ON THE DIVERSITY OF COOPERATIVE SYSTEMS

Paul A. Anghel, Mostafa Kaveh

Dept. of ECE, Univ. of Minnesota, 200 Union St. SE, Minneapolis, MN 55455, USA
Email: {panghel,kaveh}@ece.umn.edu

ABSTRACT

This paper addresses some of the opportunities and the challenges that could arise in the design and analysis of multi-hop systems that utilize cooperation among several intermediate regenerative relays to provide reliable high-quality communication between a source and a destination. This mode of communication can be viewed as a network-embedded distributed, or extended MIMO system. Using the infrastructure provided by the uplink cellular system, we develop and analyze a distributed space-time coding (DSTC) system based on the Alamouti design. We show that with limited feedback from the base station, a DSTC system with two relays, which act as tetherless antennae, is able to induce and collect diversity in a distributed MIMO setup.

1. INTRODUCTION

While short term fades may not be disastrous for establishing or maintaining connections, or for supporting a desired quality of service when there is some node mobility, *strong shadowing*, *shielding* and or other longer term link degradations can be major detriments to the connectivity of parts of the cellular system. All the deleterious effects of the channel become more severe with the potential operation at higher frequencies, which may be needed for transceiver compactness and desired higher data rates. The envisioned solution based on a distributed space-time framework is to use cooperating relay nodes as tetherless multiple antennas to effect distributed spatial diversity and low-power connectivity. Depending on the nature and complexity of the system, the nodes can serve as simple amplify-and-forward relays (i.e., non-regenerative relays) as in [1, 2, 3]) or became sophisticated proxies that can carry out detection, storage, regeneration and coding and aid in routing. In either case, the virtual arrays provide a structure that can be exploited as an *extended MIMO system* [4, 5, 6].

Since the introduction of cooperative networks more attention has been awarded to the analysis of systems using non-regenerative relays because of the tractability of the resulting relay channel [1, 3, 7]. Except for a thorough outage capacity analysis at high signal-to-noise ratio (see [6]), little is know about the performance of systems with parallel regenerative relays. In this paper we contribute to the area of regenerative relay networks by proposing and analyzing distributed space-time systems with one and two regenerative relays. Unlike non-regenerative relays, regenerative relays do not naturally induce diversity in the system [8]. However, the proposed schemes are designed to induce and collect diversity in the distributed MISO channel by allowing statistical channel feedback to the relays and error probability feed-forward. The schemes are tailored for uplink cellular systems, but can be very well utilized in multi-hop networks without centralized control.

This work was supported in part by the National Science Foundation under the Wireless Initiative Program, Grant #9979443

2. SYSTEM MODEL

We consider an uplink cellular communication system that achieves mobile user separation at the base station (BS). For the brevity of our argument we select a time-division multiple access (TDMA) scheme, but any multiple access schemes that guarantees user separations is equally promising. In addition to the mobile users and the base station (BS), we also consider *fixed* wireless relay stations distributed especially in areas in which the mobile users might experience strong shadowing. The relay stations cannot transmit and receive using the same channel resources because the signal received by a relay would be affected by strong interference from the relay's own transmitter (i.e., self-interference). In order to avoid self-interference and to provide the possibility of diversity reception, a cooperative system requires the separation of input and output signals at each relay via time, frequency, or if possible polarization duplexing.

Using a unidirectional transmit antenna at the relay and/or trying to cancel self-interference at the relay after estimating relevant propagation gains, like it is suggested in [4], would require extra pilot tones and highly separated receive and transmit signal paths in order to reduce internal signal leakage. Since self-interference could drive the relay's receive amplifier into saturation, it cannot be mitigated after the decoding block. In order to *eliminate self-interference* we need to assume two orthogonal subspaces for the signals received and transmitted by the relays despite incurring some loss of bandwidth efficiency. If the relays use two perfectly orthogonal signal subspaces, they can also eliminate multiple-relay-interference (MRI), which is the interference collected by one relay from all the other active relays in the system. Highly directional antennas are not guaranteed to eliminate MRI. In addition they can have a detrimental effect when two relays lie almost on a straight line with the base station.

There are several ways of generating two orthogonal signal subspaces. For example, we can allocate 2 different frequency bands, or 2 different time slots for transmitting and receiving signals at the relays, or we could carefully design a system that uses orthogonal polarizations. Because we want to capitalize on the TDMA setup, we select 2 different time slots for transmitting and receiving signals at the relays. More precisely, the relays turn off their transmitters and use that time slot only for receiving the information signal from the active mobile user, say user m. In the next time slot the relays turn off their receivers and forward the information signal to the BS (see Fig. 1). With a time-slotted communication system we can satisfy the stringent limitations imposed on the size of the cellular radios by using *only one antenna* at each transceiver.

Through a relay discovery process and protocol, which is not the focus of this paper, it is assumed that the mobile user m has access to 2 relay stations, R_1 and R_2. The relay stations decode

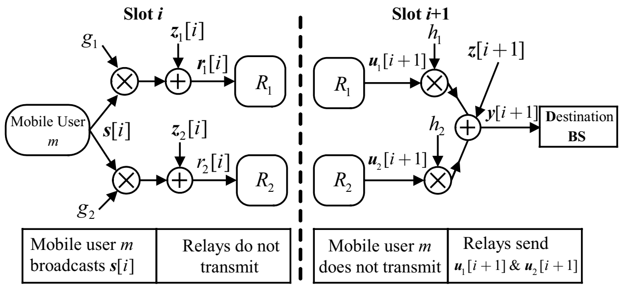

Fig. 1. Discrete-time equivalent system in active state

the information symbols received from mobile user m and in the next time-slot forward the regenerated symbols to the BS. In order to simplify the exposition let us assume, without loss of generality, that two information symbol are transmitted in each time-slot. Hence, during the generic time-slot i the two relays receive and decode a signal containing the block $\boldsymbol{s}[i] = [s[2i], s[2i+1]]^{\mathrm{T}}$ transmitted by user m. During time-slot $i+1$ the relays turn off their receivers and transmit $\boldsymbol{u}_1[i+1]$ and $\boldsymbol{u}_2[i+1]$, which are functions of the estimates obtained for $\boldsymbol{s}[i]$ at R_1 and R_2. For the moment we assume that there is no direct communication link between the mobile user m and the BS. This usually happens when strong shadowing and extra-cell interference affects the communication between the mobile user m and the BS. Nevertheless, we will relax this assumption later. If the transmissions suffer from the effects of slowly time-varying flat fading, we can write the signals received at the relay R_q and the BS during the ith and $i+1$th transmission slots as

$$\begin{aligned} \boldsymbol{r}_q[i] &= g_q\sqrt{E}\boldsymbol{s}[i] + \boldsymbol{z}_q[i], \;\; q \in \{1,2\}, \\ \boldsymbol{y}[i+1] &= h_1\boldsymbol{u}_1[i+1] + h_2\boldsymbol{u}_2[i+1] + \boldsymbol{v}[i+1], \end{aligned} \tag{1}$$

where E is the energy of the BPSK symbols $s[2i]$ and $s[2i+1]$ transmitted by the mobile user m. We assume that $\{\boldsymbol{z}_q[i]\}_{q=1}^2$ and $\boldsymbol{v}[i] := [v_1[2i], v_2[2i+1]]^{\mathrm{T}}$ are mutually independent complex circular Gaussian noise vectors with zero mean and covariance matrix $N_0\boldsymbol{I}_2$. The effect of the slowly time-varying flat fading is captured by the random variables $\{g_q\}_{q=1}^2$, and $\{h_q\}_{q=1}^2$, which we assume to be independent and with variances $\{\Lambda_q\}_{q=1}^2$, and $\{\Omega_q\}_{q=1}^2$, respectively. We also assume that the relay R_q, knows the channel g_q perfectly. Hence, given a realization g_q of the channel between user m and relay R_q, the decision vector for $\boldsymbol{s}[i]$ with maximum likelihood decoding is $\boldsymbol{\xi}_q[i] = \boldsymbol{r}_q[i]/(\sqrt{\varepsilon}g_q)$. The relay R_q quantizes $\boldsymbol{\xi}_q[i]$ in order to obtain an estimate of $\boldsymbol{s}[i]$, which can be written as $\hat{\boldsymbol{s}}_q[i] = [\hat{s}_q[2i], \hat{s}_q[2i+1]]^{\mathrm{T}} = 2\,\mathrm{sign}(\boldsymbol{\xi}_q[i]) - 1$. The probability of error at the relay R_q is $\varepsilon_q := Q(\sqrt{2|g_1|^2\varepsilon/N_q})$, $q \in \{1,2\}$, where $Q(z) := \int_z^\infty \exp(x^2/2)dx/\sqrt{2\pi}$. Even though each relay has only one antenna, the two relays can cooperate in order to implement a distributed space-time coding (DSTC) system based on the Alamouti design [9]. To implement the DSTC system, we select $\boldsymbol{u}_1[i+1] := \alpha_1[\hat{s}_1[2i], -\hat{s}_1^*[2i+1]]^{\mathrm{T}}$ and $\boldsymbol{u}_2[i+1] := \alpha_2[\hat{s}_2[2i], \hat{s}_2^*[2i+1]]^{\mathrm{T}}$. The only differences between $\boldsymbol{u}_1[i+1]$, $\boldsymbol{u}_2[i+1]$ and the classical Alamouti pairs (see [9]) are the positive coefficients α_1 and α_2, which will prove to be fundamental for enabling diversity in the system.

3. RECEIVERS FOR THE DSTC SYSTEM

The main focus of this paper is to propose and analyze the performance of several base station receivers for the DSTC system in Fig. 1. Since it simplifies the analysis, we first drop the dependency on the block index i and then write (1) as a single input-output equation

$$\boldsymbol{y} = h_1\alpha_1\begin{bmatrix} \theta_1[0]\,s[0] \\ -\theta_1[1]\,s^*[1] \end{bmatrix}^{\mathrm{T}} + h_2\alpha_2\begin{bmatrix} \theta_2[0]\,s[0] \\ \theta_2[1]\,s^*[1] \end{bmatrix}^{\mathrm{T}} + \boldsymbol{v}, \tag{2}$$

where $\theta_q[n] \in \{-1,1\}$ with $q \in \{1,2\}$ are two random processes that characterize the error event at the relays. More precisely, if an error occurs at relay q at time n, then $\theta_q[n] = -1$ and the error probability is $\Pr\{\theta_q[n] = -1\} = 1 - \Pr\{\theta_q[n] = 1\} = \varepsilon_q$. If we process $\boldsymbol{y}$ in (2) with the 2×2 orthogonal matrix $\boldsymbol{H}^{\mathrm{H}} := [\alpha_1 h_1^*, -\alpha_2 h_2; \alpha_2 h_2^*, \alpha_1 h_1]$, we obtain $[x_1, x_2]^{\mathrm{T}} := \boldsymbol{H}^{\mathrm{H}}\boldsymbol{y}$. Due to the detection errors at the relays, $\boldsymbol{H}^{\mathrm{H}}$ does not remove the inter-symbol interference (ISI) introduced by the MISO channel. Unlike the standard Alamouti system in [9], which is equivalent to a system with twice the bandwidth efficiency and a maximum ratio combiner receiver, the DSTC system is not equivalent with a system that optimally combines orthogonal transmissions from R_1 and R_2. To maintain the simplicity of an Alamouti-type system, the BS will only use

$$\begin{aligned} x_1 =& (\alpha_1^2|h_1|^2\theta_1[0] + \alpha_2^2|h_2|^2\theta_2[0])\,s[0] \\ &+ h_1^* h_2\alpha_1\alpha_2(\theta_2[1] - \theta_1[1])\,s[1] + h_1^*\alpha_1 v_1 - h_2\alpha_2 v_2 \end{aligned} \tag{3}$$

in order to estimate $s[0]$, even though discarding x_2 is suboptimal since information about $s[0]$ is also contained in x_2. Note, however, that if

$$\theta_1[n] = \theta_2[n] \;\; \forall n, \tag{4}$$

the ISI is eliminated. Of course, if in addition to (4), $\theta_1[n] = 1$, $\forall n$ (i.e., no errors at the relays), then the system in (2) reverts to the standard Alamouti system.

3.1. Unknown $\{\varepsilon_q\}_{q=1}^2$ at the BS

If the BS does not know $\{\varepsilon_q\}_{q=1}^2$, it cannot make use of the statistics of $\{\theta_q[n]\}_{q=1}^2$ and there is little do be done in order to come up with a receiver at the BS. We can assume without loss of generality that $\alpha_1 = \alpha_2 = \sqrt{E}$ since we can include the differences between the energies of the transmitted symbols at R_1 and R_2 as part of the average channel energies Ω_1 and Ω_2. Because $\theta_1[n]$ and $\theta_2[n]$ are not perfectly correlated, (4) does not hold for all n. However, given that the relays do not introduce "too many errors", it is reasonable to assume that $\theta_1[n] = \theta_2[n] = 1$, $n \in \{0,1\}$, in (3). In this case we decide that

$$s[0] = 1 \text{ has been transmitted only if } x_1 > 0. \tag{5}$$

The bit error probability (BER) for the detection criterion in (5) is $P_a = \Pr(\mathrm{Re}\{x_1\} < 0/s[0] = 1)$ and after some manipulations, which are not detailed in the paper due to lack of space, we obtain

$$\begin{aligned} P_a =& (1-\varepsilon_s+2\varepsilon_p)[(1-\varepsilon_s)Q(\alpha_s/\sigma_v) + \varepsilon_d Q\,(\mathrm{Re}\{\alpha_d\}/\sigma_v) + \varepsilon_1] \\ &+ .5(\varepsilon_s - 2\varepsilon_p)\{(1-\varepsilon_s)[Q(\mathrm{Re}\{\beta_1\}/\sigma_v) + Q(\mathrm{Re}\{\beta_2\}/\sigma_v)] \\ &+ \varepsilon_d[Q(\mathrm{Re}\{\beta_3\}/\sigma_v) + Q(\mathrm{Re}\{\beta_4\}/\sigma_v)] + 2\varepsilon_1\}, \end{aligned} \tag{6}$$

where $\varepsilon_s := \varepsilon_1 + \varepsilon_2$, $\varepsilon_p := \varepsilon_1\varepsilon_2$, $\alpha_s := \alpha_1^2|h_1|^2 + \alpha_2^2|h_2|^2$, $\alpha_d := \alpha_1^2|h_1|^2 - \alpha_2^2|h_2|^2$, $\alpha_p := \alpha_1\alpha_2 h_1^* h_2$, $\beta_1 := \alpha_s + 2\alpha_p$, $\beta_2 := \alpha_s - 2\alpha_p$, $\beta_3 := \alpha_d + 2\alpha_p$, $\beta_4 := \alpha_d - 2\alpha_p$, and $\sigma_v^2 := \alpha_s N_0/2$. The average BER is $\overline{P}_a := E\{P_a\}$, where the expectation is taken over the channels $\{g_q\}_{q=1}^2$ and $\{h_q\}_{q=1}^2$. It is now easy to show that the receiver in (5) does not collect any diversity, e.g., with Rayleigh fading channels the slope of $\overline{P}_a$ becomes -1 as E/N_0 increases to infinity.

3.2. Known $\{\varepsilon_q\}_{q=1}^2$ at the BS

Let us digress for a moment and assume that relays R_1 and R_2 transmit using two orthogonal channels (e.g., two non-overlapping frequency bands), and consequently, instead of $\boldsymbol{y}$, the BS receives $y_1 = h_1\theta_1[0]s_1[0] + v_1$ and $y_2 = h_2\theta_2[0]s_1[0] + v_2$. Note that the bandwidth efficiency of this system is half the bandwidth efficiency of the DSTC system in (2). The maximum likelihood (ML) detection rule is $s[0] = 1$ only if $p([y_1, y_2]^{\mathrm{T}}/s[0] = 1) > p([y_1, y_2]^{\mathrm{T}}/s[0] = -1)\}$, where $p([y_1, y_2]^{\mathrm{T}}/s[0] = j)$ is the probability density function (PDF) of $[y_1, y_2]^{\mathrm{T}}$ given $s[0] = j$. After some computations, which are not detailed in the paper, the decision rule becomes

$$4\,\mathrm{Re}\{y_1h_1^* + y_2h_2^*\}/N_0 + \ln\left[\frac{(1-\varepsilon_s) + \varepsilon_1 \mathrm{e}^{\frac{-4}{N_0}\mathrm{Re}\{y_1h_1^*\}} + \varepsilon_2 \mathrm{e}^{\frac{-4}{N_0}\mathrm{Re}\{y_2h_2^*\}}}{(1-\varepsilon_s) + \varepsilon_1 \mathrm{e}^{\frac{4}{N_0}\mathrm{Re}\{y_1h_1^*\}} + \varepsilon_2 \mathrm{e}^{\frac{4}{N_0}\mathrm{Re}\{y_2h_2^*\}}}\right] \underset{-1}{\overset{1}{\gtrless}} 0. \qquad (7)$$

.

We notice that if we remove the second term in (7), we obtain the detection rule for a one-hop two-path system with a maximum ratio combiner receiver. The second term in (7) accounts for the errors at the relay and it is a non-linear combination of y_1 and y_2. If one is not concerned too much with bandwidth efficiency, then one should select orthogonal transmissions at the relays, and implement the optimum combiner in (7) as it offers the best BER. Hence, the performance of the DSTC system with twice the bandwidth efficiency could be at most equal to the performance of the optimum combiner. This is achieved by the Alamouti system only for one-hop transmissions. We have established in (3) that in the DTSC system the Alamouti receiver matrix $\boldsymbol{H}^{\mathrm{H}}$ only mitigates ISI, and consequently, we expect the DSTC system to perform worse than the optimum combiner in (7).

The fact that the optimum combiner is a non-linear function of y_1 and y_2 is not very helpful in the design of the DSTC receiver. What we are looking for is a linear combiner even though it is suboptimal. One could easily find $\rho_1 \in [0, 1]$ and $\rho_2 \in [0, 1]$ that would minimize the BER of a cooperative system with orthogonal transmissions at the relays and using the detection rule

$$\mathrm{Re}\{y_1h_1^*\rho_1 + y_2h_2^*\rho_2\} \underset{-1}{\overset{1}{\gtrless}} 0, \qquad (8)$$

or equivalently, one could find the optimum ρ for a system that selects $s[0]$=1 only if $\mathrm{Re}\{y_1h_1^* + y_2h_2^*\rho\} > 0$. Hence, the optimum ρ is the one that minimizes $P_{\mathrm{c}} = (1-\varepsilon_s)\,Q(\sqrt{2\rho_s/N_0}) + \varepsilon_2 + (\varepsilon_1-\varepsilon_2)Q(\rho_d/\sqrt{\sigma_\rho})$, which is the system's BER with the detection rule in (8), and where $\rho_s := |h_1|^2 + |h_2|^2\rho$, $\rho_d := |h_1|^2 - |h_2|^2\rho$, $\sigma_\rho := \rho_s N_0/2$. In this paper we are not interested in using the performance maximizing ρ, or equivalently, the optimum ρ_1 and ρ_2 in the design of the DSTC system. We actually prefer the ρ_1 and ρ_2 that would maximize the SNR after the combiner $y_1h_1^*\rho_1 + y_2h_2^*\rho_2$ because we obtain a reduced complexity DSTC system. The optimum pair $\{\rho_1, \rho_2\}$ would only provide a performance lower bound for the DSTC system. Following the approach suggested in [1] for a system with one relay, we find that with two relays we have to select

$$\rho_1 = \frac{(1-2\varepsilon_1)/N_0}{1+4\varepsilon_1(1-\varepsilon_1)|h_1|^2}, \text{ and } \rho_2 = \frac{(1-2\varepsilon_2)/N_0}{1+4\varepsilon_2(1-\varepsilon_2)|h_2|^2}. \qquad (9)$$

We want to emphasize that ρ_1 depends only on ε_1 and $|h_1|$, and similar for ρ_2. We will see later why this is of paramount importance for implementing the DSTC system. Preliminary simulations using Rayleigh fading channels allow us to conjecture that there is little to gain when using (7) instead of (9).

At this point we are ready to go back to the DSTC system in (3). Using the result in (9) we could select $\alpha_q^2 = \rho_q$, $q \in \{1, 2\}$, which implicitly assumes that the BS feeds back the channel magnitudes $|h_1|$ and $|h_2|$ to the relays R_1 and R_2, respectively. Even though the relays have a fixed position, and consequently, $|h_1|$ and $|h_2|$ can be assumed quasi-static, in order to limit the feedback we prefer to select

$$\alpha_q^2 = \frac{(1-2\varepsilon_q)/N_0}{1+4\varepsilon_q(1-\varepsilon_q)E\{|h_q|^2\}}, \qquad q \in \{1, 2\}. \qquad (10)$$

Unlike (9), which ensures maximum SNR after the combiner, the result in (10) is not the outcome of an optimization. Of course, one could also take into account the ISI in (3) and select $\alpha_q^2 = (1-2\varepsilon_q)/\left(N_0 + 4N_0\varepsilon_q(1-\varepsilon_q)E\{|h_q|^2\} + 4E\{|h_{\bar{q}}|^2\}\right)$, where $\bar{q} = 1$ if $q = 2$ and $\bar{q} = 2$ if $q = 1$, with the obvious drawback that if either channel changes both relays have to recompute their α_q. Another possibility is to find the ML detector for the channel model described in (3). With an ML decision rule we have to select

$$s[0]=1 \text{ only if } E\{p(x_1/s[0]=1)\} > E\{p(x_1/s[0]=-1)\}, \qquad (11)$$

where the expectation is taken over the distributions of $\{\theta_q[0]\}_{q=1}^2$, $\{\theta_q[1]\}_{q=1}^2$, and $s[1]$. Writing (11) in terms of $\{\varepsilon_q\}_{q=1}^2$, $\{h_q\}_{q=1}^2$, and $\{\alpha_q\}_{q=1}^2$ does not pose any problem and the simulation of the detector in (11) is straight forward. However, deriving a closed form expression for the system's BER, $P_{1a} := \Pr(E\{p(x_1/s[0] = 1)\} < E\{p(x_1/s[0] = -1)\}/s[0] = 1)$, in terms of $\{\alpha_q\}_{q=1}^2$ and finding the optimum pair $\{\alpha_1, \alpha_2\}$ that minimize P_{1a} under some power constraints at the relay is quite a challenging task. In addition, the optimum pair $\{\alpha_1, \alpha_2\}$ has to be computed at the BS every time one of the cooperative channel parameters (i.e.,$\{|h_q|\}_{q=1}^2$, $\{|\varepsilon_q|\}_{q=1}^2$) changes and afterwards it has to be piggybacked to the relays. It becomes clear now why we do not favor using the BER minimizing $\{\alpha_q\}_{q=1}^2$ or why we do not select $\alpha_q^2 = \rho_q$, where the pair $\{\rho_1, \rho_2\}$ minimizes P_c.

The final purpose of our analysis is not to find the optimum DSTC receiver, but to find a receiver that achieves the right balance between performance and complexity. With $\{\alpha_q\}_{q=1}^2$ given in (10), the BS only feeds back $E\{|h_1|^2\}$ to relay R_1 and $E\{|h_2|^2\}$ to relay R_2. In order to decode $s[0]$ in (3) we select the same detector as in (5) with the only difference that α_q is now a function of ε_q. Estimating ε_q at the BS is not a trivial task. The idea we are pursuing in [10] is to allow some of the pilot symbols inserted by the mobile user m to be amplified at the relays instead of being regenerated like the information sequence $s[n]$. In this paper, however, we assume that the DSTC system has perfect knowledge of $\{\varepsilon_q\}_{q=1}^2$ at the BS. The BER of the DSTC system with perfect channel state information is given in (6). We denote the BER formula with P_{2a} to differentiate it from P_a in (6), which is not a function of $\{\varepsilon_q\}_{q=1}^2$. Note that the argument of the Q-function in (6) is now dependent on $\{\varepsilon_q\}_{q=1}^2$, and consequently, on $\{|g_q|\}_{q=1}^2$. In order to find $\overline{P}_{2a} := E\{P_{2a}\}$, we numerically average P_{2a} over the channel statistics. Lower and upper bounds on $\overline{P}_{2a} := E\{P_{2a}\}$ will be presented in [10].

4. DSTC SYSTEM WITH ONE RELAY

It is enough to consider only one relay when the mobile user m has a direct link to the BS. In this case the mobile user m would perform the same task as relay R_1 during slot $i + 1$. Unlike the system in Fig. 1, which could only achieve a maximum diversity of 2, the one relay system could achieve a maximum diversity of 3 since the BS collects the same information signal from 3 sources during 2 consecutive time slots (e.g., time slot i and $i+1$). If we consider h_1 to be the channel between the mobile user m and the BS, we can specialize (3) as follows:

$$\begin{aligned} x_1 =& (\alpha_1^2|h_1|^2 + \alpha_2^2|h_2|^2\theta_2[0])\, s[0] \\ &+ h_1^* h_2 \alpha_1 \alpha_2 (\theta_2[1]-1)\, s[1] + h_1^* \alpha_1 v_1 - h_2 \alpha_2 v_2 \\ x_3 =& h_2 \alpha_3 s[0] + v_3, \end{aligned} \qquad (12)$$

where x_3 is received by the BS from the mobile user m during time slot i. The noise v_3 is complex circular Gaussian distributed with zero mean and variance $N_0/2$ per dimension, and it is independent of v_1, and v_2.

The ML detection rule for (12) is equivalent to selecting

$$s[0] = \underset{s\in\{-1,1\}}{\arg\max} \left\{ L\left([x_1, x_3]^{\mathrm{T}}, s \right) \right\}, \qquad (13)$$

where $L\left([x_1,x_3]^{\mathrm{T}}, s\right) := e^{\frac{2\,\mathrm{Re}\{x_3 h_2^*\} s}{N_0}} \left\{ (1-\varepsilon_1)^2 \exp\left(\frac{|x_1-\alpha_s s|^2}{-2\sigma_v^2}\right) + \varepsilon_1(1-\varepsilon_1) e^{\frac{|x_1-\alpha_d s|^2}{-2\sigma_v^2}} + .5\varepsilon_1(1-\varepsilon_1)\left[\exp\left(\frac{|x_1-\beta_1 s|^2}{-2\sigma_v^2}\right) + \exp\left(\frac{|x_1-\beta_2 s|^2}{-2\sigma_v^2}\right)\right] + .5\varepsilon_1^2 \left[\exp\left(\frac{|x_1-\beta_3 s|^2}{-2\sigma_v^2}\right) + \exp\left(\frac{|x_1-\beta_4 s|^2}{-2\sigma_v^2}\right)\right] \right\}$. Similar to (8), we can also derive a linear combiner receiver which selects $s[0]=1$ only if $\mathrm{Re}\{x_1\alpha_s + x_3 h_2^* \rho\} > 0$, where ρ minimizes the system's BER, i.e., $\Pr\left(\mathrm{Re}\{x_1\alpha_s + x_3 h_2^*\rho\} < 0/s[0]=1\right)$.

5. PERFORMANCE COMPARISONS

In order to compare the performance of the different receivers introduced in this paper for the system in Fig. 1, we assume that $\{g_q\}_{q=1}^2$, and $\{h_q\}_{q=1}^2$ are complex circular Gaussian random variables with zero mean and average energy $\Lambda_1 = \Lambda_2 = 1$, and $\Omega_1 = \Omega_2 = 1$ (equally balanced channels). In Fig. 2 we first plot P_a and we observe that the Alamouti receiver without knowledge of the error probabilities at the relays is not able to collect any diversity from the relay channel. Second, we plot the performance of the weighted-Alamouti receiver described in Subsection 3.2 with the weights given in (10), i.e., P_{2a}, and we notice that the BER of the system has almost slope -2. In Fig. 2 we also plot P_{1a}, and we observe that there is little to gain when using an ML detector with the weights given in (10). The weights in (10) are not optimum for the ML receiver and that could explain why there is no performance improvement. For comparison, we also plot P_o, which is the performance of the optimum combiner given in (7) for a system that uses 2 relays with orthogonal channels to the BS and BPSK transmissions. Even though this system should actually use a higher order constellation to account for the loss of bandwidth efficiency, we want to point out the performance gap between P_a and P_o, which becomes zero only when the relays decode perfectly the information symbols transmitted by the mobile user (i.e., the relay channel in Fig. 1 becomes a standard 2×1 MISO channel). We also want to emphasize that P_{2a} is quite close to P_o, which is an important result given the sub-optimality of the weighted-Alamouti system. As a reference, we plot the performance of the Alamouti receiver on the 2×1 MISO channel, which we expect to be better than P_o since we have not considered path-loss and shadowing in the channel model.

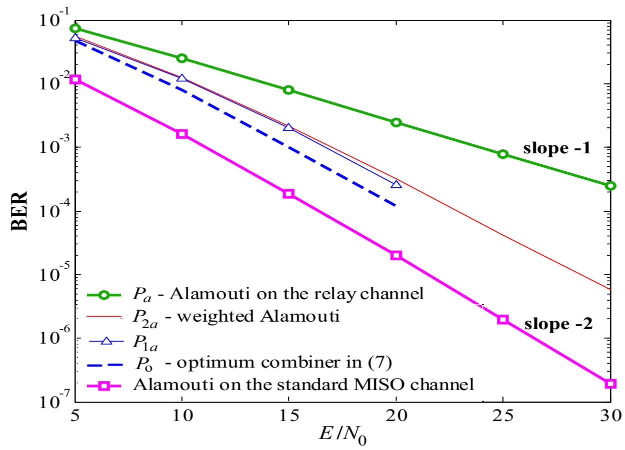

Fig. 2. Performance comparisons for equally balanced channels

6. REFERENCES

[1] J. N. Laneman and G. W. Wornell, "Energy-efficient antenna sharing and relaying for wireless networks," in *Proc. of IEEE Wireless Commununication and Networking Conference*, Chicago, IL, Mar. 2000, pp. 7–12.

[2] V. Emamian and M. Kaveh, "Combating shadowing effects for systems with transmitter diversity by using collaboration among mobile users," in *Proc. of International Symposium on Communication*, Taipei, Taiwan, Nov. 2001, vol. 9.4, pp. 105.1–105.4, Also published in the Journal of the Chinese Institute of Electrical Engineering, vol. 4, 2002, pp. 323–329.

[3] P. A. Anghel, G. Leus, and M. Kaveh, "Multi-user space-time coding in cooperative networks," in *Proc. of IEEE International Conference on Acoustics, Speech, and Signal Processing*, Hong Kong, Sept. 2003, pp. IV 73–IV 76.

[4] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity - Part I and II," *IEEE Trans. on Communications*, submitted 2002, download at `http://eeweb.poly.edu/~elza/Publications.htm`.

[5] P. A. Anghel and M. Kaveh, "Relay assisted uplink communication over frequency-selective channels," in *Proc. of IEEE Conference on Signal Processing Advances in Wireless Communications*, Rome, Italy, Jun. 2003.

[6] J. N. Laneman and G. W. Wornell, "Distributed space-time coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Transastions on Information Theory*, vol. 49, pp. 2415–2425, 2003.

[7] Y. Hua, Y. Mei, and Y. Chang, "Parallel wireless mobile relays with space-time modulations," in *Proc. of IEEE Workshop on Statistical Signal Proc.*, St. Louis, MO, Sept. 2002.

[8] J. Boyer, D. D. Falconer, and H. Yanikomeroglu, "Multihop diversity in wireless relaying channels," *IEEE Transactions on Communications*, submitted 2002, download at `http://www.sce.carleton.ca/faculty/yanikomeroglu/Pub/tcomm_jb.pdf`.

[9] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Select Areas in Comm.*, vol. 16, pp. 1451–1458, 1998.

[10] P. A. Anghel and M. Kaveh, "On the diversity of collaborative systems," 2003, *in preparation.*