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Improvement Performance of TH-UWB System Using Spatiotemporal Chaotic Sequences

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Abstract. The residential environments are an important scenario for Ultra Wide Band (UWB) communication systems. In this paper, the performance of correlating receivers operating in a Line-Of-Sight (LOS) scenario in these environments is evaluated. In such channel the interference between users is an additional source of noise, that may deteriorate the performance of the system. In this research axis; it aims to exploit the richness of chaotic and spatiotemporal sequences with respect to topologic properties. We check through simulations, that chaotic sequences are shown to have improved performance compared to the Gold sequences in terms of Bit Error Rate (BER).
Keywords: Time hopping Utra wide band, Chaotic sequences, Multi-path channel, Spatiotemporal..

1 Introduction

Ultra-wideband (UWB) systems [1] use ultrashort impulses to transmit information which spreads the signal energy over a very wide frequency spectrum of several GHz. The sucess of UWB systems for short-range wireless communications [1,4] is due to the fact that they potentially combine reduced complexity with low power consumption, low probability-of-intercept (LPI) and immunity to multipath fading. In 2004, the IEEE 802.15.4a group presented a comprehensive study of the UWB channel over the frequency range 2-10 GHz for indoor residential, indoor office, industrial, outdoor and open outdoor environments [5]. In this work we are concerned with the indoor residential environment channel.
In time-hopping format (TH-UWB) TH codes are used as multiple user diversity and pulse position modulation (PPM) as data transmission [1,4]. As any wireless communication system, the interference between users is an additional source of noise, that may degrade the performance of the system. Thus the choice of the modulation type, the multiple access techniques, the codes allowing multiple access is important in the determination of the system performance. Different works have tackled the statistical characteristics of the

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Multi-User Interference (MUI). Many of them have modeled the MUI as a random Gaussian process [1,4,6]. Due to this assumption, no code optimization has been considered.
Other works have dealt with the optimization of the performance by code selection [2,3]. In [3], the authors considered the asynchronous case, multi channel propagation such IEEE 802.15.3a channel model and rake receiver; they derived a criterion to find optimal codes that minimizes the variance of the MUI of a reference user. The proposed criterion appears as a significant measure to design TH-codes that optimize the performance of a reference user.

In [7] a criterion named Average Collision Number (ACN) that minimize the MUI variance has been defined then the average BER of active users was computed to confirm the relevance of this criterion, it has been shown that sequences having smaller ACN allow better BER. As we show later this criterion is unsuitable in some cases for selecting codes. In this contribution, instead of the ACN criterion we will use the new criterion called Average of Squared Collision Number (ASCN). Based on this criterion we will analyse how much chaoticity of the chaotic codes affects the performance of the considered TH-UWB system. To validate our criterion, the performance in terms of BER is computed by simulating the TH-UWB system with line-of-sight (LOS) multipath and AWGN channel in a residential environment IEEE 802.15.4a.

This paper is organized as follows. Section 2 gives a detailed description of the TH-UWB system; after introducing the TH-UWB-PPM system model, we give the format of the channel model IEEE 802.15.4a and the statistics of correlation receiver. In Section 3 the ASCN criterion is defined and compared to ACN [7]. In section 4 we define the different considered sequences; for chaotic sequences, the ASCN is computed versus bifurcation parameter and compared to Lyapunov exponent. In section 5, we validate our method by reporting simulation results showing the advantage of using ASCN. Finally we conclude in section 6.

2 System description

In this section, we begin by reminding the TH-UWB system model and the expression of the received signal in a synchronous TH-UWB system using the PPM modulation. Then we compute the variance of the MUI versus TH-codes when a correlation receiver is used.

2.1 System model

A typical expression of the TH-UWB transmitted signal for a user j is given by equation 1.

$$s^{(j)}(t) = \sum_{k=-\infty}^{\infty} \sum_{l=0}^{N_f-1} w(t - kT_s - lT_f - \widetilde{c}_l^{(j)} T_c - d_k^{(j)} \delta) \tag{1}$$

Where $w(t)$ is the transmitted UWB pulse shape, T_s is the period of one bit.Every bit is conveyed by N_f frames. Each frame has a duration of T_f and is divided into N_c time slots. Each time slot has a duration of T_c. $\widetilde{c}_l^{(j)}$ is the TH code sequence assigned to the user j, where $\widetilde{c}_l^{(j)} \in \{0, 1, \ldots, N_c - 1\}$. The location of each pulse in each frame is defined by the code $\widetilde{c}_l^{(j)}$. $d_k^{(j)} \in \{0, 1\}$ is the binary transmitted symbol at time k by user j, δ is the time shift associated with binary PPM, the pulses corresponding to bit 1 are sent δ seconds later than the pulses corresponding to bit 0. $N = N_c N_f$ presents the total processing gain of the system.

2.2 IEEE 802.15.4a Channel Model (CM1)

The IEEE 802.15.4a has recently proposed a channel model [5] propagation in residential area [5]. According to this model the impulse response is [5,8],

$$h^{(j)}(t) = \sum_{m=0}^{M-1} \sum_{r=0}^{R-1} \alpha_{r,m}^{(j)} \delta(t - T_m^{(j)} - \tau_{r,m}^{(j)}) \tag{2}$$

where $\alpha_{r,m}$ is the tap weight of the r-th ray (path) in the m-th cluster, T_m is the arrival time of the m-th cluster and $\tau_{r,m}$ is the arrival time of the r-th ray in the m-th cluster. The distribution of the cluster arrival times is given by a Poisson process and the distribution of the ray arrival times is given by a mixed Poisson process [5]. The small scale fading statistics are modeled as Nakagami-m distributed with different m-factors for different multipath components. The probability density function of Nakagami-m distribution is given in [5]. The ray amplitudes are lognormal distributed. The channel model which is used in the paper is for LOS scenarios in residential environments, referred to as CM1 [5]. The parameters of the channel are modeled as a function of the transmitter-receiver distance and the line-of-sight (LOS) availability.

If N_u is the number of active users transmitting asynchronously; the received signal is

$$r(t) = \sum_{j=1}^{N_u} \sum_{m=0}^{M-1} \sum_{r=0}^{R-1} \alpha_{r,m}^{(j)} s^{(j)}(t - T_m^{(j)} - \tau_{r,m}^{(j)}) + n(t) \tag{3}$$

2.3 Statistics of the correlation receiver

The output of the correlation receiver of the i^{th} user at time h is given by:

$$s_h^{(i)} = \sum_{p=0}^{N_f-1} \int_{hT_s+pT_f+\widetilde{c}_p^{(i)}T_c+\tau_{0,0}^{(i)}+T_0^{(i)}}^{hT_s+pT_f+\widetilde{c}_p^{(i)}T_c+T_c+\tau_{0,0}^{(i)}+T_0^{(i)}} r(t)v(t-hT_s-pT_f-\widetilde{c}_p^{(i)}T_c-\tau_{0,0}^{(i)}-T_0^{(i)})dt \tag{4}$$

where $v(t)$ is the receiver's template signal defined by $v(t) = w(t+\delta) - w(t)$. An accurate value of $\tau_{0,0}^{(i)}$ can be obtained by UWB acquisition techniques such as [13]. From the previous equations and after variable changes, we obtain

$$s_h^{(i)} = T_U(i) + T_{ISI}(i) + T_I(i) + T_N(i) \tag{5}$$

with

T_U is the useful signal, T_{ISI} is inter-symbol interference signal, T_I is the MUI and T_N is the term corresponding to the noise.

In [7], we defined a criterion named ACN for selecting codes in synchronous and single-path TH-UWB system. Also we have shown numerically, that this criterion is adequate even in the multi path channel.
Indeed in the synchronous case, it has been shown that

$$T_I(i) = E_w \sum_{j=1, j\neq i}^{N_u} \alpha^{(j)}(2d_h^{(j)} - 1)cn(i,j) \tag{6}$$

where E_w is the amplitude which controls the transmitted power, $\alpha^{(j)}$ is the tap weight of the user j, $d_h^{(j)}$ is the binary sequence, $cn(i,j)$ is the number of collision between codes $\widetilde{c}^{(i)}$ and $\widetilde{c}^{(j)}$. $\widetilde{c}^{(j)}$ can be computed by taking into account the developed Time-Hopping Codes (DTHC) [9] corresponding to TH codes as follows, for a given code $\widetilde{c}^{(j)}$, the DTHC is a binary code of length N_cN_f and is defined by

$$c_r^{(j)} = \begin{cases} 1 \; if \; r = \widetilde{c}_l^{(j)} + lN_c, r = 0\ldots, N_cN_f - 1. \\ 0 \; otherwise. \end{cases} \tag{7}$$

$$cn(i,j) = \sum_{l=0}^{N_fN_c-1} c_l^{(i)} c_l^{(j)} \tag{8}$$

The Average Collision Number ACN of the sequence set $(\widetilde{c}^{(j)})$, $j = 1, \ldots N_u$ is therefore defined by [7]:

$$ACN = \frac{1}{N_u(N_u-1)} \sum_{i=1}^{N_u} \sum_{j=1, j\neq i}^{N_u} cn(i,j) \tag{9}$$

3 ASCN criterion

In [7] we have defined the ACN criterion, and we have showed that the experimental results validate the relevance of the ACN as an 'off-line' performance evaluation criterion for codes sequences. These results motivated us to use the ACN as a tool to predict the performance of code sequences.
However, we found intuitively that this criterion may in some cases be unsuitable for code selection. For example we take three users ($N_u = 3$). For scenario A, the THC are respectively $\widetilde{c}_l^{(1)} = [\,0\,0\,1\,1\,]$, $\widetilde{c}_l^{(2)} = [\,1\,1\,1\,1\,]$ and $\widetilde{c}_l^{(3)} = [\,0\,0\,2\,2\,]$. We find that the total number of collisions is equal to 4. For scenario B, the THC are respectively $\widetilde{c}_l^{(1)} = [\,0\,0\,1\,1\,]$, $\widetilde{c}_l^{(2)} = [\,0\,0\,1\,1\,]$ and $\widetilde{c}_l^{(3)} = [\,2\,2\,2\,2\,]$. Also the total number of collisions is equal to 4. In both scenarios, $ACN = \frac{4}{6}$.
To remedy to this drawback, we defined a new criterion called Average of

Squared Collision Number ASCN which is defined as:

$$ASCN = \frac{1}{N_u(N_u-1)} \sum_{i=1}^{N_u} \sum_{j=1, j\neq i}^{N_u} cn^2(i,j) \tag{10}$$

This is motivated by the observation that when the collisions are regrouped on few positions the performance are significantly degraded.
Now if we consider this new criterion; for scenario A, $ASCN = \frac{8}{6}$. For scenario B, $ASCN = \frac{16}{6}$. In this work, we propose to use the ASCN criterion to examine the performance of the TH-UWB system.
This is confirmed by Table 1 where we represented the BER for the two scenarios with $N_u = 3$ and $N_c = 4$. We can see that the BER of scenario A is almost the half of the BER of scenario B.

Table 1. ACN vs ASCN with BER simulation.

	ACN	ASCN	BER
Scenario A	4/6	8/6	0.0728
Scenario B	4/6	16/6	0.1662

4 ASCN optimization using chaotic sequences

Chaotic sequences have some properties that motivate researchers to use them in various applications: determinism, long term unpredictability and high sensitivity to initial conditions. Especially chaotic sequences generated by one dimensional non linear transformation have been used in cryptography, watermarking, spectrum spreading systems [10].

We begin by defining Gold and chaotic sequences that will be considered in this work; then we define the ASCN for chaotic sequences versus their bifurcation parameter, and analyse how chaoticity measured by Lyapunov exponent is correlated with the ASCN.

Gold sequences

The Gold sequence based TH codes are generated as shown in [11], where we illustrate how is generated a sequence taking values in $\{0, 1, \cdots, N_c - 1 = 7\}$ and with a length $N_f \leq 29$.

Sequences generated by Skew tent map

Chaotic sequences are generated by the Skew tent map defined by:

$$x_{n+1} = \begin{cases} \frac{x_n}{r}, & 0 \leq x_n \leq r \\ \frac{1-x_n}{1-r}, & r < x_n \leq 1 \end{cases} \tag{11}$$

The skew tent map exhibits chaotic behavior for every value of the bifurcation parameter $r \in [0\ 1]$.

Sequences generated by Logistic map

The logistic map is given by the following equation:

$$x_{n+1} = rx_n(1 - x_n) \tag{12}$$

The logistic map exhibit alternatively regular and chaotic behavior when r belongs to [3 4].

Figures 1 and 2 show the Lyapunov exponent and ASCN versus the bifurcation parameter r for different chaotic sequences. We can see that the curves of the ASCN follow the one of Lyapunov exponent and that the greater the exponent is the smaller the ASCN. For logistic map $r = 4$ gives the best value of Lyapunov exponent and ASCN. For skew tent map $r = 0.5$, have the best ASCN and Lyapuonv exponent. According to these two examples, we showed

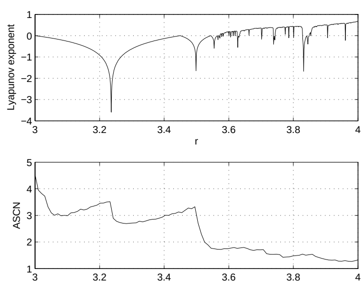

Fig. 1. Lyapunov exponent and ASCN for logistic.

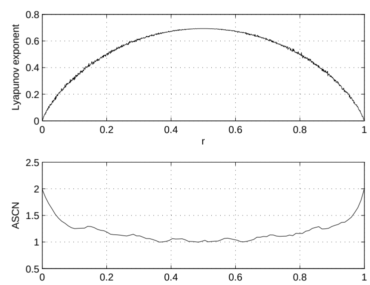

Fig. 2. Lyapunov exponent and ASCN for skew tent map.

numerically that the ASCN of a quantized chaotic sequence depends on the chaoticity of these sequences measured by their Lyapunov exponent.

In Figure 3, we represent the ASCN versus user number for $N_c = 8$; for Gold sequences considered here as a reference and the two quantized chaotic sequences defined above; the ASCN of chaotic sequences are averaged over 100 realizations. For both logistic and skew tent maps we considered the bifurcation parameter that gives the best ASCN, i.e. $r = 4$ for logistic map and $r = 0.5$ for skew tent.

The results show that skew tent map chaotic sequences, have a better ASCN than Gold sequences. We can notice likewise that Gold sequences show better performance compared to the chaotic sequence when $N_u < 6$, this is because of the orthogonality of this sequences.

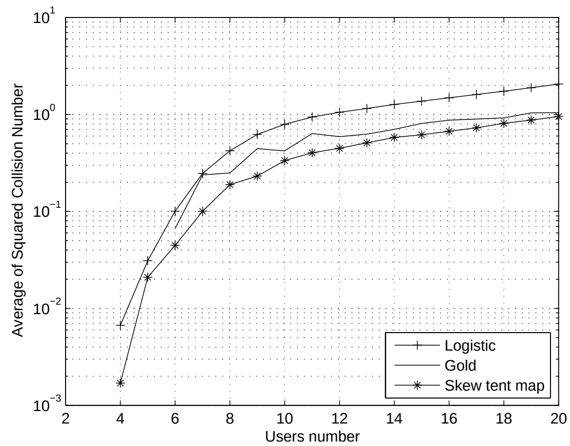

Fig. 3. ASCN versus user number for different types of codes. $N_c = 8$.

Sequences generated by spatiotemporal chaotic systems

Spatiotemporal chaotic systems have been the subject of intensive research in physics in the 80's to model and study some physical phenomena exhibiting chaotic behavior in time and space at once, such as turbulence, convection in chemical reactions and engineering. They have generally been modeled by networks of coupled lattice or CML (Coupled Map Lattices). Different models of CML have been proposed in the literature [12]. In our work we are interested only to the family of CML given by:

$$x_{i+1}(k+1) = (1-\epsilon)f\left[x_{i+1}(k)\right] + \epsilon f\left[x_i(k)\right] \tag{13}$$

Where:

- i is the space index, $i = 1, \cdots, M$, M the system dimension
- k is the time index, $k = 1, \cdots, N$
- f is a one dimensional chaotic map defined in the interval [0 1].
- ϵ is the coupling coefficient.

Spatiotemporal systems exhibit greater complexity compared to classical chaotic systems. They also provide more chaotic sequences, this increases the chaoticity of the system is a property of great importance in the use of CML to generate code sequences.

5 Performance comparaison of classical and chaotic codes sequences

In this section, we present the performance of MA-TH-UWB system in a residential environment CM1 channel by simulating the system and computing the

BER; we consider the correlation receiver and the Gaussian pulse defined by:

$$w(t) = (1 - 4\pi(\frac{t}{\tau})^2)\exp(-2\pi(\frac{t}{\tau})^2) \tag{14}$$

The simulation parameters are listed in table 2. For simplicity, we assume that

Table 2. Simulations parameters of TH-UWB system

Simulation parameters	Acronym	Value
Pulse duration	τ	0.2ns
Sampling frequency	F_s	8GHz
Chip duration	T_c	1ns
Number of sampling	N_e	50
Number of chip	N_c	8
Number of frame	N_f	4
Number of bits for each user	Nb	10^5
Factor for spread spectrum Gold	N	31
Number of path	L	10
Signal to Noise Ratio	SNR	10dB

the number of paths L is the same for all users.
For chaos based TH-codes we used logistic and skew tent maps with parameters $r = 4$ and $r = 0.5$ respectively. These values correspond to the minimal of ASCN (the maximal of Lyapunov exponent) in the two cases. The simulation results are shown in Fig. 4 where we presented the BER of the system versus user number for Gold and the two chaos based sequences. We can see that skew tent map based sequences allow the best performance however logistic map based ones allow the worst performance. These results compared to the results shown in Fig. 3 prove that the ASCN is a suitable criterion to select TH-codes.

The ASCN of the used skew tent map is equal to 1 however it is equal to

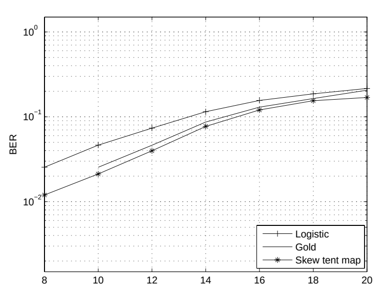

Fig. 4. BER performance of asynchronous TH-UWB system for different TH codes.

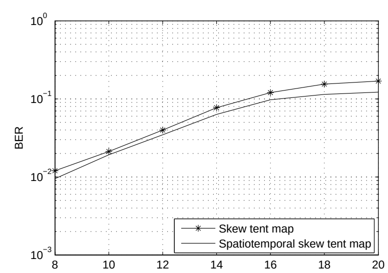

Fig. 5. BER performance of asynchronous TH-UWB system: Skew tent map vs. spatiotemporal.

almost 1.3 for the used logistic map. This explains the superiority of skew tent map based sequences with respect to the logistic map based ones. In Fig.

5 we represent the BER versus user number for the skew tent map and the spatiotemporal system (13) based on skew tent map, for a coupling coefficient $\epsilon = 0.97$, the spatiotemporal are averaged over 100 realizations and the bifurcation parameter is set to the value that gives the best ASCN, i.e. $r = 0.5$. We can see clearly that the THC generated by the CML can get better performance than THC generated by the skew tent map. Thus, the proposed spatiotemporal chaotic system considered is not only advantageous in terms of synchronization, but can also generate THC outperform the conventional chaotic system.

6 Conclusion

In this contribution we considered code selection problem for MA-TH-UWB systems. We defined the ASCN criterion to choose codes and we showed that the lower the ASCN the better the performance. Based on this result, we chose to look for codes with low ASCN by using the features of chaotic transformation; we found that the ASCN of chaotic map based sequences depends on the chaoticity of the map measured by Lyapunov exponent; we showed specifically that the higher the Lyapunov exponent the lower the ASCN; and subsequently the better the performance.
On the other hand, the use of THC generated by spatiotemporal chaotic system has shown better performance in term of BER that other sequences used in this article. This improves the quality and the security of the transmission, and shows the significance of using chaos specifically spatiotemporal chaotic system in communication.

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