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Proposal and Evaluation of CoMP System with Alamouti Transmission Diversity and MIMO Configuration

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Abstract

The low communication quality at a cell boundary is a long-standing problem in mobile communication systems. This is because the reception power level decreases and the fading margin becomes insufficient at the cell boundary. Coordinated multipoint transmission/reception (CoMP) technology has been introduced to overcome this problem. In this paper, we propose a CoMP system with Alamouti transmission diversity and a multiple input and multiple output (MIMO) configuration to further improve the average bit error rate (BER) at a cell boundary and the channel capacity. We show the effectiveness of our proposed system in terms of the coverage probability and channel capacity.

1. Introduction

The low communication quality at a cell boundary is a long-standing problem in mobile communication systems. This is because the reception power level decreases and the fading margin becomes insufficient at the cell boundary. CoMP technology coordinates and transmits signals using multiple base stations and was introduced to overcome this problem. Among the few types of CoMP, we assume the use of the joint transmission method in this paper, in which multiple base stations coordinate and transmit signals coherently to increase the quality at the cell boundary. Alamouti transmission diversity is a space-time block code used to improve the statistical variation of received signals [1]. We previously proposed a CoMP system with Alamouti transmission diversity, where the two transmission antennas are in different locations [2], whereas the location of the transmission antennas were in the same location in Ref.[1]. In this paper, we propose a CoMP system with Alamouti transmission diversity and a MIMO configuration to further improve the average BER at a cell boundary and the channel capacity. Unlike in [2], the proposed system forms two streams using the Alamouti transmission diversity.

2. Proposed CoMP System

The proposed CoMP system consists of two base stations and one mobile station as shown in Fig. 1. In order to divide the cell into the inner cell and cell boundary in the cell configuration, we define the cell division ratio $m:n$ in terms

of the radius. The mobile station inside the cell receives signals from one of the two base stations. On the other hand, the mobile station at the cell boundary receives signals from both base stations, whose signals are coordinated and transmitted coherently.

We form two streams using Alamouti transmission diversity equivalent to the CoMP transmission of the two base stations by precoding. Figure 2 shows the transmission model of the proposed system. The proposed system has a 4×2 MIMO-CoMP configuration and each station has two antennas. Figure 3 shows the equivalent transmission model of the proposed system that forms two streams using Alamouti transmission diversity. Let base station A have transmission antennas 1 and 2, base station B have transmission antennas 3 and 4, and each mobile station has reception antennas 1 and 2. We implement the Alamouti transmission diversity consisting of the stream of transmission antennas 1 and 3 and reception antenna 1, and the stream of transmission antennas 2 and 4 and reception antenna 2. Each base station transmits two precoded signals at the two successive times, and the mobile station receives the two signals and produces a gain equal to that of the two branches by maximal-ratio combining (MRC) by computation with the two reception signals and two equivalent channels.

Figure 1: Cell configuration in proposed system

Figure 2: Transmission model in proposed system

Figure 3: Equivalent transmission model in proposed system

3. Theoretical Analysis

When we form two streams using Alamouti transmission diversity equivalent to the CoMP transmission of the two base stations by precoding, the weight matrix W is

$$HW = H' \quad (1)$$

$$\begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \end{bmatrix} \begin{bmatrix} w_{11} & w_{12} & w_{13} & w_{14} \\ w_{21} & w_{22} & w_{23} & w_{24} \\ w_{31} & w_{32} & w_{33} & w_{34} \\ w_{41} & w_{42} & w_{43} & w_{44} \end{bmatrix} = \begin{bmatrix} h'_{11} & 0 & h'_{13} & 0 \\ 0 & h'_{22} & 0 & h'_{24} \end{bmatrix}$$

where H is the channel matrix and H' is the channel matrix of the equivalent transmission model.

The relation between the transmission signal X and reception signal Y is

$$Y = HWX = H'X \quad (2)$$

We set the first and second transmission signals X_1, X_2 , and the first and second reception signals Y_1, Y_2 as follows:

$$X_1 = \begin{bmatrix} s_1 \\ s_2 \\ s_3^* \\ s_4^* \end{bmatrix}, X_2 = \begin{bmatrix} s_3 \\ s_4 \\ -s_1^* \\ -s_2^* \end{bmatrix} \quad (3)$$

$$Y_1 = H'X_1 = \begin{bmatrix} y_{11} \\ y_{12} \end{bmatrix}, Y_2 = H'X_2 = \begin{bmatrix} y_{21} \\ y_{22} \end{bmatrix}$$

where s_i ($i=1, \dots, 4$) are the signals.

We calculate the independent MRC reception using the equivalent channel coefficient h' and the reception signal y as follows:

$$Y^e = \begin{bmatrix} h'_{11}y_{11} - h'_{13}y_{21}^* \\ h'_{22}y_{12} - h'_{24}y_{22}^* \\ h'_{13}y_{11}^* + h'_{11}y_{21} \\ h'_{24}y_{12}^* + h'_{22}y_{22} \end{bmatrix} = \begin{bmatrix} \left(|h'_{11}|^2 + |h'_{13}|^2 \right) s_1 \\ \left(|h'_{22}|^2 + |h'_{24}|^2 \right) s_2 \\ \left(|h'_{11}|^2 + |h'_{13}|^2 \right) s_3 \\ \left(|h'_{22}|^2 + |h'_{24}|^2 \right) s_4 \end{bmatrix} \quad (4)$$

We set a particular solution of the weight matrix W as

$$W = \begin{bmatrix} h_{22} & h_{12} & h_{22} & h_{12} \\ -h_{21} & -h_{11} & -h_{21} & -h_{11} \\ h_{24} & h_{14} & h_{24} & h_{14} \\ -h_{23} & -h_{13} & -h_{23} & -h_{13} \end{bmatrix} \quad (5)$$

When the channel coefficient h follows the complex Gaussian distribution, the approximate probability density function (pdf) of the reception carrier to noise ratio (CNR) $p(\gamma)$ is

$$p(\gamma) = \frac{f(\alpha_1, \alpha_1) + f(\alpha_1, \alpha_2) + f(\alpha_2, \alpha_1) + f(\alpha_2, \alpha_2)}{4} \quad (6)$$

$$f(a, b) = \frac{1}{a\Gamma_A - b\Gamma_B} \left\{ \exp\left(-\frac{\gamma}{a\Gamma_A}\right) - \exp\left(-\frac{\gamma}{b\Gamma_B}\right) \right\}$$

where Γ_A and Γ_B are the CNR from base stations A and B , respectively, and α_1 and α_2 are constants depending on the channel coefficient h .

We convolute the pdf of the reception CNR and the theoretical BER formula under the Gaussian noise [3] and derive the BER formula of 4x2 MIMO-CoMP transmission with Alamouti transmission diversity P_{BER} as

$$P_{BER} = \frac{g(\alpha_1, \alpha_1) + g(\alpha_1, \alpha_2) + g(\alpha_2, \alpha_1) + g(\alpha_2, \alpha_2)}{4} \quad (7)$$

$$g(c, d) = B_1 \left\{ 1 - \frac{1}{c\Gamma_A - d\Gamma_B} \left(\frac{c\Gamma_A}{\sqrt{1 + \frac{1}{B_2 c\Gamma_A}}} - \frac{d\Gamma_B}{\sqrt{1 + \frac{1}{B_2 d\Gamma_B}}} \right) \right\}$$

$$- \frac{2B_1 - 1}{2(ac\Gamma_A + 1)(ad\Gamma_B + 1)} \left\{ 1 - \frac{1}{c\Gamma_A - d\Gamma_B} \left(\frac{c\Gamma_A(ad\Gamma_B + 1)}{\sqrt{1 + \frac{ac\Gamma_A + 1}{B_2 c\Gamma_A}}} - \frac{d\Gamma_B(ac\Gamma_A + 1)}{\sqrt{1 + \frac{ad\Gamma_B + 1}{B_2 d\Gamma_B}}} \right) \right\}$$

where B_1, B_2 , and α are constants depending on the modulation method. The BER formula Eq.(7) is applied to various modulation methods from BPSK to 256 QAM. When the modulation method is QPSK, $B_1=1/2$, $B_2=1/2$, and $\alpha=1$.

The link budget is expressed as

$$P_r = P_t + G_t(\theta) - L_{Ct} - L_p(d) - L_{Cr} + G_r \quad (8)$$

where P_r [dBm] and P_t [dBm] are the transmission and reception powers, $G_t(\theta)$ [dBi] and G_r [dBi] are the transmission and reception antenna gains, L_{Ct} [dB] and L_{Cr} [dB] are the transmission and reception cable losses, and $L_p(d)$ [dB] is the path loss, respectively. Note that, for simplicity, we consider only dominant loss components, ignoring the connector loss, etc. The path loss is given by the extended Hata model and is expressed as

$$L_p(d) = 46.3 + 33.9 \log_{10} f - 13.82 \log_{10} h_t - \{(1.1 \log_{10} f - 0.7)h_r - (1.56 \log_{10} f - 0.8)\} + (44.9 - 6.55 \log_{10} h_t) \log_{10} d \quad (9)$$

where f [MHz] is the radio frequency, h_t [m] is the transmission antenna height, h_r [m] is the reception antenna height, and d [km] is the distance between the base station and mobile station. The transmission antenna gain of a directional antenna is expressed as

$$G_t(\theta) = 17 - \min \left[12 \left(\frac{\theta}{70} \right)^2, 23 \right] \quad (10)$$

where θ [°] is the angle of the mobile station against the front direction of the transmission antenna. The reception CNR Γ^{dB} [dB] is expressed as follows:

$$\Gamma^{\text{dB}} = P_r - N \quad (11)$$

where N [dBm] is the noise power.

We evaluate the required reception CNR by the BER formula Eq.(7). We evaluate the coverage probability of CoMP transmission with the Alamouti transmission diversity as

$$P = \left\{ 1 - \frac{1}{S} \sum_i \frac{1}{2} \operatorname{erfc} \left(\frac{\Gamma_A^{\text{dB}} + \Gamma_B^{\text{dB}} - \Gamma_{th}^{\text{dB}}}{2\sigma} \right) \cdot \Delta s_i \right\} \cdot 100 \quad (12)$$

where Γ_A^{dB} [dB] and Γ_B^{dB} [dB] are the reception CNR from base stations A and B , respectively. Γ_{th}^{dB} is the required reception CNR, σ [dB] is the standard deviation, s [m²] is the total area of the divided small areas, and Δs_i [m²] are the divided small areas.

When we set the total transmission power S [dBm] and allocate the power equally to each transmission antenna, the channel capacity in the proposed system is given by

$$C = E \left[\log_2 \left\{ 1 + \frac{S}{4N} \left(|h'_{11}|^2 + |h'_{13}|^2 \right) \right\} + \log_2 \left\{ 1 + \frac{S}{4N} \left(|h'_{22}|^2 + |h'_{24}|^2 \right) \right\} \right] \quad (13)$$

where N [dBm] is the noise power.

4. Numerical Results

Figure 4 shows the relation between the ratio of the

reception CNRs from the two base stations $\zeta = \Gamma_B / \Gamma_A$ and the normalized distance from base station A . When the distance between the two base stations is D [km], the normalized distance is $\delta = d/(D/2)$. When $\delta=0$ (inside cell), the two reception CNRs are unbalanced and the diversity gain is lowest. When $\delta=1$ (cell boundary), the two reception CNRs are equal and the diversity gain is highest. Even if the distance D changes, the relation between the normalized distance and cell division ratio does not change.

We investigate the coverage probability using the system specifications given in Table 1. The modulation method is QPSK and the reference BER is $P_{BER}=10^{-3}$. The comparison methods are given in Table 2. We focus on the transmission power satisfying 95% coverage probability.

Figure 4: Ratio of reception CNRs from two base stations

Table 1: System specifications

Modulation method	QPSK
Reference BER P_{BER}	10^{-3}
Distance between base stations D	1 km, 3 km
Cell division ratio $m:n$	1:1
Path loss model	Extended Hata model
Frequency f	2 GHz
Bandwidth B	10 MHz
Transmission cable loss L_{Ct}	5 dB
Reception antenna gain G_r	0 dBi
Reception cable loss L_{Cr}	0 dB
Transmission antenna height h_t	30 m
Reception antenna height h_r	1.5 m
Noise power N	-104 dBm
Standard deviation σ	4 dB

Table 2: Comparison methods

Method name	Target area	Transmission power condition	Reception method
Proposed	Cell boundary area	Each base station transmits in P_t [dBm]	MRC reception
4×2 MIMO-CoMP	Cell boundary area	Each base station transmits in P_t [dBm]	Coherent reception
Single	Cell boundary area	Single base station transmits in P_t [dBm]	Single reception

Figure 5 shows the coverage probability at the cell boundary area when the distance is $D=1$ km and the cell division ratio is $m:n=1:1$. The transmission power margin satisfying 95% coverage probability for the proposed method is 18.4 dB in the single transmission method and 15.9 dB in the 4×2 MIMO-CoMP method. Figure 6 shows the coverage probability at the cell boundary when $D=3$ km. The transmission power satisfying 95% coverage probability in Fig.6 increases with increasing the distance between the base stations, compared with Fig.5.

We assume that the cell division ratio $m:n$ is the best when the transmission power satisfying 95% coverage probability is the same both inside the cell and at the cell boundary in the proposed system. Figure 7 shows the transmission power satisfying 95% coverage probability inside the cell and at the cell boundary in the proposed method when the cell division ratio changes and the distance is $D=1$ km. The horizontal axis in Fig.7 shows the percentage of $m/(m+n)$ ($m+n=100$). The best cell division ratio is $m:n=31:69$.

Finally, we investigate the channel capacity at the cell boundary. Figure 8 shows the channel capacity when the total transmission power is the same for each method and is equally provided for each transmission antenna. The channel capacity of the proposed method is 1 bits/s/Hz larger than that of the 4×2 MIMO (SDM) method.

5. Conclusions

We have proposed a CoMP system with Alamouti transmission diversity and a MIMO configuration in order to further improve the average BER at the cell boundary and the channel capacity. The transmission power margin satisfying 95% coverage probability for the proposed method is 18.4 dB in the single transmission method, and 15.9 dB in the 4×2 MIMO-CoMP method. The channel capacity of the proposed method is 1 bits/s/Hz larger than that of the 4×2 MIMO (SDM) method. Therefore, we have shown the effectiveness of our proposed system in terms of the coverage probability and channel capacity.

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Figure 5: Coverage probability at cell boundary ($D=1$ km, $m:n=1:1$)

Figure 6: Coverage probability at cell boundary ($D=3$ km, $m:n=1:1$)

Figure 7: Transmission power satisfying 95% coverage probability in proposed system

Figure 8: Channel capacity at cell boundary