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# Hybrid Multi-Carrier CDMA Modulation based on VLSI

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## Abstract

CDMA is a multiple access technique, which is based on spread spectrum modulation scheme. It allows a multiple users to access the channel simultaneously, with each user's data being multiplied by a unique and orthogonal pseudo-random code sequence. Spread spectrum, as the name suggests, modulates the narrow band data and spreads it over a much wider bandwidth, thus transmitted data has a very low power spectral density. Moreover the inherent interference rejection capability of CDMA makes it suited to radio frequency environment. CDMA is interference limited, due to the multiple access interference of multiple users. Although orthogonal codes could result in no multiple access interference (MAI), in flat fading channels, the orthogonality will not be guaranteed in frequency selective fading channels because of inter-chip interference, which will cause MAI and degrade the system performance. One approach to suppress the effect of inter-chip interference in frequency selective fading channels is the combination of CDMA and multi- carrier modulation, such as OFDM that can achieve high spectral efficiency because the spectrum of successive sub- carriers is allowed. The combined CDMA system with OFDM is mainly categorized into MC/DS-CDMA and MCCDMA.

**Keywords:** Baseband receiver, code-division multiple access (CDMA), multi-carrier modulation.

## 1. Introduction

Direct Sequence spread-spectrum (DSSS) code division multiple access (CDMA) is a multiple access scheme adopted in the third generation (3G) cellular communication standard to provide high capacity and high transmission rate over conventional multiple access methods such as frequency-division multiple access (FDMA) and time-division multiple access (TDMA). However, it is also well known that frequency-selective multi- path fading inevitably encountered in broadband wireless channels can severely degrade DSSS CDMA system performance. Although coherent Rake combining can exploit path diversity and enhance receiver performance, a large number of paths to be resolved in broadband systems entail high receiver complexity. What is worse, multiple access interference (MAI) caused by channel dispersion cannot be effectively suppressed using Rake combining. Recently, a new multi-carrier modulation scheme, orthogonal frequency-division multiplexing (OFDM) attracts much attention from the communications research community.

In an OFDM communication system, a frequency-selective- faded wide- band signal is partitioned into a large number of flat-faded narrowband signals. The adverse channel effects can consequently be mitigated by using a simple one-tap frequency- domain equalizer (FEQ). The longer symbol duration in OFDM systems also makes their signals more resistant to time dispersion caused by the channel. With the guard interval between every pair of symbols, inter-symbol interference (ISI) can be contained and eliminated. In addition to the above advantages, the mutually overlapped spectra of the subcarriers provide efficient utilization of the allocated spectrum given that cross-symbol discontinuities are smoothed by time-domain windowing, filtering, or a combination of both. In light of these advantages, OFDM has been adopted in several standards, such as digital video broadcasting-terrestrial (DVB-T), digital subscriber line (DSL), and IEEE 802.11a/g wireless LAN. In the third generation partnership project (3GPP), a feasibility study of OFDM for universal mobile telecommunications system terrestrial radio access network (UTRAN) enhancement is conducted to evaluate its potential benefits and has taken into consideration the possibility of incorporating the OFDM technique [1].

As such, multi- carrier CDMA (MC-CDMA), which combines OFDM and CDMA techniques, has been proposed in [2]–[4]. Inheriting advantages from both multi-carrier modulation and CDMA, MC-CDMA is capable of combating frequency-selective fading channels as well as offering high data rate transmission in a multi-user environment. Moreover, the adopted orthogonal variable spreading factor (OVSF) codes spread the original data symbol over several subcarriers, making frequency diversity reception multi-rate transmission possible. In light of all the above advantages, MC-CDMA has become one of the attractive candidates for next- generation mobile communications. Field trials of MC-CDMA systems have been conducted in Japan and several ongoing projects regarding MC-CDMA standardization in future broadband mobile systems are under way in Europe [3], [4]. Although wireless communication solutions using OFDM are mature and plentiful [5], [6], applying OFDM in the mobile cellular communication environment can be quite different. In the cellular environment, time- varying fast-fading channels caused by high mobility pose a severe challenge to synchronization and channel estimation tasks in the MC-CDMA receiver.

A robust tracking mechanism for the synchronization parameters must be established since multi- carrier modulation is notorious for its vulnerability to synchronization errors. In fast-fading mobile cellular environments, the MC-CDMA receiver must have an agile and precise channel estimation algorithm to follow variation in channel responses. In addition, owing to larger cell size and thus longer delay spread, the MC-CDMA system must use a smaller subcarrier bandwidth. This entails more subcarriers in OFDM modulation and the receiver complexity will be much higher. In this paper, a downlink baseband receiver architecture using MC-CDMA suitable for mobile cellular communication in urban areas is proposed. The MC-

CDMA receiver can support up to 21.7-Mbps (uncoded) downlink data transmission and has compatible carrier frequency and bandwidth with the current 3G wide-band CDMA (W- CDMA) standard. The receiver IC dissipates only 9.9 mW at 5.76-MHz operating frequency from a supply voltage of 1.1 V. Features of the proposed receiver include the following: provision of a robust and precise tracking mechanism for carrier frequency offset (CFO) and sampling clock offset (SCO).

- Provision of a smart-channel estimation mechanism according to Doppler frequency;
- Adoption of a specialized channel interpolation algorithm with increased accuracy of channel estimation in fast fading channels. Two circuit design techniques are also adopted in the IC, including:
- Implementation of a custom-designed bit- reversal architecture with reduced SRAM requirements;
- Implementation of allow-complexity high- performance equalizer architecture.

The paper is organized as follows. Description as well as parameters of the MC-CDMA system is first introduced in Section II. Then, the baseband transceiver function blocks are presented in Section III. Section IV describes the baseband transceiver architecture and several implementation issues crucial to achieving low power and small area. In Section V, the physical design of the proposed chip and its measurement results are given. Finally Section VI concludes this paper.

## 2. System description

Jing in Table I, we summarize several important parameters of the proposed MC-CDMA system [7], [8]. The proposed system uses the same RF frequency and signal bandwidth as those of the 3G standards, i.e., 2 GHz and 5 MHz, since its major goal is to increase the downlink data rate of the current 3G W-CDMA cellular communication system in urban areas. Moreover, we reserve 5% bandwidth on both ends of the signal band as guard bands. To facilitate future dual-mode receiver design, the ADC sampling rate is set to 5.76 MHz, 1.5 times the chip rate in the W- CDMA system (3.84 MHz).

The channel models provided by 3GPP [9] specify that the maximum excess delays are 2.14 s and over 10 s in typical urban and bad urban areas, respectively, and the highest mobility supported is up to 120 km/h. Accordingly, we set the guard interval to be longer than 10 s. Also, the maximum Dopple shorter frequency, 222 Hz, limits the OFDM symbol duration to be than 200 s, such that the signal-to- interference ratio can be made higher than 25 dB [10], [11]. Given the sampling rate and the symbol duration, the fast Fourier transform (FFT) size is set to 1024.

Out of the 1024 subcarriers, 768 subcarriers are used to transmit data and 33 pilot subcarriers are uniformly inserted for synchronization/channel estimation. Three signal constellations, namely, quadrature phase-shift keying (QPSK), 16 quadrature amplitude modulation (QAM), and 64 QAM can be used and the maximum uncoded data rate reaches 21.7 Mbps. The orthogonal variable spreading factor (OVSF) codes [12] spread the user data onto a number of subcarriers. The same FFT size, guard interval ratio, and guard band ratio are adopted in the feasibility study of the 3GPP UTRAN OFDM enhancement [1].

**Table I: MC-CDMA System Parameter**

| | |
|---|---|
| RF Frequency | 2 GHz |
| Signal Bandwidth | 5 MHz |
| Sampling Frequency | 5.76 MHz |
| FFT Size (N) | 1024 |
| Subcarrier Spacing | 5.625 KHz |
| Guard Interval | 11.1 µs |
| Symbol Time | 188.9 µs |
| Number of Data Subcarriers | 768 |
| Number of Pilot Subcarriers | 33 |
| Maximum Data Rate (Uncoded) | 21.7 Mbps |

## 3. Transmitter Design

The transmitter block diagram is shown in Figure.1. Data from each user first pass through a constellation mapper, get spread by respective OVSF code, and then are combined with signals from other users. Since the length of the OVSF code may be less than 768, thus one may transmit several pieces of data in one MC-CDMA symbol. To achieve maximum frequency diversity, we spread the data onto subcarriers that are as far apart as possible. In other words, adjacent subcarriers are assigned to different pieces of data that have been spread by the same chip of the OVSF code [13]. Comb-type uniformly distributed pilot subcarriers are inserted to facilitate synchronization and channel estimation tasks in the receiver.

An OFDM modulator then transforms the frequency-domain signals to time-domain MC-CDMA signals. Afterwards, training symbols are transmitted periodically in the time domain so as to ensure continuous and reliable communication links. The training symbols play an important role when a receiver starts up and they also provide for frequency-domain channel estimation in stationary and quasi-stationary channels. A training symbol consists of two identical halves [14], making all odd-numbered subcarriers zero. With such an arrangement, the receiver can achieve more robust symbol boundary detection than the design that uses only the cyclic prefix. Moreover, the even- numbered subcarriers in the training symbol are differentially encoded with a pseudo noise (PN) sequence to expedite integer CFO acquisition [15].

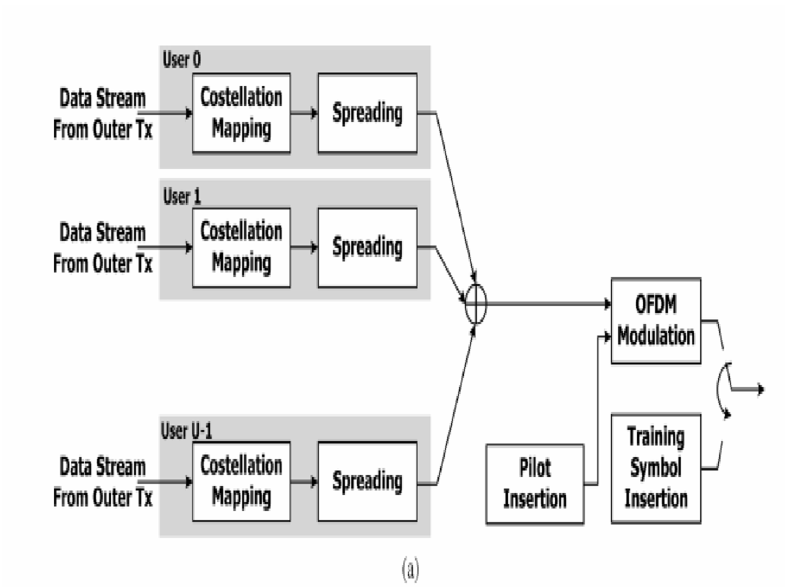


**Figure.1Transmitter Block Diagram**

## 4. Architecture and Circuit Design

In the following, the architecture and circuit design of a low power downlink baseband receiver will be described. Then, the effectiveness of this design in hardware saving and power saving will be presented.

### Word Length Optimization

The downlink cellular communication baseband receiver integrates synchronization and detection modules that support multiple users as well as constellations up to 64- QAM. As such, its complexity can be quite high and so signal word lengths in this receiver must be optimized. Such design optimization not only reduces hardware complexity, but also guarantees acceptable system performance. Toward this end, the signal-to-noise ratio (SNR) at the desperate output (before slicer or soft-input error correcting decoder) is adopted as the performance metric and it is defined as where is the number of symbols in the first quadrant of the transmitted constellation, e.g., in the 16-QAM, and is the desired user data after dispreading is the number of data belonging to the symbol after being sliced is the real part and the imaginary part of its argument respectively. The specified implementation loss due to quantization error is set to be smaller than 0.5 dB when the symbol error rate. Signal word lengths of several key signals in the receiver.

**FFT Module**

FFT is a key component in multi-carrier transceivers. It is both computation intensive and communication intensive. The FFT size in our application is quite large; therefore we use the radix- algorithm to accomplish the 1024-point FFT [16]. With the radix-2/4/8 algorithm, the FFT module requires only three complex multipliers and associated twiddle factor tables. Complex multipliers plane are realized in three real multiplications and five real additions/subtractions [17].

$$(A+jB)(C+jD)=[C\times(A-B)+B\times(C-D)] \\ +j[D\times(A+B)+B\times(C-D)].$$

Furthermore, symmetry in the sine/cosine functions is exploited and the look-up table stores only the sine and cosine values from 0 to ∏\4. For data scheduling in the FFT architecture, several delay buffers of various lengths are required. Longer delay buffers are implemented with two single-port SRAM modules, which consume less area and power than one two-port SRAM module. Nonetheless, delay buffers shorter than 64 are implemented by D flip-flops that are configured in a pointer first-in–first-out (FIFO) configuration. A ring counter with only one active cell is used to activate one word for read-out and one word for write-in. This arrangement greatly reduces data transitions and thus power consumption. More power can be saved by using one ring counter for several delay buffers. Channel Estimation As mentioned earlier, we provide two modes of channel estimation. One is the LS channel estimator for the slow-fading channels, which simply examines the complex gain between the received signals and the transmitted signals. Then, phase rotation caused by the SCO effect is also corrected. The other is the frequency-domain channel interpolator. In the mobile cellular environments, the received signals may suffer fast fading and it is very important to attain accurate channel estimation in fast fading channels. Normally, the receiver uses LS channel estimation. If the LS channel estimation cannot track channel ariation, frequency-domain channel interpolation is then activated.

**Performance of the MC-CDMA system**

In Figure 2, L, = 16 was chosen to assess the performance of the MC-CDMA system since it seems to be a good compromise for the coding rates used, according to the previous results. The joint assignment of the number P of spreading codes and the coding rate R provides different data rates. Table introduces the code number/coding rate pairs that lead MC-CDMA data rates values that are very close of the ones of the MBOA solution. Fig. 5 exhibits the results obtained in the ideal case of perfect channel estimation for the data rates of Table

| Data rate (Mbit/s) | Modulation | Coding rate (*R*) | $L_c$ | Load (*P*) | Coded bit per symbol |
|---|---|---|---|---|---|
| 51.2 | QPSK | 1/3 | 16 | 4 | 48 |
| 76.7 | QPSK | 1/3 | 16 | 6 | 72 |
| 115.1 | QPSK | 1/3 | 16 | 9 | 108 |
| 153.6 | QPSK | 1/3 | 16 | 12 | 144 |
| 192 | QPSK | 1/2 | 16 | 10 | 120 |
| 307 | QPSK | 1/2 | 16 | 16 | 192 |
| 409 | QPSK | 2/3 | 16 | 16 | 192 |
| 460 | QPSK | 3/4 | 16 | 16 | 192 |

**Figure. 2 ideal case of perfect channel estimation for the data rates of Table**

## 5. Conclusion

In this paper we have presented some methods to optimize the performance of an UWB system based on the MC-CDMA waveform. In particular, we have selected an adjacent subcarrier scheme and introduced a code selection approach to reduce the SI. In addition, the spreading code length effects have been studied versus the coding rate in order to find the best compromise to exploit at best the channel diversity without degrading the performance by introducing too much SI. We can conclude that an optimal working of the MC-CDMA system consists in increasing the spreading factor when the coding rate is getting higher. To complete these results, we have plotted the performance of the SS-MC-MA system for a given spreading code length. We have hereby shown that the optimized new system outper- forms MBOA, which tends to prove that the new waveform is more adapted to face frequency selectivity.

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