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A Flexible Spread-Spectrum Multi-Carrier Multiple-Access System for Multi-Media Applications

Stefan Kaiser and Khaled Fazel
German Aerospace Research Establishment (DLR), Institute for Communications Technology
D-82234 Oberpfaffenhofen, Germany, Tel.: +49 8153 28-2805, Fax: +49 8153 28-1442
e-mail: Stefan.Kaiser@dlr.de, Khaled.Fazel@dlr.de

Abstract

This paper presents a novel multiple access scheme designed for mobile multi-media applications. The scheme is referred to as spread-spectrum multi-carrier multiple-access (SS-MC-MA) and exploits the advantages given by the combination of the spread-spectrum technique with multi-carrier modulation, known from multi-carrier code division multiple access (MC-CDMA) schemes. In contrast to MC-CDMA, the SS-MC-MA separates the users' signals according to an FDMA scheme on sub-carrier level. Thus, the novel scheme avoids multiple access interference (MAI) within a cell. SS-MC-MA can use the same radio interface for the up- and the down-link. Its bandwidth efficiency is comparable to the high bandwidth efficiency achievable with MC-CDMA in the down-link. By providing a high degree of flexibility, this system can be a good candidate for the future universal mobile telecommunications systems (UMTS).

1 Introduction

Personal communication services are of great importance for the third-generation mobile radio communications systems such as UMTS [1]. The objectives of the third-generation systems go far beyond that, what is known from the second-generation systems such as IS-54, GSM, or IS-95, especially with respect to the wide range of multi-media services (speech, audio, image, video, data) with bit rates up to 2 Mbit/s, the high quality of service requirements (speech/image quality, bit error rate (BER) performance, and user capacity), and the operation in mixed cell scenarios (macro, micro, pico) and different environments (indoor/outdoor, business/domestic, cellular/cord-less). Present second-generation systems are primarily designed as low-rate voice and data systems (usually single-environment such as indoor or outdoor) and fall short of meeting important requirements of the third-generation systems.

A CDMA scheme could be a potential candidate for a third-generation system [2, 3]. However, it has to cope with the presence of MAI. The recently proposed SS-MC-MA scheme [4] avoids MAI due to an FDMA scheme on sub-carrier level by nevertheless exploiting the diversity gain offered by the spread-spectrum technique. Furthermore, the same radio interface can be used for the up- and the down-link. SS-MC-MA is related to CDMA schemes using orthogonal multi-carrier modulation, known as MC-CDMA or orthogonal frequency division multiplexing (OFDM)-CDMA [5, 6]. Thus, SS-MC-MA achieves similar performance as MC-CDMA. Performance comparisons between direct sequence (DS)-CDMA and MC-CDMA for the down-link of a mobile communication system show that MC-CDMA can achieve a higher bandwidth efficiency than DS-CDMA [7, 8]. The application of MC-CDMA for the up-link has rarely been investigated. The main problem encountered here, is the design of an efficient channel estimation technique for the up-link.

In this paper an SS-MC-MA scheme is investigated for the up-link of a mobile radio system by taking into account channel coding with soft decision decoding and real channel estimation. The multiple access scheme is based on a combination of the spread-spectrum technique and orthogonal multi-carrier modulation. The basic difference between SS-MC-MA and MC-CDMA is that with SS-MC-MA the code division is used for simultaneous transmission of the data of a single user on the same sub-carriers, where in the case of MC-CDMA the code division is used for the transmission of the data of different users on the same sub-carriers. SS-MC-MA assigns each user exclusively its own sub-carriers according to an FDMA scheme. Since all superimposed modulated spreading codes of one sub-set of sub-carriers are affected by the same channel fading, a simple channel estimation can be realized. For joint detection of the data of a single user a low complex maximum-likelihood sequence estimation (MLSE) is applied.

The SS-MC-MA scheme provides a high degree of flexibility due to variable sub-carrier allocation for variable data rate transmission and can offer unequal error protection due to variable spreading code mapping.

2 SS-MC-MA System

The basic idea of SS-MC-MA is to exploit the diversity gain offered by the spread-spectrum technique and interleaving by nevertheless avoiding MAI within a cell. This can be achieved by using synchronous MC transmission, where the multiple access is performed in the frequency domain on sub-carrier level. The data of each active user are mapped to a set of sub-carriers, which is exclusively assigned to this user. In order to exploit the frequency diversity of the channel, a user spreads the data over its set of sub-carriers and superimpose them by code multiplex. The superimposing of the data assigned to a single

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user introduces self interference which is comparable to MAI in MC-CDMA systems. However, the self interference can easy be counteracted by use of an MLSE, since implicitly knowledge about the used spreading codes exists. In the case of MC-CDMA with MLSE, knowledge about the actually used spreading codes of the other users is required, which additionally increases the signaling overhead.

2.1 Transmitter

Fig. 1 shows the block diagram of an SS-MC-MA transmitter (same for up- and down-link) for the data of user i, $i = 1 \ldots N_u$, where N_u is the number of active users within a cell. After channel encoding, interleaving, and

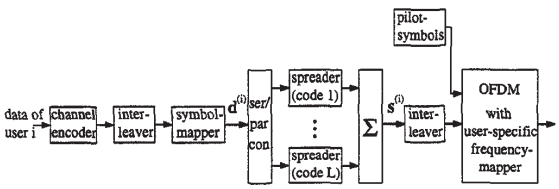

Figure 1: SS-MC-MA transmitter for the data of user i.

symbol mapping, L subsequent complex-valued data-symbols $d_l^{(i)}, l = 1 \ldots L$, of user i are serial to parallel converted. The vector $\mathbf{d}^{(i)}$ represents one block of L parallel data-symbols of user i,

$$\mathbf{d}^{(i)} = (d_1^{(i)}, d_2^{(i)} \ldots d_L^{(i)})^{\mathrm{T}}, \tag{1}$$

where $(.)^{\mathrm{T}}$ denotes transposition. Each of the L data-symbols is multiplied with an orthogonal spreading code (e.g. Walsh-Hadamard code [9]) of length L. The $L \times L$ matrix $\mathbf{C}$ represents the L orthogonal spreading codes. The modulated spreading codes are symbol- and with that chip-synchronously added, resulting in the transmission vector

$$\mathbf{s}^{(i)} = \mathbf{C} \cdot \mathbf{d}^{(i)} = (S_1^{(i)}, S_2^{(i)} \ldots S_L^{(i)})^{\mathrm{T}}, \tag{2}$$

consisting of L chips. To increase the robustness of the SS-MC-MA scheme e.g. against inter cell interference, less than L modulated spreading codes of length L can be added to one transmission vector $\mathbf{s}^{(i)}$.

The chips of M subsequent vectors $\mathbf{s}^{(i)}$ are frequency- and time-interleaved and fed to the OFDM unit, which also performs a user-specific frequency mapping, illustrated in Fig. 2. The frequency mapping may be equidistant or pseudo-random. After the mapping, the chips $S_l^{(i)}, l = 1 \ldots L$, are interpreted as complex frequency values of the sub-carriers. Each user of a cell transmits on a sub-set of sub-carriers, where the sub-sets of sub-carriers of the users within a cell are disjunct. To exploit the frequency diversity of the whole transmission channel, the sub-carriers assigned to a user are distributed over the whole transmission bandwidth. Finally, each OFDM-symbol of duration T_s is cyclic extended by a guard interval Δ in the OFDM unit to prevent inter symbol interference (ISI) in multipath channels. In order to perform coherent detection at the receiver and to

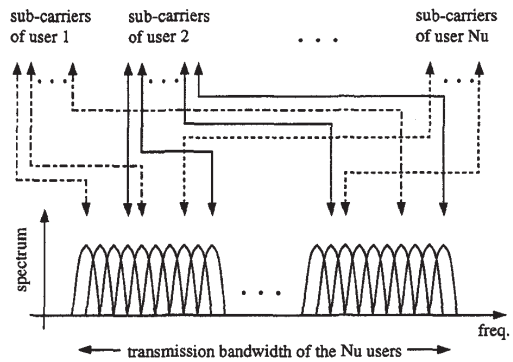

Figure 2: Pseudo-random user-specific frequency-mapping and -demapping.

guarantee robust time and frequency synchronization, pilot-symbols are multiplexed in the transmitted data.

2.2 Receiver

The block diagram of the SS-MC-MA receiver with coherent detection of the data of the i-th user is shown in Fig. 3. The received data are fed to the inverse OFDM

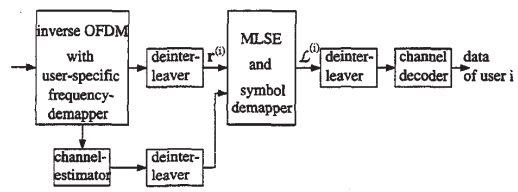

Figure 3: SS-MC-MA receiver for the data of user i.

unit which performs the user specific frequency demapping (see Fig. 2) and, furthermore, extracts the pilot-symbols from the symbols with user data. The symbols with user data are frequency and time deinterleaved, resulting in the vector

$$\mathbf{r}^{(i)} = \mathbf{H}^{(i)} \cdot \mathbf{s}^{(i)} + \mathbf{n}^{(i)} = (R_1^{(i)}, R_2^{(i)} \ldots R_L^{(i)})^{\mathrm{T}}. \tag{3}$$

The $L \times L$ diagonal matrix $\mathbf{H}^{(i)}$ describes the complex channel fading on the L sub-carriers of user i, and the vector $\mathbf{n}^{(i)}$ represents additive white Gaussian noise. The vector $\mathbf{r}^{(i)}$ is fed to the detector.

From the received pilot-symbols, the channel estimator estimates the channel state information (CSI), represented by the $L \times L$ diagonal matrix $\hat{\mathbf{H}}^{(i)}$, which is also frequency- and time-deinterleaved and used for coherent detection.

Joint detection with MLSE is applied for the superimposed data of a user. In the SS-MC-MA system we have the advantage that the MLSE in one estimation decides on $2L$ code bits of a single user if QPSK mapping is used. Thus, compared to MC-CDMA, the complexity of the MLSE per bit reduces by a factor of $2L$ in the downlink. Conventional and other joint detection techniques

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known for MC-CDMA receivers [10] can also be applied in SS-MC-MA receivers.

The MLSE evaluates the squared Euclidean distances $\delta^2_{m,I}$ and $\delta^2_{m,Q}$ between the received and all possible transmitted sequences $\mathbf{s}_m, m = 1 \ldots 2^{L+1}$, separately for the I- and the Q-components of $\mathbf{s}^{(i)}$ to reduce the complexity of the MLSE,

$$\delta^2_{m,I} = \| \Re\{\hat{\mathbf{H}}^{(i)*} |\hat{\mathbf{H}}^{(i)}|^{-1} \mathbf{r}^{(i)} - |\hat{\mathbf{H}}^{(i)}| \mathbf{s}_m\}\|^2 , \quad (4)$$

$$\delta^2_{m,Q} = \| \Im\{\hat{\mathbf{H}}^{(i)*} |\hat{\mathbf{H}}^{(i)}|^{-1} \mathbf{r}^{(i)} - |\hat{\mathbf{H}}^{(i)}| \mathbf{s}_m\}\|^2 , \quad (5)$$

where $\Re\{.\}$ and $\Im\{.\}$ denote the real and the imaginary part of a complex-valued vector. So, for QPSK-mapping instead of 2^{2L} only 2^{L+1} possible transmitted sequences have to be evaluated in the MLSE. The QPSK symbol demapping is inherently performed in the detection process. From the Euclidean distances the log-likelihood ratios for the received code bits are calculated as presented in [11, 4]. The log-likelihood ratios can be approximated by

$$\mathcal{L}^{(i)} \approx \frac{E_s}{N_0}(\delta^2_{m'} - \delta^2_{m''}) , \quad (6)$$

where m' is the index of the possible sequence with the smallest squared Euclidean distance δ^2_m where the estimated channel coded bit is equal to -1 and m'' is the index of the possible sequence with the smallest squared Euclidean distance δ^2_m where the estimated channel coded bit is equal to +1. Finally, after de-interleaving, the channel decoder exploits the log-likelihood ratios, yielding the detected data bits of user i.

3 Synchronization and Channel Estimation

The data transmission can be based on OFDM-frames, where each frame consists of a group of several OFDM-symbols. Each OFDM-frame may start with a null symbol (without signal energy) that is used in the receiver for coarse time-synchronization and for noise and interference estimation [12]. The fine time synchronization can be achieved by frequency domain processing of the pilot-symbols inserted into the OFDM-frame. The frequency synchronization can use a frequency offset estimation technique also based on the pilot-symbols [12].

For a synchronous transmission of the user data, the null symbol can be used to enable each user a self-synchronization. This can be achieved by searching only the null symbol in the OFDM frames transmitted by the other active users. If a larger guard-time Δ is chosen, a higher tolerance especially for the up-link on the accuracy of the synchronous transmission can be allowed.

Pilot-symbol-aided channel estimation is used for coherent detection. For the up-link one-dimensional filtering in time direction is used, where in the down-link, a more efficient two-dimensional filtering is preferable [13] since the down-link corresponds to a simple broadcasting scenario. In this paper, we focus on the up-link and thus apply one-dimensional FIR filters dimensioned as Wiener filters for the worst case channel conditions. The FIR filters are designed as Wiener filters with rectangular Doppler power spectrum, where $f_{D_{max}} = 333.3$ Hz is chosen as worst case condition. The pilot symbol spacing is chosen to 2× oversample the dynamics of the fading in time direction, given $f_{D_{max}} = 333.3$ Hz. The one-dimensional FIR filter is realized with 5 taps, which is a good choice between performance and complexity [13].

4 Flexibility and Robustness

The proposed SS-MC-MA scheme inherently offers the following flexibilities and advantages:

Variable data rate transmission: It is not necessary, that the transmission vector $\mathbf{s}^{(i)}$ of length L uses L sub-carriers per OFDM-symbol for its transmission. Since, in contrast to MC-CDMA, the chips of $\mathbf{s}^{(i)}$ contains the data of only one user, each user can transmit on a different number of sub-carriers. With that, the transmission of a wide range of multi-media services with different data rates (speech, audio, image, video, data, etc.) can be easily supported by a SS-MC-MA scheme. For instance, the transmission of low data rate services will need to choose only one or few sub-carriers (see Section 5). However, for the transmission of high data rate (video, data of about 2 Mbit/s) the majority or all of the sub-carriers should be used. The required data rate is transmitted to the base station, which allocates an appropriate set of sub-carriers. The number of active users depends on the number of available sub-carriers.

Flexible TDMA component: Since a synchronous transmission is assumed, we can easily introduce a time division multiple access (TDMA) component in the OFDM-frame structure. With a TDMA component different groups of users can be supplied in subsequent OFDM-frames, resulting in an increasing number of active users.

Unequal error protection: To increase the robustness of the SS-MC-MA scheme e.g. against inter cell interference, less than L modulated spreading codes of length L can be added to one transmission vector $\mathbf{s}^{(i)}$, resulting in a higher redundancy, i.e. protection, due to spreading for a specific user.

Same radio interface for up- and down-link: Since the SS-MC-MA scheme prevents MAI within a cell, the same SS-MC-MA radio interface can be used for the up-link as well as for the down-link.

Near-far resistance: Due to the absence of MAI, the near-far resistance of SS-MC-MA is only limited by the dynamic range of the receiver. However, power control in the up- and the down-link, adapted to each user separately, would minimizes the inter cell interference. Information about the transmitted power of each user in the up-link is not necessary for detection, hence reducing the complexity of the system.

When considering inter cell interference, it is of advantage that adjacent cells operating in the same frequency band uses different frequency mapping patterns, so that the sub-carriers of a user only partly overlap with the sub-carriers used by a user of the adjacent cell. Thus, when the SS-MC-MA system is not fully loaded, the

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distortion due to inter cell interference can be reduced. Naturally, this frequency mapping concept is also of advantage for MC-CDMA systems.

To meet the requirements of the third-generation mobile radio systems the SS-MC-MA system should in addition be combined with a flexible channel coding, where different BERs for different services have to be guaranteed by using different error-protection schemes. For instance, for speech or audio transmission a BER of about 10^{-3} is needed, where in this case one may use a simple convolutional code [14]. However, for video transmission (such as MPEG-1 or MPEG-4) one may need a much lower BER of less than 10^{-6}. In this case, a good choice would be to use a concatenated coding scheme (outer block code and inner convolutional code). Alternatively, the use of an adaptive Turbo coding scheme with different interleaver sizes can be used, where especially for larger interleaver sizes (applicable where greater delays are acceptable) significant performance improvements can be achieved [11].

Furthermore, the transmission parameters (guard-time, pilot-symbols) of an SS-MC-MA system can easily be adapted to the transmission environment by offering for instance two different modes (indoor and outdoor). The indoor channel (pico-cell) has a Doppler-shift and delay-spread much lower than the outdoor channel. This environment needs a short guard-time of about 100 ns and much less error-protection. However, the outdoor environment needs higher protection and a much longer guard time of about 20 μs. In addition, the amount of pilot-symbols used for channel estimation, depending on the Doppler-frequency and delay-spread, can be matched to the requirements of the different modes.

5 System Performance

In the following investigations, the up-link of a SS-MC-MA system is considered. The available transmission bandwidth is $B = 2$ MHz and the used carrier frequency is $f_c = 1.8$ GHz. By applying OFDM, the bandwidth B is split into $N_c = 256$ sub-channels with a sub-carrier spacing of 7.81 kHz. The resulting OFDM-symbol duration is $T_s = 128\mu s$. The OFDM and inverse OFDM is realized by an IFFT and a FFT, respectively. A guard interval of $\Delta = 20\mu s$ is inserted between adjacent OFDM-symbols.

The SS-MC-MA system has a TDMA component, where, in a cycle of 4 frames (each frame consists of 31 OFDM-symbols, see Fig. 4), each frame transmits the data of another group of 32 users. Thus, $4 \times 32 = 128$ active users can transmit with a net data rate of 10.46 kbit/s. The speech encoder of the mobile station delivers a data rate of 10.46 kbit/s to the channel encoder. The binary data are convolutionally encoded with rate $R = 1/2$ and memory 6. A block of 348 code bits is randomly interleaved and QPSK-mapped into 192 data-symbols. A block of 8 serial data-symbols is serial to parallel converted and spread with orthogonal Walsh-Hadamard codes of length $L = 8$, where each of the 8 data-symbols is multiplied with another spreading

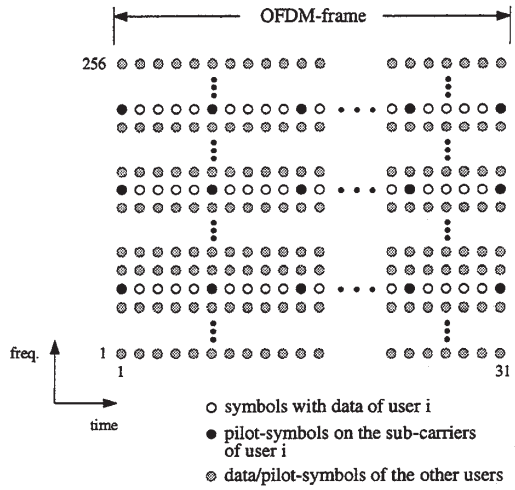

Figure 4: OFDM frame with 256 sub-carriers and 31 OFDM-symbols.

code. The 8 data modulated spreading codes are added symbol-, and with that, chip-synchronously, resulting in a transmission sequence of 8 chips. A block of 192 chips of 24 subsequent transmission sequences are randomly frequency- and time-interleaved. In the OFDM unit 8 chips are modulated on 8 sub-carriers per OFDM-symbol, where the user-specific sub-carriers are located in distances of 250 kHz, distributed over the whole bandwidth.

The receiver applies an MLSE which detects the received data-symbols of a user separately in the I- and Q-components by exploiting the estimated CSI. The CSI is estimated by FIR filtering (with 5 filter taps) of the received pilot-symbols on the user-specific sub-carriers over the time. To achieve $2\times$ oversampling of the fading process in time direction a pilot-symbol spacing of 5 is required for the given scenarios (c.f. Fig. 4) [13].

The performance of the SS-MC-MA system is investigated for four propagation scenarios defined in COST 207 [15] by taking into account different velocities of the mobile users:

BU3: Bad urban channel with maximum delay of $10\mu s$. The velocity of the mobile user is 3 km/h, resulting in a maximum Doppler frequency of 5 Hz.

TU50: Typical urban channel with maximum delay of $7\mu s$. The velocity of the mobile user is 50 km/h, resulting in a maximum Doppler frequency of 83.3 Hz.

HT100: Hilly terrain with maximum delay of $20\mu s$. The velocity of the mobile user is 100 km/h, resulting in a maximum Doppler frequency of 166.7 Hz.

RA250: Rural area with maximum delay of $0.7\mu s$. The velocity of the mobile user is 250 km/h, resulting in a maximum Doppler frequency of 416.7 Hz. This channel should demonstrate that the proposed SS-MC-MA scheme with real channel estimation operates even in this worse scenario.

In the four channels, the Doppler spectrum is chosen according to isotropic scattering. The BER P_b versus the signal to noise ratio (SNR) E_b/N_0 of SS-MC-MA with

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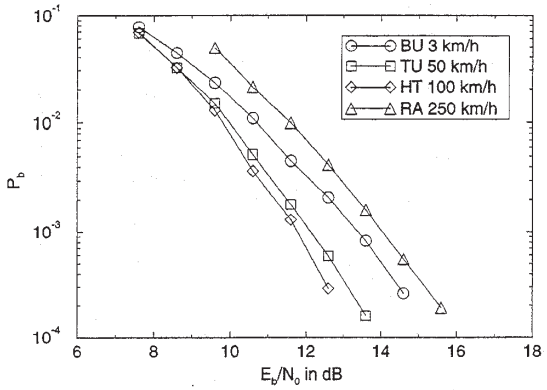

Figure 5: Performance of SS-MC-MA in different propagation scenarios with full system load.

real channel estimation is presented in Fig. 5. E_b is the average energy per received bit (data and pilot symbols are assumed to be transmitted with the same energy) and N_0 is the one-sided noise spectral density. The performance is given for a full system load, resulting in a bandwidth efficiency of 0.67 bit/s/Hz. The total SNR loss due to the guard interval Δ and the pilot symbols is 1.6 dB and is taken into account in the results of Fig. 5. It can be observed from Fig. 5, that even in a scenario with velocity of 250 km/h in a rural area, a SNR of 14 dB is sufficient to guarantee a bit error rate of $P_b < 10^{-3}$. Less critical propagation conditions requires up to 2 dB less E_b/N_0 due to higher frequency/time diversity gains and better channel estimates, respectively.

In Table 1 the SNR degradation in dB due to the proposed channel estimation scheme at a BER of 10^{-3} compared to perfect channel estimation is given for the four mobile radio channels. The loss in SNR with the

	BU3	TU50	HT100	RA250
SNR degrad.	3.1 dB	2.8 dB	2.7 dB	4.1 dB

Table 1: SNR degradation due to real channel estimation compared to perfect channel estimation.

HT100 scenario is smallest since the assigned Doppler power spectrum with $f_{D_{max}} = 166.7$ Hz best matches to the filter function of the channel estimator (c.f. Section 3) by guaranteeing 2× oversampling of the fading process.

6 Conclusions

The suitability of a novel multiple access scheme based on the spread spectrum technique and orthogonal multi-carrier modulation for mobile multi-media applications has been demonstrated. The scheme is referred to as SS-MC-MA and is based on FDMA on sub-carrier level by additionally exploiting the frequency diversity gain offered by the spread-spectrum technique. Due to the absence of MAI, SS-MC-MA is suitable for the up- and the down-link. The high flexibility of SS-MC-MA has been shown and its robustness in quite different propagation scenarios has been demonstrated, taking into account channel coding and real channel estimation. For data detection a low complex MLSE was used. The presented results show that SS-MC-MA can be applied in a typical urban environment where a mobile user has a velocity of 50 km/h @ 1.8 GHz with an SNR of $E_b/N_0 = 12$ dB to guarantee a bit error rate of $P_b = 10^{-3}$ with full system load. This yields a bandwidth efficiency of 0.67 bit/s/Hz, for the up-link as well as for the down-link.

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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 used in the novel FDD/MC-CDMA is to break the total available bandwidth into subbands and interleave the subbands used for the 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).

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

Balasubramaniam Natarajan and Carl R.Nassar
Department of Electrical and Computer Engineering
Colorado State University
Fort Collins, CO - 80523-1373
Phone : (970)-491-6259, Fax : (970)-491-2249
email : nbalsu@engr.colostate.edu

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-

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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 kth 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 ith chip of the kth 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 ith subcarrier fade and the jth 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 ith and the jth 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 ith 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 kth 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

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

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

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

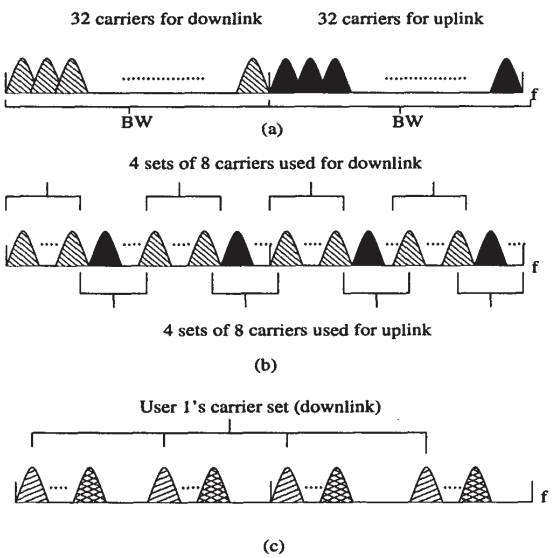

Figure 1: Frequency allocations in (a) Traditional MC-CDMA with FDD (b) Novel FDD/MC-CDMA (c) FDM/MC-CDMA with novel FDD

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 sys-

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tems with traditional FDD.

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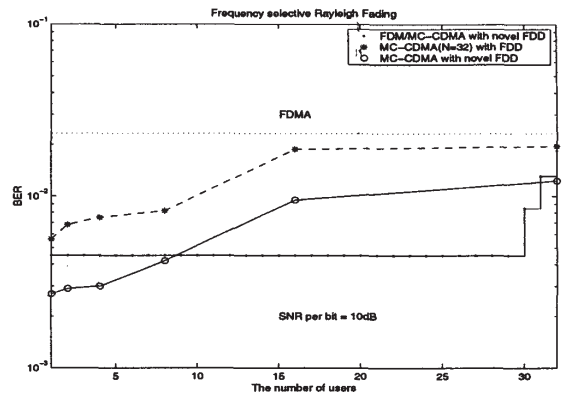

Figure 2: BER comparison between MC-CDMA system with traditional FDD and (1) novel FDD (2) FDM with novel FDD (best case user)

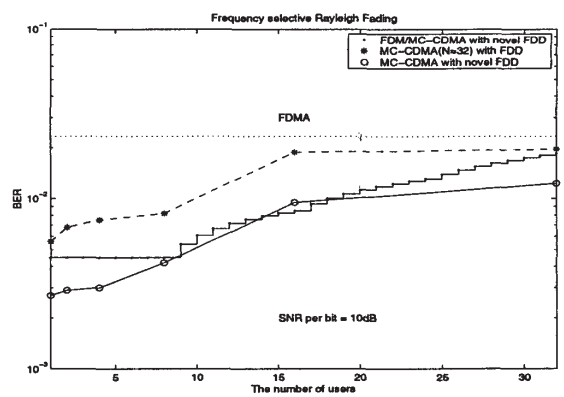

Figure 3: BER comparison between MC-CDMA system with traditional FDD and (1) novel FDD (2) FDM with novel FDD (average BER)

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