Energy-Efficient Cooperative Transmission over Multiuser OFDM Networks: Who Helps Whom and How to Cooperate

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Abstract— **Cooperative transmission has been shown to be able to greatly improve the system performance by exploring the broadcasting nature of wireless channels and cooperation among users. While most of existing works concentrate on improving the peer-to-peer link quality, we focus, in this paper, on resource allocation among users such that the system performance can be improved. In this work, two important questions are answered: who should help whom among the distributively located users, and how the users should cooperate to improve the performance. To quantify the questions, a power management problem is formulated over a multiuser OFDM network to minimize the overall system transmit power under the constraint of each user's desired transmission rate. Then, we develop an algorithm to find solutions for a two user case. From the simulation results, the proposed scheme achieves up to 50% overall power saving for the two-user system.**

I. Introduction

Resource allocation such as power control has long been regarded as one of an effective way to dynamically combat channel fluctuations and reduce co-channel interferences in wireless networks. The power control constantly adjusts the transmitted power so as to maintain the received link quality. In some applications such as wireless sensor networks, in which each user is powered by a battery, optimizing the power management can greatly extend the network lifetime.

Cooperative transmission protocols are designed to combat fading induced by multipath propagations in the wireless networks. The underlying techniques exploit spatial diversity available through cooperating terminals that relay signals for one another. In addition, the broadcasting nature of wireless channels provides an opportunity for multi-node diversity among users. This allows each user to achieve the spatial diversity without the requirement of physical arrays. In this paper, we discuss resource allocation among distributed users to optimize the system performance over this new paradigm of cooperative transmission strategy.

The pioneer work on cooperative transmission can be found, e.g. in [1], where a general information theoretical framework about relaying channels is established. Recently in [2], [3], a CDMA-based two-user cooperative modulation scheme has been proposed. The main idea is to allow each user to retransmit estimates of their partner's received information such that each user's information is transmitted to the receiver at the highest possible rate. This work is extended in [4] where the outage and the ergodic capacity behavior of various cooperative protocols, e.g. detect-and-forward and amplify-and-forward cooperative protocols, are analyzed for a three-user case under quasi-static fading channels. The work in [5] analyzed the schemes based on the same channel without fading, but with more complicated transmitter cooperation schemes involving dirty paper coding. In [6], a cooperative broadcast strategy has been proposed with an objective to maximize the network lifetime. Recent work in [7] presented theoretical characterizations and analysis for the physical layer of multihop wireless communications channels with different channel models.

Orthogonal frequency division multiplexing (OFDM) [8] is a mature technique to mitigate the problems of frequency selectivity and inter-symbol interferences. The optimization of subcarrier assignment for different users offers substantial gains to the system performances [9]-[11]. In addition, the fact that each user can assign the transmission over different subcarriers gives an opportunity for cooperative transmission among users.

Most of existing works concentrate on improving the peer-to-peer link quality. However, there are many questions for multiple user resource allocation over cooperative transmission that remain unanswered. The most important ones are "who helps whom" and "how to cooperate". In this paper, we concentrate on solving these two major problems in cellular networks or wireless local area networks. First, we construct a cooperative transmission framework over a multiuser OFDM network. To optimize the system performance, we formulate a power minimization problem under users' cooperation with a constraint on each user's transmission rate. The optimization is performed by modifying the subcarrier assignment matrix for cooperation and its corresponding power allocation. We develop an algorithm to solve the proposed problem. From the simulation results, the cooperative communications scheme can save up to 50% of the overall transmit power for a two-user system. Moreover, we analyze the situation where either the cooperation or noncooperation (traditional waterfilling) should be applied, i.e., we answer the question of "who helps whom". In addition, we analyze the percentage of OFDM subcarriers that should be used for helping others, i.e., we answer the question of "how to cooperate".

The rest of the paper is organized as follows: In Section II, the system model is given and the noncooperation transmission solution using the traditional waterfilling method is provided. We formulate the power control cooperative transmission problem as an assignment problem in Section III. We also provide an algorithm to solve the problem for a two-user case in Section IV. Simulations results are provided in Section V, and some insight investigations are explained. Finally, Section VI concludes the paper.

II. System Model and Noncooperative Solution

For an uplink multiuser OFDM system, suppose that there are N subcarriers and K users in the network. We represent T_i as a transmission rate of the i^{th} user and the rate is splitted onto N subcarriers in which r_i^n denotes the transmission rate at the n^{th} subcarrier with the corresponding transmit power P_i^n. From the information theory [12], we have

$$r_i^n = W \log_2 \left(1 + \frac{P_i^n G_i^n}{\sigma^2 \Gamma} \right), \tag{1}$$

where Γ is a constant for the capacity gap, G_i^n is the channel gain, and σ^2 is the thermal noise power. Without lost of generality, we assume that the noise power is the same for all subcarriers and all users.

In the current OFDM system such as the IEEE 802.11a/g standard [13], the MAC layer provides two different wireless access mechanisms for wireless medium sharing, namely, the distributed coordination function (DCF) and point coordination function (PCF). The DCF achieves automatic medium sharing among users by using carrier sense multiple access with collision avoidance (CSMA/CA). The PCF, however, is a centralized control mechanism. In both mechanisms, time division multiple access (TDMA) technology is utilized for all users to share the channel, i.e., at each time, only one user occupies all the bandwidth.

The goal of this paper is to minimize the overall power consumption, under the constraint on each user's minimal rate. If there is no cooperation among users, because of the TDMA utilization, the overall power minimization problem is the same as minimizing each user's power independently. We define $\mathbf{P}_i = [P_i^1, \ldots, P_i^N]$ as an power assignment vector, the i^{th} user's power minimization problem can be expressed as:

$$\min_{\mathbf{P}_i} \sum_{n=1}^{N} P_i^n \tag{2}$$

$$\text{s.t.} \sum_{n=1}^{N} r_i^n = T_i.$$

From (1), the above constrained optimization can be solved by the traditional waterfilling method. By representing

$$I_i^n = \frac{\Gamma \sigma^2}{G_i^n}, \tag{3}$$

the optimal solution of the waterfilling method is given by

$$P_i^n = (\mu_i - I_i^n)^+ \text{ and } r_i^n = W \log_2 \left(1 + \frac{P_i^n}{I_i^n} \right) \tag{4}$$

where $y^+ = \max(y, 0)$ and μ_i is solved by bisection search of the following expression

$$\sum_{n=1}^{N} W \log_2 \left(1 + \frac{(\mu_i - I_i^n)^+}{I_i^n} \right) = T_i. \tag{5}$$

Note that, the solution in (4) is based on the assumption that all users do not cooperate with each other. Due to the broadcasting nature of the wireless channels, not only base station but also other users are able to receive the transmitted information. Therefore, if other users can cooperate and help relaying the information, multiple node diversity can be explored and the system performance can be significantly improved. One fundamental question to answer is how to group users for cooperation, i.e., "who helps whom?". In the next section, we construct the cooperative transmission framework and then formulate the cooperation problem as an assignment problem.

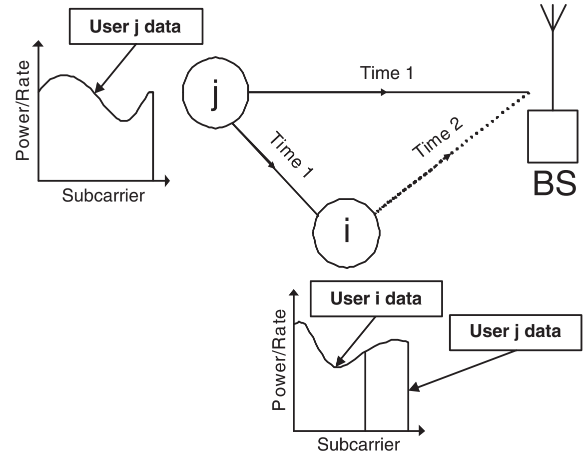

Fig. 1: Cooperation Transmission Scheme Example

III. Cooperative Transmission Framework

In the proposed cooperative transmission framework, we adopt a similar concept to the "amplify-and-forward" scheme in [4]. The difference is that our framework does not require a stage dedicated to relay or transmission. At one time period, a user transmits its data and all other users including base station (BS) can listen. In the next time period, another user tries to transmit his/her own data, while he/she can help others to transmit if his/her location and channels are better. One example is shown in Fig. 1 in which user i relays user j's data to the BS. At time one, user j transmits data, while all other users including the BS can listen. In the next time period, user i tries to transmit his/her own data, while he/she can help user j to transmit at the same time if his/her location and channels are good. User i can allocate some of his/her subcarriers to relay user j's data, so as to reduce user j's transmission power. In doing so, user i has to transmit his/her own data in the rest of his/her own subcarriers. Consequently the power for user i will be increased to maintain his/her own data transmission. So there are tradeoffs on whether or not to help others. From the system optimization point of view, the overall power of both user i and user j can be minimized by selecting the proper number of subcarriers for cooperation, i.e., the question of "how to cooperate". Moreover, because of the users' different locations and channel conditions, some users are more effective to help others' transmissions. Hence, it is essential to find the optimal cooperative groups, i.e., the question of "who helps whom". First, we will try to formulate the cooperative transmission problem as an assignment problem.

We define $\mathbf{A}_{KN \times KN}$ in Fig. 2 as an assignment matrix whose element $\mathbf{A}_{u,v} \in \{0, 1\}$ where $u = 1, \cdots, KN$ and $v = 1, \cdots, KN$. For notation convenience, we denote $(a, n) =$

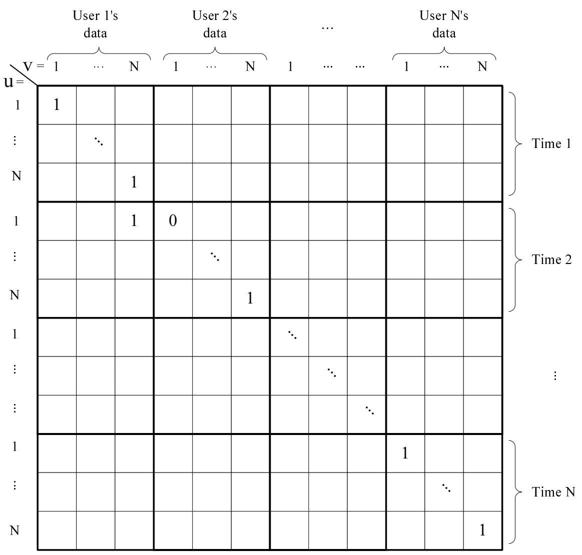

Fig. 2: Assignment Matrix

$(a-1)N+n$. We use (i,n) to represent the helping user i at subcarrier n, and (j,n') as the helped user j at subcarrier n'. Note that the user index i and $j \in 1,\cdots,K$. The value of each element of $\mathbf{A}$ has the following interpretations:

1) $\mathbf{A}_{(i,n),(i,n)} = 1$ means the i^{th} user's n^{th} subcarrier transmits its own information to the BS.
2) $\mathbf{A}_{(i,n),(j,n')} = 1$, for $i \neq j$ means the i^{th} user's n^{th} subcarrier relays transmit information from the j^{th} user's n' th subcarrier .

We can observe that $\sum_{v=1}^{KN} \mathbf{A}_{u,v} = 1, \forall u = 1,\ldots,KN$, i.e., each subcarrier contains only information from one user at a time. Note that, in case of $\mathbf{A} = \mathbf{I}_{KN\times KN}$, the solution of the proposed scheme is the same as the one using the waterfilling method in Section II. We also show as an example in Fig. 2 where user 2 uses its subcarrier 1 to relay the data for user 1 at the N^{th} subcarrier, i.e. $\mathbf{A}_{(2,1),(1,N)} = 1$. As shown in Fig. 2, each set of N rows represents data transmitted at a specific time and each set of N columns represents whose data are being transmitted at that time.

We define $\mathbf{P}_{K\times N} = [\mathbf{P}_1',\ldots,\mathbf{P}_K']'$ as the power allocation matrix and $\mathbf{G}_{KN\times KN}$ as the channel gain matrix whose its elements obey the followings

1) $G_{(j,n'),(i,n)}$, for $i \neq j$ denotes the channel gain from the j^{th} user at the n' subcarrier to the i^{th} user at the n^{th} subcarrier.
2) $G_{(i,n),(i,n)}$ represents the channel gain from the i^{th} user at the n^{th} subcarrier to the BS.
3) In order to prevent $\mathbf{A}_{(i,n),(i,n')} = 1$, for $n \neq n'$, we define $G_{(i,n),(i,n')} = 0, \forall n \neq n'$, and $\forall i$.

For the amplify-and-forward cooperation scheme, the receiver at the BS combines the directly received signal and the relayed signal together by the maximal ratio combining. In what follows, we will derive the r_i^n in (1) that incorporates cooperative transmission. Based on Fig. 1, we express the signal-to-noise ratio (SNR) that results from the direct transmission from the j^{th} user at the $(n')^{th}$ subcarrier to the BS by

$$\Gamma_j^{n'}(d) = \frac{\mathbf{A}_{(j,n'),(j,n')} P_j^{n'} G_{(j,n'),(j,n')}}{\sigma^2} \tag{6}$$

Next, we consider the SNR at the BS that results from user i relays user j information to the BS. Assuming that $X_{j,i}$ is the transmit signal from user j to user i, the received signal at user i is

$$R_{j,i} = \sqrt{P_j^{n'} G_{(j,n')(i,n)}} X_{j,i} + \sigma \tag{7}$$

User i amplifies $R_{j,i}$ and relays it to the BS in which the received signal is

$$R_{i,BS} = \sqrt{P_i^n G_{(i,n)(i,n)}} X_{i,BS} + \sigma \tag{8}$$

where

$$X_{i,BS} = \frac{R_{j,i}}{\sqrt{E|R_{j,i}|^2}} \tag{9}$$

is the transmit signal from user i to BS that is normalized to have unit power.

Substituting (7) into (9) and by using (8), we obtain

$$R_{i,BS} = \frac{\sqrt{P_i^n G_{(i,n)(i,n)}}\left(\sqrt{P_j^{n'} G_{(j,n')(i,n)}} X_{j,i} + \sigma\right)}{\sqrt{P_j^{n'} G_{(j,n')(i,n)} + \sigma^2}} + \sigma. \tag{10}$$

Using (10), the relayed SNR for the n'^{th} subcarrier of the j^{th} user, which is helped by the n^{th} subcarrier of the i^{th} user, is given by:

$$\Gamma_j^{n'}(r) = \frac{P_i^n P_j^{n'} G_{(i,n)(i,n)} G_{(j,n')(i,n)}}{\sigma^2 \left(P_i^n G_{(i,n)(i,n)} + P_j^{n'} G_{(j,n')(i,n)} + \sigma^2\right)}. \tag{11}$$

Therefore, by (6) and (11), we can rewrite (1) as:

$$r_j^{n'} = W \log_2 \left(1 + \frac{\Gamma_j^{n'}(d) + \Gamma_j^{n'}(r)}{\Gamma}\right). \tag{12}$$

The problem in this case can be considered as the cooperation group problem. Specifically, we determine the assignment matrix $\mathbf{A}$ and the corresponding power allocation matrix $\mathbf{P}$ that minimize the overall power and satisfy all the constraints. The optimization problem can be formulated as:

$$\min_{\mathbf{A},\mathbf{P}} \sum_{i=1}^{K} \sum_{n=1}^{N} P_i^n \tag{13}$$

$$\text{s.t.} \begin{cases} \text{Transmission Rate: } \sum_{n=1}^{N} r_i^n = T_i,\ \forall i; \\ \text{Assigment: } \sum_{v=1}^{KN} \mathbf{A}_{uv} = 1, \forall u = 1,\ldots,KN; \\ \text{Positive Power: } P_i^n \geq 0, \forall i, n. \end{cases}$$

In case of $\mathbf{A} = \mathbf{I}_{KN\times KN}$, the problem in (13) is exactly the same as (2) and the waterfilling method can be used to find the optimal solution.

Note that the problem in (13) can be viewed as a generalized assignment problem, which is an NP hard problem [14]. In order to solve (13), we divide the problem into two subproblems. The first subproblem is to find the optimal $\mathbf{P}$ for a fixed $\mathbf{A}$. Then in the second subproblem, we try to find the optimal $\mathbf{A}$.

IV. The Proposed Algorithm

In this section, we provide algorithms to solve the problem in (13). We first solve the problem of finding optimal power allocation $\mathbf{P}$ with fixed assignment matrix $\mathbf{A}$. After that we try to find the best $\mathbf{A}$.

A. Power Minimization Algorithm with Fixed $\mathbf{A}$

In this case, we assume that the assignment matrix $\mathbf{A}$ is known. We show the characteristic of the solution by the following theorem.

Theorem 1: For a fixed $\mathbf{A}$, there is only one local optimum which is also the global optimum for (13).

Proof: All the users are divided into two groups. The first group of users does not cooperate with others, i.e., $A_{(i,n),(j,n')} = 0, \forall i \neq j$ or $n \neq n'$. Therefore, the problem can be considered in the same way as the single user case and the waterfilling method can be used to find the only local optimum which is the global optimum for this kind of users.

The second group of users does cooperate with other users, i.e., $\exists A_{(i,n),(j,n')} = 1, \forall i \neq j$ or $n \neq n'$. For a fixed $\mathbf{A}$, the optimization problem for this kind of user can be expressed as

$$\min_{\mathbf{P}} \sum_{i=1}^{K} \sum_{n=1}^{N} P_i^n \tag{14}$$

$$\text{s.t.} \begin{cases} P_i^n \geq 0, \forall i, n; \\ \sum_{n=1}^{N} r_i^n = T_i, \ \forall i. \end{cases}$$

Observe that the optimization goal is linear, and the first constraint is linear as well. We express the second constraint by the use of (1) as:

$$\prod_{n=1}^{N} \left(1 + \frac{\Gamma_i^n(d) + \Gamma_i^n(r)}{\Gamma} \right) = 2^{\frac{T_i}{W}}. \tag{15}$$

For a fixed $\mathbf{A}$ and using (6) and (11), all power components (P_i^n or $P_j^{n'}$) have a quadrature form, i.e., the expression in the above equation is a polynomial function with the maximum order of two. Moreover, all of the coefficients are positive, hence, the constraint is convex. From [15], we know that the only local optimum for this kind of convex optimization problem is also the global optimum. Since the transmission of information of all users is divided into different time slot in TDM, the optimal solutions for the above two groups of users are also the optimal solution for (13). ■

With the fixed $\mathbf{A}$, any nonlinear or convex optimization methods [15] can be used to solve (14). For example, we can user barrier method to covert the constrained optimization problem in (14) to an unconstrained optimization problem and solve it iteratively. Within each iteration, we can use the Newton method to solve the unconstrained optimization problem. In this paper, we use the MATLAB FMINCON function to solve the optimization problem in (14).

TABLE I: Two User Searching Algorithm for $\mathbf{A}$

Initialization: $\mathbf{A} = I_{2N \times 2N}$, and Calculate (14).
Iteration: Hypotheses: If user 1's subcarrier n helps user 2's subcarrier n': $[\mathbf{A}]_{n,n} = 0$ and $[\mathbf{A}]_{n,n'+N} = 1$; If user 2's subcarrier n' helps user 1's subcarrier n: $[\mathbf{A}]_{n'+N,n'+N} = 0$ and $[\mathbf{A}]_{n+N,n'} = 1$; Solve (14). Among all hypotheses, find the maximal power reduction.
End when no power reduction, return $\mathbf{A}$ and $\mathbf{P}$.

B. Finding Optimal $\mathbf{A}$

In this section, we show a method to find the optimal assignment matrix $\mathbf{A}$. Because any element of $\mathbf{A}$ has a value of either 0 or 1 and the dimension of $\mathbf{A}$ is $KN \times KN$, we can use full search to find the optimal solution. For any specific $\mathbf{A}$, we calculate the overall transmit power, and select the one that generates the minimal power. However, the computational complexity is extremely high, especially when a large number of subcarriers are utilized and there are a substantial number of users in the OFDM systems. Some simplified algorithms such as Branch-and-Bound [14] can be applied to reduce the complexity.

In this paper, we propose a two-user greedy algorithm to find the optimal $\mathbf{A}$ as given in Table I. The basic idea is to modify $\mathbf{A}$ for one subcarrier per time. Initially, $\mathbf{A}$ is assigned as an identity matrix, which is basically the waterfilling scheme. Then, among N subcarriers of users, we make N hypotheses that the n^{th} subcarrier is assigned to help the other user and the remaining subcarriers are unchanged. Among all of these hypotheses, the algorithm selects the one that maximally reduces the overall power and the rest $N-1$ subcarriers make another hypotheses. This process is stopped when the power cannot be further reduced. Note that in this case the searching complexity of the proposed algorithm is N^3 and the algorithm is suboptimal because of the greedy local search. It is worth to mention that the proposed algorithm does not need to be applied in realtime. The BS can calculate the conditions for different types of cooperation off line, and then apply the corresponding cooperation according to different conditions on line.

V. Simulation Results and Discussions

To evaluate the performances of the proposed scheme and analyze the questions like "who helps whom" and "how to cooperate", we set simulation parameters as follows: There were totally $K = 2$ users in the OFDM network. A BS was located at coordinate (0,0), user 1 was fixed at coordinate (10m,0), and user 2 was randomly located within the range of [-40m 40m] in both x-axis and y-axis. The propagation loss factor was set to 3. The noise level was $\sigma^2 = 0.01$ and we selected $\Gamma = 1$. An OFDM modulator for each user utilized $N = 32$ subcarriers and each subcarrier occupies a bandwidth of $W = 1$.

In Fig. 3, we show a comparison of the overall power in (dB) of the waterfilling scheme, user 1 helps user 2 (1-H-2) scheme, and user 2 helps user 1 (2-H-1) scheme. In this simulation, user 2 moved from location (-40m,0) to (40m,0). The transmission

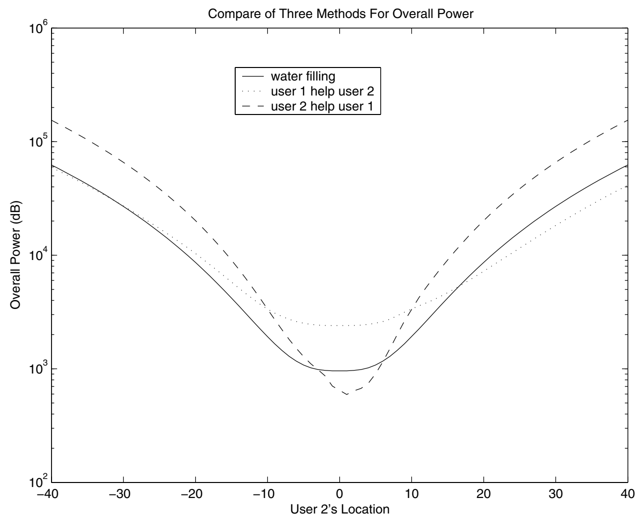

Fig. 3: Comparison of Overall Power of Three Different Methods

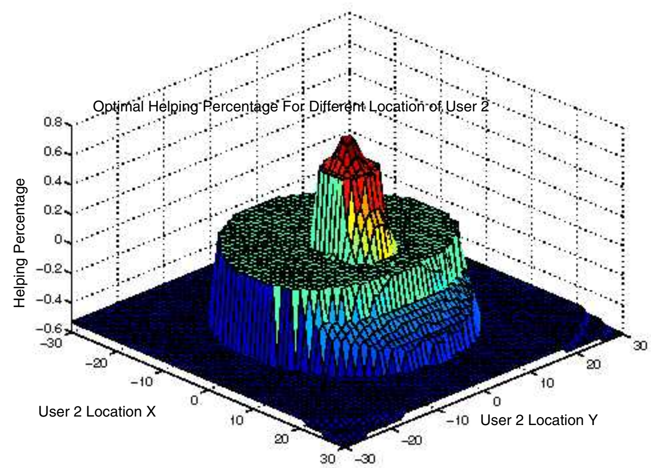

Fig. 5: Cooperation Percentage For Two User System

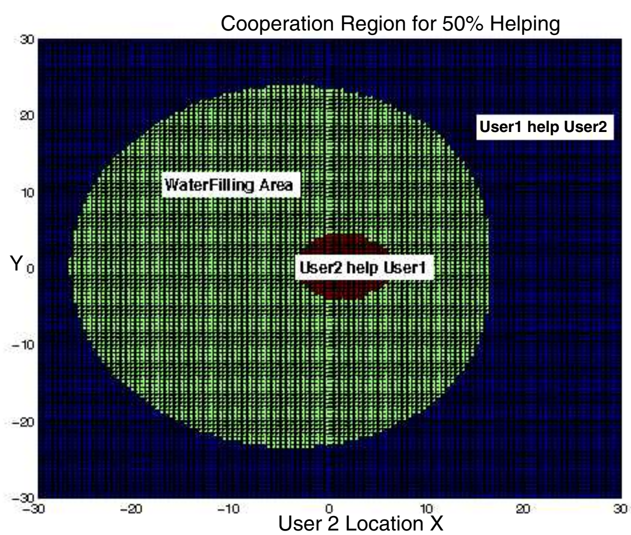

Fig. 4: Cooperation Region For Two User System

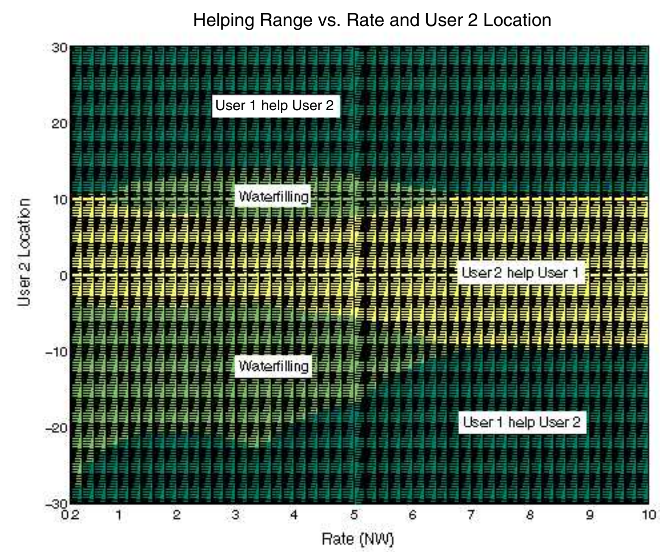

Fig. 6: Cooperation Region vs. User's Rate

rate for each user was $T_i = 2NW$ and half of the subcarriers were used for helping others. We observe that when the user 2 was located close to the BS, the 2-H-1 scheme can reduce the overall power up to 50%. The reason is that user 1 can use user 2 as a relay node to transmit the user 1's information such that user 1's power can be reduced, while user 2 was close to the BS that even with only half of subcarriers to carry his/her own information, the power increase for user 2 is still inferior to the power reduction for user 1. On the other hand, when user 2 was located far away from the BS, even in the opposite direction to user 1 such as (-40m,0), the 1-H-2 scheme can reduce the overall transmit power. This can be explained by the same reason as above. In the extreme case, when the user 2 was located very far away from the BS compared with the distance of user 1 to the BS, both of the user 1 and the BS can be considered as multiple sinks for user 2's signal. This phenomenal can be viewed as the so called "virtual multiple antenna diversity".

In Fig. 4, we show the region where different schemes should be applied based on the user 2's location. With the same simulation setups as in the previous case, we can see that when the user 2's location was close to the BS or sat in between the location of the user 1 and the BS, The 2-H-1 scheme is prefer. When the user 2 is located far away from the BS, the 1-H-2 scheme dominates. In case of the user 2's location was in between the above two cases, the Waterfilling scheme is the optimum choice. This figure answers the question of "who helps whom".

In Fig. 5, we answer the question of how the users should cooperate with each other. The simulation setups was the same as in the previous case except that we find the optimal percentage of subcarriers that was used for helping others. We show the helping percentage as a function of different user 2's locations. When the percentage is positive, the 2-H-1 scheme is activated; when the percentage is zero, the waterfilling scheme is chosen; when the percentage is negative, the 1-H-2 scheme is applied. Observing from the Figure that the closer of the

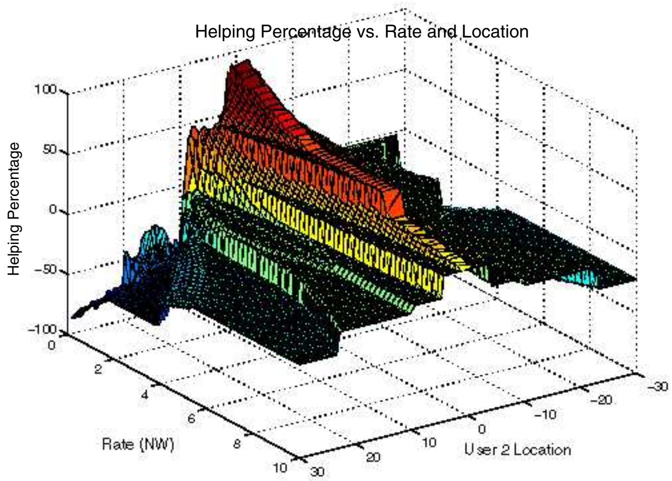

Fig. 7: Helping Percentage vs. User's Rate

user 2's location to the BS, the larger percentage user 2 will help user 1. This observation follows the fact that user 2's own transmission virtually costs nothing in terms of power usage. On the other hand, when the user 2 moved far away from the BS, user 1 helps user 2 more and more. Therefore, the figure gives us an insight investigation of the optimal way on how the users should cooperate with each other.

Fig. 6 and Fig. 7 show the effects of user's transmission rate T_i on who should help who and how users should cooperate. We modified T_i from $0.5NW$ to $10NW$ for all users. The user 2 moved from (-30m,0) to (30m,0). As we can see in Fig. 6, the helping regions are changed with increases of the transmission rate. The waterfilling regions increase to maxima around the rate equal to $3.4NW$, then the waterfilling regions are reduced until all regions are occupied by 1-H-2 or 2-H-1 regions. The reason is that when the power grows exponentially with increasing of the transmission rate, the helping with little percentage can reduce a lot of power in the proposed OFDM cooperative network. In Fig. 7, however, we observe that the helping percentages are shrinking as the users' rates keep increasing. This is because the users need more subcarriers to carry their own data, so the number of subcarriers to help others is reduced. Note also from the figure that when the transmission rate is high, the original waterfilling area becomes the 1-H-2 or 2-H-1 area. But the percentage of helping is very small.

VI. CONCLUSIONS

We constructed a power control cooperative transmission framework over multiuser OFDM networks. We are able to improve the system performance by exploring the broadcasting nature of the wireless channels and the possibility of cooperation among users. We formulated the problem as an assignment problem and proposed an algorithm to solve it. From the simulation results, the proposed scheme can save up to 50% of overall transmit power. The major contributions of this paper are to analyze "who helps whom" and "how to cooperate" for the distributed users in the network, which gives some insights on the design of future wireless cooperative transmission protocols.

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