Future Network and MobileSummit 2010 Conference Proceedings
Paul Cunningham and Miriam Cunningham (Eds)
IIMC International Information Management Corporation, 2010
ISBN: 978-1-905824-16-8

Effects of Power Allocation and Reuse Distance in Relay-Assisted Wireless Communications with Mutual Interference

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Abstract: Cooperative communication techniques effectively improve performance and coverage of wireless networks. This requires to find proper methods to allocate power among source and relay nodes. When others cells with sources, destinations, and relays are present, the mutual interference can be a limiting factor which needs to be characterized. In this paper we investigate the effects of relay position and power allocation strategy for cooperative communications employing space-time codes (STCs) under interference constraints due to a second cell with relay that reuse the resources. We characterize links between each source, relay, and destination to analyze power allocation methods with interference in realistic scenarios. The frame error rate at the destination for various channel conditions, available diversity, relays positions, power allocation, and amount of interference is then obtained. Results are shown for cooperative pragmatic STC in block fading channel (BFC) and provide insights on how to allocate the power based on links geometry and mutual interference considerations.

Keywords: Wireless cooperative networks, power allocation, interference, pragmatic space-time codes, block fading channel, performance evaluation.

1. Introduction

In conjunction with MIMO techniques, cooperative communication is considered an enabling technique for 4G wireless systems as a new paradigm in wireless networks to cope with fading, increase capacity and diversity gain, and extend coverage. In addition to physical antenna arrays, the relay channel model enables the exploitation of distributed antennas belonging to multiple relaying terminals. This form of space diversity is referred to as cooperative diversity because terminals share antennas and other resources to create a virtual array through distributed transmission and signal processing [1,2]. Several issues arise with cooperative diversity schemes such as, among others, channel modeling and implementation aspects [3, 4], protocols and resource management [5], the choice of proper relays [6], power allocation among cooperating nodes [7], and cooperative/distributed space-time codes (STCs) [8,9].

In a cellular network with relays, other issues arise and affect the performance at the destinations, such as the intercell interference caused by sources and relays transmissions from cells that spatially reuse the same resources (in time and frequency). This calls for power allocation methods that consider also the geometry and the amount of interference generated by sources and relays, and try to minimize the reuse distance for a given target performance at the destination.

With the introduction of STCs it has been shown how, with the use of proper trellis codes, multiple transmitting antennas can be exploited to improve system performance obtaining both diversity and coding gain, without sacrificing spectral efficiency [10]. In [11] a pragmatic approach to STCs, called pragmatic space-time codes (P-STCs), has been proposed: it simplifies the encoder and decoder structures and also allows a feasible method to search for good codes in block fading channel (BFC) [12–14] (P-STC consists in the use of standard convolutional encoders and Viterbi decoders over multiple transmitting and receiving antennas). In [15] a design methodology of P-STCs for relay networks was provided.

MIMO networks with interference are gaining interest in the literature. The capacity of such networks is obtained in [16]. In this paper we consider the presence of relay nodes and the problem of power allocation among nodes to optimize the performance metric not in terms of capacity but of frame error rate (FER) or outage probability at the destination.

In our framework we look carefully at the quality of the links involving the relay (i.e., source-to-relay and relay-to-destination) in the presence of mutually interfering cells for both useful and interfering links with three-folds goal: (i) evaluate the performance in a more realistic scenario where both the geometry and the link quality impact the effectiveness of cooperation and the performance at the destination, (ii) investigate the impact of interference to power allocation strategies and performance, and (iii) provide some insight on how to determine the reuse distance based on both geometrical and link quality conditions, and power utilization.

2. System Model

We consider the downlink of two cells with reuse distance d_{reuse} between the two sources and relays in fixed positions at a distance d_{SR} from the source (all distances are normalized to source-relay distance, i.e $d_{\text{SR}} = 1$). Destinations are mobile and, in the one-dimensional example scenario shown in Fig. 1, they move around the respective sources.

The cooperative scheme follows time-division channel allocations with orthogonal cooperative diversity transmission [8]. Each source S divides the time-slot in two equal segments, the first from time t_1 to $t_1 + \Theta$ and the second from $t_2 = t_1 + \Theta$ to $t_2 + \Theta$, where Θ is the segment duration. In the first segment the source broadcasts its coded symbols, in the second segment all the active relays (which are able to decode the message) forward the information through proper encoding to take advantage of the total available diversity. Thus, the design of proper STCs for the two phases is crucial to maximize both achieved diversity and coding gain.

We assume n transmitting antennas at each terminal, m_r and m_{D} receiving antennas

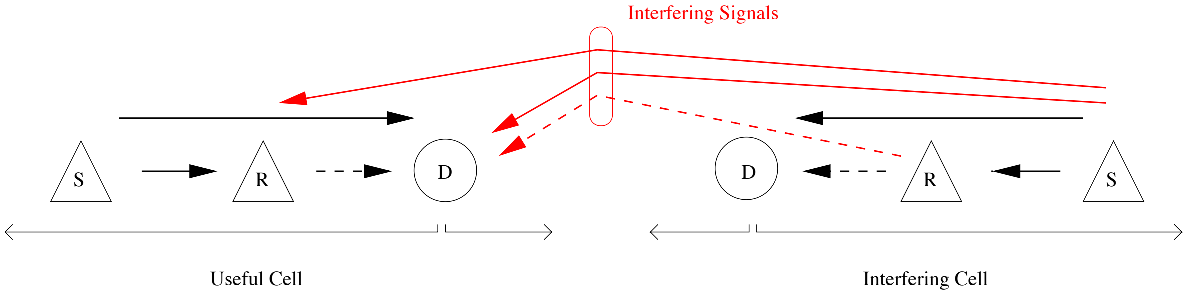

Figure 1: One-dimensional example of two-phase relaying scheme: phase 1 (continuous line), phase 2 (dashed line). Source, relays and destination nodes are denoted with S, R, D, respectively. Interfering signals in phases 1 and 2 are in red.

at the relay r and at the destination, respectively. Hence, $n_1 = n$ transmitting antennas will be used in the first phase and a total of $n_2 = Rn$ transmitting antennas will be used in the second phase, where R is the number of potential relays.[1] The positions of destinations are initialized at the beginning of a data communication session and are kept unchanged over the session.

We indicate with $c_{r,i}^{(t)}$ and $q_{r,i}^{(t)}$ the modulation symbols transmitted by node r ($r = 0$ for the source) on the antenna i at discrete time t for the useful and the interfering cell, respectively. Each symbol is assumed to have unit norm. Note that symbols $c_{0,i}^{(t)}$ and $q_{0,i}^{(t)}$ are transmitted at time $t_1 + t$, while symbols $c_{r,i}^{(t)}$ and $q_{r,i}^{(t)}$ for $r > 0$ are transmitted at time $t_2 + t$. In the first phase, symbols $c_{0,i}^{(t)}$ and $q_{0,i}^{(t)}$ are received by each relay of the respective cell; if correctly decoded[2] then the relay re-encodes and forwards to the destination. The received signals corresponding to all symbols $c_{r,i}^{(t)}$ and $q_{r,i}^{(t)}$ are jointly decoded by the destinations, respectively for the useful and the interfering cell, at the reference time t. We also denote with $\mathbf{C}^{(t)}$ and $\mathbf{Q}^{(t)}$ the super-symbols, which are the vector of the $(R+1)n$ outputs of the "virtual encoder" constituted by source and relays encoders for the two cells, respectively. A codeword is a sequence of N super-symbols generated by the source and relays' encoders of the two cells. These codewords are interleaved (i.e., permutation in time $t \to \sigma_t$, see [15]) and sent through the BFC.

The channel model includes additive white Gaussian noise (AWGN), additive interference, and multiplicative flat fading, with Rayleigh distributed amplitudes assumed constant over blocks of B consecutive transmitted space-time symbols and independent from block to block [12–14]. Perfect channel state information is assumed at the decoder for each node, whereas the transmitters only know the mean channel gain for power allocation.

For the destination D the transmitted super-symbol at time σ_t goes through a compound channel described by the $(n_1 + n_2) \times m_{\mathrm{D}}$ channel matrix

$$\mathbf{H}^{(\sigma_t,\mathrm{D})} = [H_0^{(\sigma_t,\mathrm{D})}, \dots, H_R^{(\sigma_t,\mathrm{D})}]^T$$

where $H_r^{(\sigma_t,\mathrm{D})} = \left\{h_{r,i,s}^{(\sigma_t,\mathrm{D})}\right\}$, and $h_{r,i,s}^{(\sigma_t,\mathrm{D})}$ is the channel gain between transmitting antenna i ($i = 1, \dots, n$) of the terminal r and receiving antenna s at the destination D ($s = 1, \dots, m_{\mathrm{D}}$). The channel matrix for the links between interferers and destination in the useful cell is $\mathbf{G}^{(\sigma_t,\mathrm{D})} = [G_0^{(\sigma_t,\mathrm{D})}, \dots, G_R^{(\sigma_t,\mathrm{D})}]^T$ where $G_r^{(\sigma_t,\mathrm{D})} = \left\{g_{r,i,s}^{(\sigma_t,\mathrm{D})}\right\}$, and $g_{r,i,s}^{(\sigma_t,\mathrm{D})}$ is the channel gain between transmitting antenna i ($i = 1, \dots, n$) of the terminal r and receiving antenna s at the destination D ($s = 1, \dots, m_{\mathrm{D}}$). In the BFC model these channel matrices do not change for B consecutive transmissions, hence we actually have only $L = N/B$ possible distinct channel matrix instances per codeword.[3] Similarly, in the first phase the $r^{\underline{\text{th}}}$ relay R_r of the useful and the interfering cells experience a channel described by the $(n_1 \times m_r)$ channel matrix $H_0^{(\sigma_t,\mathrm{R}_r)} = \left\{h_{i,s}^{(\sigma_t,\mathrm{R}_r)}\right\}$ for the useful and $G_0^{(\sigma_t,\mathrm{R}_r)} = \left\{g_{i,s}^{(\sigma_t,\mathrm{R}_r)}\right\}$ for the interfering cell; $h_{i,s}^{(\sigma_t,\mathrm{R}_r)}$ and $g_{i,s}^{(\sigma_t,\mathrm{R}_r)}$ are the channel gains

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[1] The notation is kept general in the number of relays R while the results will be obtained for $R = 1$.

[2] We assume CRC perfectly recognizing if a codeword is correctly decoded.

[3] For the sake of simplicity we assume N and B such that L is an integer. When $B = 1$ we have the ideally interleaved fading channel (i.e., independent fading levels from symbol to symbol), while for $L = 1$ we have the quasi-static fading channel (fading level constant over a codeword); by varying L we can describe channels with different correlation degrees.

between transmitting antenna i ($i = 1, \ldots, n$) of the source and receiving antenna s at the relay $\mathbf{R}_r$ ($s = 1, \ldots, m_r$).

We now define $\mathcal{K}^{(\mathrm{D},1)}$ and $\mathcal{K}^{(\mathrm{D},2)}$ the set of interferers seen by the destination in phase 1 and 2, respectively. The sequence of received signal vectors at the destination is after de-interleaving $\left(\mathbf{R}^{(1,\mathrm{D})}, \ldots, \mathbf{R}^{(N,\mathrm{D})}\right)$, where the received vector at time $t = 1, \ldots, N$ is $\mathbf{R}^{(t,\mathrm{D})} = \left[r_1^{(t,\mathrm{D},1)} r_1^{(t,\mathrm{D},2)} \cdots r_{m_\mathrm{D}}^{(t,\mathrm{D},1)} r_{m_\mathrm{D}}^{(t,\mathrm{D},2)}\right]^T$ with

$$r_s^{(t,\mathrm{D},1)} = \sqrt{E_0}\sum_{i=1}^{n} h_{0,i,s}^{(\sigma_t,\mathrm{D})} c_{0,i}^{(t)} + \sum_{k \in \mathcal{K}^{(\mathrm{D},1)}} \sqrt{E_{\mathrm{I},k}} \sum_{i=1}^{n} g_{k,i,s}^{(\sigma_t,\mathrm{D})} q_{k,i}^{(t)} + \eta_s^{(t,\mathrm{D},1)} \tag{1}$$

$$r_s^{(t,\mathrm{D},2)} = \sum_{r=1}^{R} \sqrt{E_r} \sum_{i=1}^{n} h_{r,i,s}^{(\sigma_t,\mathrm{D})} c_{r,i}^{(t)} + \sum_{k \in \mathcal{K}^{(\mathrm{D},2)}} \sqrt{E_{I,k}} \sum_{i=1}^{n} g_{k,i,s}^{(\sigma_t,\mathrm{D})} q_{k,i}^{(t)} + \eta_s^{(t,\mathrm{D},2)} \tag{2}$$

for phase 1 and 2, respectively, with $s = 1, \ldots, m_\mathrm{D}$. In this equation $r_s^{(t,\mathrm{D},l)}$ is the signal-space representation of the signal received by antenna s at time t in phase l, the noise terms $\eta_s^{(t,\mathrm{D},l)}$ are independent, identically distributed (i.i.d.) complex Gaussian random variables (r.v.s), with zero mean and variance $N_0/2$ per dimension, and the r.v.s $h_{r,i,s}^{(\sigma_t,D)}$ and $g_{k,i,s}^{(\sigma_t,D)}$ represent the de-interleaved complex Gaussian fading.

Similarly, we define $\mathcal{K}^{(\mathrm{R}_r,1)}$ the set of interferers to the relay r in phase 1 and its received signal vector at time t is $\mathbf{R}^{(t,\mathrm{R}_r)} = \left[r_1^{(t,\mathrm{R}_r)} \cdots r_{m_r}^{(t,\mathrm{R}_r)}\right]^T$ with components

$$r_s^{(t,\mathrm{R}_r)} = \sqrt{E_0}\sum_{i=1}^{n} h_{i,s}^{(\sigma_t,\mathrm{R}_r)} c_{0,i}^{(t)} + \sum_{k \in \mathcal{K}^{(\mathrm{R}_r,1)}} \sqrt{E_{\mathrm{I},k}} \sum_{i=1}^{n} g_{k,i,s}^{(\sigma_t,\mathrm{R}_r)} q_{k,i}^{(t)} + \eta_s^{(t,\mathrm{R}_r,1)} \tag{3}$$

for $s = 1, \ldots, m_{\mathrm{R}_r}$. We assume spatially uncorrelated channel gains independent, non-identically distributed (i.n.i.d.) Complex Gaussian r.v.s with zero mean and variance per dimension given by

$$\begin{cases} \Delta_{\mathrm{SD}}/2 & \text{for } h_{0,i,s}^{(t,\mathrm{D})}, \\ \Delta_{\mathrm{R}_r\mathrm{D}}/2 & \text{for } h_{r,i,s}^{(t,\mathrm{D})} \text{ with } r > 0, \\ \Delta_{\mathrm{SR}_r}/2 & \text{for } h_{i,s}^{(t,\mathrm{R}_r)}, \\ \Delta_{\mathrm{I,SD}}/2 & \text{for } g_{0,i,s}^{(t,\mathrm{D})}, \\ \Delta_{\mathrm{I,R}_r\mathrm{D}}/2 & \text{for } g_{r,i,s}^{(t,\mathrm{D})} \text{ with } r > 0, \\ \Delta_{\mathrm{I,SR}_r}/2 & \text{for } g_{i,s}^{(t,\mathrm{R}_r)}, \end{cases} \tag{4}$$

where, if we normalize all the distances to source-relay distance $d_{\mathrm{SR}_r} = d_{\mathrm{SR}}\ \forall r$, we have

$$\begin{aligned} \Delta_{\mathrm{SD}} &= \left(d_{\mathrm{SD}}/d_{\mathrm{SR}}\right)^{-\beta} \\ \Delta_{\mathrm{SR}_r} &= \left(d_{\mathrm{SR}}/d_{\mathrm{SR}}\right)^{-\beta} = 1 \\ \Delta_{\mathrm{R}_r\mathrm{D}} &= \left(d_{\mathrm{R}_r\mathrm{D}}/d_{\mathrm{SR}}\right)^{-\beta} \\ \Delta_{\mathrm{I,SD}} &= \left(d_{\mathrm{I,SD}}/d_{\mathrm{SR}}\right)^{-\beta} \\ \Delta_{\mathrm{I,SR}_r} &= \left(d_{\mathrm{I,SR}_r}/d_{\mathrm{SR}}\right)^{-\beta} \\ \Delta_{\mathrm{I,R}_r\mathrm{D}} &= \left(d_{\mathrm{I,R}_r\mathrm{D}}/d_{\mathrm{SR}}\right)^{-\beta} . \end{aligned}$$

Here, as an example, $d_{\mathrm{R}_r\mathrm{D}}$ is the distance between relay $\mathbf{R}_r$ and destination of the useful cell, and $d_{\mathrm{I},\mathrm{R}_r\mathrm{D}}$ is the distance between relay $\mathbf{R}_r$ of interfering cell and destination of the useful cell. A path-loss proportional to d^{β} is assumed at the distance d.

3. Outage Probability

A performance metric for cooperative wireless networks which can drive the power allocation methods is the outage probability.[4]

We evaluate the outage probability for a simplified cooperative system which captures main characteristics of the cooperating links (e.g., the diversity achieved) and enables us to obtain insights on power allocation methods. We aim to capture the role of diversity for a system with multiple input multiple output (MIMO) links by means of a tractable model.

We consider two simplifying assumptions. The first assumption is that each link works as a single-input multiple-output system with $n \times m$ outputs where the receiver combines signals over multiple antennas through maximal ratio diversity processing; here, the interference comes at each receiver antenna from N_{I} sources, where N_{I} is the number of interfering nodes multiplied by n. The second assumption is that the destination selects the signal with the greater signal-to-noise ratio (SNR), among the one from the source or those from the relay. This enables us to investigate the power allocation between source and relay independently of the particular space-time cooperative scheme if it achieves full diversity on each link.

We restrict here our derivation to the case with one relay ($R = 1$). The source transmits with energy per symbol $x_{\mathrm{S}}E_{\mathrm{s}}$ and the relay forwards the message to the destination with energy per symbol $x_{\mathrm{R}}E_{\mathrm{s}}$ if it is not in outage (i.e, the error probability at the relay is lower than a target error probability and, consequently, the SNR is greater than the required SNR ρ_{th}). The constraint on the total energy per symbol over the two phases gives x_{S}, $x_{\mathrm{R}} \in [0, x_{\mathrm{t}}]$ and $x_{\mathrm{S}} + x_{\mathrm{R}} = x_{\mathrm{t}} = 2$.

The selection diversity between signals from source and relay gives the following outage probability at the destination

$$\begin{aligned} P_{\mathrm{out}} &= \left[1 - \mathbb{P}\left\{\rho_{\mathrm{SR}} \geq \rho_{\mathrm{th}}\right\} \mathbb{P}\left\{\rho_{\mathrm{RD}} \geq \rho_{\mathrm{th}}\right\}\right] \mathbb{P}\left\{\rho_{\mathrm{SD}} < \rho_{\mathrm{th}}\right\} \\ &= \left[1 - \left(1 - F_{\mathrm{SR}}\left(\rho_{\mathrm{th}}\right)\right)\left(1 - F_{\mathrm{RD}}\left(\rho_{\mathrm{th}}\right)\right)\right] F_{\mathrm{SD}}\left(\rho_{\mathrm{th}}\right) \end{aligned} \tag{5}$$

The cumulative distribution function (c.d.f.) of the SNR $\gamma_{\mathbb{L}}$ on the link $\mathbb{L}$ (the reader may substitute SD, SR, or RD to $\mathbb{L}$ depending on the link considered) and for N_{I} interfering signals with equal power and maximal ratio combining (MRC) is given by [19]

$$\begin{aligned} F_{\mathbb{L}}(z) &= 1 - e^{-z/\overline{\gamma}_{\mathbb{L}}} \sum_{d=0}^{D_{\mathbb{L}}-1} \sum_{\substack{d_0,\ldots,d_{N_{\mathrm{I}}} \\ \sum d_n = d}} \frac{1}{d_0!}\left(\frac{z}{\overline{\gamma}_{\mathbb{L}}}\right)^{d_0} \\ &\times \left[\frac{1}{1 + z\overline{\gamma}_{\mathrm{I},\mathbb{L}}/\overline{\gamma}_{\mathbb{L}}}\right]^{N_{\mathrm{I}}} \left[\frac{z\overline{\gamma}_{\mathrm{I},\mathbb{L}}/\overline{\gamma}_{\mathbb{L}}}{1 + z\overline{\gamma}_{\mathrm{I},\mathbb{L}}/\overline{\gamma}_{\mathbb{L}}}\right]^{d-d_0} \end{aligned} \tag{6}$$

which depends on the diversity $D_{\mathbb{L}}$ and mean SNR $\overline{\gamma}_{\mathbb{L}}$ from the useful and $\overline{\gamma}_{\mathrm{I},\mathbb{L}}$ from the interfering link. By considering the channel model assumptions made in the previous

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[4] The concept of outage probability in wireless communications is well known. For application to digital communications with a given target error probability see, e.g., [17, 18].

section, we have: $N_{\text{I}} = n$ at each link, $\overline{\gamma}_{\text{SD}} = x_{\text{S}}\Delta_{\text{SD}}\overline{\gamma}$, $\overline{\gamma}_{\text{SR}} = x_{\text{S}}\Delta_{\text{SR}}\overline{\gamma}$, $\overline{\gamma}_{\text{RD}} = x_{\text{R}}\Delta_{\text{RD}}\overline{\gamma}$, $\overline{\gamma}_{\text{I,SD}} = x_{\text{I,S}}\Delta_{\text{I,SD}}\overline{\gamma}$, $\overline{\gamma}_{\text{I,SR}} = x_{\text{I,S}}\Delta_{\text{I,SR}}\overline{\gamma}$ and $\overline{\gamma}_{\text{I,RD}} = x_{\text{I,R}}\Delta_{\text{I,RD}}\overline{\gamma}$, where $\overline{\gamma}$ is the SNR E_{s}/N_0. The $x_{\text{I,S}}, x_{\text{I,R}}$ are the fractions of power allocated to source and relay in the interfering cell, respectively.

4. Power Allocation Methods

The average transmitted energy per symbol E_{s}, when the relay $(R = 1)$ is active, is equal to $E_{\text{s}} = (E_0 + E_1)/2$. The energy transmitted per information bit is $E_{\text{b}} = E_{\text{s}}/(hR_{\text{c}})$ where h is the number of bits per modulation symbol and R_{c} is the code-rate of the cooperative space-time code.

As far as power allocation (PA) among source and relays is concerned (i.e., the way to fix values of x_{S}, x_{R}) we consider the following strategies:

- *Uniform PA*: the source and all relays transmit with equal power $E_0 = E_1 = E_{\text{s}}$ in both the useful and the interfering cells (thus $x_{\text{S}} = x_{\text{R}} = x_{\text{I,S}} = x_{\text{I,R}} = 1$);

- *Balanced PA*: the power among source and relay is balanced such that the average received power at the destination in phase 2 is the same of the received power at the relay in phase 1. Thus, the source transmits with E_0 and the relay with $E_1 = E_0 \; \Delta_{\text{SR}_r}/\Delta_{\text{R}_r\text{D}}$ leading to $x_{\text{S}} = 2E_{\text{s}}/\left(1 + \Delta_{\text{SR}_r}/\Delta_{\text{R}_r\text{D}}\right)$. We also evaluate *half-compensation* power control [20, 21] for which $\Delta_{\text{SR}_r}/\Delta_{\text{R}_r\text{D}}$ is substituted by

  $$\sqrt{\Delta_{\text{SR}_r}/\Delta_{\text{R}_r\text{D}}}\,.$$

- *Outage-based PA*: the power among source and relays are balanced to minimize the maximum between outage probabilities at the destinations of the useful and the interfering cells. This requires a genius that allocates the power looking at the channel gains of both cells. When this is not available, one can minimize the outage probability at the destination of each cell without considering the performance in the other cell. In this case, if we denote the outage probability at the destination as $P_{\text{out}}(x_{\text{S}}, x_{\text{I,S}}, x_{\text{I,R}})$ to emphasize the dependence on power allocation of the two mutually interfering systems, we get x_{S} as solution of the problem

  $$\min_{x\in]0,2]} P_{\text{out}}(x, x_{\text{I,S}}, x_{\text{I,R}}) \tag{7}$$

  for a fixed value of $x_{\text{I,S}}$ which represents an arbitrary estimation of power allocation in the interfering cell. When $x_{\text{I,S}} = x_{\text{I,R}} = 0$, PA ignores the interference: for this simple case, some analytical approximated solutions are discussed in [22].

5. Cooperative space-time code for Relaying

In the case of the relay scheme shown in Fig.1, the probability of transmission failure over the two phases depends on the number of relays available for cooperation and on the quality of links SD, SR, and RD, as well as the amount of interference on receivers of the two phases.

Depending on terminals' positions the relays are set by looking at those that are able to guarantee effective cooperation with the source and to satisfy the target performance at the destination. Sometimes, due to fast fading fluctuations, it may happen that a relay is not able to decode the source codewords in the first phase. Let us denote by $P_{\mathrm{e}}^{(\mathrm{SD})}$ the error probability for source-destination link, $P_{\mathrm{e}}^{(\mathrm{SR}_r)}$ the error probability for the source- $r^{\underline{\mathrm{th}}}$ relay link, and with $P_{\mathrm{e}}^{(\mathrm{S}\mathcal{R}\mathrm{D})}$ the error probability for the link from the source plus active relays ($\mathcal{R}$ being the set of active relays) to destination. The error probability at destination for one relay is given by

$$P_e = P_e^{(\mathrm{SR}_1)} P_e^{(\mathrm{SD})} + \left(1 - P_e^{(\mathrm{SR}_1)}\right) P_e^{(\mathrm{SR}_1\mathrm{D})} \tag{8}$$

which can be generalized for multiple relays. Note that these performance metrics are functions of system parameters as

$$\begin{aligned} P_{\mathrm{e}}^{(\mathrm{SD})} &= f^{(\mathrm{SD})}\left(E_{\mathrm{s}}, \Delta_{\mathrm{SD}}, \Delta_{\mathrm{I,SD}}, x_{\mathrm{S}}, x_{\mathrm{I,S}}, N_0\right) \\ P_{\mathrm{e}}^{(\mathrm{SR}_1)} &= f^{(\mathrm{SR}_1)}\left(E_{\mathrm{s}}, \Delta_{\mathrm{SR}_1}, \Delta_{\mathrm{I,SR}_1}, x_{\mathrm{S}}, x_{\mathrm{I,S}}, N_0\right) \\ P_{\mathrm{e}}^{(\mathrm{SR}_1\mathrm{D})} &= f^{(\mathrm{S}\mathcal{R}\mathrm{D})}\left(E_{\mathrm{s}}, \Delta_{\mathrm{SD}}, \Delta_{\mathrm{R}_1\mathrm{D}}, \Delta_{\mathrm{I,SD}}, \Delta_{\mathrm{I,R}_1\mathrm{D}}, x_{\mathrm{R}}, x_{\mathrm{I,R}}, N_0\right) . \end{aligned}$$

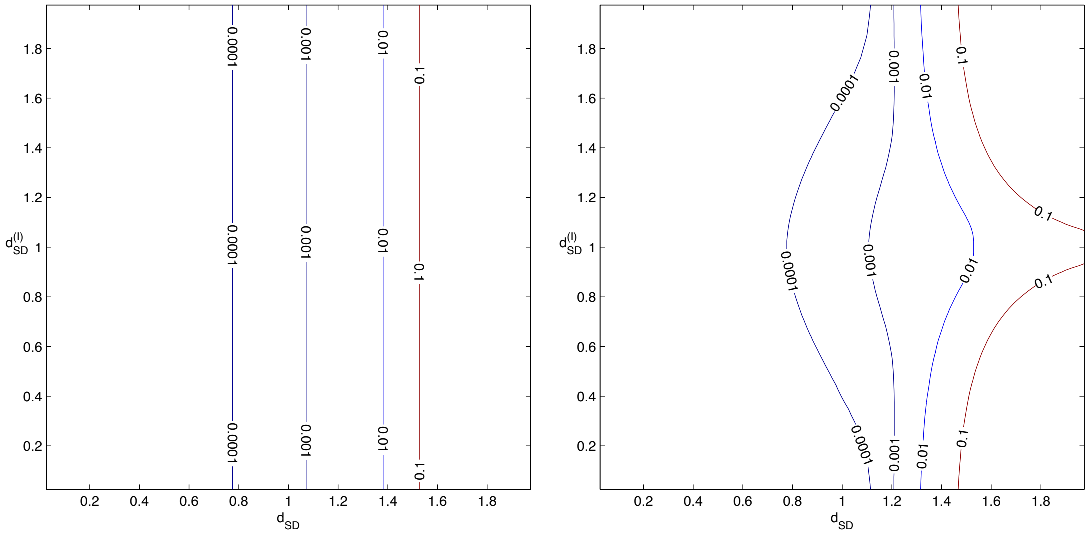
We will evaluate the error probability by simulation averaging over various positions of the destination of the interfering cell.

For the goal of our paper, we consider space-time trellis codes for relaying networks by using the pragmatic approach of [11] and the efficient search for generators of cooperative P-STCs in BFC discussed in [15].

6. Results

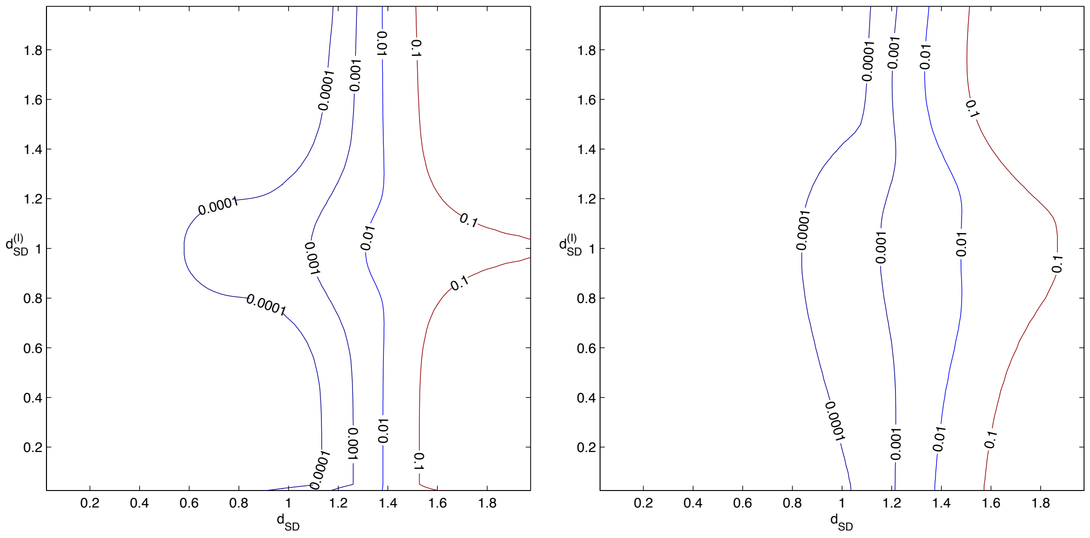
In this sections we show two sets of results: the outage probability of the simplified system which captures the diversity level achieved in each link, described in Section 3., for different power allocation strategies, and the mean FER at the destination averaged over rapid processes, such that those related to BFC evaluated for cooperative overlay pragmatic space-time code (COP-STC) as a function of destination position, reuse distance, BFC characteristics (i.e., values of L), and power allocation strategy. We refer to a system with two mutually interfering cooperative systems with one relay as in Fig. 1 with $n = 2$ transmitting antennas per node, $m_{\mathrm{R}} = 2$ receiving antennas at the relay, $m_{\mathrm{D}} = 1$ receiving antenna at the destination. All possible destinations' positions on a one-dimensional linear scenario are evaluated with distances normalized to d_{SR_r}. The source-destination distance of the useful system is denote with d_{SD}, whereas the source-destination distance of the interfering system is denoted with $d_{\mathrm{SD}}^{(I)}$. The path-loss coefficient is $\beta = 3.5$ which is feasible choice for many wireless scenarios.

Figures 2 and 3 are 2-dimensional plots that show the outage probability of the useful system as a function of each pair $(d_{\mathrm{SD}}, d_{\mathrm{SD}}^{(I)})$ of destinations' positions. The different plots are obtained for four different allocation strategies: uniform PA, balanced PA with half-compensation, outage-based PA for systems without interference and outage-based PA with $x_{\mathrm{I,S}} = 1.8$. We can note that the different strategies have different behaviors when varying $d_{\mathrm{SD}}^{(I)}$: some behave well when the interfering destination is near its source, whereas others behave worse. From these figures we can obtain the coverage region enabled by the use of the relay for a given target outage probability. As an example, from the figures, for a target of 0.01 the maximum coverage distance d_{cov} for both the destinations (the target has to be achieved for all the points $(d_{\mathrm{SD}} < d_{cov}, d_{\mathrm{SD}}^{(I)} < d_{cov})$) is 1.37 for uniform PA, 1.32 for both balanced PA and outage-based PA for systems



(a) (b)

Figure 2: Outage probability as a function of the positions d_{SD} and $d_{SD}^{(I)}$ of the two destinations. First plot is for uniform PA and second plot is for balanced PA with half-compensation. Other parameters: $d_{\text{reuse}} = 4$, $n = 2$, $m_R = 2$, $m_D = 1$, $\gamma_{th} = 10$ dB, $\eta = 0.01$.

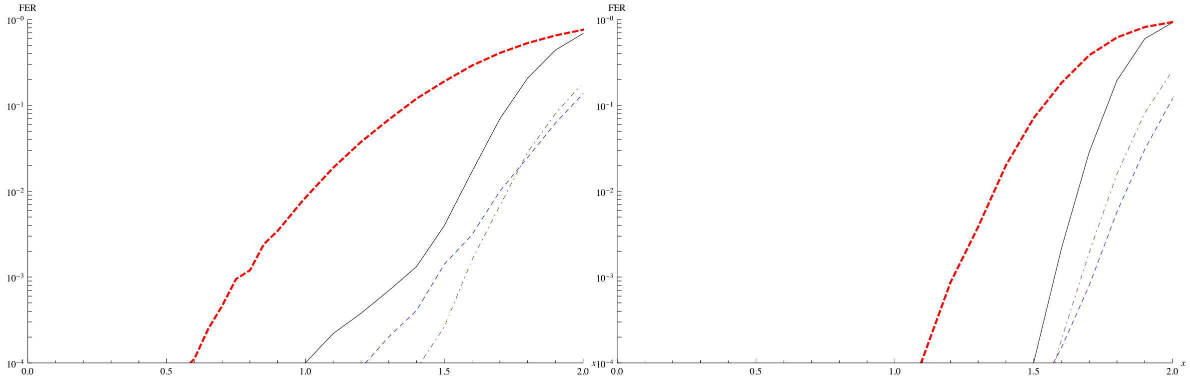


(a) (b)

Figure 3: Outage probability as a function of the positions d_{SD} and $d_{SD}^{(I)}$ of the two destinations. First plot is for Outage-based-PA with $x_{I,S} = 0$ and second plot is for Outage-based PA with $x_{I,S} = 1.8$. Other parameters: $d_{\text{reuse}} = 4$, $n = 2$, $m_R = 2$, $m_D = 1$, $\gamma_{th} = 10$ dB, $\eta = 0.01$.

without interference, 1.38 outage-based PA with $x_{I,S} = 1.8$, $x_{I,R} = 0.2$. In general the best behavior is obtained by outage-based PA, although it is not so distant from uniform PA.

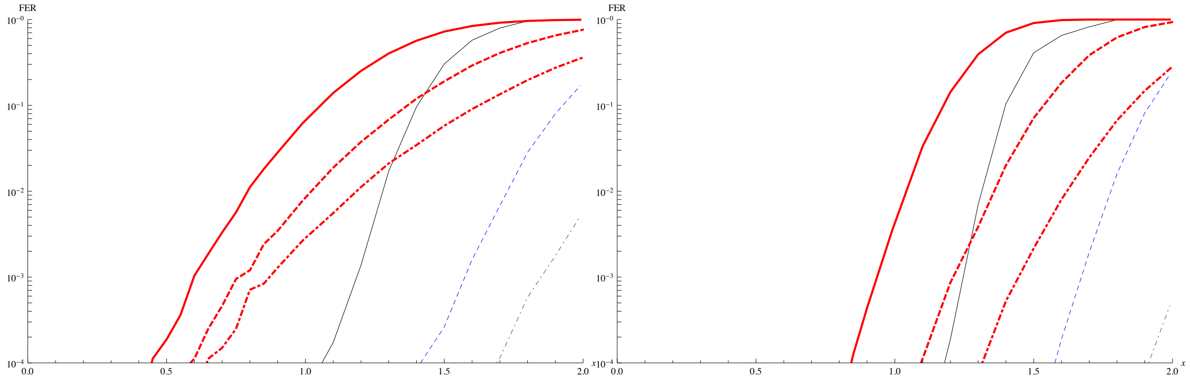
The next results in terms of simulated FER are obtained for COP-STC with 8 states and BPSK constellation signaling, code-rate $1/4$, generators $(13, 15, 11, 17)_8$ as from [15], $N = 130$, and with the power allocation strategies discussed before. Various



(a) $n = 2$, $m_\mathrm{R} = m_\mathrm{D} = 1$ and $L = 1$.

(b) $n = 2$, $m_\mathrm{R} = m_\mathrm{D} = 1$ and $L = 5$.

Figure 4: FER with uniform (continuous), balanced (dashed) and outage-based (dotdashed) PA for various destination's positions along the line containing S and R, $E_\mathrm{b}/N_0 = 20\mathrm{dB}$, $d_\mathrm{reuse} = 4$ and for L=1,5. Dashed red line inidicates the performance without cooperation.



(a) $n = 2$, $m_\mathrm{R} = m_\mathrm{D} = 1$ and $L = 1$.

(b) $n = 2$, $m_\mathrm{R} = m_\mathrm{D} = 1$ and $L = 5$.

Figure 5: FER with outage-based PA and without cooperation (red lines) for various destination's positions along the line containing S and R, $E_\mathrm{b}/N_0 = 20\mathrm{dB}$, $d_\mathrm{reuse} = 3$ (continuous), 4 (dashed),5 (dotdashed) and for L=1,5.

BFCs are considered. The SNR is defined as E_b/N_0 per receiving antenna element where E_b is the total energy per information bit over all transmitting nodes and averaged with respect to fading. In the figures we use $E_\mathrm{b}/N_0 = 20\mathrm{dB}$ and the FER is averaged over a uniformly distributed position for the destination of the interfering system in a range of 0.5 around its relay.

Figure 4 compares the behavior of different power allocation strategies in four cases of reuse distance and number of BFC. In red dash the FER for the link source-to-destination in the absence of relaying is shown to understand where the cooperative relay improves the performance. Figure 5 compares different situations for the reuse distance, after having fixed the use of outage-based PA. We observe in this case the good behavior of outage-based PA and the real benefit in coverage that the use of relay is able to achieve even in the presence of interference.

7. Conclusions

In this paper we analyzed the effect of mutual interference for relay communications and power allocation methods. The analyisis of the outage probability under simplified assumptions drives the choice of power allocation criteria that are then tested on realistic scenarios with cooperative overlay pragmatic space-time codes in block fading channels. Both the geometry and links quality affect the performance. Results of this nature can help the system designer to chose the appropriate reuse distance in cellular networks with relay.

Acknowledgments

Research supported in part by the FP7 European project OPTIMIX (Grant 214625) and the FP7 European Network of Excellence in Wireless Communications NEWCom++ that we acknowledge.

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