Spatiotemporal-Chaotic Sequences for Asynchronous DS-UWB Communication System

Ali Kotti, Safya Belghith, Zouhair Ben Jemaa

LABORATOIRE SYSCOM ENIT, BP 37 Tunis Belvedere 1002, TUNISIE
e-mail: `ali.kotti@enit.rnu.tn`, `safya.belghith@enit.rnu.tn`,
`Zouhair.benjemaa@enit.rnu.tn`

Abstract—*In previous works, the performance of DS-UWB (Direct Sequence- Ultra Wide Band) systems in a multiuser scenario with binary pulse amplitude modulation has been studied. In most of these works, tradional spread spectrum sequences such as independent identically distributed (i.i.d) random sequences and Gold sequences have been considered. Since these sequences are limited in term of correlation properties several researchers were interested in using chaotic sequences generated by non linear systems. In this paper, we propose to use spatiotemporal chaotic codes in asynchronous DS-UWB systems and investigate an analysis of Multi-User Interference (MUI) term for this family and the two classical i.i.d and Gold families. Then, the Bit Error Rate (BER) is computed to evaluate the performance of conventional receiver in both cases AWGN and multipath channel to confirm the results found about MUI.*

I. INTRODUCTION

Ultra Wide-Band (UWB) wireless communication system has recently enjoyed considerable interest in research and standardization communities due to its advantages which stem from its ultra wideband nature. In UWB system very short impulses are transmitted, these impulses are characterized by; low power density, high bandwidth, low complexity baseband transceivers and a potential for major increase in multi-access capacity.

To improve its multiple access capability, Time Hopping (TH) and Direct Sequence (DS) are the most popular multiple access methods for UWB impulse radio technology. The time-hopping spread spectrum technique was the original method proposed for multiple access UWB systems [1]. In TH-UWB systems multiples pulses per bit are sent with a time offset for each pulse determined by some user unique code and are suitable for low data rate applications.

In DS-UWB systems which can support high data rate applications, multiples pulses per bit period are transmitted using bipolar modulation for each pulse based upon a certain spreading code. In previous works, the performance of DS-UWB systems in a multiuser scenario with binary pulse amplitude modulation has been studied. In most of these works, classical codes such as (i.i.d) random sequences and Gold sequences have been considered. Since these sequences are limited in term of correlation properties several researchers were interested in using chaotic sequences generated by non linear systems.

Chaotic systems generate signals which are purely deterministic, although they show features typical of random signals. The chaotic signals are easy to generate, and in theoretically an abundant source of almost uncorrelated signals has been generated. This characteristic means that an infinite number of uncorrelated chaotic signals could be generated from the same system using different initial conditions. In this paper, we will use another family of chaotic sequences called by spatiotemporal chaotic sequences. This family is advantageous in terms of chaotic- synchronization and correlation properties.

In our work, we will show the influence of spatiotemporal-chaotic spreading sequences on the performance of conventional receiver in asynchronous DS-UWB compared to the classical codes. This will be done by analyzing the statistics of MUI term for these sequences, then by comparing the BER allowed by correlating receiver.

This paper is organized as follows. In section II, an overview of asynchronous DS-UWB system as well as the correlating receiver are provided. In section III, the generation of spreading sequences by means of the quantization of chaotic trajectories is breafly described. In section IV, the main MUI is analysed when we considered two cases of channel; AWGN and Rayleigh channels for different sequences, then performance in BER term is evaluated for the same sequences. Our conclusions are presented in section IV.

II. DS-UWB System Model And Correlating Receiver

An asynchronous direct sequence spread spectrum UWB system with K multiple access users and BPSK modulation is shown in fig (1). Every data bit is multiplied by a certain spreading sequence for the purpose of multiple accessing. Each binary data bit of T_s seconds contains N_c chips with duration of T_c seconds per chip.

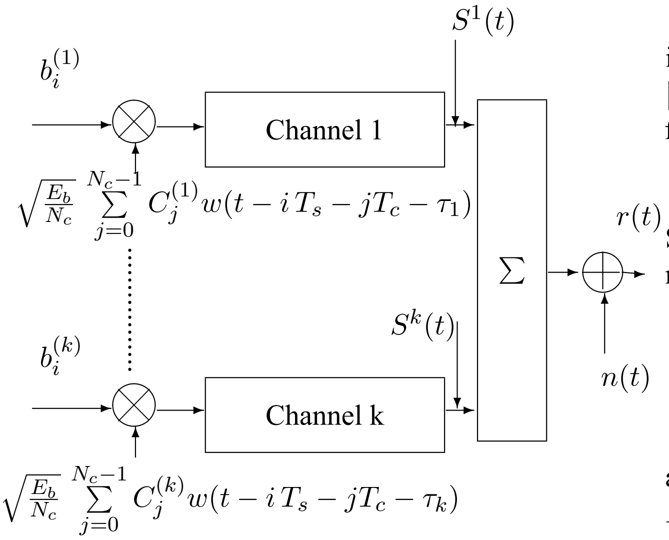

Fig. 1. DS-UWB system

The signal generated by the k^{th} transmitter is given by [2]

$$S^k(t) = \sqrt{\frac{E_b}{N_c}} \sum_{i=-\infty}^{\infty} b_i^{(k)} \sum_{j=0}^{N_c-1} C_j^{(k)} w(t - i\,T_s - jT_c) \tag{1}$$

where t is time and $\sqrt{\frac{E_b}{N_c}}$ is normalization factor that makes the system have the same unit bit energy. The chip waveform is normalized and satisfies $\int_{-\infty}^{\infty} w(t)^2\,dt = 1$. The duration pulse noted by T_w verifies $T_w << T_c$.

- T_s and T_c are symbol and chip duration respectively.
- $N_c = \frac{T_s}{T_c}$ is the number of chips per symbol.
- $C_j^{(k)}$ is the spreading sequence, each element is assumed to take values from $\{\pm 1\}$.
- $b_i^{(k)}$ is the i^{th} data bit transmitted by the k^{th} source taking values $\{\pm 1\}$.

Assuming K users are transmitting asynchronously on an AWGN channel, the received signal is given by

$$r(t) = \sum_{k=1}^{K} A_k\, S^k(t - \tau_k) + n(t) \tag{2}$$

where $n(t)$ is WGN with two-sided power spectral density $N_0/2$. $\{A_k\}$ and $\{\tau_k\}$ are attenuation and delay between reference user and user k which can be approximated by [3]

$$\tau_k = \gamma_k\, T_w + \delta T_k \tag{3}$$

where γ_k is an integer uniformly distributed in the interval $[0, N_c\, N_r]$ with $N_r = T_c/T_w$ and $\delta T_k \in [0, T_w]$. Subsequently the delay for each user satisfies $0 \le \tau_k < T_s$.

In the case of multipath channel with No Line-Of-Sight (NLOS) component, the impulse response of multipath channel corresponding to user k is

$$h^k(t) = \sum_{l=0}^{L_k-1} A_{l,k}\, \delta(t - \theta_{l,k}) \tag{4}$$

where L_k is the number of paths between user k and reference user; it is the same for all users($L_k = L \forall k = 1...K$). $\{A_{l,k}\}$ are the received amplitudes of the paths of the user k according rayleigh distribution. In this case, the composed received signal $r_k(t)$ for the k^{th} user at receiver can be expressed as

$$r_k(t) = \sum_{l=0}^{L_k-1} A_{l,k}\, S^k(t - \theta_{l,k}) \tag{5}$$

Therefore, the received signal in the receiver antenna can be written as

$$r(t) = \sum_{k=1}^{K} r_k(t) + n(t) \tag{6}$$

where $n(t)$ has the same expression given in equation 2.

We use for the two cases of channels the correlating receiver. Without loose of generality, we suppose user 1 the reference user. We assume that the receiver has achieved perfect clock and sequence synchronization with respect to the signal transmitted by the first user.

The correlation receiver computes the decision static given by

$$\alpha_i = \sum_{j=0}^{N_c-1} \int_0^{T_s} r(t) C_j^{(1)}\, w(t - j\,T_c - iT_s)\, dt \tag{7}$$

Without loose of generality, we will consider $i = 0$. Therefore $\alpha_i = \alpha_0 = \alpha$ which can be expressed as [4]

$$\alpha = S + I + M + \eta \tag{8}$$

where

- S is the contribution from the 0^{th} path of the first user
- η is a Gaussian Random Variable
- I is the Multi-User Interference (MUI) composed by the sum of signal from $K-1$ interfering users, which consists of $(K-1) * L$ terms
- M is the Self-Interference (SI) caused by multipath propagation

In the case of Rayleigh channel, we have [7]

$$S = A_{0,1}^2 \sqrt{E_b\, N_c}\, b_0^{(1)} \tag{9}$$

$$I = \sum_{k=2}^{K} I^k \tag{10}$$

where

$$I^k = \sum_{l=0}^{L-1} I^{k,l} = A_{0,1}\sqrt{\frac{E_b}{N_c}}[R(\delta T_k) \sum_{l=0}^{L-1} A_{l,k} X^{k,l}$$

$$+\hat{R}(\delta T_k) \sum_{l=0}^{L-1} A_{l,k} Y^{k,l}]$$

where

$R(\delta T_k)$ and $\hat{R}(\delta T_k)$ are defined as the autocorrelation functions of $w(t)$.

$$R(\delta T_k) = \int_0^{\delta T_k} w(t)\, w(t + T_w - \delta T_k)\, dt \tag{11}$$

and

$$\hat{R}(\delta T_k) = \int_{\delta T_k}^{T_w} w(t)\, w(t - \delta T_k)\, dt \tag{12}$$

$X^{k,l}$ and $Y^{k,l}$ are defined as follows

$$X^{k,l} = b_{-1}^{(k)} \sum_{n=0}^{\gamma_k+l} C_n^{(1)} C_{n+N_c-\gamma_k-l-1}^{(k)}$$

$$+b_0^{(k)} \sum_{n=\gamma_k+l+1}^{N_c-1} C_n^{(1)} C_{n-\gamma_k-l-1}^{(k)} \tag{13}$$

$$Y^{k,l} = b_{-1}^{(k)} \sum_{n=0}^{\gamma_k+l-1} C_n^{(1)}\, C_{n+N_c-\gamma_k-l}^{(k)}$$

$$+b_0^{(k)} \sum_{n=\gamma_k+l}^{N_c-1} C_n^{(1)} C_{n-\gamma_k-l}^{(k)} \tag{14}$$

$$\eta = \int_0^{T_s} n(t)\, A_{0,1} \sum_{j=0}^{N_c-1} C_j^{(1)}\, w(t - j\, T_c)\, dt \tag{15}$$

$$M = \int_0^{T_s} \sum_{l=1}^{L-1} A_{l,1}\, S^1(t - l\, T_c)\, A_{0,1}$$

$$\sum_{j=0}^{N_c-1} C_j^{(1)}\, w(t - jT_c)\, dt \tag{16}$$

Using the definitions functions of $X^{k,l}$, $Y^{k,l}$,$R(\delta T_k)$ and $\hat{R}(\delta T_k)$ for the first user, M can be further simplified to

$$M = \sqrt{\frac{E_b}{N_c}}\, A_{0,1}\, \hat{W} \tag{17}$$

with

$$\hat{W} = [R(0) \sum_{l=1}^{L-1} A_{l,1}\, X^{1,l} + \hat{R}(0) \sum_{l=1}^{L-1} A_{l,1}\, Y^{1,l}]$$

$$= \hat{R}(0) \sum_{l=1}^{L-1} A_{l,1}\, Y^{1,l}$$

In the case of an AWGN channel ($L_k = L = 1$) under perfect power control conditions; we assume that $\forall k = 1...K, A_k = 1$, we have $M = 0$ and the other terms S, I and η are given by

$$S = \sqrt{E_b\, N_c}\, b_0^{(1)} \tag{18}$$

$$\eta = \sum_{j=0}^{N_c-1} \int_0^{T_s} n(t)\, C_j^{(1)}\, w(t - j\, T_c)\, dt \tag{19}$$

Based on the definitions of $R(\delta T_k)$, $\hat{R}(\delta T_k)$, $X^{k,l}$ and $Y^{k,l}$ with $l = 1$

$$I = \sqrt{\frac{E_b}{N_c}} \sum_{k=2}^{K} A_k\, W_k \tag{20}$$

with

$$W_k = [R(\delta T_k) X^{k,1} + \hat{R}(\delta T_k) Y^{k,1}]$$

where $R(\delta T_k)$, $\hat{R}(\delta T_k)$, $X^{k,1}$ and $Y^{k,1}$ are defined in (11), (12), (13) and (14) respectively.

From equation (10) and (20), we can see that aperiodic correlation function defined in (21) play an important role in the determination of DS-UWB system performance. In the next section we will introduce spatiotemporal chaotic sequences and analyze their correlation properties; Peak aperiodic autocorrelation parameter AC_a and Peak aperiodic cross-correlation parameter AC_c defined in (24) and (23) respectively.

The aperiodic cross-correlation function $AC_{x,y}$ of two N period sequences x and y is given by:

$$AC_{x,y}(l) = \begin{cases} \sum\limits_{j=0}^{N-l-1} x_j y_{j+l}^* & if \;\; 0 \leq l \leq N-1 \\ \sum\limits_{j=0}^{N+l-1} x_{j-l} y_j^* & if \;\; 1-N \leq l \leq -1 \\ 0 & if \;\; l >= N \end{cases} \tag{21}$$

The auto-correlation AC_x can be represented by:

$$AC_x(l) = C_{x,x}(l) \; \forall \, l \tag{22}$$

The peak aperiodic correlation parameters are defined as:

$$AC_c = max\{|AC_{x,y}(k)| : 0 \leq k \leq N-1\} \tag{23}$$

$$AC_a = max\{|AC_{x,x}(k)| : 0 \prec k \leq N-1\} \tag{24}$$

III. SPATIOTEMPORAL-CHAOS BASED GENERATION OF SPREADING SEQUENCES

Nonlinear dynamical systems possess many properties, which make them excellent candidates for use in generating spreading sequences for spread-spectrum communication systems [11,12,15]. Indeed the signals from such nonlinear dynamical systems are broadband, noise-like, and decorrelated. Therefore, developping approaches for generating amount of sequences with better quality is always key researching matter in the field of spreading sequences communication system.

In this work, we consider spatiotemporal-chaotic system to generate spreading sequences. This class of chaotic systems is advantageous on synchronization [13,14]. Moreover, for such applications chaotic systems used in the transmitter and the receiver, must to be synchronized.
The spatiotemporal sequences are generated by the conventional Coupled Map Lattices (CML) which are defined as follows

$$x_i(k+1) = (1-\epsilon)\, f(x_i(k)) + \epsilon\, f(x_{i-1}(k)) \tag{25}$$

where
- i: is the space index, $i = 1, ..., M$, M is the system dimension.
- k: is the time index, $k = 1, ..., N$
- ϵ: is the coupling coefficient.
- $f(.)$ is a one dimensional chaotic map. In this work, we choose the picewise-linear map where $f(x) = 4\, x\, mod(1)$ and in this case the system is called CML Picewise.
- $x_0(k)$ is the key sequence which is chosen to be a series of uniformed distributed values in $[0, 1]$.

Then, the operation of quantification to obtain a spatiotemporal-chaotic sequence is as follows

$$C_i = \begin{cases} 1 & if \;\; x_i > 0.5 \\ -1 & if \;\; x_i < 0.5 \end{cases} \tag{26}$$

In fig (2) and (3), we present by using i.i.d, Gold and CML Picewise sequences the peak autocorrelation parameter AC_a and the peak cross-correlation AC_c respectively versus number of sequences, for a spreading factor $N_c = 31$.

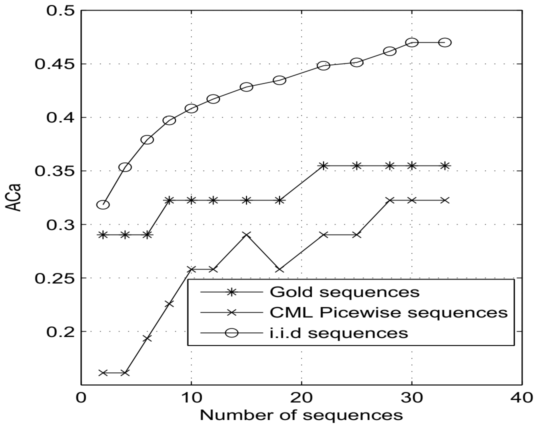

Fig. 2. **Peak auto-correlation parameter**

We show that the spatiotemporal chaotic sequences have better peak aperiodic auto-correlation parameter than Gold and i.i.d ones. However, for the number of sequences $\prec$8 sequences, the CML Picewise sequences and Gold sequences have nearly Peak aperiodic cross-correlation. For the number of sequences

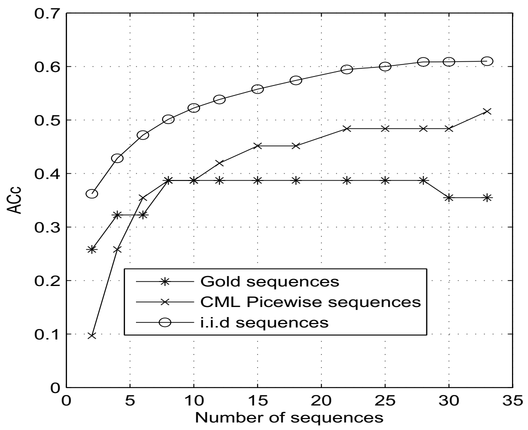

Fig. 3. **Peak cross-correlation parameter**

greater than 10, the Gold sequences have better AC_c parameter compared to CML Picewise and i.i.d sequences.

In the next section, we will analyze the MUI term versus different families of spreading sequences; traditional sequences and a CML Picewise sequences and we will evaluate the performance in BER term using the same sequences.

IV. Statistical Analysis MUI Term And BER Of Correlating Receiver

We begin by analyzing the statistics of MUI term for i.i.d random, Gold and a CML Picewise sequences. The parameters of DS-UWB system chosen for all simulation results are listed in Table 1. The pulse $w(t)$ considered in this work is given by

$$w(t) = (1 - 4\,\pi(\frac{t}{v})^2)\,e^{-2\,\pi\,(\frac{t}{v})^2}$$

where v represents a time normalization factor.

Parameter	Notation	Value
Time Normalization factor	v	0.2877ns
Chip duration	T_c	0.9ns
Pulse duration	T_w	0.5ns
Number of chips per bit	N_c	31
Number of users	K	8
Sampling Frequency	Fe	50 Ghz
Multipath number	$L_k = L$	10

TABLE I
Parameters of the DS-UWB system

We considered 10^5 symbols in the case of a noiseless channel ($N_0 = 0$) to compute the unuseful term defined by; Multi-User and Self Interference (MUSI=MUI+SI). In the case of an AWGN channel, $SI = 0$ and subsequently MUSI=MUI.

Sequences	MUI variance
i.i.d	0.0092
Gold	0.0055
CML Picewise	0.0062

TABLE II
MUI Power versus classical and spatiotemporal-chaotic sequences sequences in AWGN channel

Sequences	MUI variance
i.i.d	0.0992
Gold	0.0964
CML Picewise	0.0207

TABLE III
MUSI Power versus traditional and spatiotemporal-chaotic sequences in Rayleigh multipath channel

We can see that the MUI Power is not the same for the spreading sequences families considered in this work. Therefore, we can conclude that the performance on asynchronous DS-UWB depends on the choice of spreading sequences especially in the case of multipath channel. We will see how this is reflected on BER.

In the second part of this section, Monte Carlo simulation was used to validate our results given in the previous part.

In fig 4, the Bit Error Rate (BER) of DS-UWB assuming 7 asynchronous interferers using i.i.d, Gold and CML Picewise sequences are plotted versus SNR in AWGN channel. We observe that the Gold and CML Picewise sequences have the same performance and better than i.i.d sequences. This observation confirm the result given in fig (3) for 8 sequences, when Gold and Picewise sequences have the same Peak aperiodic cross-correlation parameter.

Fig (5) shows the BER performance as a function of SNR assuming 7 asynchronous interferers in rayleigh multipath channel using the same sequences. As seen, the system employing the CML Picewise se-

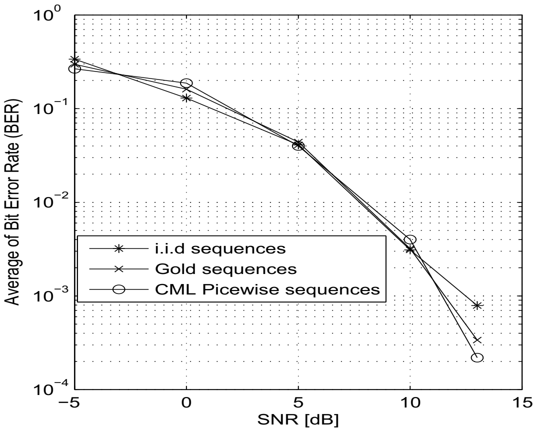

Fig. 4. **Average BER assuming 7 asynchronous interferers in AWGN channel**

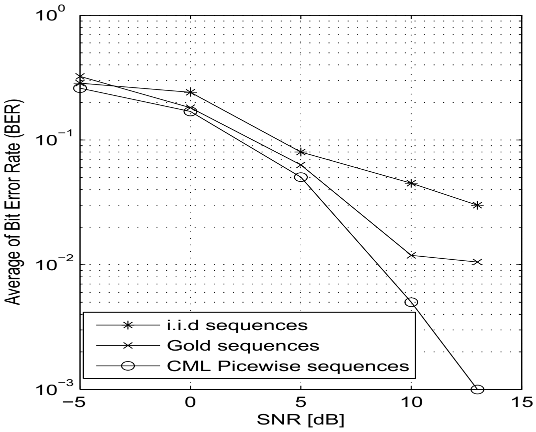

Fig. 5. **Average BER assuming 7 asynchronous interferers in Rayleigh channel**

quences had the best performance compared to classical codes. This result confirm the good Peak aperiodic auto-correlation criterion provided in fig (2).

For DS-UWB systems in AWGN channel, the MUI decreases as the cross-correlation function reduces between the considered sequences. In addition, a very good auto-correlation ensures a better reception in multipath channels by minimization the SI term.

V. CONCLUSIONS

In this work, we highlighted the importance of the choice of code sequences in the determination of the performance of DS-UWB system. This was done by computing the MUSI for three different sequences. We proposed spatiotemporal sequence to be used in DS-UWB system, we showed that these sequences are better than other sequences in the case of 8 active users especially in multipath channel, this is du to the fact that spatiotemporal sequences have good autocorrelation function, which minimizes the SI term. It is interesting to find a compromize between cross and auto-correlation function to optimize the performance of DS-UWB system in the case of multipath channel.

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