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Abstract

This paper studies higher order parallel concatenated spreading matrix OFDM (PCSM-OFDM). PCSM-OFDM was shown to greatly improve on the classic Block Spread OFDM, this paper continues the work on PCSM-OFDM and studies higher order in terms of an increased number of streams. This shows that with the increase in the streams the overall BER performance improves.

HIGHER ORDER PARALLEL CONCATENATED SPREADING MATRICES OFDM

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ABSTRACT

This paper studies higher order Parallel Concatenated Spreading Matrix OFDM (PCSM-OFDM). PCSM-OFDM was shown to greatly improve on the classic Block Spread OFDM, this paper continues the work on PCSM-OFDM and studies higher order in terms of an increased number of streams. This shows that with the increase in the streams the overall BER performance improves.[1]

Key Words-*PCSM-OFDM, BSOFDM, Frequency selective channel*

1. INTRODUCTION

Block Spread OFDM has been realized as a method to improve the BER of OFDM systems. Depending on the spreading matrix used, the performance improved and varied and in some cases showed well over 10dB gain in BER improvement [2], [7]. Primarily the Block Spread OFDM (BSOFDM), which is when the full set of subcarriers are divided into smaller blocks and using spreading matrices to spread the data across these blocks so to achieve frequency diversity across frequency selective channels [3] [4] and [5].

The BSOFDM channel model is shown in Figure 1.

$$y = Cq + n \qquad (1)$$

The output of the receiver's FFT processor is given in Equation 1 where y is the FFT output, $q \in A^N$ is the vector of transmitted symbols, each drawn from an alphabet A, C is a diagonal matrix of complex normal fading coefficients, and n is a zero mean complex normal random vector. Equalization of the received data is done through multiplication by C^{-1} and then "quantized independently on each subcarrier to form the soft or hard decision $\hat{q}$ which may be further processed if the data bits are coded" [5]. There is no loss in performance when the detection is performed independently on each carrier due to the noise being independent
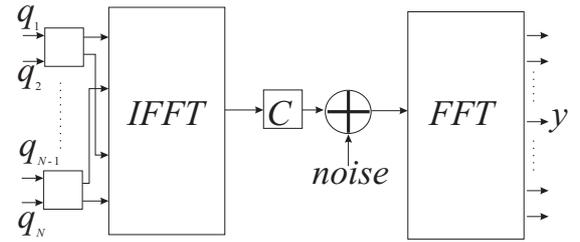
Fig. 1. Block diagram representation of the BSOFDM channel for a block length of two [5].

and identically distributed with fading been diagonal [5]. The block spreading matrices are used to introduce dependence among the subcarriers. N subcarriers are split into $\frac{N}{M}$ blocks, where $M = 2$ is used for this example. Then each of the blocks are multiplied by a 2×2 unitary matrix U_2. The length two output vectors are interleaved using general block interleaving to ensure the symbols are statistically independent so as to encounter independent fading channels. This will ensure in a dispersive frequency selective channel the data is statistically less likely to become corrupted and studies and simulations have shown this to be correct.

The transmitter's IFFT has the interleaved data passed through it and this data is sent across the frequency selective channel. The data is passed through an FFT processor at the receiver and deinterleaved before using block by block processing.

The spreading matrices are generally used to increase the correlation between the transmitted symbols after the transmission has occurred. Unlike adaptive modulation schemes where depending on the system, a higher order modulation scheme is used to retransmit the data, this scheme utilizes spreading matrices to increase the correlation between the symbols, rather than retransmitting. This is depicted in Figure 2. So for example if at the transmission the system modulates the data using QPSK modulation, with spreading matrices a higher order modulation is used to increase
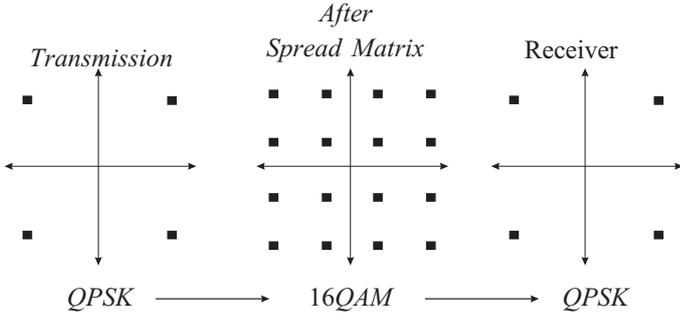
Fig. 2. The process through which the transmitted modulation is converted into a higher order modulation and then returned at the receiver.

correlation and therefore overall system performance.

In [1] we introduced a new concept for BSOFDM called Parallel Concatenated Spreading Matrices OFDM (PCSM-OFDM) and simulation results have shown this new system to improve BER performance by over 3dB in fading channels over classical BSOFDM or precoding OFDM.

This paper has the following structure. Section 2 provides the system description of the new structure and provides a discussion. Different types of spreading matrices are briefly presented in Section 3. Section 4 provides simulation results comparing the PCSM-OFDM with the classical approach to block spread OFDM, and finally a conclusion is given in Section 5.

2. SYSTEM DESCRIPTION OF THE PCSM-OFDM

Figure 3 depicts the block diagram of the new system described as Parallel Concatenated Spreading Matrices OFDM or PCSM-OFDM. As can be seen, and comparing this with the classical BSOFDM, the same data is split into two streams of block size $\frac{N}{M}$, d_1 and d_2, this is the same data and the block size $M = 2$ is used for this example, and each stream is spread using a unitary spreading matrix U of size $M \times M$. The streams of M sized blocks can be described as $d_1 U_1$ and $d_2 U_2$. The streams are multiplexed and the same process which is applied to BSOFDM is applied to PCSM-OFDM.

At the receiver, again the same process applied to BSOFDM is applied to PCSM-OFDM except the de-multiplexing is used to separate the two streams apart. To make full use of the diversity gain the two data streams are combined before de-spreading takes place and the combining is done by using Maximum Ratio Combining (MRC) and can be represented by the following equation,

$$R_1 = \frac{(\alpha_1^* r_1 + \alpha_2^* r_2)}{|\alpha_1|^2 + |\alpha_2|^2} \qquad (2)$$
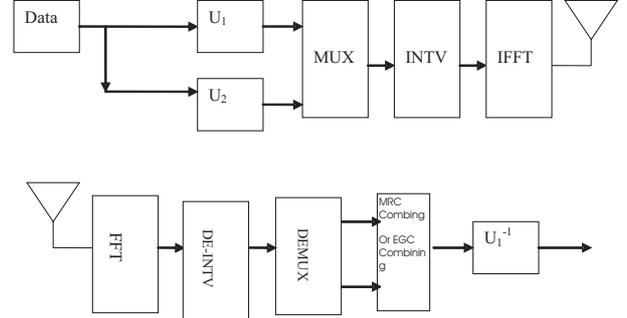

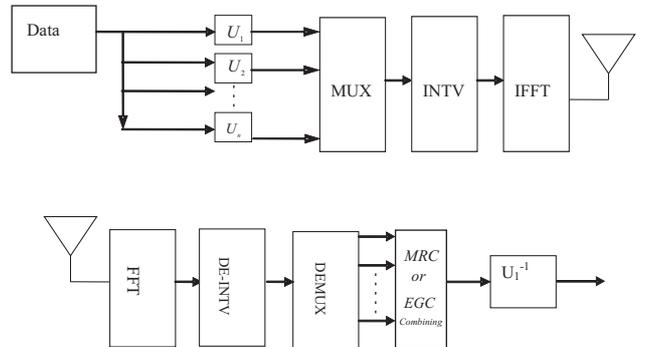**Fig. 3**. The new approach to BSOFDM, Parallel Concatenated Spreading Matrices.

Fig. 4. Higher Order new approach to BSOFDM, Parallel Concatenated Spreading Matrices.
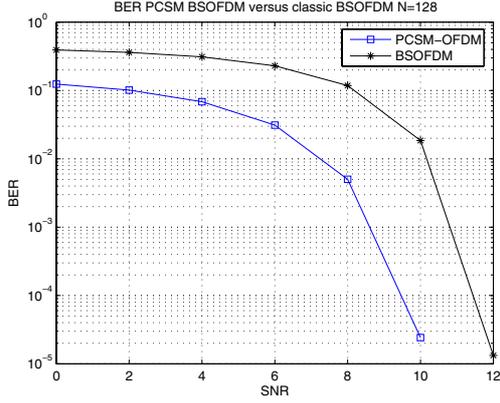
Fig. 5. PCSM-OFDM compared with BSOFDM in slow fading channel using $N = 128$.

where α_1 and α_2 are channel weights estimated and r_1 and r_2 are the useful data from each stream. One could also apply what is known as Equal Gain Combining (EGC) where the channel weights α_1 and α_2 are given equal priority of 1, and Equation 2 becomes,

$$R_1 = \frac{(r_1 + r_2)}{2} \qquad (3)$$

The Figure 4 depicts how the higher order PCSM-OFDM looks like in block diagram form, this takes into account n number of streams.

If the system was to use the higher order PCSM-OFDM, then Equation 2 would transform into,

$$R_1 = \frac{(\alpha_1^* r_1 + \alpha_2^* r_2 + \alpha_3^* r_3 + \ldots + \alpha_n^* r_n)}{|\alpha_1|^2 + |\alpha_2|^2 + |\alpha_3|^2 + \ldots + |\alpha_n|^2} \qquad (4)$$

and if you would assume that EGC is used then Equation 4 would be transformed into,

$$R_1 = \frac{(r_1 + r_2 + r_3 + \ldots + r_n)}{n} \qquad (5)$$

assuming the same conditions discussed above for the case of two streams.

Figure 5 depicts the simulation results which compares the BER performance of PCSM-OFDM and BSOFDM using $N = 128$ subcarriers. The spreading matrices used for PCSM-OFDM could be any matrix that the system required and the most common ones used are the Hadamard or the Rotated Hadamard matrix. A new form of spreading matrix is also used and was proposed in [2] and is known as the Rotation Spreading matrix. Examples of higher order matrices

of the of those mentioned can be found in [8],[9] and [10] and as can be seen from the results these spreading matrices maintained the BER improvement over the classical OFDM as expected and the Rotation Spreading matrix achieved the best result.

In this paper we studied what improvement, if any, is achievable if the number of streams increased and what dB gain is achievable. The next section presents two possible matrices that can be used with the BSOFDM and PCSM-OFDM systems.

3. SPREADING MATRICES

The spreading matrices that could be used are many, but only two are worth while mentioning. The Hadamard, and the Rotation Spreading matrix developed in [2].

3.1. Hadamard Matrix

By selecting as codewords the rows of a Hadamard matrix, it is possible to produce Hadamard codes. An $N \times N$ matrix of $1's$ and $-1's$ is a Hadamard matrix "such that each row differs from any other row in exactly $\frac{N}{2}$ locations. One row contains all zeros with the remainder containing $\frac{N}{2}$ zeros and $\frac{N}{2}$ ones" [6] (zeros and -1 are interchangeable).

$\frac{N}{2}$ is the minimum distance for these codes and as an example for $N = 2$, the Hadamard matrix U is

$$U = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \qquad (6)$$

After the modulated data is multiplied (spread) by the Hadamard matrix, a higher order modulation scheme is created which increases the correlation between the transmitted symbols, therefore achieving a better system performance. This can be seen in Figure 6, where the modulation at the transmission was QPSK.

3.2. Rotation Spreading Matrix

The Rotation spreading matrix for BSOFDM was proposed in [2] and a number of variations and studies carried out can be found in [7], [8], [9], [10] and its structure is as follows for $U_2 = 2 \times 2$,

$$U = \begin{bmatrix} 1 & tan(\alpha) \\ tan(\alpha) & -1 \end{bmatrix} \qquad (7)$$

The angle α is chosen depending on the system requirements and a simulation study comparing different angles performance can be seen in Figure 7.
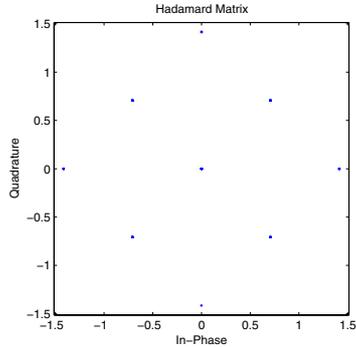
Fig. 6. After the Hadamard Matrix, the scatter plot of the data shows that it went from QPSK modulation to a higher modulation scheme.
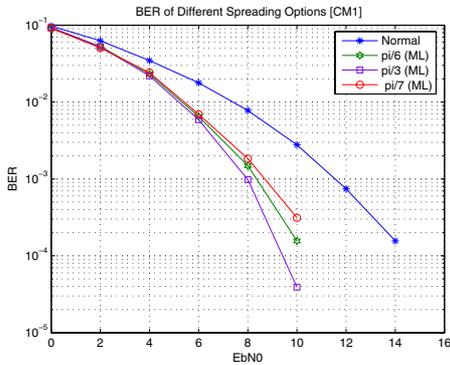

Fig. 7. Comparing the Rotation matrix with angles $\frac{pi}{6}$, $\frac{pi}{3}$ and $\frac{pi}{7}$ in UWB channel $CM1$ [7].
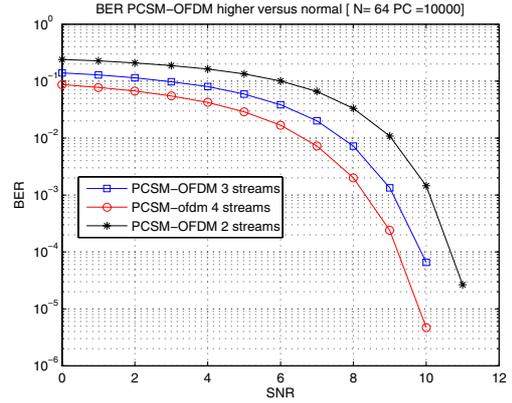

Fig. 8. PCSM-OFDM higher order4, 3 and 2 compared a slow fading channel using $N = 64$ subcarriers.

4. RESULTS

It has been confirmed through simulation results that PCSM-OFDM outperformed classical BSOFDM which outperforms OFDM. This can be seen in Figure 5 and studied in [1]. This section depicts simulation results which studies higher order PCSM-OFDM.

Figure 8 compares four, three and two streams for the PCSM-OFDM. The simulation result used $N = 64$ subcarriers with 10000 OFDM packets simulated. As can be seen from the results, as the number of streams increased, which means diversity increased, as did the BER performance and the dB gain. With each stream increase a gain of $1dB$ was achieved, Figure 9 again compares the same conditions mentioned above but with the number of subcarriers increased to $N = 128$. Both these simulations have be carried out using slow fading channels and the Equal Gain Combining is used, with Zero Forcing decoder utilized.

Other channels used in this study were frequency selective Ultra Wide Band (UWB) channels defined by the $IEEE.802.15.3a$ [11]. Again, the simulation results used the EGC for combining and ZF for decoding.

Across frequency selective channels such as the UWB defined by $IEEE802.15.3a$ from $CM1$ to $CM4$ again it can be seen in Figures 11 and 12 which depict the PCSM-OFDM across UWB channels for $N = 64$ and $N = 128$ subcarriers in UWB channels $CM3$ and $CM4$ that there is significant improvement.

5. CONCLUSION

This paper presented a continuation study of the new approach to Block spread OFDM called Parallel Concatenated Spreading Matrices OFDM (PCSM-OFDM) proposed in [1]. At the transmitter the data is split into n streams of M sized
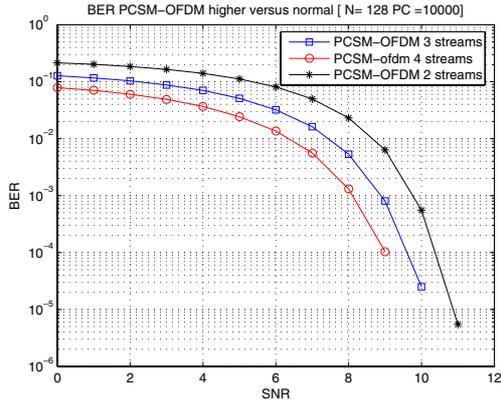
Fig. 9. PCSM-OFDM higher order4, 3 and 2 compared a slow fading channel using $N = 128$ subcarriers.
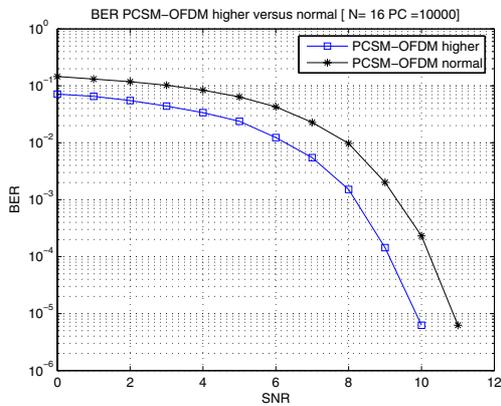

Fig. 10. PCSM-OFDM higher order 3 compared with BSOFDM in slow fading channel using $N = 16$ subcarriers.
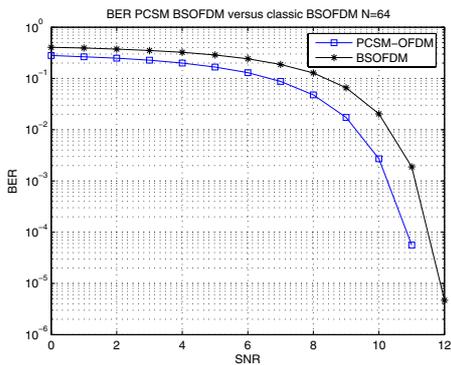

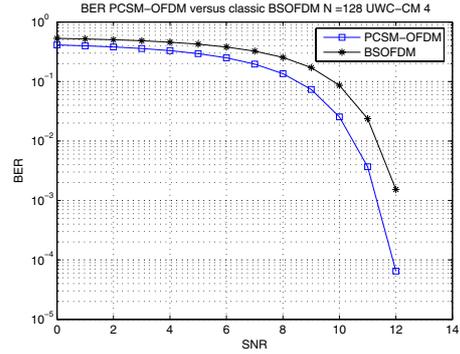**Fig. 11**. PCSM-OFDM $N = 64$ in UWB channel $CM3$.

Fig. 12. PCSM-OFDM $N = 128$ in UWB channel $CM4$ compares with BSOFDM.

blocks and these n streams are spread using the same unitary spreading matrix such as the Hadamard or the Rotation Spreading matrices. Then each of the n streams are multiplexed and the normal procedure is carried out in BSOFDM and OFDM systems. At the receiver after channel equalization the signal is de-multiplexed and combination using Maximum Ratio Combining (MRC) or Equal Gain Combining is done before the de-spreading using the inverse of the unitary matrix. In this paper Equal Gain Combining is used in the simulation results and for future work the MRC combining will be studied and discussed in which improvements are expected. From the simulation results presented, this new approach to OFDM called PCSM-OFDM outperforms the BSOFDM by greater than $4dB$ in slow fading channels and over $3dB$ in frequency selective channels such as UWB channels. With the higher order PCSM-OFDM system this paper showed that with the increase of n streams the system gained an extra $1dB$. This then is up to the designer of the system to choose if extra complexity in the system is required for these improvements. Overall, this system is recommended for wireless communication systems were OFDM and BSOFDM are used.

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