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Comparative Study: Evaluation and Application of Different Chaotic Maps in CDMA System

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Abstract. *Generation of efficient spreading sequences becomes a great challenge for the researchers in recent decades. The different applications that apply the spreading sequences were mainly depending on the traditional sequences, represented by the Pseudo random Noise sequences (PN). As a result of communication growth, the PN sequences become not satisfied, especially in the multiple access applications. A new sequences based on chaos features are generated as an alternative solution to solve these problems. The chaos based spreading sequences can be generated from different chaotic maps with improved and enhanced versions that have various attractive features. This paper presents study, analysis and evaluation for chaotic based sequences and its improved version generated from 5 different chaotic maps. The study and the analysis are performed based on 4 different features which are balance, orthogonality, normalized maximum auto correlation side lobe, and average cross correlation. The evaluation process is performed by applying the presented sequences in CDMA system and the results are compared with the Gold code as a PN code under the same conditions. The comparison is performed under different conditions and over different channels. The results show that, in many cases the improved chaotic sequences are outperforming the traditional Gold sequence.*
Keywords: Chaotic codes; Gold code; DSSS; CDMA;

1. **Introduction.** The growth of the digital communication shows a huge increase in technologies requirements in the last decades. One of the main technologies in the communication field is the spread spectrum, which depends on the spreading sequences. For long periods, spreading sequences were depending on the Pseudo random Noise sequences (PN) sequences, which show a good performance under different conditions. As the digital communication evoluted, the requirements of bandwidth, data rate and number of users are increased. These requirements showed that the traditional sequences become non efficient and non-satisfied, especially from the Multiple Users (MU) point of view. As an alternative solution, the Chaos based Sequences (CSs) are appeared with better efficiency, reliability and improved correlation properties.

Actually, CSs have significant attractive features, especially from the security point of view. CSs can be efficiently applied in encryption, and has a considerable resistant to jamming and multipath fading [1–3]. Also, it is found that CSs have many privileges such as the simplicity, as it generated from dynamic nonlinear systems called chaotic maps [4–6]. Moreover, CSs are wideband sequences non periodic, which makes the probability of detection, prediction and reconstruction very weak [7]. In addition, CSs have a unique privilege, which is its sensitivity to the initial conditions. This privilege gives the CSs the excellence to generate large uncorrelated codes [8, 9]. The aforementioned features lead to make the researchers focus on developing new enhanced sequences with improved properties [10]. As a result, CSs are applied in various digital communications techniques such as Code Division Multiple Accesses (CDMA) [7,8,10,13], Orthogonal Frequency Division Multiplexing (OFDM) [11,12], Multiple-Input Multiple-Output (MIMO) radar application [14], underwater communication [15,16], image encryption [17–21], ultra wideband signal [22,23], and much more disciplines [24–26]

In this paper, a statistical study, analysis and evaluation are presented for different chaotic maps. The chaotic maps under the study are Chebyshev, Cubic, ICMIC, SINE, and Quadratic maps. The statistical study and the analysis are performed based on 4 different features, which are the Balance, Orthogonality, Normalized Maximum Auto Correlation Side Lobe (NMACSL), and Average Cross Correlation (ACC) feature. The study and the analysis are performed for different code lengths according to the relation 2^n starting from n=5 (length of 32) up to n=11 (length of 4096). the study and the analysis are constrained with the relation of 2^n to be comparable with the Gold sequence under the same condition. The generated sequences from each map are the traditional raw sequence, in addition to the 3 improved versions. The improved versions generated from each map are the Zero Mean (ZM), Self Balanced (SB), and Zero Mean-Self Balanced (ZMSB). This means that the total number of chaotic sequences to be analyzed and evaluated become 20 different sequences, in addition to the Gold sequences. Finally, all the studied and analysed sequences are applied in CDMA system to be evaluated and compared with the Gold code. The evaluation process are performed under different number of Multiple Access Interfering (MAI) users, and different channels. The results show that most of the presented chaotic sequences outperform the Gold sequences under the same conditions.

The paper is organized as follows, section 2 illustrates the mathematical model of the presented chaotic sequences and the equations representing its improved versions. In section 3, the statistical study and the analysis are presented, illustrated, discussed, and compared with the Gold code. The study and the analysis are presented for all the proposed sequences and their improved versions. The simulation results of the proposed CDMA system are clarified and discussed in section 4, and finally the conclusion is stated in section 5.

2. **Mathematical Model.**

As mentioned before, the applied chaotic maps are Chebyshev, Cubic, ICMIC, SINE, and Quadratic maps. The basic mathematical models of the mentioned maps are represented as:

- Chebyshev map

$$x_{n+1} = cos(rcos^{-1}(x_n)), \qquad x_n \in [-1, 1], \qquad r \in [1, 4], \tag{1}$$

- Cubic map

$$x_{n+1} = x_n^3 - rx_n, \qquad x_n \in [-2, 2], \qquad r \in [1, 3], \tag{2}$$

- Sin map

$$x_{n+1} = rsin(\pi x_n), \qquad x_n \in [0, 1], \qquad r \in [0, 1], \tag{3}$$

- Quadratic map

$$x_{n+1} = r(1 - x_n^2), \qquad x_n \in [-1.4, 1.4], \qquad r \in [0, 1.4], \tag{4}$$

- ICMIC map

$$x_{n+1} = sin(\frac{r}{x_n}), \qquad x_n \in [-1, 1], \qquad r > 0, \tag{5}$$

Where, x_{n+1} is the new value of the map generated by the old value x_n , and r is the bifurcation parameter. It is clear that there is a specific range for the initial value and the bifurcation parameter for each chaotic map. These ranges for the initial values and bifurcation parameter have a significant effect on the outputs of the map.

The output of any chaotic map is real values; which cannot be applied in the digital communications. The output real value is converted into digital values by applying the zero mean threshold method represented by

$$x_{zm} = sign(g[x(t) - mean(x(t))]) \tag{6}$$

This method depends on shifting the real value for the basic chaotic code by its mean value and generate a new basic sequence x_{zm} has zero mean. The binary values is obtained by taking the ($sign$) function of the new zero mean sequence x_{zm}. This step can be considered as the first improvement, the second improvement applied on the generated sequences is the self-balancing process. The purpose of this stage is to make the number of zeros equal to the number of ones. This process is constructed from four different stages as explained in [27]. The last improvement process is the zero mean self-balanced code which can be considered as a combination between the two previous processes.

3. **Statistical study and analysis.** in this section, the study is based on four different criteria or properties, the Balance, Orthogonality, Normalized Maximum Auto Correlation Side Lobe (NMACSL), and Average Cross Correlation (ACC) property. These properties are selected due to their significant effect on the performance and the attitude of the proposed sequences, especially in case of the Multiple Access (MA) applications. The purpose of this study is to investigate the effect of each improvement process (ZM, SB, ZMSB) processes on each property for different code lengths. The analysis is performed over 8 different lengths, starting from 32 up to 4096 according to the relation 2^n.

Starting with the balance property, it gives an indication about the ratio between the number of the ones (or zeros) to the code length; the ideal desired value of this feature is 0 according to the following relation:

$$balance = \frac{|No.\,of\,zeros\, -\, No.\,of\,ones|}{sequence\,length} \tag{7}$$

Due to the huge increase in the users, especially in case of the MA applications, the orthogonality becomes one of the most important properties that should be studied. It has a significant effect on the performance efficiency of the system, and can be represented as:

$$\sum_{k=1}^{K}\sum_{i=1}^{N} x_{ki}\, x_{li}, \qquad l = 1, 2, ..., K \qquad k \neq l \tag{8}$$

Where N is the sequence length and K is the number of sequences. The desired value of the orthogonality property should be minimum as much as possible (ideally zero), in this case the effect of the MAI can be neglected.

The third property is concerning with obtaining Delta Dirac auto-correlation output function for the spreading sequences. In real case there are many side lobes due to the sequence imperfection. Most of the researches aim to minimize the ratio of the side-lobes to the main lobe. However, due to the imperfection of the generated codes this target is not ideally achieved. Due to this reason it is necessary to analysis the maximum normalized auto correlation side lobe for each map.

Regarding to the last property, it is desired to produce spreading codes having zero cross correlation function between each other, however that is not practically possible so

TABLE 1. Balance Property

Seq. Type/Length		32	64	128	256	512	1024	2048	4096
Chebyshev	Trad.	0.0694	0.0492	0.0347	0.0247	0.0175	0.013	0.0099	0.0075
	ZM	0.0426	0.0313	0.022	0.0156	0.0112	0.0082	0.0062	0.0042
	SB	0	0	0	0	0	0	0	0
	ZMSB	0	0	0	0	0	0	0	0
Cubic	Trad.	0.0371	0.0272	0.0192	0.0141	0.0102	0.0075	0.0055	0.0044
	ZM	0.0244	0.0169	0.0113	0.0077	0.0051	0.0033	0.0023	0.0016
	SB	0	0	0	0	0	0	0	0
	ZMSB	0	0	0	0	0	0	0	0
ICMIC	Trad.	0.0844	0.0593	0.0417	0.0301	0.0211	0.0159	0.0108	0.0073
	ZM	0.048	0.0347	0.0247	0.0186	0.0134	0.0101	0.007	0.0047
	SB	0	0	0	0	0	0	0	0
	ZMSB	0	0	0	0	0	0	0	0
SINE	Trad.	0.0592	0.0487	0.036	0.0307	0.0276	0.0262	0.0246	0.0241
	ZM	0.0375	0.0287	0.0199	0.015	0.0112	0.0086	0.0073	0.0061
	SB	0	0	0	0	0	0	0	0
	ZMSB	0	0	0	0	0	0	0	0
Quadratic	Trad.	0.0911	0.0877	0.0878	0.0878	0.0877	0.0876	0.0868	0.0866
	ZM	0.0451	0.0382	0.0345	0.0322	0.0309	0.0303	0.0291	0.0288
	SB	0	0	0	0	0	0	0	0
	ZMSB	0	0	0	0	0	0	0	0
Gold Sequences		0.0661	0.0379	0.0294	0.0209	0.0185	0.0124	0.0089	0.0089

the normalized average cross correlation is aimed to be minimized as possible.

$$R_{xy}(\tau) = \sum_{i=1}^{N} x_i \, y_{i+\tau} \tag{9}$$

Table 1 represents the results of the balance property for all proposed chaotic maps, in addition to the Gold code, in which the traditional and the improved sequences are listed for each map. From the results, the following conclusion can be obtained: (i) As the code length increased, the balance property is improved as its value is decreased. (ii) The ZM process improves the balance property for all the proposed maps. (iii) The cubic map has the best attitude regarding to the balance property over all the other maps, including the Gold sequences. On the other hand, the quadratic map has the worst attitude. (iv)the SB and ZMSB sequences presents perfect values for all the maps, since the number of zeros is precisely equal the number of ones. (v) Generally, the results of the ZM process outperforms the Gold code.

Table 2 illustrates the results of the orthogonality property for all the proposed chaotic sequences in addition to the Gold code all over the proposed lengths. From table 2 the following notes can be concluded; (i) In general, the orthogonality property is improved as the code length increased for all the chaotic maps. (ii) The SB process degrades the orthogonality for the same chaotic map and the same code length. (iii) The Chebyshev map has the best attitude over the entire chaotic map, while the cubic map has the worst attitude. (iv) The Gold code outperforms the performance of all the chaotic map especially at the short lengths, as the length increased the performance of the Chebyshev nearly has the same performance of the Gold code.

Table 2. Orthogonality property

Seq.	Type/Length	32	64	128	256	512	1024	2048	4096
Chebyshev	Trad.	0.1399	0.0992	0.0704	0.0495	0.0352	0.0249	0.0176	0.0124
	ZM	0.141	0.0997	0.0702	0.0496	0.0352	0.025	0.0176	0.0124
	SB	0.1946	0.1399	0.0992	0.0704	0.0495	0.0352	0.0249	0.0176
	ZMSB	0.1997	0.141	0.0997	0.0702	0.0496	0.0352	0.025	0.0176
Cubic	Trad.	0.1644	0.1169	0.083	0.0599	0.0432	0.0314	0.0227	0.0168
	ZM	0.1577	0.1146	0.0814	0.059	0.0427	0.0311	0.0226	0.0167
	SB	0.232	0.1644	0.1169	0.083	0.0599	0.0432	0.0314	0.0227
	ZMSB	0.2189	0.1577	0.1146	0.081	0.059	0.0427	0.0311	0.0226
ICMIC	Trad.	0.1535	0.1104	0.0795	0.0573	0.042	0.0315	0.0243	0.0187
	ZM	0.1535	0.1106	0.0791	0.0574	0.042	0.0314	0.0243	0.0187
	SB	0.2096	0.1535	0.1104	0.0795	0.0573	0.042	0.0315	0.0243
	ZMSB	0.2133	0.1535	0.1106	0.0791	0.0574	0.042	0.0314	0.0243
SINE	Trad.	0.1432	0.1039	0.0777	0.0552	0.0406	0.0301	0.0219	0.0168
	ZM	0.1470	0.106	0.0789	0.0553	0.0413	0.0308	0.0226	0.0171
	SB	0.2004	0.1432	0.1039	0.0777	0.0552	0.0406	0.0301	0.0219
	ZMSB	0.2034	0.147	0.106	0.0789	0.0553	0.0413	0.0308	0.0226
Quadratic	Trad.	0.1544	0.1104	0.0802	0.0607	0.0482	0.0404	0.0357	0.0339
	ZM	0.1612	0.1142	0.0816	0.059	0.0427	0.0314	0.0233	0.0177
	SB	0.2116	0.1544	0.1104	0.0802	0.0607	0.0482	0.0404	0.0357
	ZMSB	0.2297	0.1612	0.1142	0.0816	0.059	0.0427	0.0314	0.0233
Gold Sequences		0.1258	0.0674	0.0563	0.0391	0.0265	0.0202	0.013	0.0109

Table 3. Normalized Maximum Auto Correlation Side Lobe property

Seq.	Type/Length	32	64	128	256	512	1024	2048	4096
Chebyshev	Trad.	0.3580	0.2984	0.2282	0.1764	0.1343	0.1013	0.0756	0.0568
	ZM	0.3675	0.3028	0.2274	0.1774	0.1332	0.1014	0.0755	0.0568
	SB	0.4950	0.3634	0.2839	0.2074	0.1573	0.1239	0.0997	0.0881
	ZMSB	0.4849	0.3668	0.2844	0.2058	0.1573	0.1248	0.1002	0.0881
Cubic	Trad.	0.5209	0.5	0.5036	0.5037	0.5078	0.5083	0.51	0.5095
	ZM	0.5057	0.4845	0.4864	0.4926	0.4998	0.5019	0.5044	0.5049
	SB	0.5873	0.4573	0.4487	0.4733	0.4887	0.4998	0.5045	0.5081
	ZMSB	0.5671	0.4449	0.4361	0.457	0.4777	0.4919	0.4981	0.5026
ICMIC	Trad.	0.4078	0.3201	0.2803	0.2604	0.259	0.2588	0.26	0.2586
	ZM	0.4003	0.322	0.279	0.2584	0.2584	0.2585	0.2598	0.2587
	SB	0.5126	0.3977	0.316	0.2667	0.2512	0.2549	0.2572	0.2591
	ZMSB	0.5051	0.3895	0.3134	0.2617	0.2483	0.2544	0.2568	0.2588
SINE	Trad.	0.3675	0.2944	0.24	0.1902	0.1518	0.1293	0.1154	0.113
	ZM	0.3838	0.3175	0.2406	0.195	0.1707	0.1573	0.1534	0.1529
	SB	0.495	0.375	0.2813	0.2189	0.1671	0.1441	0.1274	0.1149
	ZMSB	0.505	0.3831	0.2941	0.2222	0.1754	0.1651	0.1559	0.1531
Quadratic	Trad.	0.391	0.3294	0.2649	0.2138	0.1844	0.1666	0.1613	0.159
	ZM	0.4146	0.3523	0.2995	0.2786	0.267	0.2634	0.2649	0.2649
	SB	0.5076	0.3768	0.2949	0.2391	0.2032	0.1777	0.1644	0.1607
	ZMSB	0.552	0.3808	0.3171	0.275	0.2673	0.262	0.2614	0.264
Gold Sequences		0.2903	0.2648	0.1339	0.1216	0.0646	0.093	0.0318	0.149

TABLE 4. Average Cross Correlation

Seq.	Type/Length	32	64	128	256	512	1024	2048	4096
Chebyshev	Trad.	0.1393	0.0987	0.07	0.0496	0.0351	0.0248	0.0175	0.0124
	ZM	0.1403	0.099	0.0702	0.0496	0.0351	0.0248	0.0175	0.0124
	SB	0.1373	0.1003	0.0714	0.0507	0.036	0.0255	0.018	0.0127
	ZMSB	0.1365	0.0995	0.071	0.0506	0.036	0.0255	0.018	0.0127
Cubic	Trad.	0.1619	0.1148	0.0812	0.0575	0.0407	0.0289	0.0204	0.0144
	ZM	0.1554	0.112	0.0796	0.0565	0.0402	0.0286	0.0203	0.0143
	SB	0.1534	0.1101	0.0791	0.0566	0.0405	0.0288	0.0205	0.0145
	ZMSB	0.147	0.1064	0.0774	0.0556	0.0398	0.0284	0.0202	0.0144
ICMIC	Trad.	0.1487	0.1061	0.0756	0.0538	0.0382	0.027	0.0191	0.0135
	ZM	0.1499	0.1062	0.0756	0.0538	0.0382	0.027	0.0191	0.0135
	SB	0.1489	0.1057	0.0767	0.0552	0.0392	0.028	0.0198	0.0141
	ZMSB	0.1443	0.103	0.0753	0.0547	0.0391	0.0279	0.0198	0.0141
SINE	Trad.	0.1417	0.1009	0.0717	0.0509	0.0361	0.0255	0.0181	0.0128
	ZM	0.1432	0.1021	0.0727	0.0516	0.0366	0.0259	0.0183	0.013
	SB	0.1381	0.1018	0.0722	0.0515	0.0368	0.026	0.0185	0.0131
	ZMSB	0.1385	0.1015	0.0725	0.0515	0.0369	0.0262	0.0186	0.0132
Quadratic	Trad.	0.1488	0.1069	0.0772	0.0574	0.0443	0.0368	0.0322	0.0304
	ZM	0.1554	0.1107	0.0781	0.0554	0.0392	0.0278	0.0198	0.0141
	SB	0.1469	0.1048	0.0765	0.0576	0.0448	0.0368	0.0329	0.0306
	ZMSB	0.1512	0.1013	0.0755	0.0546	0.0392	0.0279	0.02	0.0143
Gold Sequences		0.1689	0.0887	0.0739	0.0484	0.0339	0.0255	0.0162	0.0116

Table 3 illustrates the results obtained regarding to the NMACSL for all the proposed maps. The results can be concluded as follow: (i) Excluding the cubic map, the NMACSL property is improved as the code length increased, however this improvement is vary from map to another. (ii) The Chebyshev map presents the best performance over all the chaotic maps, meanwhile the cubic maps presents the worst attitude. (iii) The effect of the SB and ZM positively or negatively is varying from map to another.

The average cross correlation (CC) property measures how much the interference between the different codes. As cleared before it's desired to minimize this value as much as possible. From table 4, the following conclusions can be obtained: (i) The CC property is improved as the code length increased for all the presented sequences, including the Gold code. (ii) The quadrature map presents the worst attitude, while all the other maps nearly have the same performance, especially for the large code length values. (iii) Both the SB and ZM process have a slight effect, while the ZMSB has a positive effect.

4. **Simulation and Results.** In this section, a simulation for CDMA system is simulated using MATLAB© software. All the sequences generated from the five chaotic maps beside the Gold sequences are applied as spreading codes for users in the system. The simulation is performed by evaluating the Bit Error Rate (BER) of the system over a Signal to Noise Ratio (SNR) ranging from 2 to 12 dB. Moreover, the simulation is applied over different fading channel types such as Flat Fading and Frequency Selective Fading.

Figures 1-3 represent the system performance of the different presented sequences under 10 users with code length 31 for flat fading channel. Figure 1 shows the attitude of the different Cubic and Chebyshev sequences compared with the Gold codes. The Figure shows that generally, all the applied sequences outperform the performance of the Gold code with gain ranging from 1.5 to 3.5 dB at BER 10^{-3}. It is clear also that the cubic

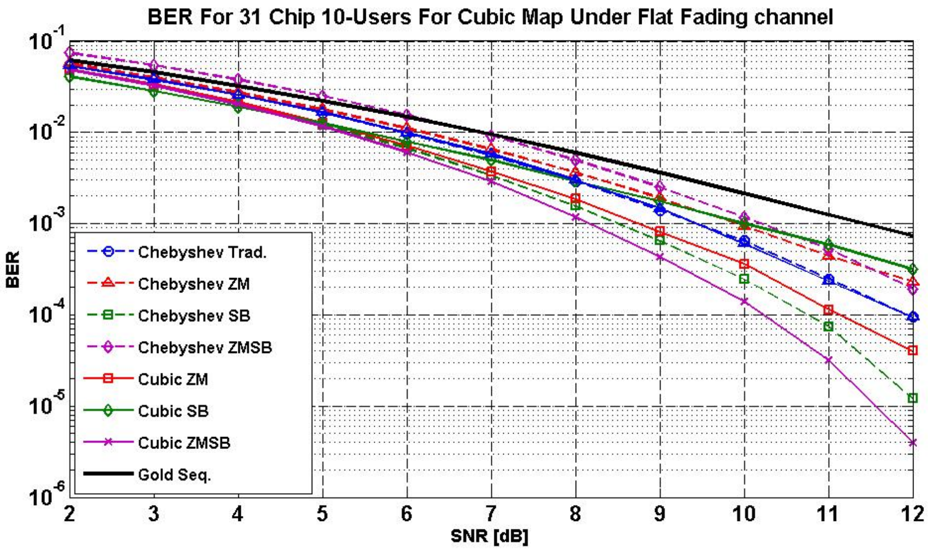

FIGURE 1. BER for 31 Chip 10-Users (Cubic and Chebyshev Maps) under Flat Fading

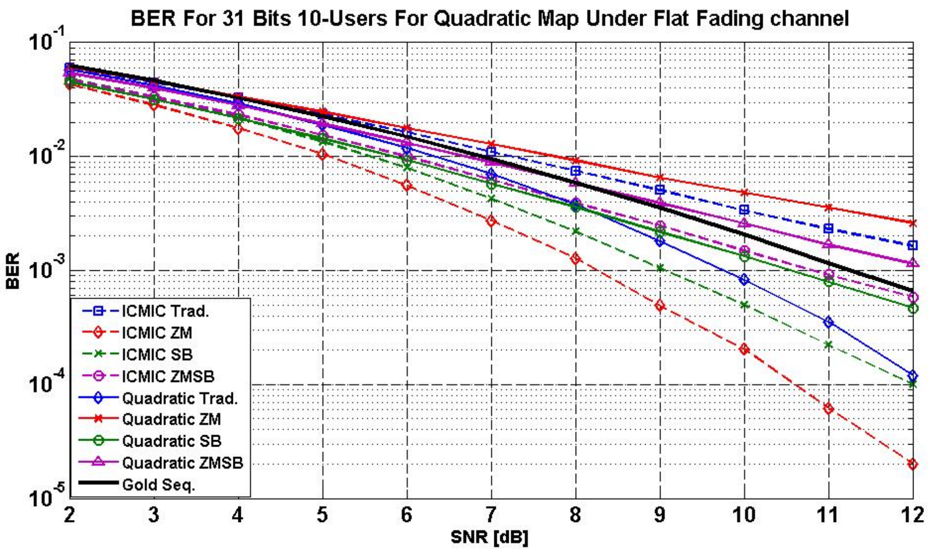

FIGURE 2. BER for 31 Chip 10-Users (ICMIC and Quadratic Maps) under Flat Fading

ZMSB has the best performance all over the chaotic sequences as it gives 4 [dB] gain at BER 10^{-3}. On the other hand, the Chebyshev ZMSB and cubic SB present the worst performance by achieving BER 10^{-3} at SNR 10 [dB]. By noting the sequences generated from the ICMIC and Quadratic maps represented in Figure 2, it is clear that the Gold sequence has a mild performance comparing to the presented sequences. It is found that traditional ICMIC, Quadratic ZM, in addition to the Quadratic ZMSB has less performance than the Gold code. On the other hand, the remaining sequences present better performance with gain ranging from 3 to 0.5 dB at BER 10^{-3}. Moreover, it is found that the ICMIC ZM has the best performance while Quadratic ZM has the worst performance. Figure 3 represents the performance comparison between the sequences

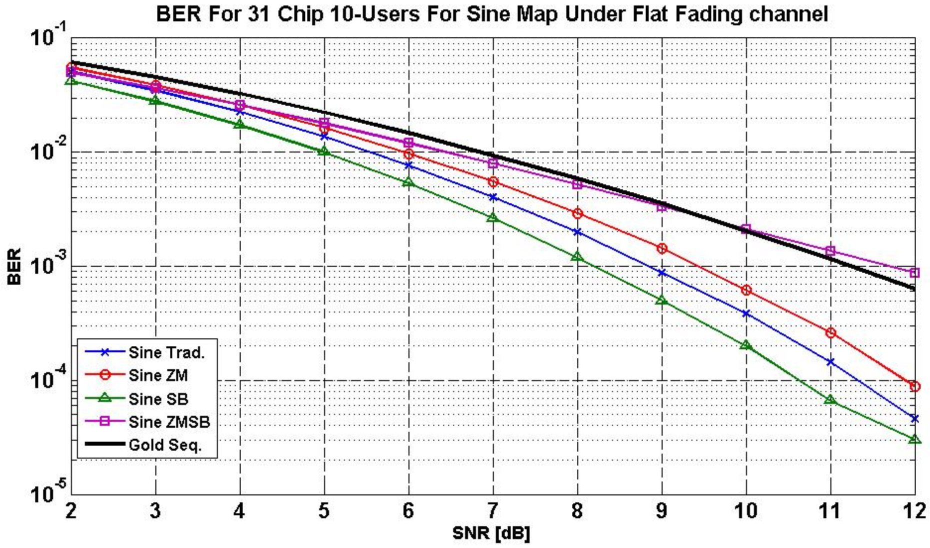

FIGURE 3. BER for 31 Chip 10-Users (Sine Map) under Flat Fading

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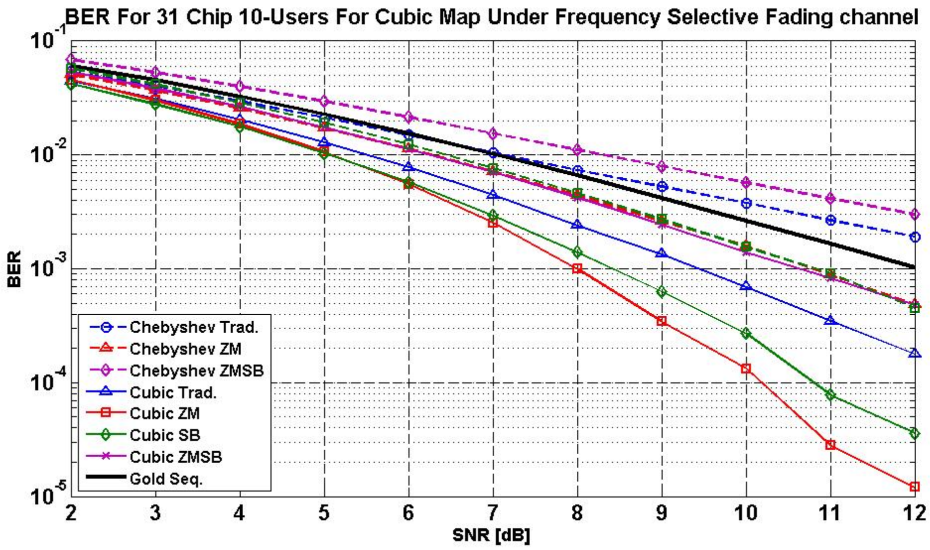

FIGURE 4. BER for 31 Chip 10-Users (Cubic and Chebyshev Maps) under Frequency Selective Fading

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generated from the Sine map and the Gold code. It is clear that most of the generated sequences have better performance over the Gold code expect the Sine ZMSB, which nearly has the same performance of the Gold code. The Figure shows also that the Sine SB sequence has the best performance all over the sequences with performance gain 3 dB at BER10^{-3}.

Taking into consideration the last channel case, which is the frequency selective fading, Figures 4-6 illustrate performance comparison of the presented sequences with the Gold code. Figure 4 represents the performance comparison of the Cubic and Chebyshev Maps under effect of the frequency selective fading channel. The Figure clarifies that the performance of all the presented sequences outperform the Gold code except the traditional and ZM Chebyshev. It is clear also that the cubic ZM has the best performance

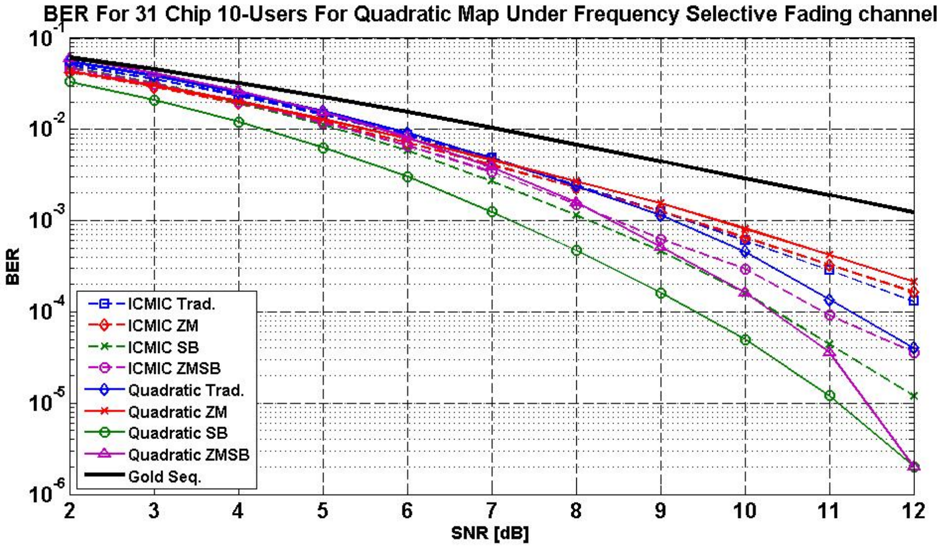

FIGURE 5. BER for 31 Chip 10-Users (ICMIC and Quadratic Maps) under Frequency Selective Fading

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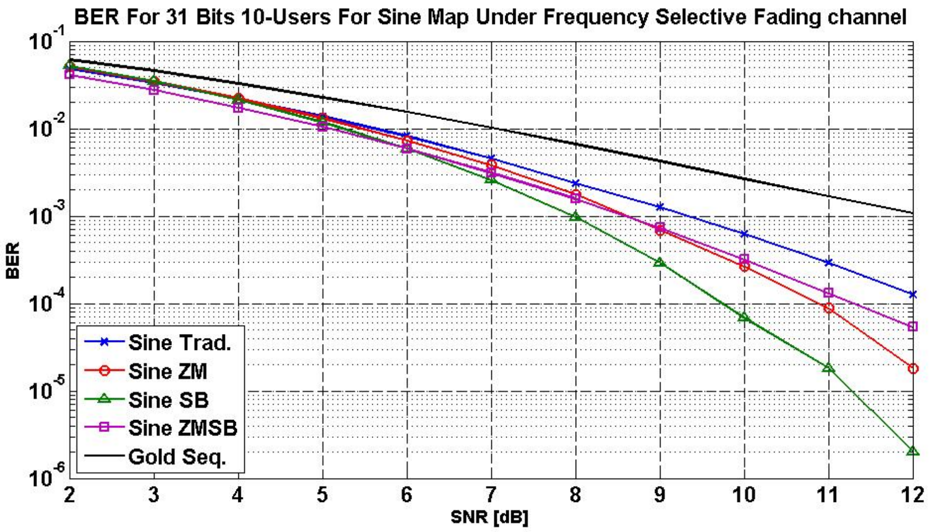

FIGURE 6. BER for 31 Bits 10-Users (Sine Maps) under Frequency Selective Fading

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with gain 4 dB at BER 10^{-3}. Regarding to the ICMIC and Quadratic Maps discussed in Figure 5, the Figure shows that all the presented sequences outperforms the performance of the Gold code. The Figure shows that the frequency selective channel has a serious degrade effect on the Gold code, while the presented chaotic sequences resist this effect. The Figure shows that the Quadratic SB sequence has the best performance with gain nearly 5 dB at BER 10^{-3}. Regarding to Figure 6, it shows that the Sine sequence resists the degradation effect resultant from the frequency selective channel and outperforms the Gold performance. It is clear that the Sine SB presents the best performance with gain 4 dB at BER 10^{-3}.

5. **Conclusion.** In this paper, a statistical study, analysis and performance evaluation is presented for different 5 chaotic maps. The proposed chaotic maps are the Chebyshev, Cubic, ICMIC, Quadratic and Sine chaotic map. The sequences to be studied and analyzed are the traditional sequences generated from the proposed maps, in addition to the enhanced generated versions. All the results obtained from the study are compared with the Gold sequence, as an example of the PN sequence. The study is based on four different criteria or properties, the balance, orthogonality, normalized maximum auto correlation side lobe (NMACSL), and average cross correlation (ACC) property. Moreover, a performance evaluation of the applied sequence is performed and compared with the Gold code. The performance evaluation is performed under different fading channels. The results of the study show that the enhancement applied on the chaotic maps has appositive effect on the mentioned properties. The results show also that most of the applied chaotic maps have better results than the Gold code. it is found that, unlike the Gold code, the applied chaotic sequences have the ability to resist the fading effect of the channel. moreover, the results prove that the applied chaotic sequence can be considered as an efficient alternative solution to the traditional PN sequences in the severe fading channels.

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