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Evaluation of ACF, CCF, RAC, RCC and MF Properties of Different Spreading Sequences Used in DS-CDMA Systems

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Abstract – This paper investigates the different sequences that can be used in direct sequence division multiple access (DS- CDMA) systems. The auto-correlation, cross correlation, the mean square correlation measurements (R_{AC}, R_{cC}) and merit factor (MF) are used for evaluating the performance of different spreading sequences. The results obtained small set of Kasami sequences is the most effective of binary sequences families in terms of correlation measure, but this set suffers from the limited number of sequences. Overall among orthogonal category, Orthogonal Gold sequences and Golay complementary sequences are a better candidate in synchronous CDMA applications.

Keywords – Direct Sequence Code Division Multiple Access, Auto-Correlation, Cross Correlation, The Mean Square Correlation Measurements, Merit Factor MF, Small Set of Kasami, Orthogonal Gold Sequences, Synchronous CDMA.

I. INTRODUCTION

In a code division multiple access (CDMA) system, a large number of users share a common channel to transmit information to a receiver [1]. That is can by use of the most commonly used methods for the spread spectrum technology wich is direct sequence spread spectrum (DS-SS). In a DS-CDMA system, each user is assigned a unique code also known as sequence that allows the user to spread the information signal. The receiver uses cross correlation to separate the appropriate signal from signals meant for other receivers, and autocorrelation to reject multipath. Code-selection has a large impact on the performance of the system.

The desirable characteristics of CDMA sequences include : (i) availability of large number of sequences to support large number of users in the system, (ii) the length of the code should be large so that the spreaded signal is able to maintain its noise like properties (ensure adequate safety of the message),(iii) impulsive autocorrelation function to ensure a good synchronization at receiver [2],(iv) zero cross-correlation values to eliminate the effect of multiple access interference at the receiver [3] and (v) ease of generation.

Sequences that can be used in DS- CDMA systems are: Walsh-Hadamard sequences [4], orthogonal variable spreading factor (OVSF) code[5], orthogonal Gold sequence, Golay complementary sequences [6], m-sequences [7], Gold sequences[8], Kasami sequences[9], Weil sequences [10], Barker sequences[11], random sequences or memory sequences[12], chaotic sequences[13], and zero correlation zone (ZCZ) sequences[14], [15]. The first four sequences are orthogonal i.e.whose mutual CCFs are zero for any time shift while the other sequences show cross-correlation values unequal to zero.

Ideally, the spreading sequences are designed to have highest possible peak ACF value and lower correlation peaks (side-lobes) at non-zero shifts and very low cross-correlations function (preferably zero) (CCF) for all time-shifts. Thus, the spreading sequences should be carefully chosen to ensure both characteristics simultaneously.

In this paper, we will present an evaluation of the ACF, CCF properties, aperiodic correlation and cross-correlation measurements and merit factor MF of the different types of spreading sequences used in DS-SS systems.

The paper is organised as follows. In the next section, we show the generation principle of defferent spreading sequences. In section III, we provide the main caracteristics used for evaluating the performance of different spreading sequences. The evaluation of correlation characteristics of spreading sequences are presented in section IV, and finally we conclude the paper.

II. CONSTRUCTION OF SPREADING SEQUENCE

A. *Walsh Hadamard Sequence*

The name of this code comes from the American mathematician Joseph Leonard Walsh and the French mathematician Jacques Hadamard [4].

The Walsh sequences are constructed from the Hadamard transform matrix. They are composed of 2^n binary sequences, each of length 2^n, they correspond to rows or columns of the orthogonal matrix $[N \times N]$ constructed recursively as follows:

$$H_0 = [0]$$

$$H_N = \begin{bmatrix} H_{N/2} & H_{N/2} \\ H_{N/2} & \overline{H_{N/2}} \end{bmatrix} \qquad (1)$$

Orthogonality is the most important property of Walsh-Hadamard sequences. Because of this orthogonality property, the cross-correlation between any two Hadamard-Walsh sequences of the same set is zero, when system is perfectly synchronized.

A. *Orthogonal variable spreading factor(OVSF)*

OVSF [4-5] sequences were first introduced for 3G communication systems. OVSF sequences are primarily used to preserve orthogonality between different channels in a communication system. OVSF sequences are defined as the rows of an *N*-by-*N* matrix, C_N, which is defined recursively as follows.

$$C_N = \begin{bmatrix} C_N(0) \\ C_N(1) \\ C_N(2) \\ C_N(3) \\ . \\ . \\ C_N(N-2) \\ C_N(N-1) \end{bmatrix} = \begin{bmatrix} C_{N/2}(0) & C_{N/2}(0) \\ C_{N/2}(0) & \overline{C_{N/2}(0)} \\ C_{N/2}(1) & C_{N/2}(1) \\ C_{N/2}(1) & \overline{C_{N/2}(1)} \\ . & \\ . & \\ C_{N/2}(N/2-1) & C_{N/2}(N/2-1) \\ C_{N/2}(N/2-1) & \overline{C_{N/2}(N/2-1)} \end{bmatrix} \qquad (2)$$

Where C_N (n) is the row vector of N elements. $N = 2^K$ (K is a positive integer) and $C_{\frac{N}{2}}\left(\frac{N}{2}-1\right)$ (n)is the binary complement of $C_{N/2}(n)$.

Note that C_N is only defined for N a power of 2. These sequences can also be defined recursively by a an OVSF tree [16], as shown in Fig.1.

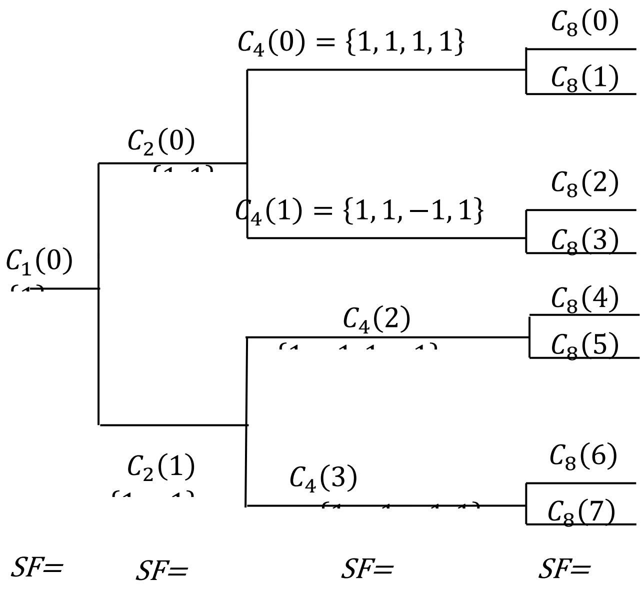

Fig 1. Code three of Orthogonal Variable Spreading Factor (OVSF) sequences.

In this figure, the OVSF sequences described as $C_{SF,i}$ where SF is the spreading factor (length of the code) and k is the code number, 0 ≤ i ≤ SF -1. All code sequences at the same hierarchical level of the tree are the same length (eg, SF = 4 for all sequences $C_{4,k}$).

B. *Orthogonal Golay complementary sequences*

Golay complementary sequences, often referred as Golay pairs, are characterised by the property thatthe sum of their aperiodic autocorrelation functions equals to zero, except for the zero shift.

Let A a set of spreading sequences consisting L sequences of length N noted A_i. Let $R_{A_i,A_i}(\tau)$ denote the autocorrelation function of the sequence A_i. Clearly, a set of sequences is a complementary [18] set if and only if :

$$\sum_{i=1}^{L} R_{A_i,A_i}(\tau) = NL\delta(\tau) \qquad (3)$$

Further, each sequence A is complementary with at least one other sequence B with:

$$R_{A,A}(\tau) + R_{B,B}(\tau) = 2N\delta(\tau) \qquad (4)$$

The orthogonal Golay complementary sequences of length N are constructed recursively as follows:

$$H_N = \begin{bmatrix} H_{N/2} & \widetilde{H}_{N/2} \\ H_{N/2} & -\widetilde{H}_{N/2} \end{bmatrix} \qquad (5)$$

where H_N is matrix of Golay of dimension $N \times N$ $(N = 2^n, n > 0)$ and $\widetilde{H}_N$ is the permuted matrix of H_N, ex., if $H_N = [A_N \quad B_N]$ where A_N and B_N are matrix of $N \times \frac{N}{2}$, so $\widetilde{H}_N \triangleq [A_N \quad -B_N]$.

C. M-sequence

M-sequence or Maximal Length Sequence are, by definition, the largest sequences that can generate by an n-stage linear feedback shift registers [7] (LFSR) as shown in Fig.2.

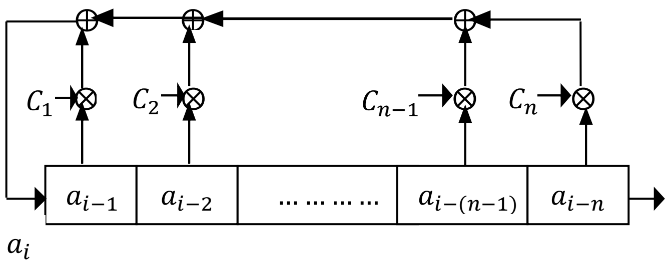

Fig 2. Linear feedback shift register of length n.

The sequence a_i is generated according to the recursive formula given as:

$$a_i = C_i a_{i-1} + C_2 a_{i-2} + \cdots + C_n a_{i-n} = \sum_{k=1}^{n} C_n a_{i-k} \qquad (6)$$

The first n bits $a_0, \ldots, a_{n-1}$ form the initial state of the register.

The feedback coefficients are usually represented by a polynomial of degree n, called generator polynomial:

$$P(x) = C_0 x^n + C_1 x^{n-1} + \cdots + C_{n-1} x + C_n \quad (7)$$

Where: $C_i \in [0,1]$ and $C_0 = C_n = 1$

The period of the binary sequence generated by an LFSR is maximal $(2^n - 1)$ when the generator polynomial is primitive.

D. Gold sequence

One important class of periodic sequences which provides larger sets of sequences with good periodic crosscorrelation is Gold sequences. A set of Gold sequences can be constructed by the XOR of two m-sequences of the same length N.

The set of Gold sequences generated with the two preferred pair of m-sequences u and v is given as:

$$G(u,v) = \{u, v, u \oplus v, u \oplus T \cdot v, u \oplus T^2 \cdot v, \ldots, u \oplus T^{N-1} \cdot v\} \qquad (8)$$

Where $\oplus$ is the sum modulo-2, T is the cyclic shift operator.

A set of Gold sequences of period $N = 2^n - 1$, consists of $N + 2$ sequences, where n is the size of the LFSR that generated the two m-sequences.

E. Orthogonal Gold sequence

These sequences are obtained by modifying original Gold sequences generated by a preferred pair of m-sequences [8]. Many cross-correlation values of Gold sequences are -1. By attaching one zero to the original Gold sequences, it is possible to make cross-correlation values to 0, with no shift between the two sequences. The total number of orthogonal Gold sequences of length N, obtained is equal to 2^n.

F. Kasami sequences

Another important type of DS- CDMA code is the code of Kasami, which was proposed by professor Kasami in 1960[4].

There are two classes of Kasami sequences: the small set and the large set.

a. Small Set of Kasami Sequences

For an m-sequence u, w is obtained by taking every qth bit of u and denoted u [q]. w is called a decimated sequence of u. By choosing $q = 2^{n/2} + 1$, where n is the degree of sequence u, w is periodic with period $2^{n/2} - 1$. By repeating w, q times, such that w is of the same length as u, a new sequence is obtained . With u and w we form a small set of Kasami sequences by adding u and w cyclically shifted.

The small set of Kasami sequence for n even can define as:

$$K_s(u) = \left\{u, u \oplus w, u \oplus Tw, \dots, u \oplus T^{2^{n/2}-2}w\right\} \quad (9)$$

It will generate $2^{n/2}$ of small set of Kasami binary sequences with period $2^n - 1$ (where n is even).

ACF of small set of Kasami sequences is three valued and takes on value in the set: $\{-1, -s(n), s(n) - 2\}$, where : $s(n) = 2^{n/2} + 1$.

Therefore, the maximum of cross-correlation of small set of Kasami sequences is:

$$\theta_{max} = s(n) = 2^{n/2} + 1 \quad (10)$$

b. Large Set of Kasami Sequences

Large set of Kasami sequences contains both small set of Kasami sequences sequences [9].

Let u be an m-sequence of period $N = 2^n - 1$ generated with a polynomial generator of order n even, Find w and v by decimating u by $2^{n/2} + 1$ and by $2^{(n+2)/2} + 1$.

The family of Kasami sequences is formed by the modulo-2 addition of u, v and w with different shifts of v and w. The number of such sequences is $M = 2^{3n/2}$ if $n = 0 (\mathrm{mod}\ 4)$ or $M = 2^{3n/2} + 2^{n/2}$ if $n = 2(\mathrm{mod}\ 4)$.

If $n = 0(\mathrm{mod}\ 4)$ the large set of Kasami sequences is defined as:

$$K_l(u, n, k, m) = \begin{cases} u & , k = -2, m = -1 \\ v & , k = -1, m = -1 \\ u \oplus T^k v & , k = 0, \dots, 2^n - 2, m = -1 \\ u \oplus T^m w & , k = -2, m = 0, \dots, 2^{\frac{n}{2}} - 2 \\ v \oplus T^m w & , k = -1, m = 0, \dots, 2^{\frac{n}{2}} - 2 \\ u \oplus T^k v \oplus T^m w & , k = 0, \dots, 2^n - 2, m = 0, \dots, 2^{n/2} - 2 \end{cases} \quad (11)$$

In which k and m are the shift parameters for the sequences v and w respectively. There are N possible circular shift.

The correlation function for the sequences takes on the values : $\{-t(n), -s(n), -1, s(n) - 2, t(n) - 2\}$, where:

$$t(n) = 1 + 2^{(n+2)/2} \qquad \text{n is even}$$

And

$$s(n) = \frac{1}{2}(t(n) + 1) \quad (12)$$

The maximum of cross-correlation of large set of Kasami sequences is:

$$\theta_{max} = t(n) = 2^{n/2} + 1 \quad (13)$$

G. Weil sequences

Weil sequences are a relatively new family of binary sequences with very good correlation properties. They exist for any length L, where L is a prime number.

Weil sequences are based on Legendre sequences and can be obtained by adding (exclusive or) of them. Legendre sequences can be generated by quadratic residues as follow [19] :

a. Quadratic residues

For a prime number L and an arbitrary positive integer a ($a < L$): we say that a is the quadratic residue modulus L if the equation $x\text{^}2 \bmod L = a$ has a solution x.

That is to say, it can be proved whether a is a quadratic residue or not by computing the value of the expression:

$$f(a) = a^{(L-1)/2} \bmod L \quad (14)$$

This expression can only take values $+1$ and -1, and the Legendre sequence is formed as follows:

$$[0\ f(1)\ \ f(2) \dots f(L-1)] \quad (15)$$

b. Weil sequences

Weil sequences "W" is obtained by the XOR addition of Legendre sequences u with a shifted replica of itself. They are given by:

- $$W(u) = \left\{u \oplus Tu \oplus T^2u, \dots T^{floor(L/2)}u\right\} \quad (16)$$

H. barker sequences

Barker sequences are short length sequences that offer good correlation properties. Known Barker sequences are tabulated in Table 1.

Table 1. List of Known Sequences Barker

Length N	sequence
2	[1 1]
2	[-1 1]
3	[1 1 -1]
4	[1 1 -1 1]
4	[1 1 1 -1]
5	[1 1 1 -1 1]
7	[1 1 1 -1 -1 1 -1]
11	[1 1 1 -1 -1 -1 1 -1 -1 1 -1]
13	[1 1 1 1 1 -1 -1 1 1 -1 1 -1 1]

III. CORRELATION CHARACTERISTICS

A. *Auto-Correlation*

Auto-correlation function (ACF) is a measure of the similarity between a code c and its time shifted replica [20-21-22]. Mathematically, it is defined as:

$$R_{i,i}[\tau] = \sum_{i=1}^{N} c_i . c_{i-\tau} \qquad (17)$$

Ideally, the spreading sequences must have highest possible peak value of ACF and lower correlation peaks (side-lobes) at non-zero shifts for ensured a good synchronization at receiver [20-21-22].

B. *Cross-Correlation*

Cross-correlation function CCF is the measure of similarity between two different code c_i and c_j. We obtain the general definition of the cross correlation replacing $c_{i-\tau}$ by $c_{j-\tau}$ in equation x:

$$R_{i,j}[\tau] = \sum_{i=1}^{N} c_i . c_{j-\tau} \qquad (18)$$

CCF indicates the correlation between the desired code sequence and the undesired ones at the receiver. Therefore, low cross-correlation value (close to 0 at all time shifts) is required in order to eliminate the effect of multiple access interference at the receiver[20-21-22].

C. *Mean Square Correlation Measures*

The performance of different PN sequences is usually evaluated by mean square aperiodic auto-correlation R_{AC} (MSAAC) and mean square aperiodic cross-correlation RCC (MSACC) measures. These correlation measures have been introduced by Oppermann and Vucetic [23]

The discrete aperiodic correlation function is defined as [21]:

$$r_{i,j}(\tau) = \frac{1}{N} \sum_{i=1-N}^{N-1} c_i(n) . c_j\,(n+\tau) \qquad (19)$$

The mean square aperiodic auto-correlation value for a code set containing M sequences is given by [21]:

$$R_{AC} = \frac{1}{M} \sum_{i=1}^{M} \sum_{\tau=1-N,\tau\neq 0}^{N-1} \left| r_{i,i}(\tau) \right|^2 \qquad (20)$$

The mean square aperiodic cross-correlation value is given by:

$$R_{CC} = \frac{1}{M(M-1)} \sum_{i=1}^{M} \sum_{j=1,j\neq i}^{M} \sum_{\tau=1-N}^{N-1} \left| r_{i,j}(\tau) \right|^2 \qquad (21)$$

D. *Merit Factor*

Another important quantitative measure of a code sequence's quality is Merit Factor or MF defined by Golay [24].

It characterizes the difference between the desired and actual ACF properties of long binary sequences. Itis given, for a binary sequence S of length N, as follows:

$$MF(S) = \frac{R_S(0)^2}{\sum_{u\neq 0} |R_S(u)|^2} = \frac{N^2}{2\sum_{u=1}^{N-1} |R_S(u)|^2} \qquad (22)$$

Where $R_S(u)^2$ is the energy of the uth peak and $R_S(0)$ is the central peak value of the ACF. The best binary sequences are those having the largest MF.

These four measures have been used as the basis for comparing the sequence sets in this paper.

IV. SIMULATIONS AND RESULTS

A. *Evaluation of Correlation Characteristics*

Different spreading sequences of desired length are generated as described in sections II, and the characteristics of ACF and CCF of the set family of each length are computed.

Fig.3 and Fig.4 shows the ACF value for different spreading sequences of length 8 and 63 bits.

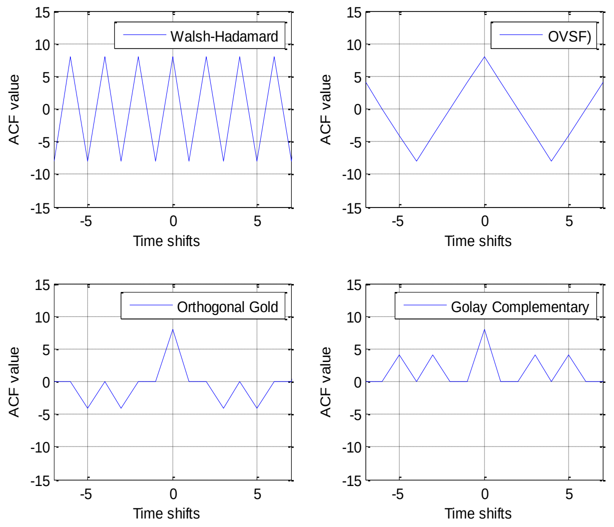

Fig 3. ACF Characteristics of orthogonal sequences of length 8.

It is observed from Fig.3 that the many side-lobes have the same value as that of peak ACF value (i.e. 8) at zero shifts for each two Walsh-Hadamard and OVSF sequences. It has been observed that orthogonal Gold sequences possess better ACF characteristics as compared to Walsh sequences; the level of secondary code peaks is much lower compared to the peak of ACF at zero shifts. Is clearly noticed from same figure that the peak side lobe level is 6 dB down compared to the peak of ACF at zero shift for complementary Golay sequences. Thus, Golay sequences possess better ACF characteristics as compared to both Walsh sequences as well as orthogonal Gold sequences.

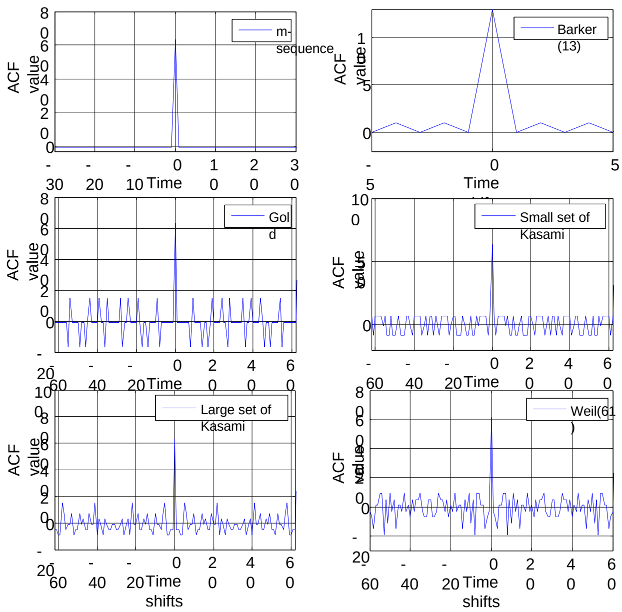

Fig. 4. ACF Characteristics of different pseudo-random sequences of length 63

It has been observed from the Fig.4 that m-sequences possess ideal impulsive ACF characteristics. It means that peak value exists at zero time-shift and zero values are present for all other time shifts i.e. no side-lobe exists in ACF characteristics. From the results, among all other sequences, Barker sequence has single peak ACF and all side lobes amplitudes are very less. For small set of Kasami sequences of length N = 63, ACF values are less than Gold and large set of Kasami sequences. It is seen from the figure also that none of Gold, large set of Kasami and Weil sequences possess the ideal 2-valued impulsive characteristics. Thus, m-sequence and Barker sequences are the best in terms of ACF characteristics.

In the similar fashion, the cross-correlation characteristics are also being plotted in Fig.5.

It has been observed from the Fig.5 that a large set of m-sequences have large cross-correlation. This implies that they are harder to be distinguished and may cause false synchronization in CDMA based systems. Comparing the cross-correlation plots for the two Gold and small set of Kasami sequences, it is clear that small set of Kasami code has lower bounds (-9,-l and 7) than that of Gold code, which bears 3-level bounds of 31, 15, -I and -17. The peak value of cross-correlation function of large set of Kasami, is larger than a small set of Kasami sequences and, in fact, is the same as for a set of Gold sequences. The peak value of cross-correlation function of Weil code has lower bounds (-15, 13) which is smaller than Gold and Large set of Kasami. Thus, small set of Kasami sequences is the most effective of binary sequences families mentioned above in terms of CCF characteristics.

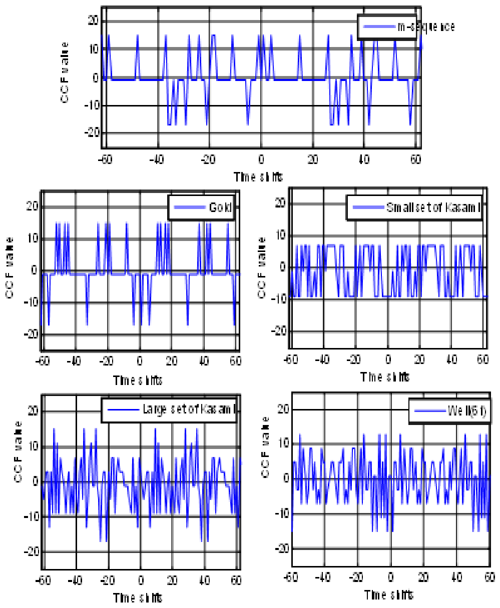

Fig. 5.CCF Characteristics of different pseudo-random sequences of length 63

B. *Evaluation of RAC, RCC and MF Properties*

The RAC, RCC and MF values are calculated for 64-bit length orthogonal sequences. The results are tabulated in Table 2.

Table 2. Aperiodic correlation and cross-correlation measurements for orthogonal sequences of length 64 bits.

Sequence	**R_{AC}**	**R_{CC}**	**MF**
m-sequence	0.4429	---------------	2.2577
Barker (13 bits)	0.0710	---------------	14.0833
Gold	0.9758	0.9849	1.0248
Small set of Kasami	0.7967	1.0003	1.2552
Large set of Kasami	0.9671	0.9979	1.0340
Weil (61bits)	0.9048	0.9815	1.1052

From the results obtained, it is observed that the Walsh-Hadamard code value R_{AC} is very high and the MF value is very low. Therefore, the spectre of these sequences do not have the characteristic of noise. The complementary Golay code takes the lowest R_{AC} values. On the other hand, its MF value is very high, which explains why its spectrum is flat and is similar to that of noise. So the complementary Golay code presents a better performance in comparison with the orthogonal Walsh-Hadamard and Gold sequences.

The R_{AC}, R_{CC} and mf values are calculated for other sequences of length 63 bits are given in Table 3 .

From the obtained results, it is observed that m-sequence and Barker sequences have low values of R_{AC}. On the other hand, the value of the MF is very high, which implies that the spectra of these sequences are flat (the amplitudes of the secondary peaks are very low). Small set of Kasami sequence have low values of R_{AC} , thus making the MF of these sequences high and therefore the corresponding spectra flat. On the other hand, large set of Kasami's sequences have R_{CC} values that are almost identical to those of Gold's sequences.

Table 3.Aperiodic correlation and cross-correlation measurements for sequences of length 64 bits

Sequence	**R_{AC}**	**R_{CC}**	**MF**
Walsh-Hadamard	10.8621	0.8583	0.0921
Orthogonal Gold	1.0259	1.0167	0.9748
complementary Golay	0.9758	1.0266	2.6982

V. Conclusion

In this paper, a comparative study is carried out to analyze the performance of different spreading sequences for a DS-CDMA system. Their performances were compared based on ACF, CCF, RAC, RCC and MF properties.

From the results obtained, it is observed that:

Small set of Kasami sequences is the most effective of binary sequences families mentioned above in terms of correlation measure(ACF, R_{AC}), but this set suffers from the limited number of sequences. Large set of Kasami sequences are the best in respect of the requirements, and are being considered for future CDMA based systems. For orthogonal sequences, orthogonal Gold sequences are a good alternative in terms of correlation, it possess better CCF characteristics as compared to all the three sequences Walsh, OVSF and complementary Golay sequences. Therefore, it is concluded that overall among orthogonal category, orthogonal Gold sequences and Golay complementary sequences are a better candidate in synchronous CDMA applications.

On the other hand, complementary Golay code presents a better performance of R_{AC}in comparison with the orthogonal Walsh-Hadamard and Gold sequences. Among all other sequence m_sequences and Barker sequences have low R_{AC} values. (amplitudes of the secondary peaks are very low). Also large set of Kasami sequences have values of R_{CC} that are almost identical to those of Gold's sequences.

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