Orthogonal MC-DS-CDMA Modem using CRCCCs

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Abstract-In this paper we describe an orthogonal multicarrier direct sequence code division multiple access (MC-DS-CDMA) modem using cyclic rotated complete complementary codes (CRCCCs). The use of CRCCCs provides an attractive alternative to conventional spreading sequences for next generation mobile digital communications. Both time and frequency domain spreading are used in order to improve the processing gain. The use of complete complementary codes (CCC) eliminates multi user interference and thus removes the need for complex multi user detection receivers. The application of CRCCCs mitigates the loss in spectral efficiency (SE) due to the use of CCCs, and returns the system to the SE of a conventional CDMA system. The performance of the systems in an asynchronous mobile uplink was compared to the existing 3G standard. The system was implemented on FPGA in a back-to-back configuration, in order to determine the feasibility of implementation of such a system.

Index terms - Direct-sequence code-division multiple access, Multicarrier code division multiple access, OFDM.

I. Introduction

The adoption of wideband code division multiple access (W-CDMA) in third generation mobile digital communications has demonstrated the usefulness of this technology [1]. Yet, the conventional spreading sequences used for CDMA have been proven to have far from perfect properties. In particular, non-perfect cross-correlation leads to significant multi user interference (MUI) in an asynchronous transmission environment, typical of a mobile uplink [2]. Complete complementary codes (CCCs) provide a significant improvement over conventional codes, such as Walsh-Hadamard sequences, as they possess perfect auto-correlation and zero cross-correlation (ZCC). Furthermore, the high chip rate associated with single carrier direct sequence CDMA (SC-DS-CDMA) requires high speed signal processing [3]. This is not desirable, as this substantially increases handset cost, as well as increasing power consumption in battery powered mobile devices. The introduction of orthogonal frequency division multiplexing (OFDM) has allowed high speed, broadband communications to take advantage of the parallel processing offered by the fast Fourier transform (FFT) algorithm [3,4]. This has the advantage of reducing the complexity of the receiver, as the chip rate can be made much less for the same data throughput and bandwidth (BW). OFDM has been adopted in most of the current technologies, because of its favourable characteristics. However, OFDM still has certain undesirable characteristics, such as weak peak to average power ratios (PAPR). A weak PAPR requires large amplifier back-offs, reducing the effective range of mobile transmitters. It is therefore desirable to have a better PAPR for mobile applications, even at the expense of other performance criteria. This paper describes how a combination of OFDM and DS-CDMA employing cyclic rotated CCCs (CRCCCs) is utilised in order to achieve better performance in an asynchronous transmission environment, with the minimum increase in complexity.

II. Cyclic Rotated Complete Complementary Codes

The use of CCC results in a significant loss in spectral efficiency (SE), as multiple sequences are required for the transmission of a single data symbol [2,5]. In general, the SE of a CDMA system using CCCs is reduced by a factor L, with L the length of the sequences used. The application of CRCCCs can mitigate this loss, by introducing additional spreading sequences without increasing the BW of the transmitted signal [6]. CRCCCs are generated by rotating the original sequences through different chips. There are L-1 possible rotated versions of each sequence. The rotated versions of a sequence are designated XY_z. For example, a system with $L = 16$ will have $X \in \{A, B, C, D\}$, $Y \in [1, 4]$, $z \in [1,15]$ and XY_z given by XY[z+1:L, 1:z]. The properties of CRCCCs are based on the perfect auto-correlation properties of the original CCCs used. As the autocorrelation has only one peak, and is zero for all other relative time shifts, additional information can be carried in each position of the correlator output, without generating MUI. A periodic correlator, based on the properties of the Fourier transform, is used for detection at the receiver. This reduces the complexity of the receiver, as only one correlator is required for each element code, as well as all of its rotations. CCC offer better processing gain (PG) per sequence length, as the PG equals the congregated length of the sequences, given by

$$PG = L\sqrt{L}.$$

III. Multi Carrier Communication

Multi carrier (MC) communication has been proven more flexible and robust than conventional single carrier (SC) communication [4,7]. MC-CDMA has been shown to provide even more flexibility when designing for broadband, wireless, mobile applications. MC-DS-CDMA extends the flexibility of MC-CDMA by combining desirable properties of both SC-DS-CDMA and MC-CDMA. As MC-DS-CDMA uses less subcarriers than MC-CDMA for the same PG, MC-DS-CDMA has a much better PAPR, essential to mobile applications. Frequency-domain spreading can be conducted using any set of orthogonal sequences, as the orthogonality is maintained during asynchronous transmission, as long as the channel is not a frequency selective fading channel [4]. This reduces the complexity of the multi user detection (MUD) receivers required for conventional time-domain spreading sequences, as only users using the same frequency-domain spreading sequences need be detected. This represents only a fraction of the users in the system. This is a significant improvement, as the complexity of MUD receivers increases at least linearly with the number of users to be detected [4]. The application of CRCCCs as time-domain spreading sequences completely eliminate the requirement for MUD receivers, as the sequences have perfect ZCC for all relative time shifts between users, and as a result, their orthogonality is maintained. Frequency-domain spreading by means of CRCCCs adds an additional degree of freedom, as orthogonality is maintained due to the ZCC properties of the sequences. Subcarrier generation by means of OFDM is preferred, as this requires the lowest complexity in both the transmitter and receiver, as well as resulting in the minimum transmitter BW. For this system, frequency domain spreading with a factor of two was used ($L_f = 2$), in order to demonstrate the concept.

IV. Implementation

The system is implemented using a modified four dimensional modem [8], in order to utilise the complementary properties of the sequences used. An example of the implemented baseband transmitter is shown in Fig. 1.

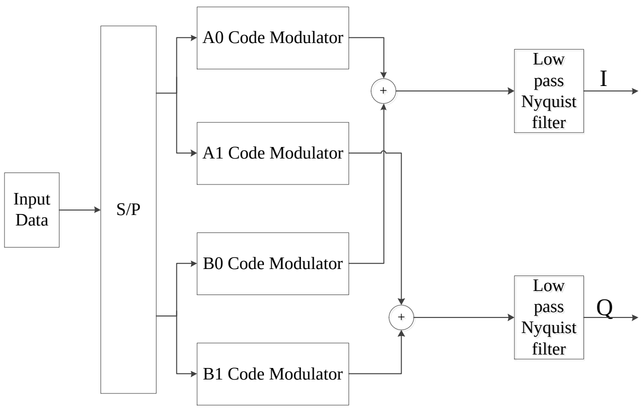

Fig. 1. Transmitter structure.

It is important that the different element codes be transmitted via different independent channels, in order to preserve the complementary properties of the sequences [2,9]. The structure of the receiver is shown in Fig. 2.

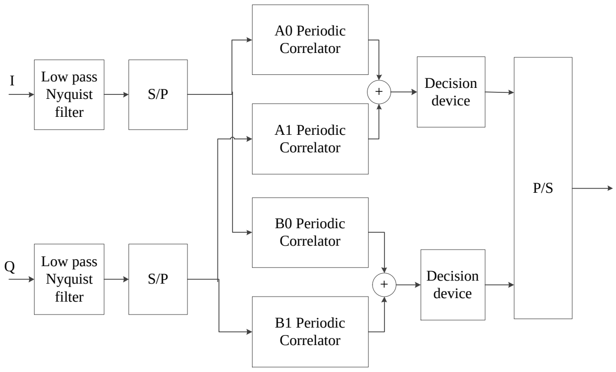

Fig. 2. Receiver structure.

The periodic correlators used are based on the FFT algorithm. The basic structure of the correlators is shown in Fig. 3.

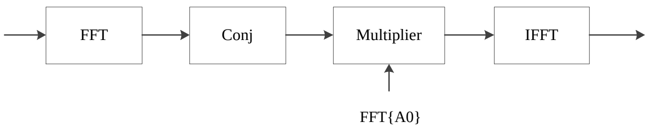

Fig. 3. Periodic correlator structure.

For the orthogonal-MC system, length 16 CRCCCs were used. The baseband transmitter structure is given in Fig. 4.

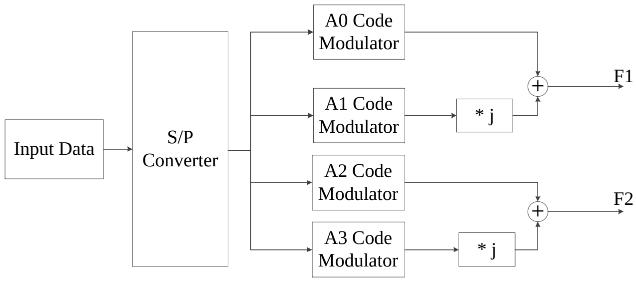

Fig. 4. Length 16 CCC transmitter structure.

Subcarrier generation was done by means of an inverse FFT (IFFT). An eight point IFFT was used to demonstrate the effect of orthogonal MC-DS-CDMA. The IFFT configuration is shown in Fig. 5.

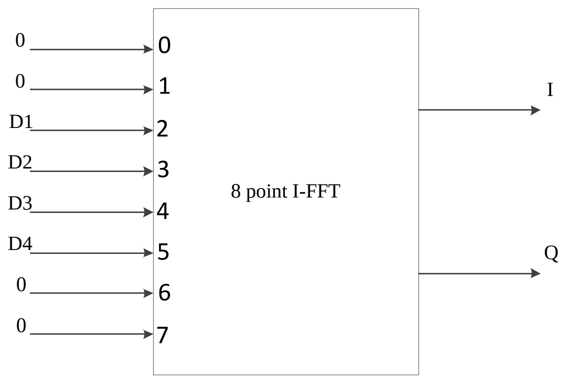

Fig. 5. IFFT configuration for subcarrier generation.

This implementation is computationally more efficient as it does not require the symbols to be repeated in conjugate form, in order to produce a real output signal [7]. The operation of this part of the system is equivalent to a conventional OFDM system. The input OFDM data symbol is generated by means of table I.

TABLE I
GENERATION OF OFDM SYMBOL.

Symbol	Formula
D1	F1 * *Fcode*[1]
D2	F2 * *Fcode*[1]
D3	F1 * *Fcode*[2]
D4	F2 * *Fcode*[2]

In table I, *Fcode* is the length two frequency-domain spreading code used, and F1 and F2 are shown in Fig. 4. The system uses the zero-padded OFDM symbol

$$S_n = [0\ 0\ D1\ D2\ D3\ D4\ 0\ 0],$$

as can be seen in Fig. 5.This forces the zero frequency term in the output to zero, making transmission easier, with a slight increase in BW. The frequency domain spreading and subcarrier mapping is shown in Fig. 6.

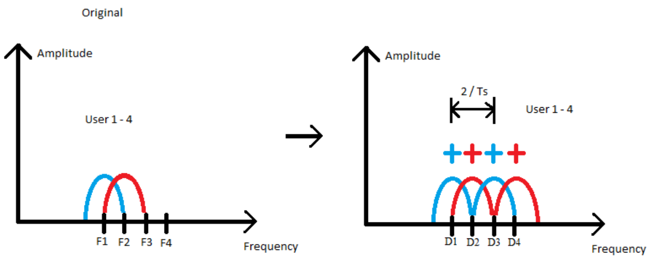

Fig 6. Frequency domain spreading and subcarrier mapping.

The receiver structure for the OFDM system is shown in Fig. 7.

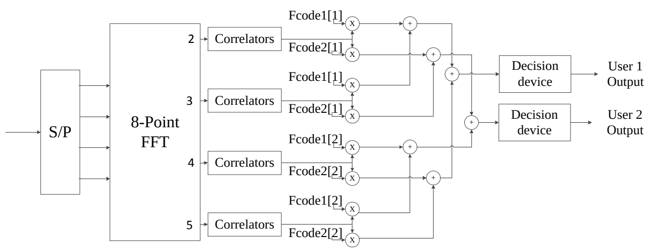

Fig. 7. OFDM Receiver with frequency-domain despreading.

V. RESULTS

Both the DS-CDMA and orthogonal MC-DS-CDMA systems were simulated. The baseband BER performance is shown in Fig. 8. This is shown for a two user system, using the length four CRCCCs and synchronous transmission. The BER performance is compared to the analytical BER performance of QPSK as well as M=16 quadrature amplitude modulation (16-QAM).

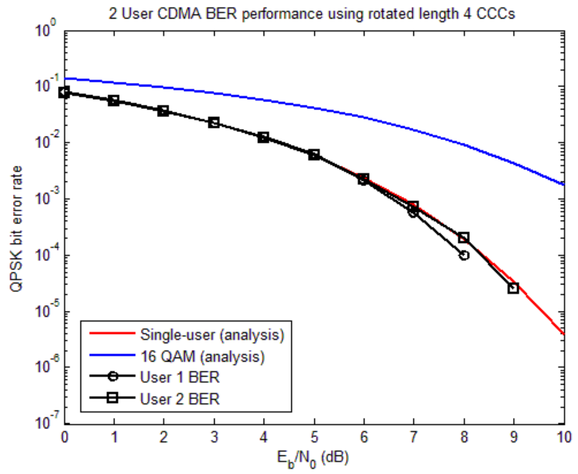

Fig. 8. BER performance of DS-CDMA system.

The BER performance of the orthogonal MC-DS-CDMA system is shown in Fig. 9. Eight users are simulated, using all four flocks of the length 16 CRCCCs and both available frequency-domain spreading codes.

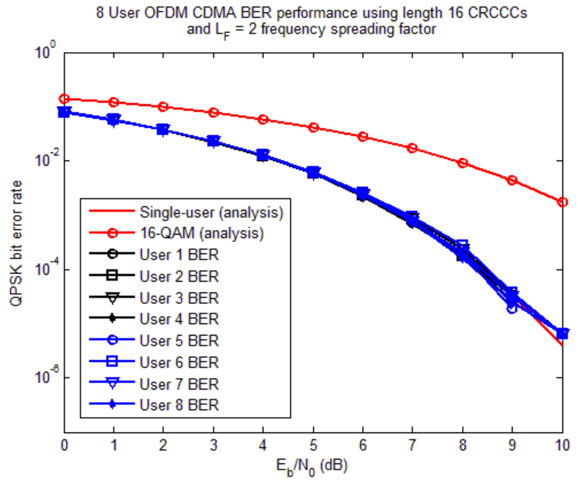

Fig. 9. BER performance of OFDM system.

It can be seen that the BER performance of both the DS-CDMA as well as the orthogonal MC-DS-CDMA remains QPSK-like. In order to measure the performance of the system under conditions more representative of a mobile environment, the baseband system was simulated with an asynchronous user present, as can typically be expected in a mobile uplink. The result is shown in Fig. 10.

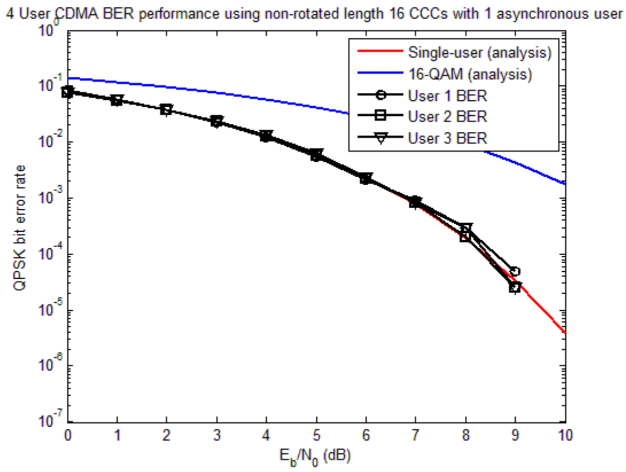

Fig. 10. BER performance of CRCCC DS-CDMA system with asynchronous user.

It can be seen that the BER performance remains QPSK-like. For comparison, the performance of a conventional system based on Walsh-Hadamard codes used in the Universal Mobile Telecommunication System (UMTS) is shown in Fig. 11.

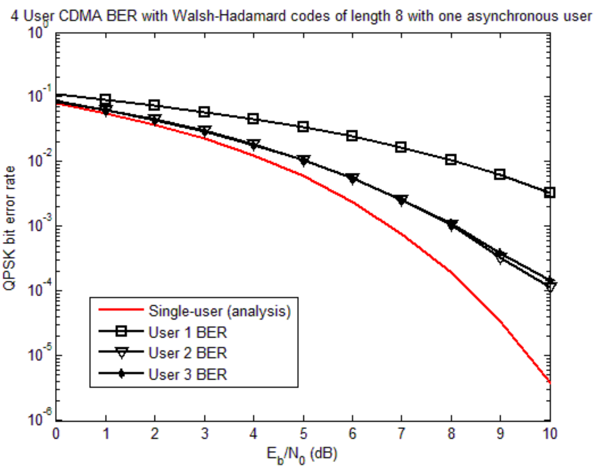

Fig. 11. BER performance of conventional DS-CDMA system with asynchronous user.

It can clearly be seen how the loss of orthogonality has led to a significant degradation in BER performance. The degradation would require the implementation of complex MUD receivers in order to mitigate the loss in performance. This differs from the result in Fig. 10, where it can be seen that no such degradation is present.

The SE of the total system, using all available time-and frequency-domain spreading sequences remains equal to the SE of the modulation scheme used, i.e. (2 bits/s/Hz for QPSK, 4 bits/s/Hz for 16-QAM). The SE per user is dependent on the length of the time-and frequency-domain spreading sequences used, as this determines the number of users on the system. For the system presented, with $L_t = 16$ and $L_f = 2$, a total of eight users are possible, each with a maximum user SE of ¼ bits/s/Hz.

Both the DS-CDMA and orthogonal MC-DS-CDMA systems have also been implemented on FPGA in order to determine the feasibility of such an implementation. The system was found to work error-free in a back-to-back configuration.

VI. Conclution

A baseband DS-CDMA system using CRCCCs has been successfully implemented. The system has also been expanded into multi-carrier communication using orthogonal MC-DS-CDMA, with subcarrier generation by means of an IFFT, similar to conventional OFDM. Both systems have been shown, through simulation, to give QPSK-like BER performance in the presence of AWGN. More significantly, the performance of both systems remains QPSK-like with an asynchronous user present. For comparison, the results from a DS-CDMA system using Walsh-Hadamard codes as in the UMTS standard have also been shown. This clearly demonstrates how the use of CRCCCs has effectively eliminated MUI caused by loss of orthogonality in an asynchronous transmission environment, typical of a mobile uplink. This results that this system does not require the implementation of complex MUD receivers in order to mitigate the loss in performance caused by the loss of orthogonality, as the sequences remain orthogonal, for all time shifts. The SE obtained by the system was equal to the maximum obtainable given the QPSK modulation used, i.e. 2 bits/s/Hz. The SE per user can be adapted using different lengths of spreading sequences. The total SE can also be improved by using multi-level modulation, instead of QPSK, although this was not investigated. Both the baseband DS-CDMA system as well as the orthogonal MC-DS-CDMA system has been successfully implemented on FPGA, showing that the implementation of CRCCCs is indeed feasible, as it requires a minimal increase in complexity.

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Frederick de Lange received his undergraduate degree with distinction in 2011 from the University of Pretoria and is presently studying towards his Honours degree at the same institution. His research interests include LTE, OFDM, and MC-CDMA.