbf{C}^T \otimes \mathbf{A})\text{vec}(\mathbf{B})$, it follows:

$$\mathbf{H}_{\text{Tx}}^{\text{MMSE}} = \arg\min_{\mathbf{H}_{\text{Tx}}} \| \text{vec}\{\mathbf{I}_M\} - (\mathbf{I}_M \otimes \mathbf{H}) \text{vec}\{\mathbf{H}_{\text{Tx}}\} \|_2^2 . \tag{16}$$

Following [23], and taken into account that $(\mathbf{I}_M \otimes \mathbf{H})$ is a block-diagonal matrix, the MMSE optimization problem can be divided into M independent optimization subproblems:

$$\begin{aligned}&\| \text{vec}\{\mathbf{I}_M\} - (\mathbf{I}_M \otimes \mathbf{H}) \text{vec}\{\mathbf{H}_{\text{Tx}}\} \|^2 \\ &\qquad = \sum_{m=1}^{M} \| \mathbf{e}_m - \mathbf{H}\mathbf{Q}_m \mathbf{h}_{\text{Tx}m} \|^2 .\end{aligned} \tag{17}$$

Matrices $\mathbf{Q}_m = [\mathbf{e}_m \otimes \mathbf{I}_{KN_t}]$, where $\mathbf{e}_m$ is a $[M \times 1]$ column vector, come from the vectorization:

$$\text{vec}\{\mathbf{H}_{\text{Tx}}\} = [(\mathbf{Q}_1 \mathbf{h}_{\text{Tx}1})^T \ldots (\mathbf{Q}_M \mathbf{h}_{\text{Tx}M})^T]^T.$$

Finally, the optimal multi-base beamformers are obtained from the least square solution:

$$\mathbf{h}_{\text{Tx}m}^{\text{MMSE}} = (\mathbf{H}\mathbf{Q}_m)^\dagger \mathbf{e}_m, \ m = 1, \ldots, M. \tag{18}$$

For the sake of simplicity, it should be noted that for the mth user, the product $\mathbf{H}\mathbf{Q}_m$ selects KN_t columns from $\mathbf{H}$, given by indices $(m-1)KN_t + 1$ to mKN_t.

IV. POWER CONTROL

Regarding the power updating, the virtual uplink-based algorithm and the downlink algorithm update the transmit powers in the same way, though the virtual uplink-based algorithm needs an additional updating of the virtual uplink powers (see [16]).

Returning to the output signal of mth user (12), signal of interest (SOI), inter-finger interference (IFI) and co-channel interference (CCI) terms can be identified by appropriately analyzing the expression.

It has been shown [18] that the minimum transmitted power of the optimization problem expressed by (13) is achieved when the SINR is equal to the target value:

$$\text{SINR}_m = \frac{E[|\text{SOI}_m|^2]}{E[|\text{IFI}_m|^2] + \sum_{i \neq m} E[|\text{CCI}_i|^2] + \sigma_n^2} = \gamma_m, \tag{19}$$

for $m = 1, \ldots, M$. Without loss of generality, an equal noise power term $\sigma_n^2 = E[|\mathbf{v}_m^H \mathbf{n}_m|^2]$ is assumed for the M users. Regarding (19), channel gains $\mathbf{H}_{mk}$ and $\mathbf{H}_{mk'}$ are assumed to be independent when $k \neq k'$ due to the large separation between BSs.

Note that in (19) all the transmitted powers for each base station-user pair are considered. In order to provide a compact expression for downlink power updating, (19) can be arranged in multi-user form as [16]:

$$\mathbf{D}\mathbf{p} = \mathbf{F}\mathbf{p} + \mathbf{u}, \tag{20}$$

where $\mathbf{p}$ is a $[KM \times 1]$ column vector defined by:

$$\mathbf{p} = [p_{11} \ldots p_{1K} \ldots p_{M1} \ldots p_{MK}]^T.$$

Matrix $\mathbf{D}$ is a $[M \times KM]$ block-diagonal matrix that includes the signal terms of the M users. Matrix $\mathbf{F}$ has dimensions $[M \times KM]$ and shows a particular partition of M sub-matrices $\mathbf{F}_i$. These sub-matrices include scaled values of the interference terms introduced by the transmission to each user. Finally, vector $\mathbf{u}$ is defined as $\mathbf{u} = \left[\gamma_1 \sigma_n^2 \ldots \gamma_M \sigma_n^2\right]^T$.

Returning to (20), its minimum norm solution by means of a Jacobi iterative method [26] may be expressed as (n_{it} denotes the iteration number):

$$\mathbf{p}(n_{it} + 1) = \mathbf{D}^\dagger (\mathbf{F}\mathbf{p}(n_{it}) + \mathbf{u}). \tag{21}$$

V. SIMULATION RESULTS

This Section presents results of Monte-Carlo simulations for the virtual uplink-based algorithm (JPCOB-VUL) of [16] and the proposed downlink algorithm (JPCOB-DL).

The main feature of extension [16] is the use of an *active set window* (ASW) parameter. The use of this parameter implies the arrangement of an *active set* (AS) of BSs for each user: only the BSs included in the AS transmit to a user (this technique is widely used in soft handover situations). For coordinated multi-cell systems, this technique can be seen as a centralized multi-base scheduling scheme (see [16] for further details).

It should be noted here that the objective of the AS technique is to evaluate the performance of JPCOB algorithms for different degrees of coordination between BSs, instead of optimizing the assignment of users to BSs in the coordinated scenario. Coordination degrees are defined by modifying ASW values. For example, an $\mathrm{ASW} = 0$ dB stands for the conventional single-base assignment. Moreover, it is straightforward to notice that for a given channel realization, each user in the system may have different number of BSs included in its active set. Recently, [27] also introduces distributed multi-base scheduling techniques with the objective of maximizing the sum capacity of the coordinated multi-cell system. This approach is somewhat different to the ASW, since each base station only schedules one user at full power.

A three-cell scenario for the coordinated multi-cell CDMA system is considered in the simulations (see Fig. 1): $K = 3$ BSs equipped with linear arrays of $N_t = 3$ antennas each are located at the center of the cells. In order to evaluate the system performance in a strong-interference scenario, M co-channel users are uniformly distributed over the shadowed area of Fig. 1.

For the sake of simplicity, a flat fading channel between each base station-user pair is simulated. However, due to the asynchronous nature of the signals, each user in the system *sees* a K multi-path channel, where each path experiences independent fadings. Downlink mk channels are generated following the model $\mathbf{h}_{mk} = \beta_p \beta_s \mathbf{g} \mathbf{R}_t^{1/2}$, where $\beta_p = r_{mk}^{-2}$ is the path loss for a distance r_{mk} between the mth user and the kth base station, β_s is the shadow fading, modeled as a random and log-normal variable with a standard deviation of 8 dB, and $\mathbf{g}$ is a $[1 \times N_t]$ vector with complex random independent and identically distributed elements ($\mathcal{CN}(0, 1)$). Matrix $\mathbf{R}_t$ defines the correlation between the antenna elements at each base station.

Wideband CDMA signals with a spreading factor of 32 are used and the per-base station power constraint is set to 43 dBm. Regarding the ASW, different values ranging from no coordination, 0 dB, and total coordination, 90 dB, are evaluated. SINR constraint values are set to 3, 7 and 12 dB after despreading. For each value of the ASW and for a given SINR constraint, the JPCOB-VUL and JPCOB-DL algorithms are simulated over 3000 independent runs. In each simulation, the algorithms have to achieve the required SINR in each user within a maximum of 30 iterations. It should be noted here that both algorithms do not detect infeasible scenarios. Hence, the feasibility of the algorithms for different SINR and ASW values is also addressed.

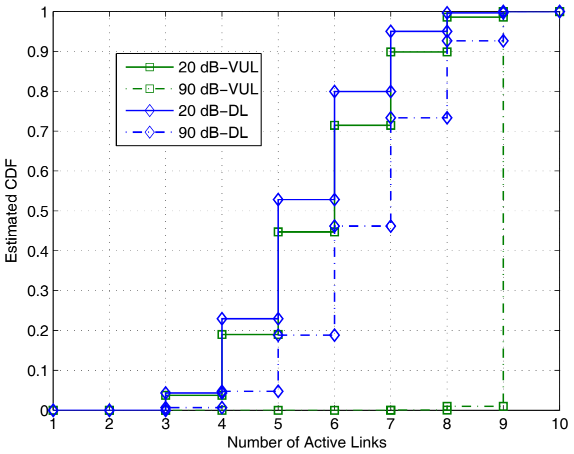

Fig. 3. CDF of the number of active $m \cdot k$ links for a QoS constraint of $\mathrm{SINR} = 7$ and $M = 3$ co-channel users active in the system.

1) Active links: Theoretically, JPCOB-VUL and JPCOB-DL algorithms should not influence the number of active links in the system, since the AS arrangement procedure only relies on the properties of the channels between each user and the K BSs. However, the analysis of the number of active links in the system reveals an attractive property of the JPCOB-DL algorithm: for a certain degree of coordination ($\mathrm{ASW} \geq 20$ dB), the JPCOB-DL algorithm automatically cancels links that were defined as *active* during the AS process.

Fig. 3 presents the cumulative distribution function (CDF) of the number of active $m \cdot k$ links in the system, for a configuration of $\mathrm{SINR} = 7$ and $M = 3$. In this case, the number of active links ranges between 3, ($\mathrm{ASW} = 0$ dB, no coordination), and 9, ($\mathrm{ASW} = 90$ dB, total coordination). For the sake of clarity, only $\mathrm{ASW} \geq 20$ dB plots are depicted.

2) Feasibility of the algorithms: It is well-known that the optimization problem (13) is feasible if and only if $\rho(\mathbf{D}^{\dagger}\mathbf{F}) \leq 1$, where $\rho(\cdot)$ denotes the spectral radius of a matrix [26]. In this paper, the optimization problem (13) is considered to be feasible when the above relation is fulfilled after convergence and the vector of per-user per-base station transmitted powers $\mathbf{p}$ is element-wise positive.

Fig. 4 shows the feasibility of the JPCOB-VUL when $M = 3$ co-channel users are active in the system ($N_t = M$). For this configuration, JPCOB-DL algorithm achieves total feasibility. As it was shown in [16], for low and medium SINR requirements, coordination between BSs can improve the feasibility of the algorithm.

Fig. 5 exhibits the effects on the feasibility of increasing the number of co-channel users to $M = 4$. JPCOB-VUL performance suffers a severe degradation for high SINR requirements. This can be explained as follows. JPCOB-VUL algorithm designs local beamformers. Since $N_t < M$, the beamformer has a limited performance. In addition, the per-base station power constraints restrict the available power to correct the beamforming mismatches.

3) Average total transmitted power: The average total transmitted power for the JPCOB-VUL and JPCOB-DL al-

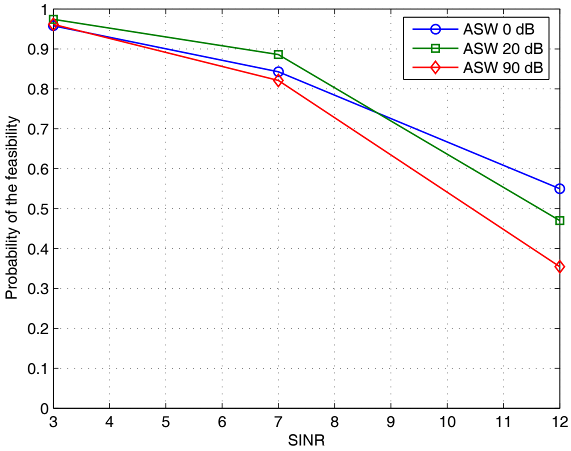

Fig. 4. Probability of the feasibility for the JPCOB-VUL algorithm when $M = 3$ co-channel users are active in the system.

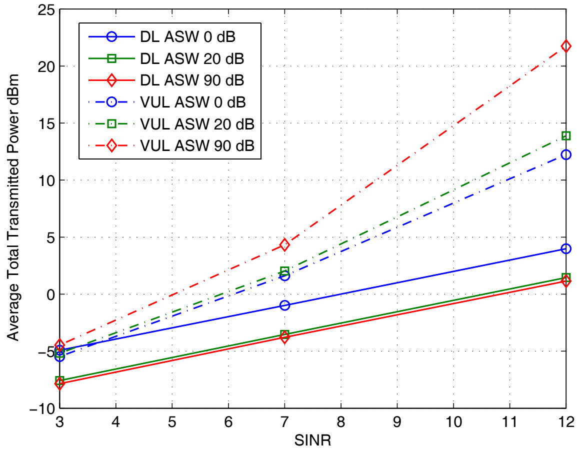

Fig. 6. Average total transmitted power (13) for the JPCOB-VUL and JPCOB-DL algorithms when $M = 4$ co-channel users are active in the system.

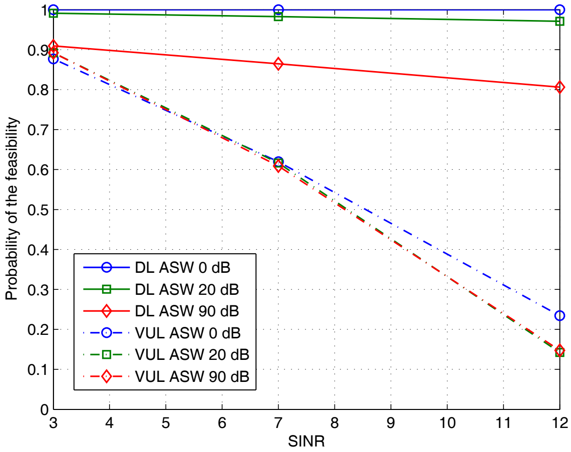

Fig. 5. Probability of the feasibility for the JPCOB-VUL and JPCOB-DL algorithms when $M = 4$ co-channel users are active in the system.

gorithms is shown in Fig. 6 for $M = 4$ co-channel users. Note that the results for the JPCOB-VUL algorithm are not meaningful for high SINR due its low feasibility. Both algorithms increase the total transmitted power when the SINR requirement is increased. Regarding the influence of the ASW value, JPCOB-DL algorithm notably decreases the total transmitted power when coordination is allowed (ASW > 0 dB). This behavior can be explained by taken into account the multi-base beamformer performance ($KN_t > M$) and the inherent suppression of links that were define as active in the AS process (see Fig. 3). Hence, less BSs are transmitting with respect to the JPCOB-VUL algorithm.

VI. CONCLUSION

In this paper, the system model for a coordinated multi-cell W-CDMA system implementing Joint Power Control and Optimal Beamforming (JPCOB) algorithms is first stated. The objective of the paper is to minimize the total transmitted power in the coordinated multi-cell system achieving individual QoS requirements in the users. Two JPCOB algorithms based on local and multi-base MMSE beamforming approaches are evaluated under severe co-channel interference conditions and realistic simulation parameters. Simulation results show that for high SINR requirements, the JPCOB-VUL algorithm achieves an unacceptable low feasibility. Interestingly, JPCOB-DL algorithm decreases the total transmitted power as the degree of coordination between base stations is increased. Moreover, for coordinated configurations, the JPCOB-DL algorithm automatically determines which base station-user links should be active, independently of the decisions made by the multi-base scheduling technique.

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