Relaying Power Allocation with User-Cooperation for OFDM-based MISO Broadcast Channels

Hyukjoon Kwon, Hui Won Je, and John M. Cioffi
STAR Lab, Stanford University, Stanford, CA 94305
Email: {hjkwon, jehw, cioffi}@stanford.edu

Abstract—This paper addresses the power allocation problem on relaying channels with user-cooperation for multi-user orthogonal frequency division multiplexing (OFDM) systems. The proposed problem is based on dual-mode mobile stations (MSs), where one interface is used to receive signals from a base station (BS) and the other is used to forward the signals to nearby MSs through out-of-band relaying. This dual-mode operation enables MSs to cooperate with one another without consuming the capacity of a broadcast channel. Theoretically, the cooperation among MSs over orthogonal relaying channels has already been defined as conferencing. The proposed scheme uses conferencing to consider a broadcast channel with user-cooperation, where mobile power is distributed among subcarriers. Simulation results demonstrate that the proposed scheme achieves improved performance over the equal-power-allocation scheme on relay channels and the conventional broadcast scheme. These results are shown by considering the average throughput and the outage throughput.

I. INTRODUCTION

In response to the growing demand for next-generation cellular networks, many wireless techniques have been developed to support high-rate data communication and reliable quality-of-service (QoS). Of the wireless techniques, multiple-antenna and multicarrier systems are promising techniques to provide high performance over wireless channels. In [1], it has been shown that multiple-input multiple-output (MIMO) systems can significantly increase a channel capacity over single antenna systems. Additionally, [2] has generated great interest for multicarrier modulation. Among many multicarrier systems, orthogonal frequency division multiplexing (OFDM) [3] has been regarded as a viable technology because of its robustness to multipath fading, and thus selected for recent standards such as WiMAX and LTE.

As a multiuser scenario is important in wireless systems, dirty-paper coding has been shown to be an optimal algorithm to achieve the sum capacity of a Gaussian broadcast channel [4]. However, this nonlinear technique is difficult to implement in a practical system because it is complex and requires the full channel side information (CSI) of all mobile stations (MSs) at the base station (BS). Instead, a zero-forcing beamforming technology is proposed in [5]. This linear method asymptotically achieves the same sum capacity as that of dirty-paper coding for a large number of MSs but with low complexity. However, this method still assumes that the full CSI of all MSs is known at the BS. Recently, [6] has analyzed the performance of zero-forcing beamforming with a limited feedback, and shows that the number of feedback bits should linearly increase with respect to the signal-to-noise ratio (SNR). Otherwise, the total throughput is bounded as the SNR increases.

As another potential technology to enhance the performance of cellular networks, relaying has been proposed in [7]. The scheme pre-installs relay stations (RSs) to balance the load among cells. This relaying has been integrated with MSs for cellular networks in the following two methods [8]. In-band relaying uses MSs at a standstill to serve as RSs. This scheme does not need to modify MSs, but the performance severely depends on the scheduling intervals of MSs as RSs. Alternatively, out-of-band relaying uses MSs equipped with multiple radio interfaces such as cellular, IEEE 802.11 (WiFi), and bluetooth. Using an ad-hoc interface in out-of-band channels, both [9] and [10] have shown that the outage probability and the multicast throughput can be enhanced, respectively. Theoretically, the orthogonal relaying among MSs has already been proposed as conferencing in [11]. Recently, this theoretic research for conferencing has been developed and it has been shown that the conferencing can increase the achievable rate in a broadcast channel [12]. Moreover, [13] analyzes the trade-off between the amount of limited feedback and the amount of cooperation where MSs can cooperate in cellular networks.

This paper is motivated by the broadcast channel model with conferencing through out-of-band relaying. Based on the results of [13], this paper presents a power allocation scheme for the out-of-band relaying channels to maximize the throughput of OFDM systems. The proposed scheme works as follows: During a training period, pilot sequences known a priori to the MSs are broadcasted and then conveyed to nearby MSs through relay channels. After estimating the broadcast channels, each MS selects the best beamforming vector and calculates the optimal relaying power allocation among subcarriers. Next, during a data transmission period, each MS uses the calculated power distribution for subcarriers when it relays the data to nearby MSs. As a result, the proposed scheme enhances the average throughput over the equal power allocation scheme on relay channels. The result also shows improved performance with respect to the relay channels’ efficiency over a zero-forcing beamforming scheme. Another advantage of the proposed scheme is the outage throughput as it achieves the reliable performance. The following summarizes the main contributions of this work:

- The direct cooperation among MSs without any RSs in multi-user OFDM systems is proposed with the relaying
power allocation problem as a novel approach.

- The original relaying power allocation scheme is a complex non-convex problem, but is transformed into a series of standard convex sub-problems that are solved easily.
- The enhanced throughput is evaluated from both average and outage perspectives.

The rest of this paper is organized as follows: Sec. II describes a multi-user broadcast channel model. In Sec. III, the cooperation scheme among MSs is explained as well as beam-forming and combining vectors. Then, Sec. IV formulates the proposed problem, and presents solutions to the optimization problem. Simulation results in Sec. V evaluate the proposed scheme, and finally Sec. VI concludes this paper.

II. SYSTEM MODEL

This paper considers an OFDM-based multi-user broadcast channel. The BS is equipped with $M$ transmit antennas and $K$ MSs, each having a single antenna, are supported in a cell. In the BS, the serial symbols for each MS are fed into $N$ subcarriers in the frequency domain and are transformed into the time domain samples by an inverse fast Fourier transform (IFFT). These samples are added with the cyclic prefix on a guard period. After removing the cyclic prefix, each MS demodulates the received signals by using a fast Fourier transform (FFT). As a result, each MS’s channels are orthogonally decomposed into parallel $N$ subchannels as

$$y_{i,n} = h_{i,n}^\dagger x_n + n_{i,n},\quad (1)$$

where $y_{i,n}, h_{i,n} \in \mathbb{C}^{M \times 1}$, and $n_{i,n}$ are the received signal, the channel frequency response, and the zero-mean complex-Gaussian noise with variance $N_0/N$ on the $n$th subcarrier at MS $i$, respectively. The channel is assumed to be block-fading, i.e., it is invariant over each block period, but varies from one block to another. The channel vectors $h_{i,n}$ are independent random vectors, each having elements independently distributed as the zero-mean complex-Gaussian with unit variance. The transmitted signal $x_n \in \mathbb{C}^{M \times 1}$ consists of the unit-norm beamforming vectors $b_{m,n} \in \mathbb{C}^{M \times 1}$ and the symbol $s_{m,n}$ for MS $m$ on the $n$th subcarrier as follows:

$$x_n = \sum_{m=1}^{M} b_{m,n} s_{m,n}.\quad (2)$$

The transmit power for the total bandwidth is available up to $P_t$ and is equally distributed to the $n$th symbol at the $n$th subcarrier as $P_t/n$. This paper assumes that the most favorable $M$ MSs are selected among $K$ MSs at each block by user-selection algorithms such as [9]. Hence, if not stated otherwise, $K$ is considered equal to $M$.

III. USER-COOPERATION IN CELLULAR NETWORKS

In this paper, MSs operate in a dual-mode, having both macro-cellular and micro-radio interfaces, as studied in [9]. Using this micro-radio interface, each MS cooperates with nearby MSs so as to relay the received signals from a cellular interface. As in [13], this paper focuses on an amplify-and-forward relaying among several other relaying strategies such as decode-and-forward or compress-and-forward [14]. This strategy has benefits to reduce the decoding complexity and to decrease delays caused by relaying, because it is relatively simple and does not require a processing time to remodulate the received signals.

A. Amplify-and-Forward Relaying

The received signal for each subcarrier is first normalized before being sent to nearby MSs. The normalized signal $\tilde{y}_{i,n}$ on the $n$th subcarrier at MS $i$ is represented by

$$\tilde{y}_{i,n} = \sqrt{E[\|y_{i,n}\|^2]} y_{i,n} = \sqrt{\frac{P_t}{MN} h_{i,n}^\dagger (\sum_{m=1}^{M} b_{m,n} b_{m,n}^\dagger) h_{i,n}} + \frac{N_0}{N},\quad (3)$$

and then, is forwarded to MS $j$ with the weighted mobile power $w_{i,n} P_t$, where $P_t$ is the maximum power assigned to each MS. The weighting scalars $w_{i,n}$ are distributed to all the subcarriers to improve the relaying performance. Since the sum of mobile power at each subcarrier is limited to $P_t$, the weighting scalars are subject to $\sum_{n=1}^{N} w_{i,n} \leq 1$. Thus, the relayed signal from MS $i$ to MS $j$ is expressed as

$$\tilde{y}_{ij,n} = \sqrt{w_{i,n} P_t} \alpha_{ij,n} \tilde{y}_{i,n} + \tilde{n}_{ij,n} = g_{ij,n} y_i + \tilde{n}_{ij,n}, \quad \forall \ i \neq j \quad (4)$$

where $\alpha_{ij,n}$ is a relay channel gain between two MSs on the $n$th subcarrier, and the channel noise $\tilde{n}_{ij,n}$ is distributed as the zero-mean complex Gaussian with the variance $N_0/N$. Correspondingly, the relay gain $g_{ij,n}$ from MS $i$ to MS $j$ is defined from (3) and (4) by

$$g_{ij,n} = \alpha_{ij,n} \sqrt{\frac{P_t}{MN} h_{i,n}^\dagger (\sum_{m=1}^{M} b_{m,n} b_{m,n}^\dagger) h_{i,n}} + \frac{N_0}{N}.\quad (5)$$

This work assumes that the channel vector $h_{i,n}$ is fully known to MS $i$ and can be conveyed to nearby selected MSs during training periods. Also, it is assumed that the relay channel gains are known to both MSs on the channel. To coordinate the relayed signals from neighboring MSs, each MS divides them by the corresponding relay gains such that the aggregate signal $\{\tilde{y}_{ij,n}\}$ at MS $j$ on the $n$th subcarrier is given by

$$\tilde{y}_{ij,n} = y_{i,n} + \frac{1}{g_{ij,n}} \tilde{n}_{ij,n} = \begin{cases} h_{i,n}^\dagger x_n + n_{i,n} + \frac{1}{y_{i,n}} \tilde{n}_{ij,n} & \forall \ i \neq j \\ h_{i,n}^\dagger x_n + n_{i,n} & \forall \ i = j. \end{cases}\quad (6)$$

In a vector form, the aggregated signals for MS $j$ on the $n$th subcarrier can be equivalently written as

$$\hat{y}_{jn} = \begin{bmatrix} \tilde{y}_{1j,n} \\ \tilde{y}_{2j,n} \\ \vdots \\ \tilde{y}_{Kj,n} \end{bmatrix} = H_{jn}^\dagger x_n + n_n + D_{jn}^{-1} \tilde{n}_{jn} = H_{jn}^\dagger x_n + G_{jn} \tilde{n}_{jn}\quad (7)$$
where \( \mathbf{H}_n \in \mathbb{C}^{M \times K} \) is a channel frequency response matrix at the \( n \)th subcarrier, whose \( i \)th column is \( \mathbf{h}_{i,n} \). The vectors \( \mathbf{n}_{i,n} \) and \( \tilde{\mathbf{n}}_{i,n} \) consist of concatenated broadcast channel noises \( \{ n_{i,n} \}_{j \neq i} \) and concatenated relay channel noises \( \{ \tilde{n}_{i,j,n} \}_{j \neq i} \), respectively. The \( j \)th element of \( \tilde{n}_{i,j,n} \) is zero because there is no need for self-cooperation. The diagonal matrix \( \mathbf{D}_{i,j,n} \) represents the noise enhancement resulting from an amplify-and-forward relaying strategy and its \( i \)th diagonal element is the relay gain \( g_{i,j,n} \). Since \( \tilde{n}_{i,j,n} \) is equal to 0, \( g_{i,j,n} \) is not important. To combine the effects of noises from both vectors, the matrix \( \mathbf{G}_{i,j,n} \in \mathbb{C}^{K \times 2K} \) and the vector \( \tilde{n}_{i,j,n} \in \mathbb{C}^{2K \times 1} \) are derived as \( \begin{bmatrix} \mathbf{I}_K \mathbf{D}_{i,j,n}^{-1} \end{bmatrix} \) and \( \{ \mathbf{n}_{i,j,n}, \tilde{n}_{i,j,n} \} \), respectively. In the derivation, \( \mathbf{I}_K \) represents a \( K \)-dimensional identity matrix.

The aggregate signal vector \( \mathbf{y}_{i,n} \) is now applied with the combining vector \( \mathbf{c}_{i,n} \in \mathbb{C}^{M \times 1} \) for MS \( i \)'s \( n \)th subcarrier so that the filter output \( z_{i,n} \) is detected with the corresponding interference and noise as follows:

\[
\begin{align*}
    z_{i,n} &= \mathbf{c}_{i,n}^\dagger \mathbf{y}_{i,n} \\
    &= \mathbf{c}_{i,n}^\dagger \mathbf{H}_{i,n} \mathbf{b}_{i,n} + \sum_{m \neq i} \mathbf{c}_{i,n}^\dagger \mathbf{H}_{i,n} \mathbf{b}_{m,n} \mathbf{s}_{m,n} + \mathbf{c}_{i,n}^\dagger \mathbf{G}_{i,j,n} \tilde{\mathbf{n}}_{i,j,n}.
\end{align*}
\]

Thus, the signal-to-interference and noise ratio (SINR) under the proposed scheme is affected by two problems: The first is how both the beamforming vector \( \mathbf{b}_{i,n} \), and the combining vector \( \mathbf{c}_{i,n} \), are decided, and the second is how the relaying power \( P_r \) at each MS is allocated among subcarriers so that the enhanced noise can be reduced.

### B. Transmit Beamforming and Receive Combining

To mitigate the effect of the multi-user interference and increase the total throughput simultaneously, this paper uses the QR decomposition (QD) of the channel matrix \( \mathbf{H}_n \) as in [13]. Even though the QD method is not proved to be optimal to maximize the performance of the proposed scheme, it can be simply implemented and is numerically stable [15]. Using this QD method, the channel matrix \( \mathbf{H}_n \) is factorized into two matrices as follows:

\[
\mathbf{H}_n = \mathbf{Q}_n \mathbf{R}_n^\dagger,
\]

where \( \mathbf{Q}_n \) is a unitary matrix and \( \mathbf{R}_n \) is a lower triangular matrix. To preserve inference for its own and cancel out the effects resulting from the beamforming vectors of other MSs, a combining vector \( \mathbf{c}_{i,n} \) for MS \( i \) is chosen from the null space of the matrix \( \mathbf{R}_n \), obtained from \( \mathbf{R}_n \) as

\[
\mathbf{R}_{i,n} = [ \mathbf{r}_{i,n} \ldots \mathbf{r}_{i-1,n} \mathbf{r}_{i+1,n} \ldots \mathbf{r}_{M,n} ] \in \mathbb{C}^{K \times (M-1)},
\]

where \( \mathbf{r}_{m,n} \) is the \( m \)th column of \( \mathbf{R}_{i,n} \). This matrix consists of column vectors of \( \mathbf{R}_{i,n} \) except \( \mathbf{r}_{i,n} \), and the corresponding combining vector for MS \( i \) is given by

\[
\mathbf{c}_{i,n} = N(\mathbf{R}_{i,n})
\]

where \( N(A) = \{ x : Ax = 0 \} \). As a result, the inner-product of \( \mathbf{c}_{i,n} \) with \( \mathbf{R}_n \) produces the vector where only the \( i \)th element remains as

\[
\mathbf{c}_{i,n}^\dagger \mathbf{R}_n = [ 0 \ldots \mathbf{c}_{i,n}^\dagger \mathbf{r}_{i,n} \ldots 0 ] \in \mathbb{C}^{1 \times M}.
\]

This result implies that only the \( i \)th column of the unitary matrix, \( \mathbf{q}_{i,n} \), affects the SINR for the \( n \)th subcarrier of MS \( i \) because the other columns are multiplied by zero. In addition, the beamforming vectors for MS \( i \), \( \mathbf{b}_{i,n} \), should be chosen as close as \( \mathbf{q}_{i,n} \) to minimize the interference caused by a limited feedback. This work uses a sub-optimal codebook created by the random vector quantization (RVQ) in [16], which is well analyzed and achieves optimality as the number of feedback bits \( B \) increases. This codebook is generated by using the codeword, \( \mathbf{f}_{i,n} \), which is isotropically and independently distributed in \( \mathbb{C}^{M \times 1} \): \( \mathbf{F} = \{ \mathbf{f} \}_{i=1}^{2^B} \). Among these codewords, the beamforming vector is chosen at MS \( i \) to be the closest vector to \( \mathbf{q}_{i,n} \) as

\[
\mathbf{b}_{i,n} = \arg \max_{\mathbf{f} \in \mathbf{F}} |\mathbf{q}_{i,n}^\dagger \mathbf{f}|^2,
\]

and the index of \( \mathbf{b}_{i,n} \) is fed back to the BS. Consequently, the SINR for MS \( i \)'s \( n \)th subcarrier is given by

\[
\text{SINR}_{i,n} = \frac{P_i}{\sum_{j \neq i} \frac{P_j}{|\mathbf{q}_{j,n}^\dagger \mathbf{f}|^2 |\mathbf{q}_{i,n}^\dagger \mathbf{b}_{i,n}|^2} + \frac{2}{M} \| G_{i,n} \|^2 + \frac{1}{\rho} \| G_{i,n} \|^2.
\]

It is observed that only \( G_{i,n} \) is adjustable to increase the SINR by allocating appropriate power to each subcarrier. The following section discusses how the mobile power should be allocated to subcarriers from this definition.

### IV. RELAYING POWER ALLOCATION ON CONFERENCING

In this section, the relaying power allocation problem across different subcarriers for each MS is formulated, and the optimal weighting variables are derived to maximize the total throughput of \( K \) MSs. The problem is given by

\[
\begin{align*}
    \text{arg max}_{\mathbf{w} = \{ w_{i,n} \}_{i=1}^N} & \quad R_{\text{sum}}(\mathbf{w}) = \frac{1}{N} \sum_{i=1}^N \sum_{n=1}^M \log_2 (1 + \text{SINR}_{i,n}) \\
    \text{subject to} & \quad \sum_{n=1}^N w_{i,n} \leq 1, \quad w_{i,n} > 0 \quad \forall i, n
\end{align*}
\]

where \( \mathbf{w} \) is a set of all the weighting variables \( w_{i,n} \) for all \( i \) and \( n \). In (14), the noise term of the SINR is a function of \( \mathbf{w} \) and can be expanded as follows:

\[
\| \mathbf{c}_{i,n}^\dagger \mathbf{G}_{i,n} \|^2 = 1 + \mathbf{c}_{i,n}^\dagger \mathbf{D}_{i,n}^{-2} \mathbf{c}_{i,n} = 1 + \sum_{j \neq i} \frac{|(\mathbf{c}_{i,n})_j|^2}{|G_{j,n}|^2} = 1 + \sum_{j \neq i} \frac{\phi_{i,j,n}}{w_{j,n}}
\]

where the scalar \( (\mathbf{c}_{i,n})_j \) is the \( j \)th element of the combining vector \( \mathbf{c}_{i,n} \). The scalar \( \phi_{i,j,n} \) is defined by

\[
\phi_{i,j,n} = \frac{|(\mathbf{c}_{i,n})_j|^2}{\| \bar{\alpha}_{j,n} \|^2} = \frac{(\mathbf{h}_{j,n}^\dagger \sum_{m=1}^M \mathbf{b}_{m,n} \mathbf{h}_{m,n}^\dagger \mathbf{h}_{j,n} + 1)^{-1}}{\rho}
\]
where $\gamma$ is the ratio of the MS's power to the BS's power, i.e., $P_i/P_t$, and $\rho$ is the SNR of the received signals from the BS for all the subcarriers, i.e., $P_i/N_0$.

This optimization problem is difficult to solve because the objective $R_{\text{sum}}(w)$ is strictly non-concave for $w$. Instead, the problem can be modified to maximize the total throughput by determining the weighting variables of only one MS, where those of other MSs are given. Then, the calculated weighting variables of each MS are sequentially updated until they converge. This iterative algorithm transforms the original non-concave problem into a series of concave sub-problems. Specifically, provided that the relay resource allocations of other MSs are fixed, only the weighting variables for MS $i$, $w^i = \{w_{i,n}\}_{n=1}^N$, remain to solve the optimization problem. As a result, the objective $R_{\text{sum}}(w^i)$ of the sub-problem for MS $i$ is defined as

$$R_{\text{sum}}(w^i) = \frac{1}{N} \sum_{n=1}^N \sum_{j \neq i}^M \log_2 \left(1 + \frac{s_{j,n}}{l_{j,n} + 1/w_{i,n}} \right)$$

where

$$s_{j,n} = \frac{P_i}{N \sum_{m \neq j} P_i} |\mathbf{r}_{j,n}/\mathbf{b}_{j,n}|^2,$$

$$l_{j,n} = \sum_{m \neq j} \frac{P_i}{N \sum_{m \neq j} P_i} |\mathbf{r}_{j,n}/\mathbf{b}_{j,n}|^2,$$

$$s_{j,n}^i = \frac{s_{j,n}}{\varphi_{j,i,n}},$$

$$l_{j,n}^i = \frac{l_{j,n}}{\varphi_{j,i,n}}.$$  

This problem is designed only for MS $i$. Therefore, there is no confusion to omit the index $i$ above. Then, the problem for the proposed scheme is reformulated to solve the following iteratively,

$$\arg \max_{w_n^i = \{w_{i,n}\}_{n=1}^N} R_{\text{sum}}(w^i) = \frac{1}{N} \sum_{n=1}^N \sum_{j \neq i}^M \log_2 \left(1 + \frac{s_{j,n}}{l_{j,n} + 1/w_{i,n}} \right)$$

subject to $\sum_{n=1}^N w_n \leq 1, \quad w_n > 0 \quad \forall n.$  

From the information obtained through the relay channels, MS $i$ can determine the optimal relaying power assignment on its own. The solution can be achieved analytically with Karush-Kuhn-Tucker (KKT) conditions when the number of MSs is 2. Generally, the solution can be calculated with the interior-point method when the number of MSs is larger than 2 [17].

A. $M \times 1$ with $M = 2$

This condition makes the objective $R_{\text{sum}}(w^i)$ in (20) transformed from a double-sum function to a single-sum function so as to derive a standard convex optimization problem for MS $j (= 1, 2)$ as follows:

$$\arg \min_{w_n} \mathcal{L}_0 = -\frac{1}{N} \sum_{n=1}^N \log_2 \left(1 + \frac{s_{j,n}}{l_{j,n} + 1/w_{n}} \right)$$

subject to $\sum_{n=1}^N w_n \leq 1, \quad -w_n < 0 \quad \forall n$  

where $l_{j,n}$ is now independent of any weighting variables. Hence, the iterative algorithm is not needed and the optimal $w_n$ can be directly calculated by using the Lagrangian as

$$\mathcal{L}(w_n, \nu, \lambda_n) = \mathcal{L}_0 + \nu \left(\sum_{n=1}^N w_n - 1\right) - \sum_{n=1}^N \lambda_n w_n$$

and the following KKT conditions as

$$\sum_{n=1}^N w_n - 1 \leq 0, \quad -w_n < 0, \quad \nu \geq 0, \quad \lambda_n \geq 0, \quad \nu \left(\sum_{n=1}^N w_n - 1\right) = 0, \quad \lambda_n w_n = 0, \quad \frac{d\mathcal{L}_0}{dw_n} + \nu - \lambda_n = 0.$$  

Combining both conditions in (25) and applying it into (23) and (24), the optimal $w_n$ is derived as the water-filling-based solution as

$$w_n = \frac{1}{2} \left[ (a_1 + a_2)^2 - 4 \left(a_1 a_2 - \mu a_2 - a_1 \right) \right]^{1/2}$$

where $[x]^+ = \max(0, x)$. The auxiliary variables $a_1$, $a_2$, and the Lagrange dual variable $\mu$ are $1/(s_{j,n} + l_{j,n})$, $1/l_{j,n}$, and $1/\nu$, respectively. A unique $\mu$ can be obtained to satisfy the condition, $g(\mu) = 0$, where the function $g(\mu)$ is defined by

$$g(\mu) = \sum_{n=1}^N w_n - 1.$$  

Using a root-finding algorithm such as a bisection method, $\mu$ is easily determined and the corresponding optimal weighting variables are obtained.

B. $M \times 1$ case with $M > 2$

The optimization problem in (20) has a concave objective and affine constraints so that interior-point methods can be applied to solve it. The logarithmic barrier function is used to remove inequality constraints and to apply Newton’s method in this interior-point method. Table I shows the details of the proposed relaying power allocation algorithm. The scheme starts by initializing all the weighting variables uniformly, and obtains the optimal variables $w^i$. Then, the algorithm repeats the same procedure for the other weighting variables until it converges.
TABLE I
RELAYING POWER-ALLOCATION ALGORITHM

<table>
<thead>
<tr>
<th>Initialization:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w^i = \frac{1}{M} [1 \cdots 1]$ for $i = 1 \cdots M$</td>
</tr>
<tr>
<td>initialize $w' = {w^i}_{i=1}^M$</td>
</tr>
<tr>
<td>Recursion:</td>
</tr>
<tr>
<td>for each $w^i \in w'$</td>
</tr>
<tr>
<td>$w'^* = \arg \max_{w'} R_i(w')$</td>
</tr>
<tr>
<td>update $w^i = w'^*$</td>
</tr>
<tr>
<td>update $w = {w^i}_{i=1}^M$</td>
</tr>
<tr>
<td>if $</td>
</tr>
<tr>
<td>else $w' = w$</td>
</tr>
<tr>
<td>Result:</td>
</tr>
<tr>
<td>$w^* = w$</td>
</tr>
<tr>
<td>$R_{\text{sum}}(w) = R_{\text{sum}}(w^*)$</td>
</tr>
</tbody>
</table>

V. SIMULATION RESULTS AND DISCUSSION

This section shows the results of computer simulation, using Monte Carlo methods to evaluate the proposed relaying power allocation scheme. The number of BS antennas $M$ is 4, and the same number of MSs is assumed to be chosen. The number of OFDM tones $N$ varies from 16 to 256. According to one of the recent standards [18], the ratio $\gamma$ of the MS’s power to the BS’s power is 0.01 (= 23 dBm/43 dBm). The power of relay channel gain $\alpha_{i,j,n}$ between two MSs is exponentially distributed with mean $\lambda(=1 \text{ to } 10)$ under the assumption that the distance among MSs is much closer to the distance from the BS. Then, a new variable $\beta$ denotes $\gamma \lambda$ to indicate relaying efficiency through conferencing. The following figures compare the performance of the proposed relaying power allocation scheme with user-cooperation (RPAUC) to two previously suggested schemes: The first is a broadcast scheme with non-cooperation and limited feedback, zero-forcing beamforming (ZFBF) in [6], and the second is a broadcast scheme with user-cooperation and limited feedback under equal relaying power allocation (EPAUC) in [13].

Fig. 1 demonstrates the total throughput of RPAUC, EPAUC, and ZFBF with respect to $\beta$ and with the practical number of feedback bits $B = 3$, respectively. As expected, the proposed relaying power allocation scheme outperforms the equal power allocation scheme for all $\beta$s. It is observed that as $\beta$ decreases, the throughput gain increases. This implies that the efficiency of power allocation on noisy relay channels is relatively superior, and those channels have much room for improvement. On the other hand, both RPAUC and EPAUC outperform ZFBF for large $\beta$ because of cooperation among MSs, as explained in [13]. However, as $\beta$ is smaller and the SNR is lower, the amplified noise on relay channels degrades the throughput so that the advantage from user-cooperation becomes negligible.

Fig. 2 compares the asymmetric advantage by the proposed relaying power allocation on the throughput across different MSs. It is shown that the relative gain on the performance is most significant for MS 4 and decreases in the reverse order of MS indices. As a result of QRD used for decoding the data symbols, this explains asymmetry on the performance. Even though its gain from power allocation is low, MS 1 achieves the highest throughput with the help of cooperation among MSs. This result shows that scheduling should be considered for the proposed scheme, but is beyond the scope of this paper.

Fig. 3 shows the outage total throughput of all the RPAUC, EPAUC, and ZFBF as the number of subcarriers $N$ increases. The $\delta$ % outage throughput is defined such that the probability of the throughput being less than the value at each block period is $\delta$ %. In many applications, this outage performance can be used as criteria to satisfy the QoS requirement. The outage throughput gain by RPAUC over EPAUC and ZFBF increases with $N$ because the frequency diversity is more efficiently used to distribute mobile power into subcarriers at a large $N$. Besides, both RPAUC and EPAUC achieve significantly higher outage throughput than ZFBF at a large $B$. This is because as the multi-user interference caused by a limited feedback is getting smaller, the effects of the cooperation among MSs are getting more substantial in the outage throughput. It is
interesting to observe that the outage throughput of both EPAUC and ZFBF also increase with $N$ without any power allocation. This increase is caused by the statistical variation of the throughput which decreases with $N$ irrespective of power allocation. Thus, the outage performance is enhanced with $N$ even though the average throughput is still the same.

Fig. 4 shows the cumulative distribution function (CDF) of the total throughput under both EPAUC and ZFBF with respect to the number of subcarriers. This graph is beneficial to demonstrate how the distribution of total throughput is changed depending on $N$, and statistically how much the throughput gain from power allocation can be obtained. The proposed scheme shifts the CDF to the right so that it has a higher probability to achieve the enhanced throughput. In addition, for a large $N$, the variation of the total throughput is small so as to maintain the reliable throughput.

VI. CONCLUSION

This paper studied the relaying power allocation problem for OFDM systems when MSs can cooperate through their ad-hoc radio interfaces. Using this cooperation on relay channels, each MS was assumed to forward the received signals from the BS to nearby selected MSs. The proposed scheme enhanced the performance of user-cooperation by minimizing the effects of noise enhanced by a simple amplify-and-forward relaying strategy. The results of computer simulation showed that the proposed scheme reduces the throughput loss and increases the efficiency of cooperation as compared to the equal power allocation scheme.

To improve this cooperation-based scheme, future work needs to consider more effective relaying strategies and the optimal combination of beamforming and combining vectors. Even though an amplify-and-forward scheme is simple and easy to reduce delay caused by remodulating signals, the performance is limited by its nature to include noise in the forwarding signals. It is also interesting how the combination of beamforming and combining vectors should be chosen to optimize the total throughput. Finally, efficient scheduling can be another stimulus to cooperate among MSs.

REFERENCES