A MULTI-DIMENSIONAL CODE-DIVISION-MULTIPLEXED OFDMA MODEM USING CYCLIC ROTATED ORTHOGONAL COMPLETE COMPLEMENTARY CODES

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Abstract: In this paper we present a novel multiple access scheme based on a combination of multi-carrier OFDMA techniques and a multi-dimensional spread spectrum modem that makes use of rotated mutually orthogonal complete complementary codes. A multi-dimensional code-division multiple access (MD-CDMA) modem with recent designs of perfectly orthogonal complete complementary codes, produces an innovative modulation technique, which is further improved upon by exploiting the rotational properties of the spreading codes to increase the throughput and spectral efficiency. The system is extended by making use of multiple carrier frequencies as in orthogonal frequency-division multiple access (OFDMA), providing additional benefits such as diversity by being able to spread the data in frequency and/or in time. The proposed modem offers multiple access interference (MAI)-free operation due to the perfect autocorrelation and zero cross-correlation properties of the spreading codes. The uniquely proposed modulation technique together with the integration of rotated complete complementary codes, produces a system with better spectral efficiency compared to a theoretical non-spread system, with high data throughput rates, better noise tolerances in harsh channel conditions and an increased user capacity. Various other benefits such as low complex channel estimation and synchronisation, rate adaption, and resistance to the near-far problem can be attributed to the system.

Key words: Code-division multiple access, cyclic rotated complete complementary codes, multi-carrier modulation, multiple access, multi-dimensional modem, orthogonal frequency-division multiplexing.

1. 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 (local-area networks, cellular telephones, to name but a few). With the growing demand of services such as digital audio/video broadcasting, the availability of spectrum has become a serious problem [1]. 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 (IEEE 802.11a,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. Meanwhile, WCDMA 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 improved anti-multipath and anti-interference features [2]. Thus, these combined systems have received significant attention as they capitalise on the benefits of both schemes and combine high bandwidth efficiency and high data rates with robustness against multipath distortion.

An important factor in the overall performance of a WCDMA multi-carrier type modulation scheme is the perfect autocorrelation and zero cross-correlation properties 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 [3], [4]. Existing problems, such as slow transmission rate, low capacity, and complex system implementation in current systems are caused by the imperfect spreading codes employed [5]. For example, according to [6], the Walsh-Hadamard sequences in the IS-95 (cdmaOne) standard and the OVSF codes in WCDMA (UMTS) 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 that combines the architecture of a multi-dimensional spread spectrum modem with recent designs of perfectly orthogonal complete complementary (CC) codes. The rotational or shift properties of the spreading codes are further exploited in a novel way to improve spectral efficiency and spreading code usage. Additionally, a low complexity periodic cross-correlation method at the receiver has been implemented to optimally despread and decode these cyclic rotated spreading codes. The entire system architecture allows for a high processing gain (PG) for interference suppression without limiting the amount of users. The system is extended by making use of multiple carrier frequencies (OFDMA) and can thus spread the information in frequency and/or in time, leading to an overall gain in diversity. Traditional CDMA-based systems (i.e. IS-95, cdma2000, and WCDMA), and even multi-carrier adaptations, have a spreading efficiency proportional to $1/L$ information bits per chip per link (where L is the sequence length) [3, 7], whereas the novel modulation technique proposed here can transmit at double the theoretical spectral efficiency (2 bits/s/Hz) of the digital modulation method used when implementing unspreaded binary phase shift keying (BPSK). This eliminates any loss in efficiency caused by spreading, resulting in greater data throughput.

The rest of the paper is outlined as follows. In the next section, we will introduce the basic multi-dimensional WCDMA modem building block. Section 3 will explain how the cyclically rotated spreading codes are generated and can be used in the system. An implementation scheme of the combined system is proposed in Section 4, together with the multi-carrier implementation and receiver design. Several concluding remarks and performance evaluations are presented in Section 5, followed by the conclusion given in Section 6.

2. MULTI-DIMENSIONAL WCDMA MODEM BUILDING BLOCK

The novel multi-layered modulation technique makes use of a MD modem to improve spreading code usage, throughput and overall performance of the system. The term *multi-layered* modulation specifically refers to the use of practically all available diversity means to modulate and spread in all possible dimensions, excluding the spatial domain, which is addressed in a future paper. The modem is implemented with cyclic rotated super-orthogonal complete complementary codes (CRCC) to offer MAI-free operation, only possible due to the perfect autocorrelation and zero cross-correlation properties of the codes. Hence, *super-orthogonality* refers to the perfect periodic and a-periodic even and odd auto and cross-correlation properties of the family of CC codes utilised.

It was shown by [8, 9], that a 4D-WCDMA 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 bit error rate (BER) performance equivalent to that of BPSK/QPSK in both additive white Gaussian noise (AWGN) and fading multipath channel scenarios, given identical spreading sequence lengths L and spreading bandwidths B_s, respectively.

2.1 *Building Block Description of a 4-Dimensional Modem*

An example of a 4D-CDMA modem transmitter building block can be seen in Figure 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 CC codes (C) 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

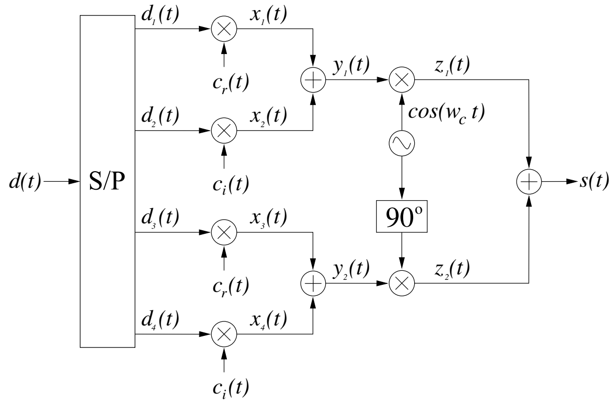

Figure 1: A 4D (CDMA) modem transmitter building block [8].

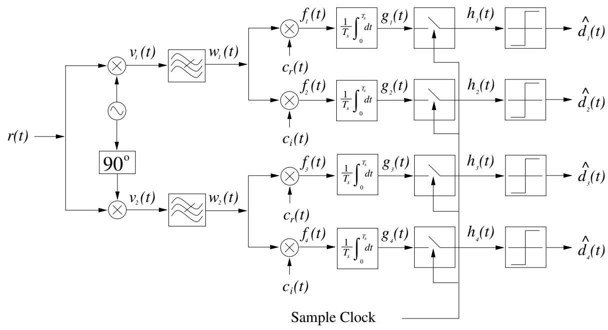

Figure 2: A 4D (CDMA) modem correlation-type receiver building block [9].

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

where $c_r = C$ and $c_i = jC$. Due to the orthogonal properties of the carrier signals, the quadrature modulated signals can be independently detected. This allows the quadrature and inphase components to optionally use the same set of codes and thus save code elements of the CRCC code family.

The building block depicted in Figure 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 [8]. Figure 2 shows a typical low complexity matched filter correlation-type receiver for a 4D modem. The receiver is depicted without the periodic cross correlation receiver structure needed when using the rotated codes (CRCC). In the newly proposed system, the modem is further exploited by cyclic rotated CC codes, which improve the throughput and negates the loss in spectral efficiency resulting from the spreading of the data.

This multi-layered building block forms the foundation of the proposed modulation technique. The signal of the novel system is generated using a combination of CDMA and OFDMA techniques. Multiple transmitter blocks are combined and parallelised by the CRCC codes to form a high throughput modulation technique which is spectrally efficient and capable of exploiting the diversity in the radio channel to improve performance. The usage of the CRCC codes enables the data from multiple combined multi-dimensional building blocks to be transmitted simultaneously with a high throughput over one channel, since the rotated spreading codes allow the data to be differentiated again at the receiver, as is the case with CDMA techniques. A collection of these combined blocks can then be spread onto different sub-carrier frequencies using OFDMA principles.

3. CYCLIC ROTATED COMPLETE COMPLEMENTARY CODES

An important factor in the performance of any WCDMA type system is the ideal orthogonality, auto and cross-correlation property of the spreading code used, since this determine the amount of users that can be accommodated in the system, 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 sidelobe values aid in filtering out multiple received signals which are delayed due to multipath propagation [10]. If a CDMA system is not MAI- 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 approximately one-third to a half of its processing gain, which is currently seen in available WCDMA based 2-3G wireless systems [6,11]. The design or selection of the spreading codes is very important at an early stage of a CDMA system design. Shortcomings in the system architecture due to the use of unsuitable codes necessitates the use of complex and very costly multi-user interference cancellation techniques. Examples thereof can be found in numerous 2G to 3G standards, where non-optimal code design was carried through to successive standards [12], [13].

3.1 Orthogonal Complete Complementary Codes

The main difference between traditional CDMA and CC codes is that the orthogonality of CC codes is based on a set of element codes called a flock, instead of a single code [7]. These codes have a zero autocorrelation for all shifts except the zero shift and zero cross-correlation function for all possible shifts [3].

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 of the codes can then be defined by $L.\sqrt{L}$, where L is the length of every element code sequence [3, 7]. The autocorrelation and cross-correlation of the code can be expressed as follows [14]:

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

$$\phi_{xy}(k)=\sum_{n=-\frac{L}{2}}^{\frac{L}{2}-1}\sum_{i=1}^{\sqrt{L}}a_{n,i}^{(x)}a_{n+k,i}^{(y)}=0, \qquad \forall k \qquad (3)$$

where ϕ_{xx} is the autocorrelation function (2) of set x, ϕ_{xy} is the cross-correlation function (3) of sets x, and y, k is the number of shifts between the sequences, and n is the nth element of each code sequence [14].

3.2 Complete Complementary Code Generation

There are various ways to construct CC codes. In [6, 13] 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. This approach however, requires a great computational load [5]. Below, a more practical approach to generating the codes is shown according to the algorithm outlined in [4].

A matrix approach is taken in generating the code sets using a $\sqrt{L}$-dimensional orthogonal matrix, where L is the length of the element code generated [13]. Define an $N\times N$ dimensional orthogonal matrix $\mathbf{A}$,

$$\mathbf{A}=\begin{pmatrix}\mathbf{A}_1\\ \mathbf{A}_2\\ \vdots\\ \mathbf{A}_N\end{pmatrix}=\begin{pmatrix}a_{11} & a_{12} & \cdots & a_{1N}\\ a_{21} & a_{22} & \cdots & a_{2N}\\ \vdots & \vdots & \vdots & \vdots\\ a_{N1} & a_{N2} & \cdots & a_{NN}\end{pmatrix}, \qquad (4)$$

consisting of a_{ik} for $i=1,2,...,N$ and $k=1,2,...3$ complex elements, such that the absolute values are $|a_{ik}|=1$ and the inner product of any two different rows in the matrix should be zero, or

$$\sum_{i=1}^{N}a_{ik}a_{mi}^{*}=0, \qquad \text{where } k\neq m. \qquad (5)$$

From this it can be shown that the autocorrelation function of the sequence or matrix $\mathbf{A}$ is zero for all N-multiple shifts, except the zero shift [15]. Then let $\mathbf{B}$ be another $N\times N$ orthogonal matrix as given above for $\mathbf{A}$, from which N sequences of length N^2 can be constructed as follows:

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

where $\mathbf{A}_i$ is the ith row of the $\mathbf{A}$ matrix [5]. Each

$\mathbf{E}_i$ $(1 \le i \le N)$ 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

$$\mathbf{C}_{ik} = (e_{i1}d_{k1}, \ldots, e_{iN}d_{kN}, e_{i(N+1)}d_{k1}, \ldots, e_{i(2N)}d_{kN}, \ldots, e_{i(N^2-N+1)}d_{k1}, \ldots, e_{i(N^2)}d_{kN}) \quad (7)$$

$$= (c_{ik1}, c_{ik2}, \ldots, c_{ikN^2}), \qquad \text{for } i,k = 1,2,...,N, \quad (8)$$

which gives N flocks of CC codes, each flock consisting of N element codes

$$\mathbf{C}_1 = \{\mathbf{C}_{11}, \mathbf{C}_{12}, \ldots, \mathbf{C}_{1N}\} \quad (9)$$
$$\mathbf{C}_2 = \{\mathbf{C}_{21}, \mathbf{C}_{22}, \ldots, \mathbf{C}_{2N}\} \quad (10)$$
$$\vdots$$
$$\mathbf{C}_N = \{\mathbf{C}_{N1}, \mathbf{C}_{N2}, \ldots, \mathbf{C}_{NN}\}, \quad (11)$$

where $\mathbf{C}_{ik}$ $(i,k = 1,2,\ldots,N)$ denotes the basic elementary code sequence of a set [13].

3.3 Cyclic Rotation Scheme for Spreading Codes

Conventional CC codes support only a limited number of users. Therefore, a cyclic rotation technique is used to extend the original code family size, allowing for more codes, increased system capacity, and spectral efficiency without loosing performance. The periodic property of the code makes it possible to transmit more data simultaneously by carrying data in each rotation of the code, thus improving the throughput significantly. The de-spreading or reception of the rotated spreading codes can be performed by a simplified periodic cross-correlation receiver structure making use of fast Fourier transform algorithms. Only the periodic cross-correlation of the original non-rotated sequence needs to be taken when using the FFT or the circular convolution theorem method to identify each rotated information bit (explained in Section 4.3).

For example, a CC code set with $M = 4$ flocks and an elementary code length of $L = 16$, can be defined as

$$\mathbf{C}_1 = \{\mathbf{C}_{11}, \mathbf{C}_{12}, \mathbf{C}_{13}, \mathbf{C}_{14}\} \quad (12)$$
$$\mathbf{C}_2 = \{\mathbf{C}_{21}, \mathbf{C}_{22}, \mathbf{C}_{23}, \mathbf{C}_{24}\} \quad (13)$$
$$\mathbf{C}_3 = \{\mathbf{C}_{31}, \mathbf{C}_{32}, \mathbf{C}_{33}, \mathbf{C}_{34}\} \quad (14)$$
$$\mathbf{C}_4 = \{\mathbf{C}_{41}, \mathbf{C}_{42}, \mathbf{C}_{43}, \mathbf{C}_{44}\}, \quad (15)$$

where $\mathbf{C}_{ik}$ $(i,k = 1,2,3,4)$ is the basic elementary code sequence of a set or flock.

From this, a combined un-rotated spreading sequence for flock 1 can be created by combining all the elementary codes of the first flock $\mathbf{C}_{11}$, $\mathbf{C}_{12}$, $\mathbf{C}_{13}$, and $\mathbf{C}_{14}$. This resulting spreading sequence of the first flock $\mathbf{C}_1$ can then be cyclically rotated $L = 16$ times, creating a new set of sequences defined as $\mathbf{C}_n^r$, where r defines the rotational index or number of cyclic rotations of the code and n still refers to the specific flock number. The orthogonality and perfect correlation properties of the codes are not destroyed by the cyclic shifting operation, so the newly defined cyclic rotated codes of the first flock ($n = 1$) can be given by

$$\mathbf{C}_1^{r=1} = \{\mathbf{C}_{11}^1, \mathbf{C}_{12}^1, \mathbf{C}_{13}^1, \mathbf{C}_{14}^1\} \quad (16)$$
$$\mathbf{C}_1^{r=2} = \{\mathbf{C}_{11}^2, \mathbf{C}_{12}^2, \mathbf{C}_{13}^2, \mathbf{C}_{14}^2\} \quad (17)$$
$$\cdots$$
$$\mathbf{C}_1^{r=L} = \{\mathbf{C}_{11}^L, \mathbf{C}_{12}^L, \mathbf{C}_{13}^L, \mathbf{C}_{14}^L\}, \quad (18)$$

where L equals the elementary code length (16 in this example). Thus, $L = 16$ rotations can be applied to the first flock before cyclically repeating the sequence.

This rotation technique produces L spreading codes from one flock and allows additional data bits to be transmitted with each rotation of the code. The rotation of the codes in the proposed system allows $4 \times r$ additional bits to be transmitted simultaneously for r-rotations of the code in one multi-dimensional building block (or $2M \times r$ for the entire system).

4. SYSTEM MODEL

The input information sequence of the Uth user is first converted into $2ML$ parallel data sequences $d_{m,r}^U$ for $m = 1,\ldots,2M$ and $r = 1,\ldots,L$, where M defines the flock or set size and L the length of every element code sequence.

The whole set of code sequences in one flock is used to spread a symbol, thus, the processing gain is large and is sometimes referred to as the *congregate processing gain* [14]. Every information symbol or bit $d_{m,r}^U$ is spread with the corresponding spreading sequence $\mathbf{C}_n^r[l]$, $n = 1,\ldots,M$ as seen in (19), where the length of $\mathbf{C}_n^r[l]$ is LM ($l = 1\ldots LM$). Then, through the novel rotation of the CRCC codes, the entire process is repeated L times, where $r = 1,\ldots,L$ refers to the rotational index. Leaving out the time index, the transmitted signal $\mathbf{S}^U$ can be described by

$$\mathbf{S}^U = \sum_{r=1}^{L}\sum_{i=0}^{\frac{M}{2}-1}\sum_{l=1}^{LM}\left[\left(d_{4i+1,r}^U\mathbf{C}_{2i+1}^r[l] + d_{4i+2,r}^U\mathbf{C}_{2i+2}^r[l]\right) + j\left(d_{4i+3,r}^U\mathbf{C}_{2i+1}^r[l] + d_{4i+4,r}^U\mathbf{C}_{2i+2}^r[l]\right)\right] \quad (19)$$

$$= \sum_{r=1}^{L}\sum_{i=1}^{\frac{M}{2}}\left(\mathbf{Z}_{i,r}^U\right). \quad (20)$$

For binary input symbols (BPSK) a total of $2LM$ symbols are spread and summed together, which enables parallel transmission, thereby improving spectral efficiency. This shows that a large number of data symbols can be processed in one instance. The spectral efficiency is not equal to $1/PG$ as in traditional CDMA systems, but instead is equal to the theoretical unspread spectral efficiency of the modulation method, except when using BPSK, in which case an improved spectral efficiency of 2 bits/s/Hz can be achieved for one user's building block if the set size

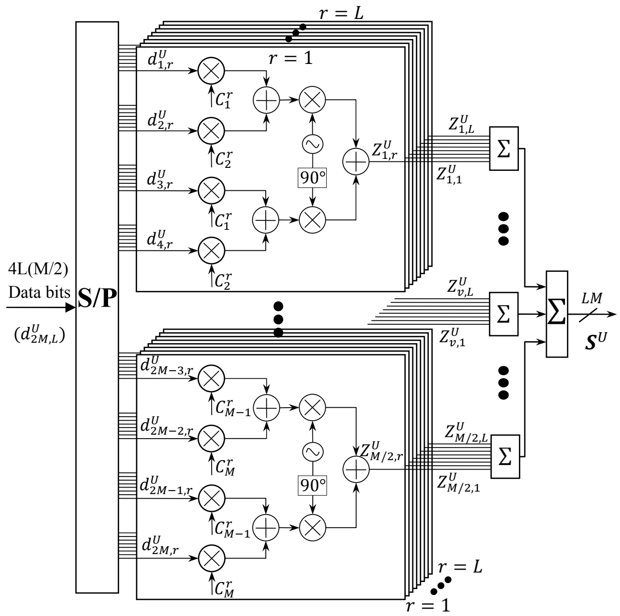

Figure 3: The transmitter structure for one user.

equals the flock size (i.e. equal to to unspread QPSK). This is only possible, because of the multi-dimensionality of the system and the use of the created CRCC codes. The multi-dimensional transmitter reduces the spreading code usage and adds an imaginary dimension to the input bits.

The simplified transmitter structure of the proposed system is portrayed in Figure 3. It describes the implementation of the Uth user's transmitter and the generated signal $\mathbf{S}^U$. Multiple access is then achieved by assigning the users to different sub-carriers, as in OFDMA, to provide multi-user and frequency diversity. The proposed system uses CDMA not to distinguish between users, which the OFDMA technique can do, but rather to improve the multi-dimensional modem design and spectral efficiency when spreading the data, and to improve the throughput.

4.1 Multiple Access/Carrier Implementation

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

To support different types of physical channel conditions, IEEE 802.16 OFDMA systems define several ways to allocate sub-channels, three for downlink: FUSC (fully utilised subchannelisation), PUSC (partially utilised subchannelisation) and AMC (adaptive modulation and coding), and two for uplink: PUSC and AMC [16] In

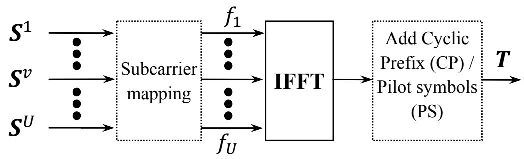

Figure 4: Multi-carrier transmission via IFFT/FFT for multiple access.

FUSC and PUSC a sub-channel consists of sub-carriers distributed over the entire spectrum, providing frequency diversity, while the AMC sub-channel consists of adjacent sub-carriers and provides for multi-user diversity [17, 18].

In the design of the novel modulation technique, the above mentioned allocation strategies of the IEEE standards can be directly implemented. The multi-carrier aspect can be designed in many ways to adapt to the requirements of the system and channel conditions. 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 it produces a better performing system in fading environments.

4.2 Combined System Model

A spread spectrum multi-dimensional code-division multiplexed system, combined with multiple access techniques such as OFDMA results in the proposed multi-layered code-division multiplexed OFDMA type system seen in Figure 5. As mentioned different types of spreading techniques in different dimensions can be used, however, in this case each user is assigned to a subset of sub-carriers according to an FDMA scheme and time spreading is not considered in this context. This achieves the highest throughput and spectral efficiency without the bandwidth efficiency loss when spreading in multiple dimensions. The system downlink transmitter of the multiple access scheme proposed is illustrated in Figure 5, which applies OFDMA for user separation and code-division multiplexing on the data belonging to each individual user. This exploits the frequency diversity by spreading over L sub-carriers. Additionally, inter-symbol interference (ISI) and inter-carrier interference (ICI) can be avoided, resulting in less complex detection techniques. Similarly, each sub-carrier is assigned to one user, making the channel estimation far less complex. It can be seen that the joint system makes use of the frequency, optionally the time and code space to achieve flexible resource allocation and diversity.

Similarly to multi-carrier CDMA systems, the proposed system takes advantage of the combination of spread spectrum techniques and multi-carrier modulation. As seen in Figure 5, one user assigns LM data symbols

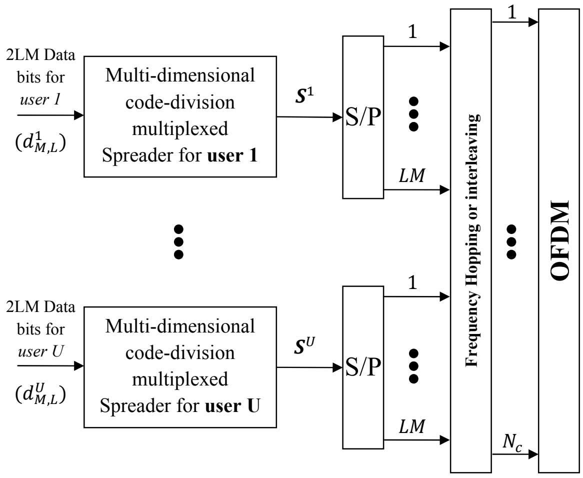

Figure 5: Downlink configuration of the code-division multiplexed OFDMA transmitter.

to one sub-system or LM sub-carriers, which are only used by that particular user. In the FDMA scheme, U users are transmitted over a total of $N_c = U \times LM$ sub-carriers. The spread symbols are transmitted on adjacent sub-carriers. This limits the frequency diversity of each symbol. Hence, to take full advantage of the frequency diversity of the entire available bandwidth the sub-carrier assignment in the frequency domain can be interleaved [19]. Various other frequency sub-carrier allocation schemes are available and these various schemes all have their tradeoffs and the system should be implemented with the optimal scheme by regarding the channel conditions in which it would operate.

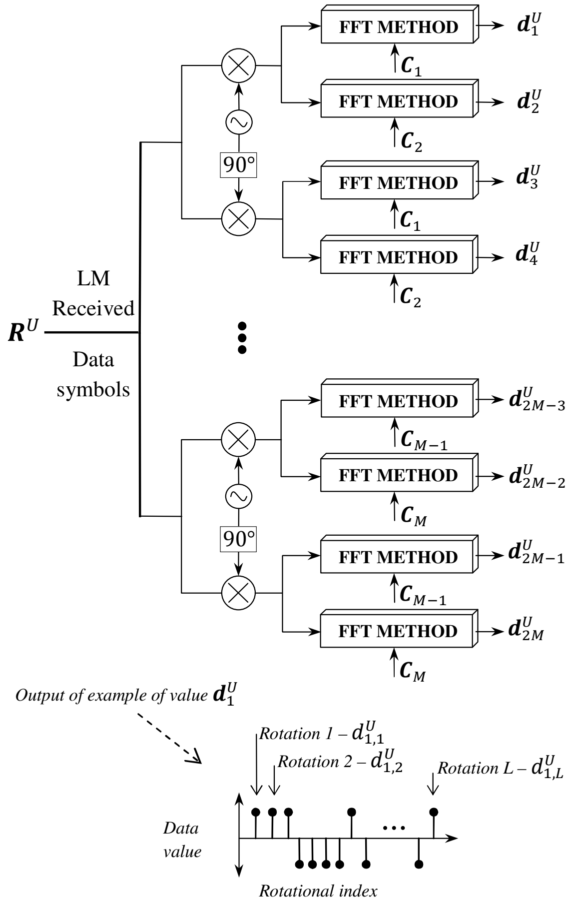

Figure 6: Proposed despreading receiver using fast Fourier transform method.

4.3 *Receiver Design*

The transmitter of the proposed system performs a user-specific frequency mapping of the user's spread signal $\mathbf{S}^U$, in which the chips are interleaved over the whole transmission bandwidth. To perform coherent data detection at the receiver, pilot symbols can be multiplexed into the transmitted data, which aids in frequency and time synchronisation.

After the transmitted signal is passed through the channel, the inverse OFDM with user-specific frequency de-mapping is performed. Additionally the pilot symbols of the user are extracted and can be used for channel estimation, as they would describe the fading and noise on the sub-carriers of user U. A variety of single-user or multi-user detection techniques can be implemented for the detection of the data. The detection can be done on the sub-carriers belonging to a single user, therefore requiring less complex detection techniques. Furthermore, the estimation of LM data symbols belonging to one user can be done simultaneously.

Multi-dimensional receivers for rotated codes: To de-correlate the spread spectrum signal, one fast Fourier periodic cross-correlation function needs to be calculated with the un-rotated original spreading sequence $\mathbf{C}_n^{r=1}$ to yield a length L vector. This vector holds each rotated data bit at its specific rotational index. This method making use of a fast Fourier transform algorithm, which is based on the convolution theorem, decreases the receiver complexity and shows a huge speed improvement in the de-correlation of the received signal. Hence, the periodic correlation functions can be determined much faster and with far less arithmetic complexity. The correlation of two finite length sequences can be found by taking the FFT of one sequence and the complex conjugate FFT of another and point-wise multiplying them, and then performing an inverse FFT of the result.

For example, a code family with a processing gain of $PG = 64$, a flock size of $M = 4$ and an elementary code sequence length of $L = 16$, can transmit or combine 16 data symbols using only one flock (or code sequence $\mathbf{C}_n$). Each data symbol would be positioned in one rotational position of the de-correlated sequence when using the FFT algorithm. When de-correlating the transmitted signal, the algorithm for de-correlating the length 64 transmitted

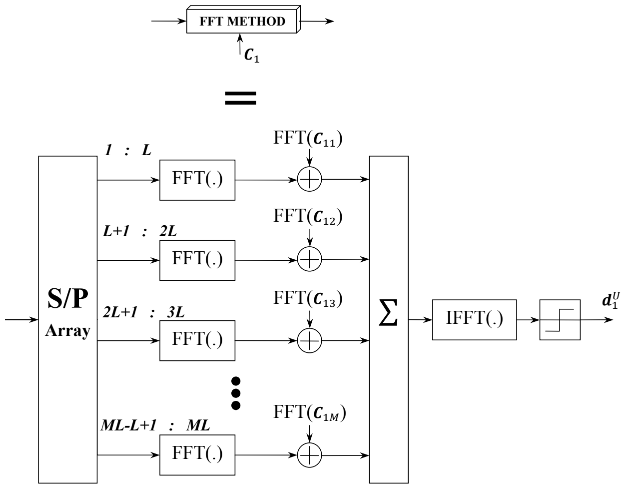

Figure 7: Fast Fourier transform method for building block depicted in Figure 6.

signal and all of its rotations can be found by

$$\begin{aligned} \mathbf{R} = \mathcal{F}^{-1}\Big(& \mathcal{F}\left(\mathbf{S}[1 \rightarrow 16]\right) \cdot \overline{\mathcal{F}\left(\mathbf{C}_{11}^{1}\right)} \\ & + \mathcal{F}\left(\mathbf{S}[17 \rightarrow 32]]\right) \cdot \overline{\mathcal{F}\left(\mathbf{C}_{12}^{1}\right)} \\ & + \mathcal{F}\left(\mathbf{S}[33 \rightarrow 48]\right) \cdot \overline{\mathcal{F}\left(\mathbf{C}_{13}^{1}\right)} \\ & + \mathcal{F}\left(\mathbf{S}[49 \rightarrow 64]\right) \cdot \overline{\mathcal{F}\left(\mathbf{C}_{14}^{1}\right)}\Big), \end{aligned} \quad (21)$$

where $S[.]$ refers to a sub-set range of values of the transmitted vector. A low complexity and faster performing receiver algorithm using the FFT method is depicted in Figure 6 and 7.

5. PROPERTIES AND PERFORMANCE OF SYSTEM

The basic system without any complex receiver structures is illustrated in this paper. The simulated uncoded bit error rate performance in AWGN for the multi-user system follows the theoretical single-user BER performance with a much greater throughput rate and spectral efficiency. As an example, a BPSK system can make use of a length 16 elementary code ($L = 16$) and a flock size of $M = 4$. This produces a 2×4-dimensional modems that can use 16 rotations to produce 128 information bits that are transmitted in 64 bits, yielding a spectrum efficiency of $8 \times 16/64 = 2$ bits/s/Hz.

Figure 8 provides the BER performance in multipath fading channels using BPSK modulated data, where the presented BER results are averaged over 32 users split by frequencies. As explained above, the number of users depends only on the FFT size and bandwidth constraints, thus similar performance is expected for an increase in number of users. The presented performance is therefore valid for a fully loaded system due to the MAI-free operation. The multi-user system perfectly follows the theoretical single-user performance curves in a multipath channel. The MAI-free operation allows the system to be

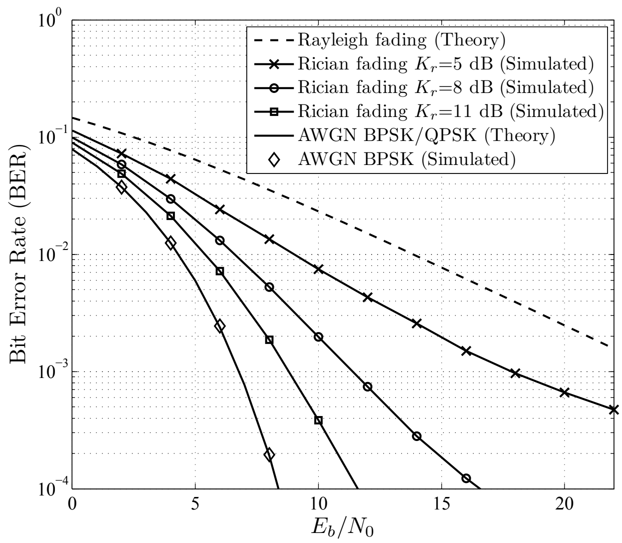

Figure 8: Simulated BER curves in a fading Rician channel for a BPSK/QPSK system with different Rician K-factors.

upper-bounded by the single user theoretical performance curve even with an increasing number of users, whereas multi-carrier CDMA (MC-CDMA) and other CDMA type schemes greatly decrease in performance with each additional user because of the present MAI.

Figure 9 illustrates the BER performance of an ordinary BPSK OFDM system with and without a guard interval in a 6 tap Rayleigh fading channel with a maximum delay less than the channel impulse response to incur flat fading if a guard band is to be applied. It can be seen that the performance without any guard band for the OFDM system is not consistent with that of the analytic result in a Rayleigh fading channel and the effect of ISI becomes more pronounced as the SNR increases. However, in the proposed system, the effect of ISI and the performance degradation is far less, considering the same system parameters. This implies that the system is just subject to flat fading and shows that the spreading codes can cope with some of the ISI and a smaller guard band is required to reduce the error floor at higher signal-to-noise ratios. A reduction in the guard band improves the bandwidth efficiency. If the system on the other hand employs a large guard band, the BER performance of the system decreases below the analytical performance curve of an ordinary OFDM system. This shows that the system is more robust and the spreading codes enable the system to perform well with a smaller guard band.

In conventional MC-CDMA systems, each user is associated with its own channel in the uplink, and the transmitted symbols undergo their own channel distortions requiring complex multi-user detection schemes to restore the orthogonality amongst users. The proposed system however, improves the performance and reduces the complexity of detection, as the transmitted symbols that generate interference are affected by the same channel distortion, since the data symbols of the same user are

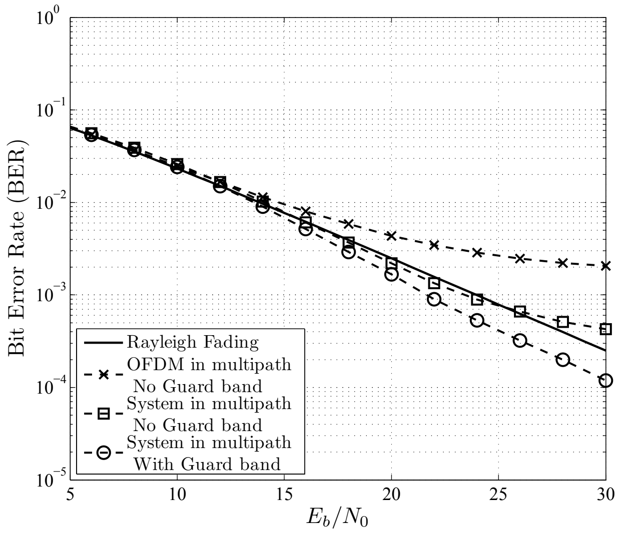

Figure 9: Simulated BER curves showing ISI effects on the performance of the system with guard bands and without. (Channel Power dB=[0 -0.9 -4.9 -8 -7.8 -23.9])

transmitted on a given set of sub-carriers.

MC-CDMA systems generally have to cope with MAI, whereas the proposed simulated system only has to cope with self-interference which is caused by the contribution of signals from the same user [12]. Thus, MAI is not present in the system. Additionally, only a single-user low complexity detection strategy is required at the receiver to achieve good performance, since the detection only needs to be applied to the sub-carriers assigned to one user. Reduced channel estimation complexity is also expected, seeing that each sub-carrier is exclusively used by one user. Since there is no MAI present, the same interface can be used for the uplink as well as for the downlink of the system. MC-CDMA systems can achieve their high bandwidth efficiency only in the downlink, whereas the presented system is more suitable for the uplink.

In multi-user systems such as MC-CDMA schemes, the near-far problem places a fundamental limit on the performance of the system, and this issue is generally not considered in many multi-carrier and multi-user system designs and evaluations. However, the presented system is resistant to the near-far problem due to the absence of MAI and the fact that each user is de-correlated independently. Hence, very costly and complex near-far mitigation mechanisms such as power control algorithms are unnecessary.

An MC-CDMA system spreads n data symbols over $n.L$ sub-carriers and is capable of exploiting more frequency diversity; however, this makes the channel estimation and reception more difficult. On the other hand, the presented system spreads $2ML$ data symbols over ML sub-carriers and looses some of the diversity, but facilitates simpler channel estimation. However, this frequency diversity loss, which cannot be exploited at the de-spreading process, can be made up for by employing channel coding. Channel coding can be assigned independently to each user, allowing for more robustness and added redundancy for that specific user. Inter-cell interference and resulting errors can thus be reduced by adding fewer spreading codes to a user's signal, by making use of fewer carriers or by well known forward error correcting (FEC) codes.

Additionally, the code-division or spreading of the data in the system allows for variable data rate transmission for each user. Thus, a wide range of multi-rate services with different data rates (video, audio, image, speech, etc.) can be supported. The system would only need to alter the amount of multiplexed spreading codes at the transmitter to change the transmission rate, without the need for implementing adaptive coding and modulation schemes in both the transmitter and receiver.

The BER performance of the system compares to conventional OFDM if the Rayleigh fading over all chips of the spreading code is flat. If either one or two-dimensional spreading is applied with interleaving of the chips in the frequency and/or time domain, the diversity performance curves are lower-bounded by the theoretical BER diversity performance curves of a Rayleigh fading channel, where the spreading code length corresponds to the diversity order. The performance of spreading in multiple domains achieves a higher processing gain and the ability to use three different dimensions adds to the flexibility of the system, as resources can be allocated in the frequency, time, and code space. Further diversity schemes like space, angle or polarisation diversity, which are not within the scope of this study, can additionally increase the overall diversity and performance of the system.

6. 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 spread spectrum multi-dimensional modulation method in a novel manner with the use of complete complementary codes and a cyclic rotation scheme, a unique flexible digital broadcasting technique, which supports high data rates and capacities over hostile radio channels, was developed. The generic architecture of the analysed system integrates existing techniques into a design that is adaptable and reconfigurable to different standards and technologies. This provides for scalability, easy integration into existing platforms and also provides opportunities for new research and development.

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 yielding an efficiency per user equal to the un-spread theoretical spectral efficiency of the modulation method used, except for BPSK modulation, in which case the system can achieve

2 bits/s/Hz (double the theoretical). Secondly, the system offers MAI-free operation. This attributes to co-channel interference reduction, capacity increase, resilience against the near-far problem and in addition, the system has an improved throughput. Thirdly, due to its spectral efficiency, the system can make use of the additionally available resources when not fully loaded, enabling it to achieve a more reliable transmission and improve the BER performance. Finally, the system achieves multiple access with the use of OFDMA techniques and is greatly flexible in the way in which it spreads the data, resulting in various design alternatives with diversity improvements. The code-division or spreading of the data can offer numerous advantages such as possible data rate adaption, less complex channel estimation and diversity gains.

Many areas of this novel technology remain underexplored and this research has created a starting point or basis for further investigation. Additionally, many questions were uncovered and a variety of problems that require further study and experimentation were highlighted. This research has provided an in-depth insight into the high potential of the novel integration of the proven technologies, namely multi-dimensional spread spectrum and multi-carrier OFDMA techniques.

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Notes

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