Adaptive MMSE Multiuser Detection (A-MMSE-MUD) in Asynchronous Cooperative CDMA Networks

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***Abstract*—Asynchronous cooperative CDMA wireless network uplink transmission is examined in this paper, where users cooperate in a relaying mode while they exchange data and channel information with the base station to achieve diversity gains. MAI occurs at both the relays and destination due to asynchronous transmission and non orthogonality of spreading waveform. In order to deal MAI, A-MMSE-MUD is been used by bank of linear adaptive filters. Two protocols of cooperative communication wireless networks are used, (i) amplify and forward at relays and A-MMSE-MUD at destination, (ii) A-MMSE-MUD at the relays and destination in a decode and forward operation. We compared our result with other multiuser detection schemes under same conditions in a cooperative communication wireless network and found that the amplify and forward scheme in use of A-MMSE-MUD remove the MAI even amplification is been performed on the relays nodes. Where as decode and forward scheme outperform all other multiuser detection scheme. Simulation experiments shows both schemes amplify and forward and decode and forward with A-MMSE-MUD provide significant improvement in the bit error rate and capacity performance of the cooperative communication CDMA networks.**

I. INTRODUCTION

Fading problem occur in CDMA wireless communication transmission due to multipath propagation of waves and severe signal attenuation. Multiple input multiple output (MIMO)[1] antenna configuration has been used from decades to overcome fading problem by sending multiple version of the original signal. Cooperative communication wireless network is a virtual MIMO scheme [2][3][4], where each node of the wireless network acts as a antenna element of MIMO system.

In this paper cooperative wireless CDMA network's adaptive multiuser detection (A-MUD) is examined with two cooperative protocols Amplify and Forward [5] and Decode and Forward [4]. Multiuser detection (MUD) deals with the de-modulation of digitally modulated signals in the presence of multiuser access (MAI) interference. Early MUD schemes presented for non cooperative CDMA networks [6][7][8][9][10][11] and later for cooperative communication wireless networks[3][4][12] are used to mitigate MAI. Adaptive MMSE Multiuser Detection (A-MMSE-MUD) is shown in [13] and specifically for single user cooperative systems in [14] by means of decision feedback estimation and soft decision at relays node.

The motivation of this paper is to present cooperative communication wireless network in use of A-MMSE-MUD to eliminate MAI with Amplify and Forward and Detect and Forward schemes and their performance analysis. A-MMSE-MUD receivers are capable of estimating the system parameters such as signal delay/timing, signal phase, signal amplitude, signatures, multi-path channel profile and the number of users in CDMA system by a training routine operated by the transmitter. The cooperative schemes shown in and analyzed in this paper:

- A simple A-MUD technique's presented and its simulation performance examine to eliminate MAI in cooperative communication CDMA network.
- An Amplify and Forward strategy is used at the relays and A-MMSE-MUD decode at the destination, in an asynchronous cooperative communication network. This system's BER performance is about 10^{-3} at a SNR of $10dB$ while the channel capacity performance of the system is nearly $4bits/s/Hz$ at the same SNR and this system's BER performance is about 10^{-5} at a SNR of $20dB$ while the channel capacity performance of the system is nearly $8bits/s/Hz$ at the same SNR.
- An A-MMSE-MUD Decode and Forward strategy is used at the relays and A-MMSE-MUD decode at the destination, in an asynchronous cooperative communication network. This system's BER performance is about 10^{-4} at a SNR of $10dB$ while the channel capacity performance of the system is nearly $6bits/s/Hz$ at the same SNR and this system's BER performance is about 10^{-5} at a SNR region of $17dB$ while the channel capacity performance of the system is nearly $9bits/s/Hz$ at the same SNR.

The rest of the paper is organized as follows: The model for a cooperative communication CDMA system is given is Section II. A-MMSE-MUD for the cooperative communication networks is in Section III and performance comparisons by computer simulation are shown in Section IV. Finally, concluding remarks are given in Section V.

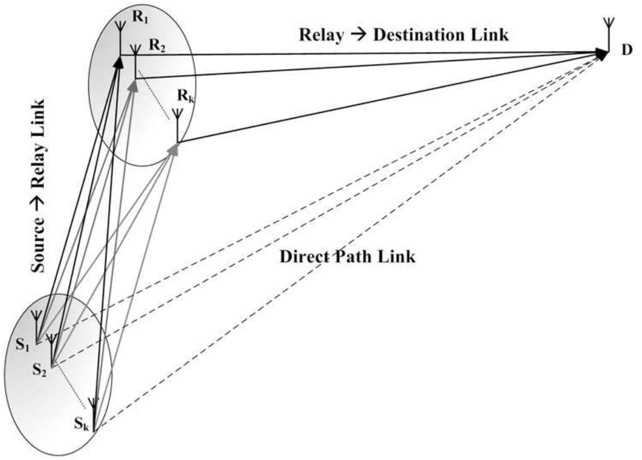

Fig. 1. General System Model

II. SYSTEM MODEL

Consider K users, denoted by $S_1, S_2, ..., S_K$, serve as sources and L users, denoted by $R_1, R_2, ..., R_L$ serve as relays[3][12]. All sources broadcast data to relays and destination where further processing by amplification to boost the signal power or MUD is performed to detect the signal, for further transmission to destination node for MUD as shown in Fig. 1 A typical cooperation strategy can is modeled with two orthogonal phases, to avoid interference between the two phases in following subsections [15].

A. Phase I (a): Transmission from Sources to Destination (Direct Path Link)

In Phase I (a), each source 'K' transmit a message with M data symbols to the destination 'D'. Let $\mathbf{x}[m] = [x_1[m], ..., x_K[m]]^\dagger$ be the BPSK data symbols transmitted by sources $S_1, S_2, ..., S_K$ during the m^{th} symbol period, where $\mathbf{x}_k[m] = \{-1, 1\}$ and

$$\begin{aligned}\mathcal{E}[\mathbf{x}[m]\mathbf{x}[p]^\dagger] &= \mathbf{I}_{(K\times K)}, \qquad if\ \ m = p\\ &= \mathbf{O}_{(K\times K)}, \quad otherwise\end{aligned}$$

Where "**I**" represents identity matrix and "**O**" represents null matrix of the order of $K \times K$. Let P_{S_k} be the power transmitted by source S_k and let $\mathbf{s}_k(t)$ be the spreading wave form (signature) of S_k. Under the asynchronous CDMA signal assumption, the signal received at the destination node in the presence of additive white Gaussian noise may be expressed as

$$y_I(t) = \sum_{m=1}^{M}\sum_{k=1}^{K} h_{S_kD}(\sqrt{P_{S_k}})x_k[m]s_k(t - mT - \tau_k) + v_I(t) \tag{1}$$

Where T is symbol period, h_{S_kD} is the complex channel coefficient from S_k to D and τ_k is the transmission delay of the k^{th} user. We assume a block fading environment where channel coefficient remain constant of the M-symbol block and are independent and identically distributed (i.i.d)from block to block. The channel coefficient h_{S_kD} is assumed to be circularly symmetric complex Gaussian with zero mean and variance $\sigma^2_{S_kD}$ (ZMCSCG) , i.e., $h_{S_kD} \sim \mathcal{CN}(0, \sigma^2_{S_kD})$, and is assumed to be independent among sources. And $v_I(t)$ is the additive white Gaussian noise (AWGN) with distribution $\mathcal{CN}(\mathbf{O}_{K\times 1}, \sigma_v^2\mathbf{R})$. If N is the spreading gain, the spreading gain waveform for S_k is given by

$$S_k(t) = 1/\sqrt{N}\sum_{i=1}^{N} c_k(t)\psi(t - iT_c), k = 1, 2..., K \tag{2}$$

where $c_k(i)$ is the i^{th} element of the ± 1 spreading sequence assigned to S_k, and $\psi(t)$ is the normalized chip T_c wave form with unit energy and duration $T_c = T/N$. Here T is symbol duration. The digital signal obtained at the input of decision device after minimization of error through adaptive filters during the m^{th} symbol period in Phase I is denoted by $y_I[m]$. The $y_I[m]$ adaptive filters output is analyzed in section III. Obtained entire symbol block is denoted by

$$\mathbf{Y}_I = [y_I[1], ..., y_I[M]] \tag{3}$$

B. Phase I (b) Transmission from Sources to Relays (Source Relay Link)

Each source broadcast the message with M data symbols to the relays $R_1, R_2, ..., R_L$. The signal observed at the adaptive MMSE filters bank of ℓ^{th} relay during the m^{th} symbol period for the decode and forward scheme is given by

$$y'_I(t) = \sum_{m=1}^{M}\sum_{k=1}^{K} h_{S_kR_\ell}(\sqrt{P_{S_k}})x_k[m]s_k(t - mT - \xi_k) + v'_I(t) \tag{4}$$

Where T is symbol period, $h_{S_kR_\ell}$ is the complex channel co-efficient from S_k to R_ℓ and ξ_k is the transmission delay assumed for the k^{th} user at ℓ^{th} relay. The channel coefficient $h_{S_kR_\ell}$ is assumed to be circularly symmetric complex Gaussian with 0 mean and variance $\sigma^2_{S_kR_\ell}$ (ZMCSCG) , i:e, $h_{S_kR_\ell} \sim \mathcal{CN}(0, \sigma^2_{S_kR_\ell})$, and is assumed to be independent among sources. And $v'_I(t)$ is the additive white Gaussian noise (AWGN) with distribution $\mathcal{CN}(\mathbf{O}_{K\times 1}, \sigma_v^2\mathbf{R})$ The signal obtained at the input of decision device after minimization of error through adaptive filters during the m^{th} symbol period given in Phase I(b) is denoted by $y'_I[m]$. The $y'_I[m]$ adaptive filters output is analyzed in section III and obtained entire symbol block is denoted by

$$\mathbf{Y}'_I = [y'_I[1], ..., y'_I[M]] \tag{5}$$

Let the symbols detected on ℓ^{th} relay is given by

$$\hat{\mathbf{X}}_\ell = [\hat{x}_\ell[1], ..., \hat{x}_\ell[M]] \tag{6}$$

C. Phase II Transmission from Relays to Destination (Relay Destination Link)

In this phase the ℓ^{th} relays forward the detected data symbols with same spreading sequence of respective sources to destination. Let assume that the detected symbols $\hat{\mathbf{X}}_\ell$ in previous section may be re-encoded into K by M symbol matrix $\mathbf{T}_\ell = f(\hat{\mathbf{X}}_\ell) = [t_\ell[1], t_\ell[2]..., t_\ell[M]]$ Where $\mathbf{t}_\ell[m] = [t_{\ell,1}[m], t_{\ell,2}[m]..., t_{\ell,K}[m]]^\dagger$ is the symbol vector transmitted by R_ℓ during the m^{th} symbol when transmit beam forming [12] is considered at relays for further transmission to destination, $\mathbf{t}_\ell[m]$ depends on the detected symbol $\hat{\mathbf{X}}_\ell$. The observation signal on bank of adaptive filters bank at destination through relays is given by

$$y_{II}(t) = \sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{\ell=1}^{L} h_{S_\ell D}(\sqrt{P_{R_\ell}}) t_{\ell,k}[m] s_k(t-mT-\zeta_\ell)+v_{II}(t) \tag{7}$$

Where T is symbol period, $h_{R_l D}$ is the complex channel co-efficient from R_ℓ to D and ζ_ℓ is the transmission delay of the ℓ^{th} relay. The channel coefficient $h_{R_\ell D}$ is assumed to be circularly symmetric complex Gaussian with zero mean and variance $\sigma^2_{R_\ell D}$ (ZMCSCG) , i.e., $h_{R_\ell D} \sim \mathcal{CN}(0, \sigma^2_{R_\ell D})$, and is assumed to be independent among relays. And $v_{II}(t)$ is the additive white Gaussian noise (AWGN) with distribution $\mathcal{CN}(\mathbf{O}_{K\times 1}, \sigma_v^2\mathbf{R})$ The signal obtained at the input of decision device after minimization of error through adaptive filters during the m^{th} symbol period given in Phase II(b) is denoted by $y_{II}[m]$. The $y_{II}[m]$ adaptive filters output is analyzed in section III. Obtained entire symbol block is denoted by

$$\mathbf{Y}_{II} = [y_{II}[1], ..., y_{II}[M]] \tag{8}$$

For amplify and forward, amplification performed at relays to forward the received signals for MUD at destination therefore the observation signal of equation (3) is multiplied by amplification factor γ.

III. A-MMSE-MUD FOR THE COOPERATIVE COMMUNICATION NETWORKS

In this section for the mathematical analysis, all bold text letter are matrices and others are scalar integers. These type of signal processing mathematical analysis has been presented for channel precoding in [12].

In A-MMSE-MUD we replace the bank of matched filters with A-MMSE filters for channel estimation and detection. We adopt an alternative approach instead of the conventional for the detecting the signal by using matched filter for each signal by ignoring the correlation between signals of different users. In single user detection every matched filter receiver is equivalent to A-MMSE receiver [13][8] but for the multiple user bank of matched filter performance degrade non linearly.

If $r_n(t)$ is received analogue symbol of duration T at the input of a adaptive filter on n^{th} node (relay or destination) and $\mathbf{r}_n[m]$ respective received digital output of the symbol from the output in chip interval T_c. In wireless communication environment non orthogonal transmitted signals from independent users arrives asynchronously at the receivers [14].The delay cause further increase in non orthogonality of the spreading codes and the existing correlation due to non orthogonality of spreading sequence further increase at receiver. The coefficient of correlation matrix $\mathbf{R}$ is given by

$$\mathbf{R} = \mathcal{E}[\mathbf{r}_n\mathbf{r}_n^*[m]] = \varrho(N, N)$$

Subscript n in following equations represent specific number of adaptive filter in the network for k^{th} user. The digital output for the m^{th} symbol period on relays or destination node is given by

$$\mathbf{r}_n[m] = \mathbf{RH}x_n[m] + \mathbf{v}_n[m] \tag{9}$$

Here $\mathbf{R}$ given by:

$$\mathbf{R} = \begin{pmatrix} \varrho(1,1) & \varrho(1,2) & ... & \varrho(1,N) \\ \varrho(2,1) & \varrho(2,2) & ... & \varrho(2,N) \\ ... & ... & ... & ... \\ \varrho(N,1) & \varrho(N,2) & ... & \varrho(N,N) \end{pmatrix} \tag{10}$$

The matrix $\mathbf{R}$ is Hermitian and can be uniquely defined by specifying the values of the correlation co-efficient $\varrho(N, N)$.

The error between the reference signal(training sequence) and the output of m^{th} symbol of the n^{th} adaptive filter is given by:

$$\epsilon_n = (x_n[m] - \hat{x}_n[m]) \tag{11}$$

where $\hat{x}_n[m]$ is the signal estimated at the receiver and is given by $\hat{x}_n[m] = \mathbf{a}_n^H[m]\mathbf{r}_n[m]$.

Here $\mathbf{a}_n^H[m]$is α dimensional complex valued weight vector of m^{th} symbol. $\mathbf{a}_n[m] = [a^1, a^2......., a^N]_n$ and $\mathbf{r}_n[m] = [r^1, r^2........., r^N]_n$ and superscript N represent the tap of filter equal to spreading gain. During the adaptation mode the weight parameters are adjusted such that mean square error J_{a_n} is minimized in m^{th} symbol time. For simplicity m is with every term but we are not mentioning it in following equations for simplicity. Mean square error is given by:

$$J_{a_n} = \mathcal{E}[\epsilon_n\epsilon_n^*] \tag{12}$$

$$J_{a_n} = \mathcal{E}[(x_n - \mathbf{a}_n^H\mathbf{r}_n)][(x_n - \mathbf{a}_n^H\mathbf{r}_n)^*] \tag{13}$$

$$J_{a_n} = \mathcal{E}[x_nx_n^*] + \mathbf{a}_n^H\mathcal{E}[\mathbf{r}_n\mathbf{r}_n^H]\mathbf{a}_n - \mathbf{a}_n^H\mathcal{E}[\mathbf{r}_nx_n^*] - \mathcal{E}[x_n\mathbf{r}_n^H]\mathbf{a}_n \tag{14}$$

The first term $\mathcal{E}[x_nx_n^*]$ in equation (14), represents the variance of the desired signal. The expectation $\mathcal{E}[\mathbf{r}_n\mathbf{r}_n^H]$ represents the $N \times N$ correlation matrix $\mathbf{R}$, earlier mentioned in equation (10). Let the third term is given by $\mathbf{Z} = \mathcal{E}[\mathbf{r}_nx_n^*]$. It is $N \times 1$ cross-correlation matrix vector between the received components and the reference sequence. And the forth term is given by

$$\mathcal{E}[x_n\mathbf{r}_n^H] = \mathbf{Z}^H$$

Differentiating the mean squared error function J_{a_n} with respect to each coefficient of the weight vector a_n yields the gradient ∇_n. The optimal weight vector $\mathbf{a}_n^{opt}$ can be determined by setting the gradient ∇_n equal to zero:

$$\nabla_n = -2\mathbf{Z} + 2\mathbf{Ra}_n = 0 \tag{15}$$

where 0 is an α by 1 is null vector at the minimum point of the error surface, the A-MMSE-MUD is optimum in the mean squared error sense, and equation can be simplified in the form

$$\mathbf{Ra}_n^{opt} = \mathbf{Z} \tag{16}$$

which is a Wiener-Hopf or normal equation, where the vector representing the estimation error is normal to the vector representing the output of the filter. One possible solution of this equation is matrix inversion,as follows:

$$\mathbf{a}_n^{opt} = \mathbf{R}^{-1}\mathbf{Z} \tag{17}$$

Another simple solution that does not require matrix inversion or explicit calculations of the correlation coefficient is the steepest decent method (SDM). The SDM is recursive procedure that can be used to calculate the optimal weight vector $\mathbf{a}_n^{opt}$. Let $\mathbf{a}_n$ and ∇_n denote the values of the weight vector and the gradient vector within the m^{th} symbol period, respectively. Then succeeding values of the weight vector are obtained by the recursive relation. After each symbol period number m the weight of the filter updated till optimum coefficient obtained. After obtaining the optimum coefficient adaptive filter either setting a threshold on Mean Square Error or on cross-correlation value, adaptive filter match the symbol in decision directed mode. Therefore,

$$\mathbf{a}_n = \mathbf{a}_n - \mu\nabla_n \tag{18}$$

Where μ is step size constant that controls stability and the rate of adaptation. If we express ∇_n in terms of instantaneous estimates $\hat{\mathbf{Z}} = \mathbf{r}_n x_n^*$ and $\hat{\mathbf{R}} = \mathbf{r}_n\mathbf{r}_n^H$ Then the equation can be simplified as LMS algorithm

$$\mathbf{a}_n[m+1] = \mathbf{a}_n[m] + 2\mu\mathbf{r}_n[m][x_n^*[m] - \mathbf{r}_n^H[m]\mathbf{a}_n[m] \tag{19}$$

which can be expressed in term of $\epsilon_n^*[m]$ as,

$$\mathbf{a}_n[m+1] = \mathbf{a}_n[m] + 2\mu\mathbf{r}_n[m]\epsilon_n^*[m] \tag{20}$$

Where $m = 1, 2, 3........$

This equation tells that the updated weight vector is computed from the current weight vector by adding the input vector scaled by the complex conjugate value of the error and by μ which control the size of correction. And approximate optimum weight of the filter obtained. The signal at the input of decision device after minimization of error through n^{th} adaptive filters during the m^{th} symbol period given for any phase is denoted by $\hat{x}_n[m]$. And for entire symbol block, comparable with equations (3),(5),(6) and (8) is given by

$$\hat{\mathbf{X}}_n = [\hat{x}_n[1], \hat{x}_n[2]....., \hat{x}_n[M]] \tag{21}$$

Simulated Bit Error Rate (BER) performance is computed by apply hard decision decoding to receive data stream at the output of the adaptive filter. The capacity performance in simulation of system in terms of the output minimum mean square error (MMSE) is given by following equation [8]

$$C = \frac{1}{2}\log\frac{1}{\epsilon_o} \tag{22}$$

Here C is capacity and ϵ_o is the output MMSE.

IV. PERFORMANCE COMPARISON AND NUMERICAL SIMULATIONS

A. Simulation System Model

Our simulation are aimed at determining the performance of AMUD for decode and forward and amplify and forward schemes in multi-user Raleigh flat fading environment. The following conditions exist in all simulations: a) Uncoded coherent BPSK is used for modulation b) Cooperative communication CDMA network is consider with two user and two relays c) Independent fading characteristics on each channel d) The training sequences are generated independently using uniformly distributed pseudo-random number generators e) The noise on each channel is additive Gaussian random variable with zero mean and a variance σ. f) We used bank of adaptive transversal finite impulse response filters for the A-MMSE-MUD and used LMS algorithm for minimization of error g) Spreading gain is 16 both at relay and destination h) Transmit beam forming used at relays[12] i)Equal gain combinig used for combining the direct path link and relay destination link transmission j) zero forcing precoding [12] scheme used for comparison of result at relays.

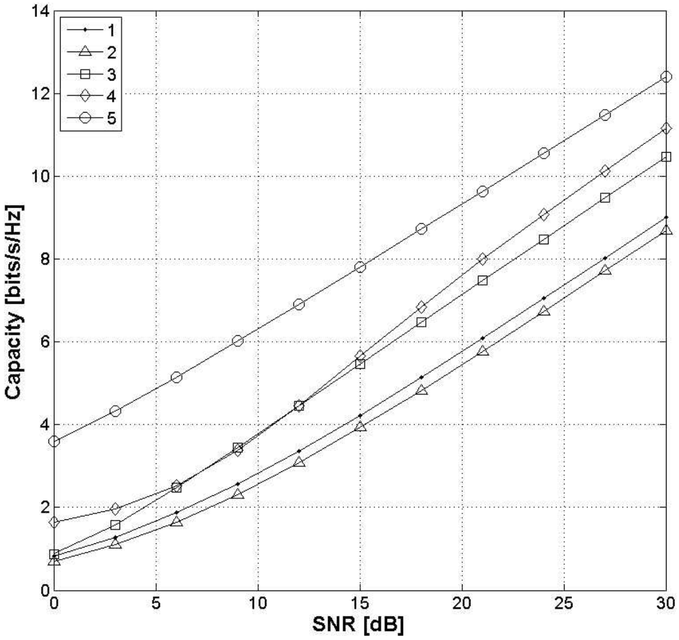

Fig. 2. Ergodic Capacity for two user channel:

1) Two Cooperative Nodes; Precoding at relay; match filtering at Destination.
2) Two Cooperative Nodes; Amplify Forward; match filtering at Destination.
3) Two Cooperative Nodes; Decode and Forward; match filtering at Relay and Destination Node.
4) Two Cooperative Nodes; Amplify Forward; AMUD at Destination.
5) Two Cooperative Nodes; AMUD at Relay and Destination Node.

B. Simulation Results

Fig.2 demonstrates the capacity performance results of two sources and two relays cooperative system where bank of matched filters approach in contrast to the A-MMSE-MUD approach is simulated. It is observed that A-MMSE-MUD at relay and destination approach achieves a channel capacity of

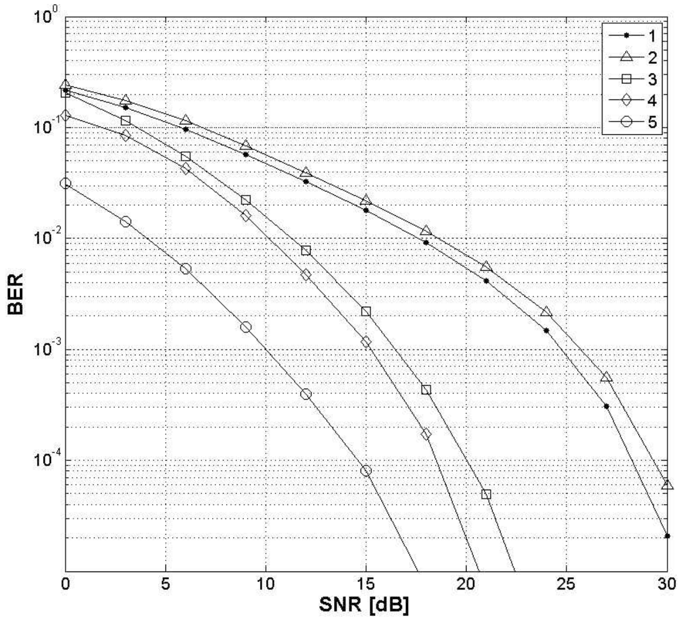

Fig. 3. Probability of Bit Error for two user channel:

1) Two Cooperative Nodes; Precoding at relay; match filtering at Destination.
2) Two Cooperative Nodes; Amplify Forward; match filtering at Destination.
3) Two Cooperative Nodes; Decode and Forward; match filtering at Relay and Destination Node.
4) Two Cooperative Nodes; Amplify Forward; AMUD at Destination.
5) Two Cooperative Nodes; AMUD at Relay and Destination Node.

about 8 bits/s/Hz at 15dB of signal to noise ratio (SNR) where as amplify and forward matched filtering and matched filtering with precoding approach provide 4 bits/s/Hz at the same SNR. It is clearly observed that amplify and forward with A-MMSE-MUD at destination node and decode and forward and matched filtering have same performance on different SNR. Therefore, A-MMSE-MUD is effective even amplification perform at relays.

We obtained consistence result for capacity of the system, demonstrated in Fig. 3 where the BER performance results of two sources and two relays cooperative system analyzed. Bank of matched filters approach in contrast to the A-MMSE-MUD approach is simulated. It is observed that A-MMSE-MUD at relay and destination approach achieves BER performance of about 10^{-4} at 15dB of signal to noise ratio (SNR) where as amplify and forward matched filtering and matched filtering with precoding approach provide 10^{-2} at the same SNR. It is clearly observed that amplify and forward with A-MMSE-MUD at destination node and decode and forward and matched filtering have same performance on different SNR. Therefore, A-MMSE-MUD is effective even amplification perform at relays.

V. CONCLUSIONS

This paper present a decentralized approach of asynchronous cooperative communication CDMA networks with an A-MMSE-MUD technique to eliminate MAI. Two protocols of cooperative communication Amplify and Forward and Detect and Forward examined in use with A-MMSE-MUD. Our computer experiment shows that Decode and forward out perform all other schemes to mitigate the MAI on each node of the wireless network where as Amplify and Forward in use with A-MMSE-MUD performance is better then other multiuser detection schemes even amplification is been performed on relay nodes. With presented A-MMSE-MUD we can improve the performance of cooperative communication wireless networks considerably. Further investigation and detailed performance analysis are needed for the presented system.

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