Cooperative MIMO Transmission Based on Multiple Base Station Coordination for OFDM Cellular Systems

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1. Introduction

OFDM (Orthogonal Frequency Division Multiplexing) modulation is attracting attention as the wireless transmission technology for the next generation (3.9G/4G) cellular mobile radio systems, due to its many advantages such as high spectral efficiency in multi-path fading channels. For this reason, various mobile radio access systems based on OFDM have been developed such as 3GPP LTE (Long Term Evolution), 3GPP2 UMB (Ultra Mobile Broadband), and Mobile WiMAX. On the other hand, the MIMO (Multi-Input Multi-Output) transmission technique, which uses multiple antennas at the both transmitter and receiver sides, is also attracting attention due to its throughput performance improvement effect. The combination of MIMO and OFDM, MIMO-OFDM, is highly favored to be used as the air interface for the downlink of the next generation mobile radio systems. In MIMO-OFDM cellular systems, it is critical to increase the throughput of cell-edge users because it is difficult for them to obtain sufficient received signal-to-interference-plus-noise power ratio (SINR) to demultiplex the different streams that are spatially multiplexed. Recently, several cooperative downlink transmission schemes, in which multiple BSs (Base Stations) synchronize to each other and coordinate their wireless transmission, have been proposed for cellular mobile radio systems in order to increase the user throughput at the cell edge [1],[2]. This paper focuses on the downlink cooperative MIMO transmission based on multiple BS coordination in order to improve the transmission performance of the cell-edge users for MIMO-OFDM cellular systems. In this paper, we propose a cooperative MIMO transmission with D-STTD (Double Space Time block coding based Transmit Diversity) [3],[4] and evaluate its performance with consideration of the frequency offset difference between local oscillators in the coordinated BSs by computer simulations. The computer simulations confirm that the proposed cooperative MIMO transmission can improve the user throughput performance at the cell edge. Moreover, we introduce the Per Site Rate Control (PSRC) technique, in which each BS independently controls its modulation level; the computer simulations clarify that the PSRC technique is effective, especially when there is a significant difference in the average received power of the signals transmitted from the coordinated BSs.

2. System Model

As shown in Figure 1, we consider downlink MIMO transmission to an MS at the cell-edge in an OFDM cellular mobile radio system assuming the two ($N_B = 2$) adjacent and coordinated BSs (i.e., master and slave BSs, hereafter, BS#1 and BS#2). BS#1 and BS#2 allocate the subcarriers to the MS with the same frequency selected by the scheduler, and simultaneously transmit the data signals to the MS. We assume here that BS#1 and BS#2 transmit different sub-streams in order to double the peak rate at the cell-edge compared to single-BS downlink transmission. The signal received at the MS receiver is the sum of the desired signals transmitted from BS#1 and BS#2, and we assume that the received signal vector is adequately combined to improve transmission performance. In this configuration, we must consider the frequency offset difference of the local oscillators in the BSs, and the timing offset difference between the received signals transmitted from BS#1 and BS#2. Let the frequency offset difference and the timing offset difference between BS#1 and BS#2 be Δf_c and $\Delta\tau$, respectively. BS#1 and BS#2 coordinate their transmit timing so as to prevent the timing offset (including the multi-path delay) from exceeding the GI (Guard Interval) period of the OFDM symbols. For this purpose, the inter-BS network and each BS are equipped with a transmit-timing controller and a buffer, respectively. In

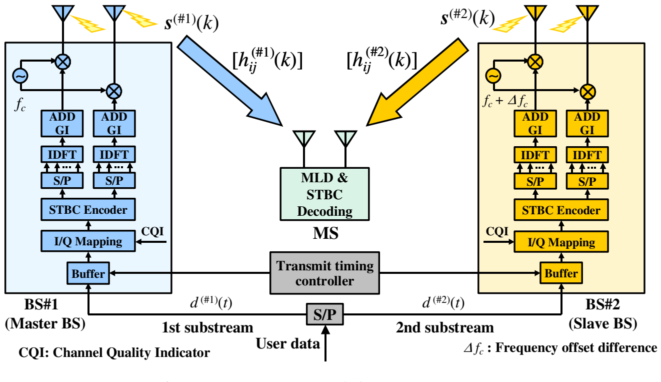

Figure 1: System model ($N_B = 2$, $N_r = 2$).

the next generation MIMO-OFDM based cellular systems, such as LTE and UMB, a 2x2 MIMO is almost assumed as the baseline configuration for downlink transmission. Accordingly, we assume that the BSs and MS are equipped with $N_{t,0} = 2$ transmit antennas and $N_r = 2$ receive antennas, respectively.

Here, we describe our proposed cooperative MIMO transmission scheme. Since each BS and MS are equipped with two transmit and receive antennas, respectively, the two BS cooperation downlink transmission system shown in Fig.1 can be virtually regarded as a 4x2 MIMO transmission system. When the number of receive antennas, N_r, is fewer than the total number of transmit antennas, $N_t = \sum_{n_B=1}^{N_B} N_{t,0}$ (i.e., $N_r < N_t$), precoding techniques are required at the transmitter side in order to decrease inter-antenna interference and to maintain the signal detection accuracy at the receiver side. In this paper, we employ Space-Time block coding based Transmit Diversity (STTD) [5] as it is a simple precoding technique in which the receiver does not require to feedback the full channel state information (full CSI) of the downlink to the transmitter, and BS#1 and BS#2 independently encode different substreams with the Space-Time Block Coding (STBC). Assuming that the timing offset difference (including the multi-path delay) does not exceed the GI, the received signal of the k-th sub-carrier at the MS is represented as

$$\begin{aligned}\begin{bmatrix} x_{1,1}(k) & x_{1,2}(k) \\ x_{2,1}(k) & x_{2,2}(k) \end{bmatrix} &= \begin{bmatrix} h_{11}^{(\#1)}(k) & h_{12}^{(\#1)}(k) \\ h_{21}^{(\#1)}(k) & h_{22}^{(\#1)}(k) \end{bmatrix} \begin{bmatrix} s_1^{(\#1)}(k) & -s_2^{(\#1)}(k)^* \\ s_2^{(\#1)}(k) & s_1^{(\#1)}(k)^* \end{bmatrix} \\ &+ \begin{bmatrix} h_{11}^{(\#2)}(k)e^{j\Delta\theta} & h_{12}^{(\#2)}(k)e^{j\Delta\theta} \\ h_{21}^{(\#2)}(k)e^{j\Delta\theta} & h_{22}^{(\#2)}(k)e^{j\Delta\theta} \end{bmatrix} \begin{bmatrix} s_1^{(\#2)}(k) & -s_2^{(\#2)}(k)^* \\ s_2^{(\#2)}(k) & s_1^{(\#2)}(k)^* \end{bmatrix} + \begin{bmatrix} n_{1,1}(k) & n_{1,2}(k) \\ n_{2,1}(k) & n_{2,2}(k) \end{bmatrix},\end{aligned} \tag{1}$$

where #1 and #2 represent BS#1 and BS#2, respectively. $x_{i,m}(k)$ denotes the m-th $(m = 1, 2)$ received signal in an STTD transmission block at the i-th $(i = 1, \cdots, N_r)$ receive antenna of the MS, $h_{ij}^{(\#\bullet)}(k)$ denotes the channel response from the j-th $(j = 1, \cdots, N_{t0})$ transmit antenna of each BS to the i-th receive antenna of the MS. $s_m^{(\#\bullet)}(k)$ denotes the m-th $(m = 1, 2)$ transmitted signal in an STTD transmission block. $n_{i,m}(k)$ denotes the receiver noise. $\Delta\theta$ denotes the phase offset caused by the frequency offset difference Δf_c.

3. Signal detection algorithm

We assume that the frequency offset difference, Δf_c, is so small that it can be ignored. This means that the proposed cooperative MIMO transmission can be regarded as Double STTD (D-STTD) [3],[4] transmission. From Eq.(1), it is found that 4x2 MIMO based D-STTD transmission system is equivalent to a virtual 4x4 MIMO transmission system model and that the following equations can be derived as

$$\mathbf{x}(k) = \mathbf{H}(k)\,\mathbf{s}(k) + \mathbf{n}(k), \tag{2}$$

$$\mathbf{x}(k) = \begin{bmatrix} x_{1,1}(k) \\ x_{1,2}(k)^* \\ x_{2,1}(k) \\ x_{2,2}(k)^* \end{bmatrix}, \mathbf{H}(k) = \begin{bmatrix} h_{11}^{(\#1)}(k) & h_{12}^{(\#1)}(k) & h_{11}^{(\#2)}(k) & h_{12}^{(\#2)}(k) \\ h_{12}^{(\#1)}(k)^* & -h_{11}^{(\#1)}(k)^* & h_{12}^{(\#2)}(k)^* & -h_{11}^{(\#2)}(k)^* \\ h_{21}^{(\#1)}(k) & h_{22}^{(\#1)}(k) & h_{21}^{(\#2)}(k) & h_{22}^{(\#2)}(k) \\ h_{22}^{(\#1)}(k)^* & -h_{21}^{(\#1)}(k)^* & h_{22}^{(\#2)}(k)^* & -h_{21}^{(\#2)}(k)^* \end{bmatrix}, \mathbf{s}(k) = \begin{bmatrix} s_1^{(\#1)}(k) \\ s_2^{(\#1)}(k) \\ s_1^{(\#2)}(k) \\ s_2^{(\#2)}(k) \end{bmatrix}, \mathbf{n}(k) = \begin{bmatrix} n_{1,1}(k) \\ n_{1,2}(k)^* \\ n_{2,1}(k) \\ n_{2,2}(k)^* \end{bmatrix}. \tag{3}$$

where $\mathbf{x}(k)$, $\mathbf{H}(k)$, $\mathbf{s}(k)$, and $\mathbf{n}(k)$ denote the equivalent received signal vector, the equivalent MIMO CSI matrix, the equivalent transmitted vector and the equivalent noise vector, respectively. The signals from BS#1 and BS#2 are not orthogonal to each other in each subcarrier, so neither the Maximum Ratio Combining (MRC), the Minimum Mean Square Error (MMSE), nor the Ordered Successive Interference Cancellation (Ordered SIC) algorithms can optimally demultiplex the transmit signals in the cooperative MIMO transmission just as in traditional D-STTD systems [3]. Therefore, we apply Maximum Likelihood Detection (MLD) [6] based demultiplexing in this paper. Let $\mathbf{s}_{\text{rep},\,l}$ be the l-th candidate of the equivalent transmitted signal vector, the transmitted signals are demultiplexed based on MLD as given by the following equation.

$$\hat{\mathbf{s}}(k) = \arg\min_{\mathbf{s}_{\text{rep},\,l}} \left\| \mathbf{x}(k) - \mathbf{H}(k)\,\mathbf{s}_{\text{rep},\,l} \right\|^2 \tag{4}$$

Unfortunately, it is well known that the original MLD algorithm suffers from extreme computational complexity when the modulation level is high or the number of substreams is large [2]. Consequently, we use the simplified exact MLD algorithm proposed for D-STTD systems [4].

4. Performance Evaluation

4.1 Simulation Conditions

We evaluated the performance of our proposed cooperative MIMO transmission by computer simulations. Simulation parameters are summarized in Table I. We assumed a two-cell model as shown in Fig.1. The sub-carrier spacing was $f_0 = 15$ kHz, the effective OFDM symbol length $T_s = 1/f_0$, and $N_{sub} = 64$ sub-carriers were used. The GI length T_g was set at a quarter of the effective OFDM symbol length $(T_g = T_s/4)$ and the frame length T was set to 12 times the OFDM symbol lengths ($T = 12(T_s + T_g)$ $= 1$ ms). The transmit data was modulated using BPSK, QPSK, or 16QAM. We assumed that all channels between each BS and the MS were quasi-static fading with spatially uncorrelated fading between the MS antennas. We used a 5-path Rayleigh fading channel with exponential decay of the average received power. The path intervals were equal between adjacent paths, the RMS (root-mean-square) delay spread was 1.1 µs, and the decay factor was 3 dB per path. All paths were subjected to mutually independent Rayleigh fading. The timing offset difference between BS#1 and BS#2 was fixed and set to 1/8 times the effective OFDM symbol length. When adaptive modulation is employed, the modulation levels at BS#1 and BS#2 are selected from NONE, BPSK, QPSK and 16QAM so as to maximize the average throughput. In the computer simulations, two cases were considered. In the case of “with PSRC”, BS#1 and BS#2 independently control the modulation levels. In the case of “without PSRC”, BS#1 and BS#2 always select the same modulation level. Note that the modulation level of “NONE” indicates that no signal is transmitted.

Table I: Simulation Parameters

Number of Base Stations		N_B =2
Number of antennas		BS: 2 (TX side), MS: 2 (RX side)
Sub-carrier spacing		f_0 = 15 kHz
Number of sub-carriers		N_{sub} = 64
Guard interval length		16.6 µs (1/4 eff. OFDM symbol lengths)
Frame length		1ms (12 OFDM symbol lengths)
Modulation		NONE, BPSK, QPSK, 16QAM (Fixed modulation/Adaptive modulation)
Space-time coding		Alamouti STBC based Double STTD
Channel model	Fading model	5-path Quasi-static Rayleigh fading (Uncorrelated fading among each path and each antenna)
	Path model	Equal path interval among each path, (Decay factor: 3dB, Delay spread: 1.1µs)
Timing offset difference		1/8 OFDM symbol lengths (fixed)
Channel estimation		Ideal
Signal detection algorithm		Simplified exact MLD algorithm [4]

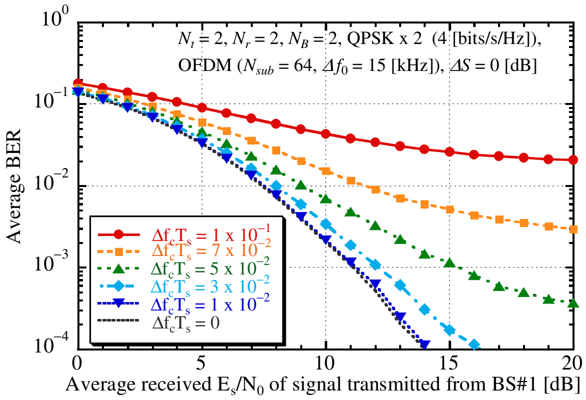

Figure 2: Total BER characteristics
(Parameter: Normalized Frequency Offset: $\Delta f_c T_s$)

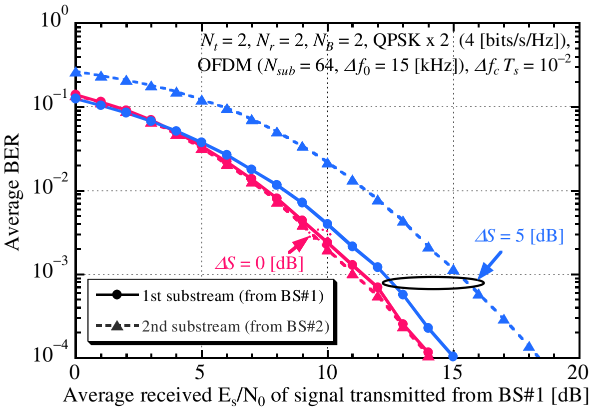

Figure 3: BER characteristics of each substream
(Parameter: Average received power difference)

4.2 Evaluation Results

Figure 2 shows the BER characteristics of the proposed cooperative MIMO transmission, the parameter is the frequency offset difference normalized by the OFDM symbol length, $\Delta f_c T_s$. In this figure, the ratio of the average received power of signals transmitted from BS#1 and BS#2, ΔS, was set to 0 dB, and the transmitted signals were always modulated using QPSK. The figure shows that the BER performance degrades as the frequency offset difference increases and that $\Delta f_c T_s$ should be lower than about 1×10^{-2} in order to avoid significant performance degradation.

Figure 3 shows the BER performance of each stream with the parameter of the average received power of signals transmitted from BS#1 and BS#2, ΔS [dB]. In this figure, the horizontal axis plots the average E_s/N_0 per receive antenna of signal transmitted from BS#1, and $\Delta f_c T_s$ is set to 1×10^{-2}. Increasing ΔS degrades the detection accuracy of the signals transmitted not only by BS#2 but also BS#1 because these signals are demultiplexed by a joint detection algorithm, i.e. MLD.

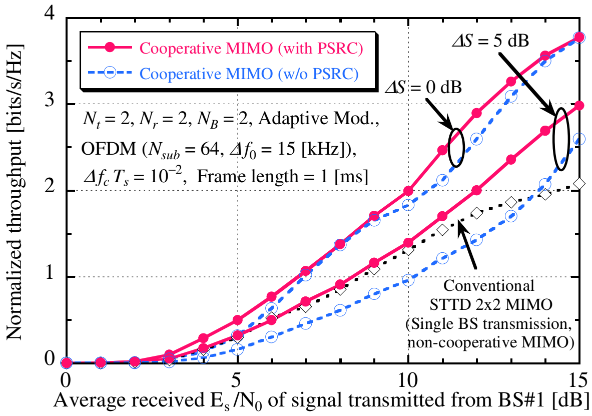

Figure 4: Throughput performance

Figure 4 shows the throughput performance of the proposed cooperative MIMO transmission with the adaptive modulation technique, the parameter is ΔS [dB]. In this figure, $\Delta f_c T_s$ is set to 1×10^{-2}, the solid lines show the performance with the PSRC, and the dashed lines show it without PSRC. Note that the dotted line shows the throughput performance of conventional 2x2 STTD MIMO transmission [5] (single-BS transmission, non-cooperative MIMO). When ΔS is 0 dB, the proposed cooperative MIMO can improve the throughput performance to about 1.4 to 1.8 times that of conventional 2x2 STTD MIMO. Moreover, using PSRC can improve the performance at the average received E_s/N_0 from about 3 dB to 5 dB and from about 10 dB to 13 dB, compared to the case without PSRC.

From Fig.4, it is confirmed that the throughput performance of the proposed cooperative MIMO transmission with/without PSRC in ΔS = 5 dB is degraded compared to that in ΔS = 0 dB, because the detection accuracy of the signals transmitted from not only BS#2 but also BS#1 are degraded when ΔS increases. When ΔS is 5 dB, using PSRC can always attain better performance than conventional 2x2 STTD MIMO. However, the case without PSRC cannot basically offer any throughput performance improvement compared to conventional 2x2 STTD MIMO, especially in the low received E_s/N_0 environment. From these results, it is found that the PSRC technique is especially effective for the proposed cooperative MIMO transmission when there is a significant difference in the average received power of the signals transmitted from BS#1 and BS#2.

5. Conclusions

This paper proposed a cooperative MIMO transmission method based on virtual D-STTD for the downlink of OFDM cellular systems. Computer simulations evaluated its transmission performance with consideration of the frequency offset difference between local oscillators in the coordinated base stations (BSs). The simulation results confirmed that the proposed cooperative MIMO transmission improves the cell-edge throughput performance compared to conventional single-BS based transmission. Moreover, we introduced the Per Site Rate Control (PSRC) technique, in which each BS independently controls its own modulation level, for the proposed cooperative MIMO transmission. The simulation results also confirmed the effectiveness of the PSRC, especially when there is a significant difference in the average received power of the signals transmitted from the coordinated BSs.

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