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REGULARIZED OPTIMUM BEAMFORMING FOR DOWNLINK CDMA SYSTEMS

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Abstract—In this paper, we propose an efficient receiver scheme to mitigate the effects of multiple access interference (MAI) and intersymbol interference (ISI) in downlink CDMA systems. This scheme comprises beamforming at the base station and a regularized zero forcing equalizer at the mobile unit. Beamforming is used to reduce the effect of the MAI. Then, a regularized zero forcing equalizer is used to reduce the effect of ISI and provide a better estimate of the data of interest. The performance of the proposed scheme is studied and compared with other traditional schemes. The simulation results show that the proposed scheme has a better performance than the other traditional schemes with a low degree of complexity at the mobile unit.

1. INTRODUCTION

Future wireless communication systems will be characterized by high data rate services accessible for a large number of users. Especially the downlink must be able to cope with considerable traffic loads in order to facilitate new multi-media information services like wireless internet or video on demand. In this context, downlink beamforming with cell-site antenna arrays is a promising means to improve the over-all system capacity and to overcome the limited bandwidth problem [1].

Beamforming is a one of the smart antenna techniques to improve the performance of the wireless mobile communication systems. It consists of an array of antennas weighted by a digital signal processing algorithm to adaptively direct the main beam of the array towards the desired user and its nulls towards the interferers and so improve the signal reception and transmission. There are many beamforming criteria such as minimum mean square error (MMSE), maximum signal to noise ratio (MSNR), maximum signal to interference and noise ratio (MSINR), and minimum variance distortionless response (MVDR) [2–5]. With the proper selection of the beamforming criterion, it is possible to point the beam towards the direction of the desired user and place nulls in the direction of the interferers. In this paper, we will use the MVDR algorithm.

The main idea of the MVDR algorithm is to find the weight vector which minimizes the total received/transmitted power except the power coming from/directed to the directions of interest [5]. Beamforming is usually called spatial processing or spatial filtering and it can be applied at both the uplink and the downlink. In any communication systems, especially data supported ones; the downlink transmission quality is of more interest than the uplink transmission quality. So, we concentrate here on the downlink beamforming as an efficient technique to improve the performance of any mobile communication system such as the CDMA system. Although downlink beamforming highly mitigates the MAI, the multi path environment causes an ISI that results from the channel delay spread and an MAI that results from the orthogonality destruction of users' spreading codes. So, there is a necessity for time processing to mitigate the ISI and the MAI and to improve the quality of transmission. We use linear equalization to mitigate the ISI and MAI effects.

This combination of downlink beamforming and equalization efficiently suppresses the different kinds of interference and so improves the performance of CDMA systems. In the previous work on the combination of downlink beamforming and equalization, the beamforming and equalization were applied at the mobile unit. It needs antenna array systems and the complexity of the mobile unit will be more complicated. So, we suggested performing the downlink beamforming at the base station and the equalization at the mobile unit.

The main contribution of this paper is the introduction of a hybrid scheme of beamforming at the base station and the equalization at the mobile unit. In this paper, time division duplexing CDMA (TDD/CDMA) is used. Thus, the calculated uplink beamforming weights will be applied for downlink beamforming. A low complexity implementation of this scheme is studied. In the proposed scheme, the estimation of the signal to noise ratio (SNR) is not required for the equalization implementation.

The rest of the paper is organized as follows: Sections 2 and 3 briefly review the beamforming and equalization. In Section 4, we explain our proposed scheme. The simulation results are discussed in

Section 5. Finally, we conclude the paper in Section 6. Throughout the paper, we use $(\ )^H$, $(\ )^T$, $E(\ )$ and $(\ )^{-1}$ as complex conjugate transpose of a matrix, transpose of a matrix, the expectation of random process, and inverse of a matrix, respectively. Vectors are represented in boldface lowercase and matrices in boldface uppercase.

2. BEAMFORMING

Beamforming is the most common spatial processing technique that an antenna array can utilize. In a cellular system, the desired and the interfering signals originate from different spatial locations. This spatial separation is exploited by a beamformer which can be regarded as a spatial filter separating the desired signal from the interference. The signals from different antenna elements are weighted and summed to optimize the quality of the signal. Figure 1 illustrates the idea of the beamforming [2–5]. With the proper selection of the beamforming criterion, it is possible to point the beam towards the direction of the desired user and/or place nulls in the direction of the interferers. If we have K total signals with distinct Angle of Arrival (AoA) impinging on an antenna array consisting of N elements, the received signal vector

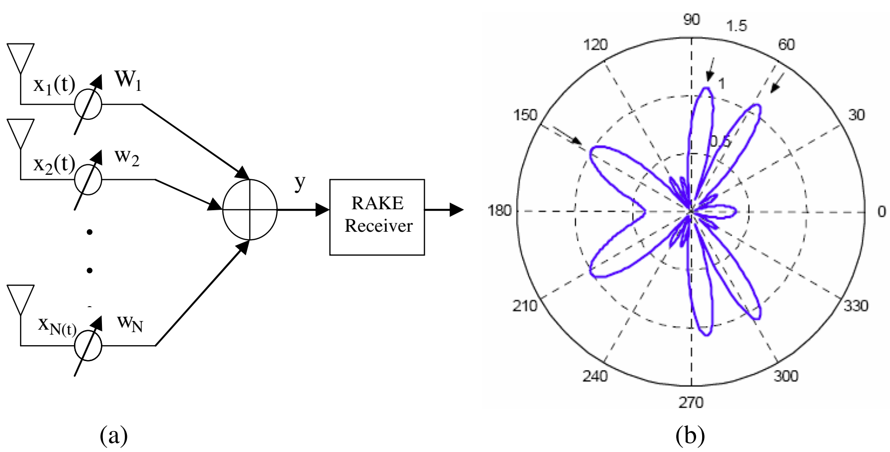

Figure 1. Beamforming (a) Beamformer principle for frequency selective channels (b) The beamforming characteristic of the multipath MVDR algorithm for a single user.

can be written as:

$$\mathbf{x}(t) = \sum_{i=1}^{K} \mathbf{s}_i(t)\mathbf{a}(\theta_i) + \mathbf{n}(t) \tag{1}$$

where $\mathbf{s}_i(t)$ is the ith signal with an AOA of θ_i, a (θ_i) is the $N \times 1$ antenna response vector for the AOA of θ_i and $\mathbf{n}(t)$ is the thermal noise vector. The output of the antenna array is given by

$$\mathbf{y}(t) = \mathbf{w}^H \mathbf{x}(t) \tag{2}$$

Here $\mathbf{w} = [w_1 \;\; w_2 \;\; \ldots \;\; w_N]^T$ is an $N \times 1$ weight vector. The weight vector is chosen to optimize some beamforming criterion. Popular adaptive beamforming algorithms include the MMSE, the MSINR, the MSNR, and the MVDR algorithms [4]. Here, we will discuss the MVDR algorithm that is used in our work.

The MVDR is a very well known algorithm to obtain the optimum weight vector which maximizes the output signal to noise and interference ratio (SNIR) of multiple antennas. The main idea of the MVDR algorithm is to find the weight vector which minimizes the total received power except the power coming from directions of interest. In the MVDR algorithm, we need to know the AoA of the desired user's paths. There are several techniques to estimate the AoAs of users, such as the MUSIC and ESPRIT methods [5–7].

The problem as analyzed in [5] is to minimize the total received/transmitted power except from/to certain directions:

$$\text{Min}\left\{ E\left|\mathbf{y}(t)\right|^2 \right) \quad \text{subject to} \quad \begin{array}{c} \mathbf{w}^H\mathbf{a}_1 = 1 \\ \mathbf{w}^H\mathbf{a}_2 = 1 \\ \vdots \\ \mathbf{w}^H\mathbf{a}_M = 1 \end{array} \tag{3}$$

where $\mathbf{y}(t)$ is the output of the beamformer, M is the number of paths per user.

This constrained optimization problem is solved using Lagrange Multiplier method to obtain the optimum weights:

$$\mathbf{w}_i^H = \mathbf{1}\mathbf{A}_i^{-1}\hat{\mathbf{a}}\mathbf{R}_{xx}^{-1} \tag{4}$$

where

$$\mathbf{1} = [\ 1\ \ 1\ \ \ldots\ \ 1\ ]^T \quad \text{is} \quad M*1 \quad \text{vector of ones}$$

$$\mathbf{A}_i = \begin{bmatrix} \mathbf{a}_{i,1}^H \mathbf{R}_{xx}^{-1} \mathbf{a}_{i,1} & \mathbf{a}_{i,2}^H \mathbf{R}_{xx}^{-1} \mathbf{a}_{i,1} & \ldots & \mathbf{a}_{i,M_i}^H \mathbf{R}_{xx}^{-1} \mathbf{a}_{i,1} \\ \mathbf{a}_{i,1}^H \mathbf{R}_{xx}^{-1} \mathbf{a}_{i,2} & \mathbf{a}_{i,2}^H \mathbf{R}_{xx}^{-1} \mathbf{a}_{i,2} & \ldots & \mathbf{a}_{i,M_i}^H \mathbf{R}_{xx}^{-1} \mathbf{a}_{i,2} \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{a}_{i,1}^H \mathbf{R}_{xx}^{-1} \mathbf{a}_{i,M_i} & \mathbf{a}_{i,2}^H \mathbf{R}_{xx}^{-1} \mathbf{a}_{i,M_i} & \ldots & \mathbf{a}_{i,M_i}^H \mathbf{R}_{xx}^{-1} \mathbf{a}_{i,M_i} \end{bmatrix} \tag{5}$$

$$\hat{\mathbf{a}} = \begin{bmatrix} \mathbf{a}_{i,1}^H \\ \mathbf{a}_{i,2}^H \\ \cdot \\ \cdot \\ \cdot \\ \mathbf{a}_{i,M_i}^H \end{bmatrix} \tag{6}$$

where $\mathbf{w}_i$ and $\mathbf{a}_{i,M_i}$ are the weight vector of the ith user and the array response of the Mth path of the ith user, respectively.

These weights enable the antenna array to receive/transmit from/to a certain user in a multipath environment.

3. LINEAR EQUALIZATION

Linear equalization is an efficient technique to suppress the ISI caused by the multipath environment and thereby improve the performance of the communication system. There are different kinds of linear equalization in frequency domain such as the linear minimum mean square (LMMSE) equalizer, the zero forcing ZF equalizer and the regularized zero forcing (RZF) equalizer. The ZF solution can be written as [8]:

$$\mathbf{W}_{ZF} = \left(\mathbf{H}^H \mathbf{H}\right)^{-1} \mathbf{H}^H \tag{7}$$

where $\mathbf{H}$ is the channel matrix. The drawbacks of the frequency domain ZF equalizer are that, it causes noise enhancement and the computations needed for matrix inversion are high. However, its advantage is that the statistics of the additive noise and source data are not required. To solve the problem of noise enhancement in the ZF equalizer, a new regularization term is added into Eq. (7) to give [9, 10]:

$$\mathbf{W}_{RZF} = \left(\mathbf{H}^H \mathbf{H} + \alpha \mathbf{I}\right)^{-1} \mathbf{H}^H \tag{8}$$

where α is a regularization parameter. The resulting equalizer in Eq. (8) is called RZF equalizer. From this equation, it is clear that the statistics of the transmitted data and the additive noise are not required in the RZF equalizer. There are another regularization schemes such as in [11]. The difference between the proposed regularized equalization scheme in this paper and the schemes in [11] is that the proposed scheme solves the problem of the noise enhancement in the zero forcing equalizer whereas the regularized equalization schemes in [11] solve the problems of the MMSE equalizer. On the other hand, the estimation of the SNR is required in the schemes in [11]. Thus the proposed regularized scheme has a lower complexity than that in [11]. Given the statistics of the additive noise and the users' data, a better equalizer is the one that can minimize the mean square error (MSE) and partially remove the ISI. This equalizer is called the LMMSE equalizer, (i.e., $\alpha = 1/\mathrm{SNR}$). It is generally preferred to the ZF linear equalizer, because of its better treatment to noise. The LMMSE solution is given by [8]:

$$\mathbf{W}_{LMMSE} = \left(\mathbf{H}^H\mathbf{H} + \frac{1}{SNR}\mathbf{I}\right)^{-1}\mathbf{H}^H \tag{9}$$

4. THE PROPOSED SCHEME

In this section, the proposed scheme is described. This scheme consists of two stages. In the first stage, the beamforming at the base station is used to reduce the effect of the MAI. The second stage uses the equalization at the mobile unit to reduce the effect of the ISI and to provide a better estimate of the data. The proposed scheme is depicted in Figure 2. The proposed scheme can be characterized by the following steps:

1. We firstly calculate the uplink beamforming weights via the MVDR algorithm to minimize the total received power while maintaining the unity power gain towards the desired user. In our work, we assume for simplicity that all users send their signals at the same time. As in Figure 2, the weights of all users are calculated as follows:

a. All users send their signals synchronously after spreading and modulation.

$$\mathbf{R} = \mathbf{A}\mathbf{H}_u\mathbf{S}\mathbf{b} \tag{10}$$

where $\mathbf{R}$ is the received data matrix at the output of the antenna array. $\mathbf{A}$ is the array response matrix of the antenna array for all active users with their paths. $\mathbf{H}_u$ is the uplink channel response matrix of all

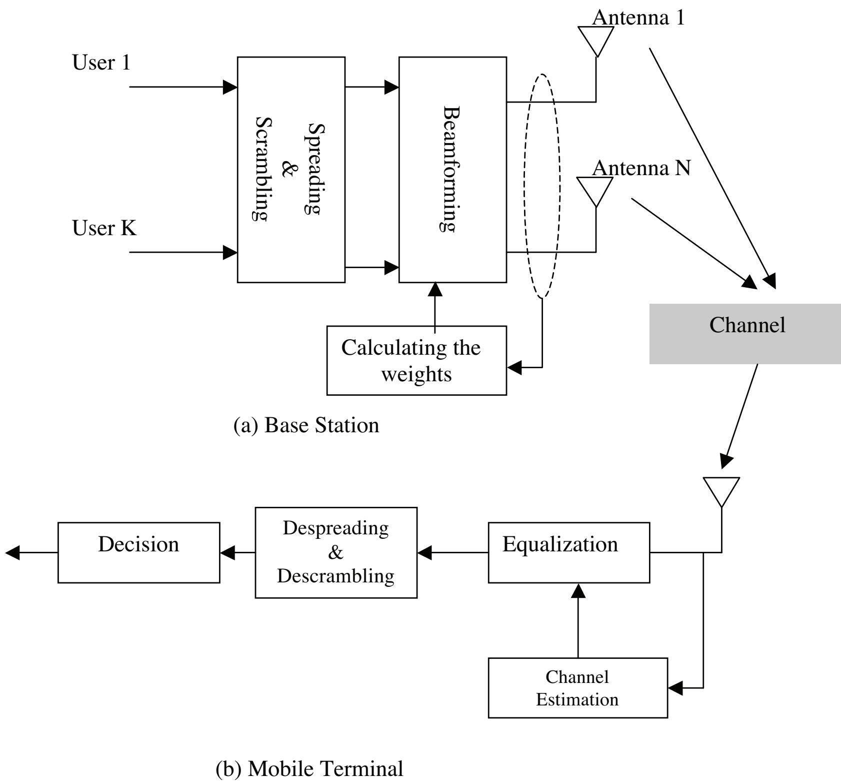

Figure 2. The proposed scheme (a) Transmitter (Base station) (b) Receiver (Mobile terminal).

active users. $\mathbf{AH}_u$ constitutes the so called spatial channel matrix that contains the Angles of Arrival (AoA) of all different active users in addition to the principal parameters of the channel such as gain, time delay, and Doppler shift. $\mathbf{S}$ is the spreading code matrix of all users, and $\mathbf{b}$ is the transmitted symbols vector of all users.

b. The MVDR algorithm is applied for calculating the weights of K active users with their M paths as follows:

i) Calculate the $N * N$ covariance matrix of the received data.

$$\mathbf{R}_{rr} = \mathrm{E}\left(\mathbf{RR}^H\right) \tag{11}$$

ii) Calculate the weight of the ith user with his M paths using Eq. (4).

iii) Repeat the previous step K times to calculate the weights of all active users.

2. After calculating the weights of all active users at the uplink, we apply these weights for downlink beamforming as follows:

$$\mathbf{r} = \mathbf{H}_d \mathbf{A}_d \mathbf{W} \mathbf{S} \mathbf{b} \tag{12}$$

where $\mathbf{r}$ is the received data vector at the desired mobile unit, $\mathbf{A}_d$ is the antenna array response matrix for downlink transmission, $\mathbf{H}_d$ is the downlink channel matrix and $\mathbf{W}$ is the weighting matrix.

3. After that, the received signal is equalized to suppress the ISI as follows:

$$\hat{\mathbf{d}} = \left(\mathbf{H}_d^H \mathbf{H}_d + \alpha \mathbf{I}\right)^{-1} \mathbf{H}_d^H \mathbf{r} \tag{13}$$

4. The resulting equalized signal is despreaded to obtain the estimate of the transmitted data of the desired user.

5. Finally, the decision process is performed.

The main advantage of the proposed scheme lies in its low complexity at the mobile unit when compared to the schemes that use both beamforming and equalization at the receiver. The optimum α that minimizes the equalization error is 1/SNR. But the problem associated with MMSE equalizer is the estimation of the SNR, which is not known at the receiver. To avoid this problem, it is better to choose α as a constant. So, in our proposed scheme we have studied the effect of α at different SNR values. Simulation results show that there is a slight difference in the performance between $\alpha = 1/\text{SNR}$ and $\alpha = 0.1$ at high SNRs. When the SNR is low, the two values nearly give the same performance. Thus, an approximation of $\alpha = 0.1$ is satisfactory. With $\alpha = 0.1$, the complexity of the proposed scheme is decreased. This is because the estimation of the SNR at the mobile unit is not required.

5. SIMULATION RESULTS

Several simulation experiments are carried out in this section to test the performance of the proposed scheme. The simulation environment is based on the downlink synchronous CDMA system, in which each user transmits BPSK information symbols. The wireless channel model used in the simulation is a Vehicular A outdoor channel. It has six Raleigh fading taps at delays of 0, 310, 710, 1090, 1730, and 2510 ns, with relative powers of 0 dB, −1 dB, −9 dB, −10 dB, −15 dB, and −20 dB, respectively [12]. The fading was modeled as quasi-static (unchanging during a block). The simulation parameters are tabulated in Table 1.

Figure 3 introduces a comparison study between the proposed LMMSE equalization with MVDR Beamforming algorithm, the

Table 1. Simulation parameters.

Transmitter	Modulation	BPSK
	Spreading Codes	OVSF codes with processing gain 16
	Number of antennas	$N = 4$
	Beam forming	MVDR beamforming
	Channel coding	Convolutional code
Channel	Fading	Vehicular A outdoor channel
	Noise Environment	AWGN
Receiver	Equalization	RZF with $\alpha = 0.1$, and LMMSE
	Channel Estimation	Perfect

LMMSE equalization, and the MVDR Beamforming algorithms. From the obtained results, it is clear that the proposed LMMSE equalization with MVDR Beamforming algorithm gives the best performance. This is because the proposed scheme removes the MAI and the ISI. However, the proposed scheme with LMMSE requires the estimation of the SNR which is not known prior to equalization. To avoid this problem, it is better to choose α as a constant. So, in the following experiments we will study the effect of α on the proposed scheme at different SNR values.

Figures 4, and 5 depict the relation between the regularization parameter (α) and the BER for the equalization and the proposed equalization with MVDR Beamforming algorithms in downlink CDMA systems at different SNR values. The two figures show that the best choice of α is found to be in the interval [0.01, 0.1]. Thus, we will choose $\alpha = 0.1$ for the next experiment.

Figure 6 demonstrates the performance of the RZF equalization, the MVDR Beamforming, and the proposed RZF equalization with MVDR Beamforming algorithms. It can be clearly seen that the proposed scheme significantly improve the BER performance, especially at high SNR values where errors are produced by the MAI and the ISI, compared to the RZF equalization and, the MVDR beamforming algorithms.

At a BER $= 10^{-3}$, an SNR reduction of about 7 dB can be achieved by using the proposed RZF equalization with MVDR beamforming algorithm as compared to the RZF equalization algorithm. At this

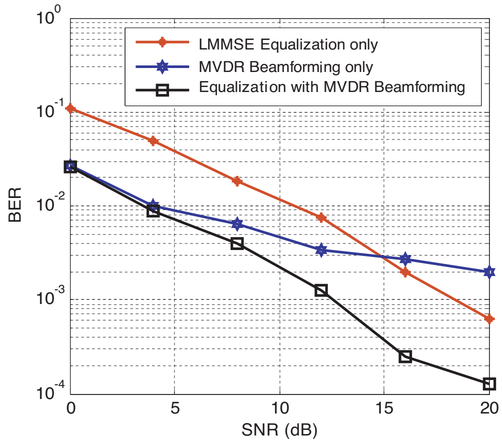

Figure 3. BER vs. SNR for different reception schemes.

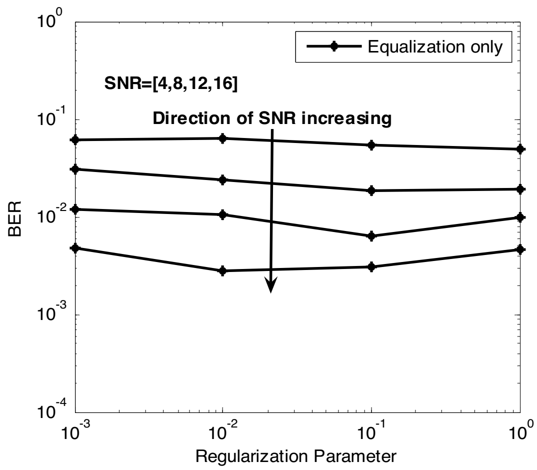

Figure 4. BER vs. regularization parameter at different SNR values for the equalization algorithm only.

value of the BER, the proposed algorithm outperforms the MVDR Beamforming algorithm. This indicates that the proposed scheme is more suitable for downlink CDMA systems.

Together, Figures 3 and 6 show that there is a slight difference in the performance between $\alpha = 1/\text{SNR}$ (LMMSE equalizer) and $\alpha = 0.1$ at high SNRs. When the SNR is low, the two values nearly give the same performance. Thus, an approximation of $\alpha = 0.1$ is satisfactory.

Figure 7 shows the effect of applying convolutional coding with the proposed scheme. It improves the performance of the proposed scheme. At a BER $= 10^{-3}$, the coded proposed scheme provides about 3 dB performance gain when compared with that of the uncoded one.

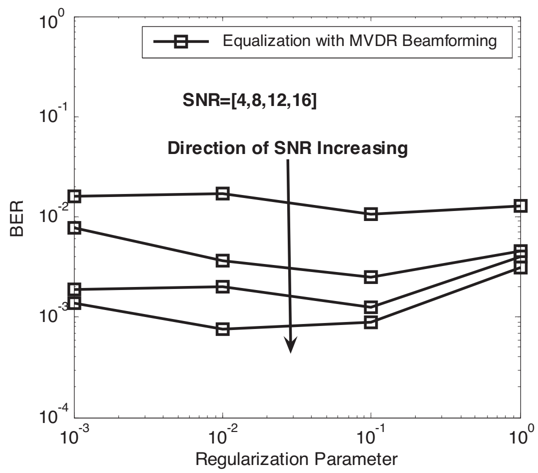

Figure 5. BER vs. regularization parameter at different SNR for the equalization with MVDR beam forming algorithm.

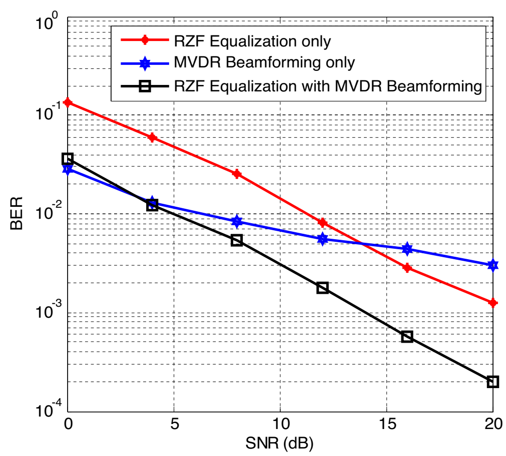

Figure 6. BER vs. SNR for different reception schemes.

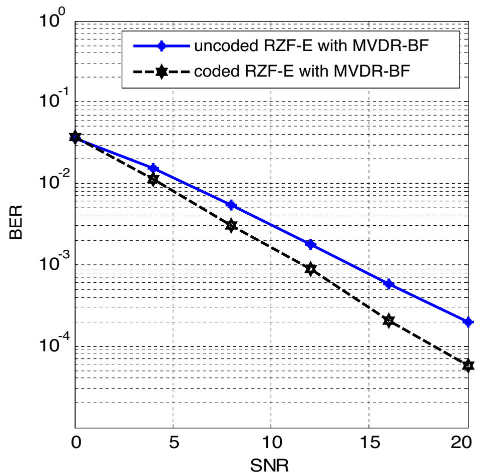

Figure 7. BER vs. SNR for uncoded and coded versions of the proposed scheme.

6. CONCLUSIONS

Downlink beamforming with linear equalization has been proposed and studied for downlink CDMA systems. It has been found that, the proposed scheme mitigates the effects of both MAI and ISI and provides better performance with low complexity at the mobile unit. The complexity of the proposed scheme is also reduced by replacing the LMMSE equalizer which need the estimation of the SNR by the regularized zero forcing equalizer. The regularization parameter is studied at different values of the SNR. It has been found that, the best choice of this parameter is 0.1. The proposed scheme performance can be improved through the use of more efficient error correcting codes.

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