Cooperative space-time coded transmissions in Nakagami-m fading channels

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***Abstract*— In this paper we evaluate outage performance of a cooperative transmission protocol over fading channels that requires a number of relaying nodes to employ a distributed space-time coding scheme. Diversity provided by this technique has been widely analyzed for the Rayleigh fading case. However, ad-hoc and sensors networks often experience propagation environments where the line-of-sight component is either non zero or, in some cases, dominates compared to the random non line-of-sight components. By considering the Nakagami-m as a generic framework for describing the statistic of the fading impairments, this paper evaluates a set of fading inequalities that define settings where the benefits of collaborative transmission from multiple relays when varying fading parameters. These *cooperative fading regions* define the propagation settings that make cooperation preferable to multi-antenna non-cooperative transmission.**

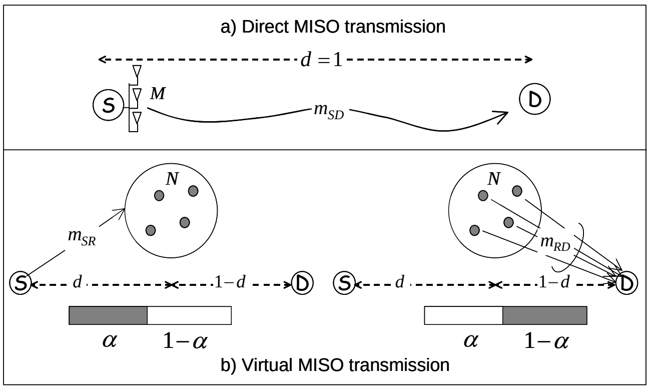

Fig. 1. Transmission setting and propagation environment for non cooperative MISO transmission (a) and cooperative (virtual) MISO (b) cases

I. Introduction

Wireless ad hoc networks consist of a number of terminals (or nodes) communicating with each other without the assistance of a wired or infrastructure network. The communication between nodes might take place through several intermediate nodes, creating a multihop network. Multipath fading is the main limitation of ad-hoc scheme that holds regardless of the size of the network as a result of constructive and destructive combination of randomly delayed, reflected, scattered and diffracted signal components and the path loss.

Depending on the nature of the radio propagation environment, there are different models describing the statistical behavior of the multipath fading envelope. Although the Rayleigh distribution is widely used to model multipath fading with no direct line-of-sight (NLOS) path, ad-hoc and sensors networks often experience propagation environments where the power of the line-of-sight (LOS) component is either non zero or, in some cases, dominate when compared to the random NLOS components. The influence of the propagation onto the overall system performance depends on the relevance of this diffusive (or NLOS) contribution with respect to the direct (or LOS) [1].

Multiple antenna at each terminal are known to provide spatial redundancy (or diversity order) to reduce fading impairments. However, this solution is often not viable due to hardware, size and cost constraints. As an alternative, it has been recently shown that cluster of nodes, with one antenna each, might form a kind of coalition to cooperatively act as a large transmit or receive array. Therefore, in the most general framework, transmission takes place between clusters of cooperating transmitters/receivers and not just between couples of nodes [2]. Transmission can thus harness the diversity (e.g., cooperative diversity [3]) provided by a multiple input (and in case multiple output) channel. Simple transmission protocols that can exploit cooperation were first investigated in [2] for ad hoc networks. In [3] cooperation diversity is assessed for the Rayleigh fading case by employing multiple coordinated relays and thus employing a (virtual) antenna array or a "distributed MISO" (Multiple Input Single Output) system.

In this paper, information theoretic analysis of cooperative diversity with fixed decode and forward relaying is evaluated for Nakagami-m as a more realistic fading distribution. With the aim of developing a general framework for performance analysis, we considered different amounts of fading (AF [4]) for all the links that are scheduled for transmission. Collaborative protocols, performed by multiple relays, are thus analyzed by revealing the propagation settings (or AFs) where cooperation is beneficial in improving the link performances (namely the outage probability) with respect to standard non-cooperative MISO transmission. Our purpose is thus to define *cooperative fading regions* as the collection of propagation settings (AFs) that make the cooperative transmission to perform at least as if conventional multiple antenna (MISO) direct transmission would be employed.

A. Propagation environment and system model

Rayleigh and Rice distributions are commonly adopted to describe the underlying physical properties of the channel models. However, some experimental data show the need of more general parametric fading distribution like Nakagami-m [4] that can be adjusted to fit a variety of empirical measurements.

Let E_S be the transmitted symbol energy for a transmission of duration T, from a generic single antenna source towards a single antenna destination, $\rho = E_S/T$ is the transmit power and ρ/N_0 is the signal to noise ratio (SNR) referred to the transmitting side with N_0 (to simplify, here we assume $N_0 = 1$) is the single sided additive white Gaussian noise (AWGN) noise power. Let g be the average channel gain (accounting for path loss and, in case, shadowing) of the link, then the SNR $\gamma(m) \sim f_\gamma(\gamma; m)$ at the decision variable depends on the Nakagami fading parameter m as [4]

$$f_\gamma(\gamma; m) = \frac{\gamma^{m-1}}{\Gamma(m-1)} \left(\frac{m}{\rho g}\right)^m \exp\left(-\frac{m\gamma}{\rho g}\right), \qquad (1)$$

where $\Gamma(x-1) = \int_0^\infty y^{x-1} \exp(-y) dy$ is the complete Gamma function. For $m = 1$ the distribution (1) reduces to Rayleigh fading and it can be mapped onto a Rice distribution with appropriate Rice-parameter K [4]. For $m = \infty$ is a pure LOS channel modelled as in boolean (or disk) channel models [5]. Thus, the Nakagami distribution can model Rayleigh and Rice distributions, as well as more general ones.

According to model settings in figure 1, the fading channel between source and destination nodes is modeled as a Nakagami-m distribution with fading figure m_{SD}. During cooperative transmission, at first a source node activates N relaying nodes by using a link with fading figure m_{SR}. Then collaborative transmission is performed only by the relays over a channel with Nakagami factor m_{RD}.

This paper is organized as follows: outage probability derivations for the high SNR regime are reviewed in Sect. II. In Sect. III-A the cooperative fading regions for fixed decode and forward transmission [2] are at first derived by comparing the achievable diversity of the cooperative and non cooperative schemes. More realistic cooperative regions are then derived in Sect. III-B by assuming a limited power budget $\rho < \infty$ to be available for transmission. Closed form bounding regions for Nakagami-m parameters are also developed. Since Rice fading is widely used to describe the physical structure of the LOS/NLOS propagation, numerical analysis in Sect. IV is based on the equivalent Rice K factors.

II. Outage probability derivation

In this section, we review the performance of the fixed decode and forward protocol in terms of outage probability (see, for example, [6]). High SNR approximation of the outage performance as well as degree of diversity [8] are also derived.

As a function of the random fading coefficients, I is the mutual information for all the considered links. For a given target rate R (b/s/Hz) and assuming static (or quasi-static) fading for the whole codeword duration, $I < R$ denotes the outage event, and $\Pr[I < R]$ denotes the corresponding outage probability. In what follows, subscripts DF, and Dir refers to the fixed decode and forward and the non-cooperative (direct) transmission, respectively.

A. Direct MISO transmission

Non-cooperative (direct) transmission is sketched in fig. 1-(a) with source node equipped with an $M \geq 1$ antenna array and the destination node with single antenna (although extension to multiantenna receiver would be straightforward). The transmission duration is T.

Space-time coding (ST) is employed to combat the fading effects by harnessing the diversity of the channel without requiring channel state information at the transmitter. The transmit power of each antenna scales as ρ/M to highlight the benefits of diversity without increasing the power. For Gaussian codebook case, the mutual information for the direct link is $I_{Dir} = \log_2(1+\gamma(m_{SD}M))$ and the outage probability for $\rho >> 1$ reads

$$\Pr(I_{Dir} < R) \simeq \frac{1}{\Gamma(Mm_{SD})} \left(\frac{Mm_{SD}\left(2^R-1\right)}{\rho g_{SD}}\right)^{Mm_{SD}}, \qquad (2)$$

g_{SD} is the average channel power for the direct link. Details around the derivation of (2) are shown in the Appendix VI. Assuming uncorrelated fading over each antenna, the (maximum) achievable diversity from (2)

$$\lim_{\rho\to\infty} \frac{-\log\left[\Pr(I_{Dir} < R)\right]}{\log(\rho)} = M \cdot m_{SD} \qquad (3)$$

scales with the number of antennas at the source node M (as ST coding is used) and with the fading parameter (m_{SD}) of the link. Therefore, the Nakagami parameter m measures an "inherent diversity" that is provided by the channel itself [1]. Notice that in case of no fading $m_{SD} = \infty$ outage probability is exactly zero for $\rho > \left(2^R - 1\right)/g_{SD}$ as for boolean (or disk) channel models [5], while for Rayleigh fading ($m_{SD} = 1$) it follows a known result.

B. Virtual MISO transmission (fixed decode and forward)

Due to hardware constraints (namely Time Division Duplex – TDD), medium access control (MAC) operation during the cooperative transmission is subdivided into two phases (or slots). As shown in figure 1-(b), at first the data to be transmitted is broadcast by the source node for a time fraction $\alpha \in (0, 1)$ of the available transmission duration T, so that N active nodes within the cluster at distance d that are willing to cooperate can decode the data to relay during the MISO transmission (the set of N active nodes is a subset of the total number of nodes in the cluster). Having N active and decoding nodes, during the second phase, the data is transmitted for the remaining time fraction $1 - \alpha$ through the $N \times 1$ MISO channel employing a distributed space-time coding (D-STC). Notice that for $N = 1$ it reduces to multihop transmission.

Aiming to develop a general model that is suited for any arbitrary space-time coding (and not only orthogonal, as in [3]), we assume that a D-STC transmission can be decoded at the destination only if all the $N > 1$ scheduled nodes can cooperatively relay the transmission by decoding the symbols from the source node (e.g., this holds for some space-time trellis code designs [7]). Extension to orthogonal ST coding case is straightforward.

Fixed (e.g., when N is given) decode and forward relay scheme [2] (herein generalized for the multirelay case) is the simplest cooperative protocol as the source node does not know whether or not all the N cooperating nodes have successfully decoded the message after the broadcast phase (this avoids any acknowledgement message exchange between the source and the relays). Therefore, as a simple extension to multihop transmission, this scheme requires the N available relays to fully decode the source information as decoding at the destination relies only on the relays-to-destination link.

Performances of fixed decode-and-forward is therefore limited by the decoding capability of the direct transmission between source and relays. We assume the probability that one relay (out of N) fails in decoding to coincide with an outage event, thus a decoding error occurs if the mutual information $I_{SR} = \alpha \log_2(1 + \gamma(m_{SR}))$ for the source-to-relay channel is $I_{SR} < R$ as in [2]. The probability that one relay fails in decoding is

$$\Pr(I_{SR} < R) \simeq \frac{1}{\Gamma(m_{SR})} \left(\frac{m_{SR} \left(2^{R/\alpha} - 1\right)}{\rho g_{SR}} \right)^{m_{SR}}, \quad (4)$$

g_{SR} is the average channel power for the link. Assuming, for simplicity, that the N relay nodes are at the same distance d from the source node and that each link is impaired with Nakagami fading with factor m_{SR}, the probability that at least one of the N relays fails in decoding (for high ρ) is $\Pr(N) = 1 - (1 - \Pr(I_{SR} < R))^N \simeq N \Pr(I_{SR} < R)$.

Being the mutual information for the relays-to-destination link $I_{RD} = (1 - \alpha) \log_2(1 + \gamma(m_{RD} N))$, the outage probability at the destination scales as

$$\Pr(I_{DF} < R) = [1 - \Pr(N)] \Pr(I_{RD} < R) + \Pr(N) \simeq$$
$$\simeq \frac{1 - \Pr(N)}{\Gamma(N \cdot m_{RD})} \left(\frac{N m_{RD} \left(2^{\frac{R}{1-\alpha}} - 1\right)}{\rho g_{RD}} \right)^{N m_{RD}} + \Pr(N). \quad (5)$$

Notice that, for the cooperative case, each terminal has a single antenna and the average channel power for each relay-to-destination link is g_{RD}. The transmit power of each collaborating terminal scales as ρ/N in order to constrain the same power consumption as for the non-cooperative case.

C. Outage performances with orthogonal ST coding

Orthogonal space–time codes can provide a diversity that scales with the random number of collaborating relays. In our model, an orthogonal space–time code is designed for a maximum of N transmit antennas. However, due to decoding errors at the relays, only a random subset of those terminals collaborate. Even if a cooperating terminal is missing, orthogonal ST coding still provides residual diversity benefits at the destination node [3], therefore. Let $\Pr(1) = \Pr(I_{SR} < R)$ from (4), the outage probability becomes:

$$\Pr(I_{DFO} < R) \simeq \textstyle\sum_{k=0}^{N} \binom{N}{k} (1 - \Pr(1))^k \Pr(1)^{N-k} \cdot$$
$$\cdot \frac{1}{\Gamma(k m_{RD})} \left(\frac{k m_{RD} \left(2^{R/(1-\alpha)} - 1\right)}{\rho g_{RD}} \right)^{k \cdot m_{RD}}, \quad (6)$$

subscript DFO stands for orthogonal DF, notice that the outage occurs if *all* the N potential relays fail in decoding, therefore with probability $\Pr(1)^N$.

III. Cooperative fading regions

In the following, we derive asymptotic $\mathcal{R}_{DF}^{\infty}$ and finite-SNR $\mathcal{R}_{DF}$ regions of fading parameters where cooperation is beneficial with respect to non-cooperative case in providing higher diversity (for $\mathcal{R}_{DF}^{\infty}$) or in improving outage performances (for $\mathcal{R}_{DF}$), respectively. In both cases, transmission is impaired by channels with a different fading figure. Analysis is based on varying channel parameters m_{SR}, m_{RD}, m_{SD}, collaborating relays N and number of antenna elements M considered here as reference non-cooperative case.

A. Asymptotic SNR cooperative fading regions

The achievable diversity for the cooperative scheme is the minimum of the diversity over the two links that is either provided by the channel itself or through ST coding

$$\lim_{\rho \to \infty} \frac{-\log [\Pr(I_{DF} < R)]}{\log(\rho)} = \min \{m_{SR}, \ N \cdot m_{RD}\}, \quad (7)$$

notice that diversity for this simple protocol is limited to one in Rayleigh fading ($m_{SR} = m_{RD} = 1$) [2]. By comparing (7) with (3), it can be easily shown that cooperation is beneficial in providing higher diversity with respect to the non-cooperative case only if $(m_{SR}, m_{RD}, m_{SD}, N, M) \in \mathcal{R}_{DF}^{\infty}$, where

$$\mathcal{R}_{DF}^{\infty} = \{m_{RD} > (M/N) \cdot m_{SD} \ , \ m_{SR} > M \cdot m_{SD}\}. \quad (8)$$

For orthogonal ST coding the diversity from (7) is $N \min\{m_{SR}, m_{RD}\}$, asymptotic region becomes:

$$\mathcal{R}_{DFO}^{\infty} = \{\min\{m_{RD}, m_{SR}\} > M/N\}. \quad (9)$$

B. Cooperative fading regions for finite SNR

Outage performances of the cooperative scheme is now compared with the non-cooperative case by assuming that only a finite amount of energy is available for the transmission.

At first, we constrain a specified outage probability at the destination P_{out} and a rate (outage capacity) of R, then, for any pair P_{out} and R, the required transmit power ρ (or energy E_S, if scaled by T) can be easily derived for non-cooperative MISO transmission by solving for ρ the equality $\Pr(I_{Dir} < R) = P_{out}$ and using approximation (2):

$$\rho \simeq \rho(M, m_{SD}) = \frac{\left(2^R - 1\right) M m_{SD}}{\left[\Gamma(M \cdot m_{SD}) \cdot P_{out}\right]^{1/M m_{SD}}}. \quad (10)$$

In (10) distance between the source and the destination is set to $d = 1$ so that, for a path loss model with exponent κ, $g_{SD} = d^{-\kappa} = 1$, when $M > 1$ available energy $E_S = \rho(M, m_{SD})T$ is equally split among each antenna. Notice that the required power diverges as $P_{out} \to 0$ or $R \to \infty$, moreover, for a given outage constraint P_{out}, it scales down by increasing the number of antenna elements M and the fading figure so that $\liminf_{m_{SD} \to \infty} \rho = 2^R - 1$ as in disk (or boolean channel models [5]) where channel is deterministic.

The same energy constraint E_S as for non-cooperative MISO transmission is applied for the cooperative scheme. During the first time fraction α the single-antenna source node broadcast the information symbols with energy αE_S (and power ρ) from (10) so that N nodes within a cluster at distance $0<d<1$ decode and cooperate with probability $1-\Pr(N)$. Next, during the remaining time fraction $1-\alpha$, the N nodes at distance $1-d$ from the destination coordinate themselves to employ a distributed space-time coding scheme with an available energy $[1-\alpha]\, E_S$. As for the non-cooperative case, this energy is equally split among each relay node (transmit energy at each relay is thus $[1-\alpha]\, E_S/N$).

Consider the decoding failure probability of the N collaborating nodes to be set to $\Pr(N)=p_N$, then the minimum required time fraction α for successful decoding of all the N selected nodes with a given probability $p_N << 1$ scales as:

$$\alpha(p_N,N)\simeq\min\left\{1,\frac{R}{\log_2\left(1+\frac{(2^R-1)\cdot\mathcal{S}(m_{SR},p_N)}{N^{1/m_{SR}}\cdot\mathcal{S}(M\cdot m_{SD},P_{out})\cdot d^{\kappa}}\right)}\right\} \quad (11)$$

and $g_{SR}=d^{-\kappa}$as d is the distance between the source node and the cooperative cluster. Time fraction increases with N and for decreasing p_N. Exact equality holds for asymptotically high ρ (or $P_{out} << 1$) and it is derived by substituting (10) into (4) and solving for α where function

$$\mathcal{S}(D,p)=\left[p\cdot(2\pi D)^{1/2}\right]^{1/D}. \quad (12)$$

From (5), the outage probability at the destination is found by optimizing the time fraction α, or equivalently by using (11) to minimize the achievable outage over p_N:

$$\min_{p_N<P_{out}} p_N+\frac{1-p_N}{\Gamma(Nm_{RD})}\left(\frac{Nm_{RD}\left(2^{\frac{R}{(1-\alpha(p_N,N))}}-1\right)}{(1-d)^{-\kappa}\cdot\rho}\right)^{Nm_{RD}}, \quad (13)$$

where ρ is the total power budget defined in (10). Feasible set for p_N should be bounded to $p_N<P_{out}$ as we search for a solution that improves the outage probability with respect to the setting of the non-cooperative case.

Lemma 1: Defining $\hat{p}_N$ and $\mathcal{P}_{out}$ as the optimal solution to (13) and the minimum achievable outage for $p_N=\hat{p}_N$, respectively, then cooperation is beneficial in providing $\mathcal{P}_{out}<P_{out}$ only if $(m_{SR},m_{RD},m_{SD},N,M)\in\mathcal{R}_{DF}$, where finite-SNR region $\mathcal{R}_{DF}$ becomes (proof is trivial, not shown here):

$$\mathcal{R}_{DF}=\left\{\frac{\mathcal{S}(Nm_{RD},P_{out}-\hat{p}_N)}{\mathcal{S}(Mm_{SD},P_{out})}>(1-d)^{\kappa}\,2^{\frac{\alpha(\hat{p}_N,N)R}{(1-\alpha(\hat{p}_N,N))}}\right\}. \quad (14)$$

1) Bounds for cooperative regions at finite SNR: In this section we develop a closed form for bounding the fading region that includes $\mathcal{R}_{DF}$ in (14).

Theorem 2: The region

$$\begin{aligned}\hat{\mathcal{R}}(P)=\{&\tfrac{Nm_{RD}-Mm_{SD}}{MN\cdot m_{SD}\cdot m_{RD}}\log_2\left[1/P_{out}\right]>\\ &>\kappa\log_2(1-d)-\mathcal{G}(Mm_{SD},Nm_{RD})+\tfrac{\alpha(P,N)\cdot R}{(1-\alpha(P,N))}\}\end{aligned} \quad (15)$$

for $\mathcal{G}(s,d)=[s\log_2(2\pi d)-d\log_2(2\pi s)]\cdot 1/(2s\cdot d)$, and $\alpha(P,N)$ in (11) has the following property: $\forall\rho>>1$ $\hat{\mathcal{R}}_{DF}\triangleq\hat{\mathcal{R}}(P_{out})\supset\mathcal{R}_{DF}$.

Proof: By using Lemma 1 and equation (14), being $\hat{p}_N<P_{out}$ the following inequality chain holds true:

$$\begin{aligned}&\frac{\mathcal{S}(Nm_{RD},P_{out})}{\mathcal{S}(Mm_{SD},P_{out})}>\frac{\mathcal{S}(Nm_{RD},P_{out}-\hat{p}_N)}{\mathcal{S}(Mm_{SD},P_{out})}>\\ &>(1-d)^{\kappa}\,2^{\frac{\alpha(\hat{p}_N,N)R}{(1-\alpha(\hat{p}_N,N))}}>(1-d)^{\kappa}\,2^{\frac{\alpha(P_{out},N)R}{(1-\alpha(P_{out},N))}},\end{aligned} \quad (16)$$

$\hat{\mathcal{R}}_{DF}$ is simply obtained by applying the logarithm to (16).

Corollary 3: Bounding region $\hat{\mathcal{R}}_{DF}$ is such that $\lim_{\rho\to\infty}\hat{\mathcal{R}}_{DF}=\mathcal{R}^{\infty}_{DF}$, moreover for $\rho>>1$ it is $\mathcal{R}^{\infty}_{DF}\supset\hat{\mathcal{R}}_{DF}\supset\mathcal{R}_{DF}$. Proof is omitted due to lack of space.

Remark: When orthogonal ST coding is used, it can be shown that the bounding region (15) becomes $\hat{\mathcal{R}}_{DFO}\triangleq\hat{\mathcal{R}}(NP_{out}^{1/N})$ such that $\lim_{\rho\to\infty}\hat{\mathcal{R}}_{DFO}=\mathcal{R}^{\infty}_{DFO}$. Comparison is shown in numerical analysis.

IV. Cooperative fading regions $\mathcal{R}_{DF}$ under Rice/Nakagami-m fading

The Rice distribution is described in terms of the ratio of the power in the LOS component to the power in the NLOS multipath random components. The SNR statistic at the decision variable can be found in [4]. As for the Nakagami case, different Rice factors can be associated to the source-to-destination, source-to-relays and relays-to-destination channels, namely K_{SD}, K_{SR} and K_{RD}. Rather than considering Nakagami-m only, here we also evaluate the cooperative fading regions in (8), (14) and (15) by using the Rice-to-Nakagami mapping that can be obtained for high ρ and for outage probability analysis as in [1].

Cooperative fading regions are thus evaluated for Rice and Nakagami-m fading assuming that a finite power budget is available for transmission. Specifically, the available power (10) is computed from the following source-to-destination link reliability requirements: $P_{out}=10^{-7}$ and $R=3\ b/s/Hz$.

Figure 2 shows finite SNR cooperative fading regions $\mathcal{R}_{DF}$ for various Nakagami factors m_{SD} and versus m_{SR} and m_{RD}. Here $N=2$ relays are available for cooperation, moreover performance comparison is given with respect to a non-cooperative system where the source node is equipped with $M=N+1$ antennas. The two shaded regions $\mathcal{R}_{DF}$ reveal the propagation settings where cooperation is beneficial in providing enhanced performances with respect to the multi-antenna case. Dashed curves refer to the closed form bounding region $\hat{\mathcal{R}}_{DF}$ in (15), dotted lines refer to the asymptotic regions for $\rho\to\infty$. When the parameter m for the direct link increases, non-cooperative transmission becomes more robust against outage events as fading becomes less severe. In this case, cooperation is beneficial only if fading impairments could be neglected, fading region is therefore confined to the top-right corner in figure. On the contrary, when direct link is affected by Rayleigh fading ($m_{SD}=1$), cooperation is advantageous even when the diffusive fading components are non-negligible, fading region is thus larger and includes more settings.

On figure 3, assuming the direct link be in NLOS ($K_{SD}=0$), we compute the (bounding) cooperative regions $\hat{\mathcal{R}}_{DF}$ for Rice fading versus K_{SR} and K_{RD}, and for varying cooperative and non-cooperative settings (N and M). Regions are indicated by arrows. Let us consider the case of $K_{RD} \simeq K_{SD} = 0$ and $M = N = 2$. Here we show that fixed decode and forward with $N = 2$ relays has same performances than those from an $M = 2$ antenna ST transmission if K_{SR} is above $12dB$ (that still might be experienced in short range communications). Improved performances can be achieved by allowing K_{RD} above $-10dB$. Notice that if orthogonal ST coding would be employed by the collaborating terminals (see corresponding region $\hat{\mathcal{R}}_{DFO}$ in dashed lines with $M = N = 2$) requirements on K_{SR} become less stringent (above 3 dB).

Although in Rayleigh fading the performances of fixed decode and forward are severely affected by the source to relay channel [2], if Rice fading for the same link can be assumed (e.g., source node is mostly in short range with the relays), regions can be derived where cooperation is beneficial in providing comparable performances to non-cooperative MISO schemes.

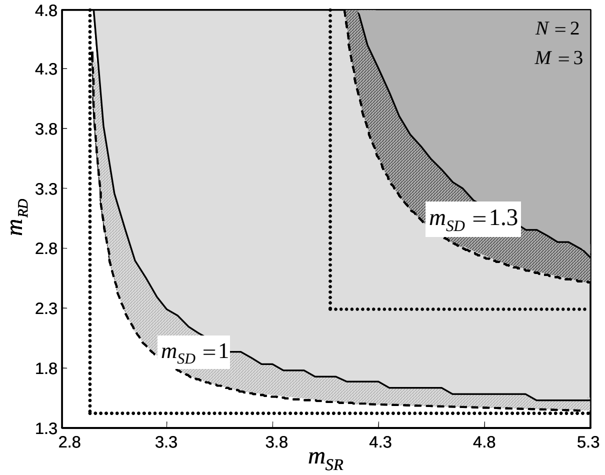

Fig. 2. Two cooperative fading regions $\mathcal{R}_{DF}$ for $m_{SD} = 1$ (Rayleigh fading) and 1.3 versus m_{RD} and m_{SR}, $N = 2$ relays and $M = N + 1$. Regions are indicated by shaded areas. Dashed curves refer to the boundaries of regions $\hat{\mathcal{R}}_{DF}$ in (15), dotted lines refer to the bounds for asymptotic regions $\mathcal{R}_{DF}^{\infty}$.

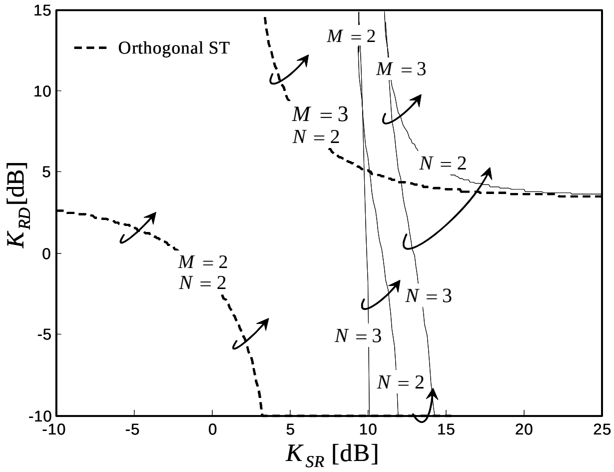

Fig. 3. Regions $\hat{\mathcal{R}}_{DF}$ for Rice fading versus K_{SR} and K_{RD} (dB) for $K_{SD} = 0$ (Rayleigh fading) and varying M and N. Dashed lines refer to the region boundaries when orthogonal ST coding is used. Regions are indicated by arrows.

V. Concluding remarks

In this paper the considered transmission protocol is based on the collaboration of a number of relaying nodes employing a distributed space-time coding scheme. Since ad-hoc and sensors networks often experience propagation environments where line-of-sight (LOS) component is non zero, benefits of cooperative transmission in terms of provided diversity and outage are analyzed by developing closed form *cooperative fading regions*. These regions define the statistical propagation settings that make collaboration among terminals beneficial in improving performances compared to multi-antenna transmission. We considered a generic framework for describing the statistics of the fading impairments among each transmission link. By limiting the analysis to the fixed decode and forward scheme, it has been shown that when fading distributions other than the Rayleigh fading are considered, relevant propagation settings exist where the protocol exhibits at least same (outage) performances of multiantenna non-cooperative schemes.

VI. Appendix: Outage probability derivation

For a direct transmission impaired by a channel with fading parameter m and originated from a source node equipped with an M antenna array (fading is uncorrelated over each branch), the MGF of the SNR distribution at the decision variable is $M_\gamma(s;m) = (1 - s \cdot g \cdot \rho/(Mm))^{-M \cdot m}$. The CDF at $\beta = 2^R - 1$ reduces to (see also [1]):

$$\int_{a-j\infty}^{a+j\infty} \frac{M_\gamma(s;m)}{2\pi js} \exp(\beta \cdot s) ds = \frac{\Psi\left(Mm, \frac{\beta Mm}{\rho g}\right)}{\Gamma(Mm-1)}, \quad (17)$$

$\Psi(a,b) = \int_0^b y^{a-1} \exp(-y) dy$ is the lower incomplete Gamma function. For $\rho g \gg \beta Mm$, it is $\Psi(a,b) \simeq (1/a) \cdot b^a$ and the outage probability is (2).

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