EFFICIENT WEIGHTED-SUM-RATE MAXIMIZATION FOR A CLASS OF HALF-DUPLEX COOPERATIVE SYSTEMS

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ABSTRACT

In many half-duplex cooperative systems, the direct formulation of the problem of finding the jointly optimal power and channel resource allocation that maximizes a weighted sum of the achievable rates can be difficult to solve. In this paper, we provide an efficient algorithm to solve this problem for a class of systems with convex achievable rate regions. For those systems, we show that the weighted-sum-rate problem can be solved using a bisection-based search in which a "target rate" problem is solved at each step. The target rate problem involves maximizing one of the achievable rates subject to target values for the other rates, and can be efficiently solved in a number of cases. We show that the proposed technique can be applied to orthogonal multiple access relay systems and that joint optimization can result in significantly larger weighted sum rates than optimization over the powers alone with a fixed channel resource allocation.

Index Terms— joint power and resource allocation; cooperative communication; convex optimization; quasi-convexity

1. INTRODUCTION

Cooperative communication systems seek to improve the quality of service that can be offered to the nodes in a network by providing the opportunity for the nodes to cooperate with each other, or with dedicated relay nodes, in the transmission of their messages; e.g., [1–3]. A convenient framework for facilitating cooperation is that in which the nodes operate in a half-duplex fashion (i.e., they do not simultaneously transmit and receive in the same band), and the messages from each user are transmitted over orthogonal channels so as to enable per-user decoding at the destination. However, the extent of the quality of service gains that can be obtained from such a framework is dependent on the appropriate allocation of the resources provided by the channel (e.g., time and bandwidth) to the messages from each node (e.g., [4]), and the appropriate allocation of the power available at each node to its transmission and relaying tasks; e.g., [5]. The focus of this paper is on jointly optimal allocation of these radio resources, and, as in [4, 5], the emphasis is on quasi-static environments that enable centralized design with full channel state information.

We will consider joint radio resource allocation problems in which the objective is to maximize a weighted sum of the rates that are achievable using a given cooperation scheme. For some schemes, when the channel resource allocation is fixed, the achievable rates of each user can be written as a concave function of the allocated powers, and hence the problem of optimizing the weighted sum rate over the allocated powers can be efficiently solved; e.g., [5]. However, for most cooperation schemes, the achievable rate of each user is not a jointly concave function of the powers and the channel resource allocation, and hence the problem of jointly optimizing the radio resource allocation so as to maximize a weighted sum of the rates can be difficult to solve. The direct formulation of that problem remains difficult to solve even for systems in which the maximum achievable rate of each user can be written as a quasi-convex (cf. [6]) function of the channel resource allocation. However, for such schemes the "target-rate" optimization problem, in which the achievable rate of one node is maximized subject to the other nodes being able to achieve given target rates, can be efficiently solved; e.g., [7–9]. (Quasi-convexity also plays a role in a somewhat different relay system [10].) That said, maximizing a weighted sum of the achievable rates often better matches the nature of the communicated traffic than the target-rate problem, and hence in those applications maximizing the weighted sum rate would be the preferred formulation of the radio resource allocation problem. Unfortunately, the sum of quasi-convex functions is not necessarily quasi-convex, and hence the search for an efficient algorithm for maximizing the weighted sum rate has continued.

In this paper, we develop an efficient algorithm for jointly optimizing the weighted sum rate over the power and channel resource allocation for a class of half-duplex cooperative systems with orthogonal transmission. In particular, we consider those systems for which the target rate optimization problem can be efficiently solved. As shown in [8], this class includes the orthogonal multiple access relay channel; cf. [3]. (It also includes the half-duplex cooperation scheme in [7, Sec. V].) For this class of systems, we show that if the jointly optimized achievable rate region (without time-sharing between system operating points) is convex, then the weighted-sum-rate maximization problem can be efficiently solved by solving a sequence of target-rate problems in a bisection-based search. (A sufficient condition for the jointly optimized achievable rate region to be convex is that the achievable rate of each user is a concave function of the allocated powers.) As we will demonstrate, joint optimization can result in significantly larger weighted sum rates than optimization over the powers alone for a fixed resource allocation.

2. SYSTEM MODEL

We will develop the main result of this paper for an abstract model that is applicable in a number of different scenarios, and in Section 4 we will show how the derived algorithm can be applied to the orthogonal multiple access relay channel. For simplicity, the development will focus on a two-user scenario, but an extension to multiple users will appear in Section 4.

We consider a two-user multiple access system that employs half-duplex relaying, either by the other user or by a dedicated relay, and we will focus on systems in which the sub-channels on which each user's message is transmitted are orthogonal to those of the other user. This framework enables per-user decoding, yet still allows for coherent combining at the receiver. We will focus on the case in which the orthogonal subchannels are synthesized in the time domain,[1] with a fraction r of each time slot being allocated to the transmission of the message from User 1, and the remaining fraction $\hat{r} = 1 - r$ being allocated to the message from User 2.

In addition to a dependence on r, the achievable rate pairs of such a system depend on the power allocated to each component of the chosen relaying protocol. We will let $\mathbf{p}_1$ denote the vector that contains the operating power levels used in the transmission of the message of User 1, and $\mathbf{p}_2$ denote the corresponding vector for User 2. We will collect these power levels in the vector $\mathbf{p} = [\mathbf{p}_1^T \ \mathbf{p}_2^T]^T$. We will consider a system in which the appropriate power constraints can be written in the form $\sum_i \lambda_{ki}[\mathbf{p}]_i \leqslant [\bar{\mathbf{p}}]_k$, for some coefficients λ_{ki} that may be affinely dependent on r, and some bounds collected in $\bar{\mathbf{p}}$. Constraints on the average power and the operating power levels can be captured in this way, as can the nonnegativity of power. Therefore, we will consider a generic power constraint of the form $\mathbf{G}(r)\mathbf{p} \preccurlyeq \bar{\mathbf{p}}$, where the inequality is to be interpreted element-wise.

We will consider a quasi-static channel environment with coherent reception. For a given power allocation $\mathbf{p}$ and resource allocation r, the achievable rate region is

$$\mathcal{R}(r, \mathbf{p}) = \left\{(R_1, R_2) \mid R_1 \leqslant \bar{R}_1(r, \mathbf{p}_1) \text{ and } R_2 \leqslant \bar{R}_2(r, \mathbf{p}_2)\right\}, \tag{1}$$

where the functions $\bar{R}_i(r, \mathbf{p}_i)$ take the form (e.g., [5, 8])

$$\bar{R}_1(r, \mathbf{p}_1) = r f_1(\mathbf{p}_1), \qquad \bar{R}_2(r, \mathbf{p}_2) = \hat{r} f_2(\mathbf{p}_2), \tag{2}$$

for some functions $f_1(\cdot)$ and $f_2(\cdot)$ that depend on the relaying strategy. Using (1), the achievable rate region of the considered systems can be written as

$$\mathcal{R}(\bar{\mathbf{p}}) = \bigcup_{\substack{r \in [0,1] \\ \{\mathbf{p} \mid \mathbf{G}(r)\mathbf{p} \preccurlyeq \bar{\mathbf{p}}\}}} \mathcal{R}(r, \mathbf{p}). \tag{3}$$

For a number of systems with centralized power and channel resource allocation, the boundary of the achievable rate region in (3) can be efficiently found by considering a set of target rate problems parametrized by the target rate for User 2, $R_{2,\mathrm{tar}}$, [7, 8]. Those problems take the form

$$\max_{\mathbf{p},\, r \in [0,1]} \quad \bar{R}_1(r, \mathbf{p}_1) \tag{4a}$$

$$\text{s.t.} \quad \bar{R}_2(r, \mathbf{p}_2) \geqslant R_{2,\mathrm{tar}}, \tag{4b}$$

$$\mathbf{G}(r)\mathbf{p} \preccurlyeq \bar{\mathbf{p}}. \tag{4c}$$

However, when operating point the system in practice, it may be more appropriate to select some weights and maximize a single weighted sum of the achievable rates.

3. WEIGHTED SUM RATE MAXIMIZATION PROBLEM

In the two-user case, the weighted-sum-rate maximization problem can be formulated as follows: Given $\mu \in [0, 1]$,

$$\max_{\mathbf{p},\, r \in [0,1]} \quad \mu \bar{R}_1(r, \mathbf{p}_1) + (1 - \mu)\bar{R}_2(r, \mathbf{p}_2) \tag{5}$$
$$\text{s.t.} \quad \mathbf{G}(r)\mathbf{p} \preccurlyeq \bar{\mathbf{p}}.$$

[1]The principles of the proposed approach can also be applied to the frequency domain case, but the technical details are somewhat different.

If the functions $\bar{R}_i(r, \mathbf{p}_i)$ are concave functions of $\mathbf{p}_i$, and if the maximization of the weighted sum rate is done over only the allocated powers, then the problem in (5) is convex and the optimal solution can be obtained efficiently; e.g., [5]. However, our goal is to maximize over both the powers and the channel resource allocation. For most systems that problem is neither convex nor quasi-convex, and can be difficult to solve. In this section, we will develop an efficient algorithm for solving this problem for the class of systems for which the jointly optimized rate region that is achievable without time-sharing between system operating points is convex and the target rate optimization problem can be efficiently solved. As an aside, we point out that a sufficient condition for the jointly optimized rate region to be convex is that the functions $\bar{R}_i(r, \mathbf{p}_i)$ are concave functions of $\mathbf{p}_i$. Although we will not prove that statement formally here, a related proof appears in Section 4.

We begin our development by reformulating the problem in (5) in a hierarchical form with inner and outer optimization problems. Let us define $R_{2,\max}(r)$ to be the maximum achievable rate of User 2 when User 1 is allocated the fraction r of the channel resources.[2] The outer problem can then be written as

$$\max_{R_2 \in [0, R_{2,\max}(0)]} \quad \mu \bar{R}_1(R_2) + (1 - \mu) R_2, \tag{6}$$

where, with a mild abuse of notation, $\bar{R}_1(R_2)$ denotes the maximum achievable rate for User 1 for a given rate of User 2. The jointly optimized achievable rate region is the component of the hypograph (cf. [6]) of the function $\bar{R}_1(R_2)$ that lies in the non-negative orthant, and since we are interested in those systems for which the jointly optimized achievable rate region is convex, then $\bar{R}_1(R_2)$ is a concave function. Therefore, the objective in (6) is concave in R_2.

Although the objective in (6) is concave, we do not have a closed-form expression for $\bar{R}_1(R_2)$, and hence conventional derivative-based algorithms cannot be applied. However, for a given value of R_2, say $R_{2,\mathrm{tar}}$, $\bar{R}_1(R_{2,\mathrm{tar}})$ is the optimal value of the target rate problem in (4); the inner problem. Therefore, (6) can be solved using a simple bisection-based search over R_2 in which (4) is invoked to compute $\bar{R}_1(R_2)$ at the specified values of R_2. One such algorithm is provided in Table 1. In a given outer loop of that algorithm, the size of the interval containing the optimal value of R_2 is reduced by a factor of 2 or 4, depending on the value of ℓ^* in Step 4. Therefore, in order to obtain an interval of length ϵ, at most $\lceil \log_2(R_{2,\max}(0)/\epsilon) \rceil$ outer loops are required. Since this depends only logarithmically on ϵ^{-1}, and since each outer loop invokes only two or three instances of the inner problem (4), when the target rate problem in (4) can be efficiently solved, the algorithm in Table 1 efficiently solves the weighted sum rate problem in (6).

In the following section, we will show that for the orthogonal multiple access relay channel, the algorithm in Table 1 can provide significant improvements in the weighted sum rate. Before we do so, however, we will provide an explicit algorithm for efficiently solving the target-rate problem in (4) for the class of systems in which the rates $\bar{R}_i(r, \mathbf{p}_i)$ in (2) are concave functions of $\mathbf{p}_i$ and the function

$$\psi(r) = \begin{cases} \max_{\mathbf{p}} \bar{R}_1(r, \mathbf{p}_1) & \\ \text{s.t. (4b), (4c)} & \text{if } R_{2,\mathrm{tar}} \in [0, R_{2,\max}(r)] \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

is quasi-convex (cf. [6]) in r. (Examples of such systems appear in [7–9].) For such systems, (4) can be efficiently solved using a

[2]The value of $R_{2,\max}(r)$ can be found by allocating all the power to the transmission of the message of User 2.

Table 1. A simple algorithm for solving (6) for $W^* = \max_{R_2} W(R_2)$, where $W(R_2) = \mu \bar{R}_1(R_2) + (1-\mu)R_2$

Set $m_0 = 0$, $m_4 = R_{2,\max}(0)$, and $m_2 = (m_0 + m_4)/2$. Calculate† $\bar{R}_1(m_0)$, $\bar{R}_1(m_2)$ and $\bar{R}_1(m_4)$ and use those values to calculate $W(m_0)$, $W(m_2)$ and $W(m_4)$. Given an arbitrary tolerance ϵ

1. Set $m_1 = (m_0 + m_2)/2$ and $m_3 = (m_2 + m_4)/2$
2. Calculate† $\bar{R}_1(m_1)$ and $\bar{R}_1(m_3)$
3. Calculate $W(m_1)$ and $W(m_3)$
4. Find $\ell^* = \arg\max_{\ell \in \{0,1,\ldots,4\}} W(m_\ell)$.
5. Replace m_0 by $m_{\max\{\ell^*-1,0\}}$, replace m_4 by $m_{\min\{\ell^*+1,4\}}$, and save $W(m_0)$ and $W(m_4)$. If $\ell^* \notin \{0,4\}$ set $m_2 = m_{\ell^*}$ and save $W(m_2)$, else set $m_2 = (m_0 + m_4)/2$ and calculate† $W(m_2)$.
6. If $m_4 - m_0 \geq \epsilon$ return to 1), else set $W^* = W(m_{\ell^*})$.

† For the class of systems considered at the end of Section 3, the algorithm in Table 2 can be used.

Table 2. A simple method for finding $\bar{R}_1(R_{2,\mathrm{tar}})$ for the class of systems considered at the end of Section 3

By inspection $\bar{R}_1(R_{2,\max}(0)) = 0$ and $\bar{R}_1(0) = \psi(1)$. For $R_{2,\mathrm{tar}} \in (0, R_{2,\max}(0))$, set $t_0 = 0$, $t_4 = 1$, and $t_2 = 1/2$. Observe that $\psi(0) = 0$ and $\psi(1) = 0$ and compute $\psi(t_2)$ using (7). Given a tolerance ε,

1. Set $t_1 = (t_0 + t_2)/2$ and $t_3 = (t_2 + t_4)/2$.
2. Compute $\psi(t_1)$ and $\psi(t_3)$ using (7).
3. Find $k^* = \arg\max_{k \in \{0,1,\ldots,4\}} \psi(t_k)$.
4. Replace t_0 by $t_{\max\{k^*-1,0\}}$, replace t_4 by $t_{\min\{k^*+1,4\}}$, and save $\psi(t_0)$ and $\psi(t_4)$. If $k^* \notin \{0,4\}$ set $t_2 = t_{k^*}$ and save $\psi(t_2)$, else set $t_2 = (t_0 + t_4)/2$ and compute $\psi(t_2)$ using (7).
5. If $t_4 - t_0 \geq \varepsilon$ return to 1), else the optimal value of r is $r^* = t_{k^*}$ and $\bar{R}_1(R_{2,\mathrm{tar}}) = \psi(r^*)$.

simple bisection-based search over r in which the convex optimization problem over $\mathbf{p}$ on the right hand side of (7) is solved at each step (if r is such that $R_{2,\mathrm{tar}} \in [0, R_{2,\max}(r)]$). An algorithm that employs the search pattern used in Table 1 is provided in Table 2.

4. APPLICATION TO OMAR SYSTEMS

In this section, we show that for orthogonal multiple access relay (OMAR) systems, the joint optimization of the weighted sum rate over the power and channel resource allocations can be efficiently solved using the algorithm developed in Section 3. The orthogonal multiple access relay system consists of a number of users (Nodes i, $i \in \{1, 2, \ldots N\}$) that independently transmit their messages over orthogonal sub-channels to a common destination (Node 0) with the help of a relay node (Node R); cf. Fig. 1. As summarized in [5,8], the achievable rate of User i, under the regenerative decode-and-forward (RDF), non-regenerative decode-and-forward (NDF), amplify-and-forward (AF), and compress-and-forward (CF) relaying strategies, can be written, respecitvely, as:

$$\bar{R}_{i,RDF} = \frac{r_i}{2} \min\bigl\{\log(1 + \gamma_{iR} P_i), \log(1 + \gamma_{i0} P_i + \gamma_{R0} P_{Ri})\bigr\}, \quad (8a)$$

$$\bar{R}_{i,NDF} = \frac{r_i}{2} \min\bigl\{\log(1 + \gamma_{iR} P_i), \log(1 + \gamma_{i0} P_i) + \log(1 + \gamma_{R0} P_{Ri})\bigr\}, \quad (8b)$$

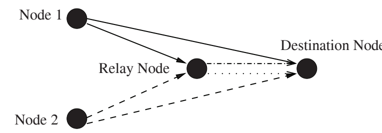

Fig. 1. A multiple access relay channel with two source nodes.

$$\bar{R}_{i,AF} = \frac{r_i}{2} \log\left(1 + \gamma_{i0} P_i + \frac{\gamma_{iR}\gamma_{R0} P_i P_{Ri}}{(1 + \gamma_{iR} P_i + \gamma_{R0} P_{Ri})}\right), \quad (8c)$$

$$\bar{R}_{i,CF} = \frac{r_i}{2} \log\Bigl(1 + \gamma_{i0} P_i + \frac{\gamma_{iR}\gamma_{R0}(\gamma_{i0} P_i + 1) P_i P_{Ri}}{\gamma_{R0}(\gamma_{i0} P_i + 1) P_{Ri} + P_i(\gamma_{i0} + \gamma_{iR}) + 1}\Bigr), \quad (8d)$$

where P_i is the power level at which User i transmits, P_{Ri} and r_i are the relay power level and the fraction of the time allocated to the transmission of the message of User i, respectively, and γ_{ij} is the squared magnitude of the (effective) channel gain between Nodes i and j; i.e., the ratio of the power gain of the channel and the noise variance at Node j. The weighted sum rate problem for this system is: Given a relaying strategy for each node, and given values μ_i such that $\sum_i \mu_i = 1$, maximize $\sum_i \mu_i \bar{R}_i$ over r_i, P_i and P_{Ri} subject to the average power constraints $r_i P_i \leqslant 2\bar{P}_i$ and $\sum_i r_i P_{Ri} \leqslant 2\bar{P}_R$, where $\bar{R}_i$ is the appropriate expression from (8). (In this problem the vector $\mathbf{p}_i$ in Section 2 contains P_i and P_{Ri}.) For the RDF and NDF strategies the rate functions in (8) are concave in the powers [5], and, it can be shown using [8] that for the AF and CF strategies the rate functions in (8) are concave in the powers if $\gamma_{i0}\bar{P}_i \geqslant \frac{1}{2}$. Furthermore, it was shown in [8] that for the RDF and NDF strategies the problem in (4) is quasi-concave in P_{Ri} and r_i, and that for the AF and CF strategies the problem in (4) is quasi-concave in P_{Ri} and r_i if $\gamma_{i0}\bar{P}_i \geqslant \frac{1}{2}$.

Now, we show that the jointly optimized rate region for the OMAR system is convex, by showing that any rate vector that can be achieved by time sharing between different operating points can also be achieved by a single operating point. Consider an N-user OMAR system that employs time sharing between M operating points with ratios α_m. At operating point m, User i is allocated a relay power level $P_{Ri}^{(m)}$ and a fraction $r_i^{(m)}$ of the time. Since the users' transmissions do not interfere (they are orthogonal), the users transmit at their maximum allowable power under the average power constraint, namely, $P_i^{(m)} = 2\bar{P}_i / r_i^{(m)}$. When averaged over the M operating points, the average time allocated to User i is $r_{i,\mathrm{avg}} = \sum_{m=1}^{M} \alpha_m r_i^{(m)}$, the average relay power level allocated to User i is $P_{Ri,\mathrm{avg}} = \frac{1}{r_{i,\mathrm{avg}}} \sum_{m=1}^{M} \alpha_m r_i^{(m)} P_{Ri}^{(m)}$, and the average transmitting power of User i is $P_{i,\mathrm{avg}} = \frac{1}{r_{i,\mathrm{avg}}} \sum_{m=1}^{M} \alpha_m r_i^{(m)} P_i^{(m)}$. Now, consider a system with a single operating point at which User i is allocated a fraction $r_{i,\mathrm{avg}}$ of the time and a relay power level of $P_{Ri,\mathrm{avg}}$, and employs a transmission power $P_{i,\mathrm{avg}}$. It is straightforward to show that the corresponding time-average powers satisfy the bounds $\bar{P}_i$ and $\bar{P}_R$, respectively. The achievable rate of User i at the new operating point is $\bar{R}_i = r_{i,\mathrm{avg}} f_i(P_{i,\mathrm{avg}}, P_{Ri,\mathrm{avg}})$, where $f_i(\cdot)$ is dependent on the relaying scheme and is implicit in (8). Since $f_i(\cdot)$ was shown to be a concave function of the powers [5], using Jensen's Inequality

$$\bar{R}_i = r_{i,\mathrm{avg}} f_i\Bigl(\sum_{m=1}^{M} \frac{\alpha_m r_i^{(m)}}{r_{i,\mathrm{avg}}} P_i^{(m)}, \sum_{m=1}^{M} \frac{\alpha_m r_i^{(m)}}{r_{i,\mathrm{avg}}} P_{Ri}^{(m)}\Bigr)$$

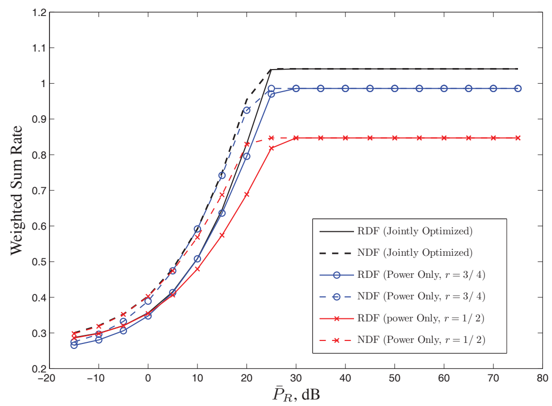

Fig. 2. Jointly optimized weighted sum rate (with $\mu = 3/4$) and the weighted sum rate optimized over power only with fixed channel resource allocation ($r = 1/2$ or $3/4$).

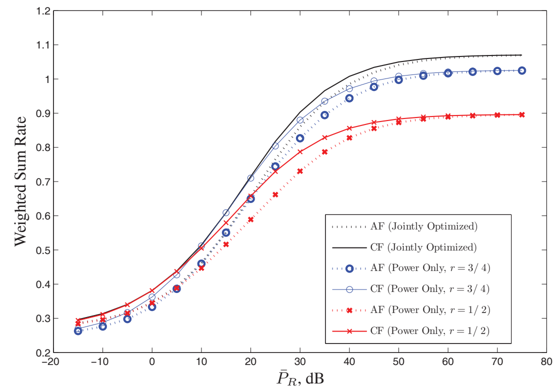

Fig. 3. Jointly optimized weighted sum rate (with $\mu = 3/4$) and the weighted sum rate optimized over power only with fixed channel resource allocation ($r = 1/2$ or $3/4$).

$$\geqslant \sum_{m=1}^{M} \alpha_m r_i^{(m)} f_i(P_i^{(m)}, P_{Ri}^{(m)}), \tag{9}$$

and hence for each of the users we can achieve a rate that is at least as high as that achieved by time sharing between the M operating points. Therefore, the jointly optimized achievable rate region is convex. As mentioned above, the target rate problem is quasi-convex [8], and hence the convexity of the achievable rate region implies that the efficient algorithms in Tables 1 and 2 can be applied.

Now that we have an efficient algorithm, it is of interest to examine the extent of the increase in the the weighted sum rate that can be obtained by joint optimization of the power and channel resource allocations over that obtained by power allocation alone for a fixed resource allocation; cf. [5]. In Figs 2 and 3 we compare the jointly optimized weighted sum rate of a two-user system with $\mu = 3/4$ to the weighted sum rate obtained by power allocation alone for the four relaying strategies in (8). (In this example, each user is assigned the same relaying strategy.) For the power allocation only case, we consider equal resource allocation, $r = 1/2$ and a resource allocation that is matched to the weighting, $r = 3/4$. We have plotted the weighted sum rate against the relay's power budget, $\bar{P}_R$ (in decibels). In the scenario that we have considered, the bounds on the users' average powers were $\bar{P}_1 = \bar{P}_2 = 2$, and the effective power gains of the channels were $\gamma_{1R} = 1.2$, $\gamma_{2R} = 0.8$, $\gamma_{10} = 0.3$, $\gamma_{20} = 0.6$, and $\gamma_{R0} = 0.4$. Fig. 2 provides the results for the regenerative and non-regenerative decode-and-forward strategies, and Fig. 3 provides the results for the amplify-and-forward and compress-and-forward strategies. From both figures, it can be seen that joint optimization over the power and channel resource allocations can provide a significant gain in the weighted sum rate. In particular, for large relay powers the gain over the equal resource allocation case is at least 20%.

5. CONCLUSION

In this paper, we have provided an efficient algorithm for jointly optimizing the power and channel resource allocations of a class of half-duplex cooperative systems so as to maximize the weighted sum rate. The algorithm was based on a decomposition of the weighted-sum-rate optimization problem into inner and outer problems, and on observations regarding the convexity of the jointly-optimized achievable rate region and the complexity of solving a target-rate optimization problem. The algorithms was applied to the orthogonal multiple access relay system, and numerical results showed that significant improvement in the weighted sum rates that can be obtained by joint optimization over those obtained by power allocation alone with fixed resource allocation.

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