Cooperative Interference Control for Spectrum Sharing in OFDMA Cellular Systems

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Abstract—This paper studies cooperative schemes for the inter-cell interference control in orthogonal-frequency-division-multiple-access (OFDMA) cellular systems. The downlink transmission in a simplified two-cell system is examined, where both cells simultaneously access the same frequency band using OFDMA. The joint power and subcarrier allocation over the two cells is investigated for maximizing their sum throughput with both centralized and decentralized implementations. Particularly, the decentralized allocation is achieved via a new cooperative interference control approach, whereby the two cells independently implement resource allocation to maximize individual throughput in an iterative manner, subject to a set of mutual interference power constraints. Simulation results show that the proposed decentralized resource allocation schemes achieve the system throughput close to that by the centralized scheme, and provide substantial throughput gains over existing schemes.

I. INTRODUCTION

In traditional cellular networks, the base stations (BSs) in different cells independently control the transmission with their associated users. The inter-cell interference is avoided or minimized by adopting different frequency reuse patterns, which only allow non-adjacent cells to reuse the same frequency band. The frequency reuse factor is assigned to specify the rate at which the same frequency band can be used in the network. Due to emerging high-rate wireless multimedia applications, traditional cellular systems have been pushed towards their throughput limits. As a result, it has been proposed to increase the frequency reuse factor such that each cell can be assigned with more frequency bands to increase the attainable throughput. In the special case where all cells can share the same frequency band for simultaneous transmission, this corresponds to the factor-one or universal frequency reuse. However, with more flexible frequency reuse, the inter-cell interference control becomes an essential problem in cellular systems, which has recently drawn significant research attentions (see, e.g., [1]−[4]).

For multicell systems with a universal frequency reuse, two promising approaches have been proposed to resolve the inter-cell interference problem (see, e.g., [1] and the references therein): interference coordination and network MIMO (multiple-input multiple-output). In the former approach, the performance of a multicell system is optimized via joint resource allocation among all cells, based on their shared channel state information (CSI) of all direct and interfering links across different cells. Furthermore, if the baseband signal synchronization among the BSs of different cells is available and the transmit messages of different cells are shared by their BSs, a more powerful cooperation can be achieved in the downlink via jointly encoding the transmit messages of all BSs. In this so-called network MIMO approach, the combined use of antennas at different BSs for joint signal transmission resembles the conventional single-cell multiantenna broadcast channel (BC) [1]. In this paper, the former interference coordination approach is adopted due to its relatively easier implementation in practical systems.

More specifically, we study the inter-cell interference coordination for a two-cell OFDMA downlink system with universal frequency reuse. All BSs and user terminals are assumed to be each equipped with a single antenna, and thus the system of interest can be modeled as a parallel interfering SISO (single-input single-output) BC. Promising applications of this two-cell system model are illustrated in Fig. 1 which shows a geographically symmetric setup with two adjacent macrocells, as well as a non-symmetric setup with one macrocell and one inside femtocell. This paper investigates the joint power and subcarrier allocation over the two cells to maximize their sum throughput, for both centralized and decentralized implementations. Specifically, for the centralized allocation, with the assumption of a global knowledge of all channels in the network, we propose a scheme to jointly optimize power and subcarrier allocation over the two cells by applying the Lagrange duality method from convex optimization [5]. This centralized scheme provides a performance benchmark for the decentralized schemes studied subsequently.

For the decentralized resource allocation, this paper proposes a new cooperative interference control approach, whereby the two cells independently optimize resource allocation to maximize individual throughput subject to a set of preassigned mutual interference power constraints, in an iterative manner until the resource allocation in both cells converges. Two types of interference power constraints are further examined: one is to constrain the total interference power across all subcarriers from each cell to the active users in its adjacent cell, termed joint subcarrier protection (JSP); and the other is to limit the interference power over each individual subcarrier, termed individual subcarrier protection (ISP). Also, the optimal resource allocation rules for each cell to maximize individual throughput with JSP or ISP are derived.

The rest of this paper is organized as follows. Section II
Section V presents simulation results and discusses the optimization problem for resource allocation. Section III introduces the two-cell downlink OFDMA system, and formulates the centralized resource allocation scheme. Section IV proposes two decentralized schemes via the cooperative interference control approach with JSP and ISP, respectively. Section V presents simulation results and pertinent discussions. Finally, Section VI concludes the paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

As shown in Fig. 1, we consider a two-cell system sharing the same frequency band with each cell having a downlink OFDMA transmission. We use \( m \in \{1,2\} \) to denote each of the two cells, which are referred to as the 1st and 2nd cells in this paper, respectively. For convenience, let the 1st cell refer to the macrocell and the 2nd cell refer to either the macrocell or the femtocell in Fig. 1. The total system bandwidth shared by the two cells is assumed to be \( B \) Hz, which is equally divided into \( N \) subcarriers (SCs) indexed by \( n \in \Lambda = \{1,2,...,N\} \). Each SC is assumed to be used by at most one user inside each cell and could be shared between two users individually selected from the two cells. In addition, the users in the network are indexed by \( k_1 \in \Delta_1 = \{1,2,...,K_1\} \) in the 1st cell and \( k_2 \in \Delta_2 = \{1,2,...,K_2\} \) in the 2nd cell, where \( K_1 \) and \( K_2 \) are the total numbers of users in each corresponding cell.

Furthermore, we denote the channel power gains (amplitude squares) from the two BSs to their respective users, saying users \( k_1, k_2, \) in each cell as \( h_{nk_1} \) and \( h_{nk_2} \), respectively. The inter-cell interference channel gain from BS1 to BS2 is denoted by \( g_{nk_2} \), while that from BS2 to BS1 is by \( g_{nk_1} \). We assume that the noise at each user’s receiver has independent circularly symmetric complex Gaussian (CSCG) distribution over SCs with zero mean and variance \( \sigma^2 = z_0B/N \), denoted by \( \mathcal{CN}(0,\sigma^2) \), where \( z_0 \) is the noise power spectral density. In addition, the transmit power allocated to user \( k_1 \) at SC \( n \) is denoted by \( p_{nk_1} \). Thus, over all users and SCs in the 1st cell, we can define a power allocation matrix \( P_1 \) (\( K_1\)-by-\( N \)) with the non-negative elements denoted by \( p_{nk_1}, n \in \Lambda, k_1 \in \Delta_1 \). \( P_1 \) is assumed to satisfy an OFDMA-based power allocation (OPA), in which there exists at most one element in each column being larger than zero and all the other elements are equal to zero. This OPA constraint can be expressed as \( P_1 \in S_1 = \{ P_1 \geq 0 \mid p_{nk_1}p_{nk_1'} = 0, \forall k_1 \neq k_1', \forall n \} \).

Similarly, we can define the power allocation matrix for the 2nd cell as \( P_2 \in S_2 \) (\( K_2\)-by-\( N \)) matrix under a similar OPA constraint. The \( n \)th columns of \( P_1 \) and \( P_2 \) are denoted by two vectors \( p_{1n} \in S_{1n} \) and \( p_{2n} \in S_{2n} \), where \( S_{1n} \) (\( S_{2n} \)) is drawn from the \( n \)th column of \( S_1 \) (\( S_2 \)).

With the above system model and assuming that the inter-cell interference is treated as additional Gaussian noise at each user’s receiver, the signal-to-interference-plus-noise-ratio (SINR) of user \( k_1 \) at SC \( n \) in the 1st cell is given by

\[
SINR_{nk_1} = \frac{p_{nk_1}h_{nk_1}}{\sum_{k_2=1}^{K_2} p_{nk_2}g_{nk_1} + \sigma^2}.
\]

Similarly, the SINR of user \( k_2 \) at SC \( n \) in the 2nd cell is denoted by \( SINR_{nk_2} \). Thus, the achievable sum-rate of user \( k_m \in \Delta_m, m \in \{1,2\} \) is given by

\[
r_{km} = \frac{1}{N} \sum_{n=1}^{N} \log_2 (1 + SINR_{nk_m}).
\]

We consider the weighted-sum-rate (WSR) in each cell i.e.,

\[
R_m = \sum_{k_m=1}^{K_m} w_{km} r_{km}, m \in \{1,2\},
\]

where \( w_{km} \) is the (non-negative) rate weight of user \( k_m \) in the \( m \)th cell. With individual transmission power constraint at each BS, the following optimization problem can be formulated to maximize the system throughput defined as

\[
\max_{P_1, P_2} R_1 + R_2
\]

subject to

\[
\sum_{k_m=1}^{K_m} \sum_{n=1}^{N} p_{nk_m} \leq P_m^B, m \in \{1,2\},
\]

where \( P_m^B \) is the given power constraint at BS\( m \), and

\[
P_m \in S_m, m \in \{1,2\}
\]

is the OPA constraint for the \( m \)th cell.

III. CENTRALIZED ALLOCATION

In this section, we study the centralized optimization for jointly allocating resources in the two cells so as to maximize the system throughput, which corresponds to solving Problem (4) globally with constraints (5) and (6). For the centralized allocation, it is assumed that all channel gains in the network are collected by a central controller, which is capable of performing a centralized resource allocation and informing the allocation results to each cell for data transmission.

Due to the non-convex OPA constraint and the non-concave objective function over \( P_1 \) and \( P_2 \), the optimization problem in (4) is non-convex and thus cannot be solved efficiently for the global optimum. Nevertheless, the Lagrange duality method (6) can be applied to this problem to obtain a suboptimal solution. Interestingly, according to (6), it has been shown that a so-called “time-sharing” condition usually holds for resource allocation problems in OFDMA, and the duality gap for such problems solved by the Lagrange duality method becomes asymptotically zero as the number of subcarriers in

Fig. 1. System model for two-cell applications.
the system becomes large. Accordingly, in the sequel, we apply the Lagrange duality method to solve Problem 4.

First, we express the partial Lagrangian of Problem 4 as

\[ L(\mathbf{P}_1, \mathbf{P}_2, \lambda_1, \lambda_2) = \sum_{n=1}^{N} L_n(\mathbf{p}_{1n}, \mathbf{p}_{2n}, \lambda_1, \lambda_2) + \lambda_1^1 P^{\text{BS}}_1 + \lambda_2^2 P^{\text{BS}}_2, \]

where, for each SC \( n \in \Lambda \),

\[ L_n(\mathbf{p}_{1n}, \mathbf{p}_{2n}, \lambda_1, \lambda_2) = \sum_{k=1}^{K_n} w_{nk_k} r_{nk_k} + \lambda_1 \sum_{k=1}^{K_n} P_{nk_k} - \lambda_2 \sum_{k=2}^{K_n} P_{nk_k}, \]

and \( \lambda_1, \lambda_2 \) are non-negative dual variables associated with the power constraints in 5 with \( m = 1 \) and 2, respectively. The Lagrange dual function is then given by

\[ g(\lambda_1, \lambda_2) = \max_{\mathbf{p}_1 \in \mathbf{S}_1, \mathbf{p}_2 \in \mathbf{S}_2} L(\mathbf{P}_1, \mathbf{P}_2, \lambda_1, \lambda_2). \]

Hence, the dual problem can be defined as

\[ \min_{\lambda_1 \geq 0, \lambda_2 \geq 0} g(\lambda_1, \lambda_2). \]  

(10)

For a given pairs of \( \lambda_1 \) and \( \lambda_2 \), we have

\[ g(\lambda_1, \lambda_2) = \sum_{n=1}^{N} g_n(\lambda_1, \lambda_2) + \lambda_1 P^1 + \lambda_2 P^2, \]  

(11)

where \( g_n(\lambda_1, \lambda_2), n \in \Lambda \), is obtained by solving the following per-SC maximization problem

\[ g_n(\lambda_1, \lambda_2) = \max_{\mathbf{p}_{1n} \in \mathbf{S}_{1n}, \mathbf{p}_{2n} \in \mathbf{S}_{2n}} L_n(\mathbf{p}_{1n}, \mathbf{p}_{2n}, \lambda_1, \lambda_2). \]  

(12)

The maximization problem in 11 is thus decoupled into \( N \) per-SC resource allocation problems given by 12. Due to the OPA constraints, for one particular SC \( n \), it can be simultaneously assigned to one pair of users \((k_1, k_2)\) from the two cells when the resultant \( L_n(\mathbf{p}_{1n}, \mathbf{p}_{2n}, \lambda_1, \lambda_2) \) in 11 attains its maximum value (with the optimized \( p_{nk_1} \) and \( p_{nk_2} \)). This user pair can be obtained by searching over all possible combinations from users \( k_1 \in \Delta_1, k_2 \in \Delta_2 \). Thus, the optimal SC and power allocation that solves the problem in 12 is

\[ (\bar{k}_1, \bar{k}_2) = \arg \max_{k_1 \in \Delta_1, k_2 \in \Delta_2} \left\{ \max_{p_{nk_1} \geq 0, p_{nk_2} \geq 0} L_n^{(k_1, k_2)} \right\}, \]  

(13)

where \((\bar{k}_1, \bar{k}_2)\) is the selected user pair to share SC \( n \), and

\[ L_n^{(k_1, k_2)} = w_{k_1} r_{nk_1} + w_{k_2} r_{nk_2} - \lambda_1 p_{nk_1} - \lambda_2 p_{nk_2}. \]  

(14)

is obtained from 11. For a given pair of \((k_1, k_2)\), the optimal \( p_{nk_1} \) and \( p_{nk_2} \) to maximize \( L_n^{(k_1, k_2)} \) in 13 have no closed-form solutions due to the non-convexity of this problem. However, an iterative search based on, e.g., Newton’s method 5 can be utilized to find a pair of local optimal solutions for \( p_{nk_1} \) and \( p_{nk_2} \). Then, we can check all possible user combinations to determine the optimal SC allocation according to 13 with optimized power allocation.

After solving the per-SC problems in 12 for all \( n \)'s, a subgradient-based method, e.g., the ellipsoid method, can be adopted to solve the dual problem in 10 so that the power constraints in 5 at both BSs are satisfied. The details are thus omitted for brevity. Note that Problem 4 can be solved in polynomial time with an overall complexity with order \( O(Itr_{out}NK_1K_2Itr_{in}) \) in its dual domain. Specifically, for one particular SC, we search for \( K_1K_2 \) combinations of user pairs and determine the power allocation for each user pair with \( Itr_{in} \) iterations. In addition, \( Itr_{out} \) is the number of iterations for solving the dual problem in 10. However, this centralized allocation needs a system level coordination with all channel conditions in the two cells, which is a demanding requirement for practical applications. In the next section, we propose decentralized schemes for resource allocation, which can be implemented by each cell independently.

IV. DECENTRALIZED ALLOCATION

In this section, a new cooperative interference control approach is applied to design decentralized resource allocation schemes for the two-cell OFDMA downlink system. In this approach, each cell independently optimizes its resource allocation to maximize individual WSR under its BS’s own transmit power constraint, as well as a set of newly imposed constraints to regulate the leakage interference power levels to the active users in its adjacent cell. The above operation iterates between the two cells, until both cells obtain a converged resource allocation under their mutual inter-cell interferences. Specifically, two decentralized allocation schemes are studied in this section corresponding to two different types of interference power constraints, namely JSP and ISP.

A. Joint Subcarrier Protection (JSP)

In this subsection, we solve the optimal resource allocation problem of maximizing the 1st cell’s WSR subject to its BS’s power constraint and a given JSP constraint to the active users in the 2nd cell. Similar problem formulation and solution apply to the resource allocation in the 2nd cell and are thus omitted.

Consider the resource allocation problem in the 1st cell subject to the leakage interference constraint for the 2nd cell. In order to characterize the leakage interference to the 2nd cell, BS 1 needs to know the interference channel gains from it to all active users over different SCs in the 2nd cell. Let \( \tilde{k_2} = \pi_2^2 \in \Delta_2 \) denote the active user at SC \( n \) in the 2nd cell, with the corresponding interference channel gain from BS 1 to \( \tilde{k_2} \) being \( g_{nk_2} \). It is then assumed that \( g_{nk_2} \) has been perfectly estimated by user \( k_2 \) in the 2nd cell and fed back to BS 2. After collecting \( g_{nk_2} \) for all \( n \)'s from its active users, BS 2 sends these channel gain values to BS 1 (via a backhaul link connecting these two BSs). Note that if a particular SC \( n \) is not used by any user in the 2nd cell, the corresponding interference channel gain \( g_{nk_2} \) sent from BS 2 to BS 1 is set to be zero regardless of its actual value, so that this SC can be used by the 1st cell without any interference constraint.

To maximize the WSR of the 1st cell, the following problem is formulated as

\[ \max_{\mathbf{P}_1} R_1 \]  

(15)
subject to
\[
\sum_{k_1=1}^{K_1} \sum_{n=1}^{N} p_{nk_1} \leq P_1^{\text{BS}}, \quad (16)
\]
\[
\frac{1}{N} \sum_{n=1}^{N} \sum_{k_1=1}^{K_1} p_{nk_1} g_{nk_2} \leq T_2, \quad (17)
\]
where \( T_2 \) is the given JSP power constraint for protecting all the active users in the 2nd cell. Note that \( T_2 \) limits the interference power averaged over all the SCs; thus, the corresponding resource allocation scheme is referred to as the Average scheme for convenience.

We assume the non-negative dual variables associated with \( (16) \) and \( (17) \) are \( \lambda, \mu \). Similarly as in the case of centralized allocation, for a given pair of \( \lambda, \mu \), Problem \( (15) \) can be decoupled into \( N \) per-SC problems in its dual domain, and the optimal allocation for SC \( n \in \{1, \ldots, N\} \) in the 1st cell is derived as
\[
\tilde{k}_1 = \arg \max_{k_1 \in \Delta_1} \left\{ \max_{p_{nk_1} \geq 0} \lambda \mu \right\}, \quad (18)
\]
where \( \lambda \mu \mu_{nk_1} = \frac{w_{nk_1}}{N \ln 2} + \frac{I_{21}^0}{h_{nk_2}} \left( 1 + \frac{g_{nk_2}}{N} p_{nk_1} \right) \) is the non-negative dual variable associated with \( (20) \).

According to \( (21) \) and \( (22) \), the optimal SC and power allocation can be determined for all \( n \)'s with any given \( \lambda \geq 0 \). Then, the bisection method \( (5) \) can be used to adjust \( \lambda \) so that the BS transmit power constraint \( (16) \) is satisfied.

Nevertheless, it is not computationally efficient to individually optimize \( T_2^m \) \( (T_2^m) \) for each SC, thus two special schemes are further identified. One scheme is to set \( T_1^m = T_2^m = +\infty, \forall n \in \Lambda \), which means that each cell is not aware of its interference to the adjacent cell, named as the No Protection scheme. The other scheme is to set uniform peak interference power constraints over all SCs, i.e., \( T_1^m = T_1^m = T_2^m = T_2^m, \forall n \in \Lambda \), named as the Peak scheme.

V. Simulation Results

In this section, simulation results are presented to evaluate the performance of the proposed schemes for the two-cell downlink OFDMA system. It is assumed that \( B = 100 \) MHz and \( N = 64 \). In addition, all users’ rate weights are assumed to be one, and the noise power spectral density \( z_0 \) is set to be \(-100 \) dBm/Hz. Assuming independent (time-domain) Rayleigh fading with six independent, equal-energy multipath taps, the frequency-domain channel gains \( \{h_{nk_1}, \} \), \( \{h_{nk_2}, \} \), \( \{g_{nk_1}, \} \), and \( \{g_{nk_2}, \} \) are modeled as independent CSCG random variables distributed as \( \mathcal{CN} (0, a) \), \( \mathcal{CN} (0, b) \), \( \mathcal{CN} (0, c) \) and \( \mathcal{CN} (0, d) \), respectively. For convenience, we normalize \( a = 1 \), and adjust \( b, c \) and \( d \) to generate different channel models. Figs. 2 and 3 show the results for two macrocells with \( K_1 = K_2 = 8 \) and Fig. 4 for the case with one macrocell and one femtocell with \( K_1 = 8 \) and \( K_2 = 2 \) (cf. Fig. 1).

Fig. 2 shows the system throughput, \( R_1 + R_2 \), achieved by different interference power constraints \( T_1 \) and \( T_2 \) using the proposed decentralized scheme with JSP (i.e., the Average scheme) in Section IV.A for one particular channel realization. The channel gains are obtained by setting \( b = 1 \) and \( c = d = 0.2 \), while the transmit power limits at two BSs are set equally to be \( P_1^{\text{BS}} = 1 \) watt. In this figure, we have marked one local maximum point obtained by the iterative search method in [7]. Also, we have marked the system throughput obtained by the centralized scheme proposed in Section III (Optimal scheme). It is observed that the system throughput achieved by...
the decentralized Average scheme is suboptimal as compared to that by the centralized Optimal scheme. Fig. 2 shows the system throughput against the average inter-cell interference channel gain for various schemes. The channels are generated via $b = 1$ and $c = d = g$, with $g$ being the average interference channel gain ranging from $10^{-4}$ to 1. The proposed decentralized Average scheme achieves the system throughput close to that by the centralized Optimal scheme for all values of $g$, when the searched optimized values of $T_1$ and $T_2$ are applied [7]. If instead the preassigned values for $T_1$ and $T_2$ are applied, throughput degradations are observed to be negligible in the case of $T_1 = T_2 = 0.1p$ for the low inter-cell interference regime with small values of $g$, and in the case of $T_1 = T_2 = 0.01p$ for the high inter-cell interference regime with large values of $g$. In addition, the Half scheme (each cell orthogonally uses half of the overall frequency band) and the No Protection scheme are observed to perform poorly for small and large values of $g$. Moreover, the Average scheme with JSP performs superior over the Peak scheme with ISP, especially when $g$ becomes large.

Finally, Fig. 3 shows the system throughput for a macrocell with a femtocell inside it. The channel gains are $b = 5$, $c = 0.1$, and $d = 0.5$. The transmit power constraint at the macrocell’s BS is assumed to be 1 watt, while that at the femtocell’s BS is changed from 0.02 to 2 watts. It is observed that all proposed centralized and decentralized resource allocation schemes outperform the No Protection scheme in the achievable system throughput, which eventually becomes saturated with the increased inter-cell interference. At low femtocell SNR, there exists a noticeable throughput gap between the Average and Peak schemes, which is due to the fact that when the femtocell suffers detrimental interference from the macrocell, the Average scheme can opportunistically allocate the femtocell transmit power to a small portion of SCs with best channel conditions. On the other hand, at high femtocell SNR, both Average and Peak schemes tend to perform close to the Optimal scheme.

VI. CONCLUSION

In this paper, the downlink cooperative interference control in a two-cell OFDMA system is investigated with centralized and decentralized implementations for joint power and subcarrier allocation to maximize the system throughput. It is shown that the proposed decentralized recourse allocation schemes via the new approach of inter-cell interference power protection achieve a performance close to that of the centralized scheme in various system settings. In addition, the joint subcarrier protection (JSP) with average interference power constraint is shown to achieve a larger system throughput than the more stringent individual subcarrier protection (ISP) counterpart with peak interference power constraint.

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