CENTRALISED AND DISTRIBUTED POWER ALLOCATION ALGORITHMS IN COOPERATIVE NETWORKS

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ABSTRACT

Cooperation among network nodes provides transmit diversity in cases where wireless transmitters, due to size and power limitation, cannot support multiple antennas. We consider cooperation among M nodes, where each node achieves space diversity by using other nodes' antennas as relays. Cooperation among nodes has been shown to achieve impressive bit error rate (BER) gains as compared to a non-cooperative system while maintaining the same information rate, transmit power, and bandwidth [1, 2, 3, 4]. Firstly, this paper formulates an optimum, centralised power allocation scheme appropriate for a cooperative network that employs transparent relaying. It will be shown that the proposed allocation scheme significantly outperforms the equal power allocation scheme, e.g., by up to 5 dB for a 3-user case at a bit error rate of 10^{-3}. Secondly, this paper proposes a distributed power allocation scheme where each node independently calculates its power allocation factors, and it will be shown that it converges to the optimum allocation yielded by the centralised approach. Finally, this paper presents a distributed power allocation algorithm to optimise the BER performance of cooperative networks only with partial knowledge of the channel state information (CSI) of the non-adjacent nodes.

1. INTRODUCTION

The relaying process used in cooperative networks can be either transparent or regenerative. In transparent relaying, the signal stream is received, amplified, and retransmitted whereas with regenerative relaying the signal is decoded, re-encoded, and retransmitted. Since a mobile terminal cannot relay information at the same time and in the same frequency band, practical multiple access methods that can be employed include frequency division multiple access (FDMA), time division multiple access (TDMA), hybrid FDMA-TDMA, and space division multiple access (SDMA). In this paper, it is assumed that an orthogonal bandwidth (FDMA) and time slot (TDMA) (i.e., hybrid FDMA-TDMA) allocation scheme with transparent relaying is used.

The end-to-end performance of the system in terms of e.g., BER and capacity, depends on the performance of each relaying node, which itself is dictated by the allocation of time slots, bandwidth, and transmission power. An optimum resource allocation system assigns different fractional bandwidth, time slots, and power for the transmission between each pair of nodes.

Most previous work on power allocation in cooperative networks considers centralised approaches, e.g., [5]. This implicitly assumes the existence of a network controller that monitors and calculates the power allocated for each of the direct and cooperative links. This approach has two major drawbacks: First, there are the storage and computational demands placed on the network controller since it needs to know the signal-to-noise-ratio (SNR) of each of the cooperative/inter-node links. Second, the loss in timeslots/bandwidth efficiency due to the need to broadcast the inter-node information to the network controller as well as for the network controller to inform the various nodes of their power allocation factors.

In this paper, the case of transparent relaying will be examined. A method to optimise the end-to-end BER performance in both a centralised and a distributed manner is proposed and results obtained using numerical optimisation are presented. While the centralised approach results in optimum performance, it will be shown that the distributed approach also achieves close to this optimum performance. The performance of the proposed resource allocation strategy is found to be effective for an arbitrary number of cooperating nodes. Finally, motivated by the need to reduce the quantity of non-adjacent link CSI needed to calculate the power allocation factors, this paper presents a method to optimise the BER performance of cooperative networks having only partial CSI. Note that in this paper, CSI is defined to be the mean channel SNR.

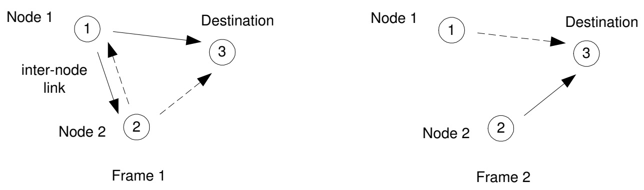

Fig. 1. Cooperation transmission scheme.

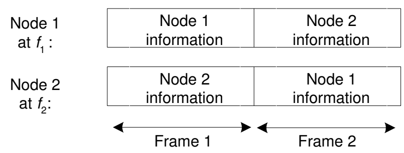

Fig. 2. Implementation of node cooperation using hybrid FDMA-TDMA.

2. SYSTEM MODEL

The cooperative scenario illustrated in Figs. 1 and 2 shows an amplify-and-forward (AF) scheme between two transmitting nodes and one destination node. The modulation is assumed to be binary phase shift keying (BPSK), and each node receiver maintains the instantaneous channel fading coefficients. Coherent detection with Maximum Ratio Combining is employed. The channels between nodes (inter-node channels) and from each node to the destination (uplink channels) are mutually independent and subject to flat fading. Each node is allocated different frequency bands (f_1 and f_2) and in each band a node transmits signals in two different time frames, one frame is dedicated for its own bits and the other is for relaying the partner's bits. In the nth time frame, node 1 transmits $b_1(n)$ and the received signal at node 2, $y_2(n)$ can be expressed as

$$y_2(n) = h_{12}\sqrt{E_b/2}\, b_1(n) + w_2(n), \tag{1}$$

where E_b is the energy per transmitted bit in the case of direct (non-cooperative) transmission, b_1 are the BPSK modulated symbols with unit energy, h_{ij} captures the effect of path loss and static fading on transmissions from node i to node j, and $w_j(n)$ models additive receiver noise, which is white Gaussian with a variance of N_0. Note that in the 2-node cooperation scheme, to maintain the same total power consumption, the energy available per bit for the cooperative scheme is half of that for the direct transmission scheme (hence the factor of 1/2).

In the $(n+1)$th time frame node 2 amplifies the signal by the relay gain α_2 and transmits:

$$d_2(n+1) \;=\; \alpha_2\, y_2(n) \tag{2}$$

During the two consecutive time frames, the destination, i.e., node 3, receives:

$$\begin{aligned} y_3(n) &= h_{13}\sqrt{E_b/2}\, b_1(n) + w_3(n) && (3)\\ y_3(n+1) &= h_{23}\, \alpha_2 \Big(h_{12}\sqrt{E_b/2}\, b_1(n) \\ &\quad + w_2(n)\big) + w_3(n+1). && (4) \end{aligned}$$

One choice for the relay power gain, which amplifies the received signal to a power level similar to that of a node's signal power level before relaying it to the destination, is given in [3] as

$$\alpha_2^2 = \frac{1}{h_{12}^2 + (N_0/(E_b/2))}. \tag{5}$$

Finally, note that this approach may be extended to the situation where more than two nodes cooperate in a straight forward manner.

3. POWER ALLOCATION STRATEGY

The performance of cooperative networks can be characterised in terms of BER performance, ergodic capacity, outage capacity, and outage probability [3, 4, 5]. In this paper we focus on BER performance as the metric to be optimised. Utilising the approximate expression for BER in [6], we can find an optimum power allocation such that the end-to-end average BER performance is minimised.

For M-node cooperative diversity, the approximate BER expression for node l communicating with destination node d is [6]

$$Pe_l \approx \frac{C(M)}{k^{M+1}} \frac{1}{\beta_{l,l}\bar{\rho}_{ld}} \prod_{i=1}^{M} \left(\frac{1}{\beta_{l,l}\bar{\rho}_{li}} + \frac{1}{\beta_{i,l}\bar{\rho}_{id}} \right). \tag{6}$$

where $\beta_{n,m}$ is the fraction of power node n dedicated to transmit the data of node m, M is the number of cooperating nodes between the node l and destination d, $\rho_{ij} = |h_{ij}|^2 \frac{E_b}{2N_0}$ and $C(M) = \frac{\prod_{k=1}^{M+1}(2k-1)}{2(M+1)!k^{(M+1)}}$ is a constant depending on the number of cooperating nodes. Note that

$$0 \le \beta_{n,m} \le 1, \;\; n,m = 1,\dots,M \tag{7}$$

and

$$\sum_{m=1}^{M} \beta_{n,m} = 1, \;\; n,m = 1,\dots,M. \tag{8}$$

This power control problem can be approached in a centralised or a distributed manner, as will be described in the following sections.

3.1. Centralised Power Allocation

With centralised power alloation, the nodes firstly inform the network controller about the quality of their channels to the destination and to other nodes. Then the network controller calculates the optimum power allocation factors for each link. Finally, the network controller conveys the results to the various nodes, which will then adjust their transmit power accordingly.

In the centralised approach, the problem of finding a set of power allocation factors, $\beta_{n,m}$ that minimises the total BER can be posed as follows.

$Problem \ \ (P_1)$: Find the set of power allocation factors $\beta_{n,m}$, for $n, m = 1, \ldots, M$ which solves the following constrained optimisation problem

$$\min \frac{1}{M} \sum_{l=1}^{M} Pe_l(\beta_{1,l}, \ldots, \beta_{M,l}), \tag{9}$$

subject to the linear constraints (7) and (8).

To analytically illustrate the optimisation method, let us consider the 2-node highly symmetrical scenario where the mean uplinks and inter-node link SNRs are similar, i.e., $\overline{\rho}_{13} = \overline{\rho}_{12} = \overline{\rho}_{23}$. Note that in this highly symmetrical case the power allocation factors, $\beta_{1,1} = \beta_{2,2} = \beta$ and $\beta_{1,2} = \beta_{2,1} = 1 - \beta$. We can obtain the optimum value of parameter β by differentiating the average end-to-end BER with respect to β and setting the resulting expression to zero. The resulting optimum cooperation level in this case is $\beta = 2/3$, which is independent of the uplink SNRs. On the contrary, in the existing literature the value of $\beta = 1/2$ is often used (e.g., [3]).

The result of the optimisation using the centralised approach in (9) serves as the reference value for the lowest achievable total average BER. In the next section, a distributed power allocation scheme is proposed and its performance is outlined.

3.2. Distributed Power Allocation

One of the main objectives of the distributed power allocation approach is to reduce the computational burden at the network controller. Furthermore, in some scenarios, for example in sensor networks, a network controller might not be available, in which case a centralised approach might be infeasible.

For the proposed distributed approach, power allocation is calculated at each node. In the distributed approach, each node determines its own power allocation factors only, this is in contrast to the centralised approach where the network controller is responsible for calculating the power allocation factors of every node. To be specific, in the distributed approach, a node is assumed to have knowledge of its partners' CSI and some initial values for their power allocation factors. A particular node then optimises its power allocation with respect to these assumptions and it broadcasts the results to its partners. Alternatively a node may deduce its partners' power allocation factors based on the received mean SNR. The other nodes will use this information to optimise their power allocation. The last transmitting node will optimise its power allocation based on the real power allocation of its neighbours. The allocation procedure then returns to the first node and it optimises its power allocation based on the new power allocation of its $M - 1$ partners. This process can continue for the desired number of iterations. These steps can be formulated as follows.

$\overline{\rho}_{23}$		i=1	i=2	i=3	i=4	centralised
5 dB	$\beta_{1,1}$	0.70125	0.75139	0.75381	0.75394	0.75394
	$\beta_{2,2}$	0.74256	0.75336	0.75391	0.75394	0.75394
10 dB	$\beta_{1,1}$	0.7873	0.82329	0.82457	0.82462	0.82462
	$\beta_{2,2}$	0.76188	0.77156	0.77193	0.77195	0.77194

Table 1. Comparison between fractional power allocation values obtained by distributed and centralised approach in the two-node scenario with $\overline{\rho}_{12} = 0$ dB, $\overline{\rho}_{13} = 5$ dB, and varying $\overline{\rho}_{23}$

$Problem \ \ (P_2)$: At the i-th iteration, the n-th node finds the set of power allocation factors $\beta^{(i)}_{n,m}$, $m = 1, \ldots, M$ which solves the following constrained optimisation problem

$$\min \frac{1}{M} \sum_{l=1}^{M} Pe_l(\beta_{1,l}, \ldots, \beta_{M,l}) \mid_{\beta_{j,m} = \beta^{(i-1)}_{j,m}}, \qquad m = 1, \ldots, M, \ \ j \neq n, \tag{10}$$

subject to the linear constraints (7) and (8).

The resulting values of $\beta^{(i)}_{n,m}$ from the i-th step are then substituted into the optimisation problem of the $i+1$-th step.

Table 1 shows that as the number of iterations increases, the power allocation converges to the optimum one given by the centralised approach. Note that for the simulation results described in Table 1, the initial values used are those for equal power allocation. This method is similar to the successive line minimisation algorithm for multidimensional optimisation [8]. In successive line minimisation dealing with a contour described by N basis vectors, we search along the direction of the first vector to its minimum, then from there along the second direction to its minimum, and so on, cycling through the whole set of directions as many times as necessary, until the function stops decreasing. Note that since the probability of error is not very sensitive to small errors in the power allocation factor, one iteration is actually enough for most cases. More iterations may be used if the network is static or slowly varying and the additional computational burden is acceptable.

3.3. Distributed Power Allocation with Partial CSI of Non-Adjacent Links

The main drawback of the distributed power allocation scheme proposed in the previous section is the quantity of CSI required by each node to compute its power allocation. Practically, each node can easily monitor the CSI of its adjacent links, however to monitor non-adjacent ones may require additional transmissions from its neighbor. This will incur loss in timeslots/bandwidth efficiency. Also, when the nodes are mobile the requirement of accurate CSI may mean frequent update and a high computational load, which is certainly undesirable. In this section we will demonstrate that even with only a limited amount of CSI the proposed power allocation scheme still gives good results.

With uncertainty in the CSI, the power allocation problem can be formulated as follows.

$Problem\ \ (P_3)$: At the i-th iteration, the n-th node finds a set of power allocation factors $\beta_{n,m}^{(i)}$, $m = 1, \ldots, M$ which solves the following constrained optimisation problem

$$\min P_r^{(i)}(\beta_{n,m}) \mid_{\beta_{j,m}=\beta_{j,m}^{(i-1)}}, \quad m = 1, \ldots, M, j \neq n \quad (11)$$

subject to the linear constraints (7) and (8) where

$$P_r^{(i)} = E\left\{ \frac{1}{M} \sum_{l=1}^{M} \frac{C(M)}{k^{M+1}} \frac{1}{\beta_{l,l}\overline{\rho}_{ld}} \prod_{i=1}^{M} \left(\frac{1}{\beta_{l,l}\overline{\rho}_{li}} + \frac{1}{\beta_{i,l}\overline{\rho}_{id}} \right) \right\}.$$

Note that $E(.)$ is the expectation with respect to the non-adjacent link SNRs. For the simulation results that will be presented in this paper, each node assumes that the mean SNR of the non-adjacent links falls within a specified range with equal probability (i.e., a uniform distribution). In this case the range is from 0.5*actual mean SNR to 1.5*actual mean SNR.

4. NUMERICAL SIMULATION

To test the effectiveness of the proposed power allocation strategies, numerical simulations have been performed. The channel is assumed to obey flat Rayleigh fading. For the situation where the nodes are mobile, the power allocation factors need to be updated dynamically to ensure an optimum end-to-end performance. However, if the nodes are of low mobility there will be enough time to properly update the power allocation factors. Note that for high mobility applications operating in a fast fading environment, there are other alternatives to exploit diversity, e.g., coding. In this section, the performance of the proposed power allocation schemes will be investigated. The centralised scheme and the distributed scheme with full CSI schemes are optimum in the sense of minimising the total average probability of error.

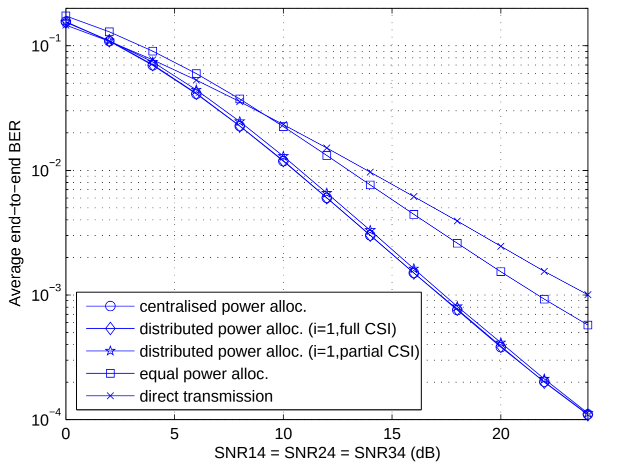

Fig. 3. Three node cooperation with symmetrical mean uplink channels, $\overline{\rho}_{14} = \overline{\rho}_{24} = \overline{\rho}_{34}$ and similar mean inter-node channel SNR, $\overline{\rho}_{12} = \overline{\rho}_{13} = \overline{\rho}_{23} = 5$ dB.

Fig. 3 shows that in 3 node cooperation schemes with symmetrical mean uplink SNRs and inter-node channel SNRs of 5 dB, the proposed centralised and distributed power control strategies achieve a gain of 4.7 dB, over equal power allocation at a BER of 10^{-3} and outperforms direct transmission by 6.9 dB. Note that the curves of centralised power allocation and distributed power allocation ($i = 1$, full CSI) overlap. Also we observed that the proposed power control technique is likely to be able to achieve more significant gains as the number of users (and therefore, the number of parameters to be optimised) is increased.

Results for the case of highly asymmetrical uplinks and inter-node links are shown in Fig. 4, where $\overline{\rho}_{24} = \overline{\rho}_{14} - 5$ dB, $\overline{\rho}_{34} = \overline{\rho}_{14} + 5$ dB, and different inter-node SNRs, $\overline{\rho}_{12} = 5$ dB, $\overline{\rho}_{13} = 10$ dB, $\overline{\rho}_{23} = 20$ dB. In this case centralised power allocation achieves gains over equal power allocation for user 1, 2, and 3 at a BER of 10^{-3} of 4.6, 2.3, and 0 dB, respectively. The gain over direct transmission for user 1, 2, and 3 at a BER of 10^{-3} are 9.1, 14.9, and 5.5 dB, respectively. It can be seen that optimised power control is very important especially if there are some links with poor SNR.

From Figs. 3 and 5 it can be seen that the performances of the distributed power allocation proposed in Section 3.2 approach that of the optimum (i.e., centralised) approach, even when only one iteration (i=1) is used.

For distributed power allocation with uncertainty in the partners' mean CSI, the partners' channels which have no direct connection with a particular node u, are assumed to have an SNR which is distributed uniformly over the range [0.5*actual SNR, 1.5*actual SNR]. For example, from the point of view of node 1, it knows exactly the mean SNRs between link 1-2, 1-3, 1-4, i.e., $\overline{\rho}_{12}, \overline{\rho}_{13}, \overline{\rho}_{14}$. However all it knows about the other links which it has no direct connection with is that they have mean SNRs that fall within a specified range as stated previously. Figs. 3 and 5 show that the proposed power allocation is robust in the sense that without the knowledge of actual non-adjacent link SNRs significant performance gains are achieved over equal power allocation. Note that in both figures, the average BER performances for the case of partial partners' CSI are very close to those for the situation with full partners' CSI.

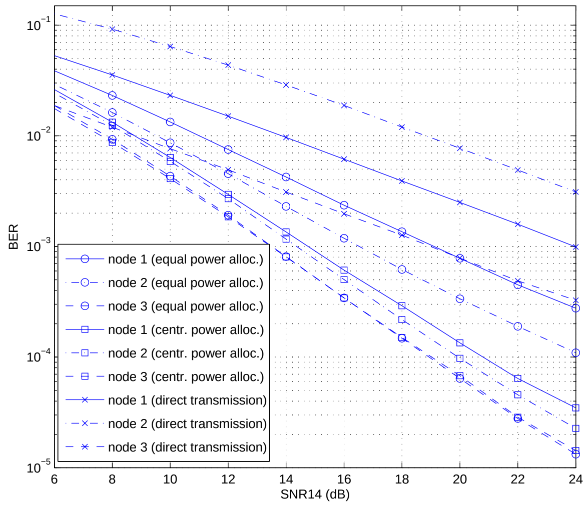

Fig. 4. Three node cooperation with asymmetrical uplink channels, $\overline{\rho}_{24} = \overline{\rho}_{14} - 5$ dB, $\overline{\rho}_{34} = \overline{\rho}_{14} + 5$ dB, and different inter-node SNRs, $\overline{\rho}_{12} = 5$ dB, $\overline{\rho}_{13} = 10$ dB, $\overline{\rho}_{23} = 20$ dB.

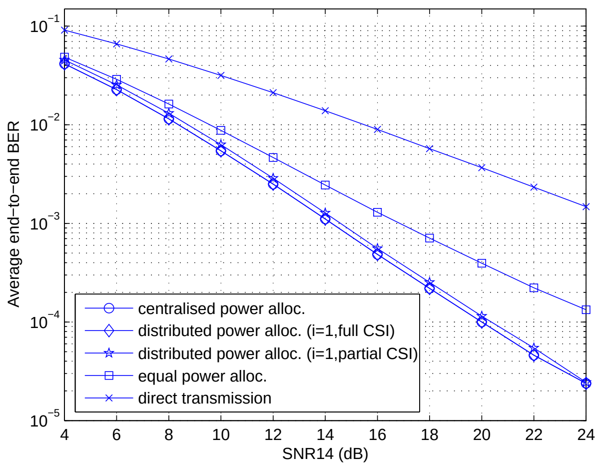

Fig. 5. Three node cooperation with asymmetrical uplink channels, $\overline{\rho}_{24} = \overline{\rho}_{14} - 5$ dB, $\overline{\rho}_{34} = \overline{\rho}_{14} + 5$, and different inter-node SNRs, $\overline{\rho}_{12} = 5$ dB, $\overline{\rho}_{13} = 10$ dB, and $\rho_{23} = 20$ dB.

5. CONCLUSION

This paper presents centralised and distributed power allocation strategies employing transparent relaying in cooperative networks. The aim is to minimise the average end-to-end BER. As compared to the equal power allocation strategy, the proposed centralised strategy is shown to yield an SNR gain of up to 4.7 dB over the equal power allocation strategy and 14.9 dB over direct transmission at a BER of 10^{-3}. The performance of the distributed approach approximates that of centralised one as the number of iteration is increased. This paper also proposes a power allocation method for the scenario where the non-adjacent links CSI are not exactly known. Specifically, we consider the case where the non-adjacent links CSI are believed to lie between a certain range of SNR values. Simulation results show that the performance of this technique is very promising.

6. REFERENCES

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