SPATIOTEMPORAL CHAOTIC SEQUENCES FOR ASYNCHRONOUS DS-UWB SYSTEMS

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ABSTRACT

In this study, we address the effect of spreading sequences on the performance of asynchronous direct-sequence (DS) ultra-wideband (UWB) systems. We consider the two cases of short and long sequences in a multipath environment. In particular, we propose the use of sequences generated with a family of spatiotemporal chaotic systems, namely Piecewise Coupled Map Lattices (PCML), as spreading sequences. Such sequences are shown to reduce the MUI variance with regard to i.i.d. and Gold sets for both short and long sequences. Furthermore, simulation results show that the use of long PCML codes improves the average bit error rate (BER) of the system, which hence can accomodate more active users.

1. INTRODUCTION

Ultra Wide-Band (UWB) communication systems have recently drawn considerable attention among both, researchers and standardization communities, for their advantageous features; low power density, large bandwidth, low complexity and excellent multipath immunity. Time Hopping (TH) [1] and Direct Sequence (DS) [1, 2] are the main multiple access (MA) approaches for UWB Impulse Radio (IR) technology. In this paper, we focus on asynchronous DS-UWB systems demodulated by a Rake receiver. Just like conventional code division multiple access (CDMA), DS-UWB systems are based on direct-sequence spread spectrum technique to ensure multiple access.

In most of the recent works [2, 3] on DS-UWB technology, conventional codes such as independent identically distributed (i.i.d.) and Gold sequences have been considered. Due to their poor correlation properties their performance is however affected by the multi-user interference (MUI) and inter-symbol interference (ISI) terms which represent the main degradation cause, hence a capacity limitation in terms of the users number. The ISI term is not so important if the channel is short enough compared to the symbol period. However, the MUI is inherent to the DS-UWB system and can be mitigated only by properly designing the codes. The MUI has been assumed to be a random Gaussian process in free-space communications [2] or in multipath channels [3, 4].

According to this assumption, the resulting MUI does not depend on the code realization, and thus, no code optimization has been done. The authors in [9] have derived a more general expression of the MUI variance for short codes, which involves the correlation properties of the spreading codes. They have further proposed a codes-selection criterion in the sense of the minimization of the MUI variance,

which is independent of the number of fingers of the Rake receiver. However, to our knowledge, no study has been done using long spreading sequences in DS-UWB systems.

In this work, we address the two cases, short and long codes. We consider a family of spreading codes which are generated with chaotic dynamical systems. In this context, a number of contributions, using chaotic [5, 6] or spatiotemporal chaotic [7] spreading codes for DS-UWB communication system have been done by several researchers. In [7], the authors have studied the correlation properties of the spatiotemporal chaotic sequences and have also evaluated the performance of the DS-UWB system in AWGN and Rayleigh multipath channels. In this paper, we propose the use of a family of spatiotemporal chaotic systems, namely Piecewise Coupled Map Lattices (PCML), which has been considered in previous works for DS-CDMA systems [8]. Firstly, when they are used as short codes, the proposed PCML sequences are shown to outperform conventional ones, namely Gold and i.i.d., in the sense of the codes-selection criterion which has been proposed in [9]. Secondly, we investigate the DS-UWB system performance, in terms of bit error rate (BER), with respect to the spreading codes. Simulation results show that long PCML codes achieve the best performance levels and increase consequently the system capacity in terms of users number, as compared to long i.i.d., short PCML and short Gold sequences.

This paper is organized as follows. In section 2, a brief presentation of the system model and the Rake receiver structure is given. Then, we present the selection criterion enabling the choice of short codes minimizing the MUI variance. In section 3, we explain the generation of PCML codes. In section 4, we discuss the simulation results obtained with respect to the codes-selection criterion as well as the BER performance. Some conclusions are drawn in section 5.

2. TRANSMISSION MODEL

We consider an asynchronous direct-sequence UWB system with K interfering users using a binary phase-shift keying (BPSK) modulation. The baseband system model is shown in figure 1. The transmitted signal of the kth user is given by [2]:

$$S_k(t) = \sqrt{P_k} \sum_{i=-\infty}^{\infty} b_k(i) \sum_{j=0}^{N_c-1} C_k(j) w(t - i T_s - j T_c - \tau_k), \quad (1)$$

where

- P_k is the transmitted signal power of user k,
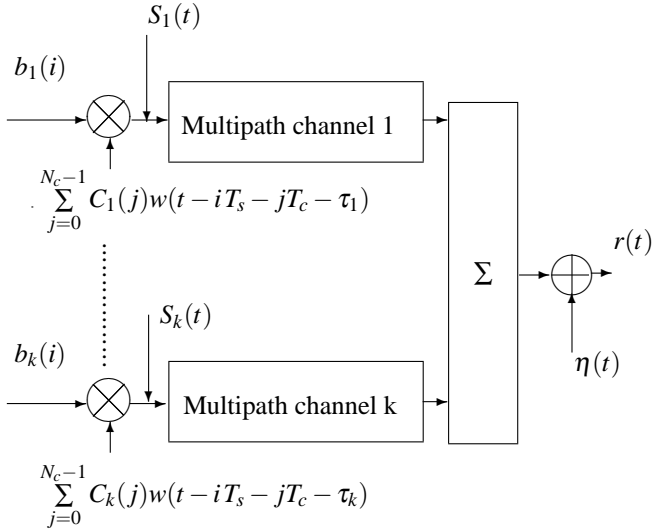- T_s is the symbol time,

Figure 1: A model of an asynchronous DS-UWB system in a multipath channel

- T_c is the chip duration,
- N_c is the number of chips per symbol,
- $w(t)$ is a pulse waveform of duration $T_w << T_c$ and is normalized to satisfy $\int_{-\infty}^{\infty} w(t)^2 \, dt = 1$,
- $b_k(i) \in \{-1, +1\}$ are the information symbols of user k assumed to be independent and identically distributed,
- C_k is the spreading sequence taking values in the set $\{-1, +1\}$,
- τ_k denotes the time asynchronism, assumed to be a uniform random variable within $[0, T_s]$.

2.1 UWB fading channel model

According to [10], the channel impulse response of the kth user is modelled as

$$h_k(t) = \sum_{l=1}^{L} A_{l,k} \delta \left(t - \theta_{l,k} \right) \quad (2)$$

We assume that the delays verify $\forall l, k, \; \theta_{l,k} < \theta_{l+1,k}$. For simplicity, L is the number of paths, assumed to be the same for all users. The amplitude $A_{l,k}$ is usually assumed to be dependent on the delay $\theta_{l,k}$ as $A_{l,k} = a_{l,k} f(\theta_{l,k})$, where $a_{l,k}$ are independent and zero-mean random variables (rv) which account for the amplitude statistics (independent of $\theta_{l,k}$) and $f(\theta_{l,k}) = e^{-\theta_{l,k}/2\gamma}$, where γ is the path power decay time. For sake of simplicity, we also consider that the channel response is normalized $\sum_{l=1}^{L} \left[A_{l,k}^2 \right] = 1$ to have unit energy in order to remove the path loss factor. In the following we put $I_{l,k} := \mathbb{E}_a \left[(A_{l,k})^2 \right] = \sigma_a^2 . f^2 \left(\theta_{l,k} \right)$ where $\sigma_a^2 = \mathbb{E}_a \left[(a_{l,k})^2 \right]$.

2.2 Rake Receiver Structure

After propagation through the multipath channel, the received input signal is the sum of the attenuated and delayed transmitted signals from the different users. Its expression is given by

$$r(t) = \sum_{k=1}^{K} \left(\sum_{l=1}^{L} A_{l,k} S_k(t - \theta_{l,k}) \right) + \eta(t), \quad (3)$$

where $\eta(t)$ is an Additive White Gaussian Noise (AWGN) with two-sided power spectral density $N_0/2$. In order to capture most of the energy carried by the large number of resolvable paths, typically, over one hundred, we assume that the channel estimation algorithm can provide the correlator template and we consider maximal-ratio combining (MRC) Selective rake (SRake) receiver with $N \leq L$ fingers. We also assume that the receiver is synchronized on user 1, so $\tau_1 = 0$. Thus, the Rake receiver output for the first symbol of the first user is

$$Z = \sum_{n \in \mathcal{N}} A_{n,1} \int_0^{T_s} r(t + \theta_{n,1}) \, \upsilon_1(t) \, dt = S + I_c + I_s + I_\eta \quad (4)$$

where $\upsilon_1(t) = \sum_{j=0}^{N_c-1} C_1(j) \, w(t - jT_c)$ is the receiver template for user 1, $\mathcal{N}$ represents a set of paths for the desired user with card $(\mathcal{N}) = N$. S and I_η are the energy collected from the user of interest and the filtered Gaussian noise, respectively and their expressions do not depend on the multiple access code.

- I_s is the ISI for the desired user, and is expressed as

$$I_s = \sqrt{P_1} \sum_{n \in \mathcal{N}} A_{n,1} \sum_{l \neq n = 1}^{L} A_{l,1} y_{l,n,1}(0) \quad (5)$$

- I_c is the MUI, and is given by

$$I_c = \sum_{n \in \mathcal{N}} A_{n,1} \sum_{k=2}^{K} \sqrt{P_k} \sum_{l=1}^{L} A_{l,k} y_{l,n,k}(\tau_k) \quad (6)$$

where,

$$y_{l,n,k}(\tau_k) = \int_0^{T_s} \sum_{i=-\infty}^{\infty} b_k(i) \sum_{j=0}^{N_c-1} C_{k,i}(j) \quad (7)$$
$$w(t - iT_s - jT_c - \tau_k - \triangle\theta_{l,n,k}) \upsilon_1(t) \, dt,$$

with $\triangle\theta_{l,n,k} = \theta_{l,k} - \theta_{n,1}$.

Using short sequences, the same code $C_{k,i} = C_k$ for all bits of user k is considered. Hence, the cross-correlations between users remain unchanged over time. In the case of long sequences, information bits of a given user are spread with different spreading codes. Thus, the MUI changes randomly from bit to bit where we employ the fact that the $C_{k,i}$ denotes the code for bit i of user k.

The ISI term is related to the autocorrelation of the code of user 1 and is not so important if the channel is short enough compared to the symbol period. However, the MUI can only be mitigated by a judicious choice of the multiple access codes.

2.3 Variance Expression of the MUI

The authors in [9] have proposed an approach for the optimization of spreading sequences in asynchronous DS-UWB systems. In particular, they have derived a selection criterion (β) of optimal sequences which is based on minimizing the MUI variance. However, they have considered only short-type sequences. The expression of the MUI variance denoted

by $\sigma_S^2 := \mathbb{E}_{a,b,\theta,\tau}\left[I_c^2\right]$, which is averaged over the channel amplitude $a_{l,k}$, the symbol b_k, the asynchronism τ_k and the delay θ_k, is given by (8)

$$\sigma_S^2 = \frac{\gamma_1}{T_s} \sum_{k=2}^{K} P_k \psi_k \beta_{1,k} \qquad (8)$$

where

$$\gamma_1 = \int_{-\infty}^{\infty} r_{ww}^2(t)\,dt, \qquad (9)$$

$$r_{ww}(s) = \int_{-\infty}^{\infty} w(t)\,w(t-s)\,dt, \qquad (10)$$

$$\beta_{1,k} = \sum_{q=0}^{N_c-1} \left[\mathscr{C}_{1,k}^{-2}(q) + \mathscr{C}_{1,k}^{+2}(q)\right], \qquad (11)$$

$$\mathscr{C}_{m,n}^{-}(q) = \sum_{k=0}^{q-1} C_m(k)\,C_n(k-q), \qquad (12)$$

$$\mathscr{C}_{m,n}^{+}(q) = \sum_{k=q}^{N_c-1} C_m(k)\,C_n(k-q), \qquad (13)$$

$$\psi_k = \sum_{n \in \mathscr{N}} \mathbb{E}_\theta\left[I_{n,1}\right] \sum_{l=1}^{L} \mathbb{E}_\theta\left[I_{l,k}\right]. \qquad (14)$$

The expression (8) clearly shows the dependance of the MUI variance on the pulse shape through the parameter γ_1, and on the codes through $\beta_{1,k}$ and on the channel through ψ_k. The interesting formulation of this expression is that the codes contribution appears in factor of the other terms and thus, can be optimized independently from the channel and the pulse waveform. So, it is necessary to find *good* sequences to minimize the MUI variance and to improve consequently the system performance in terms of BER.

The Average BER of user of interest 1 is minimum, if and only if, the set of pairs of DS codes $\{(C_1, C_k), k=2,....,K\}$, satisfies

$$\sum_{q=0}^{N_c-1} \left[\mathscr{C}_{1,k}^{-2}(q) + \mathscr{C}_{1,k}^{+2}(q)\right] = N_c \qquad (15)$$

Clearly we can see the importance of the criterion $\beta_{1,k}$ which must verify Eq. (15), to minimize the MUI variance and therefore, to improve the system performance.

3. GENERATION OF SPREADING SEQUENCES WITH SPATIOTEMPORAL CHAOTIC MAPS

Chaotic dynamics have been shown to have interesting properties for the generation of spreading sequences in several spread-spectrum applications, such as DS-CDMA systems. Indeed, owing to their broadband feature, chaotic sequences have been shown to improve the system performance with regard to conventional sequences (m-sequence, Gold, Gold-Like,...) [11, 12]. A large family of chaotic systems have been considered in the literature for this purpose. In this work, we address a kind of spatiotemporal chaotic systems, namely the Piecewise Coupled Map Lattices (PCML) [8, 13] defined by :

$$x_i(k+1) = (1-\varepsilon)\,f(x_i(k)) + \varepsilon\,f(x_{i-1}(k)), \qquad (16)$$

where

- i is the space index, $i = 1,...,M$,
- k is the time index, $k = 1,....,N$,
- ε is the coupling coefficient, we here choose $\varepsilon = 0.98$,
- $f(.)$ is a one dimensional chaotic map. In this paper, we consider the piecewise-linear map defined by $f(x) = 4x\,mod(1)$,
- $x_0(k)$ is the key sequence which is chosen to be a series of uniformly distributed values in $[0,1]$.

This system can generate a set of M-long sequences, each of which is a series of N real values
: $\{x_i(k) \in [0,1], i = 1\cdots M, k = 1\cdots N\}$. These sequences can be transformed to binary sequences by applying a quantization in the following way :

$$\begin{cases} Q(x_i(k)) = -1 \;\; if \; x_i(k) \leq 1/2 \\ Q(x_i(k)) = +1 \;\; if \; x_i(k) > 1/2. \end{cases} \qquad (17)$$

The so obtained sequences can then be used as spreading codes C_k for the DS-UWB system as we shall show in the following sections.

4. SIMULATION RESULTS

In this section we propose to assess the effect of the choice of spreading sequences on the performance of asynchronous DS-UWB systems. We consider three families of spreading sequences, namely Gold, i.i.d. and PCML sequences (as generated in section 3) and we treat the two cases of short and long codes. Regarding the pulse waveform, we consider the Scholtz monocycle pulse defined by the second derivative of the Gaussian pulse and which is given by

$$w(t) = (1 - 4\pi(\frac{t}{\tau_p})^2)\,e^{-2\pi(\frac{t}{\tau_p})^2} \;\; for \; t \in [0, T_w] \qquad (18)$$

where τ_p represents a time normalization factor.

4.1 Selection criterion β for short sequences

We first consider the case of short codes and try to compare the performance of the three considered families with respect to the criterion β. We choose a spreading factor $N_c = 31$. We report in table (1) the minimum values achieved by $\beta_{m,n}$ over different possible sequence pairs (m,n). For the i.i.d. and PCML codes, we consider a set of 1000 sequences, whereas the number of Gold codes is limited by construction to 33 ($N_c = 31$). The table shows that the PCML codes achieve the least value of $min\,\beta$, and that the Gold ones achieve the largest value with a great gap (91 against 379). The i.i.d. codes achieve a medium value which is closer to the PCML than the Gold ones (159).

min $\beta_{m,n}$	Value
Short i.i.d. sequences	159
Short Gold sequences	379
Short PCML sequences	91

Table 1: Values of min $\beta_{m,n}$ for the short code families

For a further investigation of this criterion, we plot in figures 2, 3 and 4 the distribution of the number of code pairs versus the values of $\beta_{m,n}$ for the three code families, Gold, i.i.d. and PCML, respectively.
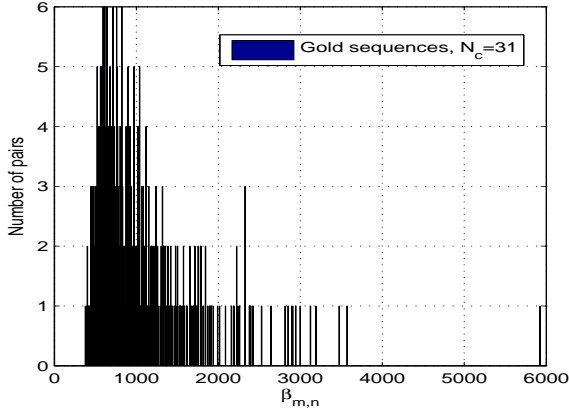
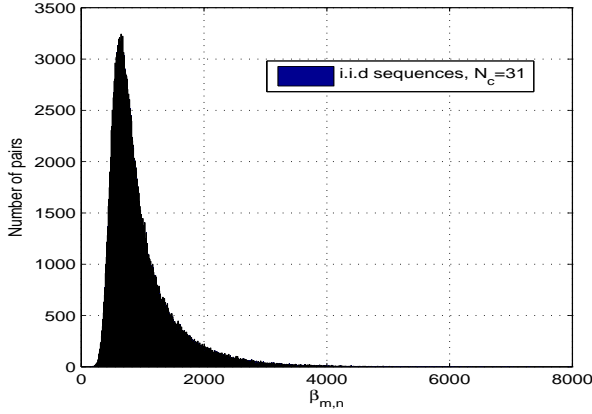Figure 2: **Distribution of $\beta_{m,n}$ using short Gold sequences**

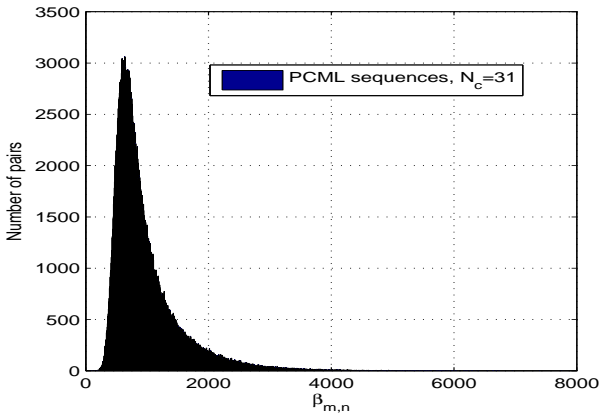Figure 3: **Distribution of $\beta_{m,n}$ using short i.i.d. sequences**

Figure 4: **Distribution of $\beta_{m,n}$ using short PCML sequences**

The figures show that the three families have similar shapes, but the i.i.d. and the PCML have very close behaviours with smoother shapes than the Gold ones. The smoothness can be explained by the large number of sequences considered for the two former families (1000 against 33 for Gold). However, apart from this smoothness, we can notice that there are more clustering pairs around low values of β with regard to the Gold codes. This behaviour can be interpreted in the following way; there is likely more *good* sequence pairs among short i.i.d. and short PCML families than among the Gold one, in the sense of the minimization of the criterion β. Thus, short i.i.d. and PCML codes do not only achieve lower values of β, but can contain more β-minimizing sequences than Gold families. Hence, the minimization of the MUI variance according to (8). These results will be corroborated by the performance evaluation of an asynchronous DS-UWB system in the case of multipath fading channel.

4.2 BER for short and long sequences

The following system parameters are assumed: K=8, N_c= 31, T_w=0.5 ns, T_c=0.9 ns and τ_p=0.2877 ns. Fading delays and amplitudes are generated according to the IEEE 802.15.3a [10]. Specifically, the CM1 model is considered, and the mean delay spread is 5 ns. Slow fading is assumed so that the symbols are transmitted in the coherence time of the channel. A different channel realization provided by IEEE 802.15.3a is assigned to each user. Monte Carlo simulations have been carried out and the BER curves are then obtained by averaging 200 realizations. For short i.i.d. and PCML sequences, at each realization we randomly choose K among 1000 generated sequences.
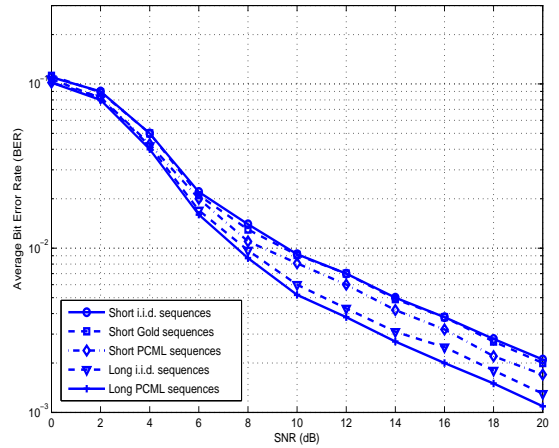

Figure 5: **Average BER versus SNR with K=8 users**

For the SRake receiver, the strongest 20 fingers are selected. Figure 5 depicts the BER versus signal-to-noise ratio (SNR) using both short and long sequences. When short sequences are considered, the graphical plots show that all spreading sequences families provide similar performance for small values of SNR ($\leq 6dB$); however, it is clear that DS-UWB system performance depends on the choice of the spreading sequences for medium and large SNR values. It is also observed that the PCML codes achieve the lowest level
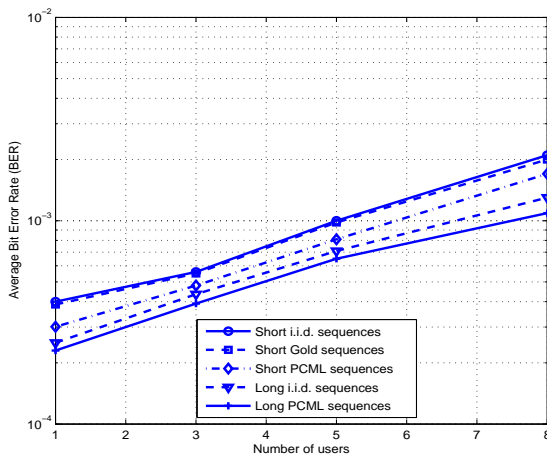
Figure 6: **Average BER versus number of users with an SNR=20 dB**

of BER compared to i.i.d. and Gold ones. An improvement of around 1 dB at a BER of $5 * 10^{-3}$ was obtained for PCML codes over the i.i.d. codes. This result corroborates the previous one with respect to the distribution and the lowest value of the selection criterion β. The average minimization of β (hence MUI variance) achieved with respect to the codes choice (PCML then i.i.d. then Gold) results in an improvement of the system performance. On the other hand, the long sequences (i.i.d. and PCML) are shown to outperform the short ones (i.i.d., PCML and Gold). Moreover, the PCML codes perform much better than i.i.d. As one can see that the long PCML codes can achieve an improvement of around 4 dB at a BER of $3 * 10^{-3}$ over the short i.i.d. codes.

Figure 6 represents the BER performance versus number of users with SNR=20 dB. As we can see, the long PCML sequences improve the performance of the system, which can hence accomodate more users for a given BER level. For a BER=$4 * 10^{-4}$, we observe that long PCML codes can increase the system capacity up to 2 users compared to short i.i.d. ones.

5. CONCLUSIONS

In this work, we have highlighted the importance of the choice of spreading-sequences on the performance of asynchronous DS-UWB systems. We have considered three families of sequences, namely Gold, i.i.d. and PCML which have been generated with a spatiotemporal chaotic system. We have shown that short PCML sequences can achieve the best level of a code-selection criterion, in terms of MUI minimization, as compared to short i.i.d. and Gold sets. Furthermore, long PCML are shown to improve substantially the average BER of the system with regard to all short and long code sets which have been considered.

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