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On the effects of spreading sequences over MIMO systems

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Abstract

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Keywords

systems, sequences, spreading, over, effects, mimo

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On the Effects of Spreading Sequences over MIMO Systems

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***Abstract*— In this paper, we develop a Software Defined Radio (SDR) test bed to evaluate the Multiple Access Interference (MAI) effects over SISO and 2×1 MIMO systems. It can be observed that under asynchronous transmissions, the Gold code leads to the best performance over both systems due to the fact that it has the best correlation properties. We also find the MAI effects in terms of the spreading sequences pairs on MIMO-STS systems. We propose a criterion for selecting promising spreading sequences for MIMO systems. Based on the measured results, we identify pairs of spreading sequences which have improved BER compared to other pairs in the same set of spreading sequences. We infer that the choice of spreading sequence pairs in a MIMO-STS system in the presence of MAI sources is an important factor to be considered.**

Keywords—MAI; spreading sequences; MIMO; SDR; pairs

I. INTRODUCTION

Significant interference of the Multiple Input and Multiple Output Space-Time-Spreading (MIMO-STS) systems can occur due to multiple access interference (MAI). Many studies have been presented in the last decade on mitigating the MAI effect over both conventional Single Input Single Output (SISO) systems and MIMO systems and argue that the overall MAI effects of MIMO-STS systems mainly refer to the cross-correlation properties of spreading sequences employed [1,2,3]. The asynchronous MAI usually refers to the delayed signals from other users which can be evaluated by the sequences' correlation properties .

This paper attempts to investigate the MAI effects over both SISO and MIMO-STS systems over families of orthogonal spreading sequences with different cross-correlation properties and select the most promising sequences for use in the MIMO-STS systems. The research on spreading sequences is a traditional topic. Many orthogonal codes have been proposed for CDMA applications previously, for example, the Walsh–Hadamard code, or orthogonal Gold code [3]. The most popular family of such spreading sequences is the sets of Walsh- Hadamard sequences, and other studies in [2] have found under an uplink application quasi-orthogonal sequences may lead to a better performance on MAI due to the fact that Gold codes possess better cross-correlation properties. In [4] Chen argues the major drawback of these orthogonal codes refers to the lack of consideration of real application scenarios, varying signs in the data stream, and multipath propagation. This can be illustrated with the example that making a synchronous transmission by multiple users in an uplink scenario is difficult.

In this paper, we locate more promising spreading sequences with different selecting criteria in terms of pairs of spreading codes rather than between single spreading codes within existing spreading code families. By employing these improved pairs of spreading sequences, the MIMO-STS systems are expected to perform better in terms of mitigating the MAI effect than the randomly selected codes.

Towards this end, a test bed developed by Software Defined Radios (SDR) are needed to investigate the MAI effect over the realistic uplink applications. Specifically, four existing spreading sequences families are tested over this test bed within this study, which includes Walsh-Hadamard, modified Walsh-Hadamard [5], orthogonal Gold and Gold codes.

The rest of this paper is outlined as follows. Section II will introduce the MIMO-STS systems and SISO systems and explain the differences of selective criteria between them. Section III presents our SDR-based test bed. Section IV presents the measurement results. Section V provides the conclusion and future work.

II. SISO AND MIMO-STS SYSTEM

Conventional wireless systems, SISO, have been used in wireless communications for decades. Typically, the single antenna is employed as a transmitter and the single antenna is employed by the receiver [6]. However due to rapidly growing demand for higher transmission speeds and reliability, the SISO systems cannot meet the requirements of the next generation telecommunication systems in terms of 3GPP and LTE [7]. Therefore, MIMO systems, which provide improved properties of link capacity and transmission speed, have been adopted by the 3GPP and LTE frameworks.

A. *MIMO-STS systems*

Consider a STS system, which constitutes two transmit antennas and a single receiver. In [8] the STS algorithm firstly separates the data stream into the odd and even symbols, denoted as b_1 and b_2. Then the odd and even data streams are encoded with the following method :

$$\begin{cases} T1 = (b_1c_1 + b_2c_2) + D(b_3c_3 + b_4c_4) \\ T2 = (b_2c_1 - b_1c_2) + D(b_4c_3 - b_3c_4) \end{cases} \quad (1)$$

where T1 denotes the signal of antenna 1 and T2 is the signal transmitted via antenna 2, c_1 and c_2 denote the corresponding spreading sequences. D denotes the parameter for simulating the Near-Far effects of the systems, b_3, b_4 are the interfering transmitter's data and c_3,c_4 are their corresponding spreading sequences. The received data d is presented as:

$$d = Hb + v' \quad (2)$$

where the channel coefficients are:

$$H = \begin{bmatrix} h_1 & h_2 \\ -h_1 & h_2 \end{bmatrix} \quad (3)$$

and

$$\begin{cases} b = [b_1 \quad b_2]^T \\ v' = \begin{bmatrix} c_1^H n \\ c_2^H n \end{bmatrix} \end{cases} \quad (4)$$

v' is the combined noise and interference term comprising channel noise and MAI sources.

B. *SISO systems*

In conventional SISO systems, there is a single antenna at the transmitter and one antenna at the receiver. Thus,the transmitter can be described as :

$$T = b_1c_1 + Db_2c_2 \quad (5)$$

where T is the signal transmitted via the antenna of interest and D denotes the parameter in order to simulate the Near-Far effects, b_2 are the interfering transmitter's data and c_2 are their corresponding spreading sequences. At the receiver, the channel coefficient is H_1 found in:

$$d_1 = H_1b_1 + v' \quad (6)$$

C. *Selective criteria of spreading sequences pairs*

We have located more promising spreading sequences by employing different selecting criteria as before, which the proposed criteria is selected sequences with low cross-correlation in terms of pairs of sequences rather than single sequences. The reason of using different criteria can be simply explained by the differences between SISO and MIMO systems. As mentioned before, MIMO-STS systems utilize more than one spreading sequences per user within one transmission whereas the conventional SISO employs one spreading sequence per user during transmission. This can be further explained by their decoding process.

Assuming there are two transmission antennas and only one receiver antenna in MIMO-STS. Then the received signal at the receiver antenna 1 can be described as:

$$R_1 = [(b_1c_1 + b_2c_2)h_1 + (b_2c_1 - b_1c_2)h_2 + M_a + N] \quad (7)$$

then it is decoded in the following manner :

$$D_1 = [(b_1c_1 + b_2c_2)h_1 + (b_2c_1 - b_1c_2)h_2 + M_a + N] \times (c_1 + c_2) \quad (8)$$

where M_a means the other users' signal, as MAI , and N means channel noise.

M_a can be then specifically expressed as :

$$Mai = \sum_{i=2}^{I}[(b_{i1}c_{i1} + b_{i2}c_{i2})h_1 + (b_{i2}c_{i1} - b_{i1}c_{i2})h_2] \quad (9)$$

Substituting (9) in (8) results in:

$$D_1 = \sum_{i=1}^{I}[(b_{i1}c_{i1} + b_{i2}c_{i2})h_1 + (b_{i2}c_{i1} - b_{i1}c_{i2})h_2 + N] \times (c_1 + c_2) \quad (10)$$

The difference between the two systems can be shown by equation (10), which shows the MIMO-STS systems with two transmission antennas use a pair of spreading sequences per user within one transmission. This difference indicates that MAI of a MIMO-STS system is determined by the cross-correlation properties between pairs of spreading sequences rather than the cross-correlation properties between single sequences. Therefore in order to select more promising spreading sequences for a MIMO systems the low-correlation between pairs of sequences should be considered.

Towards this end ,we firstly define the pairs of sequences for one pair of sequences per user's case, which the pairs of sequences are defined as:

$$\begin{cases} x = (c_1 + c_2)/2^2 \\ y = (c_{m1} + c_{m2})/2^2 \end{cases} \quad (11)$$

where x in (11) means the user's spreading pair and y means the MAI users' spreading pairs. The constant 2^2 is used to normalize the pair of sequences for comparison to a single sequence.

For comparing cross correlation performance:

$$P_{cross-corelation} = \frac{1}{M}\sum_{y=1}^{M}|C_{x,y}| \quad (12)$$

where M means the number of MAI users in the systems and

$C_{x,y}$ refers to the discrete aperiodic correlation function:

$$\sum_{\tau=1-N}^{N-1}|C_{x,y}(\tau)| \quad (13)$$

For comparing auto-correlation performance :

$$P_{autocorrelation} = |C_{x,x}| \quad (14)$$

as introduced in (11),x in (14) means the user's spreading pair: x = $(c_1 + c_2)/2^2$ and $C_{x,x}$ and refer to:

$$\sum_{\tau=1-N}^{N-1}|C_{x,x}(\tau)| \quad (15)$$

For more than a pairs of sequences per user's case , the expression for (11) can be defined as :

$$\begin{cases} x = (c_1 + c_2 + \cdots c_h)/h^2 \\ y = (c_{m1} + c_{m2} + \cdots c_{mh})/h^2 \end{cases} \quad (16)$$

where constant h^2 is used to normalize the pair of sequences and h refers to the number of spreading sequences per user. By normalizing the pairs values by h it is possible to make a comparison of the $P_{\text{cross-corelation}}$ for pairs of different number of sequences. For MIMO-STS applications, we want the values of (12) and (14) to be as small as possible.

In order to randomly search for the best pairs, a Monte Carlo search criteria were adopted in the simulation part rather than doing an exhaustive search as there is a large number of the different possible combinations of pairs.

III. SDR TEST BED

In this paper, four different families of sequences were first tested over the Software Defined Radio (SDR) test bed and their corresponding BER performances were recorded and used in the following analysis.

The test bed was developed from the GNU Radio, which is a free software toolkit for building and developing SDR. Within this research, specifically, a computer with GNU Radio installed, a USRP1 board, two RFX2400 Transceiver daughter boards and two PATCH2400 antennas are needed at transceiver whereas one PC with GNU Radio installed, a USRP1 board, one RFX2400 Transceiver daughter board and one PATCH2400 antenna are needed at the receiver. The flowchart of the SDR is shown in Fig. 1.

A. Software Defined Radio test bed

Firstly, the test bed was developed in order to test the SISO and MIMO-STS systems in terms of their MAI effect for different families of spreading sequences. The test bed was modified to install both orthogonal spreading sequences in terms of Walsh-Hadamard, modified Walsh-Hadamard [5], orthogonal Gold [3] and the quasi-orthogonal sequences, 31 bit Gold Codes [3].

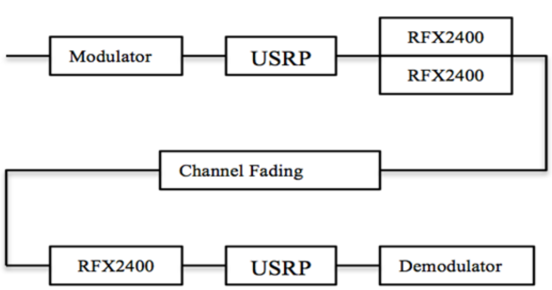

Fig. 1. The flowchart of the MIMO-STS systems SDR

The Near-Far effects are tested over this test bed as well. The model of the MIMO-STS transmitters' antennas are constructed using (1), where b1 and b2 are the intended signals and b3, b4 are the MAI users.c3, c4 are their corresponding spreading sequences with randomly inserted chip delays between 1-9 chips.

At the receiver, the sets of zeros are received as pilot signals, which are then used to estimate the channel coefficients. After the two channels' coefficients have been estimated, the following data received from both transmitter antenna 1 and 2 are decoded and then reconstructed and decoded using the equations [10]:

$$\begin{cases} H = \begin{bmatrix} h1 & h2 \\ -h1 & h1 \end{bmatrix} \\ b = \begin{bmatrix} b1 \\ b2 \end{bmatrix} \\ v = \begin{bmatrix} c_1^H n \\ c_2^H n \end{bmatrix} \end{cases} \quad (17)$$

Therefore d= Hb+v , where d denotes the received data.

Specifically:

$$\begin{cases} d1 = (b1h1 + b2h2) \\ d2 = (b2h1 - b1h2) \end{cases} \quad (18)$$

Then b can be described as:

$$\begin{cases} b1' = \frac{(b1h1-b2h2)}{|h1|^2-|h2|^2} \\ b2' = \frac{(b2h1-b1h2)}{|h1|^2+|h2|^2} \end{cases} \quad (19)$$

The b1' and b2' are then found by applying the Maximum Likelihood Decision Rule: $(\mathcal{R}\{b'\}) \geq 0$ then B=1 else B=0

IV. SIMULATION RESULTS

In SISO and MIMO systems, bit error rate(BER) performance is an important measure as it shows the quality of the system. In this research, we tested the systems' BER performance by employing different sequences

In this simulation the overall Near-Far effects and asynchronous transmissions in uplink channels over the SISO and the MIMO-STS system were simulated. Specifically, the interfering user were allocated energy levels indicative of being two times nearer to the receiver than the user of interest and the MAI user was allowed to randomly suffer a chips delay between 1-9 chips.

In this simulation, one of the most popular orthogonal spreading sequences families, Walsh-Hadamard, was used. Also, the modified Walsh–Hadamard codes proposed by Wysocki et. al. in [5] and orthogonal Gold codes are tested as well. Apart from the orthogonal sequences, the quasi-orthogonal sequences, 31 bits Gold Codes were tested over the test bed in this study. In [11, 12,13] it was reported that Gold codes' cross-correlation properties are the best of all the tested codes. Also, it is shown that better correlation properties occur for the modified Walsh-Hadamard codes compared to Walsh-Hadamard codes in [14,15].

A. The MAI effects on SISO systems

Many papers[16,17,18] argue orthogonal codes are perfectly suited in synchronous case whereas Gold codes lead to a better BER performance in asynchronous case, but these codes are not orthogonal. Four families of spreading codes are compared over the SISO system in this study. Three of them are orthogonal codes which are Walsh-Hadamard, modified Walsh –Hadamard codes proposed by Wysocki et. al [5] and the orthogonal Gold codes. The last one is the quasi-orthogonal sequence set, the Gold code.

In this simulation, we are interested in the asynchronous case. We assume there are two users in this case and one of them is the intended transmitter in this SISO system. We also assume that the interfering user is two times nearer than the intended user to the receiver.

Fig.2 shows the BER performance when four different families, three orthogonal codes (length 32) and one near orthogonal, the Gold code (length 31), are employed in a single transmit antenna and single reciever antenna system. The spreading sequences of the intended user and the interfering user are randomly selected.

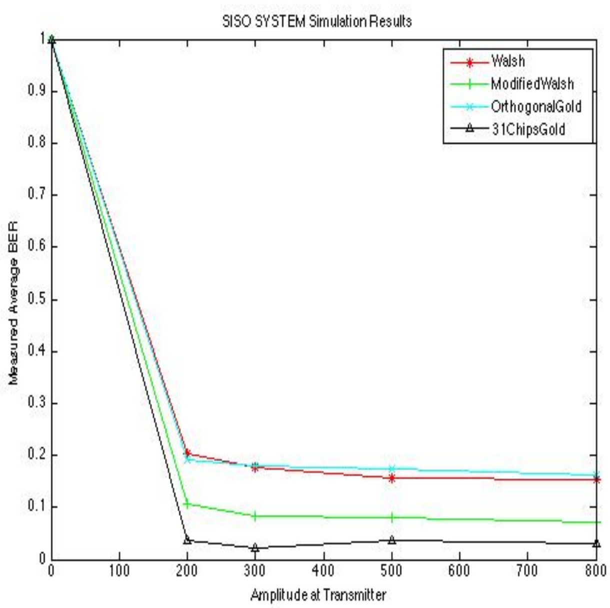

Fig. 2. Comparison of performance of modified walsh codes, orthogonal gold codes, 31 gold codes versus Walsh Hadamard codes in the presence of 1 MAI interferer at amplitude from 200 level to 500 level for randomly chosen chips delay from 1 to 9 on SISO systems

Comparing the results in Fig. 2, it can be observed that the Gold codes performed better in an asynchronous SISO system. The reason for this result is Gold codes's cross-correlation properties are the best of all four families. Apart from this, the 32 length modified Walsh code shows a superior performance than Walsh code as the original properties have improved cross-correlation properties.

B. The MAI effects on MIMO-STS systems

Similar to SISO systems, in the MIMO-STS case, four families of spreading codes are compared over the MIMO-STS system in this study.

Fig.3 shows the BER performance when four different families, including three orthogonal codes (length 32) and Gold code (length 31), are employed in a two transmit antennas and single receiver antenna system. The spreading sequences of the intended user and the interfering user are randomly selected.

Comparing the results in Fig.3, it can be observed that the Gold codes bring about the best performance in asynchronous case of a MIMO-STS system. However, this time the 32 length modified Walsh code does not show a superior performance to the Walsh code but a very similar performance to the Walsh code and orthogonal Gold code sets.

This could be explained by suggesting that poor combination pairs of the modified Walsh code were employed in the simulation. This issue indicates that instead of looking for spreading sequences with low cross-correlation between, in particular for a MIMO systems, we should adopt the criterion that measured correlation between pairs of sequences as a more important criterion.

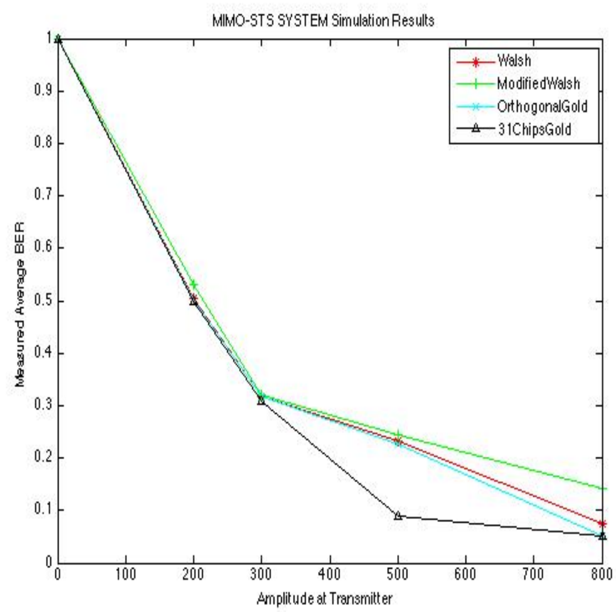

Fig. 3. Comparison of performance of modified walsh codes, orthogonal gold codes, 31 gold codes versus Walsh Hadamard codes in the presence of 1 MAI interferer at amplitude from 200 level to 500 level for randomly chosen chips delay from 1 to 9 on MIMO-STS systems

C. The MAI effects in terms of spreading sequences pairs on MIMO-STS systems

In order to investigate the MAI effects on the basis of spreading sequences pairs over MIMO-STS systems, we assumed there were two users transmitting simultaneously and each of them employed two transmitting anttenas.The 32 length Walsh code was adoptted as the spreading sequences family. Initially, eight different sequences out of 32 from a 32*32 Walsh-Hadamard matrix were chosen to build different pairs. Then two of them were chosen as MAI user's spreading sequences. We then changed the intended user's spreading sequences with different combinations of pairs to test their corresponding BER performances.

In the simulation, the transmit amplitude of the test bed was fixed at the 500 level and each time 128 bit data were transimitted over both antennas. Thus 256 bits of data were transmitted in one interval over this MIMO system. After 768 bits were transmitted in three time intervals, the average BERs were calculated. The results are shown in Table I.

TABLE I. PROPERTIES OF SPREADING SEQUENCES PAIRS USED IN MAI ON MIMO-STS SYSTEMS SIMULATIONS VERSUS BER FOR DIFFERENT SPREADING SEQUENCE PAIRS WHEN AMPLITUDE AT 500 LEVEL WITH 9 CHIPS DELAY

Combination No.: sequences No.	**BER**	**Auto-correlation**	**Cross-correlation**
1:1-2	0.0164	0.5079	0.0635
2:1-3	0.0357	0.5079	0.1270
3:1-4	0.0317	0.5079	0.1270
4:2-3	0.0345	0.5079	0.1270
5:2-4	0.0318	0.5079	0.1270
6:2-5	0.4343	0.5079	0.5079
7:2-6	0.4267	0.5079	0.5079
8:3-4	0.0368	0.5079	0.1270
9:3-5	0.3846	0.3889	0.5714
10:3-6	0.3809	0.3810	0.5714
11:4-5	0.3609	0.3810	0.5714
12:4-6	0.4023	0.3889	0.5714
13:5-6	0.2612	0.2857	0.5079

Comparing the results in Table I, it can be observed that with different properties of spreading sequences pairs the corresponding BER performances are different. According to these results, the worst pair is pair number 6 which lead to 0.4343 in BER whereas the best pair is pair number 1 which resulted in an average BER of 0.0164. The a-periodic auto-correlation of these two pairs are the same whereas the corresponding pair a-periodic cross-correlation of pair 1 is 0.0635which is the lowest value of the sample of tested pairs and that for pair number 6 is 0.5079.

Apart from this, it was noted that pair number 13 lead to a better BER result compared with other high pair a-periodic cross-correlation combinations. The corresponding pair a-periodic auto-correlation of pair 13 is 0.2857 which is the lowest value of all the tested pairs.

It is worth noting that some of the pairs lead to very poor BER performances around 0.4, which would nearly be considered a non existent communications link approaching the same chance as tossing a two sided coin (at 0.5).

To find out the MAI effects of spreading sequences pairs with different MAI users ,the best pair in the above simulation and a randomly chosen pair of spreading sequences were then chosen to do the second simulation which tests the BER performance versus different number of MAI users.

TABLE II. NUMBER OF MAI INTERFERERS VERSUS BER FOR DIFFERENT SPREADING SEQUENCE PAIRS WHEN AMPLITUDE AT 500 LEVEL AND 9 CHIPS DELAY

Combination No.: sequences No.	**Number of MAI interfere users**	**BER**
1:1-2	1	0.0164
1:1-2	2	0.0465
Randomly chosen pair	1	0.2412
Randomly chosen pair	2	0.7423

The simulation model is similar to the previous scenario, however, the number of MAI users is now increased from 1 to 2 and the second MAI user adopts the same pair of spreading sequences of Walsh-Hadamard codes within the simulation. After 768 bits were transmitted in three time intervals, average BER was computed and this is shown in Table II.

Acording to the results shown in Table II, it can be observed that the selective pair brings about a satisfactory BER performance under both one and two MAI interfering users' whereas the randomly chosen one lead to a worse BER performance when the number of interfering users was one. It is noticed that when the number of MAI users was increased to two the randomly chosen pair's BER was very poor.

The differeces between the selective pair and randomly chosen comfirmed that we need to adopt the criteria in pairs in order to find better spreading sequences for MIMO-STS systems.

V. CONCLUSION

In this paper, we developed a SDR test bed to test the MAI effects over SISO and MIMO systems. It can be observed that in the case of asynchronous transmission the Gold code lead to the best performance over both systems due to the fact that it has the best cross-correlation properties.

Apart from this, we found the MAI effects in terms of spreading sequences pairs on MIMO-STS systems, which motivated us to propose the selective criteria of low cross-correlation as a function of pairs of spreading sequences for a MIMO system. Based on the test bed measurements, more promising sets of pairs of spreading sequences have been found by employing our proposed selective criteria. Further work involves the research on generating novel new spreading codes or modifing existing sets of spreading codes on the basis of a selective criteria which includes properties associated with cross-correlations between pairs of spreading codes.

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