Introducing Novel FDD and FDM in MC-CDMA to Enhance Performance *

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Abstract - This paper presents a method of efficiently incorporating frequency division duplex (FDD) and frequency division multiplexing (FDM) into MC-CDMA systems to exploit frequency diversity and reduce multiple access interference (MAI). The approach in novel FDD/MC-CDMA is to break the total available bandwidth into subbands and interleave the subbands used for downlink and uplink. It is shown that this technique significantly improves the performance relative to an MC-CDMA system employing a traditional FDD scheme where the spectrum is divided into a single uplink block and a single downlink block. Furthermore, FDM is introduced in the novel FDD scheme to reduce MAI in MC-CDMA (without any loss in the capacity of the overall system).

1 Introduction

The exploding use of CDMA (code division multiple access) [1] in wireless communications, and the growing popularity of multi-carrier modulation [2], has led to the development of CDMA schemes employing orthogonal multi-carrier modulation. In these schemes, known as MC-CDMA (multi-carrier code division multiple access) [3], each chip of a spreading code is applied to a separate information bearing carrier. At the receiver, the total transmitted signal is separated into its carrier components, and combined in an attempt to (1) offer frequency diversity benefits (by resolving the frequency selectivity of the multipath channel) and (2) eliminate MAI (multiple access interference).

FDM (frequency division multiplexing) systems, on the other hand, completely avoid MAI by separating user's signals in frequency, but suffer severe performance degradation in fading channels. Efforts have been made to combine FDM with CDMA systems in [4] and [5]. However, to the best of the authors' knowledge, no attempts have been made to apply FDM to a typical MC-CDMA system.

Frequency Division Duplex (FDD) with CDMA has been approved for the Universal Mobile Telecommunications System (UMTS)[6]. In FDD, one frequency band is used for uplink and a neighboring band is used for downlink transmissions.

In this paper, we first propose a novel method of utilizing the spectrum in an MC-CDMA system with FDD. Specifically, we explore the separation of uplink and downlink frequencies into multiple subbands that are non-contiguous. It is shown that dividing the available uplink and downlink spectrum into subbands that are spaced over the entire spectrum better exploits the available diversity and provides significant performance benefit over MC-CDMA utilizing the traditional FDD approach.

Next we incorporate FDM into the novel FDD/MC-CDMA architecture. Here, rather than allowing all users to share all the carriers (typical of MC-CDMA) we support smaller numbers of users on small subsets of carriers. A number of small subsets used concurrently maintains the total capacity of the system. Different subsets are frequency division multiplexed (FDM'd) such that users of one subset do not interfere with users of another subset. This scheme not only performs better relative to the traditional FDD/MC-CDMA, it also offers the flexibility of providing different users with different QOS.

Section 2 describes the traditional MC-CDMA system model - the transmitter, channel and receiver. Section 3 presents MC-CDMA with novel FDD and also explores the use of FDM in the novel FDD/MC-

*Research supported by 1999 Colorado Advanced Software Institute Grant - "Software based Simulator for Carrier Interference Multiple Access (CIMA)".

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CDMA. Section 4 presents performance results.

2 MC-CDMA

Consider an MC-CDMA system employing a total of N carriers, supporting K active users, and deploying orthogonal Hadamard-Walsh(HW) codes (characteristic of the downlink). This MC-CDMA system can support a maximum of $K = N$ users. The transmitted signal output by the k^{th} user to send one bit corresponds to

$$s_k(t) = \sum_{i=1}^{N} a_k c_k^i \cos(2\pi f_i t) \cdot p(t), \quad (1)$$

where user k's input data symbol, a_k, is assumed to be binary antipodal, $c_k^i = \pm 1$ represents the i^{th} chip of the k^{th} user's spreading code, $f_i = f_c + i\Delta f$ where Δf is carefully selected to ensure orthogonality among carriers and $p(t)$ is defined to be a unit amplitude pulse that is non-zero in the interval of 0 to T_b (T_b is the bit duration). The total transmitted signal considering all users is

$$s(t) = \sum_{k=1}^{K}\sum_{i=1}^{N} a_k c_k^i \cos(2\pi f_i t) \cdot p(t). \quad (2)$$

The channel model is frequency selective slow fading. Frequency selectivity refers to the selectivity over the entire bandwidth of transmission, and not over each of the subcarrier transmissions. That is,

$$1/T_b << (\Delta f)_c < BW \quad (3)$$

where $(\Delta f)_c$ is the coherence bandwidth and BW is the total bandwidth of the multicarrier system [7]. In the case of MC-CDMA with FDD, the BW stands for the bandwidth available for downlink (or uplink) transmission.

With N carriers residing over the entire bandwidth, BW, each carrier undergoes a flat fade, with the correlation between the i^{th} subcarrier fade and the j^{th} subcarrier fade characterized by [8]

$$\rho_{i,j} = \frac{1}{1 + ((f_i - f_j)/(\Delta f)_c)^2} \quad (4)$$

where $(f_i - f_j)$ indicates the frequency separation between the i^{th} and the j^{th} subcarriers. Generation of fades with correlation has been discussed in [9].

The received signal in the downlink is characterized by

$$r(t) = \sum_{k=1}^{K}\sum_{i=1}^{N} \alpha_i a_k c_k^i \cos(2\pi f_i t + \phi_i) \cdot p(t) + \eta_i(t) \quad (5)$$

where α_i is the gain and ϕ_i the phase offset due to the channel fade on the i^{th} subcarrier, and $\eta_i(t)$ represents AWGN (additive white gaussian noise). To simplify the analysis, exact phase synchronization is assumed.

At the receiver for user k, $r(t)$ is projected onto the orthonormal basis of the transmitted signal and multiplied by the respective chips of the k^{th} user's spreading code, outputting $\underline{r} = (r_1, r_2, ..., r_N)$ where

$$r_i = \alpha_i a_k + \sum_{j=1, j\neq k}^{K} \alpha_i a_j c_k^i c_j^i + \eta_i. \quad (6)$$

Here, η_i is a Gaussian random variable with mean 0 and variance $N_o/2$.

Next a suitable combining strategy is used to create a decision variable, D, which then enters a decision device with output $\hat{a}_k$. Throughout this work, we employ minimum mean square error combining (MMSEC), as it has been shown to produce the best performances in MC-CDMA [9]. Employing MMSEC results in the decision variable D given by the linear sum

$$D = \sum_{i=1}^{N} r_i . [\frac{\alpha_i}{(K\alpha_i^2 + N_o/2)}] \quad (7)$$

3 MC-CDMA with novel FDD and FDM

Figure 1(a) shows the traditional method of employing FDD in MC-CDMA. It is evident from the figure that the total bandwidth in this case is $2 \cdot BW$, with equal bandwidth allocation for uplink and downlink. This implies that there is frequency diversity benefit unexploited by a division of the spectrum as shown in Figure 1(a).

The novel FDD scheme proposed here employs multiple subbands spread over the entire uplink/downlink bandwidth, $2 \cdot BW$. Specifically, the frequency subbands for uplink and downlink are interleaved in a manner that creates enhanced diversity gains for both links. Figure 1(b) shows an example of implementing this novel FDD scheme in MC-CDMA with $N = 32$ carriers when the channel offers 4-fold frequency diversity over the entire bandwidth, $2 \cdot BW$. Here, the novel FDD uses four subbands with 8 carriers in each for the downlink (and uplink), distributed as shown in the Figure 1(b). This spacing between the subbands creates the full 4-fold diversity gain for uplink/downlink, a gain that was limited to 2-fold diversity in the traditional FDD scheme of Figure 1(a).

In general, the proposed FDD/MC-CDMA scheme employs n subbands each containing p carriers in the downlink (and uplink), where n is chosen to satisfy

$N = n \cdot p$, $n \in$ I, $p \in$ I, and $n \geq L$ (where L is the order of diversity available over $2 \cdot BW$).

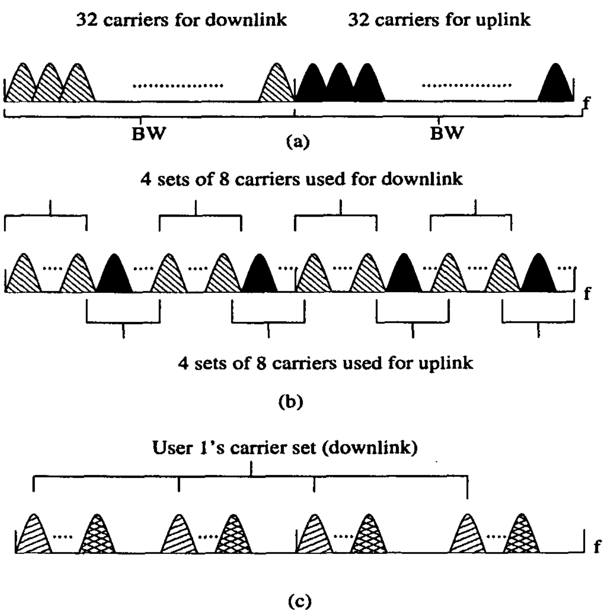

Figure 1: Frequency allocations in (a) Traditional MC-CDMA with FDD (b) Novel FDD/MC-CDMA (c) FDM/MC-CDMA with novel FDD

We can also incorporate FDM into the MC-CDMA system with novel FDD. Here, fewer than N carriers are deployed per user. An illustration of this for user 1 is shown in Figure 1(c). Here, a set of $n < N$ equally spaced carriers, one per FDD subband, are selected as the MC-CDMA carriers for $k \leq n < N$ users.

The n carriers used by each user make full use of the L-fold diversity, thereby combating fading. Each user (in one of the p n-carrier sets) experiences MAI only from a maximum of $(n-1)$ other users of that set. This value is far smaller than the $N-1$ user multiple access interference in standard MC-CDMA.

In FDM/MC-CDMA, for each set of n carriers, a lower dimension HW code suffices as the spreading code (since $n < N$). With frequency separation of n-carrier sets, identical codes are used in each of the p FDM'd sets.

As more and more users enter the FDM/MC-CDMA system, frequency allocation can be performed sequentially in a manner that minimizes MAI. Alternatively, FDM/MC-CDMA enables allocation strategies which permit different QOS (quality of service) to different users.

4 Performance Results

The downlink of an MC-CDMA system with $N = 32$ carriers and employing the traditional FDD scheme was simulated using orthogonal HW codes and a slowly fading frequency selective channel. The channel supports $L = 4$ fold diversity gain over the total uplink/downlink bandwidth, $2 \cdot BW$, and hence only $L = 2$ fold diversity in the spectrum of concern for downlink MC-CDMA. In Figures 2 and 3, the dashed line represents the Bit Error Rate (BER) performance for this MC-CDMA system.

When the novel FDD scheme is employed with n=4 and p=8 (Figure 1(b)), the simulations show significant performance enhancements (the solid line in Figures 2 and 3). It is observed that the MC-CDMA system employing novel FDD with 32 users has BER comparable to that of MC-CDMA with traditional FDD supporting only 10 users. This is a direct consequence of increased frequency diversity benefit in the novel FDD system.

The stepwise increasing curve in Figures 2 and 3 represent the BER performance of the FDM/MC-CDMA with the novel FDD system. Figure 2 shows the BER performance assuming that the concerned user is in the carrier set that is last to receive an interfering user, and hence can be considered a "best case user". The system can also be perceived with respect to an average BER, the mean of the BERs of all the users. Figure 3 shows the average performance curve of the FDM/MC-CDMA system with novel FDD.

It is observed that the FDM/MC-CDMA system with 25 users demonstrates an average BER equal to that of a standard MC-CDMA system with only 11 users. The best-case user in FDM/MC-CDMA maintains a QOS (measured by BER) that does not increase until user 30 enters the system.

5 Conclusions

This paper introduces an efficient deployment of FDD and FDM in MC-CDMA to exploit diversity gains and reduce MAI. A novel FDD scheme is provided to better utilize the total available bandwidth. This scheme is shown to significantly improve the BER performance of the MC-CDMA system over that using the traditional FDD method. FDM principles were also overlaid in the novel FDD technique. This is done by using a smaller number of carriers per user and FDM-ing multiple carrier sets, thereby reducing the amount of MAI per user. Simulation results show notable improvement in BER performance of FDM/MC-CDMA systems with novel FDD over MC-CDMA systems with traditional FDD.

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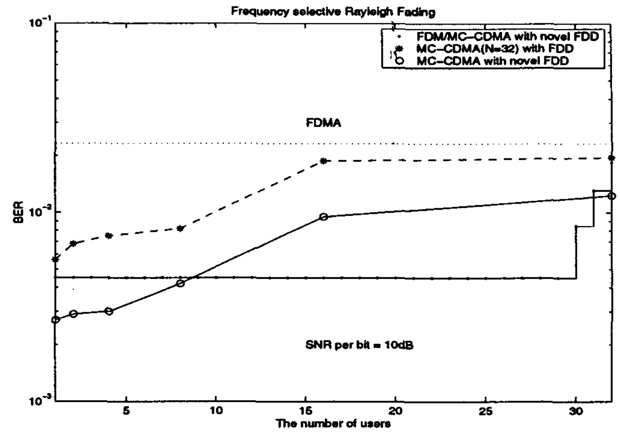

Figure 2: BER comparison between MC-CDMA system with traditional FDD and (1) novel FDD (2) FDM with novel FDD (best case user)

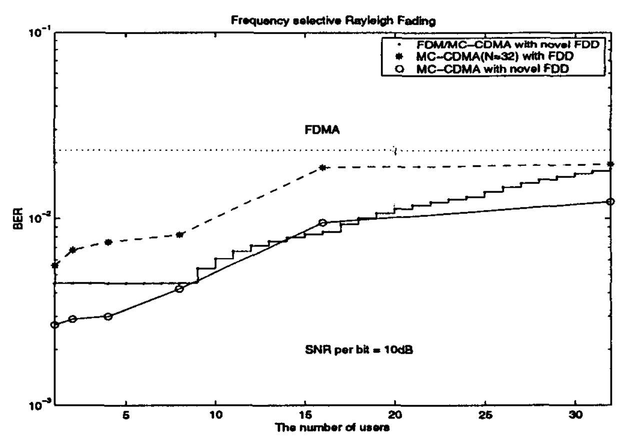

Figure 3: BER comparison between MC-CDMA system with traditional FDD and (1) novel FDD (2) FDM with novel FDD (average BER)