A COMPARATIVE ANALYSIS OF CDM-OFDMA AND MC-CDMA SYSTEMS

Wei Zhang and Jürgen Lindner
Department of Information Technology, University of Ulm
Albert-Einstein-Allee 43, 89081 Ulm, Germany
{wei.zhang,juergen.lindner}@uni-ulm.de

Abstract In this paper we investigate CDM-OFDMA and MC-CDMA systems comparatively. The impacts of frequency offsets on both systems are studied. Conventional CDM-OFDMA, interleaved CDM-OFDMA, conventional MC-CDMA, interleaved CDM-OFDMA and MC-CDMA with maximum frequency diversity are considered. Three aspects are taken into account: system structure, parameter estimation and system performance. It is shown that interleaved CDM-OFDMA is possibly more suitable for uplink transmission than MC-CDMA because of its less parameter estimation complexity.

1. Introduction

CDM-OFDMA (Code Division Multiplexing - Orthogonal Frequency Division Multiple Access, also called SS-MC-MA by S. Kaiser) and MC-CDMA are the combination of multi-carrier (OFDM) and spread spectrum techniques in different ways [1]. In CDM-OFDMA users are separated in frequency. The simultaneously transmitted symbols of an individual user are spread over his own subcarriers to attain frequency diversity. In MC-CDMA systems, however, all subcarriers are available for any individual user such that the maximum frequency diversity can be obtained. User separation is realized by distinct spreading codes.

In this paper the systems are compared in the presence of frequency offsets. For simplicity time synchronization is assumed. A typical channel model in case of wireless communication, frequency selective fading channel, is considered in the simulation. By comparing CDM-OFDMA with MC-CDMA in terms of system structure, parameter estimation and system performance, we try to find out which system should be preferred with respect to implementation.

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The reminder of the paper is organized as follows. In section 2 the system models of CDM-OFDMA and MC-CDMA are described, and influences of frequency offsets and frequency selective fading channels are studied briefly. In section 3 we compare both systems and section 4 concludes the paper.

2. System Model

2.1 Downlink Transmission

A vector-valued downlink transmission model of CDM-OFDMA in the presence of frequency offset can be expressed as [1]:

$$\tilde{\mathbf{x}}_{*,i} = \exp(j2\pi i\epsilon(1+\frac{N_g}{N_f}))\hat{\mathbf{E}}\mathbf{H}\mathbf{T}\mathbf{U}\mathbf{x}_{*,i} + \mathbf{n}_i, \qquad (1)$$

where $\mathbf{x}_{*,i}$ contains the transmit symbols from all active users, which are convolutionally encoded and then PSK-mapped. $\mathbf{H}$ is the channel matrix in frequency domain with channel transfer functions on its main diagonal. ϵ represents the frequency offset (FO) normalized to subcarrier spacing. $\hat{\mathbf{E}}$ stands for the influence of a frequency offset on OFDM in frequency domain, and $\exp(j2\pi i\epsilon(1+\frac{N_g}{N_f}))$ is the time-variant phase error due to frequency offset. N_f and N_g are the length of $\mathbf{x}_{*,i}$ and the length of guard interval, respectively. $\mathbf{U}$ represents a spreading matrix. Let $\mathbf{U}_k$ denote the user-specific spreading matrix of user k with the structure

$$\mathbf{U}_k = \begin{pmatrix} 0 & & & \mathbf{0} \\ & \ddots & & \\ & & \mathbf{W}_k & \\ & & & \ddots \\ \mathbf{0} & & & 0 \end{pmatrix}_{N_f \times N_f} \qquad (2)$$

where $\mathbf{W}_k$ is called the user-specific spreading submatrix of size $P \times P$. Each column of $\mathbf{W}_k$ is a spreading codeword, e.g., from an Walsh-Hadamard code. For any l and k, $1 \le l, k \le K$, $\mathbf{W}_l$ and $\mathbf{W}_k$ can be either the same or distinct. So $\mathbf{U} = \sum_{k=1}^{K} \mathbf{U}_k$ is a block diagonal matrix with $\{\mathbf{W}_k\}_{k=1}^{K}$ on the main diagonal. In (1) the square matrix $\mathbf{T}$ specifies the subchannel assignment scheme. It works as a subcarrier interleaver. In conventional CDM-OFDMA $\mathbf{T} = \mathbf{I}$ is an identity matrix. Interleaved CDM-OFDMA is defined, if subcarriers of a certain user are selected with an equidistance greater than one.

The expression in (1) is also suitable for MC-CDMA, except that some notations should be redefined. First of all, $\mathbf{x}_{*,i}$ symbols from distinct users are assigned in a interleaved order in comparison to that in CDM-OFDMA. Secondly, although $\mathbf{U} = \sum_{k=1}^{K} \mathbf{U}_k$ holds, the structure of $\mathbf{U}_k$

is redefined as

$$\mathbf{U}_k = \begin{pmatrix} \mathbf{W}_{k,1} & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \mathbf{W}_{k,2} & \dots & \mathbf{0} \\ \mathbf{0} & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \dots & \mathbf{W}_{k,P} \end{pmatrix}_{N_f \times N_f}, \tag{3}$$

where the user-specific spreading submatrix $\mathbf{W}_{k,p}$ is a $K \times K$ matrix. Its kth column is a spreading sequence of user k on the pth subchannel. All elements in other columns are zero. For any p and q, $\mathbf{W}_{k,p}$ and $\mathbf{W}_{k,q}$ can be the same or different, but $\mathbf{W}_{l,p}$ and $\mathbf{W}_{k,q}$ must be different for any $l \neq k$. An interleaved scheme is defined, if subcarriers assigned to a symbol of a certain user are distributed in a interleaved way. An alternative is that each symbol is spread over all available subcarriers, and thus the maximum frequency diversity can be obtained. In such case each symbol has an individual spreading code to distinguish the symbols of a certain user.

2.2 Uplink Transmission

The general description for the uplink transmission of CDM-OFDMA is given by [1]

$$\tilde{\mathbf{x}}_{*,i} = \sum_{k=1}^{K} \exp(2\pi i \epsilon_k (1 + \frac{N_g}{N_f}))\hat{\mathbf{E}}_k \mathbf{H}_k \mathbf{T}\mathbf{U}_k \mathbf{x}_{*,i} + \mathbf{n}_i. \tag{4}$$

The joint operation of $\mathbf{TU}_k$ extracts the $\mathbf{x}_{k,i}$ from $\mathbf{x}_{*,i}$, spreads them and assigns them to the subcarriers belonging to user k. It ensures that the vector after spreading ($\mathbf{U}_k$) has the same form as the unspread vector in OFDMA. A simplified expression can therefore be given (see [1]). If (4) is used for MC-CDMA, according to (3) each individual user will occupy all available subcarriers. Eq. (4) can not be simplified then.

2.3 Influence of Frequency Offset and Frequency Selective Fading Channel

Consider the downlink transmission of MC-CDMA and CDM-OFDMA in the presence of a frequency offset. In case of an ideal channel, according to $\hat{\mathbf{E}}$, the orthogonality between OFDM-subcarriers is destroyed by the frequency offset, which gives rise to amplitude reduction and phase rotation of desired OFDM-symbols as well as intercarrier interference (ICI). Furthermore, the ICI destroys the orthogonality between code-division subchannels [1, 7]. The resulting interference can be classified to self-interference (SI) from the same user and multiuser interference (MUI) from other users, which degrade the system performance. In addition, if the frequency offset is not compensated, a time-variant phase error $\exp(j2\pi i\epsilon(1+\frac{N_g}{N_f}))$ should be taken into account.

In a multipath propagation scenario, the frequency selective behavior of the channel also destroys the orthogonality of code division subchannels. In the presence of frequency offset, channel transfer functions scale the desired OFDM-symbols and the amount of the crosstalk between OFDM-subcarriers. After despreading the interference is caused by the joint effects of frequency offset and frequency selective fading channel.

3. Comparison of CDM-OFDMA and MC-CDMA

3.1 Comparison of System Structure

Both MC-CDMA and CDM-OFDMA are the combination of multicarrier and spread spectrum techniques. From the system description above we can see that the structure of MC-CDMA is similar to that of CDM-OFDMA. The essential difference between CDM-OFDMA and MC-CDMA is their multiple access mode: in the former case users are separated in frequency (OFDMA) and in the latter case by distinct spreading codes (CDMA). Compared with single user OFDM transmission, the system complexity of CDM-OFDMA and MC-CDMA will increase.

CDM-OFDMA is an extension of the OFDMA. It takes advantage of spread spectrum to achieve frequency diversity in a given subcarrier group. The simultaneously transmitted symbols of a certain user are separated by different spreading codes. Therefore, the power efficiency is limited by the number of subcarriers belonging to each individual user.

MC-CDMA, however, is an extension of CDMA with spreading in frequency domain. the maximum frequency diversity can be obtained if a symbol is spread over all available subcarriers.

3.2 Comparison of Parameter Estimation

Parameter estimation in communication systems is of importance, because estimation errors can degrade the overall system performance. In the following the estimation complexity in CDM-OFDMA and MC-CDMA will be analyzed. We begin with the downlink transmission.

In the downlink, at the mobile terminal receiver received symbols experience the same physical channel and have the same frequency offset. Therefore, the synchronization and channel estimation approaches

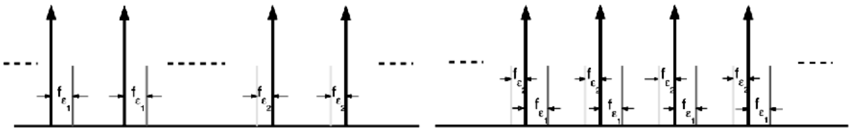

Figure 1. Frequency offsets distribution in the uplink of CDM-OFDMA (left) and MC-CDMA (right) systems.

for single user OFDM can be implemented in CDM-OFDMA and MC-CDMA downlink without or with slight change according to the special transmission schemes.

In the uplink, received signals at the base station receiver are from all active users which undergo different different channels and possibly have different frequency offsets. The distinction of multiple access mode determines that different parameter estimation complexity in CDM-OFDMA and MC-CDMA uplink. Figure 1 illustrates the distribution of frequency offsets in the uplink of both systems. On any individual subcarrier, in CDM-OFDMA only one frequency offset plays the main role, since users are roughly separated in frequency and each subcarrier carries the signals from an individual user; whereas in MC-CDMA multiple FOs belonging to different users are of the same importance. Therefore, in the former case the estimation of frequency offsets will possibly be simpler than in the latter case.

For the same reason, in the CDM-OFDMA uplink channel estimation for a certain user can be done simply in frequency domain under assumption of perfect synchronization. This implies that synchronization and parameter estimation approaches developed for OFDMA uplink can be implemented without change or with slight change. Furthermore, phase rotation due to frequency offsets can still be detected even if the interference from other users exists.

In MC-CDMA uplink after FFT on each subcarrier the received signal is the superposition of symbols weighted by different channel transfer functions and possibly with different frequency offsets. This coexistence leads to the increase of parameter estimation complexity. After despreading users are roughly separated from one another, but the information of channel characteristics is also destroyed, especially in the presence of synchronization error. The parameter estimation hereby becomes a crucial task in the uplink of MC-CDMA.

3.3 Comparison of System Performance

To compare the system performance, a linear minimum mean square error multiuser detector (LMMSE-MUD) is implemented in the mobile

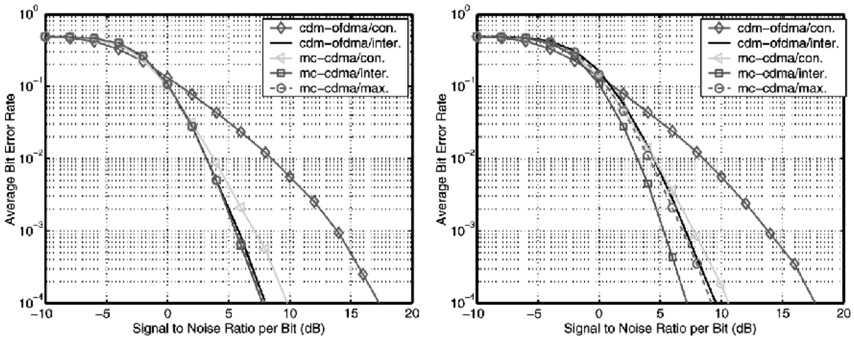

Figure 2. The average BER performance in the downlink transmission over frequency selective fading channel with (right) and without (left) frequency offset.

terminal and base station receiver. The symbol vector before the decision becomes then

$$\tilde{\mathbf{r}}_{*,i} = (\mathbf{R}^H\mathbf{R} + \frac{\sigma_n^2}{\sigma_s^2}\mathbf{I})^{-1}\mathbf{R}^H\tilde{\mathbf{x}}_{*,i}. \qquad (5)$$

$\mathbf{R} = \sum_{k=1}^{K} \hat{\mathbf{E}}_k\mathbf{H}_k\mathbf{T}\mathbf{U}_k$ is the equivalent channel matrix. σ_s^2/σ_n^2 represents signal to noise ratio (SNR).

In the simulations perfect timing is assumed. Furthermore, we assume that perfect knowledge of channel state information and frequency offsets are available. The channels are supposed to be frequency selective Rayleigh fading with impulse responses generated according to a 8-tap Rayleigh fading power delay profile [7]. The channel impulse responses (CIR) keep constant during one vector duration, i.e., block fading is assumed. The normalized frequency offsets are uniformly distributed in the range of [-0.33, 0.33]. The transmit symbols are first encoded by convolutional encoder C(133,171) of rate $R = 1/2$, and then QPSK-mapped. Walsh-Hadamard codes are used as spreading codes. In the simulation $N_f = 64$, $N_g = 16$ and $K = 4$. The time-variant phase error due to frequency offset is not taken into account in the simulation.

Figure 2 illustrates the average bit error rate (BER) performance of downlink transmission over frequency selective fading channel. It can be seen that without frequency offset the similar performance is obtained by interleaved CDM-OFDMA, interleaved MC-CDMA and MC-CDMA with the maximum frequency diversity (marked ‘mc-cdma/max.’ in the figure). Compared with transmission over AWGN channel (left figure in Fig. 3), about $5 \sim 6$ dB performance loss results from frequency selective behavior of the channel. In the presence of frequency offsets, the performance of different transmission systems degrade differently. Conventional MC-CDMA, MC-CDMA with the maximum frequency

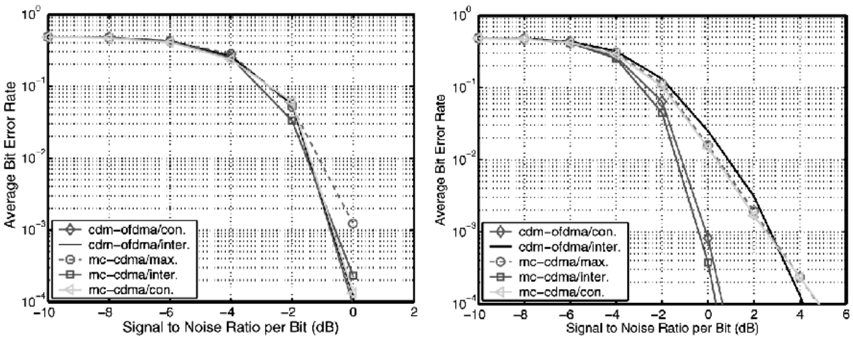

Figure 3. The average BER performance in the uplink transmission over AWGN channel with (right) and without (left) frequency offsets.

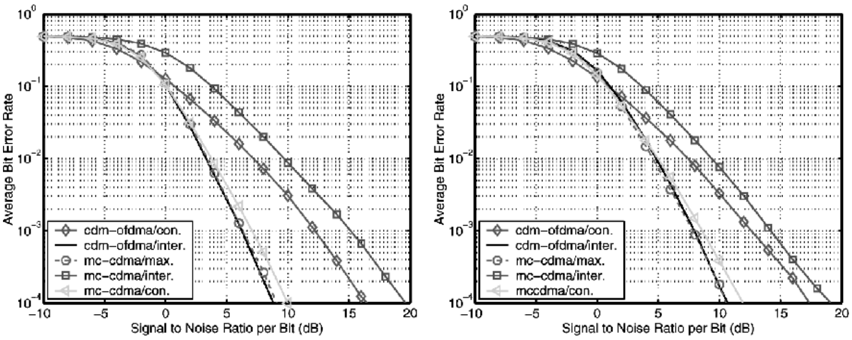

Figure 4. The average BER performance in the uplink transmission over frequency selective fading channels with (right) and without (left) frequency offsets.

diversity and interleaved CDM-OFDMA have about 1.3 dB performance loss due to frequency offsets at a given BER of 10^{-3}. Conventional CDM-OFDMA has the worst performance in downlink transmission.

Figure 3 illustrates the average BER performance in AWGN channel with and without frequency offsets. It is shown that the similar performance is obtained for all proposed systems if only white noise degrades the system performance. In the presence of frequency offsets, the performance of different transmission systems degrade differently. Conventional MC-CDMA, MC-CDMA with the maximum frequency diversity and interleaved CDM-OFDMA have about 2.5 $\sim$ 3 dB performance loss due to frequency offsets in comparison to interleaved MC-CDMA, although FOs are compensated by LMMSE-MUD.

Figure 4 depicts the uplink transmission in an multipath scenario. A severe performance degradation occurs for interleaved MC-CDMA, whereas the best average BER is obtained by interleaved CDM-OFDMA and MC-CDMA with the maximum frequency diversity. With less frequency diversity, conventional MC-CDMA has a slight performance loss. It should be noted that performance loss due to frequency offsets is less than for AWGN channel. Comparing Fig. 3 with 4, it is easy to see that the channel characteristics are the dominating factor that degrades the system performance. In general, interleaved CDM-OFDMA is one of the most promising candidates for the wireless uplink transmission.

4. Conclusions

CDM-OFDMA and MC-CDMA have been compared in terms of system structure, parameter estimation and BER performance. It has been shown that MC-CDMA with the maximum diversity and interleaved CDM-OFDMA are good candidates for future wireless communication systems. Furthermore, interleaved CDM-OFDMA is possibly more suitable for uplink transmission than MC-CDMA because of its less parameter estimation complexity.

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