SPACE-TIME PRECODED CDMA-OFDMA EMPLOYING SUPER-ORTHOGONAL COMPLETE COMPLEMENTARY CODES

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Abstract: This paper addresses and illustrates, both analytically as well as by means of simulation, the equivalence of a cyclically rotated complete complementary coded (CRCCC) code division multiple access orthogonal frequency division multiplexed (CDMA-OFDM) BPSK/QPSK system and a narrowband uncoded BPSK/QPSK reference system. The equivalence can be attributed to the MUI-free characteristic performance of CRCCCs. It is demonstrated that when employed in a multiple-input multiple-output (MIMO) antenna configuration along with orthogonal space-time block codes (OSTBCs), the maximum theoretical diversity order of $N_{Tx}N_{Rx}$ is achieved. Most significantly, simulations show that CDMA-OFDM using CRCCCs is capable of rendering additional multipath diversity gain at no additional processing cost. This signifies improved performance when compared with conventional ST-OFDM systems.

Key words: CRCCC, OSTFBC, STF-CDMA-OFDM, diversity, multi-user-interference (MUI) free, multiple-access (MA)

1. INTRODUCTION

In the process of striving to achieve higher data rates and improved performance within limited bandwidth, engineers are often forced to employ new combinations of well established techniques to meet the said objectives. One example of the latter is the use of multiple-input multiple-output (MIMO) techniques that have emerged to become pivotal in meeting the capacity demands of modern wireless cellular networks. By employing multiple antennas using MIMO principles, additional spatial degrees of freedom have been added to existing already saturated temporal, frequency and coded (spread) diversity domains. Although this may seem to have provided much needed relief to the improved capacity demand, it introduced a number of new challenges. In its infancy MIMO promised remarkable increases in capacity [1]. Unfortunately this was obtained at the cost of exceedingly complex detection algorithms under idealistic operating conditions. However, the Bell Labs layered space-time (BLAST) architecture did indeed demonstrate that it was possible to achieve the predicted capacity [2]. On the other hand, it was shown that it is possible to achieve transmit diversity while maintaining a remarkably simple linear receiver structure [3]. Further investigation into this field spawned the use of space-time coding, and more specifically, orthogonal space-time block codes (OSTBC) [4]. One major conclusion from these studies is that capacity and diversity are irreconcilable gains offered by MIMO.

The introduction of multiple antennas has done nothing to address the pressing concerns of multiple users in modern wireless cellular networks. With the roll-out of fourth generation (4G) networks, orthogonal frequency division multiple access (OFDMA) emerged as a technology of the future. OFDM is primarily favoured as the preferred modulation scheme, because of the reduced complexity offered by the use of the Fast Fourier Transform (FFT) algorithm. The FFT has been combined with space-time block codes (STBC) resulting in ST-OFDM [4], and application of OFDMA to this scenario is one solution.

Another approach is to use code division multiple access (CDMA) along with OFDM [5]. This combination will henceforth be referred to as space-time-frequency-(spread) CDMA-OFDM (STF-CDMA-OFDM). Historically CDMA alone is not favoured due to its inability to scale and its suboptimal performance in third generation networks. The latter can be primarily attributed to oversimplified choices of non-perfect suboptimal (Gold and Walsh-Hadamard) spreading (channelisation) sequences in present CDMA systems. The latter set of sequences hardly possess acceptable autocorrelation (AC) properties, while their cross-correlation (CC) only produce zero values at zero relative time shifts, with large sub-peaks at a distance of as little as ± one sampling interval from the origin. This narrow zero cross-correlation margin calls for extremely accurate and stable clock recovery in order to prevent excessive inter-code and/or multi-user interference (MUI). This form of distortion is the primary cause of CDMA performance loss and diminishing processing gain as a result of non-perfect spreading sequence design. The maturing of the field led to the reviving of families of spreading sequences with perfect priodic and aperiodic cross-correlation and auto-correlation properties (requirements of super-orthogonality), originally proposed by Golay [6].

The best results are attained when new innovation is applied to render remarkable improvements compared to previous results. A further refinement of the orthogonal complete complementary (OCC) codes proposed in [7] provided a solution to the rate loss and scaling issue of CDMA orthogonal variable spreading factor (OVSF) codes. The modified OCC codes are termed super-orthogonal cyclically rotated complete complementary codes (CRCCC) [8]. CCC is regarded as ideal orthogonal codes, in contrast to Walsh-Hadamard or OVSF codes, whose orthogonality is lost if used in asynchronous transmission systems, such as uplink channels in a mobile cellular scenario [8, p236].

This work presents a novel layered [9] modulation scheme that combines ST-OFDM and super-orthogonal CRCCCs to achieve transmit diversity. The elegant combination of these techniques leads to another interesting outcome: while providing multiple access (MA), the spreading codes also distribute energy from all symbols over all OFDM sub-carriers without destroying sub-carrier orthogonality. The result of this is a triply orthogonal modulator that achieves transmit diversity, extracts additional multipath (frequency) diversity and requires only a linear receiver to achieve maximum likelihood (ML) detection performance in the presence of fading. It should be emphasized that the choice of a combination of CDMA and OFDM was made to yield a multi-layered multi-user interference (MUI) free multiple-access modulation scheme that would be particularly robust under fading multipath channel conditions, as apposed to conventional OFDMA approaches primarily aimed at achieving maximum capacity. One typical application of the said modulation method is the primary control channel of a long distance surveillance remote piloted vehicle (RPV).

2. SYSTEM MODEL

The proposed system operates by mapping several independent multi-carrier (MC) CDMA sequences to an array of antennas according to an OSTBC with maximal rate. The MC-CDMA sequences are generated by spreading independent symbol blocks with the same family of CRCCCs and then multiplexing the resulting sequence onto orthogonal sub-carriers via the IFFT. Each of these modulation operations serves a particular purpose in a wireless communication system. The OFDM allows the multipath channel to be affectively divided into many flat faded channels with a significantly reduced complexity. OSTBCs add a transmit diversity advantage with multiple antennas with linear detectability. Furthermore, the CRCCCs provide a means for multiple users to share the same physical propagation medium without excessive MA interference (MAI).

2.1 *Cyclically rotated complete complementary codes*

In order to illustrate the potential of CRCCCs, certain assumptions must be made. Firstly, the code sequences must be synchronised in much the same way as the downlink of a cellular network. Secondly, it was assumed that the system has perfect timing and frequency synchronisation, and thirdly, perfect channel state information (CSI) is available. With this in mind, consider an OCC code family composed of K flocks (groups) of sequences, each made of M length N sequences. Thus, each flock is of length MN. OCC code families exhibit ideal correlation properties, i.e., the CC between two flocks for any cyclic chip shift is given by:

$$R_{c_a,c_b}[n] = \sum_{i=1}^{N-n} \sum_{j=1}^{M} c_{i,j,a} c_{j,j+n,b} = 0 \quad \forall\, n, \tag{1}$$

and the AC of each flock is given by:

$$R_{c_a,c_a}[n] = \sum_{i=1}^{N-n} \sum_{j=1}^{M} c_{i,j,a} c_{j,j+n,b} = \begin{cases} MN & n = 0 \\ 0 & \text{otherwise} \end{cases}. \tag{2}$$

$R_{c_a,c_b}[n]$ represents the aperiodic CC between two complementary sequences, c_a and c_b. Interestingly, it has been shown that if a family of complementary sequences exhibits these ideal properties for aperiodic correlation, they also exhibit these properties for periodic correlation [7]. With a classical OCC code family a maximum of K symbols may be transmitted simultaneously. By imposing the synchronised code constraint, the symbol rate may be increased to NK. This is achieved by extending the OCC code family as follows - Taking the first of K flocks and cyclically rotating each of the element codes by one chip period, a new flock is created that maintains orthogonality with the original parent flock. Repeating the procedure for each of $N-1$ remaining chips, a total of N OCC flocks can be generated from flock one. Extending the procedure to each of the remaining $K-1$ flocks, an OCC family may be extended to a total of KN flocks of CRCCCs. Finally, if a super orthogonal complementary code (SOCC) family is used (i.e., an OCC code family with K=M), the CRCCC family size equals MN. This implies that MN symbols may be transmitted simultaneously, i.e., a rate of

$$\begin{aligned} R &= \tfrac{KN}{MN} \\ &= 1 \quad symbol/chip \end{aligned} \tag{3}$$

may be achieved, when compared with conventional MC-CDMA systems, which only provides $1/N$ symbols/chip. It should be noted that the summation of CRCCC codes leads to a multilevel signal that affects the Peak-to-Average Power Ratio (PAPR) of the system. However, by applying a Generalized Boolean Function (GBF) approach as described in [10], a considerable improvement in PAPR can be obtained for our system, when compared to traditional OFDM systems. When quadrature phase shift keying (QPSK) is employed as the underlying digital modulation scheme, a spectral efficiency of 2 bits/s/Hz may be attained, while maintaining the bit error probability (BEP) performance of binary phase shift keying (BPSK) in AWGN [8]. Although the need for synchronisation of the codes may be a disadvantage, only the code sequences generated by cyclically rotating a single flock need to maintain relative synchronism. This is because the correlation properties of the OCC code sequences hold for both the periodic and non-periodic (aperiodic) correlation functions ensuring that the perfect complete complementary properties of the new family of CRCCC sequences are maintained. Therefore, by assigning an extended flock of CRCCCs to a single user, it is possible to provide significant increase in rate and spectral efficiency. The grouping of sequences belonging to an extended flock is further motivated by the ability to decode groups of sequences in a single FFT operation. This is achieved by performing fast correlation according to:

$$R_{\mathbf{r},\mathbf{c}_k^0} = \sum_{m=1}^{M} \mathcal{F}^{-1}\left\{\mathcal{F}\{\mathbf{r}^{(m)}\}\cdot\left[\mathcal{F}\left\{\mathbf{c}_{m,k}^0\right\}\right]^*\right\}, \quad (4)$$

where $\mathcal{F}[.]$ and $\mathcal{F}^{-1}[.]$ represents the FFT and IFFT operations, respectively, $(.)^*$ denotes the complex conjugate and $\mathbf{r}^{(m)}$ is the mth sequence of received symbols corresponding to the mth element code. Each symbol in the resulting sequence is a sufficient statistic for the detection of the data transmitted using one of the cyclically rotated extension sequences corresponding to the decoding sequence $c_k^0 = [c_{1,k}^0\ c_{2,k}^0\ \ldots\ c_{M,k}^0]$ (i.e., the original parent code of the CRCCC extended flock). The index of the decision variable corresponds to the number of cyclic chip rotations that was performed on the parent flock.

2.2 *Space-time orthogonal frequency division multiplexing*

The CRCCCs have been shown to perform identical to BPSK in a single antenna environment [8]. This is extended to the multi-antenna environment in this paper, by employing the combination of OSTB and space-time-frequency OFDM (STF-OFDM). This approach achieves a diversity order of $N_{Tx}N_{Rx}$, i.e., the product of the number of transmit and receive antennas, as opposed to a diversity order of N_{Rx} in the case of spatial multiplexing. However, there is a compromise to be made: spatial multiplexing yields large capacity gains predicted for multiple antennas when $N_{Rx} \geq N_{Tx}$, but at the cost of an increase in non-linear detection complexity. This is normally not applicable to the forward channel where the mobile mostly uses a single antenna and also has limited computational resources. OSTBs may have reduced capacity, but it is due to this reduction that improved performance is achievable with a single receive antenna. The maximum rate achievable with OSTBCs is [9]:

$$R_{max} = \frac{m+1}{2m}, \quad (5)$$

where $N_{Tx} = 2m-1$ or $N_{Tx} = 2m$. Let $\mathbb{N}$ denote the set of all natural numbers, so that $\{m \in \mathbb{N} | m \leq 8\}$. Taking n_s blocks of data symbols and performing the modulation operations common to single antenna systems, produces a set of vectors

$$\mathbf{s}_i = \Phi\mathbf{W}^H\mathbf{C}\mathbf{d}_i \quad i = 1,2,\ \ldots\ n_s, \quad (6)$$

where $\mathbf{d}_i$ is the ith vector of digitally modulated symbols, $\mathbf{C}$ is a matrix with columns formed by the flocks of the extended CRCCC, $\mathbf{W}$ is the discrete Fourier transform matrix and Φ is a cyclic extension matrix. Taking the rows of the resulting matrix in (6) and mapping them to a sequence of matrices,

$$\{\mathbf{s}_1[n]\ \mathbf{s}_2[n]\ \ldots \mathbf{s}_{n_s}[n]\} \rightarrow \{\Phi[n]\}n = -CP, -CP+1,\ \ldots,\ N_{FFT}-1, \quad (7)$$

according to an OSTBC, the triply orthogonal modulation is completed. This mapping is mathematically equivalent to mapping the entire OFDM symbols according to the OSTBC before transmission. The index n represents the discrete time index of the MC-CDMA sequences, N_{FFT} is the FFT length (also equal to MN for the system concerned) and CP is the cyclic prefix length. The transmitter is depicted in Figure 1 and the receiver in Figure 2.

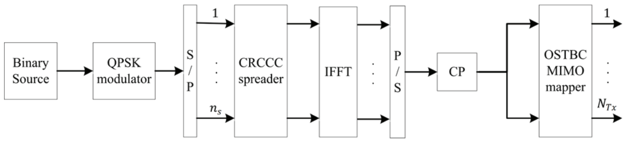

Figure 1: The modulation process performed at the transmitter

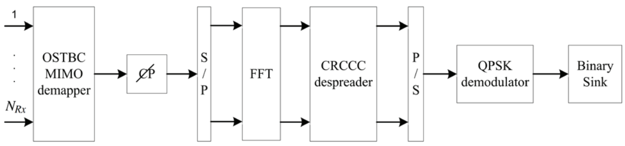

Figure 2: The demodulation process performed at the receiver

The received symbols are described by

$$\mathbf{Y}[n] = \sum_{l=0}^{L} \mathbf{H}_l\Phi[n-l] + \mathbf{N}_\sigma[n] \quad n = 0,1,\ \ldots,\ N_{FFT}-1. \quad (8)$$

The ith column of $\mathbf{Y}[n]$ corresponds to the samples received at time n during the ith OFDM symbol period (n is relative to the beginning of the symbol period), $\mathbf{H}_l$ is the lth matrix channel tap value of a length $L+1$ channel impulse response, and $\mathbf{N}_\sigma[n]$ is a matrix containing *i.i.d.* AWGN samples with zero mean and standard deviation σ_n. With this formulation of the received symbols the detection criterion for the MIMO demapping stage of the receiver is expressed as:

$$\sum_{n=0}^{N_{FFT}-1} ||\mathbf{z}[n] - \mathbf{F}[n]\hat{\mathbf{s}}[n]||^2, \quad (9)$$

where,

$$\hat{\mathbf{s}}[n] \quad = \left[\Re\left[\hat{\mathbf{s}}^T[n]\right]\ \Im\left[\hat{\mathbf{s}}^T[n]\right]\right]^T, \quad (10)$$

$$\mathbf{z}[n] = vec\left(\mathbf{Z}[n]\right), \quad (11)$$

$$\mathbf{Z}[n] = \frac{1}{\sqrt{N_{FFT}}} \sum_{k=0}^{N_{FFT}-1} \mathbf{Y}[k]e^{-j2\pi\frac{kn}{N_{FFT}}}, \quad (12)$$

and

$$\begin{aligned}
\mathbf{F}[n] &= [\mathbf{F}_a[n]\ \mathbf{F}_b[n]], \\
\mathbf{F}_a[n] &= \left[vec\left(\check{\mathbf{H}}\left[2\pi\tfrac{n}{N_{FFT}}\right]\mathbf{A}_1\right)\ \ldots\ vec\left(\check{\mathbf{H}}\left[2\pi\tfrac{n}{N_{FFT}}\right]\mathbf{A}_{N_s}\right)\right], \\
\mathbf{F}_b[n] &= \left[j.vec\left(\check{\mathbf{H}}\left[2\pi\tfrac{n}{N_{FFT}}\right]\mathbf{B}_1\right)\ \ldots\ j.vec\left(\check{\mathbf{H}}\left[2\pi\tfrac{n}{N_{FFT}}\right]\mathbf{B}_{N_s}\right)\right], \\
\check{\mathbf{H}}[\omega] &= \textstyle\sum_{l=0}^{L}\mathbf{H}_l e^{-j\omega l}.
\end{aligned} \tag{13}$$

The symbols $\Re(\cdot)$ and $\Im(\cdot)$ represent the real and imaginary parts and $vec(\cdot)$ is the matrix vectorisation operator. The sets $\{\mathbf{A}_i\}$ and $\{\mathbf{B}_i\}$ where $i = 1, 2, \ldots, n_s$ define the OSTBC in such a way that the metric (9) reduces to:

$$\sum_{n=0}^{N_{FFT}-1} \left|\left|\hat{\mathbf{s}}'[n] - \hat{\mathbf{s}}[n]\right|\right|^2, \tag{14}$$

where

$$\hat{\mathbf{s}}'[n] = \frac{\Re\{\mathbf{F}^H[n]\mathbf{z}[n]\}}{\left|\left|\check{\mathbf{H}}\left[2\pi\frac{n}{N_{FFT}}\right]\right|\right|^2}. \tag{15}$$

This is because of the property of OSTBCs that may be expressed as,

$$\Re\left\{\mathbf{F}^H[n]\mathbf{F}[n]\right\} = \left|\left|\check{\mathbf{H}}\left[2\pi\frac{n}{N_{FFT}}\right]\right|\right|^2 \mathbf{I}. \tag{16}$$

The effect of the OSTBC is to orthogonalise several MC-CDMA signals spatially. Typically, this technique would be employed to orthogonalise multiple symbols in space and in that case multipath diversity will be lost [4]. However, as can be seen from the simulation results, this is not the case for the proposed system.

3. ANALYTICAL ANALYSIS

3.1 Additive white Gaussian noise

The linear detectability of OSTBC allows the correlation of the CRCCCs to be decoupled from the spatial channel. The MIMO detection criterion is applied to the received signal resulting in the equivalent of n_s direct sequence CDMA received signals of the form

$$\mathbf{r}_i = \tilde{\mathbf{s}}_i + \tilde{\mathbf{n}}_i \quad i = 1, 2, \ldots, n_s, \tag{17}$$

where $\tilde{\mathbf{s}}_i = \mathbf{C}\mathbf{d}_i$ and $\tilde{\mathbf{n}}_i$ is the transformed noise vector. Each of these n_s vectors are then in turn correlated with the CRCCCs using the fast correlation algorithm. This operation is equivalent to the matched filter (MF) receiver, traditionally employed for detection in spread-spectrum systems. It is known that the MF receiver is sub-optimal due to the non-zero correlation coefficients amongst all pairs of codes in the family. Fortunately the CRCCCs do not suffer from this drawback. To illustrate this the correlation of one of the n_s received sequences with one of the flocks from the parent OCC code is investigated in the presence of AWGN:

$$R_{\mathbf{r}_i,\mathbf{c}_k}[n] = R_{\tilde{\mathbf{s}}_i,\mathbf{c}_k}[n] + R_{\tilde{\mathbf{n}}_i,\mathbf{c}_k}[n] \tag{18}$$

$$= d_{k,i}R_{\mathbf{c}_k,\mathbf{c}_k}[n] + \sum_{a=1,\ a\neq k}^{MN} d_{a,i}R_{\mathbf{c}_a,\mathbf{c}_k}[n] + R_{\tilde{\mathbf{n}}_i,\mathbf{c}_k}[n] \tag{19}$$

where $\mathbf{c}_k$ is the kth flock of the CRCCC and $d_{k,i}$ is the kth symbol of the ith data block. The first term in the expression represents the desired symbol (note that the fast correlation algorithm decodes multiple symbols simultaneously, but the result is equivalent to correlation with each flock of the CRCCC individually), the second term represents the multi-user interference (MUI) due to CC between pairs of flocks and the third term represents the noise. Typical CDMA systems incur a performance penalty because the second term in (19) is non-zero. However, in our case the expression reduces to,

$$R_{\mathbf{r}_i,\mathbf{c}_k}[0] = MNd_{k,i} + R_{\tilde{\mathbf{n}}_i,\mathbf{c}_k}[0]. \tag{20}$$

Finally, by dividing by the spreading gain MN in order to normalise the bit energy, the decision variable is expressed as.

$$D_{k,i} = d_{k,i} + R_{\tilde{\mathbf{n}}_i,\mathbf{c}_k}[0]/MN. \tag{21}$$

The bit error probability (BEP) for the kth user may be expressed as,

$$\begin{aligned}
P_e &= \tfrac{1}{2}\left[P\left(\mathcal{N}\left(\sqrt{\varepsilon_b}, \tfrac{N_0}{2}\right) > 0\right) + P\left(\mathcal{N}\left(\sqrt{\varepsilon_b}, \tfrac{N_0}{2}\right) < 0\right)\right] \\
&= P\left(\mathcal{N}\left(\sqrt{\varepsilon_b}, \tfrac{N_0}{2}\right) > 0\right)
\end{aligned}, \tag{22}$$

where ε_b is the bit energy and BPSK modulation is assumed. The noise term in the decision variable maintains the original one-sided power spectral density N_0 of the AWGN. The well known BPSK BEP is given by,

$$P_e = Q\left(\sqrt{\frac{2\varepsilon_b}{N_0}}\right) \tag{23}$$

where $Q(\cdot)$ is the Gaussian Q-function. This expression is equivalent to that of QPSK in the presence of AWGN.

3.2 Frequency non-selective Rayleigh fading

Equations (21) - (23) illustrate the equivalence of the CRCCCs and BPSK modulation in the presence of noise. It stands to reason that the BEP in frequency non-selective fading would also be equivalent to that of BPSK. Consider to this end the received signal with fading,

$$\mathbf{r}_i = \alpha_i\tilde{\mathbf{s}}_i + \tilde{\mathbf{n}}_i \quad i = 1, 2, \ldots, n_s, \tag{24}$$

where α_i is a Rayleigh distributed random variable. Since the fading coefficient is assumed to be constant over the transmission duration for $\mathbf{s}_i$ the decision variable becomes,

$$D_{k,i} = \alpha_i d_{k,i} + R_{\tilde{\mathbf{n}}_i,\mathbf{c}_k}[0]/MN, \tag{25}$$

and the conditional BEP may be expressed as,

$$P_{e|\alpha_i} = Q\left(\sqrt{\frac{2|\alpha_i|^2\varepsilon_b}{N_0}}\right). \tag{26}$$

In order to derive an expression for the BEP that is not conditioned on α_i the following integral must be performed:

$$P_e = \int_0^\infty P_{e|\alpha_i} p(\gamma_i) d\gamma_i \tag{27}$$

where $\gamma_i = \frac{|\alpha_i|^2 \varepsilon_b}{N_0}$ represents the instantaneous received signal-to-noise ratio (SNR). This is of course for the case where a single transmit antenna and single receive antenna is employed. Combining the MC-CDMA signals with the OSTBCs introduces spatial diversity to the system by orthogonalising $N_{Tx}N_{Rx}$ spatial channels. Since the CRCCCs offer equivalent performance to BPSK (or QPSK) in both AWGN and flat fading channel conditions, we may compare the simulation results to the diversity expression for BPSK,

$$P_e = \left[\frac{1}{2}(1-\mu)\right]^L \sum_{k=0}^{L-1} \left(\begin{array}{c} L-1+k \\ k \end{array} \right) \left[\frac{1}{2}(1+\mu)\right]^k \tag{28}$$

where,

$$\mu = \sqrt{\frac{\bar{\gamma}_i}{1+\bar{\gamma}_i}} \tag{29}$$

and $\bar{\gamma}_i$ is the average received SNR.

4. SIMULATION RESULTS

Monte Carlo simulations were performed for three channel types. For all three types, the sampling frequency F_s=1 MHz, K=8, M=8, N=4, FFT size N_{FFT}=MN, code rate R=R_{max} and the bit rate F_{bit}=2$R_{max}F_s$. Firstly, the CRCCCs were employed along with the OSTBCs for various numbers of transmit and receive antennas. The experiment was then repeated with a frequency non-selective Rayleigh (flat) fading channel. Lastly, the system was simulated with two transmit and two receive antennas in the presence of a multipath channel.

4.1 Additive white Gaussian noise

Figure 3 shows the BEP vs SNR per bit performance of the proposed system when transmission took place through an AWGN channel.

It can be observed from the figure that the system achieves equivalent performance to a narrowband uncoded BPSK/QPSK system and is independent of the number of receive antennas. When the rate of the OSTBC is $R_{max} < 1$, or alternatively, $N_{Tx} > 2$, there is a performance loss of approximately 1.25 dB. This is because of the need to normalise the SNR to bit energy-to-noise density ratio (ε_b/N_0). The simulations confirm that the OSTBC orthogonalises the various MC-CDMA signals and illustrates the equivalence of the CRCCC-based system to a narrowband uncoded BPSK/QPSK system. Note that the BEP performance is the same for both single and multi-user operation, due to the total absence of MAI as a result of the perfect orthogonality of the

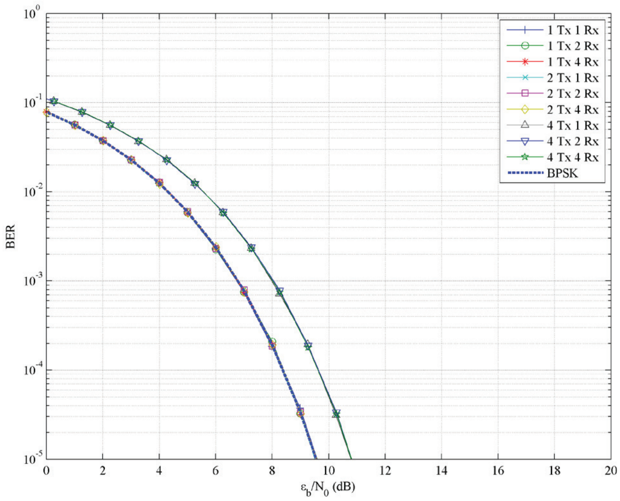

Figure 3: BEP vs SNR of the MIMO MC-CDMA system in an AWGN channel

CRCCC codes. The results are illustrated and discussed in subsequent sections.

4.2 Frequency non-selective Rayleigh fading

The BEP vs. SNR per bit performance results of the proposed system when transmission is through a frequency non-selective Rayleigh fading channel are shown in Figures 4 and 5.

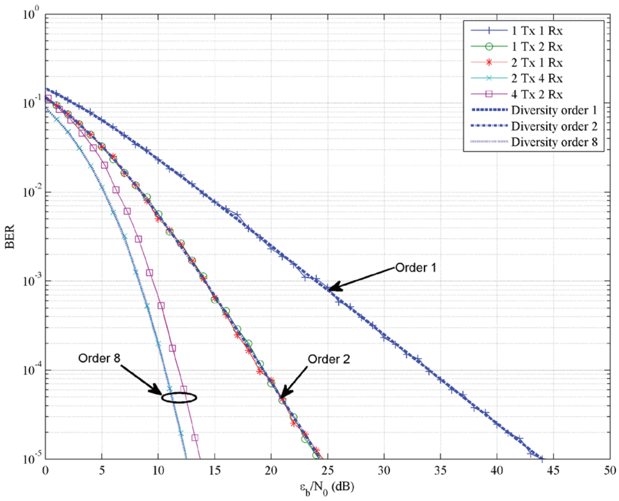

Figure 4: BEP vs. SNR of the MIMO MC-CDMA system in a frequency non-selective Rayleigh fading channel (part 1).

The results have been split into two figures so that they may be easily compared to the analytical curves. The single antenna has for reference purposes been duplicated along with the analytical curve for a diversity order of one. Fig. 4 shows the results for simulations where $N_{Tx}N_{Rx} \in \{1,2,8\}$. It is observed that the system performs identically to that of theoretical narrowband uncoded BPSK/QPSK, again confirming the equivalence. Fig. 5 depicts the results

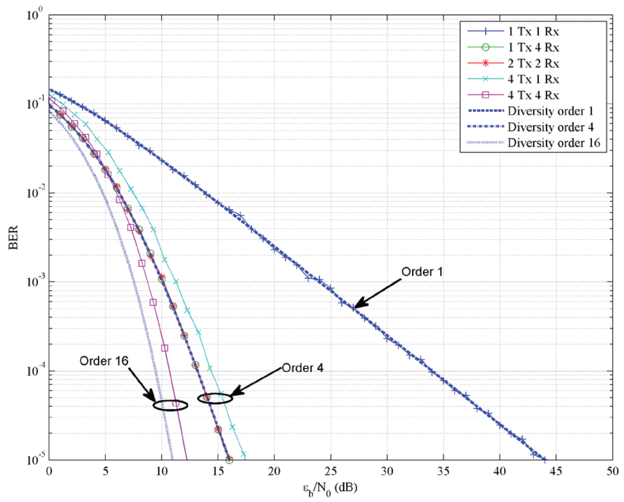

Figure 5: BEP vs. SNR of the MIMO MC-CDMA system in a frequency non-selective Rayleigh fading channel (part 2).

of simulations where $N_{Tx}N_{Rx} \in \{1,4,16\}$. Here similar conclusions as in Fig. 4 may be drawn. Both of the forging graphs also display the performance loss of approximately 1.25 dB due to the reduced rate of the OSTBC when $N_{Tx} > 2$.

4.3 Multipath Rayleigh fading

Fig. 6 illustrates the performance gain achieved by the proposed CRCCC-based OSTBC CDMA-OFDM system in a multipath channel environment, compared to a conventional narrowband uncoded BPSK/QPSK system. Employing CRCCCs provides a means to achieve multiple

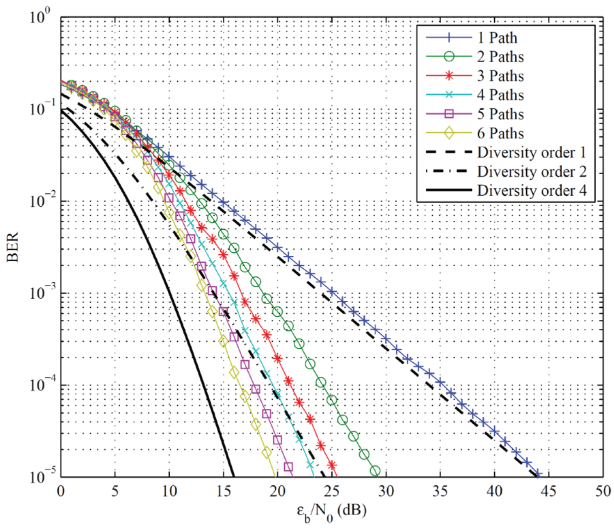

Figure 6: BEP vs. SNR of the MIMO MC-CDMA system in a multipath channel.

access (MA) in a communication system. The figure shows multipath gains in the order of 2.25 dB (L=2) to 3.75 dB (L=6) at a BEP=10^{-5}, where L denotes the number of multipaths in each case.

5. CONCLUSION

This study illustrated the equivalence of a CRCCC CDMA-OFDM BPSK/QPSK MUI/MAI-free system and a narrowband uncoded BPSK/QPSK system in terms of BEP in the presence of AWGN and frequency non-selective (flat) Rayleigh fading. This has clearly been confirmed by the results obtained from the simulations performed. It is furthermore demonstrated that the use of OCC codes, and more specifically CRCCCs, provides a means to extract otherwise non-exploitable multipath diversity (as in ST-OFDM) in a multiple antenna environment. This is achieved without incurring the expected rate and performance loss of traditional CDMA systems. This paper also highlights the prevention of uncontrolled multi-user interference (MUI) through the use of CRCCCs and illustrates the performance gains achievable with the proposed multi-layered perfectly orthogonal technologies, viz CDMA using CRCCCs, OFDM and OSTBC, while not incurring additional processing cost.

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