Power Allocation in Cooperative Space-Time Coded Wireless Relay Networks

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***Abstract*—This paper is concerned with the power allocation problem in a transmit diversity wireless system with mean channel gain information. For a given set of mean channel gains between nodes, the aim is to find the power allocation and corresponding network topology that minimizes the total transmit power for nodes involved in the cooperative communications between the source and the destination, where all of the transmitters use single omnidirectional antennas. Specifically, the selection of store-and-forward relays deploying Alamouti-type distributed space-time coding along a multihop connection is proposed for a network with randomly distributed nodes and Rayleigh fading. By adapting the transmission power, the proposed data forwarding and processing schemes control the selection of relay nodes utilizing space-time coding to minimize the total energy required to transmit the information. In addition to addressing the geometric analysis of the power-efficient topology problem, this paper also focuses on finding computationally efficient algorithms for the selection of relay nodes which will result in a topology formation requiring close to minimum energy.**

I. Introduction

Traditional wireless networks (WNs) have predominantly used direct point-to-point or point-to-multipoint transmissions, where the communicating nodes are equipped with a single transmitter and a single receiver deploying omnidirectional antennas. Recently this point-to-point, or single-input single-output (SISO), communication framework has been changed dramatically, with the introduction of the multiple-input multiple-output (MIMO) communication paradigm, where the source and the destination use multiple antennas at both sides of the wireless link. By transmitting in the same frequency band and at the same time, MIMO systems with physically co-located antenna elements and advanced signal processing are greatly increasing the capacity and reliability of wireless links. In this paper, we exploit the benefits of MIMO techniques by deploying cooperating nodes equipped with single element antennas which act as the distributed virtual antenna array [1].

A fundamental problem in wireless network design is the allocation of limited resources among the network users. In cross-layer communication protocol architectures, to achieve higher bandwidth and power efficiency in wireless systems, integrated protocol designs are pursued which involve close interactions between network and physical layers [2]. In addition, to overcome distance limitations and power constraints, a natural approach in WNs is to use relay stations, with data packets taking multihop and multiple paths toward the destination [1], [3].

Cooperative communications and networking allow different nodes in a wireless network to share resources and to collaborate through distributed transmission and processing, with each node's information being sent out not only by the source but also by the collaborating nodes. Specifically, distributed wireless nodes combat the degrading effects of signal fading by automatically adapting the space-time block coding (STBC) structure to changes in the wireless propagation environment. For a variety of processing algorithms and transmission protocols, performance improvements in terms of transmission rate and reliability have already been demonstrated by using the principles of the generalized STBC. [4].

In most of the work on cooperative relaying, wireless system models do not fully investigate the wireless broadcast advantage, where nodes overhearing the signals can be exploited to achieve much better tradeoffs between the target bit error rate (BER) performance and the required transmit power. This is a motivation for the research in this paper, where additional design options are considered for energy-efficient wireless network operation. Specifically, the design of routing protocols with multiple-stage relays utilizing STBC along a data path is proposed for a wireless network with randomly distributed nodes. This work exploits the fact that modern wireless equipment can be designed to adjust power levels automatically to the minimum needed to achieve the desired target BER, by varying the output power depending upon channel state information (CSI). [5]– [7].

II. Background

A. Power Control for SISO Model

The target BER for this research is 10^{-3} in a SISO system with Rayleigh fading, and for brevity of notation, to meet this requirement, the transmit power P_{Tx} is written as:

$$P_{Tx} \sim r^{\alpha} \tag{1}$$

where r is the distance between the transmitter and the receiver and α is the path loss exponent in the deterministic signal attenuation model. From Figure 1, where BER is presented as a function of SNR for different transmission schemes, in the SISO case for $BER = 10^{-3}$, the $SNR = 24dB$ and (1)

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implies the received signal power to be 1 W which in turn suggests that the power of noise at the receiver is 4 mW. Therefore with more practical values for the noise level at the receiver, an appropriate scaling of power should be applied to results presented in this paper. The path loss exponent, α depends upon the surrounding environment and is in a range from 2 in free space to 6 in dense urban areas.

In this paper, omnidirectional antennas and homogenous propagation conditions are assumed. The decisions about which nodes are involved in forwarding the STBC data between the source and destination pairs are based only on the distances between the nodes, which in turn are linked to the received signal strength indicator (RSSI) values. Distribution of a common database of RSSI values introduces an overhead in the proposed routing protocols [8] and is not considered here.

B. Power Control for MISO Models

To maintain $BER = 10^{-3}$ in a Rayleigh fading environment with Alamouti scheme using two transmit and one receive antennas, from Figure 1, the difference between the SNR for the MISO and SISO systems is 10 dB. Thus, when sending a signal with STBC considered in this paper, the transmit power required can be reduced by an amount equal to the difference between the two SNR. Using (1), the transmit power per antenna in the STBC coded system, P_{Tx}^{STBC}, is:

$$P_{Tx}^{\text{STBC}} = G \cdot r^{\alpha} \tag{2}$$

where G is the scaling factor representing inverse of the coding gain to obtain targeted BER and is calculated as:

$$G = \frac{SNR_{STBC}}{SNR_{SISO}} \tag{3}$$

Here SNR_{STBC} is the signal-to-noise ratio for the STBC and SNR_{SISO} is the uncoded signal-to-noise ratio (both on the linear scale).

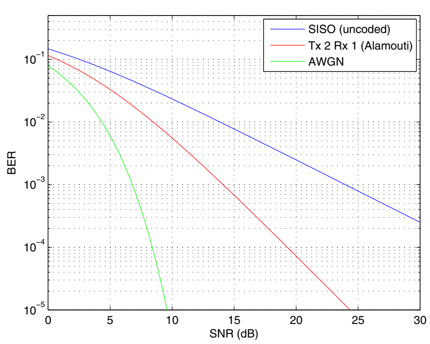

Fig. 1. BER performance for coherent BPSK modulation with a flat Rayleigh fading channel.

III. Power Allocation for Multistage Relays in STBC

To decrease performance degradation effects due to Rayleigh fading, a distributed STBC approach is deployed in this paper. Specifically, the MISO model is used to send the information from two relay nodes to a single receiver in accordance with Alamouti's scheme. In this distributed transmission scheme, the cooperating nodes are not co-located as in the original scheme, and mean receive signal powers from two nodes have to be maintained at the same level through power control to benefit from the diversity gain. In single stage transmission with the distributed STBC, shown in Figure 2, a brute force approach to select the two cooperating relays is to use an exhaustive search over all possible combinations of two relays to find the minimum power topology. The exhaustive search is even more complex for double-stage distributed STBC strategy shown in Figure 4. Therefore, a computationally efficient solution is proposed here for selecting the relay nodes. With this approach, it is anticipated that proposed selection of relays will minimize the power consumption, with savings comparable to those achieved by exhaustive search methods.

A. Single-Stage Strategy

Figure 2 represents a wireless network that contains a source, a destination and two cooperative relay nodes, R_1 and R_2. Transmission from the source to the destination is divided into two phases.

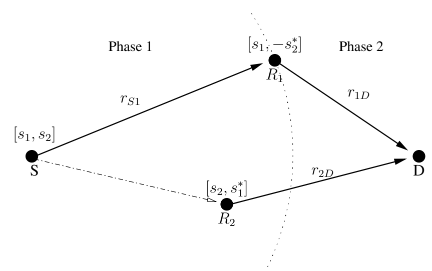

Fig. 2. Transmission with a single-stage strategy using STBC.

The first phase involves transmission from the source to the relay nodes R_1 and R_2. In order to save power and time slots, the transmitted signal is broadcast to both nodes at the same time. The transmit power used for this broadcast should ensure that both relay nodes receive the information reliably. This is achieved by sending the information with sufficient transmission power to reach reliably the farther relay node of the two. For the first phase, the power is represented as:

$$P_1 = \max(r_{S1}^{\alpha}, r_{S2}^{\alpha}) \tag{4}$$

In the next phase, the two relay nodes R_1 and R_2 are used to send the information to the destination simultaneously. From (2), the total transmit power in the second phase for both antennas is:

$$P_2 = G \cdot r_{1D}^{\alpha} + G \cdot r_{2D}^{\alpha} \tag{5}$$

Finally, the sum of the transmission power required for the two phases is calculated to arrive at the total transmission power:

$$P^{S-STBC} = \max(r_{S1}^{\alpha}, r_{S2}^{\alpha}) + G \cdot r_{1D}^{\alpha} + G \cdot r_{2D}^{\alpha} \tag{6}$$

To elaborate how the selection method is performed we assume initially that the two co-located relay nodes lie on the direct path between the source and the destination. The objective is to find x, which is the distance between the source and the optimum point location that guarantees the highest savings in the total transmission power. The equation (6) can be rewritten as follows:

$$P^{S-STBC} = x^{\alpha} + 2G(r_{SD} - x)^{\alpha} \tag{7}$$

To find the minimum P^{S-STBC}, the derivative of the right-hand side of (7) is calculated with respect to x and solved for its root. This yields $x = \frac{r_{SD}\sqrt[\alpha-1]{2G\cdot\alpha}}{\sqrt[\alpha-1]{\alpha}+\sqrt[\alpha-1]{2G\cdot\alpha}}$. So, in addition to the source-destination distance r_{SD}, the optimum relay location depends upon the target BER, which affects the scaling factor, and the attenuation exponent.

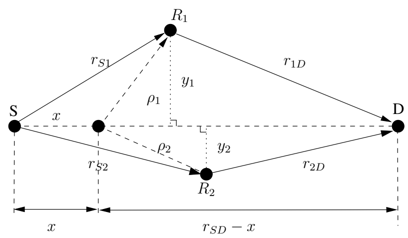

Fig. 3. Relationship between the relay node positions and the optimum point.

The situation where the relay nodes are not co-located and co-linear with the source and the destination is illustrated in Figure 3. We also show there the optimum position for relays from the earlier discussion. It can be argued by analyzing distance relations in Euclidean geometry for $\alpha = 2$ that the relays used in cooperative communication closest to the optimum point at distance x from the source on a path to the destination have the potential to offer the greatest power saving, e.g., by minimizing y_1 and y_2. The distance ρ_i for a relay R_i to the optimum point is the length of a cevian determined by Stewart's theorem and depends on x and node interdistances as follows:

$$\big(r_{SD} - x\big) \cdot r_{Si}^2 + x \cdot r_{iD}^2 = r_{SD} \cdot \Big((r_{SD} - x) \cdot x + \rho_i^2\Big) \tag{8}$$

Thus, in a network with N relay nodes, two relay nodes with the smallest ρ_i are selected to find topology with the minimized total transmit power [8] rather then calculating power using (6) over all possible pairs of relays and choosing the topology and power allocation with the minimum total transmit power.

B. Double-Stage Strategy

Here a double-stage strategy using distributed STBC is presented. Similarly as for a single-stage strategy with STBC, two relay nodes are used first to received the data from the source and also two additional relay nodes are added to represent the second stage. As illustrated in Figure 4, there is a source, S; a destination, D; and four randomly distributed relay nodes, R_i, where $i \in 1, 2, 3, 4$ with R_1 and R_2 representing the first stage, and R_3 and R_4 representing the second stage. In this strategy the transmission is divided into four phases.

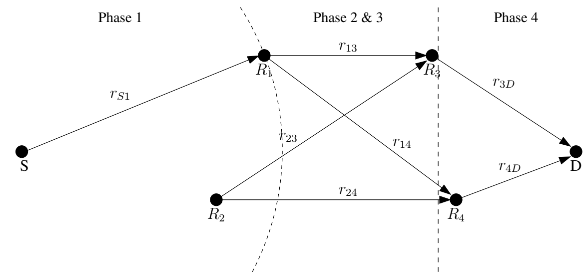

Fig. 4. Transmission with a double-stage strategy using STBC.

The first and last phase is the same as in the single-stage strategy: in the first phase the source broadcasts the information to the first stage (nodes R_1 and R_2), while the last phase represents the transmission from the two relay nodes in the second stage to the destination using STBC.

The second and third phases can be described together. These two phases involve sending the information from the first stage to the second stage. They are divided into different phases because nodes R_3 and R_4 receive the information separately in two different transmissions. These two transmissions could be made using two different frequencies or two different time slots. The required transmission power per phase is: $P_i = G \cdot r_{1i}^{\alpha} + G \cdot r_{2i}^{\alpha}$, where $i \in 3, 4$. Thus, the sum of the power required for both phases can be calculated as:

$$P_{(2,3)} = G \cdot r_{13}^{\alpha} + G \cdot r_{23}^{\alpha} + G \cdot r_{14}^{\alpha} + G \cdot r_{24}^{\alpha} \tag{9}$$

Finally, the total transmission power required to send the information from the source to the destination with the double-stage strategy using STBC is:

$$\begin{aligned} P^{D-STBC} &= \max(r_{S1}^{\alpha}, r_{S2}^{\alpha}) + G \cdot r_{13}^{\alpha} + G \cdot r_{23}^{\alpha} \\ &+ G \cdot r_{14}^{\alpha} + G \cdot r_{24}^{\alpha} + G \cdot r_{3D}^{\alpha} + G \cdot r_{4D}^{\alpha} \end{aligned} \tag{10}$$

Rather than searching for power efficient topology and the corresponding power allocation over all possible combinations of four relays out of the N available in a network, an efficient way to select the relay nodes is investigated based on the distances from two optimum points for the co-located relays in each of the two stages. The first step is to determine the optimum point location. Let assume that co-located R_1 and R_2 (representing the first stage) are on the direct path between the source and the destination at distance x from the source, and co-located R_3 and R_4 (representing the second stage) are also on the direct path between the source and the destination at distance y from the first stage. In this case, from 10 the total transmission power is:

$$P^{D-STBC} = x^2 + 4Gy^2 + 2G(r_{SD} - y - x)^2 \tag{11}$$

By solving for the roots of the two partial derivatives with respect to x and y it can be found that, the positions for two stages of the co-located relays in double-stage strategy that minimize the total energy are: $x = \frac{r_{SD}\sqrt[\alpha-1]{4G}}{1+\sqrt[\alpha-1]{2}+\sqrt[\alpha-1]{4G}}$

and $y = \frac{r_{SD}}{1+\sqrt[\alpha-1]{2}+\sqrt[\alpha-1]{4G}}$. It should be noted that the two optimum points depend upon the attenuation and the scaling factor in the same way as in the single-stage strategy. If the attenuation increases, the optimum points will move farther from the source, whereas if the scaling factor increases the optimum points will move closer to the source.

The case where the relay nodes are located away from the optimum points are handled in a similar fashion as in a single stage approach. The two cevian lengths ρ_{1i} and ρ_{2i} are calculated with respect to the two optimum points in the triangles SR_iD where $i \in 1, ..., N$ in a network with N randomly distributed relay nodes. The two nodes with the lowest ρ_{1i} will be selected to represent the first stage and the two relay nodes with the lowest ρ_{2i} will be selected to represent the second stage which offer significant computational saving over the exhaustive search for the optimum power allocation.

IV. Results

Simulations were implemented in MATLAB, in order to calculate the total transmit power for five methods: (i) direct transmission (D); (ii) store-and-forward transmission using a single-stage strategy ($S-SF$); (iii) store-and-forward transmission using a double-stage strategy ($D-SF$); (iv) STBC using a single-stage strategy ($S-STBC$); and (v) STBC using a double-stage strategy ($D-STBC$). The primary focus is on the total transmit power, with perfect knowledge of the power required to reach the nodes from each of the other nodes. These transmit powers depend upon the distances between the randomly distributed nodes and upon the path loss exponent α, which is assumed to be the same in the underlying network. The total power results are analyzed: (i) for different propagation conditions; (ii) for different numbers of relay nodes, from $N = 10$ to $N = 100$ in increments of 10; and (iii) for different sizes of area covered by the wireless network, i.e., for different node densities. The process for random positioning of the nodes and calculation of the power is repeated 1000 to obtain an average power performance.

A. Excess Power Consumption

This section examines how close the total power obtained by the proposed selection of relays is to the total power resulting from an exhaustive search. The simulations were conducted for different propagation environments, different numbers of relay nodes, and different node densities.

First, the selection approach was tested for environments with different path loss exponents α. Three types of propagation were used: (i) free space propagation where $\alpha = 2$; (ii) ground wave propagation where $\alpha = 4$; and (iii) propagation in a dense urban environment where $\alpha = 6$. Figures 5 and 6 shows the percentage of excess transmission power consumption with the use of a single- and double-stage strategy, respectively, for different numbers of nodes in a network area of 25×25. It is clear from the figures that as α increases, the excess power consumption resulting from this simplified scheme for node selection is not very high in comparison to the power consumption obtained by the exhaustive search.

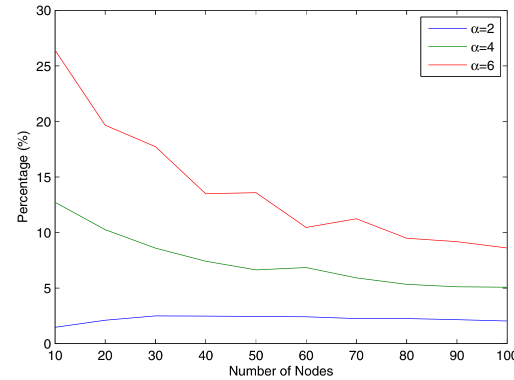

Fig. 5. Excess power consumption in comparison with the exhaustive search method for an area of 25×25 using single-stage transmission.

However, with the double-stage strategy power efficiency losses are higher, especially for lower node densities and higher values of α. The difference in power performance as measured by the percentage of excess power consumption for different values of α decreases as the number of nodes increases. Overall, the loss of power efficiency when using the proposed scheme is not that high when one consider reduction in the computational complexity of the algorithm selecting the topology.

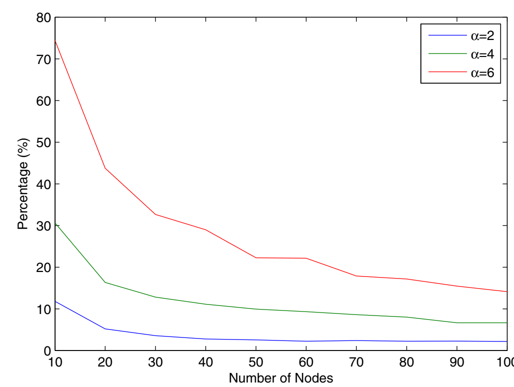

Fig. 6. Excess power consumption in comparison with the exhaustive search method for an area of 25×25 using double-stage transmission.

The effect of different numbers of potential relay nodes on the transmission power in the proposed approach was then examined. From Figure 5 it can be seen that in general, with an increasing number of relay nodes the percentage of excess power consumption decreases. The percentage usually decreases rapidly until the number of relay nodes reaches 50, after which the percentage begins to stabilize. However, in the case of free space propagation with the single-stage strategy, it can be seen that the lowest percentage is 1.5% when 10 relay nodes are used; this value increases to 2.5% and then decreases to 2% when 100 relay nodes are used.

Finally, the performance results for the selection approach were investigated for different network area sizes. the simulation results showed that the curve behavior for the different network sizes is almost the same for a given STBC strategy.

B. Results with Good Channel Estimation

In this section, the simulation results are presented under the assumption of reliable CSI. In the simulations the relay nodes were distributed in areas with three different sizes: 25×25, 50×50 and 100×100. Simulations are shown for numbers of nodes ranging from 10 to 100 in increments of 10.

For the area with size 25×25, the graphs in Figures 7 and 8 show the normalized power with respect to the power consumption obtained for direct mode transmission with free space propagation and ground wave propagation respectively.

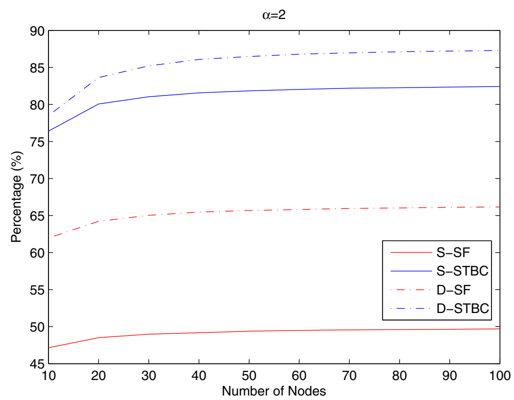

Fig. 7. Power savings in comparison with direct transmission for an area of 25×25, with free space propagation.

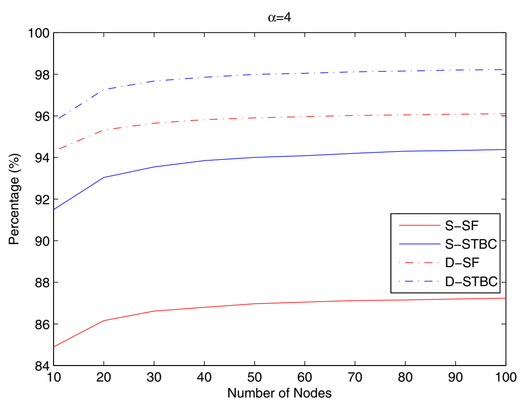

Fig. 8. Power savings in comparison with direct transmission for an area of 25×25, with ground wave propagation.

With free space propagation, the transmission power consumed with the use of STBC is the lowest. It can also be seen that with the use of STBC even the proposed selection approach in the single-stage strategy is better than store-and-forward transmission in the double-stage strategy. In comparison with direct transmission, power savings with the use of STBC are 82.4% for the single-stage and 87.3% for the double-stage strategy, as shown in Figure 7.

With ground wave propagation, it can be seen that the proposed selection approach with STBC in a double-stage strategy offers the lowest total transmit power. However, the single-stage strategy requires more transmit power than store-and-forward transmission using a double-stage strategy. From Figure 8, it can be seen that ground wave propagation yields up to 94.4% power savings with a single-stage and up to 98.2% power savings with a double-stage strategy.

Figure 9 illustrate the percentage power savings achieved in comparison to direct transmission for an area of 50×50 with free space propagation. By comparing Figures 7 and 9 together, it can be seen that as the distance increases, the power savings remain the same.

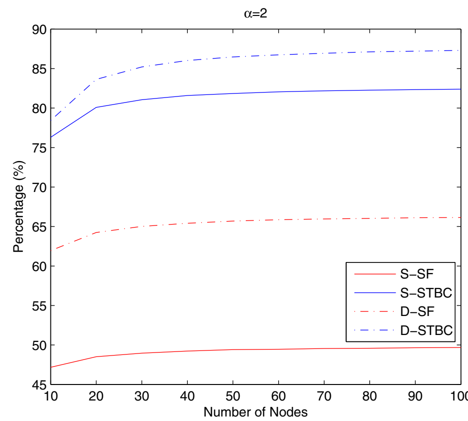

Fig. 9. Power savings in comparison with direct transmission for an area of 50×50, with free space propagation.

V. Summary

The main contribution of this paper is the development of a method with low computational complexity for selection of the relay nodes with a corresponding power allocation to minimize the total transmit power in systems using distributed STBC. Two transmission strategies are considered in this paper: the single-stage strategy and the double-stage strategy in an ad-hoc wireless network. In addition, this paper calculates the power savings achieved for the proposed approach and compares them with power used in other methods for selecting the relay nodes and forwarding the data in different propagation environments and with different numbers of relay nodes.

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