Opportunistic Multipath for Bandwidth-Efficient Cooperative Multiple Access

Alejandro Ribeiro, *Student Member, IEEE,* Xiaodong Cai, *Member, IEEE,* and Georgios B. Giannakis, *Fellow, IEEE*

***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.**

***Index Terms*— Fading, diversity, cooperative diversity, CDMA.**

I. Introduction

COOPERATIVE Networks (CNs) are gaining increasing interest in the wireless community as a new diversity enabler [1], [2], [3], [4]. Analogous but distinct from *co-located* multi-antenna transceivers, CNs form *distributed* multi-antenna systems via relaying among single-antenna cooperating users who retransmit the original (or related) information to provide the destination with replicas of the source's information bearing signal. It is well appreciated by now that CNs offer a viable fading countermeasure, particularly suited to alleviate shadowing [3], [4].

A delicate feature of CNs is the tradeoff between error performance and multiplexing since, in general, the diversity provided by CNs is obtained at the cost of requiring an increased number of orthogonal channels with a corresponding increase in the required bandwidth. Specifically, let $\bar{\gamma}$ denote average signal-to-noise-ratio (SNR) at the receiver and $W^{(nc)}(\bar{\gamma})$ the bandwidth required by a non-cooperative protocol operating at SNR $\bar{\gamma}$. Likewise, let $W^{(c)}(\bar{\gamma})$ be the bandwidth required by an otherwise equivalent cooperative protocol operating also at receive SNR $\bar{\gamma}$. If we define spectral efficiency as

$$\mathcal{E} := W^{(nc)}(\bar{\gamma})/W^{(c)}(\bar{\gamma}), \quad (1)$$

then it holds true that state-of-the-art CNs have $\mathcal{E} \leq 1/2$.

In this letter, we introduce a CN protocol that retains the diversity advantage while having $W^{(nc)}(\bar{\gamma}) = W^{(c)}(\bar{\gamma})$, and corresponding spectral efficiency $\mathcal{E} = 1$. Unlike existing works on cooperative diversity that focus on a *single-source/single-destination* setup, our protocol is designed for a *spread-spectrum multiple access* scenario. The novel protocol capitalizes on the fact that in direct sequence code division multiple access (DS-CDMA) with long pseudo-noise (PN) sequences employed as spreading codes, the error probability performance depends on the signal-to-interference-plus-noise-ratio (SINR), but is not affected by the number of spreading codes used [5].

Through this bandwidth efficient protocol, a new paradigm for CNs becomes available where user cooperation is regarded as a form of (opportunistic) multipath. In light of this paradigm it is not surprising that DS-CDMA can effect 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). Viewing node cooperation as a form of multipath was also used in [6], where the focus is on low-bit rate wireless ad-hoc links to reach far distances, a goal distinct from the objective of this work to enable spectrally efficient cooperative communications. Notice also that the term opportunistic is used here in a context different from the one in the opportunistic scheduling/beamforming approach of [7]. While [7] aims to "opportunistically" exploit the instantaneous channel strength variation that may appear across user channels, we aim to "opportunistically" exploit the improved signal reception that idle users may enjoy relative to active ones when accessing the destination. Different from [7] that enables multiuser diversity without user cooperation, our OM protocol enables cooperative diversity by relying on user cooperation, while avoiding the spectral efficiency loss incurred by existing CN protocols.

The rest of the paper is organized as follows. We start with a description of DS-CDMA multiple access in Section II-A to later introduce the OM protocol in Section II-B and a multicode alternative in Section II-C. We then move to Section III to analyze the BER performance of these two protocols and on to Section IV where we show how we can effect a significant increase in uplink user-capacity with respect to conventional DS-CDMA systems. We conclude the paper in Section V.

Manuscript received January 19, 2004; revised July 26, 2004, February 22, 2005, and October 16, 2005; accepted October 31, 2005. The editor coordinating the review of this letter and approving it for publication was Prof. K. B. Lee. This work was prepared through collaborative participation in the Communications and Networks Consortium sponsored by the U. S. Army Research Laboratory under the Collaborative Technology Alliance Program, Cooperative Agreement DAAD19-01-2-0011. The U. S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation thereon.

Part of the results from this paper appeared in the *Proceedings of ICASSP*, Montreal, Canada, May 17-21, 2004.

A. Ribeiro and G. B. Giannakis are with the Dept. of Electrical and Computer Engineering, University of Minnesota, 200 Union Street SE, Minneapolis, MN 55455 (email: {aribeiro, georgios}@ece.umn.edu).

X. Cai is with the Dept. of Electrical and Computer Engineering, University of Miami, P.O. Box 248294, Coral Gables, FL 33124-0620 (email: x.cai@miami.edu).

Digital Object Identifier 10.1109/TWC.2006.04021.

II. Opportunistic Multipath

In this section, we present a spectrally efficient CN protocol, that relies on the idea of intentionally introducing multipath components in a DS-CDMA transmission with long PN sequences employed as spreading codes. These intentional multipath components are opportunistically introduced by cooperating terminals, that happen to have reliable reception of the source (S) terminal.

A. DS-CDMA with PN Codes – Preliminaries

Consider a DS-CDMA link comprising a destination D (access point) a set of N idle terminals $\mathcal{T} := \{T_n\}_{n=1}^{N}$ and a set of $M+1$ active information sources $\mathcal{S} := \{S_m\}_{m=0}^{M}$ communicating with D through flat fading Rayleigh channels with coefficients $h_{S_m D}$ and power $\mathrm{E}(|h_{S_m D}|^2) = \bar{h}^2_{S_m D}$, $\forall m$. The m^{th} source spreads its L-bit data block $\mathbf{d}_{S_m} = \{d_{S_m}(l)\}_{l=0}^{L-1}$ with a KL-chip PN sequence $\mathbf{c}_{S_m} = \{c_{S_m}(k)\}_{k=0}^{KL-1}$ so that

$$x_{S_m}(Kl+k) = d_{S_m}(l)c_{S_m}(Kl+k), \tag{2}$$

where $\mathbf{x}_{S_m} := \{x_{S_m}(k)\}_{k=0}^{KL-1}$ is a vector representing the transmitted packet and the indices range are $l \in [0, L-1]$ and $k \in [0, K-1]$ [5], [8, Ch.2]. We will use the notation $\mathbf{x}_{S_m} = \mathbf{d}_{S_m} \circ \mathbf{c}_{S_m}$ to represent the spreading operation in (2).

Different user codes are assumed normalized and statistically orthogonal meaning that the expected value of their inner product is equal to a Kronecker delta; i.e., with $\mathcal{H}$ denoting conjugate-transpose

$$\mathrm{E}(\mathbf{c}^{\mathcal{H}}_{S_{m_1}} \mathbf{c}_{S_{m_2}}) = \delta(m_1 - m_2). \tag{3}$$

We stress that the number of codes satisfying (3) can be as large as 2^K; e.g., by choosing binary chips $c_{S_m}(k)$ such that $\Pr\{c_{S_m}(k) = 1\} = \Pr\{c_{S_m}(k) = -1\} = 1/2$. For specific examples and practical implementation issues of PN codes, we refer the reader to [9].

The block $\mathbf{z}_D := \{z_D(k)\}_{k=0}^{KL-1}$ received at D comprises the superposition of the blocks transmitted by the $M+1$ active sources

$$\begin{aligned} z_D(Kl+k) &= \sum_{m=0}^{M} h_{S_m D} x_{S_m}(Kl+k) + n(Kl+k) \\ &= \sum_{m=0}^{M} h_{S_m D} d_{S_m}(l) c_{S_m}(Kl+k) + n(Kl+k), \end{aligned} \tag{4}$$

where $\mathbf{n} := \{n(k)\}_{k=0}^{KL-1}$ denotes the additive white Gaussian noise (AWGN) at D. To decode the source of interest, say $S_0 \equiv S$, $\mathbf{z}_D$ is de-spread by chip-level multiplication with the code $\mathbf{c}_S$, to construct the decision vector $\mathbf{r}_S := \{r_S(l)\}_{l=0}^{L-1}$ with entries $r_S(l) := K^{-1}\sum_{k=0}^{K-1} z_D(Kl+k)c_S(Kl+k)$:

$$\begin{aligned} r_S(l) &= h_{SD} d_S(l) + \frac{1}{K}\sum_{k=0}^{K-1} n(Kl+k)c_S(Kl+k) \; + \\ &\quad \frac{1}{K}\sum_{m=1}^{M} h_{S_m D} d_{S_m}(l) \sum_{k=0}^{K-1} c_{S_m}(Kl+k)c_S(Kl+k) \\ &:= h_{SD} d_S(l) + \tilde{n}(l) + i_S(l). \end{aligned} \tag{5}$$

In (5) we defined the noise vector $\tilde{\mathbf{n}} := \{\tilde{n}(l)\}_{l=0}^{L-1}$, and the multiuser interference vector $\mathbf{i}_S := \{i_S(l)\}_{l=0}^{L-1}$. Note that with normalized PN sequences we have $\mathrm{E}(\tilde{\mathbf{n}}\tilde{\mathbf{n}}^{\mathcal{H}}) = \mathrm{E}(\mathbf{n}\mathbf{n}^{\mathcal{H}})/K := (\eta/K)\mathbf{I}$, where $\mathbf{I}$ denotes the identity matrix. With respect to the multiuser interference $\mathbf{i}_S$, we consider average power control to be in effect so that the received power is equal for all users; i.e., $P := \mathrm{E}[|h_{S_m D} d_{S_m}(l)|^2]$, $\forall m \in [0, M]$, which requires the power transmitted by S_m to be $P_{S_m} := \mathrm{E}[|d_{S_m}(l)|^2] = P/\mathrm{E}[|h_{S_m D}|^2]$. It then follows that the interference power is [c.f. (3) and (5)]

$$\mathrm{E}[|i_S(l)|^2] = \frac{1}{K}\sum_{m=1}^{M} \mathrm{E}[|h_{S_m D} d_{S_m D}(l)|^2] = MP/K. \tag{6}$$

If the single-user detector $\hat{\mathbf{d}}_S = \arg\min_{\mathbf{d}_S}[(\mathbf{r}_S - h_{SD}\mathbf{d}_S)^{\mathcal{H}}(\mathbf{r}_S - h_{SD}\mathbf{d}_S)]$ is used, the pertinent performance metric is the instantaneous SINR given by [c.f. (5) and (6)]

$$\mathrm{SINR} = \frac{|h_{SD}|^2 P_S}{\eta/K + MP/K} = \frac{|h_{SD}|^2 K P_S/P}{\eta/P + M}. \tag{7}$$

Building on these preliminaries, we introduce the OM protocol in the next subsection.

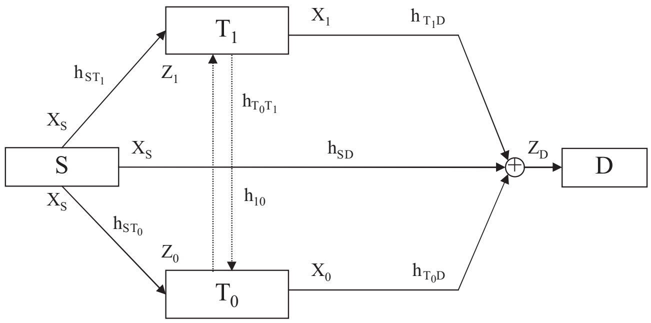

Fig. 1. Terminals T_0 and T_1 take turns in cooperating with S.

B. OM protocol with two cooperators

With each active user $S_m \in \mathcal{S}$ we associate two idle terminals $T_{m0}, T_{m1} \in \mathcal{T}$ capable of decoding S_m's data and relaying the information to D (see Fig. 1). For simplicity, let us focus on the reference source $S \equiv S_0$, and denote $T_0 \equiv T_{00}$ and $T_1 \equiv T_{01}$. As usual, time is divided into slots during which a frame is transmitted and the two terminals T_0, T_1 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 $\mathbf{d}_S(0)$ spread by the PN code $\mathbf{c}_S$. During the same time slot, T_0 listens to this transmission that is going to repeat in the next time slot 1, but with spreading code $\mathbf{c}_{T_0}$. Being in transmit mode during slot 1, T_0 misses the frame $\mathbf{d}_S(1)$, but this frame is received by T_1, which in turn retransmits it in time slot 2 using the code $\mathbf{c}_{T_1}$. This process continues while the transmission lasts. In general, for the $(2i)th$ and the $(2i+1)st$ time slots the blocks transmitted by S, T_0, and T_1 are:

$$\begin{aligned} &\mathbf{x}_S(2i) = \mathbf{d}_S(2i) \circ \mathbf{c}_S, && \mathbf{x}_S(2i+1) = \mathbf{d}_S(2i+1) \circ \mathbf{c}_S, \\ &\mathbf{x}_0(2i) = \mathbf{0}, && \mathbf{x}_0(2i+1) = \tilde{\mathbf{d}}_S(2i) \circ \mathbf{c}_{T_0}, \\ &\mathbf{x}_1(2i) = \tilde{\mathbf{d}}_S(2i-1) \circ \mathbf{c}_{T_1}, && \mathbf{x}_1(2i+1) = \mathbf{0}, \end{aligned} \tag{8}$$

where $\mathbf{x}_S$ is the block transmitted from S, $\mathbf{x}_j$ the one from T_j, $j = 0, 1$, $\mathbf{d}_S(i)$ stands for the frame at time slot i, and

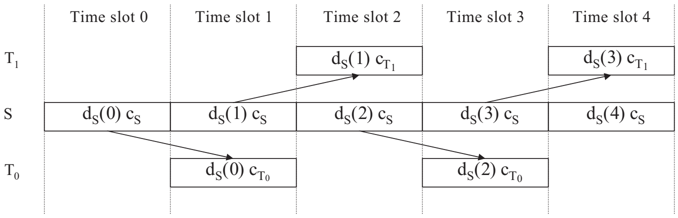

Fig. 2. T_0 repeats the even frames in odd time slots while T_1 repeats the odd frames in even time slots.

$\tilde{\mathbf{d}}_S(i)$ is such that

$$\tilde{\mathbf{d}}_S(i) = \begin{cases} \mathbf{d}_S(i) & \text{if } \mathbf{d}_S(i) \text{decoded correctly} \\ \mathbf{0} & \text{else.} \end{cases} \tag{9}$$

Note that (9) ensures that packets at T_0, T_1 are forwarded only when correctly decoded. This requires some form of packet error detection; e.g., by using a cyclic redundancy check (CRC) code.

Let us now consider the blocks received by T_0, T_1, that we denote respectively as $\mathbf{z}_0$ and $\mathbf{z}_1$. What T_0 receives in even time slots as well as what T_1 receives in odd time slots is irrelevant as it is considered lost information because they are in transmit-mode during these time slots. The relevant signals for T_0, T_1 are those received by T_0 in even time slots, namely $\mathbf{z}_0(2i)$, and those received by T_1 in odd time slots, namely $\mathbf{z}_1(2i+1)$:

$$\begin{aligned} \mathbf{z}_0(2i) &= h_{ST_0}\mathbf{d}_S(2i)\circ\mathbf{c}_S + h_{T_1T_0}\tilde{\mathbf{d}}_S(2i-1)\circ\mathbf{c}_{T_1} + \mathbf{w}_0(2i), \\ \mathbf{z}_1(2i+1) &= h_{ST_1}\mathbf{d}_S(2i+1)\circ\mathbf{c}_S + h_{T_0T_1}\tilde{\mathbf{d}}_S(2i)\circ\mathbf{c}_{T_0} + \mathbf{w}_1(2i+1). \end{aligned} \tag{10}$$

In (10), h_{AB} represents the flat fading channel coefficient from node A to node B and $\mathbf{w}_j(i)$ is a zero-mean Gaussian vector accounting for thermal noise as well as interference from other users. The covariance matrix of $\mathbf{w}_j(i)$ is $\mathrm{E}[\mathbf{w}_j(i)\mathbf{w}_j^{\mathcal{H}}(i)] = \mathbf{I}P_{\mathbf{i}}$ with $P_{\mathbf{i}} := \sum_{m=1}^{M}[\bar{h}^2_{S_mT_j}P_{S_m} + \bar{h}^2_{T_{mj}T_j}P_{T_{mj}}] + \eta$. Each terminal de-spreads the received signal using $\mathbf{c}_S$, which yields the post-processing received vectors [c.f. (5)]

$$\begin{aligned} \mathbf{r}_{ST_0}(2i) &= h_{ST_0}\mathbf{d}_S(2i) + \mathbf{i}_{T_1}(2i) + \tilde{\mathbf{w}}_0(2i), \\ \mathbf{r}_{ST_1}(2i+1) &= h_{ST_1}\mathbf{d}_S(2i+1) + \mathbf{i}_{T_0}(2i+1) + \tilde{\mathbf{w}}_1(2i+1). \end{aligned} \tag{11}$$

The blocks $\{\mathbf{i}_{T_j}(i)\}_{j=0,1}$ account for the interference that each cooperating terminal is introducing to its peer and have covariance matrices $\mathrm{E}[\mathbf{i}_{T_j}(i)\mathbf{i}^{\mathcal{H}}_{T_j}(i)] = \mathbf{I}(\bar{h}^2_{T_1T_0}P_{1-j})/K := \mathbf{I}(P_{\mathbf{i}_{T_j}}/K)$, $j = 0, 1$. Based on $\mathbf{r}_{ST_0}$ and $\mathbf{r}_{ST_1}$, the estimates $\hat{\mathbf{d}}_S(2i)$ and $\hat{\mathbf{d}}_S(2i-1)$ of the original frames $\mathbf{d}_S(2i)$ and $\mathbf{d}_S(2i-1)$, are constructed and, if correctly decoded, they are transmitted to the destination D, which in turn can use exactly the same procedure to separate $\mathbf{x}_0$ and $\mathbf{x}_1$ from the direct (source-destination) transmission $\mathbf{x}_S$. Indeed, in even and odd time slots D receives the blocks

$$\begin{aligned} \mathbf{z}_D(2i) &= h_{SD}\mathbf{d}_S(2i)\circ\mathbf{c}_S + h_{T_1D}\tilde{\mathbf{d}}_S(2i-1)\circ\mathbf{c}_{T_1} + \mathbf{w}(2i), \\ \mathbf{z}_D(2i+1) &= h_{SD}\mathbf{d}_S(2i+1)\circ\mathbf{c}_S + h_{T_0D}\tilde{\mathbf{d}}_S(2i)\circ\mathbf{c}_{T_0} + \mathbf{w}(2i+1), \end{aligned} \tag{12}$$

where the noise-plus-interference vector $\mathbf{w}(i)$ has covariance matrix $\mathrm{E}[\mathbf{w}(i)\mathbf{w}^{\mathcal{H}}(i)] = \mathbf{I}\sum_{m=1}^{M}[\bar{h}^2_{S_mD}P_{S_m} + \bar{h}^2_{T_{mj}D}P_{T_{mj}}] + \eta\mathbf{I}$. After de-spreading $\mathbf{z}_D(2i)$ with $\mathbf{c}_S$, and $\mathbf{z}_D(2i+1)$ with $\mathbf{c}_{T_0}$, we obtain respectively the decision vectors [c.f. (12)]

$$\begin{aligned} \mathbf{r}_{SD}(2i) &= h_{SD}\mathbf{d}_S(2i) + \mathbf{i}_{T_1}(i) + \tilde{\mathbf{w}}_S(2i), \\ \mathbf{r}_{T_0D}(2i+1) &= \mathbf{i}_S(i) + h_{T_0D}\tilde{\mathbf{d}}_S(2i) + \tilde{\mathbf{w}}_{T_0}(2i+1). \end{aligned} \tag{13}$$

Notice that $\mathbf{r}_{SD}(2i)$ and $\mathbf{r}_{T_0D}(2i+1)$ provide two independent (scaled) versions of the even data blocks; namely, $\mathbf{d}_S(2i)$ directly from the source and $\tilde{\mathbf{d}}_S(2i)$ through T_0. Likewise, after despreading $\mathbf{z}_D(2i+1)$ with $\mathbf{c}_S$ and $\mathbf{z}_D(2i+2)$ with $\mathbf{c}_{T_1}$, we obtain from the corresponding decision vectors [c.f. (12)]

$$\begin{aligned} \mathbf{r}_{SD}(2i+1) &= h_{SD}\mathbf{d}_S(2i+1) + \mathbf{i}_{T_0}(i) + \tilde{\mathbf{w}}_S(2i+1), \\ \mathbf{r}_{T_1D}(2i+2) &= \mathbf{i}_S(i) + h_{T_1D}\tilde{\mathbf{d}}_S(2i+1) + \tilde{\mathbf{w}}_{T_1}(2i+2), \end{aligned} \tag{14}$$

two independent (scaled) versions of the odd data blocks; namely $\mathbf{d}_S(2i+1)$ directly from the source, and $\tilde{\mathbf{d}}_S(2i+1)$ through T_1. Furthermore, despreading $\mathbf{z}_D(2i)$ with $\mathbf{c}_{T_1}$ yields $\tilde{\mathbf{d}}_S(2i-1)$ while despreading $\mathbf{z}_D(2i+2)$ with $\mathbf{c}_S$ provides an estimate of $\mathbf{d}_S(2i+2)$.

The important observation here is that every three time slots $\{\mathbf{z}_D(2i), \mathbf{z}_D(2i+1), \mathbf{z}_D(2i+2)\}$, proper despreading allows us to recover three data blocks $\{\mathbf{d}_S(2i), \mathbf{d}_S(2i+1), \mathbf{d}_S(2i+2)\}$ directly from the source and three data blocks $\{\tilde{\mathbf{d}}_S(2i-1), \tilde{\mathbf{d}}_S(2i), \tilde{\mathbf{d}}_S(2i+1)\}$ through the cooperating terminals; and by sliding this 3-slot window we obtain two independent copies of each data block. This implies that diversity of order two becomes available without consuming extra time or extra frequency slots compared with a non-cooperative link between S and D.

Remark 1 While the cooperative protocol in (8) applies to any multiple access scheme the fact that we do not need extra bandwidth is valid only with statistically orthogonal spreading codes. Indeed, if we require deterministic spreading sequences with $\mathbf{c}^{\mathcal{H}}_{S_{m_1}}\mathbf{c}_{S_{m_2}} = \delta(m_1 - m_2)$, when implementing (8) we require three times as many codes and correspondingly three times as much bandwidth. It is only because there are up to 2^K codes satisfying (3) that we can implement (8) without increasing the bandwidth so that the spectral efficiency, as defined in (1), is $\mathcal{E} = 1$.

C. Multi-code OM with a single cooperator

The protocol we introduced in the previous section is one possible means of ensuring spectrally efficient cooperation. In this subsection, we will develop an alternative protocol which is particularly attractive because it relies on a single cooperating terminal T. This is accomplished by having each source employing two PN codes $\mathbf{c}_{S,0}$ and $\mathbf{c}_{S,1}$, and dividing the time in odd and even time slots as before. During the even time slots, S transmits a pair of frames $\mathbf{d}_S(2i)$ and $\mathbf{d}_S(2i+1)$ using

$$\mathbf{x}_S(2i) = \mathbf{d}_S(2i)\circ\mathbf{c}_{S,0} + \mathbf{d}_S(2i+1)\circ\mathbf{c}_{S,1}. \tag{15}$$

During even times slots D receives this pair of frames and T receives

$$\mathbf{z}_T(2i) = h_{ST}\mathbf{d}_S(2i)\circ\mathbf{c}_{S,0} + h_{ST}\mathbf{d}_S(2i+1)\circ\mathbf{c}_{S,1} + \mathbf{w}_T(2i). \tag{16}$$

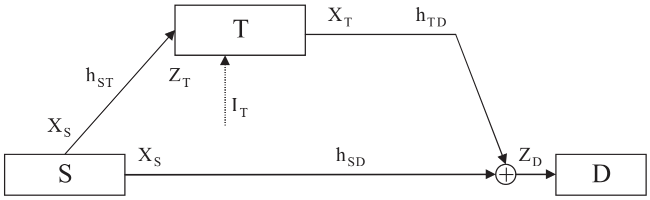

Fig. 3. A system equivalent (albeit unrealizable) to OM and multi-code OM.

To enable second-order diversity, we use the odd time slots to have T re-transmit estimates of the previously decoded frames using the same two spreading codes:

$$\mathbf{x}_T(2i+1) = \tilde{\mathbf{d}}_S(2i) \circ \mathbf{c}_{S,0} + \tilde{\mathbf{d}}_S(2i+1) \circ \mathbf{c}_{S,1}. \quad (17)$$

During odd time slots, S restrains its transmission in order to avoid interfering with T that is in transmit mode.

The channel model for this multi-code protocol is equivalent to the previous one, as can be verified after writing down the expressions for the signals received at the destination:

$$\begin{aligned} \mathbf{z}_D(2i) &= h_{SD}[\mathbf{d}_S(2i)\circ\mathbf{c}_{S,0}+\mathbf{d}_S(2i+1)\circ\mathbf{c}_{S,1}]+\mathbf{w}(2i), \\ \mathbf{z}_D(2i+1) &= h_{TD}[\tilde{\mathbf{d}}_S(2i)\circ\mathbf{c}_{S,0}+\tilde{\mathbf{d}}_S(2i+1)\circ\mathbf{c}_{S,1}]+\mathbf{w}(2i+1). \end{aligned} \quad (18)$$

Because (18) has form similar to (12), following despreading steps analogous to those in (13) – (14) we can demodulate the data blocks as in the OM protocol of the previous section. Notice that while there is no interference between T_1 and T_2, there is interference between $\mathbf{d}_S(2i)$ and $\mathbf{d}_S(2i+1)$.

This multi-code alternative requires only one terminal per active user but retains OM's spectral efficiency as explained in Remark 1. To establish the diversity advantage of these two protocols we move on to analyze their BER performance in the next section.

III. Performance Evaluation

To analyze the BER performance of the protocols in Sections II-B and II-C, we introduce the equivalent model of Fig. 3. This practically unrealizable model entails a single terminal instantaneously repeating even and odd frames, and includes an interference term $\mathbf{i}_T$ to account for the interference between T_0 and T_1 (between $\mathbf{d}_S(2i)$ and $\mathbf{d}_S(2i+1)$ for multi-code OM). For this model, the signals received at T and D are respectively given by

$$\begin{aligned} \mathbf{z}_T(i) &= h_{ST}\mathbf{d}_S(i) \circ \mathbf{c}_S + \mathbf{i}_T(i) + \mathbf{w}_T(i), \\ \mathbf{z}_D(i) &= h_{SD}\mathbf{d}_S(i) \circ \mathbf{c}_S + h_{TD}\tilde{\mathbf{d}}_S(i) \circ \mathbf{c}_T + \mathbf{w}_D(i), \end{aligned} \quad (19)$$

with $\mathrm{E}[\mathbf{w}_D(i)\mathbf{w}_D^{\mathcal{H}}(i)] = \mathbf{I}\sum_{m=1}^{M}[\bar{h}^2_{S_mD}P_{S_m} + \bar{h}^2_{T_mD}P_{T_m}] + \eta\mathbf{I}$ as in (12), $\mathrm{E}[\mathbf{i}_T(i)\mathbf{i}_T^{\mathcal{H}}(i)] = \mathbf{I}P_{\mathbf{i}_T}$ and $\mathrm{E}[\mathbf{w}_T(i)\mathbf{w}_T^{\mathcal{H}}(i)] := \mathbf{I}P_{\mathbf{i}}$. It is straightforward through proper substitutions to show that this model is indeed equivalent to either (10) – (12) or (16) – (18). Consequently, it suffices to analyze the BER performance of the protocol defined by (19). Repeating the treatment in Section II, we can find the instantaneous receive SINR in the $S \to D$ link as

$$\begin{aligned} \gamma_{h_{SD}} &:= \frac{K|h_{SD}|^2P_S}{\eta + \sum_{m=1}^{M}[\bar{h}^2_{S_mD}P_{S_m} + \bar{h}^2_{T_mD}P_{T_m}] + \bar{h}^2_{TD}P_T} \\ &= \frac{K|h_{SD}|^2P_S}{\eta + MP + \bar{h}^2_{TD}P_T}, \end{aligned} \quad (20)$$

where in obtaining the second equality we enforced the power control constraint

$$\bar{h}^2_{S_mD}P_{S_m} + \bar{h}^2_{T_mD}P_{T_m} = P, \quad \forall m. \quad (21)$$

Analogously, we can obtain the instantaneous receive SINR for the $T \to D$ link as $\gamma_{h_{TD}} := K|h_{TD}|^2P_T / [\eta + MP + \bar{h}^2_{SD}P_S]$. The aggregate SINR at the output of the maximum ratio combiner (MRC) is given by $\gamma_{MRC} := \gamma_{h_{SD}} + \gamma_{h_{TD}}$ and substituting for the respective expressions we have

$$\gamma_{MRC} = \frac{K|h_{SD}|^2P_S}{\eta + MP + \bar{h}^2_{TD}P_T} + \frac{K|h_{TD}|^2P_T}{\eta + MP + \bar{h}^2_{SD}P_S}. \quad (22)$$

Note that for a large number of sources M, the self-interference terms $\bar{h}^2_{TD}P_T$ and $\bar{h}^2_{SD}P_S$ in (22) are negligible and we can approximate the aggregate SINR as

$$\gamma_{MRC} \approx \frac{K[|h_{SD}|^2P_S + |h_{TD}|^2P_T]/P}{\eta/P + M}. \quad (23)$$

Contrasting (23) with (7) and considering the average power constraint in (21) we can see that as M increases the average aggregate SINR of the $T \to D$ and $S \to D$ paths approaches the average SINR of the non-cooperative case, i.e., $\bar{\gamma}_{MRC} \approx \overline{\mathrm{SINR}}$, with γ_{MRC} given as in (23) and SINR given by (7).

For the h_{ST} link, the per-hop average SNR depends on the amount of interference $\mathbf{i}_0$ present at T from other active users and is given by

$$\gamma_{h_{ST}} := \frac{KP_S|h_{ST}|^2}{\eta + P_{\mathbf{i}} + P_{\mathbf{i}_T}}, \quad (24)$$

where we recall that $P_{\mathbf{i}_T}$ captures the cross-interference in the pair of cooperating terminals and $P_{\mathbf{i}}$ accounts for other users' interference at T. Recalling these, we can compute the BER as follows.

Proposition 1 *Consider the OM (multi-code OM) protocol defined by* (8) [(15) *and* (17)], *and* (9). *Assume that* $M \leq 2^K/3$ ($M \leq 2^K/2$) *and that the* $T \to D$ *and* $S \to D$ *signals are combined with MRC. Then the average error probability is given by*

$$\bar{P}(e) \leq \frac{1}{4}(1-\mu_{SD})(1-\mu_{ST}) + \frac{1}{2}\left(1 - \frac{\bar{\gamma}_{TD}\mu_{TD} + \bar{\gamma}_{SD}\mu_{SD}}{\bar{\gamma}_{TD} - \bar{\gamma}_{SD}}\right), \quad (25)$$

where $\mu_{(.)} = \sqrt{\kappa\bar{\gamma}_{(.)}/[1+\kappa\bar{\gamma}_{(.)}]}$, κ *is a modulation dependent constant* ($\kappa = 2$ *for BPSK*) *and* $\bar{\gamma}_{(.)} = \mathrm{E}[\gamma_{(.)}]$ *with* γ_{SD}, γ_{TD} *and* γ_{ST} *given by* (20), (22) *and* (24).

Proof: Define the events $\{e_T\}$ and $\{e_T^c\}$ representing that the detection at T is correct and incorrect, respectively. We can then write

$$P(e) = P(e|e_T)P(e_T) + P(e|e_T^c)P(e_T^c), \quad (26)$$

where for simplicity the conditioning on γ_{SD}, γ_{ST} and γ_{TD} is implicit. But note that (26) can be written in terms of the function, $Q(x) := (1/\sqrt{2\ \pi}) \int_x^{\infty} e^{-u^2/2} du$ as

$$P(e) = Q(\sqrt{\kappa\gamma_{SD}})Q(\sqrt{\kappa\gamma_{ST}}) + Q[\sqrt{\kappa(\gamma_{SD}+\gamma_{TD})}][1 - Q(\sqrt{\kappa\gamma_{ST}})], \quad (27)$$

since for Gaussian noise $P(e_T) = Q(\sqrt{\kappa\gamma_{ST}})$; $P(e|e_T) = Q(\sqrt{\kappa\gamma_{ST}})$ because only S transmits; and $P(e|e_T^c) = Q(\sqrt{\kappa(\gamma_{SD}+\gamma_{TD})})Q(\sqrt{\kappa\gamma_{MRC}})$ because both S and T transmit.

We can now average over the Rayleigh distribution to obtain the average BER $\bar{P}(e) = E[P(e)]$ with $P(e)$ given as in (27) to obtain (25). ∎

Letting $\bar{\gamma}_{h_{SD}}, \bar{\gamma}_{h_{TD}}, \bar{\gamma}_{h_{ST}} \to \infty$ in (25), we obtain the limiting behavior of $\bar{P}(e)$ as

$$\bar{P}(e) \to \frac{1}{2\kappa\bar{\gamma}_{SD}} \frac{1}{2k\bar{\gamma}_{ST}} + \frac{3}{4\kappa^2\bar{\gamma}_{TD}\bar{\gamma}_{SD}}. \quad (28)$$

Since it is clear from (28) that $\bar{P}(e)/(\overline{\mathrm{SINR}})^{-2} \to \mathcal{C}$ for some constant $\mathcal{C}$, we conclude that the diversity order of OM (multi-code OM) is 2. Combining this result with Remark 1 we establish that OM (multi-code OM) achieves order-2 diversity with spectral efficiency $\mathcal{E} = 1$ [c.f. (1)].

Considering M sufficiently large, so that γ_{MRC} is approximated by (23), we can minimize the average BER in (25) by making [c.f. (21), (23) and (25)]

$$\bar{h}_{SD}^2 P_S = \bar{h}_{TD}^2 P_T = P/2\ . \quad (29)$$

The optimal power distribution in (29) corresponds to equipower reception from S and T.

Remark 2 Involving additional cooperating terminals per source-destination link we can effect a diversity order equal to the number of cooperators plus 1, similar to what is established in e.g., [3], [4]. However, we do not pursue this direction for three reasons: i) we aim at a simple (hence more practical) cooperative protocol that is bandwidth efficient even if the diversity order it enables is just two (or at most three with two cooperators); ii) the more cooperating terminals are involved, the more stringent the requirement on the number of idle users becomes; and iii) this may not be even necessary since benefits with diversity orders greater than three show up with increasingly higher SNR values not typically encountered in practice.

IV. SIMULATIONS

In this section we explore the impact OM has in the per-cell *user capacity* defined as the number of users that can communicate with D at a prescribed $\bar{P}(e)$. In our simulations, we considered a randomly placed set of active users and a twenty times larger set of idle users. For each active user we chose the two closest idle terminals as cooperators. The PN spreading codes used were constructed using the code generated by the polynomial $g(x) = x^{15} + x^{12} + x^{11} + x^{10} + x^6 + x^5 + x^4 + x^3 + x^1$ and spreading gain $K = 64$. At the destination, we considered the superposition of all the signals under perfect power control and separated them by applying

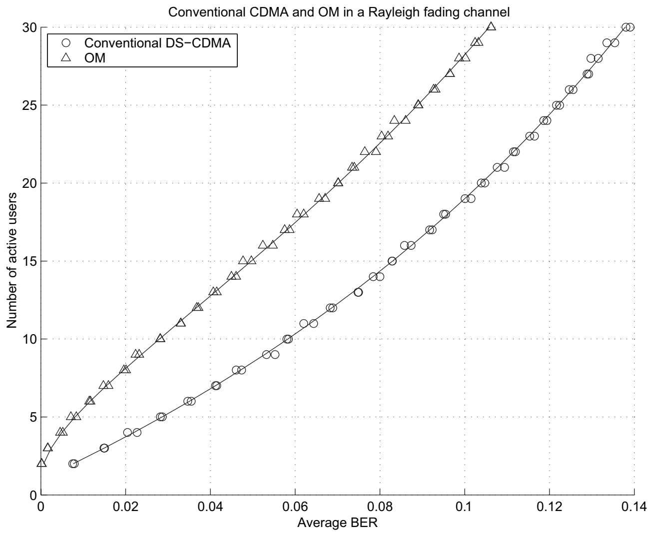

Fig. 4. Conventional DS-CDMA system and its OM counterpart (continuous lines are theoretical results, triangles and circles are simulated values). The user capacity increase is significant (BPSK spreading modulator with spreading gain $K = 64$; continuous lines are theoretical results, triangles and circles are simulated values).

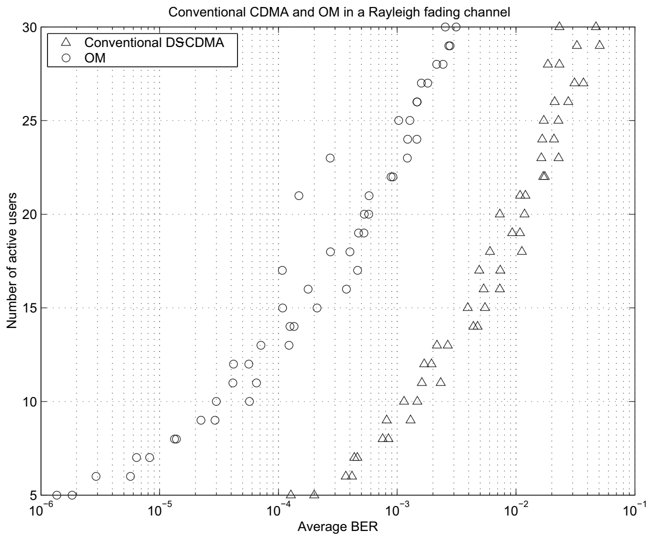

Fig. 5. Conventional DS-CDMA system and its OM counterpart. At $PEP = 10^{-1}$ user capacity is doubled (BPSK spreading modulator with spreading gain $K = 32$, $SNR := P/\eta = 0$db).

the corresponding shift of the PN sequence. To collect the available diversity, signals were combined using MRC.

From Fig. 4 we can see that (25) is an accurate predictor of the simulated behavior. Moreover, a comparison with conventional non-cooperative DS-CDMA shows a significant user capacity increase. Fig. 5 compares error performance when transmissions are error control coded with a constraint length 9, rate 1/2 convolutional code with generators $g_o = 753$ and $g_1 = 561$ in octal. The effect of coding is to broaden the performance gap between OM and non-cooperative DS-CDMA as shows a quick comparison of Figs. 4 and 5. Considering a target packet error probability (PEP) of 10^{-1} –typical operating point for e.g., voice applications– we can see that the user capacity of OM is approximately twice that of conventional DS-CDMA.

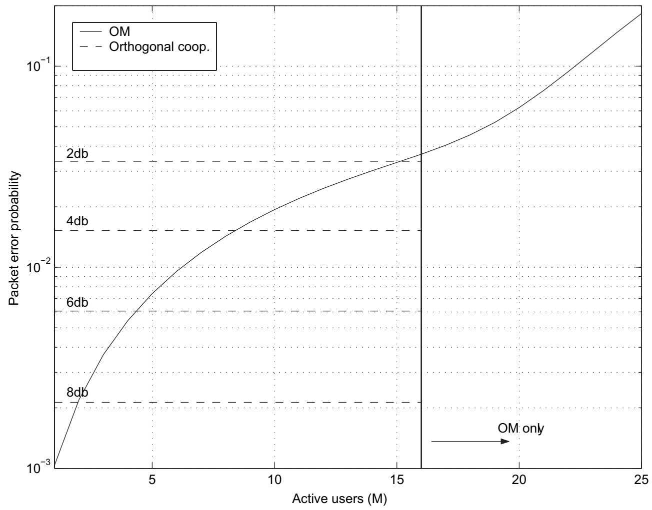

Fig. 6. Comparison of single-code OM (with diversity 2) against modified cooperative protocols using orthogonal channels (with diversity 3), both involving two cooperators per source.

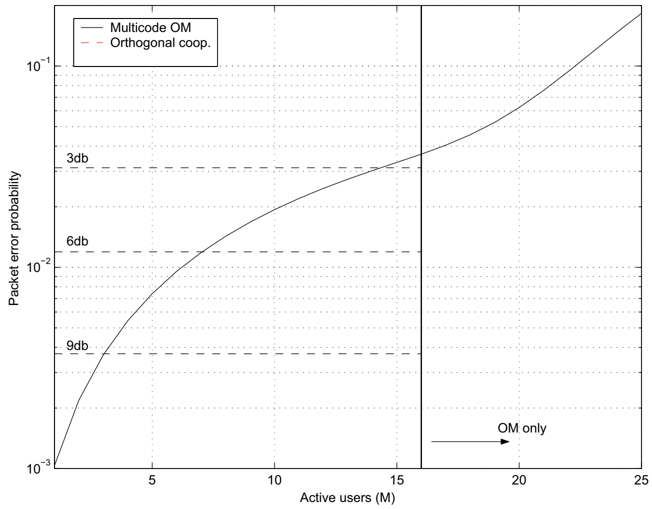

Fig. 7. Comparison of multi-code OM (with diversity 2) against modified cooperative protocols using orthogonal channels (with diversity 2), both involving one cooperator per source.

A. Comparison with cooperation over orthogonal channels

To assess the spectral efficiency claims of the OM protocol in Section II-B and its multi-code counterpart in Section II-C, with respect to existing cooperative protocols over (deterministically) orthogonal channels [3], [4], [10], it is of interest to compare their performance under the same bandwidth. To this end, consider e.g., a modified version of [4] where the source transmits in even time slots and two relays echo the source signal over the odd slots. If the deterministically orthogonal spreading sequences (e.g., TDMA or DS Hadamard codes) are used in the second (relay) phase, then $\mathcal{E} = 1/3$. But instead, we will test this system using space-time orthogonal codes which can afford $\mathcal{E} = 1/2$, as in [3]. This modified orthogonal system with two cooperators achieves diversity 3, whereas single-code OM has diversity 2. Notice that this places single-code OM at a disadvantage since with two cooperators we could have used the multi-code OM which also enjoys diversity order 3 [c.f. Remark 2]. All protocols will use BPSK and rate $1/2$ convolutional coding with constraint length 9. But since the scheme over orthogonal channels requires an extra slot relative to the protocols in this paper, we will halve its spreading gain in order to ensure identical bandwidth for all systems; i.e., we test OM and multi-code OM with $K = 32$ against the modified orthogonal scheme with $K_{\rm orth} = K/2 = 16$.

Fig. 6 depicts PEP as a function of the number of active users M, for the OM protocol in Section II-B (solid line) and the modified orthogonal scheme (dashed horizontal lines parameterized by the $SNR := P/\eta$). For $M > K/2 = 16$, only the OM remains operational, since deterministic orthogonality is impossible with spreading gain $K_{\rm orth} = 16$ in this case. For $M \leq 16$, we see that PEP of the modified orthogonal scheme improves as SNR increases from 2 to 8dB, as expected; and since perfect user separation is possible, for each SNR value the PEP curve remains flat (corresponding to the single-user performance) as M increases up to 16. It also outperforms OM for SNR$>$ 2dB, but OM is better for SNR$\leq$ 2dB even when $M \leq 16$. The solid OM curve (which has been obtained for $SNR := P/\eta = 0$dB) shows that PEP degrades gracefully as M increases, and as one can verify from the SINR expression in (7), OM's performance is less dependent on SNR and more dependent on M.

Fig. 7 is the counterpart of Fig. 6 but with multi-code OM used in lieu of the single-code OM and the modified orthogonal protocol of [3], both with a single cooperator and thus both effecting diversity order 2. Similar observations apply except that the multi-code OM is now better than the modified orthogonal scheme for SNR$\leq$ 3dB, even when $M \leq 16$. Notice that this comparison is more fair since both schemes achieve diversity 2 and are compared under identical constellations, error control codes, and spectral efficiencies. It is also worth stressing that with the pragmatic rate 1/2 convolutional codes used here, the typical SNR range is $0 - 5$dB.

The comparisons in Figs. 6 and 7 illustrate clearly not only the doubling of user capacity, but also the superiority of OM protocols in the low-to-medium SNR regime. Reliable PEP in heavily loaded systems or in relatively low-SNR is precisely what we expect from a spectrally efficient protocol.

V. Concluding Remarks

We developed novel protocols for cooperative networks, by introducing intentional multipath through one or two cooperating terminals. We showed that this protocol achieves second order diversity without incurring the spectral inefficiency associated with existing alternatives employing orthogonal channels. We showed that the proposed protocol 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, mobility management, synchronization, and hardware implementation issues.

Future research will include further study on the interaction of OM with other means of diversity (e.g., channel induced multipath), as well as integration with traditional FEC and recently introduced distributed FEC for cooperative links [10].

Finally, while compatibility with existing standards prompted us to work with PN sequences, any multiple access technique effecting statistical channel orthogonality can be used. In particular, pursuing random time hopping/frequency hopping (TH/FH) is a promising direction to devise OM-like protocols for wireless ad-hoc networks[1].

ACKNOWLEDGEMENT

The authors wish to thank Prof. Yingwei Yao of the University of Illinois at Chicago for suggesting the multi-code alternative of Section II-C and an anonymous reviewer for suggesting the comparison in Section IV-A

REFERENCES

[1] P. A. Anghel, G. Leus, and M. Kaveh, "Multi-user space-time coding in cooperative networks," in *Proc. Intl. Conf. on Acoustics, Speech, and Signal Processing 2003*, pp. 73–76.

[2] G. Scutari, S. Barbarossa, and D. Ludovici, "Cooperation diversity in multihop wireless networks using opportunistic driven multiple access," in *Proc. IEEE International Workshop on Signal Processing Advances for Wireless Communications 2003*.

[3] J. N. Laneman and G. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2415–2425, Oct. 2003.

[4] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity, part I: system description," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927–1938, Nov. 2003.

[5] K. S. Gilhousen, I. M. Jacobs, R. Padovani, A. J. Viterbi, L. A. Weaver, and C. E. Wheatley, "On the capacity of a cellular CDMA system," *IEEE Trans. Veh. Technol.*, vol. 40, no. 2, pp. 303–312, May 1991.

[6] A. Scaglione and Y. W. Hong, "Opportunistic large arrays: cooperative transmission in wireless multihop ad hoc networks to reach far distances," *IEEE Trans. Signal Processing*, vol. 51, no. 8, pp. 2082–2092, Aug. 2003.

[7] P. Viswanath, D. N. C. Tse, and R. Laroia, "Opportunistic beamforming using dumb antennas," *IEEE Trans. Inf. Theory*, vol. 48, no. 2, pp. 1277–1294, Feb. 2002.

[8] A. J. Viterbi, *CDMA Principles of Spread Spectrum Communication*. Addison-Wesley Wireless Communications Series, 1995.

[9] E. H. Dinan and B. Jabbari, "Spreading codes for direct sequence CDMA and wideband CDMA cellular networks," *IEEE Commun. Mag.*, vol. 36, no. 9, pp. 48–54, Sept. 1998.

[10] M. Janani, A. Hedayat, T. E. Hunter, and A. Nosratinia, "Coded cooperation in wireless communications: space-time transmission and iterative decoding," *IEEE Trans. Signal Processing*, vol. 52, no. 2, pp. 362–371, Feb. 2004.

[1] The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Laboratory or the U. S. Government.