BIT LOADING ALGORITHMS FOR COOPERATIVE OFDM SYSTEMS

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ABSTRACT

In this paper, we investigate the resource allocation problem for an OFDM cooperative network with a single source-destination pair and multiple relays. Assuming knowledge of the instantaneous channel gains for all links in the entire network, we propose several bit and power allocation schemes aiming at minimizing the total transmission power under a target rate constraint. First, an optimal and efficient bit loading algorithm is proposed when the relay node uses the same subchannel to relay the information transmitted by the source node. To further improve the performance gain, subchannel permutation, in which the subchannels are reallocated at relay nodes, is considered. An optimal subchannel permutation algorithm is first proposed and then an efficient suboptimal algorithm is considered to achieve a better complexity-performance tradeoff. A distributed bit loading algorithm is also proposed for ad-hoc networks. Simulation results show that significant performance gains can be achieved by the proposed bit loading algorithms, especially when subchannel permutation is employed.

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I. INTRODUCTION

In cooperative systems, a group of single-antenna nodes transmits as a ”virtual antenna array,” obtaining diversity gain without requiring multiple antennas at individual nodes. Much recent work has addressed aspects of cooperative diversity, and significant benefits can be achieved (for example, see [1]-[2]).

Orthogonal Frequency Division Multiplexing (OFDM) is the underlying physical-layer technology for IEEE802.11 (WiFi) [3], as well as for IEEE802.16 (WiMAX) [4]. The modularity of OFDM and the fact that it will be used in many current and future systems makes it very appealing for consideration in cooperative wireless networks. More importantly, the use of orthogonal signaling and the inherent frequency diversity in a well-designed OFDM system are especially useful in obtaining the maximum benefits from cooperation. Currently, relay and cooperative networks with OFDM(A) transceivers have been proposed for applications in several emerging systems. IEEE 802.16’s Relay Task Group [5] is a developing standard for 802.16-based multihop networks. Also, relaying is considered in IEEE 802.11s [6], a developing mesh networking standard.

In an OFDM system, additional significant gains can be achieved by adaptive loading. In particular, more bits are placed in subchannels with larger channel gains, while subchannels which are faded carry less or even no bits. Over the past decade, this problem has been extensively investigated (for example, see [7]). In particular, different power and bit allocation schemes with diverse optimization objectives in single-user and multiuser environments have been studied.

The resource allocation problem in cooperative networks, however, has received much less attention. In [8], adaptive loading is employed in relay-to-destination links in an OFDM cooperative network to improve the end-to-end performance. In [9]-[10], the power allocation problem for nonregenerative OFDM relay links is investigated; in this work, the instantaneous rate is maximized for a given source and relay power constraint. In [11], aiming at maximizing the achievable sum rate from all the sources to the destination, a source, relay, and subchannel allocation problem for an OFDMA relay network is studied; however, in this work, the assumption that the relay node uses the same subchannel to relay the information transmitted by the source node limits the performance gain.

In this paper, we employ subchannel permutation, in which the subchannels are reallocated at relay nodes, and devise bit loading algorithms for cooperative OFDM systems with decode-and-forward relaying strategy. We consider a single source-destination pair with multiple assisting relay nodes. Our objective is to minimize the total transmission power by allocating bits and power to each subchannel based on the instantaneous channel gains. We first devise optimal bit loading algorithms under the assumption that the relay nodes re-transmit the information in the same subchannel as the source node. Then, we consider reallocating the source subchannels to possibly different relay subchannels to further improve performance. In this regard, the optimal subchannel permutation algorithm is described. To achieve the optimum performance, however, a large number of computations and comparisons is needed. We then propose a simple and efficient subchannel permutation algorithm. Simulation results indicate that significant performance gains can be achieved by the proposed bit loading algorithms, especially with subchannel permutation at the relay nodes.

The paper is organized as follows. The system model is described in Section II. In Section III, we propose optimal and efficient bit loading algorithms without subchannel permutation. The combination of these algorithms with subchannel permutation is considered in Section IV. Simulation results are given in Section V. A distributed bit loading algorithm is proposed in Section VI. Finally, Section VII summarizes and concludes the paper.

II. System model

We consider a single source-destination cooperative system with K relay nodes, as shown in Fig. 1. The relay nodes are randomly located between the source node and the destination node. An OFDM transceiver with N subchannels is available at each node. We assume perfect time and frequency synchronization among nodes and the inclusion of a cyclic prefix that is long enough to accommodate the delay spread of the channel.

A two-stage transmission protocol, as shown in Fig.1, is adopted. In the first stage, the source transmits and the other nodes listen - the links in this stage are called the source-relay (SR) links and the source-destination (SD) link. In the second stage, the relays retransmit the message to the destination - the links in this stage are called the relay-destination (RD) links. The source node does not transmit in the second stage. Hence, the source node and the relay nodes cannot transmit at the same time. Here, we adopt a *selective* decode-and-forward relaying strategy. In particular, each source subchannel can only be relayed by one relay node. The selected relay node will fully decode the received information, re-encode it, and then forward it to the destination. In the RD links, a specific subchannel can only be used by one relay node. Different source subchannels may select different relay nodes, similar to the selective OFDMA relaying in [12]. The destination node employs maximal ratio combining (MRC) to combine the received signals from the first and second stages. With these assumptions, interference is avoided.

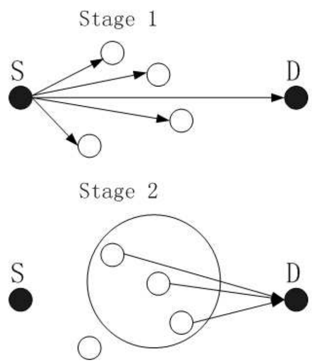

Fig. 1. Two-stage transmission protocol: In the first stage, the source transmits; in the second stage, those nodes which can decode the message from the source retransmit it to the destination.

Centralized resource allocation algorithms are considered in this paper. In particular, a central controller first collects the instantaneous channel gains of all links in the system. Then, it performs the assignment of resources and broadcasts the decisions to each node. We also assume all the channels experience slow fading. The possible application scenarios include WiFi and fixed WiMax systems, where the access point (AP) or base station can serve as the central controller.

We assume that the total required data rate is R bits per OFDM symbol (block). Let b_n denote the number of bits assigned to source subchannel n; b_n can take values in the set $B = \{0, 1, ..., B_{max}\}$. Further, denote the channel response of subchannel n from the source node to relay node k, from the source node to the destination node, and from relay node k to the destination node as $H_{sr_k}(n)$, $H_{sd}(n)$ and $H_{r_kd}(n)$, respectively. In general, these include path loss, shadowing, and Rayleigh fading. For convenience, let $G_{sr_k}(n)$, $G_{sd}(n)$ and $G_{r_kd}(n)$ denote the channel power gains, $\|H_{sr_k}(n)\|^2$, $\|H_{sd}(n)\|^2$ and $\|H_{r_kd}(n)\|^2$, respectively.

Let $\gamma(b_n)$ be the required received SNR per symbol in subchannel n for reliable reception of b_n bits/symbol. As in [13], SNR per symbol for subchannel n is

$$\gamma(b_n) = \rho * (2^{2b_n} - 1) \tag{1}$$

The parameter ρ ranges from 1 to about 6.4, depending on the degree of coding used [13]. The required received power $P_{req}(b_n)$ can be written as

$$P_{req}(b_n) = \gamma(b_n)N_0 \tag{2}$$

where N_0 is the double-sided noise power spectral density level.

Each subchannel can operate in two different modes: direct or cooperative transmission. Each subchannel compares the required power of these two modes and selects the one which has the minimum required power to achieve reliable reception at the destination node. The minimum power required for the direct transmission mode is

$$P_{sd}^{D}(n) = \frac{P_{req}(b_n)}{G_{sd}(n)} \tag{3}$$

The required power for cooperative transmission through relay node k includes two parts. The first part is the required source power to guarantee successful transmission from the source node to the relay node k. The second part is the transmission power of relay node k, which is determined by the fact that the sum of the two received powers at the destination node should be greater than the required minimum received power $P_{req}(b_n)$. We assume relay node k uses subchannel j to re-transmit the information from the source node in subchannel n. The relay node can use either the same subchannel to re-transmit the information or another subchannel. Let $P_{sr_k}^{C}(n)$ and $P_{r_k d}^{C}(n,j)$ denote the source power and the relay k power, respectively. The two powers should satisfy

$$P_{sr_k}^{C}(n)G_{sr_k}(n) \geq P_{req}(b_n) \tag{4}$$

and

$$P_{sr_k}^{C}(n)G_{sd}(n) + P_{r_k d}^{C}(n,j)G_{r_k d}(j) \geq P_{req}(b_n) \tag{5}$$

The total power for cooperative transmission is

$$P_{sr_k d}^{C}(n,j) = P_{sr_k}^{C}(n) + P_{r_k d}^{C}(n,j) \tag{6}$$

When the channel gains of the SR and the RD links are both greater than the channel gains of the SD links, i.e., $G_{sd}(n) < min\{G_{sr_k}(n), G_{r_k d}(j)\}$ for any k, cooperative transmission requires less power than direct transmission. In this case, the minimum power required for cooperative transmission through subchannel j at relay node k can then be expressed as

$$P_{sr_k d}^{C}(n,j) = P_{req}(b_n)\frac{\Delta_k(n,j)}{G_{sr_k}(n)G_{r_k d}(j)} \tag{7}$$

where $\Delta_k(n,j) = G_{sr_k}(n) + G_{r_kd}(j) - G_{sd}(n)$.

Here, for cooperative transmission, we define an equivalent channel power gain $G^C_{sr_kd}(n,j)$, given by

$$G^C_{sr_kd}(n,j) = \frac{G_{sr_k}(n)G_{r_kd}(j)}{\Delta_k(n,j)} \tag{8}$$

Thus, the minimum total power required for cooperative transmission for subchannel n through subchannel j at relay node k is

$$P^C_{sr_kd}(n,j) = \frac{P_{req}(b_n)}{G^C_{sr_kd}(n,j)} \tag{9}$$

We use $\beta(n) \in \{0,1\}$ to indicate the mode in which subchannel n operates. Let $\beta(n) = 1$ indicate direct transmission. Also, we use $\alpha_k(n,j) \in \{0,1\}$ to indicate whether or not subchannel n is used in cooperation with subchannel j at relay node k. Our objective is to allocate bits and power to each subchannel to minimize the total transmitting power P^*_T. Mathematically, we can formulate the optimization problem as

$$P^*_T = \min_{b_n \in B} \sum_{n=1}^{N} \frac{P_{req}(b_n)}{G(n)} \tag{10}$$

where

$$G(n) = \beta(n)G_{sd}(n) + \sum_{k=1}^{K}\sum_{j=1}^{N} \alpha_k(n,j)G^C_{sr_kd}(n,j) \tag{11}$$

subject to the following three constraints

$$C1 : R = \sum_{n=1}^{N} b_n \tag{12}$$

$$C2 : \beta(n) + \sum_{k=1}^{K}\sum_{j=1}^{N} \alpha_k(n,j) = 1, \forall n \tag{13}$$

$$C3 : \sum_{k=1}^{K}\sum_{n=1}^{N} \alpha_k(n,j) \leq 1, \forall j \tag{14}$$

Note that $C1$ is the rate constraint, $C2$ indicates that each SR subchannel can only be relayed by at most one relay at a given time, and $C3$ means that each RD subchannel j can be used by at most one relay.

III. Bit loading

In this section, we devise bit loading algorithms without subchannel permutation. In this case, for subchannel n in the SR links, the selected relay node also uses subchannel n in the RD links to retransmit the information. The equivalent channel power gain through relay node k is determined by the mode in which the subchannel is used. If $G_{sd}(n) < \min\{G_{sr_k}(n), G_{r_kd}(n)\}$, cooperative transmission is preferred and the equivalent channel power gain is the cooperative transmission gain, $G^C_{sr_kd}(n,n)$; otherwise, direct transmission costs less power and the equivalent channel power gain is the gain of SD links, $G_{sd}(n)$. Hence, the equivalent channel power gain through relay node k is

$$G_{sr_kd}(n) = \begin{cases} \dfrac{G_{sr_k}(n)G_{r_kd}(n)}{\Delta_k(n,n)} & if \quad G_{sd}(n) < \min\{G_{sr_k}(n), G_{r_kd}(n)\} \\ G_{sd}(n) & otherwise \end{cases} \tag{15}$$

Each subchannel should be used by the relay node, among the K nodes, which has the largest equivalent channel power gain to relay the information. Let $G_{eq}(n)$ denote this maximum equivalent channel power gain, then it can be written as

$$G_{eq}(n) = \arg \max_{k=1,..,K} G_{sr_kd}(n) \tag{16}$$

The optimization problem in (10) can be rewritten as

$$P_T^* = \min_{b_n \in B} \sum_{n=1}^{N} \frac{P_{req}(b_n)}{G_{eq}(n)} \tag{17}$$

In this case, $C2$ and $C3$ are automatically satisfied, and we only need to consider the rate constraint, $C1$.

A. Greedy Algorithm

From (17) we can see that the optimization problem is similar to that in point-to-point OFDM systems, which has been extensively researched. Among all kinds of algorithms, the greedy algorithm, first introduced in [14], is believed to yield the optimal solution. This algorithm allocates bits one by one until the target rate R is achieved. In each step, the additional power increase of each subchannel in order to transmit the additional bit in that subchannel is calculated, and the one with the minimum power increase is selected. The idea is quite simple and several efficient greedy algorithms [15] have been proposed. However, sorting and comparisons in each step make the algorithm complex, especially when the available subchannels and the target number of bits are very large, as in IEEE 802.16 systems.

B. Lagrange Optimization

As discussed in the previous subsection, the greedy algorithm has the optimal performance, but it is too complex for high data-rate systems. In this subsection, we propose an efficient bit loading algorithm. To solve the optimization problem (17), we first release the constraint that b_n must be an integer. Substituting (1) and (2) into (17), we obtain

$$\begin{aligned} P_T^* &= \min_{b_n} \sum_{n=1}^{N} \frac{\rho * (2^{2b_n} - 1) N_0}{G_{eq}(n)} \\ &= -\sum_{n=1}^{N} \frac{\rho N_0}{G_{eq}(n)} + \min_{b_n} \sum_{n=1}^{N} \frac{\rho * 2^{2b_n} N_0}{G_{eq}(n)} \end{aligned} \tag{18}$$

So the optimization problem reduces to

$$P_T^* = \min_{b_n} \sum_{n=1}^{N} \frac{\rho N_0 * 2^{2b_n}}{G_{eq}(n)} \tag{19}$$

Including the constraint, the objective function is

$$L(\lambda) = \sum_{n=1}^{N} \frac{\rho N_0 * 2^{2b_n}}{G_{eq}(n)} - \lambda(R - \sum_{n=1}^{N} b_n) \tag{20}$$

where λ is a Lagrange multiplier. After differentiating $L(\lambda)$ with respect to b_n, and setting to 0, we obtain

$$\frac{2^{2b_n}}{G_{eq}(n)} = \frac{\lambda}{2\rho N_0 * ln2} = \varphi, \forall n \tag{21}$$

where φ is a constant independent of n. Then we get

$$\left(\frac{2^{2b_n}}{G_{eq}(n)}\right)^N = \varphi^N = \prod_{n=1}^{N} \frac{2^{2b_n}}{G_{eq}(n)} = \frac{2^{2\sum_{n=1}^{N} b_n}}{\prod_{n=1}^{N} G_{eq}(n)} \tag{22}$$

Thus the number of bits in subchannel n, b_n, is

$$b_n = \frac{R}{N} + \frac{1}{2}\log_2 \frac{G_{eq}(n)}{\left(\prod_{n=1}^{N} G_{eq}(n)\right)^{1/N}} \tag{23}$$

The first part in (23) is the average number of bits per subchannel. The second part is a margin determined by the ratio of the n-th subchannel's power gain over the geometric mean of the N subchannels' power gains [7]. It is interesting to notice that eq. (23) is similar to eq. (11) in [16]; although the objective functions and constraints are different.

In the previous derivations, we removed the constraint on b_n to be an integer. Moreover, the result in (23) may be less than zero. This means that the channel gain of subchannel n is so small that we should not transmit any information. We exclude these subchannels and then repeatedly apply (23) until all the b_n are greater than zero. Next, we can adopt the algorithm in [16] to round b_n to an integer value. The required transmission power can be calculated using (17) after all the bits are allocated. Note that, in this algorithm, the number of iterations is determined by the number of subchannels with zero bits, which is much smaller than the number of iterations in the greedy algorithm.

IV. SUBCHANNEL PERMUTATION

In this section, we consider subchannel permutation to further save transmission power. We not only allocate bits and power to subchannels, but also reallocate the subchannels used for transmission in the RD links. The optimization problem (10) becomes a combinational problem and is difficult to solve. Exhaustive search can obtain the optimal solution; however, the computational complexity is too high. Here, we first propose a simplified greedy algorithm, which is still complex, especially when the number of target bits is high. Next, we propose a suboptimal algorithm, which is more efficient but which is close to optimum performance.

A. Greedy Algorithm

As discussed in Section III-A, greedy algorithms allocate bits on a bit-by-bit basis to the subchannel which has the minimum increase in power required to transmit the additional bit. In each step, the increase in power for all possible allocation schemes is calculated. When we allocate the first bit, there are N^2K possible allocation schemes, where K is the number of relay nodes and N is the number of subchannels. First, consider the inverse of the channel power gain in (8), that is,

$$\begin{aligned}\frac{1}{G^C_{sr_kd}(n,j)} &= \frac{\Delta_k(n,j)}{G_{sr_k}(n)G_{r_kd}(j)} \\ &= \delta(n)\frac{1}{G_{r_kd}(j)} + \frac{1}{G_{sr_k}(n)}\end{aligned} \tag{24}$$

where $\delta(n) = (G_{sr_k}(n) - G_{sd}(n))/G_{sr_k}(n)$ is a coefficient of subchannel n. We can see that for SR subchannel n, the channel power gain of cooperative transmission achieves the maximum value if it is paired with the *best* subchannel in the RD links, i.e., the subchannel with highest channel power gain. So, in each step of the greedy algorithm, for each relay node, subchannels in the SR links only need to be paired with the *best* available subchannel in the RD links. When allocating the first bit, we only need to calculate the channel gains for NK permutation schemes and then compare these gains to find the scheme which has minimum power increase to transmit the additional bit. Obviously, this is much more efficient than exhaustive search. The algorithm can be described as follows:

- Step 1: Initialize $b_n = 0$ for all $n = 1, ..., N$.
- Step 2: Compute the additional transmit power for subchannel n, $n = 1, ..., N$. If SR subchannel n has been paired, then computer the additional transmit power as

$$\Delta P(n) = \frac{P_{req}(b_n + 1) - P_{req}(b_n)}{G(n)}. \tag{25}$$

  Otherwise, in each relay node k, $k = 1, ..., K$, pair the SR subchannel n with the unpaired RD subchannel in relay k which has maximum channel power gain, and we denote that subchannel as $\hat{j}_k$. Calculate the equivalent channel power gain $G_{sr_kd}(n, \hat{j}_k)$, as

$$G_{sr_kd}(n, \hat{j}_k) = \begin{cases} \dfrac{G_{sr_k}(n)G_{r_kd}(\hat{j}_k)}{\Delta_k(n, \hat{j}_k)} & if \quad G_{sd}(n) < \min\{G_{sr_k}(n), G_{r_kd}(\hat{j}_k)\} \\ G_{sd}(n) & otherwise \end{cases} \tag{26}$$

  and find

$$k^* = \arg \max_{k=1,...,K} G_{sr_kd}(n, \hat{j}_k),$$

  so the equivalent channel power gain is

$$G(n) = G_{sr_{k^*}d}(n, \hat{j}_{k^*}).$$

  Then the additional transmit power can be calculated as in (25).
- Step 3: Find the minimum power increase among N subchannels

$$n^* = \arg \min_{n=1,...,N} \Delta P(n),$$

  and update $b(n^*)$ as

$$b(n^*) = b(n^*) + 1$$

Also, if SR subchannel n^* is newly paired with RD subchannel j in Step 2, then RD subchannels j of all K relay nodes are marked unavailable.

- Step 4: If rate constraint (12) is satisfied, then bit loading operation is complete; otherwise, go to step 2.

The performance of the greedy algorithm, of course, will serve as a bound for the performance of the suboptimal algorithms.

B. Suboptimal Algorithm

Although the simplified greedy algorithm is much simpler than exhaustive search, it is still quite complex when the number of target bits is large. Here, we propose an alternative algorithm which has suboptimal performance but is much more efficient. In this algorithm, we first reallocate subchannels in the SR links to subchannels in the RD links, and then we perform the bit loading algorithm proposed in Section III-B.

We know that cooperative transmission is preferred when $G_{sd}(n)$ is smaller than $G_{sr_k}(n)$ and $G_{r_kd}(j)$. So $\delta(n)$ of (23) is a value between zero and one when cooperative transmission is preferred. Then, $1/G^C_{sr_kd}(n,j)$ can be roughly approximated by the sum of $1/G_{r_kd}(j)$ and $1/G_{sr_k}(n)$. It is easy to see that we should pair good subchannels in the SR links with good subchannels in the RD links. Also, bad SR subchannls should be paired with bad RD subchannels. After permutation, the equivalent channel power gains of cooperative transmission vary greatly from subchannel to subchannel. In this case, the frequency diversity can be easily exploited by bit loading. Based on this idea, we propose the following greedy subchannel permutation algorithm. In our algorithm, the subchannel is paired in an one-by-one basis. In each step, we pair the best unpaired SR subchannel with the best unpaired RD subchannel. The details of the algorithm are summarized below.

- Step 1: For each relay k, find the maximum subchannel power gains of the SR and RD links, respectively; denote them by $G_{sr_k}(n)$ and $G_{r_kd}(j)$. Calculate the equivalent channel power gain $G_{sr_kd}(n,j)$, as in (26).
- Step 2: Compare the equivalent channel power gain $G_{sr_kd}(n,j)$ of the K relay nodes. Determine the values of n and j which maximize $G_{sr_{\hat{k}}d}(\hat{n},\hat{j})$. Pair those subchannels and denote them as $\hat{n}$ and $\hat{j}$.

- Step 3: Set the gains of the SR subchannel $\hat{n}$ and the RD subchannel $\hat{j}$ of all relay nodes to zero.
- Step 4: If all the subchannels are paired, the subchannel permutation operation is complete. Otherwise, go to Step 1.

In the subchannel permutation approach, the computational complexity mainly comes from finding the maximum channel gains of the SR links and the SD links. The number of iterations is equal to the number of subchannels, N, which is much smaller than the number of iterations for the greedy algorithms. After reallocating subchannels, the bit-loading Lagrange algorithm in Section III-B is performed to allocate the power and bits. As discussed there, the Lagrange algorithm has low computational complexity. Thus, the computational complexity can be greatly reduced by performing subchannel permutation and bit loading separately.

V. Simulations results

In this section, we present simulation results to compare the performance of the different bit loading algorithms. Consider a single source-destination pair OFDM cooperative network with K relay nodes. We assume that the K relay nodes are located in the middle of the source-to-destination path. In each node, an OFDM transceiver with $N = 64$ subchannels is employed. We also assume that each relay node has the same distance to the source and the destination. We normalize the distance from the relay nodes to the source and to the destination to one; the path loss exponent is 4. Shadowing is not considered. We assume that the channels between the source and each relay and the channels between each relay and the destination are independent. The power delay profile is assumed to be exponential with a root-mean-square delay spread $\tau_{rms} = \eta T$, where T is the time duration of one OFDM symbol (block), $T = NT_s$ and $0 < \eta \leq 0.1$. In the simulation, we use a discrete-time model with an impulse response limited to 16 samples spaced by T_s. This is sufficient to encompass all of the paths with significant energy.

We assume the target bit rate of the system is such that there are 128 bits per OFDM symbol. And b_n can take values in the set $B = \{0, 1, ..., 4\}$. So, without bit loading, each subchannel will transmit 2 bits per OFDM symbol; we call this Equal Bit Allocation (EBA) *. When there are

*Coding is not considered in this paper. It has been shown that coded bit-loading OFDM systems also greatly outperform coded OFDM systems in point-to-point networks [15]. Here, for cooperative networks, distributed coding is an interesting problem to be explored in future work.

multiple relay nodes, for each subchannel n, the best subchannel among K relays is selected.

In Fig. 2, we compare the average required transmission power for Greedy Bit Loading (GBL), Lagrange Bit Loading (LBL) and EBA. We do not consider subchannel permutation (SP) in this case, and we assume there is only one relay node, i.e., $K = 1$. It can be seen that the required transmission power for GBL and LBL are almost the same, but LBL is much less complex. We also notice that the required transmission power for GBL and LBL decreases with an increase in the delay spread, τ_{rms}. This is because an increase in delay spread corresponds to more available frequency diversity, and hence more gains can be achieved. The performance of EBA is not good because coding is not employed; thus, the frequency diversity is not exploited for EBA as implemented here. Compared to EBA, a 3-dB power saving can be achieved by LBL.

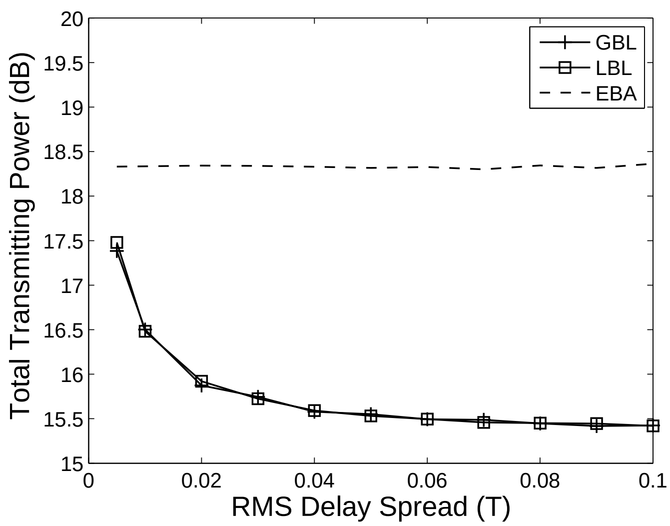

Fig. 2. Average transmission power required for different bit loading algorithms with $K = 1$.

In the following simulation, we assume $\tau_{rms} = 0.1T$, which is a reasonable delay spread for practical systems. Fig. 3 presents the block error rate (BLER) versus SNR with different numbers of relay nodes. We adopt the efficient LBL in the simulation. From the results, we can see that the performance gains of LBL over EBA decrease with an increase in K, the number of relay nodes. For $\tau_{rms} = 0.1T$, the power saving of LBL decreases from 3-dB with one relay node to 1-dB with four relay nodes. The main reason is that, for each subchannel, we compare the subchannel gains of K relay nodes and select the best one. The more relay nodes, the less subchannel gain variation after selection, and the less frequency diversity to be exploited by bit loading.

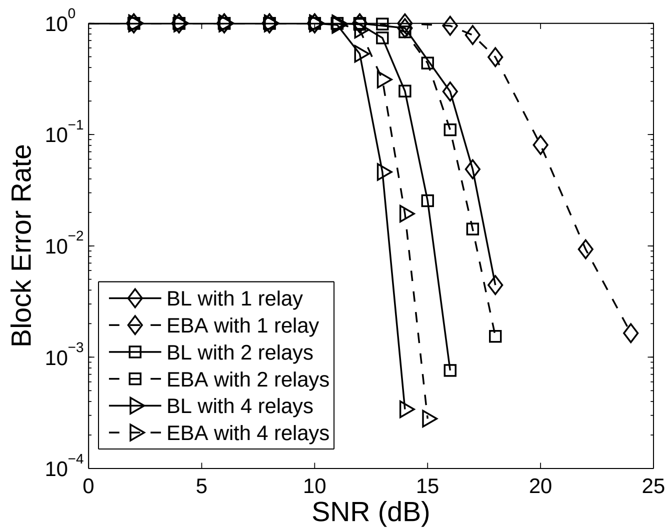

Fig. 3. Block error rate for different bit loading algorithms with $K = 1, 2, 4$.

Fig 4. shows the BLER comparison of the bit loading algorithms with and without subchannel permutation (SP). The number of relay nodes K is one in this simulation. From the results, we can see that the optimal BL with SP further improves the performance by 2-dB. Compared with EBA, a 5-dB gain can be achieved by bit loading algorithm at the expenses of extra internode communications and computations.

In Fig. 5, we present the performance of the bit loading algorithms using subchannel permutation (SP) with $K = 1, 2, 4$ relay nodes, respectively. Compared with EBA, a dramatic performance gain can be achieved by BL with SP, even in the case when four relay nodes are employed. For an outage of 10^{-2}, the performance gain is 5-dB, 4-dB, and 3-dB with 1, 2, and 4 relay nodes, respectively. As discussed in the previous section, the optimal BL with SP is too complex, especially with a large number of relay nodes. In Fig. 6, we compare the performance degradation using the suboptimal, but less complex, BL with SP. We can see that the performance gap increases with an increase in the number of relay nodes, K. At an outage of 10^{-2}, a 0.5-dB performance degradation can be observed by suboptimal algorithm when $K = 4$; although, it is still 2.5-dB better than EBA. A good complexity and performance tradeoff can be achieved by

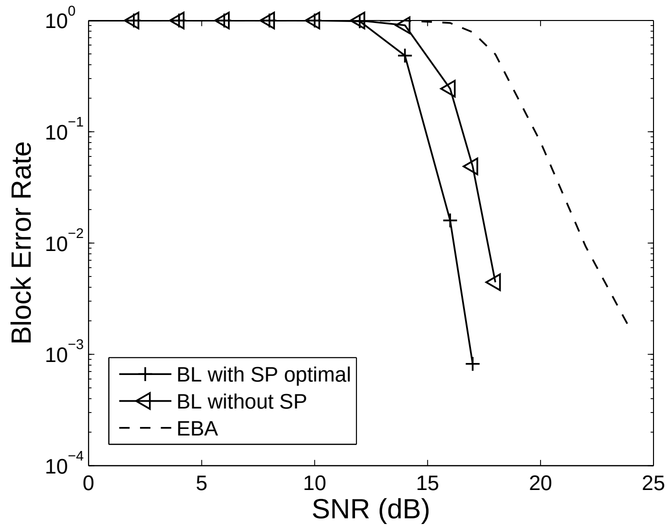

Fig. 4. Block error rate for different bit loading algorithms with subchannel permutation, $K = 1$.

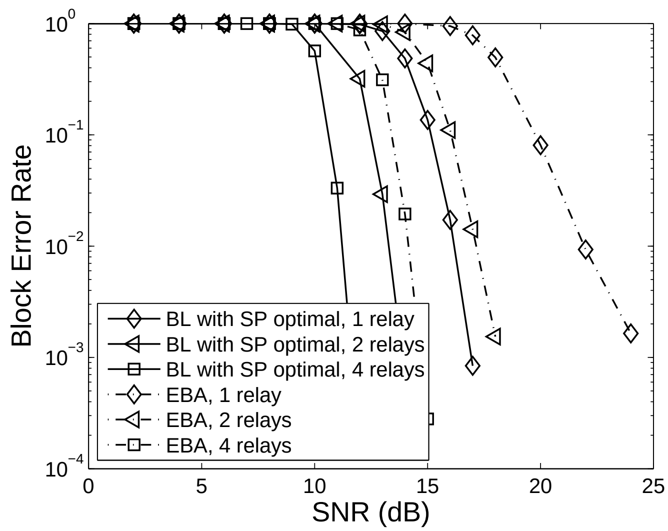

Fig. 5. Block error rate for different bit loading algorithms with subchannel permutation, $K = 1, 2, 4$.

using the suboptimal algorithm.

From these results, we can see that the proposed BL algorithm can significantly save transmission power, especially when the number of relays is small. A small number of relays on their own does not provide enough space diversity. So that even simple BL without SP can provide significant gains, compared to EBA. With an increase in the number of relays, however, space

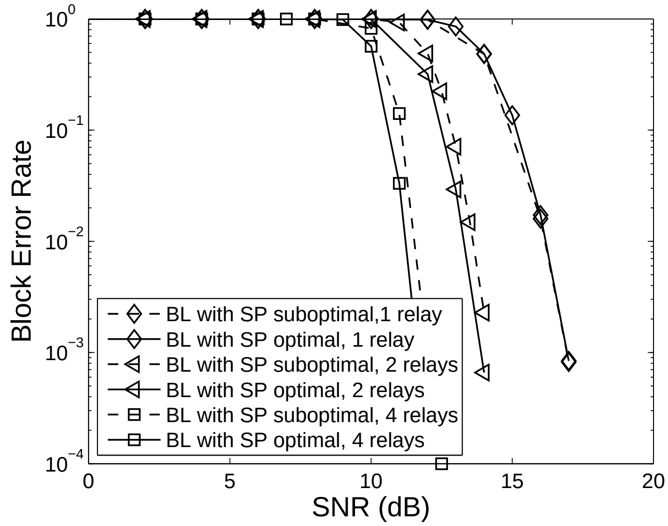

Fig. 6. Block error rate for optimal and suboptimal bit loading algorithms with subchannel permutation, $K = 1, 2, 4$.

diversity can provide good performance improvement; thus, only the BL with SP can provide significant performance gain, at the expense of complex computations.

The communications overhead of BL and EBA are similar. The instantaneous channel gains are required by both to make decisions, and these must be broadcast to nodes in the network. EBA only needs to select the good subchannels among relays. BL, however, also allocates bits to subchannels, which entails more complexity.

VI. DISTRIBUTED ALGORITHM

In the previous part, we mainly concentrated on bit loading algorithms with a central controller. Distributed algorithms are more attractive in ad-hoc networks, in which central controllers are not affordable. Here, we propose a distributed bit loading algorithm for ad-hoc networks.

In an ad-hoc network, the source node first sends a RTS (Request to Send) signal to request a transmission. The relay nodes and the destination can measure the SR and SD links through listening to the RTS signal, respectively. Then, the destination node sends a CTS (Clear To Send) signal to tell the source node that the channel is ready. We can put the channel gains of the SD link in the CTS signal so that the relay nodes can obtain them. The relay nodes can measure the RD links by listening to the CTS signal. In this way, each relay node obtains channel gains of its own SR, RD links and channel gains of the SD links. Hence, each relay node can perform bit loading algorithms and calculate the total minimum transmission power. A similar distributed relay selection algorithm as in [17] can be adopted here. In this algorithm, each relay sets a timer based on its calculated total transmission power. The smaller the total transmission power is, the shorter the timer should be. In this way, the timer of the relay with the smallest total transmission power will expire first. That relay then sends a flag signal with the resource allocation information. All other relays, while waiting for their timer to reduce to zero, are in listening mode. As soon as they hear the flag signal, they back off. So the relay node which has minimum total transmission power will participate the cooperative transmission between the source node and the destination node.

In this distributed algorithm, only one relay node are selected to participate the cooperative transmission, that is, all the subchannels are relayed by the same relay node. In the centralized algorithm, however, each subchannel may be relayed by different relay nodes, and all the relay nodes may participate the cooperative transmission. Obviously, the centralized algorithm performs better than the distributed algorithm at the expense of more communications overhead.

In the following, we compare the performance of the distributed BL algorithm and the distributed EBA algorithm. For the distributed EBA algorithm, the same process as the the distributed BL algorithm is performed. Only one relay node is selected to relay the information and all the subchannels have the same number of bits. The same simulation environment as in Section V. is adopted. The suboptimal BL with SP is employed in the distributed BL algorithm. As shown in Fig. 7, the distributed BL algorithm significantly outperforms the distributed EBA algorithm. Although the performance gain decreases with an increase in the number of relay nodes, K, a 4-db performance gain is still achieved by BL at an outage of 10^{-2}. Compared with the centralized BL algorithm with SP, 2.5-dB performance degradation can be observed with 4 relay nodes. The main reason is that only one relay node is selected in the distributed algorithm.

VII. CONCLUSIONS

In this paper, we investigated resource allocation for cooperative OFDM systems. Aiming at minimizing the total two-stage transmission power for a given transmission rate, we formulated the optimization problem and proposed several bit loading algorithms. First, without considering subchannel permutation, we showed that the optimization problem is similar to that for point-to-point OFDM systems. We proposed an efficient bit-loading algorithm and simulation results

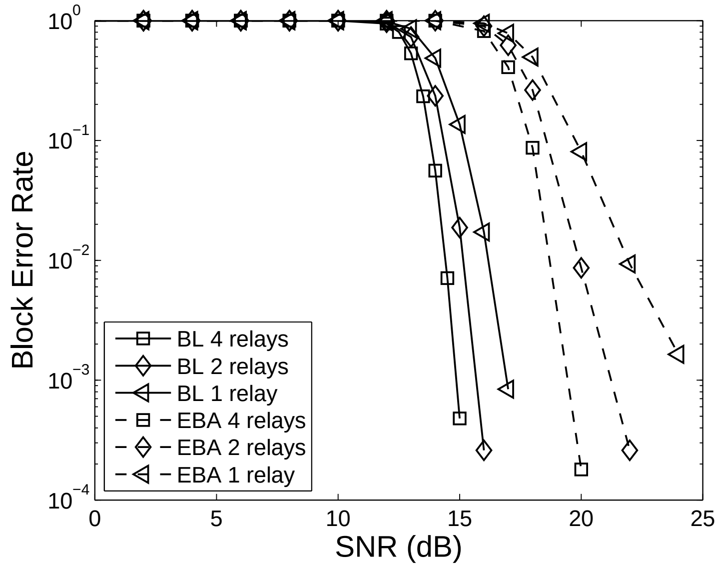

Fig. 7. Block error rate for distributed BL and EBA algorithms, $K = 1, 2, 4$.

demonstrated that the proposed algorithm has similar performance to the optimal one. Using these algorithms, the total transmitting power can be reduced by 3-dB, compared to the EBA algorithm. The performance gain, however, decreases with an increase in the number of relay nodes.

To further improve the bit loading performance gain, we considered re-allocating subchannels in the RD links, called subchannel permutation. An optimal algorithm and an efficient suboptimal algorithm were proposed for this case. Simulation results show that the optimal algorithm with subchannel permutation can further improve the performance by at least 2-dB. Even with four relay nodes, the optimal algorithm with subchannel permutation still outperforms EBA by about 3-dB. An efficient suboptimal subchannel permutation algorithm was also proposed which can achieve a good performance-complexity tradeoff.

We also propose a distributed bit loading algorithm for ad-hoc networks. A significant performance gain can be achieved by this algorithm, compared with the distributed EBA algorithm. Compared with the centralized algorithms, only a small performance degradation is observed. Devising distributed algorithms with performance as good as centralized algorithms is an interesting and challeging problem. In particular, a distributed coding approach might be a fruitful direction for future study.

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