MULTIUSER DETECTION METHOD ROBUST AGAINST FREQUENCY OFFSETS IN UPLINK MIMO-OFDM

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ABSTRACT

The increasing pupularity of mobile computing has pushed the demand for a support for a larger number of users and a very high sprectrum efficiency must be achieved in the futre wireless access systems. Multiuser multiple input multiple output (MU-MIMO) systems are attracting attention due to their frequency efficiency. However, 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 these frequency offsets is analyzed in a frequency selective fading environment. Numerical analysis shows that an error floor occurs in the bit error rate and the influence of the frequency offset becomes larger in short delay spread environments. To overcome this problem, a new multiuser detection method (MUD) is proposed to compensate for the frequency offset by introducing an auto frequency controller after frequency-space equalization in each data stream. To evaluate the effect of the proposed method in an actual indoor propagation environment, the measurement system was developed. The effect of the proposed method is evaluated in a frequency selective fading environment by computer simulations and measured results.

Key words: MIMO, multi-user, OFDM, frequency offset, carrier synchronizatoin.

1. INTRODUCTION

The recent popularity of wireless local area networks (WLANs) has strengthened the demand for a support of large number of users. 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, large number of users must be supported within a limited frequency band and increasing the spectrum efficiency is 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] [3] [4]. In independent distributed fading environments, it makes the channel capacity linear against 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 insufficient improvement in the overall spectrum efficiency when most of the MSs have only a few antenna branches.

To overcome this problem, multiuser MIMO (MU-MIMO) systems were proposed [5],[6],[7]. 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 simple MS may use the low data rate mode due to the lower transmit power. However, it causes significant degradation in the total throughput of single user MIMO (SU-MIMO) systems regardless of the number of antenna branches at an access point (AP) because the low data rate MSs occupy the most of the time reserved for the uplink. On the contrary, in MU-MIMO systems, all of the available spatial channels are assigned to multiple MSs so the spatial resources are used effectively even in the 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 the 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. In a single user scenario, the AP estimates the frequency offset from the known preamble signals and compensates the frequency offset by an auto frequency controller (AFC) before the fast Fourier transformation (FFT). Thus, the corruption of orthogonality of the frequency sub-channel can be

avoided. However, in a multiuser scenario, multiple signals from MSs are superimposed on the received signals so the different frequency offsets among multiple MSs cannot be compensated simultaneously with the same manner. To suppress the frequency offset effect, a joint-frequency offset estimation method was proposed for MU-MIMO-OFDM [8]. In [8], space-time equalization is also employed to suppress the interference from other frequency sub-channels. However, the calculation load in the decoding process becomes excessive as the number of antenna branches increases. Therefore, a new simple decoding method should be developed for uplink MU-MIMO-OFDM.

In this paper, first, the effect of the frequency offset is investigated for uplink MU-MIMO-OFDM. A numerical analysis shows that an error floor occurs in the bit error rate (BER) with a slight frequency offset and the influence of the frequency offset becomes significant in short delay spread environments. To overcome this problem, a new multiuser detection (MUD) method is proposed that employs an AFC after the frequency-space equalization in each data stream to ensure robustness against the frequency offset. In the proposed method, the signals for other spatial channels are suppressed during space-frequency equalization to adjust the proper self-interference from other frequency sub-channels. Subsequently, the frequency domain signals are converted into the time domain and the frequency offset is removed using the AFC. In the proposed method, only an additional FFT and an inverse FFT (IFFT) are required for each data stream. The effect of the proposed method is evaluated in frequency selective fading environments by computer simulations and measured results.

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 BER. Section 3 describes the proposed robust MUD for the frequency offsets and training signals used for channel response estimation. The simulation results presented in Section 4, together with measured results, confirm the effectiveness of the proposed method. Finally, Section 5 summarizes the paper

2. INFLUENCE OF FREQUENCY OFFSET

2.1. Analysis of frequency offset in multiple antenna systems

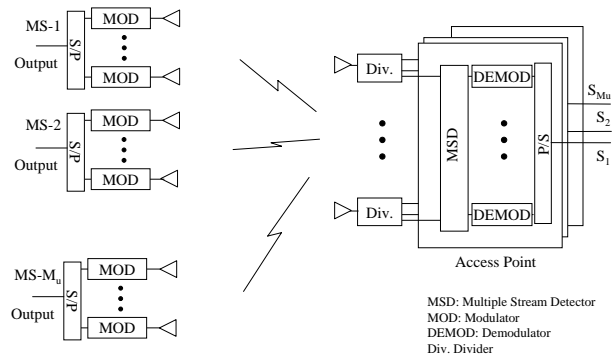Figure 1 shows the configuration of the uplink multiuser MIMO-OFDM. The AP has M_R antenna

Figure 1. Multiuser MIMO system.

branches and the p-th MS has $M_T(p)$ antenna branches. The number of MSs is P. All MSs transmit signals to the same AP simultaneously. At each MS, an independent OFDM signal stream is transmitted from each antenna branch. In multipath environment, the received signal at the antenna branch, m_R, is expressed as

$$r_{m_R}(t) = \sum_{p=1}^{P} \sum_{m_T=1}^{M_T} \sum_{l=1}^{L_P} a_{p,l}(m_R, m_T) S_{p,m_T}(t - \tau_{p,l})$$

$$+ n_{m_R}(t) \quad , \tag{1}$$

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,m_T} is the transmit OFDM signal from antenna branch mT 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_{m_R} is the noise signal at antenna branch m_R. Here, the bandwidth of the transmit signals is assumed to be so small that the difference in the arrival timing based on the transmit and reception antenna positions is considered to represent the phase shift. Taking into account the frequency offset at each MS, the transmit OFDM signal, S_{p,m_T}, is expressed as

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

where $\Delta\omega_p$ is the frequency offset at the p-th MS. At the AP, the guard interval (GI) is removed and 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. Since the frequency offsets are different among multiple MSs, the orthogonality of the frequency sub-channels at the AP is affected. 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

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

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

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

where N is the number of FFT points and $\beta(m_R, m_T, k_T)$ is defined as

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

$$\rho_{p,m_T,p',mT'}(k_R, k_T) = \frac{\mathbf{g}_{p,M_T}^{H}(k_R)\,\mathbf{g}_{p',M'_T}(k_T)}{|\mathbf{g}_{p,m_T}(k_R)|\,|\mathbf{g}_{p'},m'_T(k_T)|},$$
(6)

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

$$\mathbf{g}_{p,m_T}(k) = \left[\begin{array}{ccc} \beta_p(1, m_T, k) & \cdots & \beta_p(M_R, m_T, k) \end{array}\right]^{T},$$
(7)

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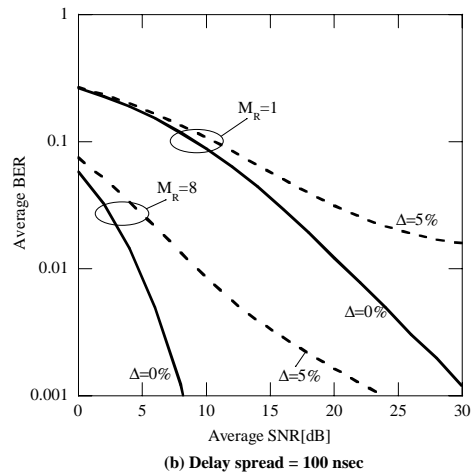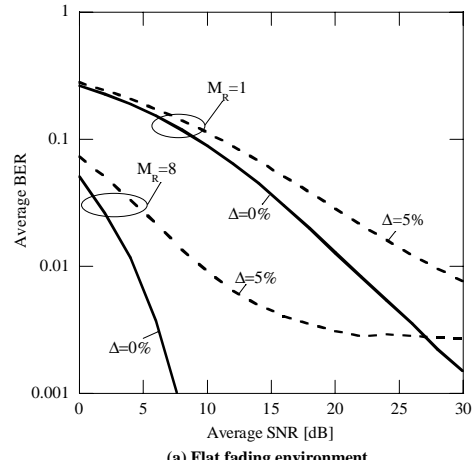

(a) Flat fading environment

(b) Delay spread = 100 nsec

Figure 2. Influence of the frequency offset in single user SISO/SIMO system.

2.2. Simulation results

Single input multiple output (SIMO) and single input single output (SISO) systems were evaluated to clarify the basic influence of the frequency offset in flat and frequency selective environments. Table 1 shows the simulation conditions. The data length was 10 OFDM symbols. The exponential delay profile with maximum delay time of $2\,T_{GI}$ was used. The frequency offset is assumed to be perfectly removed at the demodulator placed after the FFT.

Figure 2 shows the influence of the frequency offset in the flat and the frequency selective fading environments. In the following, $\Delta\%$ offset indicates the percentage of the maximum frequency offset for the sub-carrier space. As Fig. 2 shows, T_{GI} is sufficiently large and almost the same BER performance is obtained for both delay spreads when the frequency offsets do not exist. As Fig. 2(a) shows, the frequency offset causes an error floor in the flat fading environ-

Table 1. Simulation conditions

Modulation	64QAM
Bandwidth	20MHz
Subcarrier space	312.5kHz
T_{GI}	800 nsec
M_T	1
P	1
M_r	1/8
Channel model	Exponential delay profile
Delay spread	0/100 nsec

ment regardless of the number of antenna branches when the frequency offset is 5%. On the other hand, as shown in Fig. 2(b), the error floor is lowered by the receiver array antennas in the frequency selective fading environment. However, the required SNR for the BER of 10^{-3} still increases more than 10dB even with eight antenna branches at AP when the frequency offset is 5%. Since the improvement by the array antenna is limited in the short delay spread environment, some other technique is required to suppress the error floor.
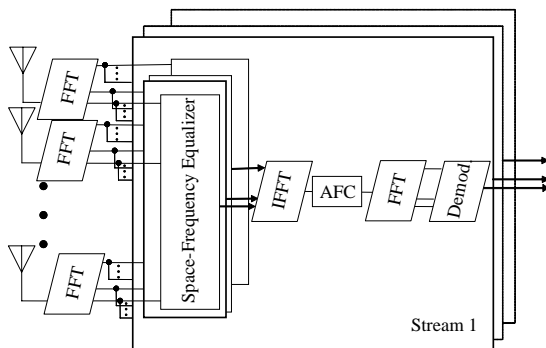
3. PROPOSED METHOD

Figure 3. Configuration of the proposed AP.

As described in the previous section, a short delay spread is expected to suppress the undesired spatial signals from the undesired spatial signal stream. On the other hand, a longer delay spread mitigates the influence of the frequency offset on the desired spatial signal stream. To satisfy these requirements, we propose a new two-stage MUD method. Figure 3 shows the configuration of the proposed MUD at AP. First, the received signals at each antenna branch are converted into the frequency dimension by the first FFT. The channel responses are estimated at each frequency sub-channel and used to determine the weights at the space-frequency equalization block. N_{tr} orthogonal signal sets are periodically assigned as training signals to consecutive N_{tr} sub-carrier sets to suppress the influence of the neighboring sub-carriers. Therefore,

in the flat fading environment, the interference from other subcarriers becomes less than -20dB for the frequency offset of 10% when N_{tr} is four.

MUD is performed at each sub-carrier to suppress the interference from other users. The minimum mean squared error (MMSE) algorithm is used to determine the weight vector at MUD. Subsequently, the magnitude of the output amplitude 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 on each spatial sub-channel 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 FFT points, zeros are inserted for the unused frequency points. Subsequently, the AFC removes the frequency offset and the time domain signals are converted again into the frequency domain signals using the second FFT. Since the AFC is placed after the space-frequency equalization 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.

4. EFFECT OF THE PROPOSED METHOD

This section compares the average BER performance of the proposed method to that of the conventional method for MU-MIMO-OFDM to confirm the effectiveness of the proposed method with / without forward error correction. Furthermore, measured results are presented to confirm the actual effect of the proposed method.

4.1. Average BER performance without coding

Figure 4 and 5 illustrates the influence of the frequency offset on the conventional and proposed methods in frequency selective fading environments. The number of users was four and the delay spread was 0 nsec or 100 nsec. Perfect channel response estimation was assumed along with no arrival timing offsets among multiple MSs. The frequency offsets of the MSs were uniformly distributed between $-\Delta_{max}$ % to Δ_{max} %, where Δ_{max} is the maximum frequency offset. The other simulation parameters were the same as those in Table 1. In the conventional method, the output of the space-frequency equalization block in Fig. 3 was directly input into the demodulator and the phase offsets were perfectly removed at the demodulator.
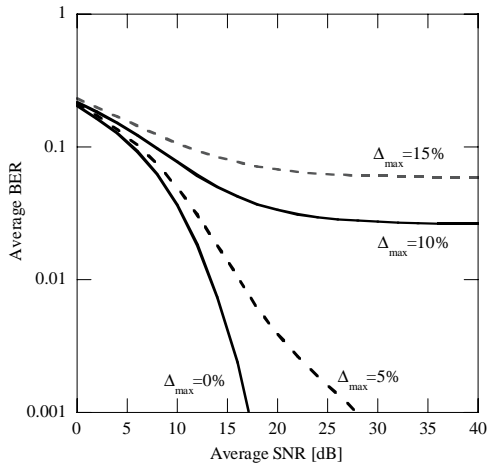
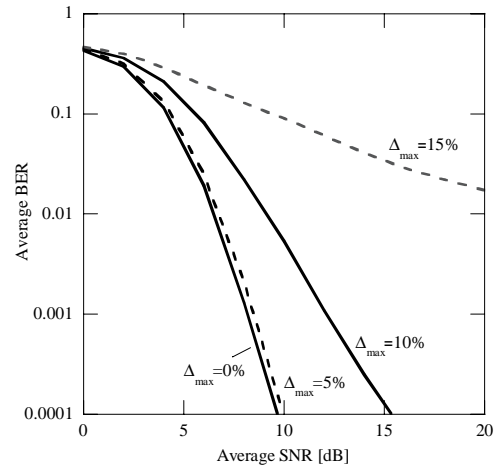*Figure 4. Average BER of conventional method without coding.*

Figure 6. Average BER of conventional method with coding.
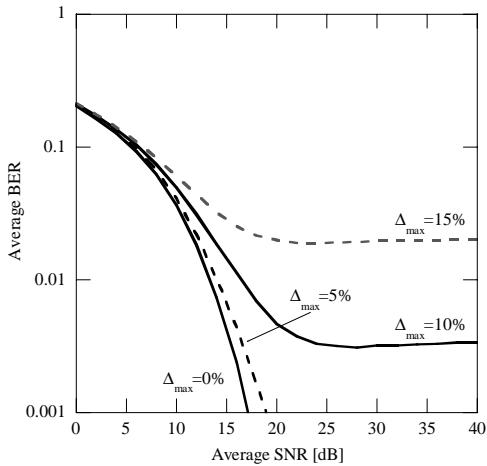

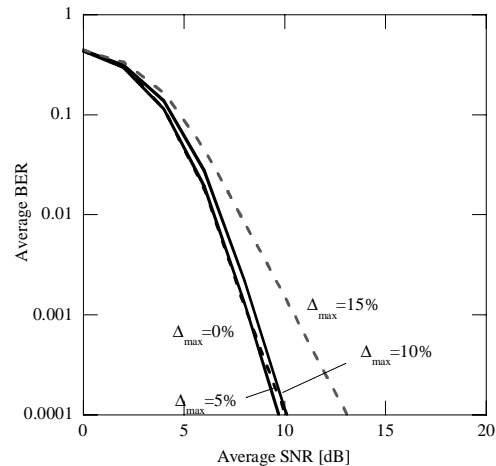*Figure 5. Average BER of proposed method without coding.*

Figure 7. Average BER of proposed method with coding.

As Fig. 4 and Fig. 5 show, a 5% frequency offset caused degradation of 2 dB in the proposed method at the average BER of 10^{-3}, while degradation was approximately 10 dB in the conventional method. We also conducted computer simulations for a flat fading environment and the proposed method achieved better performance. These results confirm that the proposed method is effective in a practical delay spread environment.

4.2. Average BER performance with coding

Figure 6 and 7 show the average BER performance with coding. The convolutional code was used and a soft-decision Viterbi decoder was used at the receiver. The convolutional encoder employed, $g_0 = 133_8$ and $g_1 = 171_8$, with rate R=1/2 [8]. An inter-

leaver and deinterleaver were used to randomize the error. The coding rate was 1/2 and the other parameters were the same as those described in the previous subsection. One hundred environments were evaluated. Figure 6 shows the average BER performance of the conventional method and Fig. 7 shows that of the proposed method. As these figures show, the influence of the frequency offset is suppressed by coding in both cases. Moreover, the proposed method with a 10% frequency offset experienced degradation in the required average SNR of less than 1dB for the BER of 10^{-4}, while degradation of greater than 5dB occurred with the conventional method. These results confirm the effectiveness of the proposed method with coding in the frequency selective environment.

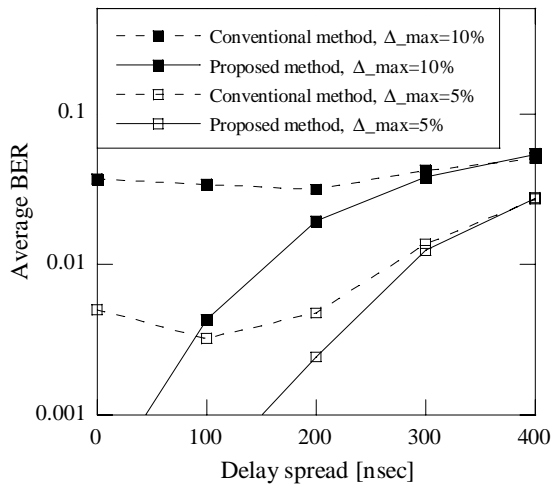Figure 9 shows the influence of the delay spread for the proposed method. The SNR was set to 20dB and

Figure 8. Influence of the delay spread.

Figure 9. Conventional method (MSE=-14.9dB).

the average BER without coding is shown in FIg. 9. As the delay spread increases, the correlation between frequency sub-channels becomes less and the advantage of the proposed method is reduced. Since the typical delay spread in the indoor environment is around 100 nsec, this result confirms that the proposed method is effective for actual indoor wireless access systems. Notet that the advantage can be maintained even for the long delay spread environment by increasing the number of sub-carriers.

4.3. Measurement results

Measurements were conducted in a typical office room of 40m 30m with metal walls. Two MSs transmitted signals simultaneously to an AP with eight antenna branches. The element space at AP was 1.0λ and each MS had single antenna. AP–MS distance was 10 m. Vertical polarization was used. The angular separation of the two MSs was 20 degrees. The center frequency was 4.85GHz and the bandwidth was 20MHz. 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 modulation of both MSs was QPSK and the frequency offset was 10% for the frequency sub-channel space. The number of training symbols was four.
Figure 9 and 10 show the constellation of MS-2. As this figure shows, the proposed method significantly improved the transmission quality. The mean squared error (MSE) of the proposed method was -21.1dB while that of the conventional method was -14.9dB. Thus, the proposed method improved the MSE by 6.2dB which confirms the effectiveness of the proposed method.
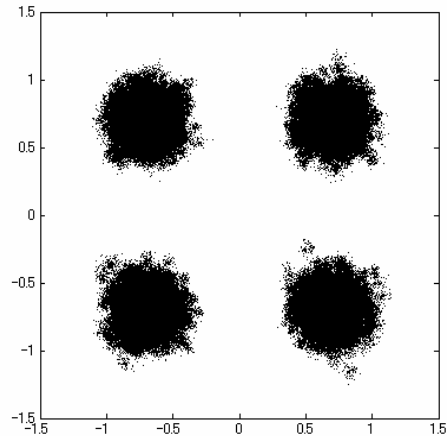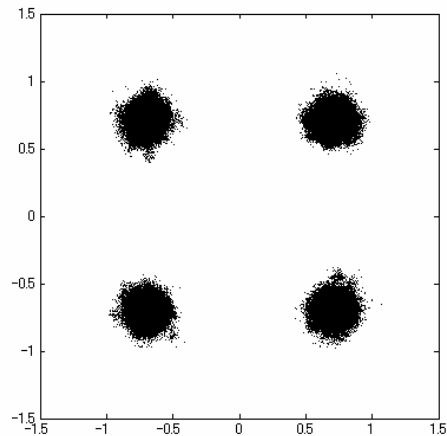

Figure 10. Proposed method (MSE=-21.1dB).

5. CONCLUSION

In this paper, the influence of the frequency offset in the uplink of MU-MIMO-OFDM was investigated. Numerical analysis showed that an error floor occurs in the BER and the influence of the frequency offset becomes larger in short delay spread environments. To overcome this problem, a new MUD method was proposed; it compensate the frequency offset by introducing AFC after frequency-space equalization in each data stream. Since the proposed method uses a common FFT at each antenna branch, hardware complexity is reasonable.

Simulation results without coding showed that a 5% frequency offset caused degradation of 2 dB with the

proposed method at the average BER of 10^{-3}, while the conventional method yielded a degradation of approximately 10 dB. Moreover, by using coding and a soft-decision Viterbi decoder, the influence of the frequency offset was significantly suppressed and the proposed method with 10% frequency offset experienced degradation in the required average SNR of less than 1 dB for the BER of 10^{-4}, while degradation greater than 5 dB occurred with the conventional method. Moreover, the measured results showed that the proposed method improved the MSE by 6.2dB in an actual indoor propagation environment. These results confirmed the effectiveness of the proposed method.

ACKNOWLEDGEMENT

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