A Distributed Approach to Interference Cancellation

K. Raghu, S. K. Mohammed, A. Chockalingam, *Senior Member, IEEE*
Department of ECE, Indian Institute of Science, Bangalore-560012. INDIA

***Abstract*—In this paper[1], we propose and analyze a novel idea of performing interference cancellation (IC) in a distributed/cooperative manner, with a motivation to provide multiuser detection (MUD) benefit to nodes that have only a single user detection capability. In the proposed distributed interference cancellation (DIC) scheme, during Phase-1 of transmission, an MUD capable *cooperating relay node* estimates all the sender nodes' bits through multistage interference cancellation. These estimated bits are then sent by the relay node on orthogonal tones in Phase-2 of transmission. The destination nodes receive these bit estimates and use them for interference estimation/cancellation, thus achieving IC benefit in a distributed manner. For this DIC scheme, we analytically derive an exact expression for the bit error rate (BER) in a basic five-node network (two source-destination node pairs and a cooperating relay node) on AWGN channels. Analytical BER results are shown to match with simulation results. For more general system scenarios, including more than two source-destination pairs and fading channels without and with space-time coding, we present simulation results to establish the potential for improved performance in the proposed distributed approach to interference cancellation. We also present a linear version of the proposed DIC.**

***Keywords*—Cooperative communications, multiuser detection, interference cancellation.**

I. Introduction

Cooperative communications have become popular in recent research, owing to the potential for several benefits when communicating nodes in wireless networks are allowed to cooperate. A classical benefit that arises from cooperation among nodes is the possibility of achieving spatial diversity, even when the nodes have only one antenna. That is, cooperation allows single-antenna nodes in a multiuser environment to share their antennas with other nodes in a distributed manner so that a given node can realize a virtual multi-antenna transmitter that provides transmit diversity benefits. Such techniques, termed as 'cooperative diversity' techniques, have been widely researched [1],[2]. Achieving cooperative diversity benefits based on a relay node merely repeating the information sent by a source node comes at the price of loss of throughput, because the relay-to-destination transmission requires a separate time slot [2]. This loss in throughput due to repetition-based cooperation can be alleviated by integrating channel coding with cooperation [3]. Also, cooperation methods using distributed space-time coding are widely being researched [4]. Our focus in this paper is not on diversity or distributed space-time coding aspects in cooperation. Instead, our focus is on the idea of *multiuser detection (MUD) through cooperation.*

Traditionally, MUD algorithms are viewed as centralized algorithms which get executed in a centralized receiver [5] (e.g., base station receiver in a cellular CDMA system). MUD implementations, with their associated high complexities, are probably justified in a centralized receiver architecture where computational resources (processor MIPS, power, etc.) can be made available. However, in MUD implementations in receivers with limited resources (e.g., mobile nodes in an ad-hoc network) could be quite challenging. In this paper, in an effort to address the issue of providing MUD capability in receivers with limited resources (e.g., receivers with only a single user detection capability), we propose to investigate the novel idea of *exploiting cooperation for multiuser detection purposes*. In particular, we focus on achieving interference cancellation in a distributed/cooperative manner.

We propose a distributed interference cancellation (DIC) scheme in this paper. In the proposed DIC scheme, during phase-1 of transmission, an MUD capable *cooperating relay node* estimates all the sender nodes' bits through multistage interference cancellation. These estimated bits are then sent by the relay node on orthogonal tones in phase-2 of transmission. The destination nodes receive these bit estimates and use them for interference estimation and cancellation, thus achieving IC benefit in a distributed manner. For a system with two source-destination pairs and a cooperating relay node (which is a basic network we consider to illustrate and analyze the proposed approach), we analytically derive an exact expression for the bit error rate (BER) on AWGN channels. Analytical BER results are shown to match with simulation results. For more general system scenarios, including more than two source-destination pairs and fading channels without and with space-time coding, we present simulation results to establish the the potential for improved performance in the proposed distributed approach to interference cancellation. We also present a linear version of the DIC.

II. Proposed DIC Scheme

In this section, we present the proposed DIC scheme and the signal model at various nodes in the two phases of transmission and detection.

A. Architecture

Consider K pairs of communicating nodes and one cooperating relay node. Figure 1 shows the system architecture for $K = 2$. Let S_k denote the kth source node wanting to communicate with the kth destination node, denoted by D_k. That is, $\{(S_1, D_1), (S_2, D_2), \cdots, (S_K, D_K)\}$ denotes the set of communicating node pairs. Let R denote the cooperating relay node. Nodes $S_1, S_2, \cdots, S_K$ share a common CDMA channel. Node S_k is assigned the spreading code c_k. Let $b_k \in \{\pm 1\}$ denote the bit that needs to be sent by node S_k to node D_k.

Phase-1: In Phase-1 (i.e., time slot 1), all source nodes S_k's, $k = 1, 2, \cdots, K$, transmit their bits b_k's using their assigned codes c_k's. These transmissions are heard at all destination nodes D_k's, $k = 1, 2, \cdots, K$, and at the relay node R. It is assumed that i) each destination node has one CDMA matched

[1]This work was supported in part by the DRDO-IISc Program on Advanced Research in Mathematical Engineering.

1930-529X/07/$25.00 © 2007 IEEE
This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE GLOBECOM 2007 proceedings.

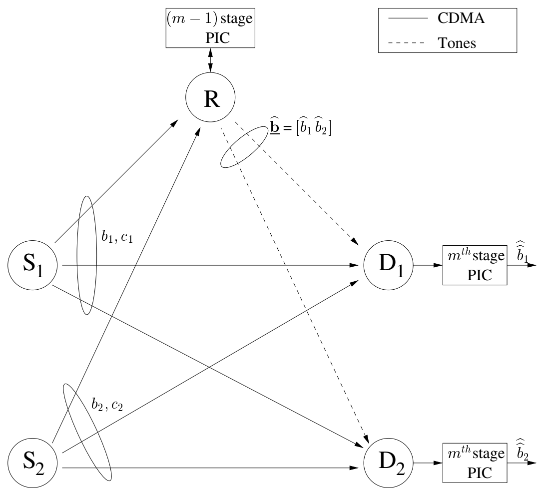

Fig. 1. Proposed distributed interference cancellation scheme for $K = 2$.

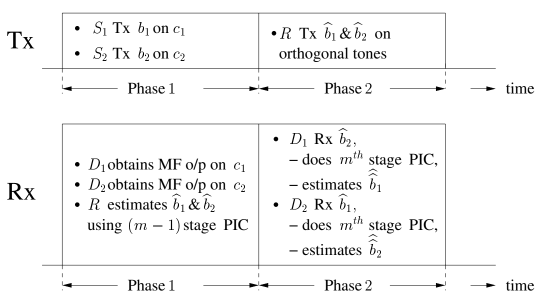

Fig. 2. Transmission and reception activities in Phase-1 and Phase-2 in the proposed DIC scheme for $K = 2$.

filter (MF) tuned to its assigned code (i.e., node D_k has a CDMA MF tuned to code c_k), and ii) the relay node R has a $(m-1)$-stage parallel interference canceller (PIC), $m \geq 2$; for example, $m = 2$ means that the relay node R has only the MF (i.e., 1st stage) outputs. At the end of Phase-1, each destination node has its MF output and the relay node has an estimated bit vector $\underline{\widehat{\mathbf{b}}} = \left[\widehat{b}_1 \widehat{b}_2 \cdots \widehat{b}_K\right]$, obtained using its $(m-1)$-stage PIC. Instead of a PIC, other MUDs [5] can also be considered at the relay.

Phase-2: In Phase-2 (i.e., time slot 2), the relay node R transmits $\underline{\widehat{\mathbf{b}}} = \left[\widehat{b}_1 \widehat{b}_2 \cdots \widehat{b}_K\right]$ on K orthogonal tones; $\widehat{b}_k$ is sent on tone-k. It is assumed that, in addition to one CDMA MF, each destination node has $K-1$ narrowband tone receivers to receive $K-1$ interfering bit estimates sent by R in Phase-2. That is, node D_k receives all $\widehat{b}_j$'s, $j \neq k$ using its $K-1$ tone receivers. Using these received $\widehat{b}_j$'s, D_k reconstructs the multiple access interference (MAI) due to the $K-1$ interfering bits in Phase-1, subtracts this MAI estimate from its CDMA MF output, and makes the final bit decision $\widehat{\widehat{b}}_k$. In other words, the destination nodes implement their respective mth stage PIC, while the relay node R implemented the first $(m-1)$ stages of the PIC. Thus, the overall PIC for a given destination node is implemented in a distributed manner. Figure 2 shows the transmission and reception activities of various nodes in time slots 1 and 2, for $K = 2$.

B. Signal Model

Let (S_k, D_k) be the desired source-destination node pair, i.e., we are interested in detecting at destination node D_k the bit $b_k \in \{\pm 1\}$ sent by the source node S_k.

Rx Signal at Destination Node D_k in Time Slot 1: The MF output at node D_k in time slot 1, denoted by $y_k^{(t1)}$, is given by

$$y_k^{(t1)} = \underbrace{A_k b_k}_{\text{desired signal}} + \underbrace{\sum_{j=1,\, j\neq k}^{K} \rho_{jk} A_j b_j}_{\text{MAI}} + \underbrace{n_k}_{\text{noise}}, \tag{1}$$

where A_k is the transmit amplitude at node S_k, $\rho_{jk} = \rho_{kj} = \int_0^T c_j(t) c_k(t) dt$ is the correlation coefficient between the signature waveforms of nodes S_k and S_j, where $c_l(t)$ is the unit energy spreading waveform of node S_l, $l = 1, \cdots, K$, defined in the interval $[0, T]$, i.e., $\int_0^T c_l^2(t) dt = 1$, and the noise component n_k is Gaussian with zero mean and $E[n_k n_j] = \sigma^2$ when $j = k$, and $E[n_k n_j] = \sigma^2 \rho_{kj}$ when $j \neq k$.

Rx Signal at Relay Node R in Time Slot 1: The relay node R has a multistage PIC to detect the bits sent by all the source nodes in time slot 1. Let the received signal vector at the output of the qth stage of the PIC, $q > 1$, at the relay node R be denoted by $\mathbf{r}^{(t1)(q)} = \left[r_1^{(t1)(q)}\ r_2^{(t1)(q)}\ \cdots\ r_K^{(t1)(q)}\right]$, where the jth node's 1st stage output (i.e., MF output) is

$$r_j^{(t1)(1)} = A_j b_j + \sum_{i=1, i\neq j}^{K} \rho_{ij} A_i b_i + z_j. \tag{2}$$

The noise term z_j has the same statistics as n_k in (1). The jth node's estimated bit at qth stage output, denoted by $\widehat{b}_j^{(t1)(q)}$, is

$$\widehat{b}_j^{(t1)(q)} = \operatorname{sgn}\left(r_j^{(t1)(q)}\right), \tag{3}$$

where $r_j^{(t1)(q)}$, $q \geq 2$, is given by

$$r_j^{(t1)(q)} = \underbrace{r_j^{(t1)(1)}}_{\text{MF output}} - \underbrace{\sum_{i=1, i\neq j}^{K} \rho_{ij} \widehat{A}_i \widehat{b}_i^{(t1)(q-1)}}_{\text{MAI estimate}}, \tag{4}$$

and $\widehat{A}_i$ is the estimate of A_i. Using a $(m-1)$-stage PIC, $m \geq 2$, node R estimates the $(m-1)$th stage output bit vector

$$\widehat{\mathbf{b}}^{(t1)(m-1)} = \left[\widehat{b}_1^{(t1)(m-1)}\ \ \widehat{b}_2^{(t1)(m-1)}\ \ \cdots\ \ \widehat{b}_K^{(t1)(m-1)}\right]. \tag{5}$$

It sends this estimated bit vector $\widehat{\mathbf{b}}^{(t1)(m-1)}$ on K narrowband tones using BPSK modulation in time slot 2; $\widehat{b}_1^{(t1)(m-1)}$ is sent on tone f_1, $\widehat{b}_2^{(t1)(m-1)}$ is sent on tone f_2, and so on.

Rx Signal at Destination Node D_k in Time Slot 2: In time slot 2, D_k receives all $\widehat{b}_j^{(t1)(m-1)}$'s, $j \neq k$ on $(K-1)$ tones f_j's, $j \neq k$. Let these received bits be denoted by $\widehat{b}_j^{(t2)(m-1)}$'s, $j \neq k$.

Final Stage Cancellation/Detection at Node D_k: The destination node D_k, using its CDMA MF output $y_k^{(t1)}$ received during time slot 1, and the $\widehat{b}_j^{(t2)(m-1)}$'s, $j \neq k$ received during time slot 2 from node R, performs the final stage (i.e., mth stage) cancellation as

$$y_k^{(t2)} = y_k^{(t1)} - \sum_{j=1,\, j\neq k}^{K} \rho_{jk} \widehat{A}_j \widehat{b}_j^{(t2)(m-1)}. \tag{6}$$

The final bit decision is then made as

$$\widehat{\widehat{b}}_k = \operatorname{sgn}\left(y_k^{(t2)}\right). \tag{7}$$

1930-529X/07/$25.00 © 2007 IEEE
This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE GLOBECOM 2007 proceedings.

III. BER Analysis

In this section, we derive an exact expression for the BER of the proposed DIC scheme for $K = 2$ (i.e., a five-node network as shown in Fig. 1) and $m = 2$ (i.e., node R has only MFs) on AWGN channel.

Let (S_1, D_1) be the desired node pair; i.e., bit b_1 from node S_1 is the desired bit to be detected at node D_1, and bit b_2 from node S_2 is the interfering bit. The final bit decision at node D_1 in time slot 2 is given by

$$\widehat{b}_1^{(t2)} = \operatorname{sgn}\left(y_1^{(t1)} - \rho \widehat{A}_2 \widehat{b}_2^{(t2)(1)}\right), \quad (8)$$

where $\rho_{12} = \rho_{21} = \rho$,

$$y_1^{(t1)} = A_1 b_1 + \rho A_2 b_2 + n_1, \quad (9)$$

$$\widehat{b}_2^{(t2)(1)} = \operatorname{sgn}\left(A_2 \widehat{b}_2^{(t1)(1)} + \eta_2\right), \quad (10)$$

where η_2 is $\mathcal{N}(0, \sigma^2)$ is the noise variable at the narrowband BPSK receiver in D_1, and

$$\widehat{b}_2^{(t1)(1)} = \operatorname{sgn}\left(r_2^{(t1)(1)}\right) = \operatorname{sgn}\left(A_2 b_2 + \rho A_1 b_1 + z_2\right). \quad (11)$$

We assume that perfect amplitude estimates available. For notational simplicity, we define

$$\widehat{\widehat{b}}_1 \triangleq \widehat{b}_1^{(t2)}, \quad \widehat{b}_{2,1} \triangleq \widehat{b}_2^{(t1)(1)}, \quad \text{and } \widehat{b}_{2,2} \triangleq \widehat{b}_2^{(t2)(1)}.$$

The final bit decision in (8) can be written as

$$\widehat{\widehat{b}}_1 = \operatorname{sgn}\Big(A_1 b_1 + A_2(b_2 - \widehat{b}_{2,2})\rho + n_1\Big). \quad (12)$$

The final bit decision $\widehat{\widehat{b}}_1$ depends not only on b_1 and n_1, but also on the residual cancellation error $(b_2 - \widehat{b}_{2,2})$. This cancellation error is a nonlinear function via $sgn\big(A_2\widehat{b}_{2,1} + \eta_2\big)$ in (10), where $\big(A_2\widehat{b}_{2,1} + \eta_2\big)$, conditioned on $\widehat{b}_{2,1}$, is a Gaussian r.v. Similarly, $\widehat{b}_{2,1}$ is a nonlinear function of $r_2^{(t1)(1)}$ (see Eqn. (11)), where $r_2^{(t1)(1)}$ conditioned on b_1 and b_2 is a Gaussian r.v. The BER of node S_1's data received at node D_1, denoted by P_{e_1}, can be written using conditional expectations as

$$P_{e_1} = E_{b_1,b_2}\left[E_{n_1}\left[P\left(b_1 \neq \widehat{\widehat{b}}_1 \Big| b_1, b_2, n_1\right)\right]\right], \quad (13)$$

where $P\big(b_1 \neq \widehat{\widehat{b}}_1 \big| b_1, b_2, n_1\big)$ is the probability of error conditioned on a particular realization of b_1, b_2 and n_1, and $E_{n_1}[.]$ and $E_{b_1,b_2}[.]$ are the expectations over n_1 and $\{b_1, b_2\}$, respectively. A detailed derivation of the expectations in (13) is given in [6]. We can obtain final expression for the BER of user 1 as [6]

$$\begin{aligned} P_{e_1} &= Q\left(\frac{A_1 + 2A_2\rho}{\sigma}\right) \\ &+ \frac{1}{4}\Big\{ F(-A_1 - 2A_2\rho, -A_1; -A_2 - A_1\rho, \infty; -A_2, \infty) \\ &+ F(-A_1 - 2A_2\rho, -A_1; -\infty, -A_2 - A_1\rho; A_2, \infty) \\ &+ F(A_1, A_1 + 2A_2\rho; A_2 + A_1\rho, \infty; -\infty, -A_2) \\ &+ F(A_1, A_1 + 2A_2\rho; -\infty, A_2 + A_1\rho; -\infty, A_2) \\ &+ F(A_1, A_1 + 2A_2\rho; -A_2 + A_1\rho, +\infty; -A_2, \infty) \\ &+ F(A_1, A_1 + 2A_2\rho; -\infty, -A_2 + A_1\rho; A_2, \infty) \\ &+ F(A_1 - 2A_2\rho, A_1 + 2A_2\rho; -A_2 + A_1\rho, \infty; -\infty, -A_2) \\ &+ F(A_1 - 2A_2\rho, A_1 + 2A_2\rho; -\infty, -A_2 + A_1\rho; -\infty, A_2) \\ &+ F(-A_1 - 2A_2\rho, -A_1 + 2A_2\rho; A_2 - A_1\rho, \infty; -A_2, \infty) \\ &+ F(-A_1 - 2A_2\rho, -A_1 + 2A_2\rho; -\infty, A_2 - A_1\rho; A_2, \infty) \\ &+ F(-A_1 - 2A_2\rho, -A_1; A_2 - A_1\rho, +\infty; -\infty, -A_2) \\ &+ F(-A_1 - 2A_2\rho, -A_1; -\infty, A_2 - A_1\rho; -\infty, A_2)\Big\}, \quad (14) \end{aligned}$$

where

$$F(\alpha_1, \alpha_2; \beta_1, \beta_2; \theta_1, \theta_2) \triangleq \int_{\alpha_1}^{\alpha_2}\int_{\beta_1}^{\beta_2}\int_{\theta_1}^{\theta_2} f_{n_1}(n_1)\, f_{z_2}(z_2)\, f_{\eta_2}(\eta_2)\, d\eta_2\, dz_2\, dn_1, \quad (15)$$

$f_{z_2}(z_2) = \frac{1}{\sqrt{2\pi\sigma^2}}\, e^{-\frac{z_2^2}{2\sigma^2}}$ and $f_{\eta_2}(\eta_2) = \frac{1}{\sqrt{2\pi\sigma^2}}\, e^{-\frac{\eta_2^2}{2\sigma^2}}$ are the Gaussian pdfs of z_2 and η_2, respectively, and $Q(x)$ is given by $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{\frac{-t^2}{2}}\, dt$.

IV. Results and Discussions

In this section, we evaluate and present the bit error performance of the proposed DIC scheme and compare it with those of the MF detector as well as the centralized PIC.

DIC performance in AWGN: First, we evaluate the BER performance for the case of $K = 2$ in AWGN that was analyzed in the previous section. In Fig. 3, we plot the BER performance of the proposed DIC scheme as a function of SNR for $K = 2$, $\rho = 0.3$, $m = 2, 3$ on AWGN. In all the performance plots, the SNRs on the source-to-relay, source-to-destination and relay-to-destination links are taken to be the same. Note that $m = 2$ means that the relay node does bit estimation using the MF outputs (i.e., 1st stage) and the destination node performs the final stage (i.e., 2nd stage) of cancellation and bit detection. Likewise, $m = 3$ means that the relay node implements a 2-stage PIC and the destination node implements the 3rd stage of the PIC. For $m = 2$, both analytical results, evaluated through Eqn. (14), as well as simulation results are plotted. For comparison purposes, we also plot the performance of the MF as well as the centralized PIC. From Fig. 3, we observe the following:

- For $m = 2$, the analytical and simulation results for the proposed DIC match, which verifies the BER expression derived. Also, the DIC scheme performs much better than the MF detector. This is due to the distributed interference cancellation benefit in the proposed scheme.
- Comparing the performance of the proposed DIC with that of the centralized PIC, we see that the performance improvement in DIC compared to MF is not as high as that in the case of centralized PIC. This is because i) the bit estimates sent by the relay to the destination can be corrupted because of the relay-to-destination link being erroneous; at high SNRs this issue can be less severe, and ii) the noise variables involved in the distributed and centralized schemes are different. The performance improvement

1930-529X/07/$25.00 © 2007 IEEE
This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE GLOBECOM 2007 proceedings.

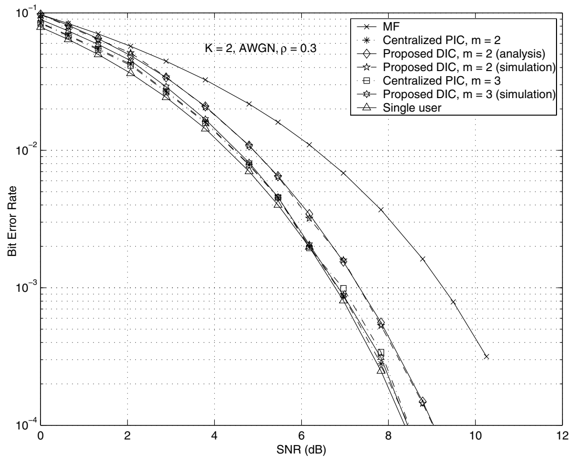

Fig. 3. BER performance of the proposed DIC scheme as a function of SNR for $K = 2$, $\rho = 0.3, m = 2, 3$ on AWGN channels.

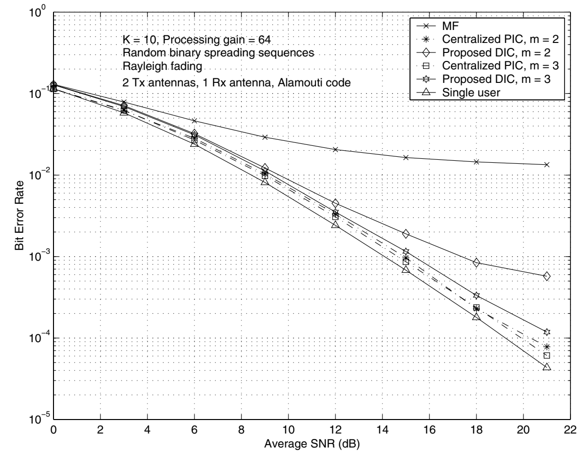

Fig. 4. BER performance of the proposed DIC scheme as a function of average SNR for $K = 10$ in Rayleigh fading channels using space-time coding. Processing gain = 64. Random binary spreading sequences. 2-Tx, 1-Rx antennas, Alamouti code.

in the proposed DIC can be further enhanced by employing more PIC stages at the relay node. This can be observed by comparing the DIC plots for $m = 2$ and 3 in Fig. 3, where performance for $m = 3$ is better than for $m = 2$. This is expected because doing more PIC stages in the relay node results in lesser residual (uncancelled) interference at the final cancellation stage output at the destination. The plot for $m = 3$ is obtained through simulations, as analysis for $m > 2$ is tedious.

DIC performance in fading with space-time codes: In Fig. 4, we present the simulated BER performance of the proposed DIC scheme with ten source-destination pairs (i.e., $K = 10$) for the case of Rayleigh fading with space-time coding. Random binary spreading sequences with processing gain 64 are used. We considered that each sender node has two transmit antennas and uses Alamouti code during Phase-1 of transmission. The relay node and destination nodes are assumed to have one receive antenna each (one can consider the relay and destination nodes to have more than one receive antenna, in which case higher order diversity can be achieved). We assume that the fades on all links are independent, quasi-static, and independent from one block to the other. Perfect knowledge of the fade coefficients are assumed at the receivers. From Fig. 4, we observe that the proposed DIC offers significant MAI cancellation benefit (see the error-floor being lowered for $m = 2, 3$ for the proposed DIC compared to MF performance), and performs close to that of the centralized PIC. In the above, we have considered centralized space-time codes (i.e., each sender node has multiple transmit antennas) with DIC. However, as future extension, one can consider investigation of the DIC approach in scenarios where distributed space-time codes (i.e., sharing of antennas among nodes) are used along with DIC.

Linear DIC: In the DIC scheme proposed above, the relay node makes use of a $(m-1)$-stage hard-decision (non-linear) PIC in Phase 1 and sends the estimated bits on narrowband tones in Phase-2. Alternately, the relay could use a linear PIC (LPIC) [7],[8] (which uses soft values of previous stage outputs in constructing the MAI estimates for cancellation in a given stage), and send the soft values of the $(m-1)$-th stage output to the destination nodes in Phase-2. We assume that these soft values reach the destination nodes perfectly.[2]. Using these soft values, the destination node performs the mth stage LPIC and makes the bit decision. This results in a linear DIC scheme, which is described below for AWGN channels[3].

Let $w_k^{(m-1)}$, $m \geq 2$, denote the kth user soft output at the $(m-1)$th stage LPIC in the relay node during Phase 1, which is given by [7],[8]

$$w_k^{(m-1)} = \underbrace{w_k^{(1)}}_{\text{MF output at } R} - \underbrace{\sum_{j=1, j\neq k}^{K} \rho_{jk} w_j^{(m-2)}}_{\text{MAI estimate at } R}, \qquad (16)$$

where the kth user MF output at relay node R, $w_k^{(1)}$, is given by

$$w_k^{(1)} \; = \; A_k b_k + \sum_{j=1, j\neq k}^{K} A_j b_j \rho_{jk} + z_k. \qquad (17)$$

The LPIC output in (16) can be written in a matrix algebraic form as [7]

$$\mathbf{w}^{(m-1)} \; = \; \underbrace{\sum_{j=1}^{m-1} \left(\mathbf{I} - \mathbf{R}\right)^{(j-1)}}_{\mathbf{G}^{(m-1)}} \; \mathbf{w}^{(1)}, \qquad (18)$$

where

$$\mathbf{w}^{(m-1)} \; = \; \left[w_1^{(m-1)} \; w_2^{(m-1)} \; \cdots \; w_K^{(m-1)}\right]^T, \qquad (19)$$

and the $K \times K$ cross correlation matrix $\mathbf{R}$ is given by

$$\mathbf{R} \; = \; \begin{bmatrix} 1 & \rho_{12} & \cdots & \rho_{1K} \\ \rho_{21} & 1 & \cdots & \rho_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{K1} & \rho_{K2} & \cdots & 1 \end{bmatrix}. \qquad (20)$$

Note that the MF output vector $\mathbf{w}^{(1)}$ can be written in the form $\mathbf{w}^{(1)} = \mathbf{R}\mathbf{x} + \mathbf{z}$, where $\mathbf{x} = [A_1 b_1, A_2 b_2, \cdots, A_K b_K]^T$, $\mathbf{z} = [z_1, z_2, \cdots, z_K]^T$, and $E[\mathbf{z}\mathbf{z}^T] = \sigma^2 \mathbf{R}$. Also, the $K \times K$ matrix $\mathbf{G}^{(m-1)}$ in (18) can be viewed as an equivalent one-shot linear matrix filter for the $(m-1)$th stage LPIC.

[2] In practice, these soft values can be quantized and sent. We have studied the effect of this quantization in our simulations. We find that a 6-bit quantizer as adequate which does not degrade the performance much compared to the ideal case (Fig. 5).

[3] Linear DIC for fading channels can also be investigated likewise as further extension.

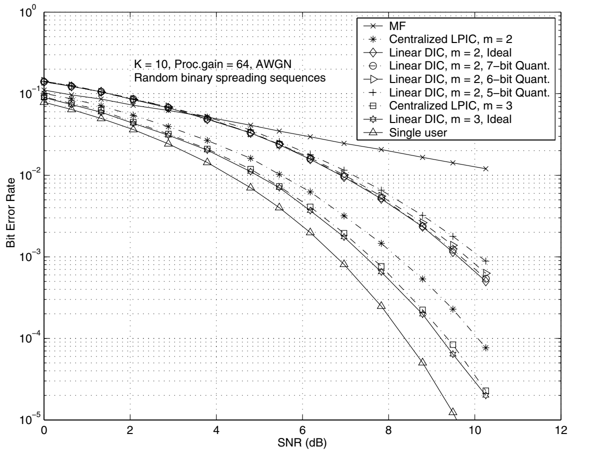

Fig. 5. BER performance of the linear DIC scheme as a function of SNR for $K = 10$ on AWGN channels. Processing gain = 64.

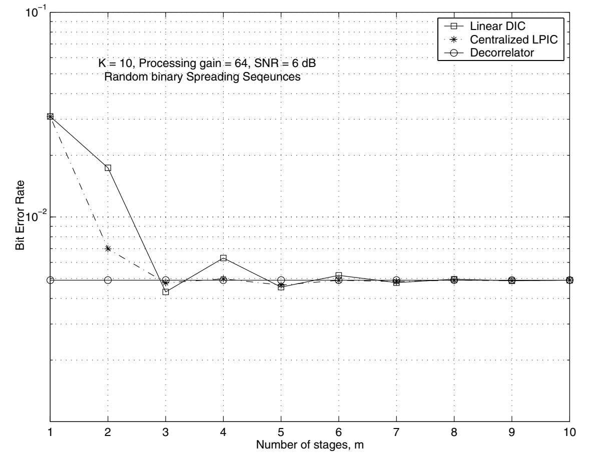

Fig. 6. BER performance of the linear DIC scheme as a function of the number of stages, m, for $K = 10$ on AWGN channels. SNR = 6 dB. Processing gain = 64.

In Phase 2, the relay node R transmits the $(m-1)$th stage soft output vector $\mathbf{w}^{(m-1)}$. The destination node D_k receives $\mathbf{w}^{(m-1)}$ and performs the mth stage LPIC. The mth stage cancelled output at node D_k, denoted by $v_k^{(m)}$, is obtained as

$$v_k^{(m)} = \underbrace{v_k^{(1)}}_{\text{MF output at } D_k} - \underbrace{\sum_{j=1, j\neq k}^{K} \rho_{jk} w_j^{(m-1)}}_{\text{MAI estimate at } D_k}, \qquad (21)$$

where $v_k^{(1)} = A_k b_k + \sum_{j=1,j\neq k}^{K} A_j b_j \rho_{jk} + n_k$ is the MF output at the destination D_k. Finally, the estimated bit at the destination D_k is obtained as $\widehat{\widehat{b}}_k = \text{sgn}\left(v_k^{(m)}\right)$. It is noted that the linear DIC output in (21) can be written in algebraic form as

$$\begin{aligned} \mathbf{v}^{(m)} &= \mathbf{v}^{(1)} + (\mathbf{I} - \mathbf{R})\mathbf{w}^{(m-1)} \\ &= \underbrace{\sum_{j=1}^{m} (\mathbf{I} - \mathbf{R})^{(j-1)}}_{\mathbf{G}^m} \mathbf{w}^{(1)} + \mathbf{n} - \mathbf{z}, \qquad (22) \end{aligned}$$

where $\mathbf{v}^{(m)} = \left[v_1^{(m)}, v_2^{(m)}, \cdots, v_K^{(m)}\right]^T$, $\mathbf{n} = [n_1, n_2, \cdots, n_K]^T$, $E[\mathbf{n}\mathbf{n}^T] = \sigma^2\mathbf{R}$, and $\mathbf{v}^{(1)} = \mathbf{R}\mathbf{x} + \mathbf{n}$.

Figure 5 shows the simulated BER performance of the linear DIC scheme for $K = 10$, random binary spreading sequences of length 64, and $m = 2, 3$ on AWGN channels. MF detector (i.e., $m = 1$) performance as well as single user (i.e., no interference) performance are also plotted. In addition, performance of centralized LPIC for $m = 2, 3$ are plotted for comparison. From these performance plots, we observe that, as with the nonlinear DIC, the linear DIC also provides the benefit of improved performance. It is noted that linear DICs have the advantage of not requiring the amplitude estimates at the receiver.

Convergence of Linear DIC for $m \rightarrow \infty$: In [7], it has been shown that the performance of the centralized LPIC in (18) approaches to that of the decorrelating (DC) detector [5] for $m \rightarrow \infty$, if the maximum eigenvalue of $\mathbf{R}$ is less than 2, i.e., $\mathbf{G}^{(\infty)} = \mathbf{R}^{-1}$ and $\mathbf{w}^{(\infty)} = \mathbf{x} + \mathbf{R}^{-1}\mathbf{z}$, where $E[(\mathbf{R}^{-1}\mathbf{z})(\mathbf{R}^{-1}\mathbf{z})^T] = \sigma^2\mathbf{R}^{-1}$. It can be shown that the linear DIC also converges to DC for $m \rightarrow \infty$, which can be seen as follows. Substituting $\mathbf{G}^{(\infty)} = \mathbf{R}^{-1}$ in (22), we can write

$$\mathbf{v}^{(\infty)} = \mathbf{R}^{-1}\mathbf{w}^{(1)} + \mathbf{n} - \mathbf{z} = \mathbf{x} + \underbrace{(\mathbf{R}^{-1} - \mathbf{I})\mathbf{z} + \mathbf{n}}_{\mathbf{N}}, \qquad (23)$$

where $E[\mathbf{N}\mathbf{N}^T] = \sigma^2\left[\mathbf{R}^{-1} + 2(\mathbf{R} - \mathbf{I})\right]$. It can be seen that the noise vectors $\mathbf{R}^{-1}\mathbf{z}$ (at LPIC output) and $\mathbf{N}$ (at linear DIC output) have the same statistics. So the linear DIC also converges to DC for $m \rightarrow \infty$. In Fig. 6, we plot the BER performance of the linear DIC as a function of stage index, m. The BER of the centralized LPIC and the DC are also plotted. We can see that, as with the centralized LPIC, the linear DIC also approaches the DC performance for large m, as shown above analytically.

V. Conclusion

We proposed a novel distributed interference cancellation approach, which exploited the cooperation extended by a MUD capable relay node in order to offer MUD benefits to low complexity nodes which have only a single user detection capability. Through BER analysis for a basic five-node network and simulations for more general system scenarios, we illustrated the effectiveness of the proposed distributed approach to interference cancellation. While this paper establishes the feasibility and usefulness of the distributed approach to MUD/IC, interesting extensions to this approach are possible; some such extensions include alternate DIC architectures, design and analysis of DIC techniques that combine virtual MIMO transmissions using distributed space-time coding, effect of imperfect channel knowledge, and performance vs complexity tradeoff studies.

References

[1] A. Sendonaris and E. Erkip, "User cooperation diversity - Part I: System aspects," *IEEE Trans. Inf. Theory,* vol. 49, pp. 2416-2425, October 2003.

[2] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory.,* vol. 50, no. 12, pp. 3062-3080, December 2004.

[3] T. E. Hunter and A. Nosratinia, "Diversity through coded cooperation," *IEEE Trans. Wireless Commun.,* vol. 5, no.2, pp. 283-289, February 2006.

[4] J. N. Laneman and G. W. Wornell, "Distributed space-time coded protocols for exploiting cooperative diversity in wireless networks" *IEEE Trans. Inf. Theory.,* vol. 49, no. 10, pp. 2415-2426, October 2003.

[5] S. Verdu, *Multiuser Detection,* Cambridge University Press, 1998.

[6] K. Raghu, "Distributed interference cancellation and MIMO detectors," M. E. Thesis, Wireless Res. Lab, Dept. ECE, Indian Institute of Science, Bangalore, India, July 2007. http://wrl.ece.iisc.ernet.in/Prep.html

[7] D. Guo, L. K. Rasmussen, S. Sun, and T. J. Lim, "A matrix algebraic approach to linear parallel interference cancellation in CDMA," *IEEE Trans. Commun.,* vol 48, no. 1, pp. 152-161, January 2000.

[8] V. Tikiya, S. Manohar, and A. Chockalingam, "SIR-optimized weighted linear parallel interference canceller on fading channels," *IEEE Trans. on Wireless Commun.*, vol. 5, no. 8, pp. 1998-2003, August 2006.

1930-529X/07/$25.00 © 2007 IEEE
This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE GLOBECOM 2007 proceedings.