User Cooperation Using Multiple Antennas

Carmen Lúcia Avelar Lessa and Gustavo Fraidenraich

Department of Communications
and University of Campinas-UNICAMP, Brazil
carmen,gf@decom.fee.unicamp.br

***Abstract*— This paper proposes user cooperation strategy using multiple antennas technology (MIMO). In a first model we used a Code Division Multiple Access (CDMA) system and in a second model we apply the techniques of the decorrelator and Singular Value Decomposition (SVD) to allow cooperation. We show how cooperation using different numbers of antennas can be accomplished. It was considered a cooperation scheme for MIMO MAC channel with two users having single antenna and the receiver with two antennas. The results show that user cooperation with multiple antennas reduces the bit error probability**

Keywords*— *User cooperation, multiple-input multiple-output (MIMO) systems, multiuser channel, decorrelator, SVD.

I. Introduction

Mobile communication systems allows the exchange of information at high rates and high quality between small and portable terminals located anywhere in the world. Thus, current cellular systems have the need to employ advanced techniques not only to increase the data rate, but also enable the system to guarantee the quality of service (QoS). The mobile radio channel suffers from fading, implying that, in time of a call, users mobile undergo several changes in signal attenuation fading. In an environment where the fading is present, the link quality can vary greatly either by the displacement of the transmitter and receiver or/and by variations of environment [1]. One way to combat the effects of fading is using some kind of diversity. In this article we propose a junction between the MIMO (Multiple Input and Multiple Output) technology and user cooperation in a CDMA system [2], [3]. The use of MIMO refers to the use of multiple antennas at transmitter and/or at receiver end. This technology provides a way to accomplish space diversity since multiple links are created between the pair transmitter-receiver. The use of multiple antennas generates a linear system with multiple inputs and outputs, characterized by a matrix channel that connects the input with the output signals. In such a channel model, the capacity grows with $\min(n_t, n_r)$, where n_t is the number of antennas at the transmitter and n_r is the number of antennas at the receiver side. This increase in capacity occurs without additional bandwidth or power. This capacity gain is defined as the multiplexing gain [1]. The cooperation of users also proposes a way to obtain the spatial diversity in wireless networks. In a system with cooperation among users, each user is assigned to one or more partners. Each user becomes responsible not only to transmit their own information, but also to transmit the information of the other user. This scheme results in retransmission of the same information by increasing the possibility of receiving the correct information at the end of transmission [2], [3].

Thus, in this article we analyze the performance of MIMO system together with user cooperation. In order to distinguish the information of each user, we used the code division multiple access, and in the sequence, we used the techniques: SVD (single value decomposition) and decorrelator. The results of our simulations confirm that the junction of these two technologies, MIMO with user cooperation and MIMO with SVD and decorrelator decreases the error rate of the system.

II. User Cooperation

The mobile user cooperation strategy is fundamentally characterized by the principle that in each cell, each user has a ”partner”. The idea of cooperation comes from the fact that both users have information of their own to send and would like to cooperate in order to send this information to the receiver at the highest rate possible and also to guarantee the quality of service. Using this strategy, a new form of spatial diversity is achieved because two transmitters geographically separated transmit their information as if they had two antennas. Thereby diversity gains are achieved via the cooperation of in-cell users.

III. User Cooperation Using Multiple Input and Multiple Output(MIMO)

The use of multiple antennas at the both transmitter and receiver provide spatial diversity due to multiple links created between the transmitter-receiver pair. The cooperation of mobile users also achieve spatial diversity through the use of the partner's antenna. The use of both techniques, user cooperation and MIMO, in a single transmission provides an increase in the spatial diversity guaranteeing a lower error probability. In this section, a potential implementation is presented for user cooperation using MIMO technology. In this paper, as described by Fig. 1, a system with two users called Tx_1 and Tx_2 , and one receiver with two antennas receiver (Rx_1 and Rx_2), will be investigated. Note that in our model illustrated in Fig. 1, the use of user cooperation enables single-antenna mobiles in a multi-user environment to share their antennas and generate a virtual multiple-antenna transmitter. In this model, the user 1 transmits its

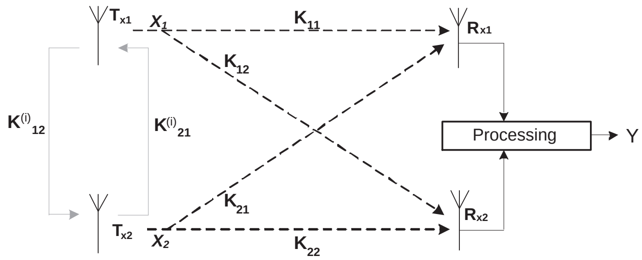

Fig. 1. Channel model consisting of two users with a single antenna and a receiver with two antennas.

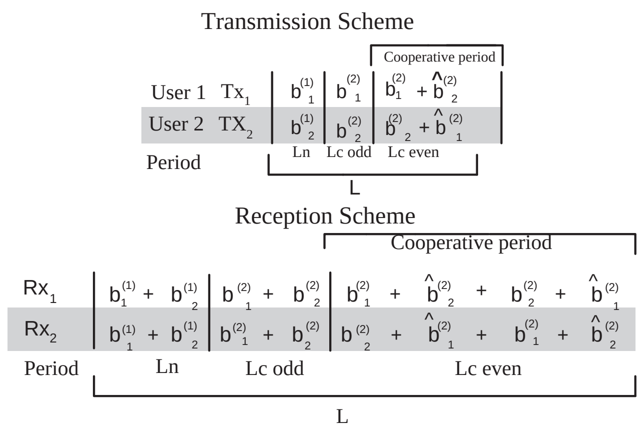

Fig. 2. Transmission and reception using a user cooperation with MIMO.

information to Rx_1 and Rx_2. This form of transmission occurs in a similar manner to the user 2, which sends its information to Rx_1 and Rx_2.

A. MIMO system with user cooperation using CDMA

For detection of signals is necessary to use a technique of combining the signals received. Since the combiner MRC (Maximum Ratio Combining) maximizes the received SNR (signal-to-noise ratio), this paper will use this technique in the first transmission model presented. The transmission and reception using user cooperation with MIMO is illustrated in Fig. 2. This model follows the implementation strategy using CDMA described in [2], [3], dividing the transmission into three periods: L_n, L_c odd and L_c even. In the period L_n, period without cooperation, the antennas Rx_1 and Rx_2 receive the following information

$$Y_{1Ln} = \sqrt{E_b}K_{11}a_{11}b_1^{(1)}c_1 + \sqrt{E_b}K_{21}a_{21}b_2^{(1)}c_2 + Z_1$$
$$Y_{2Ln} = \sqrt{E_b}K_{12}a_{12}b_1^{(1)}c_1 + \sqrt{E_b}K_{22}a_{22}b_2^{(1)}c_2 + Z_2$$

where Y_{1Ln} and Y_{2Ln} are the received signals by the antennas Rx_1 and Rx_2, respectively. $b_i^{(j)}$ is the i-th bit of user j, c_i is the spreading code of user i which has length of N_c and a_{ij}=$\sqrt{P_i/T_s}$ where P_i is user i's power, T_s is the symbol period, K_{ij} are the fading coefficients, and Z_i is the zero mean additive white Gaussian noise channel with variance σ^2 at receiver antennas, for i = 1, 2. The MRC [4] combiner will be used as a combining technique at the receiver. Assuming that user 1 will be detected, the MRC output will be given by

$$Rx_{MRC\ Ln} = Y_{1Ln}K_{11}a_{11} + Y_{2Ln}K_{12}a_{12} \tag{1}$$

During the period of no cooperation, each user sends only its own data that is received and detected by the receiver. Thus, the bit estimated during this period is given by

$$\hat{b}_1^{(1)} = \text{sign}\left(\frac{1}{N_c}Rx_{MRC\ Ln}\right) \tag{2}$$

Therefore, during these L_n periods, the bit error probability will be given by

$$P_{e\ Ln} = Q\left(\sqrt{\frac{(K_{11}^2a_{11} + K_{12}^2a_{12})N_c}{E_b\sigma^2}}\right) \tag{3}$$

where $Q(.)$ is tail probability of the standard normal distribution. In a similar way, during the L_c odd symbols the information at antenna 1 will be given by

$$Y_{1Lc\ odd} = \sqrt{E_b}K_{11}a_{11}b_1^{(2)}c_1 + \sqrt{E_b}K_{21}a_{21}b_2^{(2)}c_2 + Z_1 \tag{4}$$
$$Y_{2Lc\ odd} = \sqrt{E_b}K_{12}a_{12}b_1^{(2)}c_1 + \sqrt{E_b}K_{22}a_{22}b_2^{(2)}c_2 + Z_2 \tag{5}$$

and the receiver forms a soft statistic by calculating

$$Y_{odd} = \frac{1}{N_c}\left(Y_{1Lc\,odd}K_{11}a_{11} + Y_{2Lc\,odd}K_{12}a_{12}\right)c_1^T \tag{6}$$

where $(\cdot)^T$ is the transpose operator. This signal will be used in conjunction with Y_{even} (to be defined) to obtain a estimate of $b_1^{(2)}$. In the "odd" periods the partner's hard estimate of $b_1^{(2)}$ is given by

$$\hat{b}_1^{(2)\prime} = \text{sign}\left(\frac{1}{N_c}c_1^T\, Y_{user1}\right) \tag{7}$$

with $Y_{user1} = K_{12}^{(i)}a_{12}b_1^{(2)}c_1 + Z_3$ (Z_3 is a zero mean AWGN noise with variance $\left(\sigma_{12}^i\right)^2$) the information received by the partner and transmitted by user 1, resulting in a probability of bit error equal to

$$P_{e\ \hat{b}_{21}} = Q\left(K_{12}^{(i)}a_{12}\frac{\sqrt{Nc}}{\sigma_{12}^i}\right) \tag{8}$$

in the "even" periods the information received by Rx_1 and Rx_2, respectively are given by

$$\begin{aligned} Y_{1Lc\ even} &= K_{11}a_{11}b_1^{(2)}c_1 + K_{11}a_{11}\hat{b}_2^{(2)}c_2 + \\ &\quad K_{21}a_{21}b_2^{(2)}c_2 + K_{21}a_{21}\hat{b}_1^{(2)}c_1 + Z_1 \quad (9) \\ Y_{2Lc\ even} &= K_{12}a_{12}b_1^{(2)}c_1 + K_{12}a_{12}\hat{b}_2^{(2)}c_2 + \\ &\quad K_{22}a_{22}b_2^{(2)}c_2 + K_{22}a_{22}\hat{b}_1^{(2)}c_1 + Z_2 \quad (10) \end{aligned}$$

And the MRC output will be given by

$$\begin{aligned} Y_{even} &= \frac{1}{N_c}[Y_{1Lc\,even}(K_{11}a_{11} + K_{21}a_{21}) \\ &\quad + Y_{2Lc\,even}(K_{12}a_{12} + K_{22}a_{22})]c_1^T \quad (11) \end{aligned}$$

As in [3], the λ-MRC detector will be used (note that, in this case, the λ-MRC is in fact a "temporal" combiner) in this period combining the previous Y_{odd} given in (6) and Y_{even} given in (11), in the following way

$$\hat{b}_1^{(2)} = \text{sign}(Y_{odd} + Y_{even}) \tag{12}$$

which has a bit error probability given by

$$\begin{aligned} P_{e\,Lc} &= (1 - P_{e\ \hat{b}_{21}})Q\left(\frac{\mathbf{v}_\lambda^T \mathbf{v}_1}{\sqrt{\mathbf{v}_\lambda^T \mathbf{v}_\lambda}}\right) \\ &\quad + P_{e\ \hat{b}_{21}} Q\left(\frac{\mathbf{v}_\lambda^T \mathbf{v}_2}{\sqrt{\mathbf{v}_\lambda^T \mathbf{v}_\lambda}}\right) \end{aligned} \tag{13}$$

with the vectors $\mathbf{v}_\lambda$, $\mathbf{v}_1$, and $\mathbf{v}_2$, defined as

$$\begin{aligned} \mathbf{v}_\lambda &= [\alpha \quad \lambda(\alpha+\beta)]^T \\ \mathbf{v}_1 &= [\alpha \quad (\alpha+\beta)]^T \sqrt{Nc}/\sigma \\ \mathbf{v}_2 &= [\alpha \quad (\alpha-\beta)]^T \sqrt{Nc}/\sigma \end{aligned}$$

where $\alpha = K_{11}a_{11} + K_{12}a_{12}$ and $\beta = K_{22}a_{22} + K_{21}a_{21}$.

IV. MIMO SYSTEM WITH USER COOPERATION USING SVD AND DECORRELATOR

In the sequence we propose a system to use MIMO and user cooperation using decorrelator and singular value decomposition (SVD) methods [1]. The goal of the decorrelator is to avoid the multi-user interference. This can be accomplished by multiplying the information at the receiver by the inverse matrix of the channel. Therefore, using the decorrelator

$$Y_{dec} = (\sqrt{E_b}\,\mathbf{K}\,\mathbf{b} + \mathbf{Z})\mathbf{K}^{-1} \tag{14}$$

where $\mathbf{K}$ is channel matrix, $\mathbf{b}$ is the information vector and $\mathbf{Z}$ is an additive noise vector with zero mean and covariance matrix given by $\frac{N_0}{2}\mathbf{I}$ ($\mathbf{I}$ is the identity matrix).

The SVD method aims to increase the multiplexing gain of a MIMO system when the channel is known at both receiver and transmitter side. This technique is used to diagonalize the channel matrix and to transmit multiple data streams without interfering with each other. Given a channel matrix $\mathbf{K}$ and its singular value decomposition $\mathbf{K} = \mathbf{S}\Delta\mathbf{V}'$, where $\mathbf{V}$ and $\mathbf{S}$ are unitary matrices and $\mathbf{\Delta}$ is the a diagonal matrix with singular values. The signal $\mathbf{b}$ is multiplied by $\mathbf{V}$ at the transmitter and at the receiver by $\mathbf{S}'$, respectively, so the signal at the receiver can be written as [1]

$$Y_{SVD} = \sqrt{E_b}\,\mathbf{\Delta}\,\mathbf{b} + \mathbf{S}'\mathbf{Z} \tag{15}$$

The processing done by applying the SVD technique guarantees that the flows do not interfere with each other, since the resulting channel matrix is diagonal. The use of these techniques eliminates the use of CDMA spreading codes and therefore increases the bandwidth efficiency. Following the same scheme of cooperation detailed in the previous model, during the period $L_{c\ odd}$ we use the decorrelator schem, and during the period $L_{c\ even}$ we use the SVD scheme.

During the period $L_{c\,even}$, users 1 and 2, transmit, respectively

$$\mathbf{V}\,\mathbf{b}_1 = \mathbf{V}\,[b_1^{(2)} \quad \hat{b}_2^{(2)}]^T \tag{16}$$

$$\mathbf{V}\,\mathbf{b}_2 = \mathbf{V}\,[\hat{b}_1^{(2)} \quad b_2^{(2)}]^T \tag{17}$$

Applying the SVD technique the received signal will be given as in (15). Therefore combining both signals at the receiver

$$\hat{b}_1^{(2)} = \text{sign}(Y_{dec} + Y_{SVD}) \tag{18}$$

we obtain the following bit error probability for user 1[1](for the sake of space, the development of the bit error probability expression will not be shown here, but the validity of this is proved by simulation in the sequel)

$$P_e = P_{e0} + P_{e1} + P_{e2} + P_{e3} \tag{19}$$

where P_{e0}, P_{e1}, P_{e2}, P_{e3} are given in (20), (21), (22), and (23), respectively.

V. NUMERICAL AND SIMULATIONS REESULTS

In this section, we verify the validity of the numerical analysis method and examine the performance of the proposed cooperative system using the multiple antennas at the receiver. The bit error probability was computed assuming three symbols periods, each of the periods with an average power of P. Also, in order to estimate the cooperative bit, we are considering the λ-MRC detector with $\lambda = 1$. Moreover, due to the reciprocity of the channel, we assume that $K_{12}^{(i)}$ and $K_{21}^{(i)}$ are equal, and for simplicity of analysis that K_{11}, K_{12}, K_{22} and K_{21} are also equal. Fig. 3 shows the bit error probability for three schemes: no cooperation, user cooperation diversity and our proposed scheme. For a bit error rate of 10^{-3}, the MIMO system presents a gain of about 3 dB in relation to a pure cooperation system and a gain of 5 dB to a non-cooperative system. Fig. 4 shows the benefit of our proposed scheme for the situation where the inter user channel assumes different values. Note that as the inter user channel assumes higher values, a decrease in the bit error probability is observed.. The curves in Fig. 4 shows the bit error probability for several values of $K_{12}^{(i)}$ and $K_{21}^{(i)}$

Fig. 5 shows the bit error probability for the decorrelator+SVD scheme. As can be seen in this figure, the simulated and the analytical expression presented in (19) are in perfect agreement. The proposed scheme is a new way to implement user cooperation without the need of a spreading codes.

[1]The bit error probability for user 2 is similar and will not be presented here

$$P_{e0} = \left(1-P_{e\hat{b}_{21}}\right)\left(1-P_{e\hat{b}_{22}}\right)Q\left(\sqrt{\frac{2E_b\left(1+\mathbf{\Delta}_{11}\right)^2}{N_0\left(\left\|\mathbf{K}^{-1}\left(:,1\right)\right\|^2+\left\|\mathbf{V}\left(:,1\right)\right\|^2\right)}}\right) \tag{20}$$

$$\begin{aligned} P_{e1} &= \frac{\left(1-P_{e\hat{b}_{21}}\right)P_{e\hat{b}_{22}}}{2}\left[Q\left(\frac{\sqrt{2E_b}\left(1+\mathbf{\Delta}_{11}\left(1+\mathbf{S}_{21}\mathbf{S}_{22}-\mathbf{S}_{12}\mathbf{S}_{11}\right)\right)}{\sqrt{N_0\left(\left\|\mathbf{K}^{-1}\left(:,1\right)\right\|^2+\left\|\mathbf{V}\left(:,1\right)\right\|^2\right)}}\right)\right. \\ &\left. + Q\left(\frac{\sqrt{2E_b}\left(1+\mathbf{\Delta}_{11}\left(1-\mathbf{S}_{21}\mathbf{S}_{22}+\mathbf{S}_{12}\mathbf{S}_{11}\right)\right)}{\sqrt{N_0\left(\left\|\mathbf{K}^{-1}\left(:,1\right)\right\|^2+\left\|\mathbf{V}\left(:,1\right)\right\|^2\right)}}\right)\right] \end{aligned} \tag{21}$$

$$P_{e2} = P_{e\hat{b}_{21}}\left(1-P_{e\hat{b}_{22}}\right)\left[Q\left(\frac{\sqrt{2E_b}\left(1+\mathbf{\Delta}_{11}\left(\mathbf{S}_{11}^2-\mathbf{S}_{21}^2\right)\right)}{\sqrt{N_0\left(\left\|\mathbf{K}^{-1}\left(:,1\right)\right\|^2+\left\|\mathbf{V}\left(:,1\right)\right\|^2\right)}}\right)\right] \tag{22}$$

$$\begin{aligned} P_{e3} &= \frac{P_{e\hat{b}_{21}}P_{e\hat{b}_{22}}}{2}\left[Q\left(\frac{\sqrt{2E_b}\left(1+\mathbf{\Delta}_{11}\left(\mathbf{S}_{11}^2-\mathbf{S}_{21}^2\right)+\mathbf{\Delta}_{11}\left(\mathbf{S}_{21}\mathbf{S}_{22}-\mathbf{S}_{12}\mathbf{S}_{11}\right)\right)}{\sqrt{N_0\left(\left\|\mathbf{K}^{-1}\left(:,1\right)\right\|^2+\left\|\mathbf{V}\left(:,1\right)\right\|^2\right)}}\right)\right. \\ &\left. + Q\left(\frac{\sqrt{2E_b}\left(1+\mathbf{\Delta}_{11}\left(\mathbf{S}_{11}^2-\mathbf{S}_{21}^2\right)-\mathbf{\Delta}_{11}\left(\mathbf{S}_{21}\mathbf{S}_{22}-\mathbf{S}_{12}\mathbf{S}_{11}\right)\right)}{\sqrt{N_0\left(\left\|\mathbf{K}^{-1}\left(:,1\right)\right\|^2+\left\|\mathbf{V}\left(:,1\right)\right\|^2\right)}}\right)\right] \end{aligned} \tag{23}$$

VI. Conclusions

In this paper we proposed a system consisting of a CDMA system using MIMO technology with user cooperation. New bit error expressions were presented and validated by simulations.

Furthermore a new scheme (decorrelator+SVD) was presented. The simulated and analytical expressions were compared and they showed a perfect agreement. Since this scheme does not use spreading codes, it presents a better bandwidth efficiency.

The systems proposed achieved a reduction in the probability of bit error when compared to a system with no cooperation and systems with user cooperation with single receiving antenna.

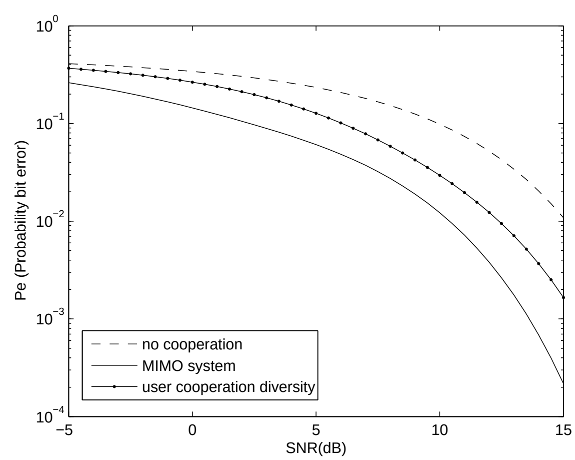

Fig. 3. Comparison of the bit error probability using cooperation, non cooperation and the MIMO proposed scheme (using CDMA). $K_{12} = K_{21} = K_{11} = K_{22}$= 0.5. $\sigma_0 = \sigma_1$=σ_2=1.0 and λ =1.0

References

[1] D. Tse and P. Viswanath, "Fundamentals of Wireless Communication," Cambridge University Press, 2005.

[2] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity Part I: System description," IEEE. Trans. Commun., vol. 51, No. 11, pp. 1927-1938, Nov. 2003.

[3] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity Part I: System description," IEEE. Trans. Commun., vol. 51, No. 11, pp. 1939-1948, Nov. 2003.

[4] J. G. Proakis, Digital Communications. New York: McGraw-Hill,1995.

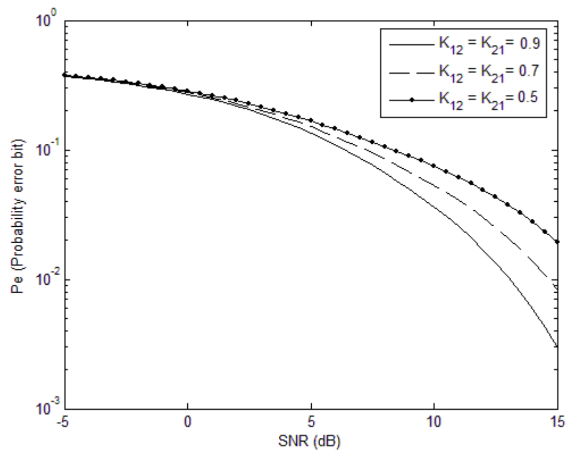

Fig. 4. Comparison of probability of the error bit for different conditions of interuser channel and no cooperation system. K_{12} = K_{21} = K_{11} = K_{22}= 0.5. σ_0 = σ_1=σ_2=1.0 and λ =1.0

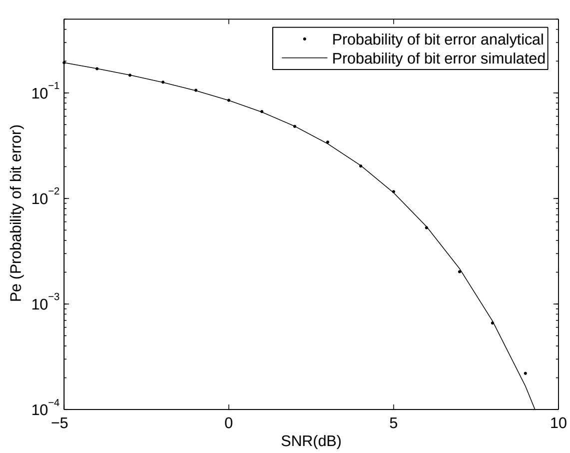

Fig. 5. Comparasion of probability of the error bit analytical and simulated of MIMO system with user cooperation using the decorrelator+SVD scheme.