FD-MC-CDMA: A Frequency-based Multiple Access Architecture for High Performance Wireless Communication[+]

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Abstract

MC-CDMA demonstrates good probability-of-error performances in frequency selective fading channels, a direct result of its ability to exploit the available frequency diversity benefits. However, MC-CDMA performances are limited by degradation due to large multiple-access interference (MAI). FD-MC-CDMA, a novel multiple access architecture proposed in this paper, exploits the available frequency diversity benefits while minimizing MAI. Instead of transmitting all users' information bits over all carriers, FD-MC-CDMA employs a subset of carriers to support a subset of users (maintaining the same overall system capacity and throughput as in MC-CDMA). By careful selection of each subset of carriers, the available frequency diversity benefits are fully exploited, while the MAI experienced by each user is minimized. Simulation results show FD-MC-CDMA outperforming MC-CDMA and FDMA in frequency selective fading channel.

I Introduction

Multi-carrier CDMA (MC-CDMA), first proposed in [1] and thoroughly outlined in [2] provides probability-of-error performance via large diversity gains, and demonstrates the potential for high network capacity. Specifically, in MC-CDMA, high diversity gains are achieved by (1) allowing transmitters to send information on N multiple carriers simultaneously, and (2) using receivers that separate the signal into carrier components to exploit frequency diversity. However, MC-CDMA experiences performance degradation due to MAI (multiple access interference) caused by the other active users sharing the same N carriers. Typically, the performance of the MC-CDMA system is limited by the amount of MAI.

FDMA (Frequency Division Multiple Access), on the other hand, completely avoids MAI by allocating each user a unique, orthogonal transmission frequency. However, in this transmission scheme, no frequency diversity gains are achieved at the receiver. As a result, FDMA systems suffer severe performance degradation in fading channels.

In this paper, we propose a new frequency based multiple access architecture, FD-MC-CDMA (frequency division multi carrier CDMA). This combines the best elements of FDMA and MC-CDMA to simultaneously exploit frequency diversity and minimize MAI.

Combining FDMA and MC-CDMA to create FD-MC-CDMA, the N subcarriers available in MC-CDMA are divided into groups: each group contains L non-contiguous subcarriers, maximally separated over the transmit bandwidth (L is the available frequency diversity gain). Each user's information bit is then sent over a set of the L non-contiguous subcarriers instead of all N subcarriers. Due to the large frequency separation between the L non-contiguous subcarriers, the frequency diversity gain available at the receiver is approximately the same as that achieved in MC-CDMA (where each user transmits over all N subcarriers). Moreover, in each group of L subcarriers, only $K \leq L$ users are supported, leading to low MAI (observed at receiver side) for each user. As a result, the performance of the novel multiple access architecture, achieving high diversity benefits and low MAI, is better than that of either MC-CDMA or FDMA, while maintaining the same network capacity (measured by number of users). Not only does this novel scheme outperform traditional MC-CDMA (as well as FDMA), but it also decreases the computational load at the receiver. Additionally, it offers the flexibility of providing different users with different QOS (quality of services).

This work is an extension of our earlier work regarding the merger of FDMA with MC-CDMA [3]. However, in that paper, the receiver was not optimized for the new multiple access scheme, and, as a direct result, performance gains were not observed.

Section II describes the transmitter structure of the novel multiple access architecture. Section III presents the receiver and the maximum likelihood combining scheme.

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Channel model and simulation results are shown in Section IV, and a conclusion follows.

II Transmitter

In a traditional MC-CDMA system, the k^{th} user's transmission corresponds to

$$s^k(t) = b_k \,\mathrm{Re}\{ \overset{N}{\underset{i=1}{}} \; \beta_i^k e^{j2\pi i\Delta f t} e^{j2\pi f_c t)} \} ?g(t) \qquad (1)$$

where b_k is user k's information bit, Δf is the frequency separation between neighboring carriers, f_c is the transmission frequency, $\beta_i^k = +1$ or -1 in accordance with known spreading codes such as Hadmard-Walsh codes, and *g(t)* is a rectangular waveform of unity height and symbol duration T_s.

Typically, fading channels in wireless systems demonstrate an L fold frequency diversity, where L is in the order of 2, 3 or 4. Here, we assume L=4 for ease in presentation. To build a multiple access system exploiting this L=4 fold diversity, while minimizing MAI, we: rather than allowing all users to share all the N carriers, we support small sets of up to L=4 users sharing a set of L=4 carriers via MC-CDMA. That is, the k^{th} user in a set of 4 users transmits $s^k(t) = b^k \,\mathrm{Re}\{ \overset{N}{\underset{i=1}{}} \; \beta_i^k e^{j2\pi i\Delta f t} e^{j2\pi f_c t} \} ?g(t)$ (as shown in equation (1)) where $\beta_i^k = +1$ or -1 at L=4 values of i and $\beta_i^k = 0$ elsewhere.

Specifically, for L=4 fold diversity and N=32 carriers: $\{\beta_i^k \llcorner \{+1,-1\}, i = 1,9,17,25\}$ and $\{\beta_i^k = 0,\ i\ ?\ 1,9,17,25\}$ for one set of four users; $\{\beta_i^k \llcorner \{+1,-1\}, i = 2,10,18,26\}$ and $\{\beta_i^k = 0,\ i\ ?\ 2,10,18,26\}$ for another four users; and so on (Figure 1).

Generally,

$$\beta_i^k = \begin{matrix} \pm 1, & i = \frac{k}{N/L}+1, \frac{k}{N/L}+\frac{N}{L}+1, \frac{k}{N/L}+2?\frac{N}{L}+1, ??, \frac{k}{N/L}+(L-1)?\frac{N}{L}+1 \\ 0 & \text{otherwise} \end{matrix} \qquad (2)$$

where x presents the closest integer which is less than or equal to x.

A total of *N/L* (e.g., 32/4=8) sets of L=4 carriers are used concurrently to maintain the total capacity of the system. Different sets of L=4 carriers are frequency division multiplexed such that the 4 users of one subset do not interfere with users of another set. For each set of L=4 carriers, a set of length 4 HW codes are used as the spreading codes.

The transmitter structure for user 1 is presented in Figure 2.

III Receiver

After transmission through a frequency selective fading channel, the received signal in FD-MC-CDMA corresponds to

$$r(t) = \overset{K}{\underset{k=1}{}} \; b_k \,\mathrm{Re}[\overset{N}{\underset{i=1}{}} \; \alpha_i \beta_i^k e^{j(2\pi f_c t+2\pi i\Delta f t+\phi_i)}]g(t) + \eta(t) \qquad (3)$$

where α_i is the gain and φ_i the phase offset in the i^{th} subcarrier, and $\eta(t)$ represents additive white Gaussian noise. Recall that for each user k β_i^k is non-zero in only L=4 of the N subcarriers.

User 1's receiver in an FD-MC-CDMA system is shown in Figure 3. Here, the received signal is decomposed into its L information-bearing carriers and despread by user 1's spreading code. The i^{th} carrier generates the decision variable

$$r_i^{(1)} = \alpha_i b_1 + \alpha_i \underset{k \llcorner U_1}{} \; b_k \beta_i^k \beta_i^1 + \eta_i \qquad i = 1,9,17,25 \qquad (4)$$

where U_1 is the set of up to four active users in user 1's carrier set.

Next, an optimal combining strategy is used to combine all L=4 carriers in user 1's set to best exploit frequency diversity and minimize MAI. To accomplish this, we employ the maximum likelihood combining scheme (MLC): Given $\vec{r}^{(1)}$, the maximum likelihood criteria requires a decision based on

$$P(\vec{r}^{(1)} \mid b_1 = 1) >< P(\vec{r}^{(1)} \mid b_1 = -1) \qquad (5)$$

where >< means if the term on the right is greater than the one on the left, output bit 1; otherwise decide -1. Assuming no knowledge of the other users' spreading codes, the MAI of different carriers can be viewed as independent, in which case

$$P(\vec{r}^{(1)} \mid b_1) = \underset{i \llcorner \{1,9,17,25\}}{\subseteq} P(r_i \mid b_1) = \underset{i \llcorner \{1,9,17,25\}}{\subseteq} P(\eta_i' = r_i^{(1)} - \alpha_i b_1) \qquad (6)$$

where η_i' is a random variable with mean 0 and variance $(K_1 - 1)\alpha_i^2 + N_0/2$, K_l is the number of active users on user 1's carrier set, and $N_0/2$ is the variance of the additive Gaussian noise. Employing a Gaussian approximation of MAI in equation (4), the maximum likelihood decision rule corresponds to:

$$D^{(1)} = \underset{i\ \{1,9,17,25\}}{} r_i^{(1)} ? \frac{\alpha_i}{(K_1 - 1)\alpha_i^2 + N_0/2} \qquad (7)$$

After the ML combining, a hard decision device makes the following decision on the output data bit:

$$\hat{b}_l = \begin{matrix} +1 & \quad if \quad D^{(l)} > 0 \\ -1 & \quad elsewise \end{matrix} \qquad (8)$$

IV Channel Model and Simulation Results

To test the performance of the proposed FD-MC-CDMA system, simulations are performed assuming a system with N=32 carriers. Four-fold diversity is assumed in the channel model, that is:

$$BW = N ?\Delta f = 4 ?(\Delta f)_c \qquad (9)$$

where BW is the total bandwidth of the system and $(\Delta f)_c$ is the coherence bandwidth of the channel. As benchmarks, a traditional MC-CDMA system using over all N=32 carriers and an FDMA system are both simulated.

Figure 4 presents the performance curves in terms of average bit error rate (BER) versus number of users for fixed SNR=10dB, and Figure 5 presents the BER versus SNR when the number of active users in the system is 8. The solid line (marked with hollow circles) represents the traditional MC-CDMA system. The dotted line (marked with solid circles) represents FDMA, and the dashed line (marked with stars) the novel FD-MC-CDMA system (with 8 sets of 4 carriers each as in Figure 1).

These results confirm that this novel scheme outperforms both FDMA and MC-CDMA. At lower loads, the performance gains are even more prominent.

It is also important to notice that (1) in the FD-MC-CDMA system, where the number of carriers employed by each user is small, the computational load for both transmitter and receiver is decreased dramatically; and (2) the FD-MC-CDMA system can be easily updated to support users with different QOS requirements; this is handled by assigning users to different subcarrier groups based on their QOS requirements.

Conclusion

A novel multiple access architecture (FD-MC-CDMA) is proposed in this paper to simultaneously exploit frequency diversity and minimize MAI. By dividing the whole transmission bandwidth into smaller sets of subcarriers, and by choosing these subcarriers to be non-contiguous, the same amount of frequency diversity is exploited with notably less MAI. Simulation results confirm that FD-MC-CDMA outperforms MC-CDMA (and FDMA) in frequency selective fading channels. Some other important benefits are also observed in the proposed architecture.

Reference:

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[2] S. Hara and R. Prasad, "Overview of multi-carrier CDMA", *IEEE Communications Magazine*, vol. 35, no. 12, Dec. 1997, pp. 126-133

[3] Balasubramaniam Natarajan, Carl R. Nassar, "Introducing Novel FDD and FDM in MC-CDMA to Enhance Performance", *Proc. of IEEE RAWCON* '00, pp. 29-32

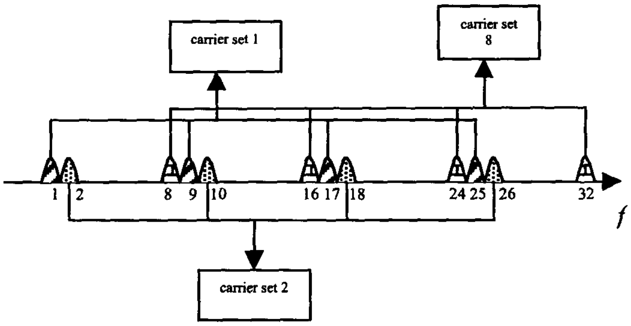

Figure 1 MC-CDMA with FDMA: N=32 carriers, L=4 fold diversity

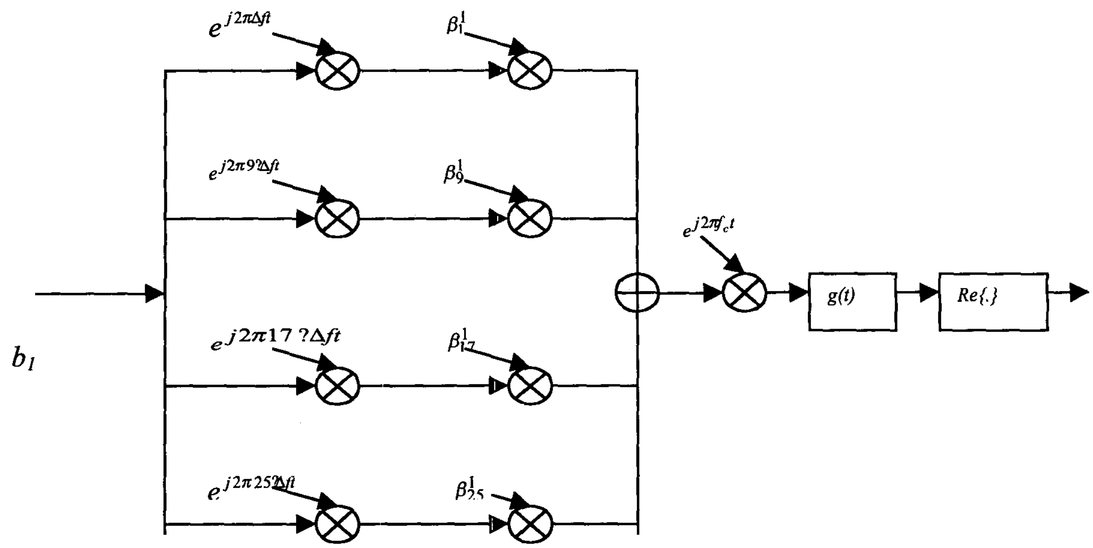

Figure 2 FD-MC-CDMA transmitter for user 1

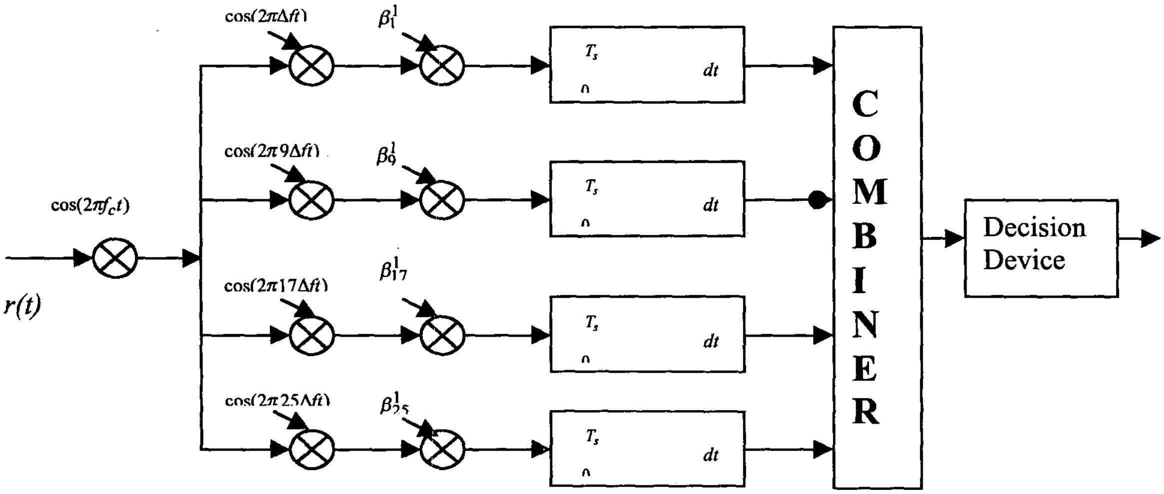

Figure 3 FD-MC-CDMA receiver for user 1

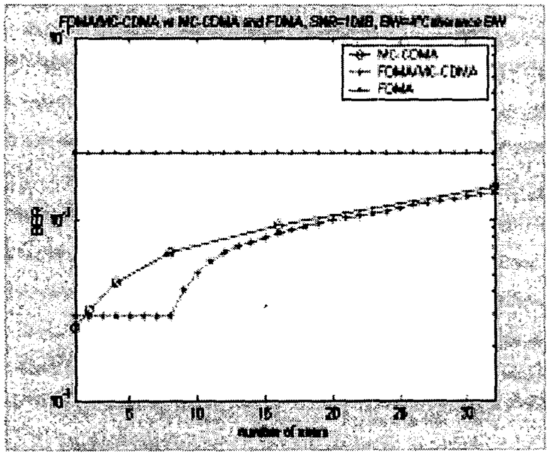

Figure 4 BER performance of FDMA/MC-CDMA for fixed SNR

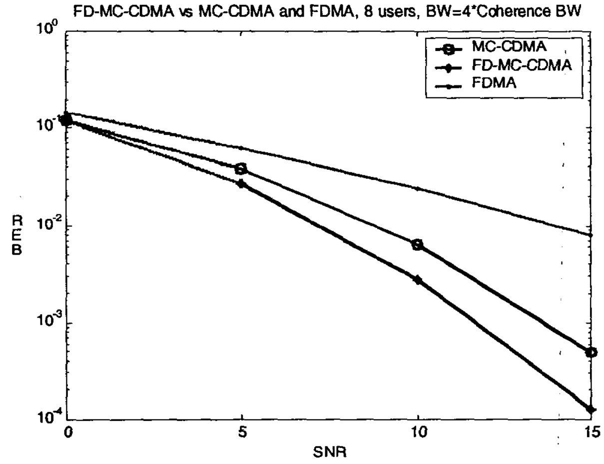

Figure 5 BER performance of FD-MC-CDMA for fixed number of use