OPPORTUNISTIC MULTIPATH
FOR BANDWIDTH-EFFICIENT COOPERATIVE NETWORKING

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ABSTRACT

Within a new paradigm, where wireless user cooperation is viewed as a form of (opportunistic) multipath, we exploit the unique capabilities of Direct-Sequence Spread Spectrum transmissions in handling multipath to design a novel spectrally efficient protocol for wireless cooperative networks. We show how and why our proposed system achieves diversity without increasing bandwidth. After analyzing its performance, we deduce that user capacity can be significantly improved with respect to existing third generation cellular systems in the uplink. This is particularly interesting since our scheme can be readily integrated in such networks without major changes in the existing standards.

1. INTRODUCTION

Cooperative Networks (CNs) are gaining increasing interest from the wireless community as a new diversity enabler [1], [4], [7]. Inspired by multi-antenna systems, CNs form distributed multi-antenna systems via cooperative signaling from other users, where cooperating users retransmit the original (or related) information to provide the destination with many copies of the source's information bearing signal. It is well appreciated by now that CNs offer a viable fading countermeasure [3], particularly suited to alleviate shadowing [1].

A delicate point in CNs is the tradeoff between performance and multiplexing, which is common also to multi-antenna systems [9]. In general, diversity in CNs is obtained at the cost of increasing the number of channels; as correctly pointed in [7], this does not necessarily imply a penalty in communication rate, because the decrease in Forward Error Correction (FEC) and/or number of retransmissions required generously overcompensates for the bandwidth expansion. However, it is still true that state-of-the-art CNs are spectrally inefficient.

In this paper, we introduce a CN protocol that is capable of retaining the diversity advantage without increasing the number of channels; it is thus, *a spectrally efficient CN protocol*. Our protocol is based on the observation that in Direct Sequence Code Division Multiple Access (DS-CDMA) with Pseudo-Noise (PN) sequences employed as spreading codes, the error probability performance depends on the power received from all users, and it is not affected by the number of spreading codes used [2].

Perhaps more interesting than the protocol itself, this paper contributes a new paradigm for CNs where user cooperation is regarded as a form of (opportunistic) multipath. In light of this paradigm it is not surprising that DS-CDMA can manage user cooperation without bandwidth penalty, since this type of networks is inherently well suited for dealing with multipath effects. This viewpoint justifies also the term, Opportunistic Multipath (OM).

The rest of the paper is organized as follows: in Section 2 we present the OM system; we move on then to Section 3 to show how and why this protocol achieves diversity without increasing bandwidth. Section 3 also introduces key concepts and parameters related to the optimization of OM. Section 4 presents simulated curves showing the BER improvement of OM relative to non-cooperative DS-CDMA, and shows that *OM can significantly improve user capacity of third generation (3G) cellular systems in the uplink.* We conclude the paper in Section 5.

2. OPPORTUNISTIC MULTIPATH

In this section we present a spectrally efficient CN, that relies on the idea of intentionally introducing multipath components in a DS-CDMA transmission. These intentional multipath components are introduced by Cooperating Terminals, CT, that happen to have reliable reception of the Source Terminal S; hence, the name Opportunistic Multipath, (OM).

Let us begin by describing a DS-CDMA signal model [8, Ch.2]; this kind of modulation employs a much larger spectrum than that occupied by the data sequence, $\mathbf{d} = \{d_i\}$. DS-CDMA relies on the spreading code $\mathbf{c} = \{c_i\}$, and for each data bit it transmits N chips (processing gain),

$$x_{Ni+j} = d_i c_{Ni+j} \ , \tag{1}$$

where $\mathbf{x} = \{x_i\}$ is a vector representing the transmitted signal. The code $\mathbf{c}$ is often periodic, and sometimes a full code is transmitted for each bit, in which case (1) specializes to easier expressions. But in order to account for long PN sequences we will introduce the operator $(\mathbf{x} \circ \mathbf{y})$, that allows us to rewrite (1) more compactly,

$$\mathbf{x} = \mathbf{d} \circ \mathbf{c} \ , \tag{2}$$

where $(\mathbf{x} \circ \mathbf{y})$ represents the modulation of one data bit of $\mathbf{x}$ with N chips of $\mathbf{y}$.

We can now turn our attention to the OM system. In considering the design of a CN protocol we must bear in mind that terminals cannot transmit and receive simultaneously over the same frequency band. This practical limitation is not a minor issue, since without this restriction it would have been trivial to design a spectrally efficient protocol based on delayed transmissions and equalization.

Subject to this restriction, we propose a scheme based on two cooperating terminals, CT_0 and CT_1, associated with each transmitting source, S (see Fig. 1). As usual time is divided into slots

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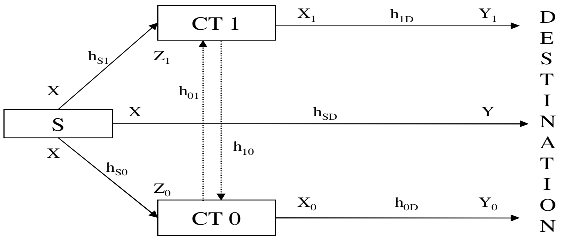

Fig. 1. Terminals CT_0 and CT_1 take turns in cooperating with S

during which a frame is transmitted and let the pair of CTs take turns in repeating the frames corresponding to odd and even time slots as depicted in Fig. 2.

Specifically, during time slot 0, S transmits the data frame $\mathbf{d}_0$ modulated by the code $\mathbf{c}_s$; during this time slot, CT_0 listens to this transmission that is going to repeat in time slot 1, but with spreading $\mathbf{c}_0$. Being in transmt mode, CT_0 misses the frame $\mathbf{d}_1$, but this frame is recovered by CT_1, which in turn retransmits it in time slot 2 using the code $\mathbf{c}_1$. This process continues while the transmission lasts; and in general we have,

$$\begin{array}{rclrcl} \mathbf{x}_S(2i) & = & \mathbf{d}_{2i} \circ \mathbf{c}_S, & \mathbf{x}_S(2i+1) & = & \mathbf{d}_{2i} \circ \mathbf{c}_S, \\ \mathbf{x}_0(2i) & = & \mathbf{0}, & \mathbf{x}_1(2i+1) & = & \hat{\mathbf{d}}_{2i-1} \circ \mathbf{c}_0, \\ \mathbf{x}_1(2i) & = & \hat{\mathbf{d}}_{2i-1} \circ \mathbf{c}_1, & \mathbf{x}_0(2i+1) & = & \mathbf{0}, \end{array} \tag{3}$$

where $\mathbf{x}_S$ is the transmission of S, $\mathbf{x}_j$ the one of CT_j, $\mathbf{d}_i$ the frame at time slot i, and $\hat{\mathbf{d}}_{i-1}$ is an estimate of the frame $\mathbf{d}_{i-1}$. The equalities on the left of (3) correspond to even time slots and those on the right to odd time slots.

Let us note that this setting allows each CT to distinguish the source signal $\mathbf{x}_S$ from the signal emitted by the other CT. It also allows the destination to distinguish the signals $\mathbf{x}_S$, $\mathbf{x}_0$, and $\mathbf{x}_1$. Furthermore, this was achieved without consuming extra time or extra frequency compared with the single transmission scenario.

There are nonetheless, a couple of salient issues behind the previous statement. First is that the spectrum is already expanded when spreading each source bit; so it is not surprising that we can accommodate not only the source bit but also CT signaling over the same bandwidth. And second, this protocol is using three different codes, implying that we utilize in principle three channels.

To address these issues we have to analyze OM in the Multiple Access scenario, which leads us to the next section.

3. PERFORMANCE EVALUATION

The introduction of a pair of cooperating terminals was done in order to comply with the pragmatic restriction that prevents simultaneous reception and transmission. For performance analysis purposes, however, it is convenient to note that the OM system is equivalent to a system with a single cooperating terminal (Fig. 3). Although this system is unrealizable in practice, its performance is identical to OM and the nomenclature is conveniently appropriate for this system too. So we are going to work with the system in Fig. 3 keeping in mind that in fact we are analyzing a theoretically equivalent system.

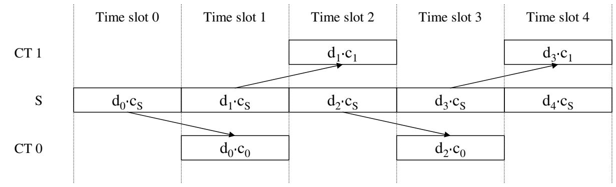

Fig. 2. CT_0 repeats the even frames in odd time slots while CT_1 repeats the odd frames in even time slots

In order to demonstrate the spectral efficiency of the OM architecture, we analyze its performance in a Multiple Access scenario. We consider a set of $M+1$ data sources, $S_0, \ldots, S_M$, that are communicating non-cooperatively with a common destination D, as would be the case in a cellular uplink scenario.

Somewhat surprisingly we begin by analyzing the performance of an individual non-cooperative user, let us say user S_M. It is well established that S_M's performance is dictated by other users' interference. If P_i denotes the power that D is receiving from user S_i, then the bit energy to noise ratio E_b/N_0 is given by [2], [8, ch.2],

$$\left(\frac{E_b}{N_0}\right)_{NC} = N \, \frac{P_M}{\eta + \sum_{i=0}^{M-1} P_i}, \tag{4}$$

where η represents the background noise power. This expression is usually employed to assess DS-CDMA user capacity, but we want to note a much simpler fact: if the total power received from other users is kept constant, then the performance of S_M remains unchanged. In particular, if we introduce a terminal that cooperates with user S_0, then the E_b/N_0 for user S_M, with spreading gain N, will be,

$$\left(\frac{E_b}{N_0}\right)_{C} = N \, \frac{P_M}{\eta + P'_{CT} + P'_0 + \sum_{i=1}^{M-1} P_i}, \tag{5}$$

where P'_{CT} is the power received from CT, and P'_0 the power received from S_0. But as long as we manage to guarantee that

$$P_0 = P'_0 + P'_{CT}, \tag{6}$$

the performance of user M will remain unchanged since (4) and (5) yield identical values. Let us remark that while (4) fails to take into account some characteristics of DS-CDMA networks, this does not affect the conclusion that user performance depends on other users received power and not on the number of codes used. We have thus established that as long as the total received power remains constant, OM does not affect the performance of other users. This is nice, but so far meaningless, unless we prove that OM enhances the performance of user S_0, what leads us to Section 3.1.

3.1. Average Symbol Error Probability (SEP)

Before analyzing the performance of the OM system, a brief discussion of relay techniques is due. The relay channel has been analyzed in e.g., [4], [1], and a number of interesting results are known. One of the most important conclusions is that Digital Forwarding (DF), meaning symbol detection and retransmission, is unable to achieve the maximum possible diversity order; given a

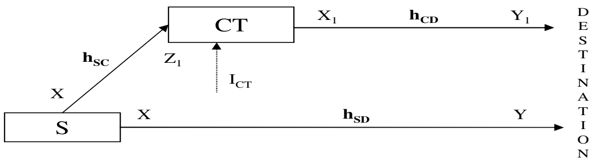

Fig. 3. An equivalent (albeit unrealizable) system to OM

set of CTs the performance still depends on $(SNR)^{-1}$, and not on a larger power of the SNR. Two techniques capable of achieving full diversity, which improves the average SEP like $(SNR)^{-M}$ for M cooperators are Analog Forwarding, (AF), and Selective digital Forwarding, (SF). In AF, no attempt is made by CTs to recover the signal, but instead the received signal is only amplified (along with noise). In SF, the signal is detected like in DF, but it is retransmitted only when the reception is error free. Because it suffers from heavy interference from other users, AF is banned from OM, and we choose (or are forced) to work with SF.

Consider the equivalent model of Fig. 3, where we have the information source, S, and the destination D, communicating over the complex Rayleigh channel h_{SD}. A Cooperating Terminal, CT, is willing to participate in this link providing D with a second copy of the original signal through the complex channels $S \rightarrow CT$, and $CT \rightarrow D$ with flat fading Rayleigh coefficients h_{SC} and h_{CD}, respectively. Similar to [3], [7], we suppose that the realizations of the Rayleigh random variables h_{SD}, h_{SC}, and h_{CD} have been acquired at the receiver ends e.g., via training. Reference [6] provides a detailed analysis of the average SEP in AF relay links for moderate to high SNR values. While [6] dealt with AF channels it is easy to modify the expressions for the SF case to obtain,

$$\bar{P}_e = \frac{3}{4k^2}\,\Big(\frac{1}{3\bar{\gamma}_{h_{SC}}} + \frac{1}{\bar{\gamma}_{h_{CD}}}\Big)\,\frac{1}{\bar{\gamma}_{h_{CD}}}. \tag{7}$$

where $\bar{\gamma}_{h_{SD}} := |\bar{h}_{SD}|^2 P_x/(I_0 + I)$ is the so called per hop average SNR of channel h_{SD}; $\bar{\gamma}_{h_{SC}}$, and $\bar{\gamma}_{h_{CD}}$ are defined analogously; and the factor I accounts for the cross interference between S and CT, and between the pair of CTs, respectively. Equation (7) holds asymptotically as the power goes to infinity.

Except for the noise, $\bar{\gamma}_{h_{SC}}$ and $\bar{\gamma}_{h_{CD}}$ in (7) are the powers received from S and CT respectively, and for a sufficiently large number of users they are subject to the constraint:

$$\bar{\gamma}_{h_{SD}} + \bar{\gamma}_{h_{CD}} = \bar{\gamma}_0, \tag{8}$$

where $\bar{\gamma}_0$ is the SNR in absence of cooperation.

From (7) and (8) we can see that OM achieves second order diversity as we can conceive different combinations of power assignments that result in a decay of the average SEP with $(SNR)^{-2}$ (set for example $\bar{\gamma}_{h_{SD}} = \bar{\gamma}_{h_{CD}} = \bar{\gamma}_0/2$). Before we quantify the average SEP in context, we wish to go a step further and find the setting that achieves the best performance in (7).

3.2. Placing cooperators optimally

As we noted before, one may naturally wonder what is the optimum distribution of power between S and CT, and also what is the role of $\bar{\gamma}_{h_{SC}}$ (S to CT link) in OM. This question happens to have a closed form answer which will also lead us to a couple of interesting properties. In fact we can reformulate this question in a slightly different manner asking for the optimum placement of a cooperating terminal. This is in some sense equivalent and sheds more light over the underlying trade-offs.

The optimality criterion is to minimize the average SEP in (7), subject to the constraint that the total power received by the destination is kept constant (8). Recall that this requirement is necessary to maintain the performance of other users.

To find the best place for a cooperator in the sense just described, we introduce a physical constraint on the average values of the fading coefficients. These average values are related to distance via the path loss model C/d^{α} [5]. Assuming that CTs are placed on the straight line connecting S to D, we have,

$$|\bar{h}_{SC}|^2 = \frac{|\bar{h}_{SD}|^2}{\rho^{\alpha}} \qquad |\bar{h}_{CD}|^2 = \frac{|\bar{h}_{SD}|^2}{(1-\rho)^{\alpha}}, \tag{9}$$

where $\rho \in (0, 1)$ is a constant determined by CT location.

Optimization of (7) for this physical model under the restriction (8) of constant total received power yields the interesting pair of solutions,

$$\rho = 0\,, \qquad P_S = P_{CT} = P_0/2\,, \tag{10}$$

implying that the CT should be placed as close as possible to S, and each of them (S and CT) should transmit identical power equal to half the power they should transmit in non-cooperative DS-CDMA. This is intuitively appealing since the power constraint prevents one from taking advantage of a smaller path loss of the link h_{CD} (i.e., moving CT close to D); so, all we can gain with a clever positioning of CT is to improve the link h_{SC} as much as possible.

For this optimum placement, the average SEP for OM is,

$$\bar{P}_e = \frac{3}{k^2\bar{\gamma}_0^2}, \tag{11}$$

which confirms that the OM system achieves second order diversity. The reader can compare (11) with $\bar{P}_e = 1/(2k\bar{\gamma}_0)$ which is valid for conventional non-cooperative DS-CDMA.

This result has two interesting side effects. The first one has to do with the near far problem as perceived by the CT; signal recovery at CT depends on the amount of power received from S relative to the amount of interfering power received from other users. This is not a problem for D, since we require a power control algorithm to be in effect, but for the CT a second superimposed power control algorithm is not a choice (this is particularly true if we want, as we do, all users to be under OM cooperation). However, this can be solved by choosing the CT as close as possible to S, which in turn is the optimum solution. Of course this can be a second independent reason for choosing this optimum cooperator. Nevertheless, our statement is stronger than that, meaning that the optimum placement for the CT, independently of the near far problem as perceived by it, eliminates this problem. Accordingly, near far effects at the relay are not of concern for OM systems.

A second issue is the implementation of SF, that is based on retransmitting only bits correctly detected at the CT. The problem with this approach is that error detection is performed on blocks and not on bits; and choosing to drop a block usually leads to dropping many useful bits. While usually fading affects a block of symbols, frames (error detection units) are typically longer. But

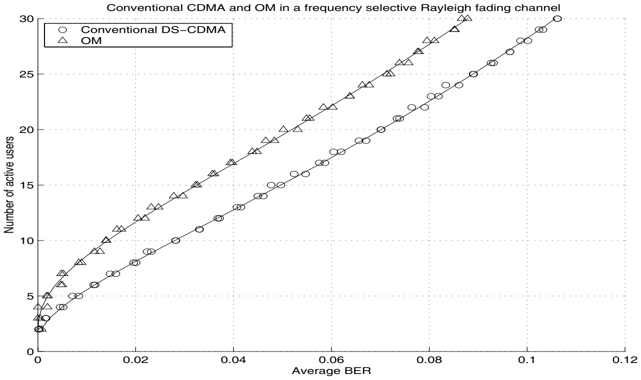

Fig. 4. Conventional DS-CDMA system and its OM counterpart. (BPSK spreading modulator with spreading gain $N = 64$; frequency selective Rayleigh fading channel with 2 paths).

the optimum CT placement makes errors at the CT extremely unlikely. Indeed, the power received from S at the CT is much more than that received from other users (the near far effect is now playing in our favor), and of course much stronger than the thermal noise. Thus, the much simpler DF strategy performs as well as the SF strategy and avoids the problems inherently associated with it, i.e., restraining good bits in a bad block.

In a nutshell, the optimality of the proposed CT placement is threefold: it achieves the best average SEP; mitigates near far effects at the CT; and reduces the SF strategy to a simpler DF one.

It must be noted that in real systems the cooperators are users randomly (as opposed to arbitrarily) placed, and there are certain possible topologies in which the results of this section do not apply. In these cases OM cannot be applied in the form presented here. Nevertheless, in many networks, notably cellular ones, the ratio of active users (sources) to the total number of users (potential cooperators) is very small and the previous scenarios should be the exception rather than the rule.

4. SIMULATIONS

Although we have proved that OM can achieve second order diversity without affecting other users' performance and can thus achieve a smaller average SEP, usually, we are not interested in very low SEPs, since after reaching some threshold further improvements may have little value in practice. What we try to show in this section is that OM can improve a more interesting parameter, namely the number of users that can transmit to a single destination, which in a cellular system is refered to as the user capacity per cell. The simple reason is that if we can achieve a better SEP with the same power, then we can also achieve the same SEP with less power. But reducing the power means less interference to other users and accordingly room for more of them. This behavior is what manifests in Fig. 4 where *the number of users supported for a given target average SEP is much larger in the OM system than in conventional CDMA*.

An aspect that requires further research is the fact that DS-CDMA makes heavy use of the available diversity, in particular multipath diversity. For practical target BERs there is a limit in what diversity can offer; so, it would be interesting to analyze the effect of diversity replacement instead of diversity enhancement (i.e. replacing a natural multipath with an opportunistic multipath). Notwithstanding, OM will be still beneficial, but gains could be different.

5. CONCLUDING REMARKS

We have developed a novel protocol for cooperative networks, based on the introduction of intentional multipath through a pair of cooperating terminals. We showed that this protocol achieves second order diversity without incurring the spectral inefficiency associated with existing alternatives. Unlike alternative cooperative protocols which enable diversity gains at the price of spectral efficiency loss, we were able to obtain a simple protocol that achieves diversity order two with (almost) the same performance of systems employing orthogonal channels without bandwidth expansion.

The integration of our scheme in third generation networks looks promising, considering that it can significantly enhance user capacity on the reverse link. Practical integration however, requires careful assessment of network issues including distribution of PN codes, cooperator selection, and mobility management.

One of the most interesting facets of our work is the new paradigm of considering user cooperation as a form of (opportunistic) multipath. This simple approach opens the possibility for exploiting the ability of DS-CDMA with PN codes in dealing with multipath in the design of spectrally efficient protocols for cooperative networks.

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