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Abstract

In this work we address the effect of spreading sequences and pulse waveforms on the performance of asynchronous direct-sequence (DS) ultra-wideband (UWB) systems. Regarding spreading sequences, we consider the two cases of short and long sequences. We derive the expression of the multi-user interference (MUI) variance using long sequences at the output of a Rake receiver, when propagating through multipath channels. We also 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. Simulation results show that the use of long PCML codes in AWGN and multipath fading channels results in an improvement of the system average BER, hence an increase of the system capacity in terms of number of active users.

I. Introduction

Ultra Wide-Band (UWB) communication systems have recently attracted a great deal of interest for their advantageous features; in particular, low power density, large bandwidth, low complexity and excellent multipath immunity. Time Hopping (TH) [1], [2] and Direct Sequence (DS) [1], [3] 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 a direct-sequence spread spectrum technique to ensure multiple access.

Several papers have investigated the performance of asynchronous multiple-access DS-UWB systems using either the AWGN channel [4], [5], [6] or other simplified multipath channels [7], [8]. However, to get representative results, it is crucial to use a realistic channel model. Recently, IEEE 802.15 standardization group has proposed a more realistic channel model for UWB systems [9]. It consists in a modified Saleh-Valenzuela (SV) model where multipath components arrive in clusters [10].

In most of the recent works on the 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 [4], [5] or in multipath channels [8]. 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 [11] 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 criterion, independent of the number of fingers of the Rake receiver, for the selection of codes which minimizes the MUI variance. 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 particular, 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 [12], [13]. 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 code selection criterion which has been proposed in [11]. Secondly, we show by simulations that the long PCML codes achieve the best performance level as compared to long iid, short PCML and short Gold sequences.

On the other hand, we address the pulse-waveform effect on MUI for different Gaussian monocycles. The numerical results in terms of average bit error rate (BER) show that higher-order Gaussian monocycles with a fixed pulse width is slightly better in an asynchronous multiple access channel but worse multipath resistance, than lower-order Gaussian monocycles. We further derive an analytical expression for the MUI variance with long codes in an asychronous DS-UWB system in a realistic multipath fading channel showing the effect of the spreading codes, the pulse waveform and the channel parameter on the system performance.

Furthermore, we investigate the DS-UWB system performance, in terms of BER, with respect to the spreading codes and the pulse waveform. Simulation results show that long PCML codes achieve the best performance levels and increase consequently the system capacity in terms of users number. This result corroborates the efficiency of the considered criterion used for the choice of spreading sequences.

This paper is organized as follows. In section 2, we introduce the notations, the transmitted signal model, the channel model and the Rake receiver structure. In section 3, we present the short code selection criterion enabling the choice of codes which minimize the MUI variance. Then, we derive the variance of the MUI for long sequences. In section 4, we explain the generation of the PCML codes. In section 5, we discuss the simulation results obtained with respect to the criterion presented in the previous sections as well as the BER performance in both AWGN and multipath channels. Some conclusions are drawn in section 6.

II. TRANSMISSION MODEL

A. DS-UWB Signal Model

We consider an asynchronous direct-sequence UWB system with K interfering users using a binary phase-shift keying (BPSK) modulation. Each user transmits a sequence of short pulses, called the monocycles, through a multipath channel. The monocycle denoted by $w(t)$ has a finite duration of T_ws, and it is zero out of the time interval $[0, T_w]$. The duration is less than one ns, yielding a bandwidth on the order of the GHz. The multiple access is ensured by the spread-spectrum technique. The baseband system model is shown in Fig. 1. The transmitted signal of the k^{th} user is given by [4] :

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

where

- P_k is the transmitted signal power of user k,
- T_s is the symbol time,
- T_c is the chip duration,
- N_c is the number of chips per symbol,
- $w(t)$ is normalized to satisfy $\int_{-\infty}^{\infty} w(t)^2\, dt = 1$ and T_w, satisfies $T_w << T_c$,
- $b_k(i) \in \{-1, +1\}$ 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 $[0, T_s]$.

B. UWB fading Channel Model

The channel model in [9] was accepted by the standardization group, IEEE 802.15.3a, as the model for the evaluation of the proposals for the UWB standardization activities. It accurately models a real UWB channel. This channel model is derived from the Saleh-Valenzuela (S-V) model [10] with some modifications to account for the properties of measured UWB channels. The S-V model is based on clustering the phenomenon observed in several channel measurements. Frequency selective fading occurs on each cluster as well as on each path within that cluster. The impulse response of the multipath model consists of *M* clusters of *L* paths and can be expressed as

$$h(t) = X \sum_{m=1}^{M} \sum_{l=1}^{L} A_l^m\, \delta(t - T^m - \theta_l^m), \tag{2}$$

- T^m is the delay of the m^{th} cluster,
- θ_l^m is the delay of the l^{th} multipath component relative to the m^{th} cluster arrival time T^m,
- A_l^m is the multipath gain coefficient,
- X models the lognormal shadowing.

In [14] the authors have studied the effect of multipath arrival clustering in channels models and it was found that the same performance curves could be generated with non-clustered arrivals. Based on this study, we consider the channel impulse response of the k^{th} user as

$$h_k(t) = \sum_{l=1}^{L} A_{l,k}\, \delta\left(t - \theta_{l,k}\right) \tag{3}$$

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 multipath channel model we employ is that provided by the IEEE 802.15.3a standard with one cluster. The amplitude $A_{l,k}$ is 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 $\theta_{l,k}$) with variance $\sigma_a^2 := \mathbb{E}_a\left[(a_{l,k})^2\right]$. The attenuation $a_{l,k}$=$p_{l,k}\,\delta_{l,k}$, where $p_{l,k}$ is equi-propable $\{\pm 1\}$ and $\delta_{l,k}$ is a log-normal rv. The function $f(.)$ is defined by $f(\theta_{l,k})$=$e^{-\theta_{l,k}/2\gamma}$, where γ is the path power decay time. The delays $\theta_{l,k}$ are assumed to be independent between users and follow a Poisson distribution with parameter λ. 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 $I_{l,k}$:=$\mathbb{E}_a\left[(A_{l,k})^2\right]$=$\sigma_a^2.f^2\left(\theta_{l,k}\right)$.

There are four different channel models (CMs) with parameters designed to fit four different usage scenarios: CM1 for 0-4 m Line-Of-Sight (LOS), CM2 for 0-4 m non-LOS (NLOS), CM3 for 4-10 m NLOS, and CM4 for NLOS with an extreme root-mean square (rms) delay spread of 25 ns. Owing the length restrictions, we focus our work on a LOS scenario employing the CM1 model.

C. 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

$$r(t) = \sum_{k=1}^{K}\left(\sum_{l=1}^{L} A_{l,k}\, S_k(t - \theta_{l,k})\right) + \eta(t), \tag{4}$$

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, several Rake receiver including the all-Rake(ARake) receiver and selective-Rake (SRake) receiver have been proposed for UWB reception [15]. It has been shown, that it is not practical to implement the ideal Rake receiver called by

ARake that combines all of the resolvable multipaths. Whereas, for a given number of fingers, the best performance can be achieved by the SRake receiver that selects the N best paths out of L and then combines them using maximal-ratio combining (MRC). In this study we assume that the channel estimation algorithm can provide the correlator template and we consider MRC Rake receiver with $N \leq L$ fingers. In the sequel, 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

$$Z = \sum_{n \in \mathcal{N}} A_{n,1} \int_0^{T_s} r(t + \theta_{n,1})\, \upsilon_1(t)\, dt \tag{5}$$

where $\upsilon_1(t)$ is the receiver template for user 1, which can be expressed as:

$$\upsilon_1(t) = \sum_{j=0}^{N_c - 1} C_1(j)\, w(t - j\, T_c) \tag{6}$$

and $\mathcal{N}$ represents a set of paths for the desired user with card ($\mathcal{N}$)=N.

Using Eqs. (6)-(4), the Rake receiver output expression becomes:

$$Z = \sum_{n \in \mathcal{N}} \ A_{n,1} \sum_{k=1}^{K} \sqrt{P_k} \sum_{l=1}^{L} A_{l,k}\, y_{l,n,k}(\tau_k) + I_\eta \tag{7}$$

where I_η is the filtered Gaussian noise which is given by

$$I_\eta = \sum_{n \in \mathcal{N}} \ A_{n,1} \int_0^{T_s} \eta(t + \theta_{n,1})\, \upsilon_1(t)\, dt \tag{8}$$

and

$$y_{l,n,k}(\tau_k) = \int_0^{T_s} \sum_{i=-\infty}^{\infty} b_k(i) \sum_{j=0}^{N_c-1} C_k(j) w(t - i\, T_s - j\, T_c - \tau_k - \triangle\theta_{l,n,k}) \upsilon_1(t)\, dt, \tag{9}$$

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

Eq. (7) can be decomposed into four terms as [11]:

$$Z = S + I_c + I_s + I_\eta \tag{10}$$

where,

- S is the energy collected from the user of interest, and is given by

$$S = \sqrt{P_1} \sum_{n \in \mathcal{N}} (A_{n,1})^2 y_{n,n,1}(0) \tag{11}$$

- I_s is the Inter-Symbol Interference (ISI) for the desired user, and is expressed as

$$I_s = \sqrt{P_1} \sum_{n \in \mathcal{N}} A_{n,1} \sum_{l \neq n = 1}^{L} A_{l,1} y_{l,n,1}(0) \tag{12}$$

- I_c is the Multi User Interference, and is given by

$$I_c = \sum_{n \in \mathcal{N}} A_{n,1} \sum_{k=2}^{K} \sqrt{P_k} \sum_{l=1}^{L} A_{l,k} y_{l,n,k}(\tau_k) \tag{13}$$

Unlike I_s and I_c, the useful part S and the filtered noise I_η do not depend on the multiple access codes. While the former 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, the later can only be mitigated by a judicious choice of the multiple access codes.

III. Variance Expression of the MUI

The authors in [11] 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. In the present work we derive the MUI variance expression when using long sequences in a multipath environment. In this section, we first recall the main results obtained in [11] for short sequences and then, we derive and discuss the expression of the MUI variance for long sequences. In the sequel, as in [11] and [16] we denote by

$$\tau_k + \triangle\theta_{l,n,k} = Q_k^{l,n}\, T_s + q_k^{l,n}\, T_c + \alpha_k^{l,n}, \tag{14}$$

with

$$Q_k^{l,n} = \lfloor (\tau_k + \triangle\theta_{l,n,k})/T_s \rfloor, Q_k^{l,n} \in \{-\infty, +\infty\}, \tag{15}$$

$q_k^{l,n}$ is an integer uniformly distributed in the interval $\{0, .., N_c - 1\}$ expressed as

$$q_k^{l,n} = \left\lfloor (\tau_k + \triangle\theta_{l,n,k} - Q_k^{l,n}\, T_s)/T_c \right\rfloor, \tag{16}$$

where $\lfloor . \rfloor$ is the floor operator and $\alpha_k^{l,n}$ is a random variable uniformly distributed over $[0, T_c\,[$ which accounts for the fractional chip displacement of the k^{th} user relative to the first user.

It is worth noting that $Q_k^{l,n}$, $q_k^{l,n}$ and $\alpha_k^{l,n}$ will be useful to select the short code criterion and to derive the MUI variance for long sequences.

A. Short sequences

First of all, let us recall that we talk about short sequences when we use the same sequence for spreading all bits of a given user. Hence, the cross-correlation properties between different users remain unchanged over time. In [16] and [11] the authors have derived 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 (17)

$$\sigma_S^2 = \frac{\gamma_1}{T_s} \sum_{k=2}^{K} P_k \psi_k\ \beta_{1,k} \tag{17}$$

where

$$\gamma_1 = \int_{-\infty}^{\infty} r_{ww}^2(t)\, dt, \tag{18}$$

$$r_{ww}(s) = \int_{-\infty}^{\infty} w(t)\, w(t-s)\, dt, \tag{19}$$

$$\beta_{1,k} = \sum_{q=0}^{N_c-1} \left[\mathcal{C}_{1,k}^{-2}(q) + \mathcal{C}_{1,k}^{+2}(q) \right], \tag{20}$$

$$\mathcal{C}_{m,n}^{-}(q) = \sum_{k=0}^{q-1} C_m(k)\, C_n(k-q), \tag{21}$$

$$\mathcal{C}_{m,n}^{+}(q) = \sum_{k=q}^{N_c-1} C_m(k)\, C_n(k-q), \tag{22}$$

$$\psi_k = \sum_{n\in\mathcal{N}} \mathbb{E}_\theta\left[I_{n,1}\right] \sum_{l=1}^{L} \mathbb{E}_\theta\left[I_{l,k}\right]. \tag{23}$$

The expression (17) 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.

Before exhibiting the Optimal Direct Sequence codes, the authors in [11] have introduced two preliminary propositions expressed as follows

Proposition 1: Let (C_m,C_n) be two Direct Sequence codes of length N_c. We have

$$\sum_{q=0}^{N_c-1} \left[\mathcal{C}_{m,n}^{-2}(q) + \mathcal{C}_{m,n}^{+2}(q)\right] \geq N_c. \tag{24}$$

Proposition 2: Let (C_1,C_k) be a pair of Direct Sequence codes satisfying $\sum_{q=0}^{N_c-1}\left[\mathcal{C}_{1,k}^{-2}(q) + \mathcal{C}_{1,k}^{+2}(q)\right]$=$N_c$.

1) If N_c is even

$$\begin{cases} |\mathcal{C}_{1,k}^{+}(q)| = |\mathcal{C}_{1,k}^{-}(q)| = 0 \qquad if\ q\ is\ even; \\ and\ \ |\mathcal{C}_{1,k}^{+}(q)| = |\mathcal{C}_{1,k}^{-}(q)| = 1\ if\ q\ is\ odd \end{cases} \tag{25}$$

2) If N_c is odd

$$\begin{cases} |\mathcal{C}_{1,k}^{+}(q)| = 1\ and\ |\mathcal{C}_{1,k}^{-}(q)| = 0 \quad if\ q\ is\ even; \\ and\, |\mathcal{C}_{1,k}^{+}(q)| = 0\ and\ |\mathcal{C}_{1,k}^{-}(q)| = 1\ if\ q\ is\ odd \end{cases} \tag{26}$$

Therefore, the Average Bit Error Rate (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

$$\sum_{q=0}^{N_c-1} \left[\mathcal{C}_{1,k}^{-2}(q) + \mathcal{C}_{1,k}^{+2}(q)\right] = N_c \tag{27}$$

Clearly we can see the importance of the criterion $\beta_{1,k}$ which must verify Eq. (27), to minimize the MUI variance and therefore, to improve the system performance.

B. Long sequences

In the case of long sequences, information bits of a given user are spread with different spreading codes. We denote by $C_{k,i}$ the spreading code of bit i of user k. 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. Thus, expression(9) can be written as follows :

$$\begin{aligned} y_{l,n,k}(\tau_k) &= \int_0^{T_s} \sum_{i=-\infty}^{\infty} b_k(i) \sum_{j=0}^{N_c-1} C_{k,i}(j) \\ & \quad w(t - i\,T_s - j\,T_c - \tau_k - \triangle\theta_{l,n,k}) \upsilon_1(t)\,dt \end{aligned} \tag{28}$$

As mentioned in [8, eq. (9)], (28) can be rewritten in the following way by:

$$y_{l,n,k}(\tau_k) = \left[R(\alpha_k^{l,n}) X_k^{l,n} + \hat{R}(\alpha_k^{l,n}) Y_k^{l,n} \right], \tag{29}$$

where

$$X_k^{l,n} = b_k(-1) \sum_{p=0}^{q_k^{l,n}} C_{1,0}(p) C_{k,-1}(p + N_c - q_k^{l,n} - l) + b_k(0) \sum_{p=q_k^{l,n}+1}^{N_c-1} C_{1,0}(p)\, C_{k,0}(p - q_k^{l,n} - l) \tag{30}$$

$$Y_k^{l,n} = b_k(-1) \sum_{p=0}^{q_k^{l,n}-1} C_{1,0}(p) C_{k,-1}(p + N_c - q_k^{l,n} - l + 1) + b_k(0) \sum_{p=q_k^{l,n}}^{N_c-1} C_{1,0}(p) C_{k,0}(p - q_k^{l,n} - l + 1) \tag{31}$$

$$R(x) = \int_0^x w(t)\, w(t + T_c - x)\, dt, \tag{32}$$

and

$$\hat{R}(x) = \int_x^{T_c} w(t)\, w(t - x)\, dt. \tag{33}$$

Let us define $\mathcal{C}_{m,n}$ the discrete aperiodic cross correlation function, which involves only the *mth* and *nth* signature sequences, as

$$\mathcal{C}_{m,n}(\lambda) = \begin{cases} \sum_{j=0}^{N_c-\lambda-1} C_m(j)C_n(j+\lambda) & if \;\; 0 \le \lambda \le N_c - 1 \\ \sum_{j=0}^{N_c+\lambda-1} C_m(j-\lambda)C_n(j) & if \;\; 1-N_c \le \lambda \le -1 \\ 0 & if \;\; \lambda \ge N_c \end{cases} \tag{34}$$

Using (34) for the two pairs of spreading sequences $\{m,n\} = \{[k,0],[1,0]\}$ and $\{m,n\} = \{[k,-1],[1,0]\}$, we obtain

$$\begin{aligned} y_{l,n,k}(\tau_k) \;\; &= \;\; b_k(0)\left[\mathcal{C}_{[k,0],[1,0]}(q_k^{l,n}-l+1)\,\hat{R}(\alpha_k^{l,n}) + \mathcal{C}_{[k,0],[1,0]}(q_k^{l,n}-l+2)\,R(\alpha_k^{l,n})\right] \\ &+ b_k(-1)\left[\,\mathcal{C}_{[k,-1],[1,0]}(q_k^{l,n}-l+2-N_c)\,R(\alpha_k^{l,n})\right. \\ &\left.+\mathcal{C}_{[k,-1],[1,0]}(q_k^{l,n}-l+1-N_c)\,\hat{R}(\alpha_k^{l,n})\right]. \end{aligned} \tag{35}$$

Keeping the same method given for short sequences, the variance of the MUI can be expressed as:

$$\sigma_L^2 = \sum_{k=2}^{K} P_k \sum_{n\in\mathcal{N}} \mathbb{E}_\theta\left[I_{n,1}\right] \sum_{l=1}^{L} \mathbb{E}_\theta\left[I_{l,k}\right] \mathbf{E}\left[y_{l,n,k}(\tau_k)^2\right] \tag{36}$$

In order to provide the expression of σ_L^2, we need to calculate σ_y^2=$\mathbf{E}\left[y_{l,n,k}(\tau_k)^2\right]$ which can be obtained by averaging $\mathbf{E}\left[y_{l,n,k}(\tau_k)^2|\alpha_k^{l,n} = \alpha^{l,n}\right]$ in terms of the distribution of $\alpha_k^{l,n}$ as $[4, eq.(65)]$.

$$\sigma_y^2 = \frac{1}{T_c}\int_0^{T_c} \mathbf{E}\left[y_{l,n,k}(\tau_k)^2|\alpha_k^{l,n} = \alpha^{l,n}\right] d\alpha^{l,n}$$

$$\begin{aligned} \sigma_y^2 \;\; &= \;\; \frac{1}{T_c}\int_0^{T_c} \hat{R}(\alpha^{l,n})^2 \mathbf{E}\left[\mathcal{C}_{[k,0],[1,0]}(q_k^{l,n}-l+1)^2 + \mathcal{C}_{[k,-1],[1,0]}(q_k^{l,n}-N_c-l+1)^2\right] \\ &+ R(\alpha^{l,n})^2 \mathbf{E}\left[\mathcal{C}_{[k,0],[1,0]}(q_k^{l,n}-l+2)^2 + \mathcal{C}_{[k,-1],[1,0]}(q_k^{l,n}-l+2-N_c)^2\right] d\alpha^{l,n}. \end{aligned} \tag{37}$$

To simplify our analysis here, let us define [17]

$$\mu_{[k,0],[m,0]}^{l}(r-l+1) = \sum_{s=0}^{N_c-1} \mathcal{C}_{[k,0],[m,0]}(s+r-l+1)^2, \tag{38}$$

$$\Gamma_{[k,-1],[m,0]}^{l}(r-l+1) = \sum_{s=1-N_c}^{-1} \mathcal{C}_{[k,-1],[m,0]}(s+r-l+1)^2. \tag{39}$$

So that we can rewrite (37) as

$$\sigma_y^2 = \frac{1}{T_c}\int_0^{T_c} \hat{R}(\alpha^{l,n})^2 \left[\mu^l_{[k,0],[1,0]}(1-l) + \Gamma^l_{[k,-1],[1,0]}(1-l)\right] + R(\alpha^{l,n})^2 \left[\mu^l_{[k,0],[1,0]}(2-l) + \Gamma^l_{[k,-1],[1,0]}(2-l)\right] d\alpha^{l,n}. \tag{40}$$

Therefore, the MUI variance term can be written as:

$$\sigma_L^2 = \frac{1}{T_c}\sum_{k=2}^{K} P_k \sum_{n\in\mathcal{N}} \mathbb{E}_\theta\left[I_{n,1}\right] \sum_{l=1}^{L} \mathbb{E}_\theta\left[I_{l,k}\right] \int_0^{T_c} \left[\hat{R}(\alpha^{l,n})^2 \left[\mu^l_{[k,0],[1,0]}(1-l) + \Gamma^l_{[k,-1],[1,0]}(1-l)\right] + R(\alpha^{l,n})^2 \left[\mu^l_{[k,0],[1,0]}(2-l) + \Gamma^l_{[k,-1],[1,0]}(2-l)\right]\right] d\alpha^{l,n}. \tag{41}$$

As shown in (41), the statistics of the MUI depends on the channel, the codes and the pulse waveform. But, the codes contribution cannot be optimized independently from the pulse waveform and the channel, which are determined through $\mu^l_{[k,0],[1,0]}(1-l)$, $\Gamma^l_{[k,-1],[1,0]}(1-l)$, $\mu^l_{[k,0],[1,0]}(2-l)$ and $\Gamma^l_{[k,-1],[1,0]}(2-l)$.

IV. 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 [18], [19]. 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,...) [20], [21], [22]. 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) [12], [13] defined by :

$$x_i(k+1) = (1-\epsilon)\, f(x_i(k)) + \epsilon\, f(x_{i-1}(k)), \tag{42}$$

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 $\epsilon = 0.98$,

- $f(.)$ is a one dimensional chaotic map. In this paper, we consider the piecewise-linear map defined by $f(x) = 4\,x\,mod(1)$,
- $x_0(k)$ 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 :

$$\begin{cases} Q(x_i(k)) = -1 \;\; if \;\; x_i(k) \leq 1/2 \\ Q(x_i(k)) = +1 \;\; if \;\; x_i(k) > 1/2. \end{cases} \tag{43}$$

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.

V. Simulation Results

In this section we assess the effect of the choice of both the spreading sequences and the pulse waveform on the performance of asynchronous DS-UWB systems. For this reason, we consider three families of spreading sequences, namely Gold, i.i.d. and PCML sequences (as generated in section IV) and we treat the two cases of short and long codes. Regarding the pulse waveform, the most commonly adopted shapes for UWB systems are Gaussian pulse, Gaussian monocycle [23], and Manchester monocycle [24]. The Gaussian pulse has the following form :

$$w(t) = e^{\left(-2\,\pi\,(\frac{t}{\tau_p})^2\right)} \tag{44}$$

and its n^{th} derivative, called too n^{th} order monocycle, is [25]:

$$w_n(t) = \epsilon_n \, \frac{d^n}{dt^n} e^{\left(-2\,\pi\,(\frac{t}{\tau_p})^2\right)}. \tag{45}$$

where τ_p represents a time normalization factor to make $w_n(t)$ independent of a specific impulse duration, and ϵ_n is a factor introduced to normalize the energy of the pulses $w_n(t)$. In the present work, the considered Gaussian monocycles are the 2^{nd} and 6^{th} orders (Fig. 2) which satisfy the emission limits for UWB systems according to the Federal Communication Commission (FCC).

A. 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 (I) 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).

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

TABLE I

VALUES OF MIN $\beta_{m,n}$ FOR THE SHORT CODE FAMILIES

For a further investigation of this criterion, we plot in figs. 3, 4 and 5 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.

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 also contain more β-minimizing sequences than Gold families. They also minimize the MUI variance according to (17). These results will be coorborated by the performance evaluation of an asynchronous DS-UWB system in both cases of AWGN and multipath fading channels.

B. BER for short and long sequences with different pulse waveforms

The main aim of our work is to show the influence of the PCML sequences on the system performance operating with multipath interference in an indoor environment. The simulation parameters that will be used for computing the numerical results are listed in Table (II). Fading delays and amplitudes are generated according to the IEEE 802.15.3a [9] with one cluster. 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 with C++ using IT++ library. 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.

Parameter	**Notation**	**Value**
Time Normalization factor	τ_p	0.2877 ns
Chip duration	T_c	0.9 ns
Pulse duration	T_w	0.5 ns
Number of chips per bit	N_c	31
Number of users	K	8,16
Path arrival rate	λ	$2.5\,ns^{-1}$
Path power decay time	γ	4.3 ns

TABLE II

PARAMETERS OF THE DS-UWB SYSTEM

Let's begin by evaluating the BER of the system operating with ISI and MUI. For the SRake receiver, the strongest 20 fingers are selected. Figs. 6 and 7 depict the BER versus signal-to-noise ratio (SNR) for Gaussian monocycles where $\{n = 2, 6\}$, respectively, 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 ($\leq 6\,dB$); 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 of BER compared to i.i.d. and Gold ones for all pulse waveforms. An improvement of around 1 dB at a BER of $5\,\mathrm{x}\,10^{-3}$ was obtained for PCML codes over the i.i.d. codes with the use of the second derivative of the Gaussian pulse. 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 $3 \, \text{x} \, 10^{-3}$ over the short i.i.d. codes using the 2^{nd} order monocycle.

Fig. 8 represents the BER performance versus the number of users with SNR=20 dB in a multipath channel using 2^{nd} order monocycle. 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. We observe that long PCML codes can increase the system capacity up to 2 users compared to short i.i.d. ones with a BER of $4 \, \text{x} \, 10^{-4}$. Let us now consider an AWGN channel, which represents an idealized channel for UWB transmissions. The simulation results carried out assuming 15 asynchronous interferers are averaged over 20 realizations.

In figs. 9 and 10, the system performance in terms of BER using both short and long sequences are plotted versus SNR for the different monocycles. Employing short sequences, we can notice that the PCML sequences improve the performance compared to i.i.d and Gold ones. An improvement of around 2 dB at a BER of 10^{-3} was obtained for PCML codes over i.i.d. codes with the use of the 2^{nd}-order monocycle. Furthermore, it can be clearly observed that the long sequences (i.i.d. and PCML) outperform the short ones (i.i.d., PCML and Gold).

The results illustrated in figs. 11 and 12, report the BER versus the number of users with SNR=20 dB for 2^{nd} and 6^{th} order monocycles, respectively. According to these figures, it is clear that long PCML sequences improve the performance of the system, which can hence accomodate more users for a given BER level. Considering the second-order monocycle with BER=10^{-4}, the use of the long PCML codes can increase the system capacity up to 3 and 5 users compared to short PCML and short i.i.d. ones, respectively.

The impact of the pulse waveform on the average BER for different Gaussian monocycle orders with fixed pulse width (i.e. fixed τ_p), is reported in figs. 13 and 14 for both cases AWGN and multipath channels, respectively. We have considered i.i.d. short sequences.

For the AWGN channels, we observe that the 6^{th}-order monocycle achieves better performance than the 2^{th} order one. Whereas, Gaussian monocycles with smaller n have smaller BER in multipath channels. Thus, we can say that the higher-order Gaussian monocycle can achieve lower BER and better SNR gain but worse multipath resistance abilities for fixed pulse width. Let's notice that our observations are consistent with the finding in [25], which states that the Gaussian monocycles with larger n yields higher SNR gain in single user and asynchronous multiple access channel but inferior interference resistance ability.

VI. Conclusions

In this work, we have highlighted the importance of short and long spreading-sequences as well as pulse-waveform choices in 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. On one hand, we have shown that short PCML sequences achieve the best level of a code-selection criterion compared to short i.i.d. and Gold sets. Therefore, we can conclude that short PCML sequences are well-chosen codes to minimize the variance of the MUI but not optimal pair of codes. Furthermore, long PCML are shown to improve substantially the average BER of the system in both AWGN and multipath fading channels with regard to all short and long code sets which have been considered. On the other hand, we have derived the expression of the MUI variance over a multipath channel model using long sequences. Our simulation results show that higher-order Gaussian monocycles have better performances in AWGN channel, than lower-order Gaussian monocycles for a fixed pulse width, which are suitable for multipath channel, specifically with long PCML sequences.

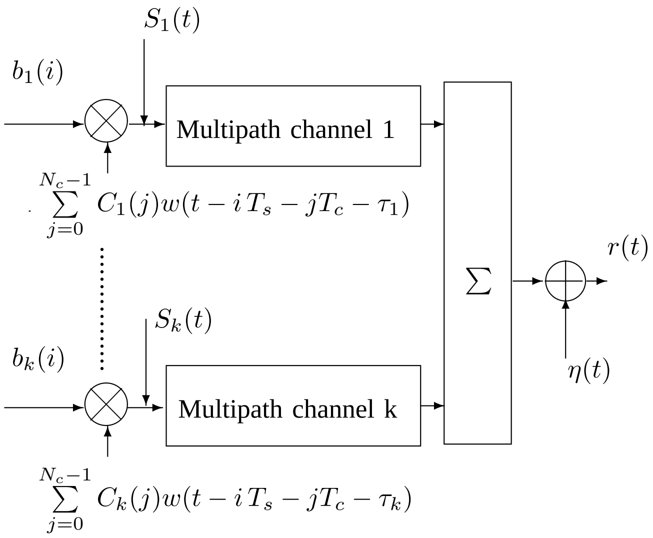

Fig. 1. A model of an asynchronous DS-UWB system in a multipath channel.

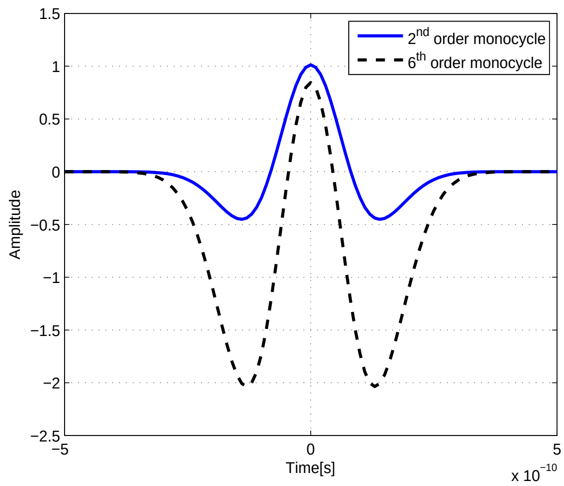

Fig. 2. **Gaussian monocycles with $\tau_p = 0.2877$ns where n=2 and 6.**

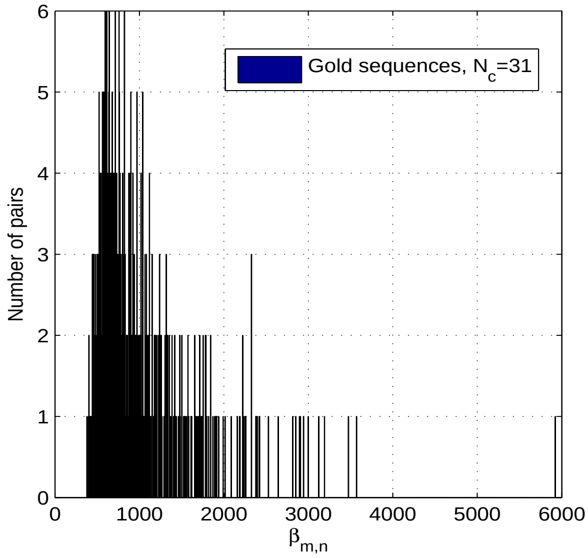

Fig. 3. **Distribution of $\beta_{m,n}$ using Short Gold sequences.**

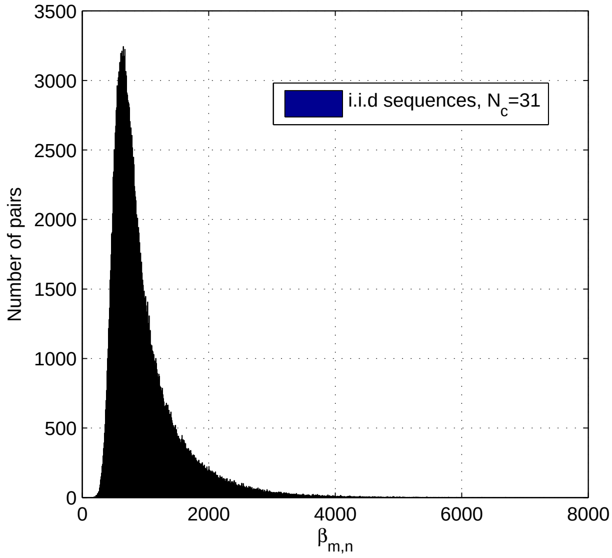

Fig. 4. **Distribution of $\beta_{m,n}$ using Short i.i.d. sequences.**

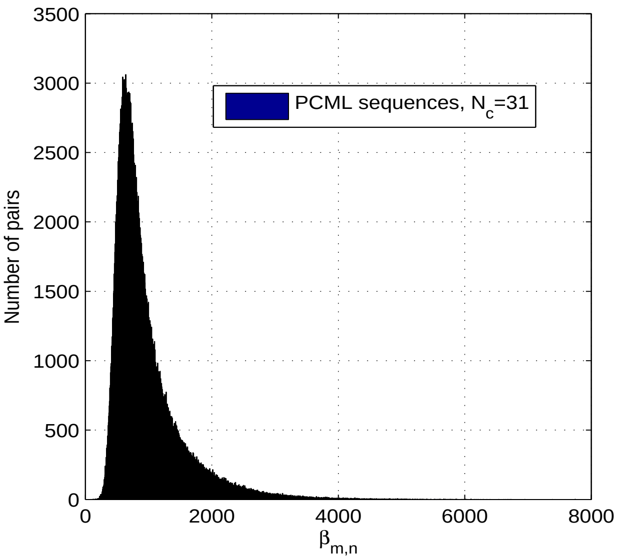

Fig. 5. **Distribution of $\beta_{m,n}$ using Short PCML sequences.**

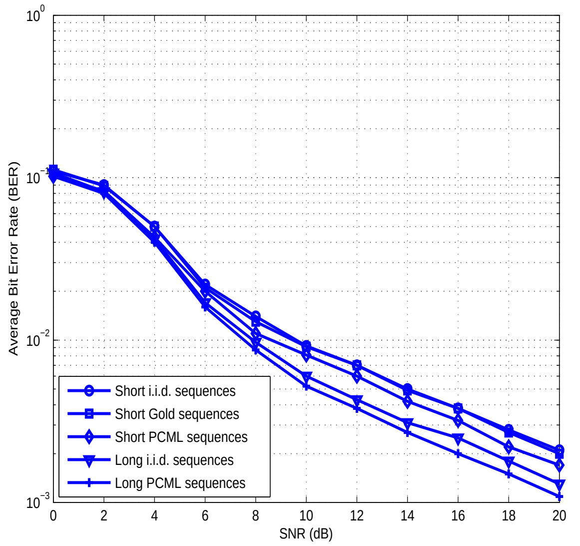

Fig. 6. **Average BER versus SNR for 2^{nd} order monocycle with *K*=8 users.**

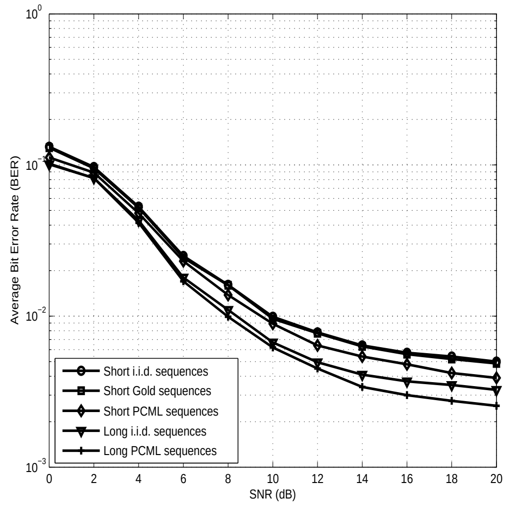

Fig. 7. **Average BER versus SNR for 6^{th} order monocycle with *K*=8 users.**

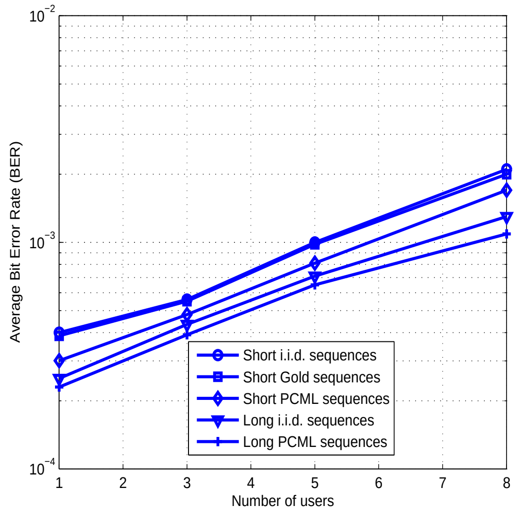

Fig. 8. **Average BER for 2^{th} order monocycle versus number of users with SNR=20 dB.**

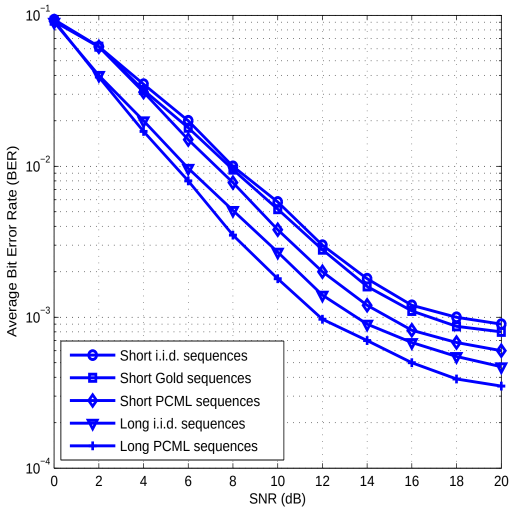

Fig. 9. **Average BER versus SNR for 2^{th} order monocycle assuming 15 asynchronous interferers.**

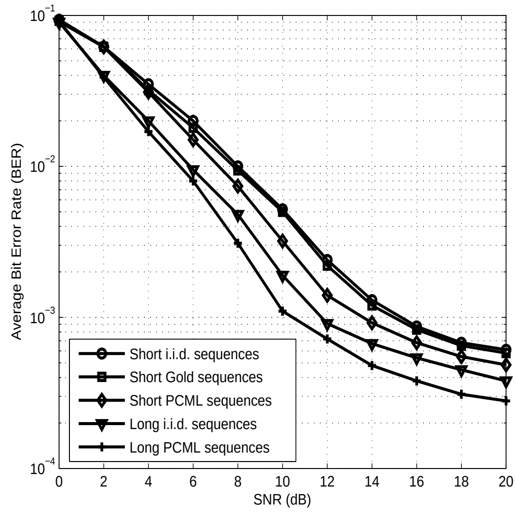

Fig. 10. **Average BER versus SNR for 6^{th} order monocycle assuming 15 asynchronous interferers.**

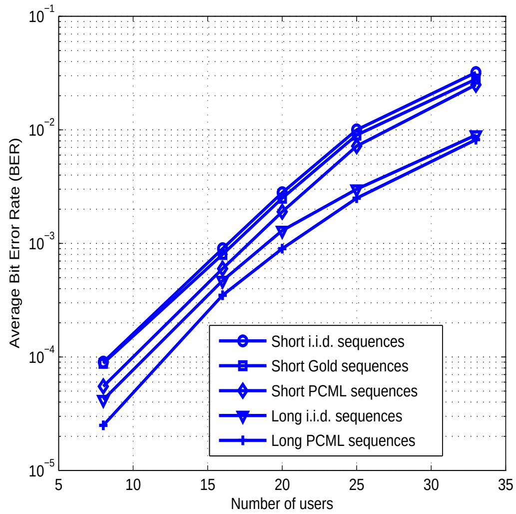

Fig. 11. **Average BER versus number of users for 2^{nd} order monocycle with SNR=20 dB.**

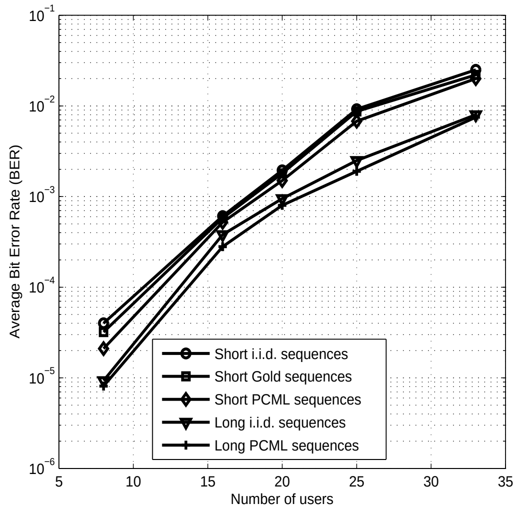

Fig. 12. **Average BER for 6^{th} order monocycle versus number of users with SNR=20 dB.**

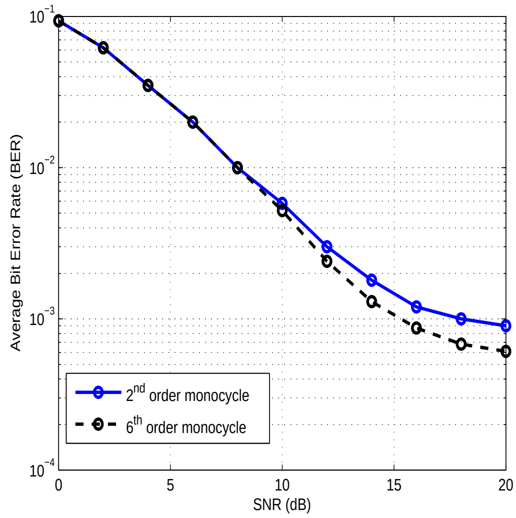

Fig. 13. **Average BER using Short i.i.d. sequences assuming 15 asynchronous interferers in an AWGN channel.**

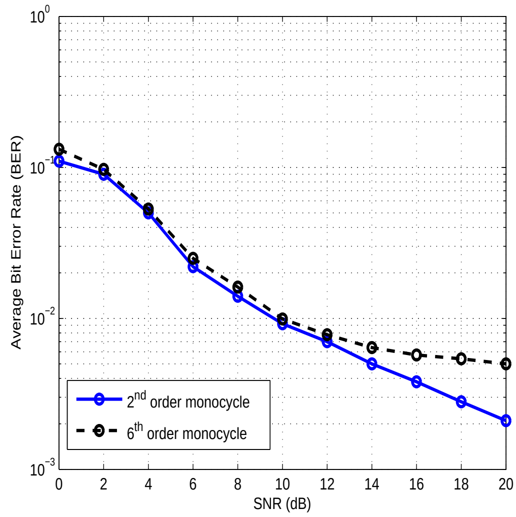

Fig. 14. **Average BER using Short i.i.d. sequences for CM1 multipath channel with *K*=8 users.**

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