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Multiple Access Chua Chaotic Communication system using Real Orthogonal Matrix Approach

Abstract-*An alternative to traditional Pseudo-Noise (PN)-Sequences, one-dimension (1D) orthogonal chaotic map sequences, and three dimensional (3D) continuous chaotic systems (x,y,z) are generated by orthonormal Gram-Schmidt process. A new Orthogonal Chua Chaotic Sequences $OCCS_s$-based Direct-Sequence/Spread-Spectrum-Code Division Multiple Access (DS/SS-CDMA) system is proposed. The proposed system combines the 3D Chua chaotic system with Real Orthogonal Matrix Approach (ROMA). Comparing to previous sequences, the $OCCS_s$ inherit all beneficial features of Chua's Circuit and ROMA scheme, such as the best correlation properties, higher capacity, Low Probability Interception (LPI), reliable security and good orthogonality. The three analytical Bit Error Rates (BERs) expressions for each orthogonal sequence $(\hat{x}_k, \hat{y}_k, \hat{z}_k)$ of $OCCS_s$ with three fingers Rake receiver under three-path Rayleigh fading channel with their spreading delays are derived. The correlation properties, capacity, randomness and security of $OCCS_s$ are evaluated. The simulations results show that the overall BER_s performances, capacity, and security of proposed $(\hat{x}_k, \hat{y}_k)$ of $OCCS_s$-based DS/SS-CDMA system outperform classical PN , 1D Logistic Map sequences and sequences of 3D Chua's circuit generated by orthonormal Gram-Schmidt process. The results also showed that at BER 10^{-4} for single and multi-user transmissions, the proposed $OCCS_s(\hat{x}_k)$ has achieved gains of 5 and 4 dB respectively in signal-to-noise (SNR) over traditional DS/SS-CDMA based on other sequences in Rayleigh fading channel.*

Keywords- *CDS/SS-CDMA, Chua's circuit, OCCSs, ROMA, Capacity, Security, BER.*

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1. Introduction

The DS/SS-CDMA system based on (PN)-sequences, like Orthogonal Variable Space Vector (OVSF), Hadamard, and Walsh codes, etc., is an efficient technology provides multiple access capability to different users to share simultaneously same bandwidth of frequency at same time [1]. The entire properties of PN-sequences play significant role in all performance and capacity of DS/SS-CDMA system. Unfortunately, the classical PN-sequences have flaws in their features [2], consequently, the system experienced many problems .The imperfect auto-correlation in multipath channel causes Inter-Symbol-Interference (ISI) and results in a synchronization problem [3]. The nonzero values of cross-correlation amongst other users' sequences can cause popping up an issue of Multiple Access Interference (MAI), which is considered a main limiting factor to system's BER performance and capacity [3]. The lower randomization and short complexity, and periodicity, they cause a weakened security trouble (High probability Interception (HPI)) and less number of generated sequences (lower capacity) [4]. However, many of designed schemes for generating chaotic sequences [5,6] based on 1D Logistic Map [3] consolidating with orthonormalization Gram-Schmidt process [7] have been shown that the BER's performance of chaos-sequences is almost approached to PN-sequences [8]. Therefore, in comparison to PN, and 1D Logistic Map sequences, the reproducing a new orthogonal spreading sequences by combining 3D Chua chaotic systems [9] with Real Orthogonal Matrix Approach (ROMA) [10] will configure Orthogonal Chua Chaotic Sequences $OCCS_s$ that possess the best auto-correlation (anti-ISI) [3,11] and lowest cross-correlation (anti-MAI) [12], and good anti-jamming [2]. Besides that the $OCCS_s$ inherit all features of 3D Chua's circuit, like sensitive dependence to initial conditions (x_0, y_0, z_0) and it's parameters (ρ , μ, γ), more dimensions (x, y, z), deterministic, wideband, no periodicity, and highest complexity and randomness and by merging with ROMA method, this will reproduce and re-create infinite uncorrelated $OCCS_s$ that cannot be decoded or intercepted by deciphers.

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Therefore, the capacity, of low probability of interception (LPI) and security of DS/SS-CDMA system are boosted [13,14]. All aforementioned chaotic properties have been qualified chaos-sequences to be applied in DS/SS-CDMA systems [15]. The enhanced properties of auto-correlation and cross-correlation of $OCCS_s$ are demonstrated by Merit Factor formula and W-index criteria respectively [6]. The highest randomization of $OCCS_s$ is experimented by National Institute of Standards and Technology (NIST) [16]. The mathematical expressions of BER performances and extra capacity of DS/SS-CDMA for each $(\hat{x}_k, \hat{y}_k, \hat{z}_k)$ of $OCCS_s$ are derived.

2. Chua Chaotic System Model

The Chua's circuit is a simple inexpensive electronic circuit (oscillator) invented in 1983 by Chua [17]. The three standard mathematical equations of Chua's model are described by [9]:

$$\begin{cases} \dot{x} = \rho\big(y - x - F(x)\big) \\ \dot{y} = x - y + z \\ \dot{z} = -\mu y - \gamma z \end{cases} \qquad (1)$$

As shown in Figure 1, $x, y,$ and z are chaotic variables states that describe chaotic behavior of the Chua's model. $F(x) = b\,x + \frac{1}{2}(a - b)(|x + 1| - |x - 1|)$, represents piecewise-linear function that plays a significant part in the chaotic Chua's circuit mechanism, (ρ,μ,γ,a,b) are Chua circuit's parameters with a= -1.37067, b= -0.732101, ρ=10,μ=18.605, and $\gamma=6.7781166 \times 10^{-6}$ [9].

3. Real Orthogonal Matrix Approach (ROMA)

Already the ROMA has been employed in [10,18] to construct Multi-Input Multi-Output (MIMO) systems. The ROMA states that any orthogonal matrix [A] of size m is an m×m orthogonal matrix with indeterminants $A_1 \pm A_2 \pm, \ldots \pm A_m$. Actually, the orthogonality is valid only if m= 2, 4, or 8 [10]. For size of m=2,$ROMA_{(m\times m)}$ can be given by:

$$[A] = \begin{bmatrix} A_1 & A_2 \\ -A_2 & A_1 \end{bmatrix}_{2\times 2} \qquad (2)$$

Now, if we denote $C_i, i = 1,2$, as the i^{th} columns of [A], in Eq.(2), it is easy to show that: $\langle C_1, C_2 \rangle = 0,$ where $\langle C_i, C_j \rangle = \sum_{l=1}^{n=2} (C_i)_l\,(C_j)_l$, $i \neq j$, is the inner product of columns C_i and C_j.Therefore, the columns C_1 and C_2 are orthogonal to each other.

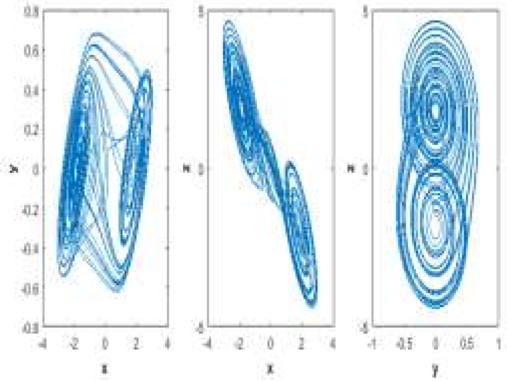

Figure1: Chua's attractors with parameters values: ρ = 10,μ = 18.605,$\gamma = 6.7781166 \times 10^{-6}$, a= -1.37067, b= -0.732101, and $x_0 = y_0 = z_0 = 0.08839$.

4. Design of the Proposed ($OCCS_s$) using $ROMA_{(2\times2)}$

As depicted in Fig.2, the Chua's entity produces three real continuous nonorthonormal chaotic sequences $\{x_k, y_k, z_k\}_{k=1}^{\infty}$. Naturally, these $\{x_k, y_k, z_k\}_{k=1}^{\infty}$ acquire all previous mentioned chaotic properties of Chua that DS/SS-CDMA system is required, but inappropriately, they are not orthogonal. For this reason, we proposed a novel scheme that combines 3D Chua's circuit and $ROMA_{(2\times2)}$ to reconstitute new orthogonal sequences. The proposed new scheme would set forth starting points to develop new ideas that support Multiplexing systems. As shown in section (2), here, ROMA $_{(2\times2)}$ is applied to every chaotic sample in each sequence $\{x_k, y_k, z_k\}_{k=1}^{\infty}$, i.e., the samples of $x_k=\{x_1,x_2,\ldots,x_\infty\}$, $y_k=\{y_1,y_2,\ldots,y_\infty\}$,and $z_k=\{z_1,z_2,\ldots,z_\infty\}$ are symbolized into equivalent locations in $ROMA_{(2\times2)}$ such that $\mathbf{x_1} \rightarrow \mathbf{A_1}$, $\mathbf{-x_2} \rightarrow \mathbf{A_2}$,..., and so on. As seen in section (3), this conversion process will form three orthogonal chaotic matrices according to sequence type $\{ROMA(\hat{x}_k, \hat{y}_k, \hat{z}_k)_{(m\times m)}\}_{k=1}^{m=2}$ .The columns or rows of $ROMA(\hat{x}_k, \hat{y}_k, \hat{z}_k)_{(2\times2)}$ are considered new orthogonal spreading sequences $OCCS_s$ according to sequence type $\left\{OCCS_S(\hat{x}_k^{(i)}, \hat{y}_k^{(i)}, \hat{z}_k^{(i)})\right\}_{k,i=1}^{\beta,N}$ where β, T_s, T_c, and N are the spreading factor, time duration of symbol ,time duration of chaotic sample and number of users, respectively. The new sequences $\left\{OCCS_S(\hat{x}_k^{(i)}, \hat{y}_k^{(i)}, \hat{z}_k^{(i)})\right\}_{k,i=1}^{\beta,N}$ have superior characteristics against the classical PN and 1D chaotic sequences [19,20] generated by orthonormalization Gram-Schmidt process or $ROMA_{(2\times2)}$, as will be proved in the next sections [7,8,9,11].

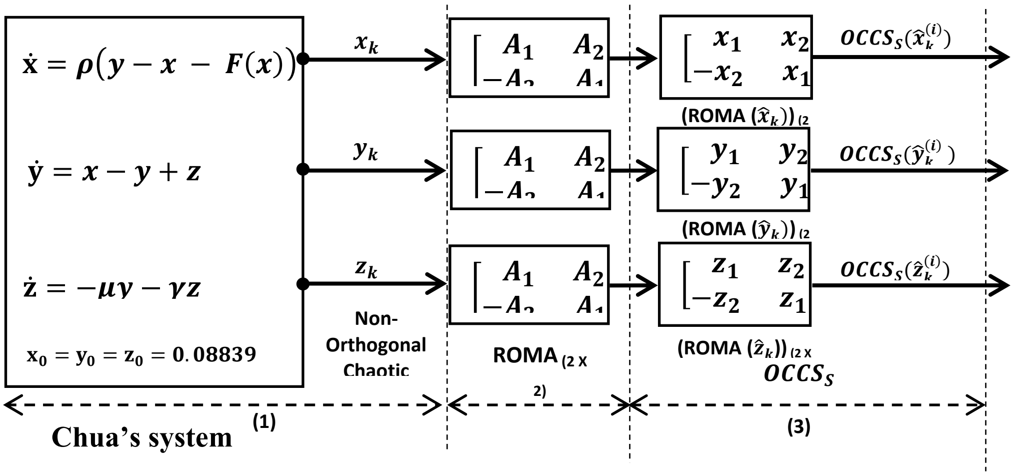

Figure 2:The $OCCS_s$ based on $ROMA_{(2\times2)}$

5. The Structure of the Proposed $OCCS_s$ based-CDS/SS-CDMA System

Figure 3 shows the block diagram of asynchronous uplink$\{OCCS_S(\hat{x}_k^{(i)},\hat{y}_k^{(i)},\hat{z}_k^{(i)})\}_{k,i=1}^{\beta,N}$ based-DS/SS-CDMA system associated with QPSK modulation. The DS/SS-CDMA consists of N-user's transmitter and N-user's receiver, each transmitter, like i^{th} user involves non-binary independent symbols source information $d^{(i)} \in \{0,1,2,3\}$ modulated by QPSK into complex-value $^*d^{(i)} \in \{\pm\frac{1}{\sqrt{2}} \pm j\frac{1}{\sqrt{2}}\}$, a single $OCCS_s$ generator reproduces three sorts of $\{\hat{x}_k^{(i)},\hat{y}_k^{(i)},\hat{z}_k^{(i)}\}_{k,i=1}^{\beta,N}$ chaotic sequences for every user to spread $^*d^{(i)}$ into $^*s_k^{(i)}$ by multiplier circuit (spreader), as given in Eq.(3), where $*$ is complex conjugate operator. To avert sending undesirable dc power, the average value for each chaotic sequence is made equivalent to zero $\{E[\hat{x}_k^{(i)}] = E[\hat{y}_k^{(i)}] = E[\hat{z}_k^{(i)}]\}_{i=1}^{N} = 0$.

$$^*\hat{s}_k^{(i)} = {}^*d^{(i)}\,\hat{x}_k^{(i)} \qquad (3)$$

The spread complex signals $^*\hat{s}_k^{(i)}$ of each user are then collected into $\hat{s}_k^*$ as given in Eq.(4), and sent through dispersed channel. The inverse operations at receivers (Despreading, Integrating and Dumping, QPSK Demodulator, and same copies of $\{OCCS_S(\hat{x}_k^{(i)},\hat{y}_k^{(i)},\hat{z}_k^{(i)})\}_{k,i=1}^{\beta,N}$ are existed and accurately synchronized with their counterparts at transmitters,) all are used to recover desired data $\{\tilde{d}^{(i)}\}_{i=1}^{N}$ for each user.

$$\hat{s}_k^* = \sum_{i=1}^{N} {}^*\hat{s}_k^{(i)} \qquad (4)$$

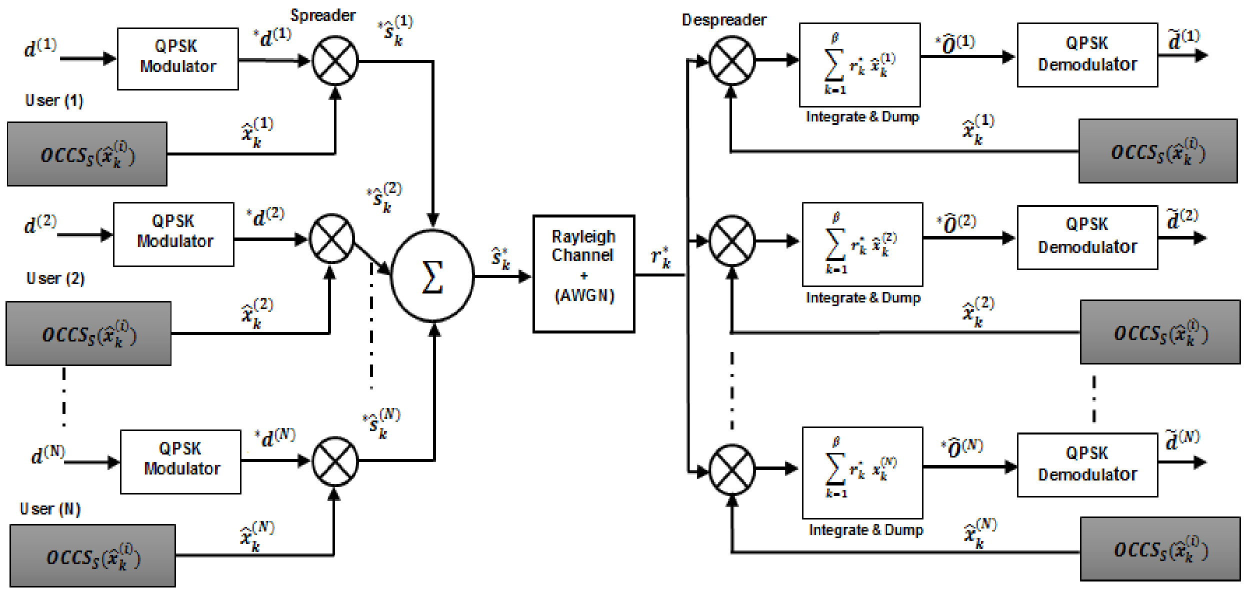

Figure 3: The CDS/SS-CDMA system based on $OCCS_s(\hat{x}_k^{(i)})$.

6. Deriving BER Probabilities under Multipath Rayleigh Fading Channel Using Gaussian Approximation (GA)

To derive theoretical BER^j probabilities of j^{th} user for each $\left\{OCCS_S(\hat{x}_k^{(j)},\hat{y}_k^{(j)},\hat{z}_k^{(j)})\right\}_{k=1}^{\beta}$ in DS/SS-CDMA system over Rayleigh channel, consider the transmitted complex signals $\hat{s}_k^*$ are affected by three paths Rayleigh fading channel as shown in Figure 4, with time response channel is given by [21]:

$$h(t) = \alpha_1\delta(t) + \alpha_2\delta(t-\tau_1) + \alpha_3\delta(t-\tau_2) \quad (5)$$

Then the output Rayleigh channel r_k^* with noise ξ_k can be described by:

$$r_k^* = \alpha_1\,\hat{s}_k^* + \alpha_2\,\hat{s}_{k-\tau_1}^* + \alpha_3\,\hat{s}_{k-\tau_2}^* + \xi_k \quad (6)$$

Where α_1, α_2 , and α_3 are independent variables of Rayleigh distribution fading channel. τ_1, and τ_2 are time delays of second and third path related to first path, respectively, with ($0 < \tau_1 < \tau_2 < \beta$) , and ξ_k is an amount of adding noise into $\hat{s}_k^*$ with zero mean and variance ($N_o/2$).

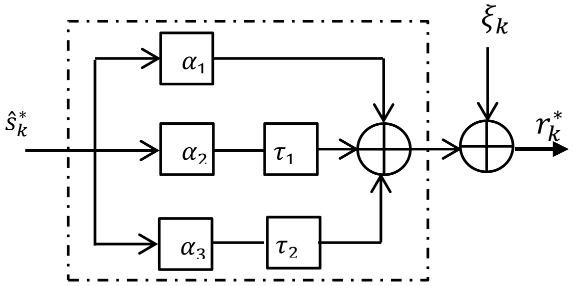

Figure 4: Three multipaths Rayleigh fading channels.

As depicted in Figure 5 for demodulation process of jth user, each autonomous receiver utilizes basically a simple correlator (Rake demodulator) [22,23] with three fingers based on one of spreading sequences synchronized with desired transmitter. Assume that the fading paths' parameters are so slow that α_1, α_2, and α_3 can be precisely calculated.

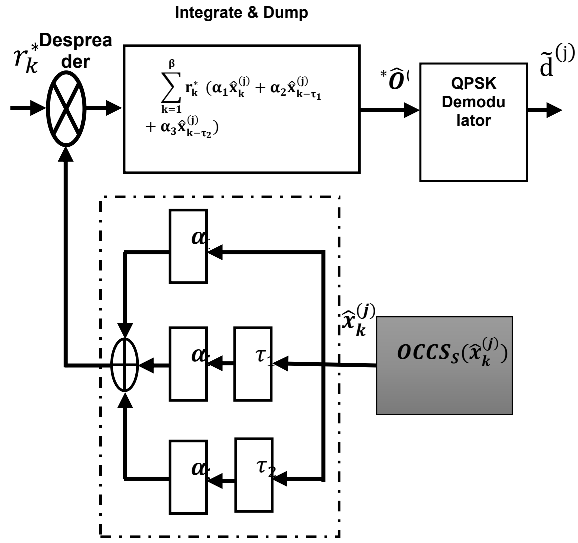

Figure 5: Components of demodulation process.

At Rake demodulator, $\hat{x}_k^{(j)}$ and their delayed versions $\hat{x}_{k-\tau_1}^{(j)}$and $\hat{x}_{k-\tau_2}^{(j)}$ are weighted by α_1, α_2, and α_3, respectively. Therefore, real and imaginary values of decision variable $\tilde{d}^{(j)}$ for output correlator $^*\hat{O}^{(j)}$ can be given by [24]:

$$\tilde{d}^{(j)} = \begin{cases} +1, \text{if } \Re(\,^*\hat{O}^{(j)}) & > 0 \\ -1, \text{if } \Re(\,^*\hat{O}^{(j)}\,) & \leq 0 \end{cases} \quad (7)$$

Where $\Re(.)$ is real operator, and

$$\hat{O}^{(j)} = \Re\left(\sum_{k=1}^{\beta} r_k^*\left(\alpha_1\hat{x}_k^{(j)} + \alpha_2\hat{x}_{k-\tau_1}^{(j)} + \alpha_3\hat{x}_{k-\tau_2}^{(j)}\right)\right)$$

$$\hat{O}^{(j)} = A + B + C + D \quad (8)$$

Where,

$$\begin{cases} A = d^{(j)}\sum_{k=1}^{\beta}\alpha_1^2(\hat{x}_k^{(j)})^2 + \sum_{i=1,\,i\neq j}^{N} d^{(i)}\sum_{k=1}^{\beta}\alpha_1^2(\hat{x}_k^{(i)})(x_k^{(j)}) + d^{(j)}\sum_{k=1}^{\beta}\alpha_1\alpha_2\hat{x}_k^{(j)}\hat{x}_{k-\tau_1}^{(j)} + \cdots \\ \quad + \sum_{i=1,\,i\neq j}^{N} d^{(i)}\sum_{k=1}^{\beta}\alpha_1\alpha_2\hat{x}_k^{(i)}\hat{x}_{k-\tau_1}^{(j)} + d^{(j)}\sum_{k=1}^{\beta}\alpha_1\alpha_3\hat{x}_k^{(j)}\hat{x}_{k-\tau_2}^{(j)} + \sum_{i=1,\,i\neq j}^{N} d^{(i)}\sum_{k=1}^{\beta}\alpha_1\alpha_3\hat{x}_k^{(i)}\hat{x}_{k-\tau_2}^{(j)} \\ B = d^{(j)}\sum_{k=1}^{\beta}\alpha_1\alpha_2\hat{x}_{k-\tau_1}^{(j)}\hat{x}_k^{(j)} + \sum_{i=1,\,i\neq j}^{N} d^{(i)}\sum_{k=1}^{\beta}\alpha_1\alpha_2\hat{x}_{k-\tau_1}^{(i)}\hat{x}_k^{(j)} + d^{(j)}\sum_{k=1}^{\beta}\alpha_2^2\left(\hat{x}_{k-\tau_1}^{(j)}\right)^2 + \cdots \\ \quad + \sum_{i=1,\,i\neq j}^{N} d^{(i)}\sum_{k=1}^{\beta}\alpha_2^2(\hat{x}_{k-\tau_1}^{(i)})\left(\hat{x}_{k-\tau_1}^{(j)}\right) + d^{(j)}\sum_{k=1}^{\beta}\alpha_2\alpha_3\hat{x}_{k-\tau_1}^{(j)}\hat{x}_{k-\tau_2}^{(j)} + \sum_{i=1,\,i\neq j}^{N} d^{(i)}\sum_{k=1}^{\beta}\alpha_2\alpha_3\hat{x}_{k-\tau_1}^{(i)}\hat{x}_{k-\tau_2}^{(j)} \\ C = d^{(j)}\sum_{k=1}^{\beta}\alpha_1\alpha_3\hat{x}_{k-\tau_2}^{(j)}\hat{x}_k^{(j)} + \sum_{i=1,\,i\neq j}^{N} d^{(i)}\sum_{k=1}^{\beta}\alpha_1\alpha_3\hat{x}_{k-\tau_2}^{(i)}\hat{x}_k^{(j)} + d^{(j)}\sum_{k=1}^{\beta}\alpha_2\alpha_3\hat{x}_{k-\tau_2}^{(j)}\hat{x}_{k-\tau_1}^{(j)} + \cdots \\ \quad + \sum_{i=1,\,i\neq j}^{N} d^{(i)}\sum_{k=1}^{\beta}\alpha_2\alpha_3\hat{x}_{k-\tau_2}^{(i)}\hat{x}_{k-\tau_1}^{(j)} + d^{(j)}\sum_{k=1}^{\beta}\alpha_3^2\left(\hat{x}_{k-\tau_2}^{(j)}\right)^2 + \sum_{i=1,\,i\neq j}^{N} d^{(i)}\sum_{k=1}^{\beta}\alpha_3^2\,\hat{x}_{k-\tau_2}^{(i)}\hat{x}_{k-\tau_2}^{(j)} \\ D = \sum_{k=1}^{\beta}(\alpha_1\xi_k\hat{x}_k^{(j)} + \alpha_2\xi_k\hat{x}_{k-\tau_1}^{(j)} + \alpha_3\xi_k\hat{x}_{k-\tau_2}^{(j)}) \end{cases} \quad (9)$$

However, to compute exact BER probability, consider effects of (ISI) between same types of sequences. According to the central limit theory and for stationary variables [25], can obtain the following statistics properties: $\left\{E\left[\hat{x}_k^{(i)}\hat{x}_{k-\tau_1}^{(j)}\right] = E\left[\hat{x}_k^{(i)}\hat{x}_{k-\tau_2}^{(j)}\right] = E\left[\hat{x}_k^{(i)}\hat{x}_k^{(j)}\right] = 0\right\}_{i=1}^{N}, i \neq j,$ and $\left\{E\left[\hat{x}_k^{(i)}\hat{x}_{k-\tau_1}^{(j)}\right] = E\left[\hat{x}_k^{(i)}\hat{x}_{k-\tau_2}^{(j)}\right] = E\left[\hat{x}_k^{(i)}\hat{x}_k^{(j)}\right] = E\left[(\hat{x}_k^{(j)})^2\right] = P_x\right\}_{i=1}^{N}, \; i = j$. Where E[.], and P_x are expectation operator and the average power of the $OCCS_s(\hat{x}_k^{(j)})$ respectively .As assumed before $E\left[\hat{x}_k^{(i)}\right]_{i=1}^{N} = 0$ and $E[\xi_k] = 0$, then E[.] values of Eqs.(9) when $d^{(j)} = +1$ can be calculated by:

$$\begin{aligned}
&E\left[\left(A|(\alpha_1,\alpha_2,\alpha_3,d^{(j)}=+1\right)\right] = (\alpha_1^2+\alpha_1\alpha_2+\alpha_1\alpha_3)\beta\, E\left[(\hat{x}_k^{(j)})^2\right] = (\alpha_1^2+\alpha_1\alpha_2+\alpha_1\alpha_3)\beta P_x \\
&E\left[\left(B|(\alpha_1,\alpha_2,\alpha_3,d^{(j)}=+1\right)\right] = (\alpha_2^2+\alpha_1\alpha_2+\alpha_2\alpha_3)\beta\, E\left[(\hat{x}_k^{(j)})^2\right] = (\alpha_2^2+\alpha_1\alpha_2+\alpha_2\alpha_3)\beta P_x \\
&E\left[\left(C|(\alpha_1,\alpha_2,\alpha_3,d^{(j)}=+1\right)\right] = (\alpha_3^2+\alpha_1\alpha_3+\alpha_2\alpha_3)\beta\, E\left[(\hat{x}_k^{(j)})^2\right] = (\alpha_3^2+\alpha_1\alpha_3+\alpha_2\alpha_3)\beta P_x \\
&E\left[\left(D|(\alpha_1,\alpha_2,\alpha_3,d^{(j)}=+1\right)\right] = 0
\end{aligned} \tag{10}$$

By substituting Eqs.(10) in Eq.(8), the overall expectation value is:

$$E\left[\left(\hat{O}^{(j)}|(\alpha_1,\alpha_2,\alpha_3,d^{(j)}=+1\right)\right] = (\alpha_1+\alpha_2+\alpha_3)^2\beta\, P_x \tag{11}$$

The variances of Eqs.(9) can be computed by applying the following formula [26, 27]:

$$\begin{aligned}
\mathrm{var}\left[\left(\hat{O}^{(j)}|d^{(j)}=+1\right)\right] &= \beta\,\mathrm{var}\left[(\hat{x}_k^{(j)})^2\right] + \sum_{k=1}^{\beta}\sum_{m=1,m\neq k}^{\beta}\mathrm{cov}\left[(\hat{x}_k^{(j)})^2,(\hat{x}_m^{(j)})^2\right] + \cdots \\
&+ \beta\, E\left[(\hat{x}_k^{(j)})^2\right]\sum_{i=1,i\neq j}^{N}E\left[(\hat{x}_k^{(i)})^2\right] + \sum_{i=1,i\neq j}^{N}\sum_{k=1}^{\beta}\sum_{m=1,m\neq k}^{\beta}E\left[(\hat{x}_k^{(i)})(\hat{x}_m^{(i)})\right]E\left[(\hat{x}_k^{(j)})(\hat{x}_m^{(j)})\right] + \frac{N_o}{2}\beta
\end{aligned} \tag{12}$$

Where var[.] is variance operator and $\mathrm{cov}[\psi,\nu]$ is covariance of ψ , ν and determined by:

$$cov[\psi,\nu] = E[\psi\,\nu] - E[\psi]E[\nu] \tag{13}$$

According to [27], the covariance and expected values of uncorrelated and orthogonal variables will be equivalent to zero, so the orthogonal chaotic signals $(\hat{x}_k^{(j)})$ generated by $OCCS_s(\hat{x}_k^{(j)})$ will be restricted by the following formula:

$$\begin{aligned}
&\mathrm{cov}\left[(\hat{x}_k^{(j)})^2,(\hat{x}_m^{(j)})^2\right] = 0\,, \quad k \neq m \\
&E\left[(\hat{x}_k^{(j)})^2,(\hat{x}_m^{(j)})^2\right] = 0\,, \quad k \neq m
\end{aligned} \tag{14}$$

Therefore, the second and fourth terms of Eq.(12) will be eliminated, and writing the average power as:

$$\left\{E\left[\left(\hat{x}_{k-\tau_1}^{(j)}\right)^2\right] = E\left[\left(\hat{x}_{k-\tau_2}^{(j)}\right)^2\right] = E\left[(\hat{x}_k^{(j)})^2\right] = P_x\right\}_{j=1}^{N} \tag{15}$$

By applying Eq.(12) and substituting Eqs.{13,14} in Eqs.(9), the var[.] values of Eqs.(9) can be calculated by :

$$\begin{aligned}
&\mathrm{var}\left[\left(A|(\alpha_1,\alpha_2,\alpha_3,d^{(j)}=+1\right)\right] = (\alpha_1^4+\alpha_1^2\alpha_2^2+\alpha_1^2\alpha_3^2)\left[\beta\,\mathrm{var}\left[(\hat{x}_k^{(j)})^2\right] + (N-1)\beta\, P_x^2\right] \\
&\mathrm{var}\left[\left(B|(\alpha_1,\alpha_2,\alpha_3,d^{(j)}=+1\right)\right] = (\alpha_2^4+\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2)\left[\beta\,\mathrm{var}\left[\left(\hat{x}_{k-\tau_1}^{(j)}\right)^2\right] + (N-1)\beta\, P_x^2\right] \\
&\mathrm{var}\left[\left(C|(\alpha_1,\alpha_2,\alpha_3,d^{(j)}=+1\right)\right] = (\alpha_3^4+\alpha_1^2\alpha_3^2+\alpha_2^2\alpha_3^2)\left[\beta\,\mathrm{var}\left[\left(\hat{x}_{k-\tau_2}^{(j)}\right)^2\right] + (N-1)\beta\, P_x^2\right] \\
&\mathrm{var}\left[\left(D|(\alpha_1,\alpha_2,\alpha_3,d^{(j)}=+1\right)\right] = (\alpha_1^2+\alpha_2^2+\alpha_3^2)\frac{N_o}{2}\beta P_x
\end{aligned} \tag{16}$$

By substituting Eqs.(16) in Eq. (8), the overall variance value is given by:

$$\begin{aligned}
\mathrm{var}\left[\left(\hat{O}^{(j)}|(\alpha_1,\alpha_2,\alpha_3,d^{(j)}=+1\right)\right] &= (\alpha_1^2+\alpha_2^2+\alpha_3^2)^2\left[\beta\,\mathrm{var}\left[(\hat{x}_k^{(j)})^2\right] + (N-1)\beta\, P_x^2\right] + \cdots \\
&\ldots + (\alpha_1^2+\alpha_2^2+\alpha_3^2)\frac{N_o}{2}\beta P_x
\end{aligned} \tag{17}$$

For brevity: writing the Φ as:

$$\Phi_x = \left\{\frac{var\left[(\hat{x}_k^{(i)})^2\right]}{P_x^2} = \frac{var\left[\left(\hat{x}_{k-\tau_1}^{(i)}\right)^2\right]}{P_x^2} = \cdots = \frac{var\left[\left(\hat{x}_{k-\tau_2}^{(i)}\right)^2\right]}{P_x^2}\right\}_{i=1}^{N}, \tag{18}$$

Where Φ is variation relying on the type of orthogonal chaotic sequences $\left\{OCCS_S(\hat{x}_k^{(i)},\hat{y}_k^{(i)},\hat{z}_k^{(i)})\right\}_{k,i=1}^{\beta,N}$ .And in same procedures, calculate $E\left[\left(\hat{O}^{(j)}|(\alpha_1,\alpha_2,\alpha_3,d^{(j)}=-1\right)\right]$ and $var\left[\left(\hat{O}^{(j)}|(\alpha_1,\alpha_2,\alpha_3,d^{(j)}=-1\right)\right]$ of Eq.(8) and confirm that:

$$\begin{cases}E\left[\left(\hat{O}^{(j)}|(\alpha_1,\alpha_2,\alpha_3,d^{(j)}=+1\right)\right] = -E\left[\left(\hat{O}^{(j)}|(\alpha_1,\alpha_2,\alpha_3,d^{(j)}=-1\right)\right] \\ var\left[\left(\hat{O}^{(j)}|(\alpha_1,\alpha_2,\alpha_3,d^{(j)}=+1\right)\right] = var\left[\left(\hat{O}^{(j)}|(\alpha_1,\alpha_2,\alpha_3,d^{(j)}=-1\right)\right]\end{cases} \tag{19}$$

Assume that $\hat{O}^{(j)}$ has Gaussian distribution, then the conditional BER_{GA}^{j} probability based on (GA) can be given by [7,28]:

$$BER_{GA}^{j} = \frac{1}{2}\mathrm{Prob}\left(\hat{O}^{(j)} \leq |d^{(j)}=+1\right) + \frac{1}{2}\mathrm{Prob}\left(\hat{O}^{(j)} > |d^{(j)}=-1\right) \tag{20}$$

As in Eq.(19),the $\mathrm{Prob}\left(\hat{O}^{(j)} \leq |d^{(j)}=+1\right) = \mathrm{Prob}\left(\hat{O}^{(j)} > |d^{(j)}=-1\right) =$

$$\frac{1}{2}\mathrm{erfc}\left(\frac{E\left[\left(\hat{O}^{(j)}|d^{(j)}=+1\right)\right]}{\sqrt{2\mathrm{var}\left[\left(\hat{O}^{(j)}|d^{(j)}=+1\right)\right]}}\right) \tag{21}$$

Where erfc(.) is complementary error function defined by [28]:

$$erfc(\theta) \equiv \frac{2}{\pi}\int_{\theta}^{\infty}\exp(-t)\; dt \tag{22}$$

Then, both Eqs.{19, 21} simplify Eq. (20) to:

$$\mathrm{Prob}\left(\hat{O}^{(j)} \leq |d^{(j)}=+1\right) = \frac{1}{2}\mathrm{erfc}\left(\frac{E\left[\left(\hat{O}^{(j)}|d^{(j)}=+1\right)\right]}{\sqrt{2\mathrm{var}\left[\left(\hat{O}^{(j)}|d^{(j)}=+1\right)\right]}}\right) \tag{23}$$

Finally, by substituting Eqs.{11,17, and 18} in Eq.(23),we obtained the final theoretical BER_{GA}^{j} probability of DS/SS-CDMA system based on one out of each $\left\{OCCS_S(\hat{x}_k^{(j)},\hat{y}_k^{(j)},\hat{z}_k^{(j)})\right\}_{k=1}^{\beta}$ sequences:

$$BER^{j}_{GA-(\hat{x}^{(j)}_k)} = \frac{1}{2} erfc\left(\left[\frac{2\alpha_r \Phi_x}{\beta} + \frac{2\alpha_r (N-1)}{\beta} + \left(\frac{\alpha_o E_{bx}}{N_0}\right)^{-1}\right]^{-1/2}\right)$$
$$BER^{j}_{GA-(\hat{y}^{(j)}_k)} = \frac{1}{2} erfc\left(\left[\frac{2\alpha_r \Phi_y}{\beta} + \frac{2\alpha_r (N-1)}{\beta} + \left(\frac{\alpha_o E_{by}}{N_0}\right)^{-1}\right]^{-1/2}\right)$$
$$BER^{j}_{GA-(\hat{z}^{(j)}_k)} = \frac{1}{2} erfc\left(\left[\frac{2\alpha_r \Phi_z}{\beta} + \frac{2\alpha_r (N-1)}{\beta} + \left(\frac{\alpha_o E_{bz}}{N_0}\right)^{-1}\right]^{-1/2}\right) \quad (24)$$

Where $\alpha_r = \frac{(\alpha_1^2+\alpha_2^2+\alpha_3^2)^2}{(\alpha_1+\alpha_2+\alpha_3)^4}$, $\alpha_o = \frac{(\alpha_1+\alpha_2+\alpha_3)^4}{(\alpha_1^2+\alpha_2^2+\alpha_3^2)}$ and $E_{bx} = \beta P_x, E_{by} = \beta P_y$ and $E_{bz} = \beta P_z$ are non–constant energy per bit of each sequence $\left\{OCCS_S(\hat{x}^{(j)}_k, \hat{y}^{(j)}_k, \hat{z}^{(j)}_k)\right\}^{\beta}_{k=1}$ respectively. In general, the first term of Eqs.(24) is variation Φ of orthogonal chaotic sequence and the second term is interfering signals affecting on the correlator, while the third term represents noise component. It can be inferred from Eqs.(24) ,the BER_s performance of proposed $OCCSs(\hat{x}_k, \hat{y}_k, \hat{z}_k)$-based DS/SS-CDMA system for large spread factor $\beta = 128$,can be disregarding the numbers of users N and variation Φ ,that means unique strongest features do not exist in other traditional spreading sequences based-DS/SS-CDMA systems, so the Eqs.(24) can be approximated to :

$$BER^{j}_{GA-(\hat{x}^{(j)}_k)} \cong \frac{1}{2} erfc\left(\left[\left(\frac{\alpha_o E_{bx}}{N_0}\right)^{-1}\right]^{-1/2}\right)$$
$$BER^{j}_{GA-(\hat{y}^{(j)}_k)} \cong \frac{1}{2} erfc\left(\left[\left(\frac{\alpha_o E_{by}}{N_0}\right)^{-1}\right]^{-1/2}\right) \quad (25)$$
$$BER^{j}_{GA-(\hat{z}^{(j)}_k)} \cong \frac{1}{2} erfc\left(\left[\left(\frac{\alpha_o E_{bz}}{N_0}\right)^{-1}\right]^{-1/2}\right)$$

And deriving Eq.(24) for number of users (N) (capacity of system) is resulting:

$$N_x = \frac{\beta}{2\alpha_r\left(erfc^{-1}\left(2 * BER^{j}_{GA-(x^{(j)}_k)}\right)\right)^2} + 1 - \Phi_x - \frac{2\alpha_r}{\beta}\left(\frac{\alpha_o E_{bx}}{N_0}\right)^{-1}$$
$$N_y = \frac{\beta}{2\alpha_r\left(erfc^{-1}\left(2 * BER^{j}_{GA-(\hat{y}^{(j)}_k)}\right)\right)^2} + 1 - \Phi_y - \frac{2\alpha_r}{\beta}\left(\frac{\alpha_o E_{by}}{N_0}\right)^{-1} \quad (26)$$
$$N_z = \frac{\beta}{2\alpha_r\left(erfc^{-1}\left(2 * BER^{j}_{GA-(\hat{z}^{(j)}_k)}\right)\right)^2} + 1 - \Phi_z - \frac{2\alpha_r}{\beta}\left(\frac{\alpha_o E_{bz}}{N_0}\right)^{-1}$$

7.The Results of Correlation Properties Tests

To assess the goodness of auto-correlation properties of $OCCS_s(\hat{x}_k, \hat{y}_k, \hat{z}_k)$, OVSF, and Logistic Map, the formula called Merit Factor (MF) [6] is utilized. Suppose $\hat{x}^{(i)}_k$ sequence with length β and aperiodic auto-correlation is given by:

$$C_{i,i}(\tau) = \begin{cases} \sum_{k=1}^{\beta-1-m} \hat{x}^{(i)}_k \, \hat{x}^{(i)}_{*k+m} & 0 \le m < \beta - 1 \\ \sum_{k=1}^{\beta-1+m} \hat{x}^{(i)}_{k-m} \, \hat{x}^{(i)}_{*k} & 1 - \beta \le m < 0 \\ 0 & |m| \ge \beta \end{cases} \quad (27)$$

Then, (MF) is denoted by:

$$MF = \frac{C_{i,i}{}^2(0)}{2\sum_{\tau=1}^{\beta-1}|C_{i,i}(\tau)|^2} \quad (28)$$

The large values of MF imply that the sequence possesses best auto-correlation function [6]. As depicted in Figure 6 and in comparison with $OCCS_s(\hat{z}_k)$,OVSF, and Logistic Map, the $OCCS_s(\hat{x}_k, \hat{y}_k)$ have large scale probability of MF values and possess Kronecker delta function. Such sequences are enabling the system to synchronize a various codes smoothly at receivers. The W-index given by Eq.(29) [6] is a measure of MAI in multi-user environment is exploited to evaluate cross-correlation properties. The large value W-index is less MAI in multiplexing systems [6]. As shown in Figure 7, the $OCCSs(\hat{x}_k, \hat{y}_k)$ have large values W-index contrast to $OCCSs(\hat{z}_k)$, OVSF, and Logistic Map. Therefore, applying these sequences will reduce MAI, increase capacity, and boost the performance of DS/SS-CDMA system.

$$W = \frac{2}{\frac{1}{|C_{j,j}(0)|^2}\sum_{\tau=1-\beta}^{\beta-1} 2E^{i\neq j}_{\hat{x}_i,\hat{x}_j}\left[|C_{i,j}(\tau)|^2\right] + \cdots} \cdots$$
$$\cdots \frac{1}{\ldots + 3\beta * Re\left\{E^{i\neq j}_{\hat{x}_i,\hat{x}_j}\left[C_{i,j}(\tau) \; {}^*C_{i,j}(\tau+1)\right]\right\}} \quad (29).$$

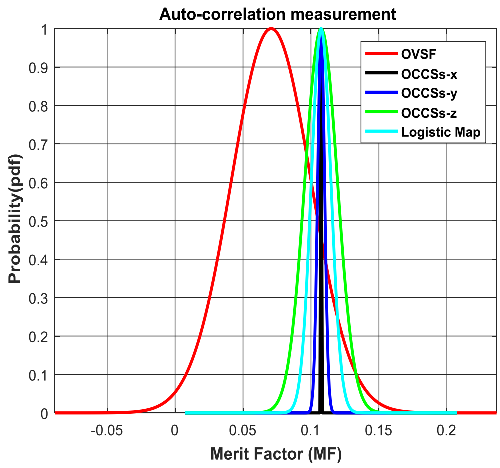

Figure 6: Auto-correlation properties measured by Merit Factor method.

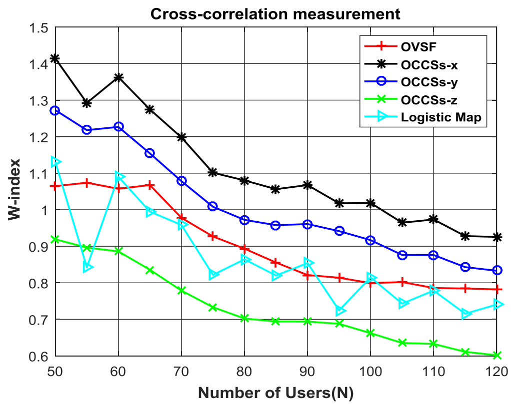

Figure 7: Cross-correlation properties measured by

W-index method.

8. The Results of Capacity Tests

According to Eqs.(26), Figure 8 exhibits the relationship between given BERs and capacity (number of users) of DS/SS-CDMA system .It is obviously that capacity of system based on $OCCS_s$ $(\hat{x}_k, \hat{y}_k)$ exceeds $OCCS_s(\hat{z}_k)$,OVSF ,and Logistic Map, e.g. at signal-to-noise ratio SNR=20 dB and BER=10^{-4} the $OCCS_s(\hat{x}_k, \hat{y}_k)$ scheme able to achieve 21 and 12 users more than OVSF, and 16 and 7 users more than Logistic Map, respectively. The low capacity of $OCCS_s(\hat{z}_k)$ result of its low values of W-index.

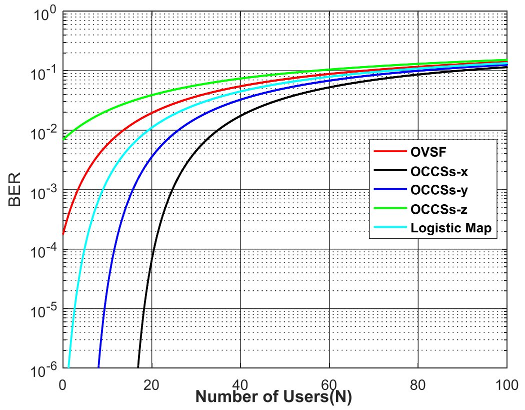

Figure 8: Capacity of DS/SS-CDMA based on $OCCS_s$.

9. The Results of Security Tests

The security level of DS/SS-CDMA system is determined by complexity of generator system for spreading sequences, which in turn-based on a source type and its dimensions. Therefore, the choosing of a suitable source type with its dimensions will result in superior complex spreading sequences accompanied by highest randomness and entropy. Since, the flow type chaotic systems (Chua's circuit) with 3D has more complexity and randomness than its counterparts with similar dimensions (chaotic Map) and PN-sequences (OVSF), therefore, the proposed $OCCS_s$ will acquire all security's benefits of Chua's system and ROMA scheme such as, anti-jamming ability, low probability detection and interception [2,14]. According to entropy Eqs.{30,31,32} and (NIST) randomness tests [16] and as shown in Figure 9, and Table 1, respectively, the $OCCS_s(\hat{x}_k, \hat{y}_k)$ have highest entropy values and P-values of randomness.

$$H_x = -\sum_{i=1}^{N}\sum_{k=1}^{\beta} P\left(\hat{x}_k^{(i)}\right) log\left(P\left(\hat{x}_k^{(i)}\right)\right) \quad (30)$$

$$H_y = -\sum_{i=1}^{N}\sum_{k=1}^{\beta} P\left(\hat{y}_k^{(i)}\right) log\left(P\left(\hat{y}_k^{(i)}\right)\right) \quad (31)$$

$$H_z = -\sum_{i=1}^{N}\sum_{k=1}^{\beta} P\left(\hat{z}_k^{(i)}\right) log\left(P\left(\hat{z}_k^{(i)}\right)\right) \quad (32)$$

Where H_x , H_y, and H_z are entropies of $\hat{x}_k^{(i)}$, $\hat{y}_k^{(i)}$, and $\hat{z}_k^{(i)}$ sequences respectively.

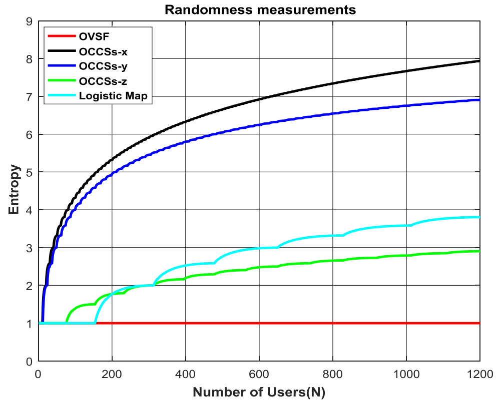

Figure 9: Entropy of various spreading sequences.

Additionally, the security level is relied also on three fundamental factors. These are variation bit duration, sensitive dependence to initial conditions (x_0,y_0,z_0) and mismatching system's parameters (ρ,μ,γ)[20].Unlike PN-sequences , the $OCCS_s(\hat{x}_k, \hat{y}_k, \hat{z}_k)$ and Logistic Map have variable bit duration [20],which puts difficult barriers in front intruder that tries to break down the spreading sequences and hack the desired data. Even though [29,30] had proposed attacker methods to decipher the spreading sequences ,the initial conditions (x_0,y_0,z_0) and system's parameters (ρ,μ,γ) of $OCCS_s$ provide a super security keys for DS/SS-CDMA system ,therefore, it is difficult for the eavesdropper to decode the spreading sequences and capture information [4]. As shown in Figure 10, the security level of DS/SS-CDMA system against an intruder increases when a small mismatch is occurred in initial conditions or chaotic parameters between transmitter and target receiver ; this leads up to increasingly reproduce bit errors in symbols QPSK modulation. $OCCS_s(\hat{x}_k)$ has six security levels, and is more invincible when the number of occurring mismatch in initial conditions and parameters are exceeded, e.g., at SNR=25 dB and no mismatching case the $BER_{\hat{x}_k} = 4 \times 10^{-3}$ while the security boosted gradually with mismatching case $\Delta x_0 = 0.0001$ and $BER_{\hat{x}_k} = 4 \times 10^{-2}$ and so on the security be more durability. Such spreading sequence $OCCS_s(\hat{x}_k)$ has obscure characteristics do not exist in other spreading sequences and provide the system with confidential security.

Table 1: P-values Randomness of $OCCS_s$, OVSF, and Logistic Map.

Tests	P-value				
	$OCCS_s(\hat{x}_k)$	$OCCS_s(\hat{y}_k)$	$OCCS_s(\hat{z}_k)$	OVSF	Logistic MAP
Frequency (Monobit)	0.9597	0.7893	0.4958	0.2501	0.4113
Frequency(Block)	0.8946	0.5638	0.3551	0.1403	0.3121
Run Test	0.9531	0.6301	0.5761	0.1061	0.1937
Cumulative Sums (Forward)	0.9771	0.7133	0.4670	0.3431	0.2979
Discrete Fourier Transform	0.8797	0.7350	0.6310	0.0000	0.2341
Linear Complexity test	0.9710	0.8790	0.6961	0.0000	0.0000
Approximate Entropy Test	0.9119	0.7991	0.6931	0.3573	0.2731

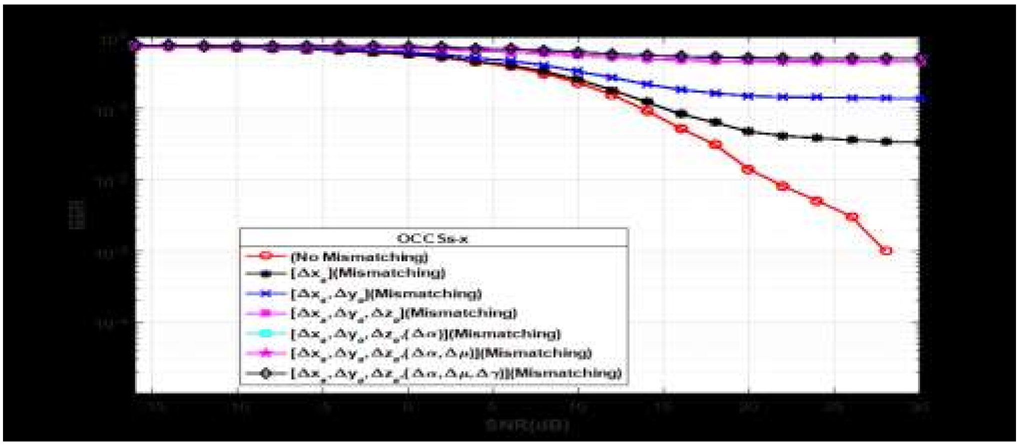

Figure 10: Security levels of DS/SS-CDMA based on 〖OCCS〗_S (x^_k) in Rayleigh channel.

10. Simulation parameters

An entire simulation scheme for proposed $OCCS_s(\hat{x}_k)$ based-DS/SS-CDMA system exhibited in Figure 3 has been applied using Matlab/Simulink program (Ver:8.5.0.197613, R2015a). In same way, another diagram for OVSF, Logistic Map,3D Chua's sequences (x,y,z) generated by Gram-Schmidt based-DS simulation /SS-CDMA system with similar simulation parameters has been also applied for the aim of performances comparison. In all simulation outputs, the simulation's parameters are chosen according to Table 2.

Table(2):Simulation Parameters

Spreading Factor (β), time duration symbol (T_s), Time duration chaotic sample (T_c).	β=128, T_s=6.4 msec., T_c= 50.2083×10^{-6} μsec.
Coefficients Multipath Rayleigh channels	$\alpha_1 = \alpha_2 = \alpha_3 = \frac{1}{\sqrt{\beta}}$
Time Delays(τ_1, τ_2)	$\tau_1 = 3T_c$, $\tau_2 = 6T_c$,
Chua's parameters at certain chaotic initial condition	a= -1.37067, b=-0.732101, ρ=10,μ=18.605, and γ=6.7781166 ×10^{-6} (x_0= y_0= z_0=0.0884)
Number of users(N)	N=1,4,8,12,16,20,32

11. Simulation Results

Figure 11 compares BER's performances of proposed $OCCS_s(\hat{x}_k, \hat{y}_k, \hat{z}_k)$ based-DS/SS-CDMA system with various spreading sequences for single user transmission in Rayleigh channel. It is clear that BER's performances of proposed $OCCS_s(\hat{x}_k, \hat{y}_k)$ and Logistic Map based on ROMA scheme except $\hat{z}_k$ outperform traditional OVSF and their counterparts, $OCCS_s(\hat{x}_k, \hat{y}_k, \hat{z}_k)$ and Logistic Map which are regenerated by orthonormal Gram-Schmidt process. In the other word, at BER of 10^{-4}, the proposed $OCCS_s(\hat{x}_k, \hat{y}_k)$can achieve SNR gains of 5 dB and 1.5 dB over traditional OVSF in Rayleigh fading channels respectively. This simulation results confirm the theoretical results obtained by Eq.(28) that the $OCCS_s(\hat{x}_k, \hat{y}_k)$ based on ROMA scheme have best MF (Higher auto-correlation coefficients) than traditional OVSF and sequences based on Gram-Schmidt process.

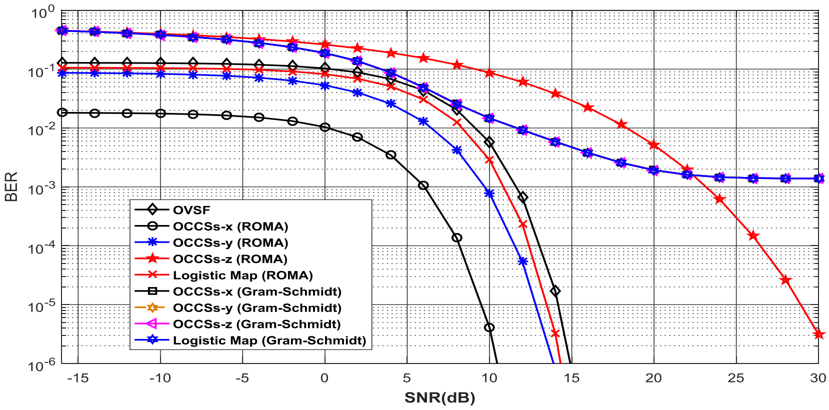

Figure 11: The single user BER performances of $OCCS_s$ based-DS/SS-CDMA in Rayleigh channel.

Figure 12 shows BER's performances for 32-user transmission in Rayleigh channel. Here, only $OCCS_s(\hat{x}_k)$ based on ROMA scheme exceeds all sequences, at BER of 10^{-4} a gain of 4 dB can be obtained over traditional OVSF and $OCCS_s(\hat{y}_k)$ and Logistic Map which are based on ROMA and have similar BER's performances. It is also seen that $OCCS_s(\hat{x}_k)$ based on Gram-Schmidt is outstanding among sequences based on same scheme, as shown in Fig.12 which clearly prove the results of Eq.(29) that $OCCS_s(\hat{x}_k, \hat{y}_k)$ and Logistic Map have best W-index factor (lowest cross-correlation coefficients) than other sequences. Figure 13 compares the exact BER_x of Eq.(24) with approximated BER_x Eq.(25) for $OCCS_s(\hat{x}_k)$ and can infer that increasing in numbers of users to 12 users with an adequate large spreading factor β=128 will not affect BER_x performances of $OCCS_s(\hat{x}_k)$ based-DS/SS-CDMA system. This affirms presumption of approximated BER in Eq.(25) and capacity results N of Eq.(26).

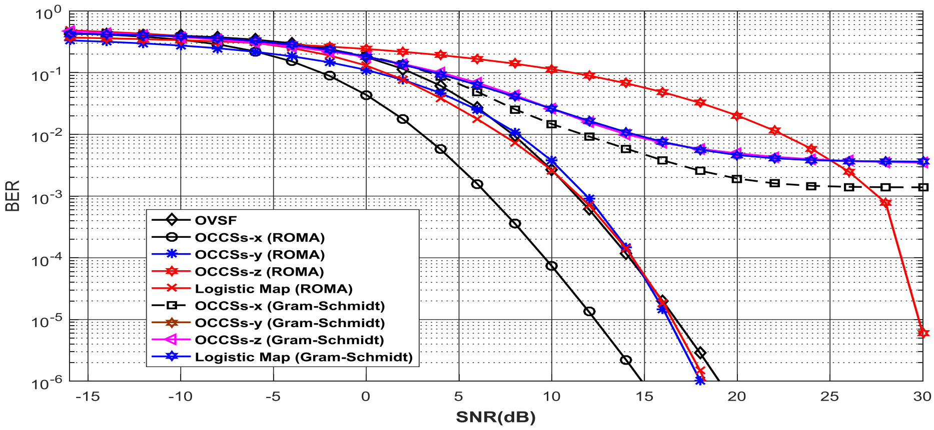

Figure 12: The 32 users BER performances of $OCCS_s$ based-DS/SS-CDMA in Rayleigh channel.

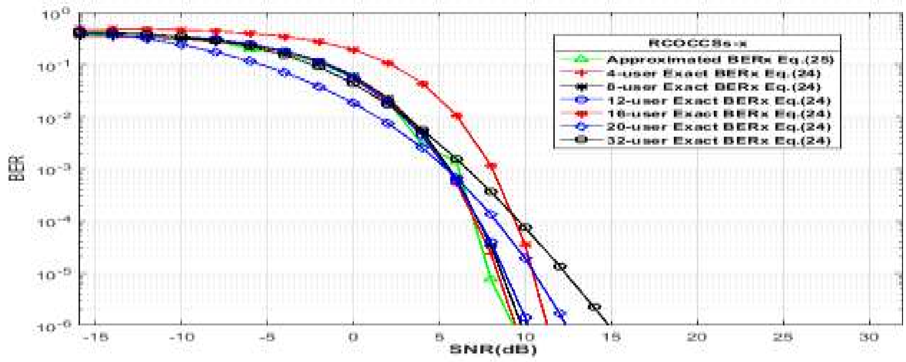

Figure 13: Comparison between exact and approximated BER_x performances of Eq.(24) and Eq.(25) respectively, for $OCCS_s(\hat{x}_k)$ based-DS/SS-CDMA.

7. Conclusions

The overall performances of DS/SS-CDMA system can be considerably promoted by employing the $OCCS_s(\hat{x}_k, \hat{y}_k)$ from 3D Chua's circuit merged with ROMA scheme as spreading sequences. The $OCCSs(\hat{x}_k, \hat{y}_k)$ based on ROMA provided ideal auto-correlation and cross-correlation properties, extra capacity, and reliable security. This best integration is the reason behind its best performances in fading channels as compared with the classical OVSF and Logistic Map based on ROMA or Gram-Schmidt process, or 3D Chua's circuit based on Gram-Schmidt process. The $OCCS_s(\hat{x}_k, \hat{y}_k, \hat{z}_k)$ generated from different 3D Chua's circuit outputs have various performances; so, the one of the best performance sequences $OCCSs(\hat{x}_k, \hat{y}_k, \hat{z}_k)$ can be chosen to realize the best enhancement. Finally, as the theoretical analysis and simulation results show, the $OCCSs(\hat{x}_k)$ has almost the same performance independently to the number of users when associated with an adequate large spreading factor β=128 in Rayleigh channel, which is a unique advantage as compared with other sequences.

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