A Multi-levelled OFDM-CDMA Modem Using Complete Complementary Codes

Alexander Merensky[1], Jacques van Wyk[2] and Louis P. Linde[2]
Department of Electrical, Electronic and Computer Engineering
University of Pretoria, South Africa
Telephone: (082) 837–3415, Fax: (012) 362–5000
Email: alexmerensky@tuks.co.za[1]; {jacques.vanwyk, louis.linde}@up.ac.za[2]

***Abstract*—In this paper, we introduce a novel multiple access scheme based on a combination of a multi-levelled modem and multi-carrier techniques with the use of complete complementary codes. This modulation technique combines a multi-dimensional code division multiple access (CDMA) modem with recent designs of perfectly complete complementary orthogonal codes. The rotational properties of the spreading codes are further exploited to improve the modulation technique, throughput, spectral efficiency, and capacity. Additionally, the system is extended by making use of multiple carrier frequencies as in OFDM, with the additional benefits of being able to spread data in frequency and/or in time. The modem offers multiple access interference MAI-free and multipath interference MI-free operation in both asynchronous and synchronous communication, due to perfect autocorrelation and zero cross-correlation properties of the spreading codes. The unique multi-levelled multiple access modulation technique together with the integration of complete complementary codes, produces a spectrally efficient output signal with high data throughput rates, better noise tolerances in harsh channel conditions and an increased user capacity.**

***Index Terms*—Code-division multiple access (CDMA), orthogonal frequency-division multiplexing (OFDM), multi-carrier modulation, complete complementary codes.**

I. Introduction

THE need for a modulation technique that can reliably transmit at high data rates and with high bandwidth efficiency has risen in the last decades, due to the enormous growth of wireless services (wireless local-area networks, cellular telephones, etc.). Orthogonal frequency division multiplexing (OFDM) has been applied extensively in many high speed wireline and wireless communication standards, such as in ADSL, VDSL, WiMAX, WLAN radio interfaces (IEEE802.11a,b,g,n) and in many other mobile broadband solutions, due to its efficient usage of the available frequency bandwidth and robustness to frequency selective fading environments. However, it is limited by its spectral efficiency and with the growing demand of digital audio/video broadcasting, the availability of spectrum becomes a serious problem [1]. Meanwhile, code division multiple access (CDMA) has proven its spectral efficiency through flexible frequency reuse and multiple access techniques [1], [2].

The combination of multiple access techniques like CDMA and OFDM, demonstrated increased spectral efficiency, flexibility in radio resource allocation and anti-multipath and anti-interference features [2]. Thus, these combined systems have received significant attention as they capitalise on the benefit of both schemes and combine high bandwidth efficiency and high data rates with robustness against multipath distortion. The implementation of the fast Fourier transform (FFT) allows for high spectral efficiency, due to the minimum frequency spacing in carriers and for a low complexity transmitter and receiver design [3]. Various multi-carrier schemes which use the combination of CDMA and OFDM have been proposed, these can be mainly categorised according to the direction of spreading. The spreading of the data is either done in the time domain or frequency domain or even both [2], [4].

An important factor in the overall performance of a CDMA multi-carrier type modulation scheme is the perfect autocorrelation and zero cross-correlation property of the spreading codes. Due to non-ideal spreading codes used in current standardised CDMA systems, such as those used in existing 2-3G systems, problems of self-interference are evident [5], [6]. These existing problems in current systems such as slow transmission rate, low capacity, and complex system implementation are caused by the imperfect spreading codes implemented [7]. For example, according to [8], the Walsh-Hadamard sequences in the IS-95 standard and the OVSF codes in WCDMA standards made it impossible to ensure symmetric data throughput at the very beginning of the system design, because of their imperfect correlation characteristics in asynchronous and synchronous transmission modes.

This article presents an innovative modulation technique, by combining the architecture of a multi-dimensional modem with recent designs of perfectly orthogonal complete complementary codes. The shift or rotational properties of the spreading codes can further exploited in a novel way to improve the modulation technique, spectral efficiency and spreading code usage. A periodic cross-correlation method at the receiver has been devised to optimally obtain the cyclic rotated complete complementary codes (CRCC). The architecture allows for a high processing gain (PG) for interference suppression without limiting the amount of users. Additionally, the system is extended by making use of multiple carrier frequencies (OFDM) and can thus spread the information in frequency and/or in time. Traditional CDMA-based systems (i.e., IS-95, cdma2000, and W-CDMA), and even multi-carrier adaptations, have a spreading efficiency of $1/L$ information bits per chip per link (where L is the sequence length) [5], [9], whereas the novel modulation technique can transmit at 2 information bits per chip per link or channel user.

II. Multi-dimensional modem building block

The novel modulation technique makes use of a multi-dimensional modem to improve spreading code usage, throughput and overall performance of the system. The modem is implemented with rotated complete complementary codes to offer MAI-free and MI-free operation, due to the perfect autocorrelation and zero cross-correlation properties of the codes.

It was shown by [10], [11] that a 4-dimensional modem building block (without the newly implemented CRCC codes) has data throughput rates equivalent to that of a 16-ary quadrature amplitude modulated (16-QAM) WCDMA modulation scheme, but with the BER performance equivalent to that of BPSK/QPSK in both AWGN and fading multipath channel scenarios.

A. Description of the 4-dimensional transmitter

An example of a 4-dimensional modem transmitter building block can be seen in Fig. 1. The input sequence is split up into four parallel data streams $d_1(t)$ to $d_4(t)$. The upper two streams are spread using orthogonal complete complementary codes to produce the inphase component and likewise, the lower two streams are spread to produce the quadrature component. The inphase and quadrature components are then modulated onto quadrature carriers and summed to produce a transmitted signal as given by

$$s(t) = [d_1(t)c_r(t) + d_2(t)c_i(t)]\cos(\omega_c t) + [d_3(t)c_r(t) + d_4(t)c_i(t)]\sin(\omega_c t) \quad (1)$$

$$\mathbf{s} = (d_1\mathbf{c}_r + d_2\mathbf{c}_i) + j.(d_3\mathbf{c}_r + d_4\mathbf{c}_i). \quad (2)$$

Due to the orthogonality property of the carrier signals, the modulating signals can be independently detected. This allows the quadrature and inphase components to optionally use the same set of codes and thus save codes elements of the CRCC code family.

The building block depicted in Fig. 1 can be extended to more dimensions by adding more 4D-blocks in parallel, each using additional spreading codes from the family of CRCC codes. This can be achieved while still maintaining the respective BER performance of one original building block [10].

Fig. 2 shows a typical low complexity matched filter correlation-type receiver for a 4-dimensional modem. The receiver is depicted without the periodic cross correlation receiver structure needed when using the rotated codes (CRCC).

In [10], [12] it was shown that the data throughput rate of one basic 4-dimensional building block is twice that of a direct sequence spread spectrum (DSSS) QPSK modulation system, yielding a spectral efficiency of $4/L$ b/s/Hz, i.e., equal to that of M=16-QAM, but with the BER performance of BPSK/QPSK assuming equal spreading sequence lengths, bandwidths and without the addition of rotating CRCC codes.

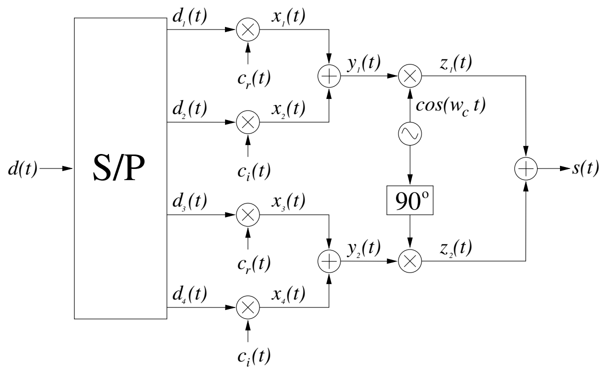

Fig. 1. A 4-Dimensional (CDMA) modem transmitter building block [11].

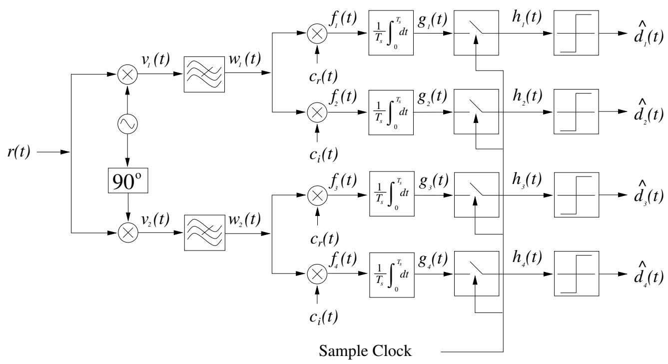

Fig. 2. A 4-Dimensional (CDMA) modem correlation-type receiver building block [11].

This multi-dimensional building block forms the foundation of the proposed modulation technique. Multiple transmitter blocks are combined and parallelised to form a high throughput modulation technique, which is spectrally efficient and exploits the diversity in the radio channel to improve performance. The usage of the rotated complete complementary codes enables the data from multiple combined multi-dimensional building blocks to be transmitted simultaneously over one channel, since the codes allow the data to be differentiated again at the receiver as in CDMA techniques. A collection of these combined blocks can then be spread onto different sub-carrier frequencies using multiple access OFDM principles.

III. Complete Complementary Orthogonal Codes

The performance of any CDMA type system depends on the spreading codes. An important factor in the performance of the spreading code is based on its ideal auto and cross-correlation properties, since they determine the robustness in harsh channel conditions and the division amongst the different users. If the correlation functions are not ideal, every user or additional data stream can be viewed as another source of noise. Therefore, low cross-correlation values between spreading codes allow the receiver to separate user signals, whereas low autocorrelation values aid in filtering out multiple received signals, which are delayed due to multipath propagation [13].

If a CDMA system is not multiple access interference (MAI)-free and multipath interference (MI)-free, due to non-ideal cross-correlation and autocorrelation properties respectively, then the capacity of the overall system can merely achieve capacity equal to approximately one-third to a half of its processing gain, which is currently seen in available CDMA-based 2-3G wireless systems [8], [14].

The proposed system is based on complete complementary code spreading, which can achieve interference-free performance and high capacity due to their inherent ideal auto/cross-correlation properties. These ideal spreading codes, as used in the proposed modulation scheme, suppress MAI and MI effects, hence the performance is limited only by noise.

The main difference between traditional CDMA codes and complete complementary codes is that the orthogonality of complete complementary codes is based on a set of element codes called a flock, instead of a single code [9]. These codes have a zero autocorrelation for all shifts except the zero shift and zero cross-correlation function for all possible shifts [5]. Orthogonality of the codes is maintained even for an asynchronous case.

The family size or number of flocks is equal to the number of element codes in one flock and can be defined as $M = \sqrt{L}$. The processing gain (PG) of the codes can then be defined by $L.\sqrt{L}$, where L is the length of every element code sequence [5], [9].

The autocorrelation and cross-correlation of the code can be expressed as follows [15]:

$$\phi_{xx}(j) = \sum_{n=-\frac{L}{2}}^{\frac{L}{2}-1} \sum_{i=1}^{\sqrt{L}} a_{n,i}^{(x)} a_{n+j,i}^{(x)} = \begin{cases} L\sqrt{L}, & j = 0 \\ 0, & j \neq 0 \end{cases} \quad (3)$$

$$\phi_{xy}(j) = \sum_{n=-\frac{L}{2}}^{\frac{L}{2}-1} \sum_{i=1}^{\sqrt{L}} a_{n,i}^{(x)} a_{n+j,i}^{(y)} = 0 \quad (4)$$

where ϕ_{xx} is the autocorrelation function (3) of set x, ϕ_{xy} is the cross-correlation function (4) of sets x and y, j is the number of shifts between the sequences, and n is the nth element of each code sequence [15].

A. Complete Complementary Code generation

There are various ways in constructing complete complementary codes. In [8], [16] an algebraic method is used to generate super complementary code sets called the real environment adapted linearisation (REAL) approach. The REAL approach generates interference-free CDMA code sets with perfect auto- and cross-correlation properties, however, the approach requires a great computational load [7]. Below, a more practical approach to generating the codes is shown according to the algorithm outlined in [6].

A matrix approach is taken in generating the code sets using a $\sqrt{L}$-dimensional orthogonal matrix, where L is the length of the code generated [16]. Define an $N \times N$ dimensional orthogonal matrix $\mathbf{A}$ such that $|a_{ij}| = 1$ and

$$\sum_{i=1}^{N} a_{ij} a_{ki}^{*} = 0, \qquad \text{where } j \neq k. \quad (5)$$

Then let $\mathbf{B}$ be another $N \times N$ orthogonal matrix from which N sequences of length N^2 can be constructed as follows:

$$\begin{aligned} \mathbf{E}_1 &= (b_{11}\mathbf{A}_1, b_{12}\mathbf{A}_2, \ldots, b_{1N}\mathbf{A}_N) = (e_{11}, e_{12}, \ldots, e_{1N^2}) \\ \mathbf{E}_2 &= (b_{21}\mathbf{A}_1, b_{22}\mathbf{A}_2, \ldots, b_{2N}\mathbf{A}_N) = (e_{21}, e_{22}, \ldots, e_{2N^2}) \\ &\vdots \\ \mathbf{E}_N &= (b_{N1}\mathbf{A}_1, b_{N2}\mathbf{A}_2, \ldots, b_{NN}\mathbf{A}_N) \\ &= (e_{N1}, e_{N2}, \ldots, e_{NN^2}). \end{aligned} \quad (6)$$

where $\mathbf{A}_i$ is the ith row of the $\mathbf{A}$ matrix [7]. Each $\mathbf{E}_i$ $(1 \leq i \leq N)$ has an autocorrelation of zero for any shift except the zero shift and the cross-correlation of any two sequences is zero for all shifts. Again let $\mathbf{D}$ be another N-dimensional orthogonal matrix from which the final spreading sequences can be constructed by

$$\begin{aligned} \mathbf{C}_{ij} =& (e_{i1}d_{j1}, e_{i2}d_{j2}, \ldots, e_{iN}d_{jN}, e_{i(N+1)}d_{j1}, \\ & e_{i(N+2)}d_{j2}, \ldots, e_{i(2N)}d_{jN}, \ldots, \\ & e_{i(N^2-N+1)}d_{j1}, \ldots, e_{i(N^2)}d_{jN}) \quad (7) \\ =& (C_{ij1}, C_{ij2}, \ldots, C_{ijN^2}), \qquad \text{for } i, j = 1, 2, ..., N \quad (8) \end{aligned}$$

where $\mathbf{C}_{ij}$ is the jth sequence in the ith flock [7], [16].

Conventional complete complementary codes support only a limited number of users. Therefore, a cyclic rotation technique is used to extend the original code family size, which allows for more codes/users and increases the system capacity and spectral efficiency without loosing performance.

IV. System Model

The signal of the novel system is generated using a combination of CDMA and OFDM techniques. Multiple transmitter blocks are combined and parallelised by the complete complementary codes to form a high throughput modulation technique, which is spectrally efficient and exploits the diversity in the radio channel to improve performance and still keep the original bit error rate performance.

A total of $2LM$ data symbols are spread and summed together, similar to offset stacked spreading modulation (OSM), which enables parallel transmission and thus improves spectral efficiency. This shows that a large number of data symbols can be processed in one instance. The spectral efficiency (SE) is not equal to $1/PG$ as in traditional CDMA systems, instead, it is equal to $1/M$. This system does not use the spreading codes as in a conventional spreading system. The bit stream is not aligned in time 1 bit after the other, but rather a new bit be stacked onto the other. When assuming a BPSK modulation and considering the multi-dimensionality of the novel transmission scheme, a spectral efficiency of 2 bits/s/Hz can be achieved for one user's building block if the set size equals the flock size. The simplified transmitter structure of the proposed system is portrayed in Fig. 3 (detail omitted technique used can not be explained further - patent pending). It describes the implementation of the Uth user's transmitter and the generated signal S^U. Multiple access is then achieved by assigning the users to different sub-carriers, as in orthogonal frequency-division multiple access (OFDMA), to provide multi-user and frequency diversity. The proposed system uses CDMA not to distinguish between users, which the OFDMA technique does, but rather it improves the multi-dimensional modem design and spectral efficiency when spreading the data.

A. Multiple access implementation

The generated signal of the Uth user is fed through an inverse fast Fourier transform (IFFT) to produce a multi-user system by assigning subsets of sub-carriers to individual users. The multiple access implementation of the system can be seen as an OFDMA modulation technique. The use of the simple IFFT/FFT operations in the generation of the signal results in a low complexity transmitter and receiver structure.

A block diagram of the multiple access implementation is shown in Fig. 4. It depicts how the signal S^U from Fig. 3 is transmitted further via OFDM techniques to produce a multi-user or multiple access system. Multiple access is achieved by assigning different OFDM sub-channels to different users, using various subcarrier allocation strategies. For example, a group of adjacent subcarriers or subbands can be assigned to each user in both frequency and time, or users can be assigned to interleaved or randomly chosen subcarriers.

In the design of the novel modulation technique, various allocation strategies of the IEEE standards can be directly implemented before the IFFT. The multi-carrier aspect can be designed in many ways to adapt to the requirements of the system and channel conditions. After the subcarriers and subchannels are assigned and sent through the IFFT, a guard interval or cyclic prefix can be inserted into the signal to eliminate intersymbol interference from the previous symbols. The cyclic prefix allows for simple frequency domain processing, such as channel estimation and equalisation, due to the circular convolutional properties of the repeated end-part of the symbols when taking its discrete Fourier transform (DFT). Pilot symbols can additionally be inserted to aid in the measurement of the channel conditions and can also be used to avoid time and frequency synchronisation problems, which can cause intersymbol interference (ISI) and inter-carrier interference (ICI) respectively [17]. The pilot and guard subcarriers placement parameters can be found in the various subcarrier usage strategies as defined in the IEEE standards [17].

The implemented multiple access scheme allows different users to transmit over different portions of the broadband spectrum. When a broadband signal experiences frequency selective fading, different users perceive different channel qualities (multi-user diversity). For example, a deep faded channel for one user can still be favourable to another user. The use of the OFDMA technique allows for efficient use of the spectrum with simple FFT processing and produces a better performing system in fading environments.

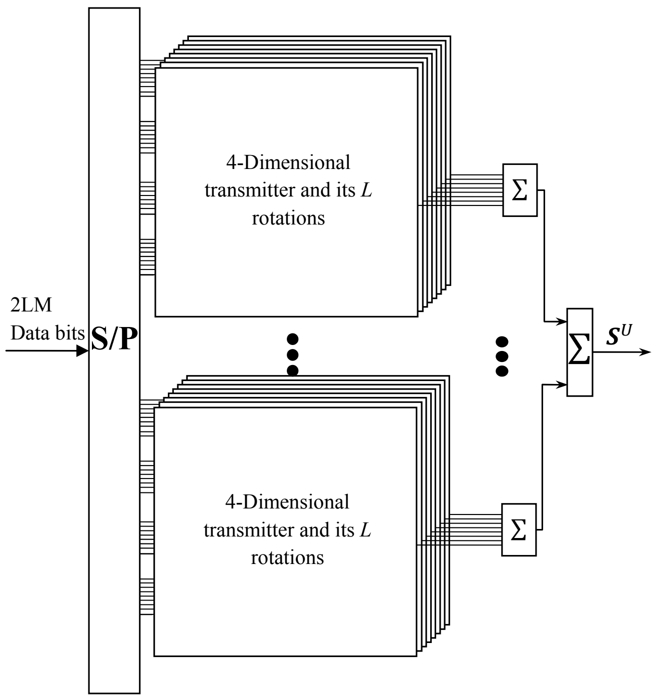

Fig. 3. The transmitter structure of the proposed system.

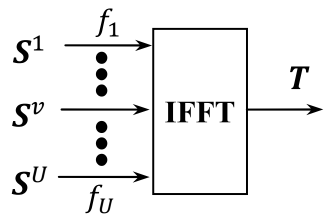

Fig. 4. Multi-carrier transmission via IFFT/FFT for multiple access.

V. Discussion

The integration of a multi-dimensional modem with the multi-carrier functionality of OFDMA, produces a novel system that is not only applicable to cellular technology and wireless broadband solutions, but also in wired digital data communications technologies such as in digital subscriber lines (DSL). By making use of orthogonal complete complementary code families with a multi-levelled modulation technique, a method is devised which greatly improves throughput and spectrum efficiency of the basic transmission scheme.

The system is capable of supporting multiple users making use of OFDMA techniques. The different users all experience the same noise effects in AWGN and thus the system performance does not degrade with an increase in the number of users, because perfect codes were used. The system can dynamically assign users to different subcarriers and control the amount of channels available to each user. Thus, the throughput for a specific user could be increased or decreased depending on the channel conditions and required throughput or quality of service needed by a user. Similar performance advantages are expected in multipath fading channels, but results fall out of the scope of this paper.

The system can be adapted to any required design criteria and shows an improvement of the basic modulation and transmission technique used in various currently available standards. Although no complex channel coding is applied, the design holds high application potential in future generation communication systems and shows to be a promising technique which can improve currently implemented systems.

VI. Conclusion

The primary objectives of next-generation wireless networks for mobile and broadband services, is to make use of the limited radio spectrum in order to achieve higher data rates and throughput with higher bandwidth efficiency and user-capacity. By combining OFDMA and a modified multi-dimensional modulation method in a novel manner with the use of complete complementary codes and a cyclic rotation scheme, a unique digital broadcasting technique, which supports high data rates and capacities over hostile radio channels, was developed.

The proposed communications system shows improvements to the fundamental modulation technique without the aid of complex forward error correcting (FEC) codes. The system lays a powerful foundation which can outperform previous designs where the basis lacks in efficiency, performance and throughput. Therefore, the proposed system would show greater improvements and would reach the Shannon Bound more easily with the addition of channel coding, interleaving and equalisation, compared to previously designed systems implementing the same improvement techniques.

The system possesses several advantages over currently available 2G and 3G mobile cellular systems. It can, firstly, achieve a much higher bandwidth efficiency than conventional CDMA systems by conveying as much as two bits of information in each chip width, yielding a spreading efficiency equal to two, using the same processing gain. Secondly, the system offers MAI-free and MI-free operation in both synchronous and asynchronous channels. This attributes to co-channel interference reduction and capacity increase and in addition, the system has an improved throughput.

The benefits of both OFDM and a CDMA type modulation scheme are combined and further improved by the multi-dimensionality and spreading of cyclically rotated orthogonal complete complementary codes. This novel combination forms an attractive modulation technique for next-generation communication systems that require high data rates, high spectral efficiency, diversity and robustness in harsh channel conditions.

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Alexander Merensky holds a B.Eng(2009) and an Honours-B.Eng(2010) (cum laude) degree from the University of Pretoria and is presently working on his Master of Science dissertation in Electronic Engineering at the same institution. His research interests include digital communications, OFDM, CDMA, estimation, equalization, coding and signal processing for mobile communication systems.