Robust Beamforming Method for Frequency Offsets in Uplink Multiuser OFDM-MIMO

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Abstract

In uplink MU-MIMO systems, different frequency offsets among multiple mobile stations (MSs) significantly degrade the transmission quality especially when orthogonal frequency division multiplexing (OFDM) is used. In this paper, the influence of the frequency offset is analyzed in a frequency selective fading environment. Moreover, a new beamforming method is proposed to compensate for the frequency offset by introducing an auto frequency controller after the space-frequency equalization in each data stream. The effect of the proposed method is evaluated in a frequency selective fading environment by computer simulation.

1. INTRODUCTION

The recent popularity of wireless local area networks (WLANs) has strengthened the demand for ever higher data rates. However, frequency resources are limited and most frequencies in the microwave band, which are suited to WLANs, have already been assigned to various radio systems. Thus, broadband services must be provided with a limited frequency band and increasing the spectrum efficiency is now one of the most important issues facing the next generation WLAN systems [1]. Multiple–Input–Multiple–Output (MIMO) is one of the most attractive candidates with respect to this issue [2]. In independent distributed fading environments, it can linearly increase the channel capacity with the number of antenna branches. However, the channel capacity depends on the number of antenna branches at the mobile stations (MSs) so the possible improvement in the channel capacity for simple MSs is limited. This results in an overall degradation in throughput when some of the MSs have only a few antenna branches.

To overcome this problem, multiuser MIMO (MU-MIMO) systems were proposed [4],[5],[6]. In MU-MIMO systems, multiple MSs are considered as a large virtual array antenna so that a large MIMO effect is expected even with simple MSs. The MU-MIMO effect is expected not only in the downlink, but also in the uplink. In the uplink, the data rate may be lower than that in the downlink. However, the low data rate MS causes significant degradation in the total throughput regardless of the number of antenna branches at an access point (AP) because the low data rate MSs occupy the most of the time duration for the uplink. On the contrary, in the MU-MIMO systems, all the available spatial channels are assigned to multiple MSs and the spatial resources are effectively used even in a low data rate multiple MS scenario. In the rest of the paper, we will focus on uplink MU-MIMO systems.

In uplink MU-MIMO systems, since a different oscillator is used at each MS, the AP must cope with the frequency offsets among multiple MSs. The influence of the frequency offset becomes significant in orthogonal frequency division multiplexing (OFDM) systems because it corrupts the orthogonality of the frequency sub-channels in OFDM. To suppress the frequency offset effect, a joint-frequency offset estimation method was proposed for MU-OFDM-MIMO [7]. In [7], space-time equalization is also employed to suppress the interference from other frequency sub-channels. However, the calculation load in the decoding process becomes considerable as the number of antenna branches increases. Therefore, a new simple decoding method should be developed for uplink MU-OFDM-MIMO.

In this paper, a new beamforming (BF) method is proposed that employs an auto frequency controller (AFC) after the space-frequency equalization in each spatial channel to ensure robustness against frequency offsets. In the proposed method, only an additional fast Fourier transformation (FFT) and an inverse FFT (IFFT) are required for each spatial channel.

In the rest of the paper, Section 2 analyzes the influence of the frequency offset in a multiple antenna system and shows that the frequency offset causes an error floor in the bit error rate (BER). Section 3 describes the proposed BF method. The simulation results are presented in Section 4 and confirm the effectiveness of the proposed method. Finally, Section 5 summarizes the paper.

2. INFLUENCE OF FREQUENCY OFFSET

A. Analysis of frequency offset in multiple antenna systems

Figure 1 shows a configuration of the uplink MU-OFDM-MIMO. The AP has M_R antenna branches and the p-th MS has $M_T(p)$ antenna branches. The number of users is P. Each MS transmits an independent OFDM signal stream from each antenna branch. The received signal at the antenna branch, m_R, is expressed as

$$r_{m_R}(t)=\sum_{p=1}^{P}\sum_{m_T=1}^{M_T}\sum_{l=1}^{L_p}a_{p,l}(m_R,m_T)s_{p,m_T}(t-\tau_{p,l})+n_{m_R}(t), \quad (1)$$

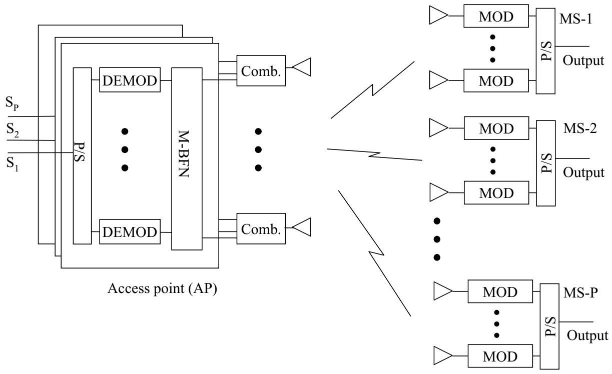


Fig. 1: Configuration of uplink multiuser OFDM-MIMO

where L_p is the number of multi-path waves from the p-th MS to the AP, $a_{p,l}(m_R.m_T)$ is the complex amplitude of the l-th multipath wave from antenna branch m_T at the p-th MS to antenna branch m_R at the AP, $S_{p,mT}$ is the transmit OFDM signal from antenna branch m_T at the p-th MS, $\tau_{p,l}$ is the delay time of the l-th multipath wave from the p-th MS, and n_{mR} is the noise signal at antenna branch m_R. Here, the bandwidth of the transmit signals is assumed to be sufficiently small so the difference in the arrival timing based on the transmit and reception antenna positions is considered as the phase shift. Taking into account the frequency offset at each MS, the transmit OFDM signal, $S_{p,mT}$, is expressed as

$$s_{p,m_T}(t) = \sum_{k_T=1}^{N_{SC}} s_{p,m_T,n}(t) e^{j(\omega_{k_T}+\Delta\omega_p)}, \quad (2)$$

where $\Delta\omega_p$ is the frequency offset at the p-th MS. At the AP, the guard interval (GI) is removed and the FFT is performed for the reception signals. To focus on the influence of the frequency offset, the maximum delay time is assumed to be less than the GI duration, T_{GI}, in the following discussion. The channel response between the k_R-th sub-carrier component at the m_R-th antenna branch of the AP and the k_T-th sub-carrier component at the m_T-th antenna branch of the p-th MS is represented as

$$h_{m_R,p,m_T}(k_R,k_T) = \alpha_p(k_R,k_T)\beta_p(m_R,m_T,k_T), \quad (3)$$

where $\alpha_p(k_R, k_T)$ is defined as

$$\alpha_p(k_R,k_T) = \frac{1}{N}\sum_{n=1}^{N} e^{j(\omega_{k_T}-\omega_{k_R}+\Delta\omega_p)\frac{(n-1)}{N}T}, \quad (4)$$

and $\beta_p(m_R,m_T,k_T)$ is defined as

$$\beta_p(m_R,m_T,k_T) = \sum_{l=1}^{L_p} a_{p,l}(m_R,m_T) e^{-j(\omega_{k_T}+\Delta\omega)\tau_{p,l}}. \quad (5)$$

When the frequency offset, $\Delta\omega_p$, equals zero and k_R is not equal to k_T, $\alpha_p(k_R, k_T)$ becomes zero and the interference from adjacent frequency sub-channels vanishes. However, as $\Delta\omega_p$ increases, the interference from adjacent sub-carriers affects the orthogonality among multiple frequency sub-channels. The spatial correlation at the k_R-th sub-carrier between the desired signal and the interference signal from the k_T-th sub-carrier component of the m_T'-th antenna branch at the p'-th MS is represented as

$$\rho_{p,m_T,p',m'_T}(k_R,k_T) = \frac{\mathbf{g}^H_{p,m_T}(k_R,k_R)\mathbf{g}_{p',m'_T}(k_R,k_T)}{\left|\mathbf{g}_{p,m_T}(k_R,k_R)\right|\left|\mathbf{g}_{p',m'_T}(k_R,k_T)\right|}, \quad (6)$$

where superscript H denotes the conjugate transposition and $\mathbf{g}_{p,mT}(k_R,k_T)$ is defined as

$$\mathbf{g}_{p,m_T} = \left[\beta_p(1,m_T,k_T) \ \cdots \ \beta_p(M_R,m_T,k_T)\right]^T, \quad (7)$$

where superscript T denotes the transposition of the vector or matrix. In a flat fading environment, $\beta_p(m_R,m_T,k_T)$ is independent of k_T, and $\rho_{p,mT,p',mT'}(k_R,k_T)$ becomes independent of k_T. Therefore, for $p' = p$ and $M_T' = M_T$, $\rho_{p,mT,p,mT}(k_R,k_T)$ becomes equal to one and the influence of the frequency offset cannot be suppressed by the reception BF regardless of the number of antenna branches at the receiver. This also indicates that the interference suppression performance for other spatial channels is not degraded even with a large frequency offset in a short delay spread environment. On the other hand, in a long delay spread environment, $\rho_{p,mT,p,mT}(k_R,k_T)$ becomes less than one and the influence of the frequency offsets from the neighboring sub-carriers of the desired spatial channel is mitigated while the amount of interference from other spatial channels increases. Therefore, the interference from other frequency sub-channels of the desired spatial channel affects the transmission quality in a short delay spread environment, while the interference from other spatial channels does so in a long delay spread environment.

B. Simulation result

Single input multiple output (SIMO) and single input single output (SISO) systems were evaluated to clarify the basic influence of the frequency offset in a flat fading environment by the computer simulation. The number of users was one, the number of antenna branch at the MS was one and the number of antenna branches at the AP was one or eight. The modulation was 64QAM, the sub-carrier space was 312.5 kHz, the number of sub-carriers was 48, and T_{GI} was set to 25% of the OFDM symbol. The data length was 10 data symbols. The exponential delay profile, where the maximum delay time was 2 T_{GI}, was used. Figure 2 shows the influence of the frequency offset in the flat fading environment. In the following, Δ % offset indicates the percentage of the frequency offset for the sub-carrier space. As Fig. 2 shows, the frequency offset causes an error floor in the flat fading

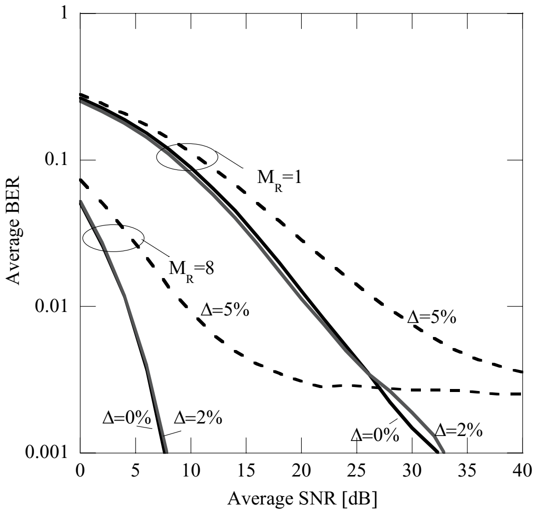


Fig. 2: Influence of frequency offset in single user SISO and SIMO systems

environment regardless of the number of antenna branches when the frequency offset is 5%.

Since the improvement by the array antenna is limited in the short delay spread environment, the interference suppression for the other frequency sub-channels of the desired spatial channel should be achieved without using adaptive BF.

3. PROPOSED METHOD

Figure 3 shows the configuration of the proposed AP BF. In this configuration, first, the GI of the received signals at each antenna branch is removed and those are converted to the frequency dimension by the first FFT. The channel responses are estimated at each frequency sub-channel and used for BF, which is performed at each sub-carrier to suppress the interference from other spatial channels. After the BF, the magnitude of the BF output at each frequency sub-channel is equalized to retain the proper magnitude of the self-interference from the other frequency sub-channels. Next, IFFT is conducted to convert the frequency domain signals to the time domain ones. When the number of available frequency sub-channels is less than that of the IFFT points, zeros are inserted for the unused frequency points. After the IFFT, zeros are inserted to the time domain signals in each OFDM symbol to make the symbol length equal to that of the transmitted signals including the GI. Subsequently, the AFC removes the frequency offset and the time domain signals are converted again to the frequency domain signals by the second FFT. Finally, the signals are demodulated at the demodulator. With this configuration, the influence of the frequency offset is eliminated in the flat fading environment because $\rho_{p,mT,p,mT}(k_R,k_T)$ becomes equal to one for any combination of (k_R,k_T) so the BF block requires only one degree of freedom to suppresses the interference from all sub-carriers in the same undesired spatial channel. The control methods of the BF and the AFC are as follows.

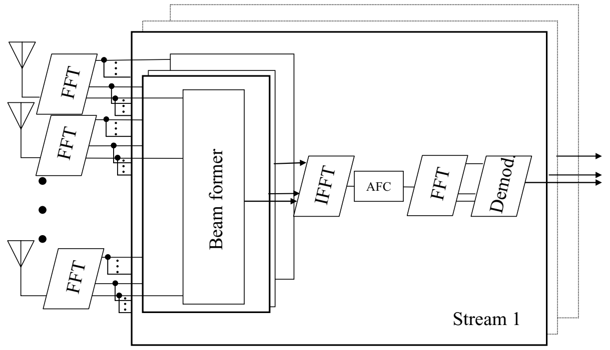


Fig. 3: Proposed AP configuration

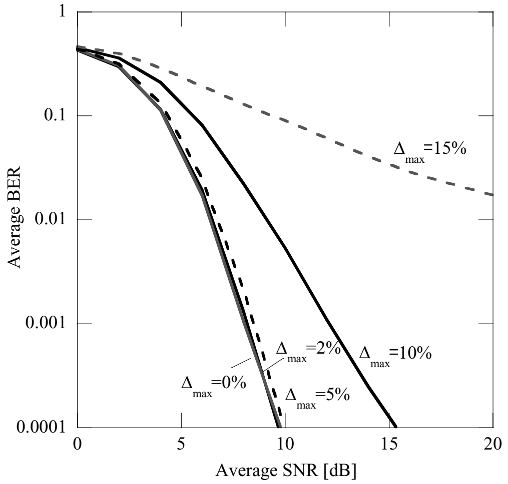
For the BF, training signals are transmitted from each MS at the different time slot to estimate the channel responses between antenna branches at AP and those at each MS. The training signals consist of N_{tr} orthogonal signal sets and the signal sets are periodically assigned to consecutive N_{tr} sub-carrier sets to suppress the influence of the neighboring sub-carriers. The minimum mean squared error (MMSE) algorithm is used to determine the BF weights.

Since the AFC is placed after the BF block in the proposed method, the preambles for the AFC are transmitted simultaneously from all MSs. This simultaneous preamble transmission greatly improves the frame efficiency for the short packet case. Using the preamble, the frequency offset of each spatial channel is estimated respectively and the estimated frequency offset is transferred to AFC. The residual frequency offset is compensated at the demodulator where the phase offset is estimated from multiple pilot sub-carriers during the OFDM data symbols.

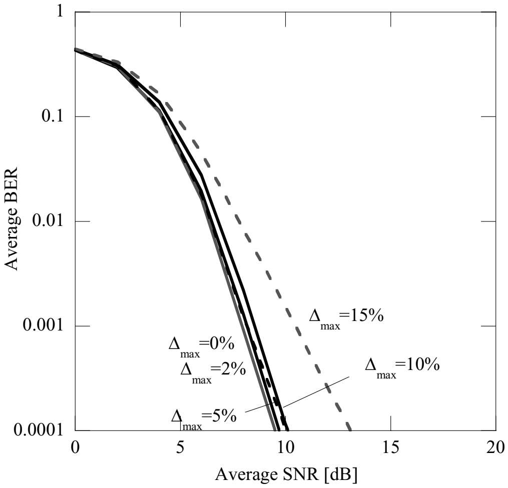
Note that the first FFT blocks are commonly used by multiple spatial channels in the proposed method. Thus, only an additional FFT and an IFFT are required for each spatial channel. In addition, no additional functions and hardware are required at MS so the proposed method is suitable for a multiple simple MS scenario.

4. EFFECT OF THE PROPOSED METHOD

Figure 4 illustrates the influence of the frequency offset for the conventional and proposed methods in the frequency selective fading environments. The number of antenna branches was eight and the number of users was four. The modulation was 64QAM and the delay spread was 100 nsec. The convolutional code is used and a soft-decision Viterbi decoder is applied to the receiver. The convolutional encoder employed, $g_0=133_8$ and $g_1=171_8$, of rate $R=1/2$ [8]. An interleaver and deinterleaver were used to randomize the error. The coding rate was 1/2 and the other parameters are the same as those described in the previous subsection. The perfect channel response estimation was assumed and no arrival timing offsets among multiple MSs were assumed. The frequency offsets of the MSs were uniformly distributed



(a) Conventional method



(b) Proposed method

Fig.4: Average BER performance with coding (r = 1/2)

between $-\Delta_{max}$ % to $+\Delta_{max}$ %, where Δ_{max} is the maximum frequency offset. The other simulation parameters were the same as those in Section 2. In the conventional method, the output of the BF block in Fig. 3 was directly input into the demodulator and the phase offsets were perfectly removed at the demodulator. One hundred environments were evaluated and the average BER performance for all MSs is shown in Fig. 4. Figure 4(a) shows the average BER performance of the conventional method and Fig. 4(b) shows that for the proposed method.

As these figures show, the proposed method with a 10% frequency offset experienced degradation in the required average SNR of less than 1 dB for the BER of 10^{-4}, while degradation of greater than 5 dB occurred in the conventional method. The results confirmed the effect of the proposed method in the frequency selective environment.

5. CONCLUSION

In this paper, the influence of the frequency offset in MU-OFDM-MIMO in the uplink was investigated. Numerical analysis showed that an error floor occurs in the BER and the influence of the frequency offset becomes larger in a short delay spread environment. To overcome this problem, a new BF method was proposed to compensate for the frequency offset by introducing the AFC after the space-frequency equalization in each spatial channel. Since the proposed method uses a common FFT at each antenna branch for all spatial channels, adequate hardware complexity is required. Simulation results with coding showed that the proposed method with a 10% frequency offset experienced degradation in the required average SNR of less than a mere 1 dB for the BER of 10^{-4}, while degradation of greater than 5 dB occurred in the conventional method. These results confirmed the effectiveness of the proposed method.

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