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Spreading Codes for Multicarrier CDMA based Wireless Mobile Communication

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Abstract: *Multicarrier CDMA is one of the most potential candidates for meeting the future demands of next generation wireless systems. It is a combination of multicarrier modulation and CDMA which is very effective in combating severe multipath interference and provides multiple access simultaneously. The objective of this paper is to highlight the desirable characteristics of spreading codes required for a CDMA based wireless systems and present a comparative overview of various types of orthogonal and non-orthogonal spreading codes.*

Keywords: *CDMA, Multicarrier, Orthogonality, Peak to Average Power Ratio, Spreading Codes, Correlation.*

I. INTRODUCTION

CDMA is the most potential candidate for meeting the future demands of wireless mobile and personal communication systems [1]-[2]. The introduction of new broadband wireless services like live video transmission, wireless internet, mobile games and various location based services have posed great challenge in the development of next generation wireless systems. The scarcity of new radio frequency bands has further aggravated the problem. The main challenges in the development of broadband wireless systems are:

- Bandwidth efficiency (2-10 b/s/Hz).
- Frequency selective fading due to large bandwidth of the order of 100 MHz.

In order to counter the challenges posed by the broadband nature of next generation of wireless mobile, a CDMA system combined with multicarrier modulation using orthogonal sub-carriers has been reported in the literature [3]-[5]. This combination effectively exploits frequency diversity and counter severe frequency selective fading which occur due to bandwidth intensive services. A typical Multicarrier Direct Sequence (DS) CDMA modulator [8] is shown in Figure 1.

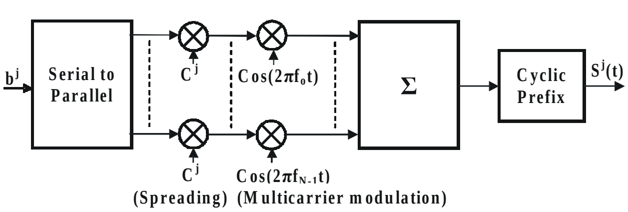

Figure 1: Schematic of MC-DS-CDMA Modulator.

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It is well known that CDMA is based on spread spectrum [6]-[7] multiple access which allows the multiple users to operate in the same frequency band simultaneously. It employs a high rate unique pseudo random code for each user to spread the data over a commonly used wider bandwidth. The receiver performs a time correlation operation to detect only the specific desired code word. All other code words appear as noise due to decorrelation.

For detection of the message signal the receiver needs to know the code word used by the transmitter. Each user operates independently with no knowledge of other users. Thus the performance of a CDMA based wireless systems is largely dependent on the characteristics of these pseudo-random spreading codes. In this paper, a detailed overview of various spreading codes like PN codes, Gold codes, Kasami codes, Orthogonal Gold codes, Walsh-Hadamard codes and Golay complementary codes has been provided with special emphasis on their generation and correlation properties.

This paper is organized as follows. In Section II, the various desirable characteristics affecting the choice of spreading codes have been discussed in detail. In Section III, the generation and properties of various Orthogonal and Non-orthogonal codes have been presented. Finally, Section IV presents some conclusions.

II. DESIRABLE CHARACTERISTICS OF SPREADING CODES

When designing a CDMA system, the proper choice of spreading codes is of prime importance since it has considerable effect on the performance of the receiver (i.e. its ability to discriminate between different users) and consequently on the capacity of the whole system. The various desirable characteristics that affect the choice of spreading codes for future generation wireless CDMA systems are investigated below.

A. Impulsive Auto-Correlation

Auto-correlation [6] is a measure of the similarity between a code *C(t)* and its time shifted replica. Mathematically, it is defined as:

$$\psi_a(\tau) = \int_{-\infty}^{\infty} c(t) * c(t-\tau)dt \qquad (1)$$

Ideally, this auto-correlation function (ACF) should be impulsive. This is required at receiver side to distinguish the desired user from other users producing MAI. Thus, spreading codes should be carefully chosen to ensure highest possible peak value of auto-correlation function and lower correlation peaks at non-zero shifts (sidelobes).

B. Zero Cross-Correlation

Cross-correlation [6] is the measure of similarity between two different code sequences $C_1(t)$ and $C_2(t)$. Mathematically, it is defined as:

$$\psi_c(\tau) = \int_{-\infty}^{\infty} c_1(t) * c_2(t-\tau)dt \qquad (2)$$

Cross-correlation function (CCF) in-fact indicates the correlation between the desired code sequence and the undesired ones at the receiver. Therefore, in order to eliminate the effect of multiple access interference (MAI) at the receiver, the cross-correlation value must be zero at all time shifts. The codes for which $\psi_c(\tau) = 0$ i.e. zero cross-correlation value at all time shifts, are known as orthogonal codes. Therefore, it is desirable to have a code dictionary consisting of spreading codes which possess both impulsive ACF and all zero CCF characteristics. But unfortunately no such code family exists which possess both characteristics simultaneously.

C. Large Size of Code Set

In order to support large number of users in the system, code family must be very large. It is very difficult to ensure a large code dictionary consisting of codes having desirable properties because such codes are very few in number. Therefore, one has to optimize the requirements. Further the length of the code should also be large so that the spreaded signal is able to maintain its noise like properties. This will also ensure adequate safety against eaves droppers.

D. Variable Spreading Factor

Multimedia services like video conferencing, MMS, etc. require support of variable data rate channels instead of fixed rate data channels. Moreover, more than one data channel and that too with different data rates will be required to be dedicated to each user. Thus, in order to ensure constant chip rate after spreading of variable rate data channels, spreading codes with variable spreading factors (VSF) [7]-[8] are required.

E. Peak to Average Power Ratio (PAPR)

One of the most important challenges faced by CDMA system combined with multicarrier modulation (Figure 1) is high peak to average power ratio of the transmitted signal [9]. Depending on input data, the summation of subcarriers may result in a signal with a large amplitude, or small amplitude. As a result the peak signal power is much greater than the average power. And high PAPR causes out of band radiations due to non-linear power amplifier. This PAPR is significantly affected by the correlation functions of the codes selected in the system.

III. SPREADING CODES FOR MOBILE CDMA

Broadly on the basis of correlation properties, the spreading codes for mobile CDMA may be divided into two categories: Orthogonal codes and Non-orthogonal codes. As already discussed, the orthogonal spreading codes bear zero cross-correlation value at all time shifts which results into zero MAI. However, such codes possess poor ACF characteristics. On the other hand, non-orthogonal codes have large length and much better ACF characteristics. Therefore, the properties of both type of codes need to be investigated for wireless mobile applications. The orthogonal codes explored here include Orthogonal Gold codes, Walsh-Hadamard codes and Golay complementary codes; whereas the non-orthogonal codes include PN codes, Gold codes and Kasami codes.

1. Walsh-Hadamard Codes:

Walsh-Hadamard codes make useful sets for CDMA based wireless systems because of their orthogonality and VSF characteristics. Walsh functions are generated by mapping codeword rows of special square matrix called Hadamard matrix [7]. The Hadamard matrix of desired length can be generated by the following recursive procedure:

$$\mathbf{H}_1 = [0];\ \mathbf{H_2} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix};\ \mathbf{H_{2N}} = \begin{bmatrix} H_N & H_N \\ H_N & H_N \end{bmatrix} \qquad (3)$$

where N is a power of 2 and overscore denotes the binary complement. Each row of the matrix presents a Walsh-Hadamard code by mapping 0 to 1 and 1 to –1. These codes have zero cross-correlation between each other and therefore these codes are orthogonal. However, these codes have poor ACF characteristics. The support for multiple and variable data rates can be provided by the VSF property of Walsh-Hadamard codes. Variable spreading factor is achieved through generation of tree structured codes based on modified Walsh-Hadamard matrix. The code tree for generation of OVSF Walsh codes is shown in Figure 2.

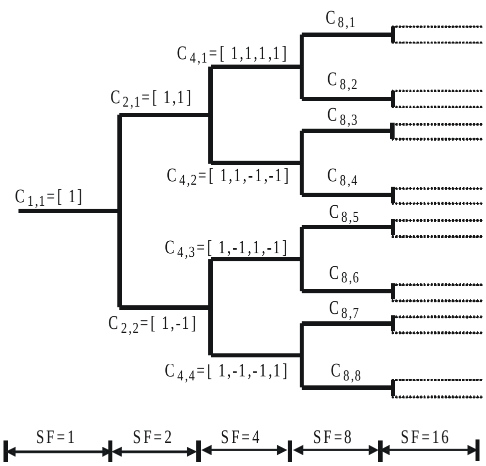

Figure 2: Code Tree for Generation of OVSF Walsh Codes

Here the generated codes of the same layer form a set of Walsh functions and these are orthogonal. Also, any two codes of different layers are orthogonal except for the case that one of the two codes is a mother code of the other.

2. Orthogonal Gold Codes:

Orthogonal Gold codes [8] are also particularly attractive in terms of zero CCF, ease of generation and support of variable data rate communication. These codes are obtained by modifying original Gold codes [10] generated by preferred pair of maximal PN sequences by attaching an additional "0" to the original Gold codes. Such a set of modified codes excluding the m-sequence delayed for generation forms a family of Orthogonal Gold (Ogold) codes having zero CCF value. This set of K number of orthogonal Gold codes each having length $K = N + 1$, can be represented in the form of a matrix G_K of order $K*K$ by mapping 0 to 1 and 1 to –1.

Orthogonal Gold codes can also be made to support multi-rate data transmissions in a similar fashion to that of Walsh-Hadamard codes. The set of Orthogonal Gold codes of length M for variable rate transmission can be represented in the form of a matrix G_M of order $M*M$. This matrix is constructed by using Ogold code matrix G_K and Hadamard matrix H_P of order $P*P$, where $M = K*P$. Ogold code matrix G_K is substituted at places where "0" is present in Hadamard matrix H_P and $\overline{G_K}$ (overscore denotes binary complement) is substituted at places where "1" is present. This results into a matrix G_M of order $M*M$. For example, G_{32} matrix of multirate Ogold codes is obtained from G_8 and H_4 matrices as mentioned below.

$$G_{32} = \begin{bmatrix} G_8 & G_8 & G_8 & G_8 \\ G_8 & \overline{G_8} & G_8 & \overline{G_8} \\ G_8 & G_8 & \overline{G_8} & \overline{G_8} \\ G_8 & \overline{G_8} & \overline{G_8} & G_8 \end{bmatrix}; \; H_4 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix} \quad (4)$$

Now when the data rate is doubled, spreading factor will have to be reduced by half and matrix will generatematrix as shown below.

$$G_{16} = \begin{bmatrix} G_8 & G_8 \\ G_8 & \overline{G_8} \end{bmatrix}; \; H_2 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \quad (5)$$

Thus, for a given length K of orthogonal Gold code and maximum spreading factor $SF_m = \left(\dfrac{fixed\ chip\ rate\ R_c}{\min data\ rate\ R_b} \right)$, maximum order P of Hadamard matrix can be determined by $P = SF_m / K$. Thus, a suitable combination of Orthogonal Gold code matrix and Walsh-Hadamard matrix provides support for variable data rate channels. Tree structured generation for Orthogonal Gold codes is similar to that of Walsh codes with a difference that in case of Ogold code tree, at each layer a code matrix (e.g G_8) is present instead of single code as in Walsh code tree. Therefore, care must be taken in assigning Ogold codes from different tree layers for multirate applications so that orthogonality condition is maintained.

3. Golay Complementary Codes:

Golay complementary sequences are another important candidate for CDMA wireless applications because of their orthogonality. An orthogonal set of Golay complementary sequences can be recursively obtained [11] by:

$$H_2^C = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}; \; H_{2N}^C = \begin{bmatrix} H_N^C & \overline{H_N^C} \\ H_N^C & -\overline{H_N^C} \end{bmatrix} \quad (6)$$

where $\overline{H_N^C}$ is composed of H_N^C of which the right half columns are reversed. The codes of desirable length thus obtained have zero CCF and hence these codes are orthogonal. These codes may also be used in conjunction with Hadamard matrix in order to support variable rate data transmission. The auto-correlation properties of these codes are found better than Walsh codes.

4. Maximal Length Pseudo-Noise (PN) Codes:

Maximal length sequences (m-sequences) [6]-[7] are, by definition, the largest codes that can be generated by a given shift register or a delay element of a given length. The m-sequence generator structure using linear feedback shift register is shown in Figure 3.

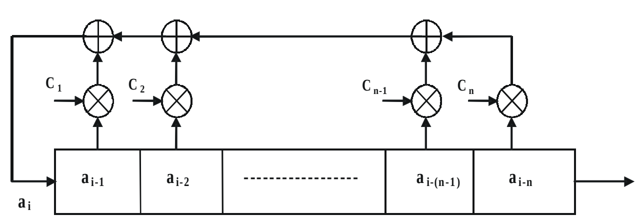

Figure 3: M-sequence Generator Structure

Each clock time the register shifts all contents to the right. The sequence a_i is generated according to the recursive formula:

$$a_1 = C_1 a_{i-1} + c_2 a_{i-2} + \text{.........} + C_n a_{i-n} = \sum_{k=1}^{n} C_k a_{i-k} \quad (7)$$

Here, all terms are binary (0 or 1), and addition and multiplication are modulo-2.

The m-sequences satisfy the following three randomness properties in every period of length $N = 2^n - 1$. (i) The number of 1's is always one more than the number of 0's. This property is called the balance property. (ii) Half the runs of 1's and 0's have length 1, ¼th are of length 2, 1/8 have length 3, and $1/2^k$ have length k ($k < n$). (iii) The autocorrelation function of an m-sequence is binary valued (i.e. two-valued) that give the least probability of false synchronization. But these are not immune to cross-correlation problems, and they have large cross-correlation values.

4. Gold Codes:

Gold sequences are useful because of the large number of codes they supply [6]-[7]. They can be chosen so that over a set of codes available from a given generator, the cross-correlation between the codes is uniform and bounded.

Finding preferred pairs of m-sequences is necessary in defining sets of gold codes. Let a and a^1 represent a preferred pair of m-sequences having period $N = 2^n - 1$. The family of codes defined by $\{a, a^1, a + a^1, a + Da^1, a + D^2 a^1, \ldots, a + D^{N-1} a^1\}$ where D is the delay element is called the set of Gold codes for this preferred pair of m-sequences. With the exception of sequences 'a' and 'a^1', the set of Gold sequences are not maximal sequences. Hence, their autocorrelation functions are not two valued, but cross-correlation functions are three valued.

5. Kasami Codes:

Kasami sequence sets are one of the important types of binary sequence sets because of their very low cross-correlation. There are two different sets of Kasami sequences: the small set and the large set of Kasami sequences [7]. The small set of Kasami sequences is generated by modulo-2 addition of the bits from an m-sequence 'a' and bits from another m-sequence 'a^1' and all $2^{n/2}-2$ cyclic shifts of the bits from a^1; where 'a' is an m-sequence of period 2^n-1 with n even and 'a^1' is obtained by decimation of 'a' by $2^{n/2} + 1$. Thus, by including 'a' in the set, we obtain a set of $2^{n/2}$ binary sequences of length $N = 2^n-1$. The small set of Kasami sequences is optimal because of their very low cross-correlation.

The large set of Kasami sequences again consists of sequences of period 2^n-1, for n even, and contains both the Gold sequences and the small set of Kasami sequences as subsets. Let m-sequences a^1 and a^{11} be formed by the decimation of 'a' by $2^{n/2}+1$ and $2^{(n+2)/2} + 1$, and take all sequences formed by adding a, a^1, a^{11} with different shifts of a^1 and a^{11}. The number of such sequences is $M = 2^{3n/2}$ if $n = 0$ (mod 4), and even larger $M = 2^{3n/2} + 2^{n/2}$, if $n = 2$ (mod 4). The large set of Kasami sequences is not optimal unlike the small set.

IV. CONCLUSIONS

A CDMA system combined with Multicarrier modulation using orthogonal sub-carriers effectively exploits frequency diversity and counter severe frequency selective fading which occur due to bandwidth intensive services. The desirable characteristics of spreading codes required for a CDMA based system include (i) availability of large number of codes (ii) impulsive auto-correlation function (iii) zero cross-correlation value (iv) low Peak to Average Power Ratio (PAPR) value and (v) support for variable data rates. The characteristics and the desirable properties of the orthogonal codes as well as non-orthogonal codes have been investigated. Orthogonal category of codes provide zero MAI, possess VSF property but these codes have poor ACF characteristics and small code dictionary. On the other hand, non-orthogonal codes have large code dictionary, better ACF properties but non-zero CCF values. Therefore, a communication engineer is required to optimize his requirements.

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