Impact of Synchronization Errors and Multiple Access Interference to the Performance of UWB Impulse Radio Systems

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***Abstract*— This paper deals with the comparison of different multiple access techniques and different impulses in a multiple access communication systems based on Ultra Wide Band (UWB) impulse radio technology under non-ideal conditions. Several multiple access techniques and impulses have been designed and compared in the past, but mainly with the assumption of perfect synchronization of the users and perfect recovering of frame synchronization at the receiver. In this paper this unpractical assumptions are dropped. The results have been obtained by computer simulations. The sensitivity to synchronization errors of the Time Hopping PPM and the Direct Sequence multiple access techniques has been carried out with two different pulse shapes: the Gaussian monocycle and the Doublet. The impact of multiple access interference is also reported in the paper in order to have an exhaustive comparison of the UWB systems.**

I. Introduction

UWB technology is foreseen as a possible solution for future wireless short range indoor applications. In UWB systems the signal energy is spread over a very large frequency bandwidth thus obtaining a very low power spectral density. UWB communications are supposed to be accomplished over the frequency actually used by other communication standards. The development of the UWB system claims for a standardization of the coexistence with existing operating systems: this is currently one of the major task to be fulfilled by the main standardization bodies, e.g., ETSI in Europe pand the FCC in USA.

As it is known, there are several UWB systems, but here we will focus on the UWB impulse radio. This technique uses very narrow pulse waveform to generate the UWB spectrum. Two different pulse waveforms have been considered: the Gaussian monocycle and the Doublet. The former is a simple Gaussian pulse with length T_p while the latter is obtained by using two amplitude reversed Gaussian pulses of length T_d with a time gap between the pulses of length T_g [1] ($T_d + T_g = T_p$). A comparison in terms of performance of these two pulses is reported in the paper.

Basically, two multiple access techniques are currently considered for UWB communications, namely Time-Hopping UWB (TH-UWB), and Direct Sequence UWB (DS-UWB). These two techniques have been studied and compared in the literature, but mainly with the assumption of perfect synchronization at the receiver. In this paper a comparison of the performance of the two previously mentioned techniques is presented. First these techniques are compared under the assumption that the receiver is able to perfectly recover the frame and code synchronism of the user of interest, then this assumption is dropped in order to highlight the performance degradation when the synchronization error increases. The synchronization error, i.e., the misalignment between the received chip waveform and the one at the receiver has been modeled herein as a random Gaussian variable with standard deviation σ_τ.

Moreover, the interfering users have been supposed not-synchronized with the desired user, i.e., they arrive at the receiver with a random delay.

Summarizing, the performance of two UWB impulse radio systems based on the multiple access techniques TH and DS respectively have been compared in the following different cases:

- pulse waveform: Gaussian monocyle and Doublet;
- multiple access interference: synchronous users and asynchronous users;
- synchronization errors.

II. System Model

In this section we will describe the system model of the considered UWB communication system.

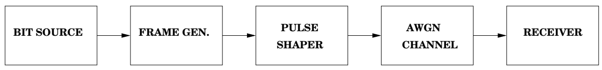

Fig. 1. Transmission Chain

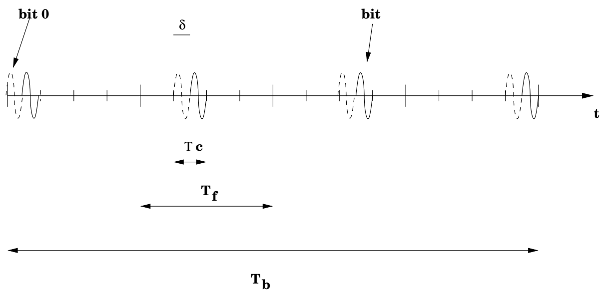

Fig. 2. TH-PPM UWB Frame Time

A. *UWB signal definition*

As it is known, a signal is defined as UWB if the following equation is verify:

$$B_f = \frac{2(f_H - f_L)}{f_H + f_L} \geq 0.20 \quad (1)$$

where B_f is the fractional bandwidth of the signal with f_H and f_L are the cutoff frequencies.

B. *The UWB Transmitter*

In fig. 1 the system chain implemented is shown in the case of single user system. The first block is the BIT-SOURCE generator whose output is a binary data stream having uniformly distributed statistic.
The FRAME-GENERATOR block generates the frame TH-PPM or DS depending on the system we are looking at. The output frames are depicted in figs. 2 and 3.

The antenna effect has been modelled as a derivation of the transmitted signal [2].

C. *TH-PPM UWB System*

The time hopping concept is generally associated to the impulse radio systems [3], and it based on the periodic transmission with period T_f of a pulse waveform of length T_p. In TH-PPM the bit interval T_b is divided into N_f frame interval, i.e., $T_b = N_f T_f$ and each frame is further divided into N_c chips of length T_c, i.e., $T_f = N_c T_c$. The time hopping instants are decided based on a pseudo-random time-hopping code. If the pulses inside the chips are shifted of a quantity δ, then the transmitted bit is "1", on the contrary the receiver will decide for "0" (fig. 2). Obviously, the duty cycle in TH-PPM mode is less than 100%, i.e., $\frac{T_p}{T_c} < 1$. With these definitions, the bit-rate can be expressed as $R_b = \frac{1}{T_b} = \frac{1}{N_f T_f}$ and the maximum number of active users is defined by the number of possible positions that a pulse can occupy inside a frame, i.e., N_c contemporary users can be allocated in a TH-PPM UWB system without interference. The length of the time-hopping code is independent on the number of chips per frame, but it only depends on the number of frames per bit. Different TH codes will be assigned to each user sharing the UWB radio resource. If the pulse of each user occupies a different position inside a frame, the multiple access interference (MAI) is avoided. If the time repetition of the pulse T_f is smaller than the delay spread of the channel, the inter-symbol interference (ISI) can be naturally avoided by the UWB system.

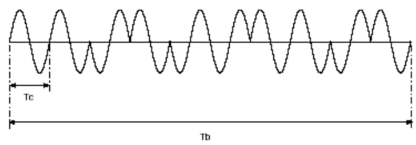

Fig. 3. DS UWB Frame Time

The expression of the UWB transmitted signal in the time domain for the mth user in the nth symbol interval is the following [4]:

$$s_m^{(n)}(t) = \sum_{j=0}^{N_f-1} w(t - nN_f T_f - jT_f - c_{m,j}T_c - d_m^{(n)}\delta) \quad (2)$$

where $w(t)$ is the pulse waveform, $d_m^{(n)} \in \{0, 1\}$ is the nth data bit of the mth user, $c_{m,j} \in \{0, 1, \ldots, N_c - 1\}$ is the jth element of the pseudo-random time-hopping code of user m, δ is the PPM shift, T_c is the chip time, T_f is the frame interval and N_f is the number of frame inside a bit interval ($T_b = N_f T_f$).

D. *DS UWB System*

Alternatively, the UWB signal can be generated by using the well known Direct Sequence spread spectrum concept (fig. 3). In this case the pulse waveform occupies the entire chip interval, i.e., $T_p = T'_c$, thus the duty cycle is 100%. It is important to note that in the DS the chip duration is halfed

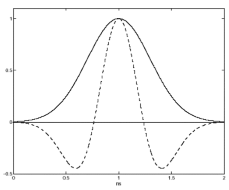

Fig. 4. The Gaussian pulse (solid line) and its second derivative (dashed line).

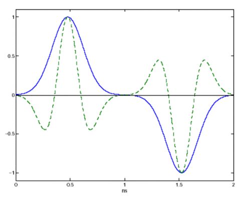

Fig. 5. The Doublet pulse (solid line) and its second derivative (dashed line).

compared to the chip duration of the TH-PPM system ($T_c' = 1/2T_c$). Again the bit-rate can be defined as $R_b = \frac{1}{T_b} = \frac{1}{SFT_p}$ where $SF = 2N_f N_c$ is the length of the spreading code.

When using the Doublet, the bit-rate is little bit lower compared to the standard Gaussian pulse due to the time gap T_g inside the Doublet.

The expression of the UWB transmitted signal of the mth user in the nth symbol interval when using a BPSK modulation is the following:

$$s_m^{(n)}(t) = \sum_{j=0}^{SF-1} w(t - nT_b - jT_c')c_{m,j}d_m^{(n)} \qquad (3)$$

where $w(t)$ is the pulse waveform, $d_m^{(n)} \in \{-1, 1\}$ [1] is the nth data bit of the mth user and $c_{m,j} \in \{-1, 1\}$ is the jth chip of the spreading code of the mth user.

Each user is distinguished by the others depending on the assigned code. 32 Orthogonal-Gold sequences have been used in this work.

E. The Pulse Waveform

In this paper two pulse waveforms have been used: the standard Gaussian pulse (fig. 4) and the Doublet pulse (fig. 5). The mathematical expression of the Gaussian waveform is [5]:

$$w(t) = \frac{e^{\frac{-(t-m)^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}} \qquad (4)$$

where $\sigma = T_p/2\pi$, T_p is the standard deviation of the pulse and m is the mean value.

The Doublet waveform is composed by two amplitude reversed Gaussian waveforms (4) of length T_d with a time gap T_g between the pulses. The Doublet waveform is shown in fig. (5).

In order to take into account the antennas effect (Tx and Rx) the second derivative of the above pulses is transmitted.

[1]In the DS case the data bit $\{0, 1\}$ are mapped in $\{-1, 1\}$.

F. The UWB Receiver

A correlating receiver is here considered. In UWB applications this simple receiver can assure good performance thanks to the impulse radio nature and the very large frequency bandwidth of the UWB systems.

The received signal $r(t)$ is multiplied by the referring waveforms and integrated over a bit interval [6]. The expression of the received signal is:

$$r(t) = \sum_{n=-\infty}^{+\infty} \sum_{m=1}^{M} s_m^{(n)}(t) + n(t) \qquad (5)$$

where $n(t)$ is the AWGN noise.

Defining $v_m^{(n)}(t) = \ddot{w}_m^{(n)}(t) - \ddot{w}_m^{(n)}(t - \delta)$, the nth decision variable for the mth user in a TH-PPM UWB system is

$$y_{m[TH]}^{(n)} = \sum_{j=0}^{N_f-1} \int_{\tau_m+nT_b+jT_f}^{\tau_m+(n+1)T_b+(j+1)T_f} r(t) \cdot v_m^{(n)}(t - nT_b - \tau_m - jT_f - c_{m,j}T_c)dt \qquad (6)$$

where $\ddot{w}$ is the second derivative of w to take into account the effects of the antennas and τ_m is the signal delay time. If $y_{m[TH]}^{(n)} > 0$ the receiver will decide for the bit "0", on the contrary it will decide for "1".

In the DS case, the decision variable for the mth user in the nth bit interval is

$$y_{[DS]}^{(n)} = \sum_{j=0}^{SF-1} \int_{\tau_m+nT_b+jT_c'}^{\tau_m+(n+1)T_b+(j+1)T_c'} r(t) \cdot \ddot{w}(t - \tau_m - nT_b - jT_c')c_{m,j}dt \qquad (7)$$

If $y_{m[DS]}^{(n)} > 0$ the receiver will decide for the bit "0", on the contrary it will decide for "1".

III. Multiple Access Interference

The interfering users are firstly supposed synchronous and then they are supposed to arrive at the receiver with different delays (asynchronous case). In the latter case, the user delay has been modeled as a random variable with uniform statistic ($\tau_m \in [0, T_b)$).

A. TH-PPM UWB

In TH-PPM UWB systems, when the users are synchronous the MAI is totally avoided because the pulse of different users occupy different chip time inside the bit interval. The interference starts when the number of users is increased over N_c. In our simulations, $N_c = 4$ and the number of users arises from 1 to 12, that means that one of the users between the 5th and the 8th has at least one pulse interfering with one pulse of the user of interest [2], while one of the users between the 9th and the 12th has at least another one pulse that causes interference in the bit interval of the desired user. Obviously when the users are not synchronous the interference avoidance may not be assured even if the number of users is lower than N_c.

B. DS UWB

In a DS UWB system as in a classical DS spread spectrum system, the MAI mitigation is assured by the low cross-correlation of the spreading codes. When using DS technique, the pulses fill the entire chip interval and the code length is the number of chips per bit. The Gold codes assure low cross-correlation properties if the user codes are synchronous, but it not guaranteed in the asynchronous case. In the simulations we have used 32 orthogonal Gold codes and the number of users sharing the same channel arises till 16 (50% of system load).

The results are shown in figs. 6 and 7.

IV. Synchronization Errors

In several papers dealing with the performance comparison of UWB impulse radio systems, perfect synchronization between the received stream and the frame generated at the receiver has been normally assumed. Several techniques, as TH and DS, and different pulse waveforms, as the Gaussian monocycle and the Doublet, have been compared. In practical UWB systems, the code and frame synchronization has to be accurately recovered by the receiver before starting the data detection process. This operation is not as easy as we can suppose and errors may be normally present in the process. In such a case, the decision variables (6) and (7) can be expressed as

$$\tilde{y}^{(n)}_{m[TH]} = \sum_{j=0}^{N_f-1} \int_{\tau_m+\Delta_m^{(n)}+nT_b+jT_f}^{\tau_m+\Delta_m^{(n)}+(n+1)T_b+(j+1)T_f} r(t) \cdot v_m^{(n)}(t-\tau_m-\Delta_m^{(n)}-nT_b-jT_f-c_{m,j}T_c)dt \quad (8)$$

[2]We have supposed in the simulations that the user of interest is the first without loss of generality.

for the TH-PPM and

$$\tilde{y}^{(n)}_{[DS]} = \sum_{j=0}^{SF-1} \int_{\tau_m+\Delta_m^{(n)}+nT_b+jT'_c}^{\tau_m+\Delta_m^{(n)}+(n+1)T_b+(j+1)T'_c} r(t) \cdot \ddot{w}(t-\tau_m-\Delta_m^{(n)}-nT_b-jT'_c)c_{m,j}dt \quad (9)$$

for the DS UWB system. The term $\Delta_m^{(n)}$ represents the misalignment between the received code of the user of interest and the code generated at the receiver in the nth symbol interval. This synchronization error may decrease the pick of the auto-correlation function and a performance degradation is inevitable. The goal of this paper is to highlight the performance degradation of the UWB systems when such errors are present. So, TH and DS techniques as well as Gaussian and Doublet pulse waveforms have been tested in a UWB system that suffers from synchronization errors. This error has been modelled as a Gaussian random variable (it is generated once per bit in the simulations) with zero mean and standard deviation σ_Δ arising from 0 to $0.3T_c$.

V. Numerical Results

In this section the simulation parameters and the results are given. The complete UWB system chain from transmitter to receiver has been simulated using a C++ simulator developed by us [7]. The following system parameters have been used:

- Gaussian pulse length: $T_p = 2ns$,
- Number of frame per bit: $N_f = 4$,
- Number of chip per frame: $N_c = 4$,
- Pseudo-random time-hopping code of length 4,
- Orthogonal Gold code of length 32 for the DS mode,
- Number of users: $\{1, 5, 10\}$,
- Standard deviation of the synchronization error (σ_Δ): $\{0, 0.05, 0.1, 0.15, 0.2, 0.3\}T_c$,
- Number of bit per simulation: 100000.

In Figs. 6 and 7 the effect of the MAI is shown in the synchronous and asynchronous case, respectively. In the synchronous case, the TH-PPM suffers from the MAI when the number of users is more than N_c, while the DS UWB just evidences a slightly performance degradation when the MAI is increased. When the interfering users are asynchronous the TH mode exhibits better performance for high system loads.

As expected the synchronization error causes hard problems to UWB system. Both the TH and the DS techniques provides very low performance when the standard deviation of the synchronization error is increased over $0.15T_c$ (Fig. 8). The DS technique is better than TH for low synchronization errors, but it converges to the performance of the TH when $\sigma_\Delta > 0.2T_c$.

From the pulse waveform point of view, the Gaussian monocycle is less sensitive to synchronization errors compared to the Doublet, but they both provide same performance for high σ_τ (Figs. 10) and 9.

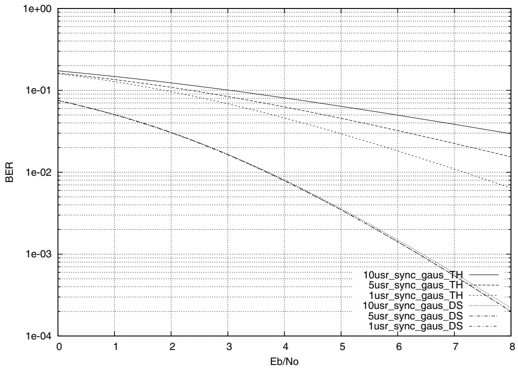

Fig. 6. BER vs SNR for the UWB system using TH and DS. Users are synchronous.

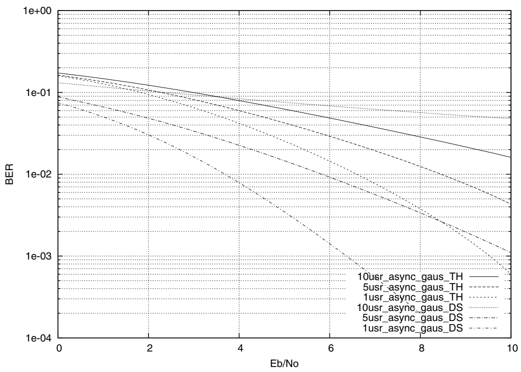

Fig. 7. BER vs SNR for the UWB system using TH and DS. Users are asynchronous.

VI. CONCLUSIONS

In this paper an exhaustive comparison of Time-Hopping PPM and Direct Sequence UWB impulse radio systems have been investigated. The TH and DS techniques have been compared in terms of performance when multiple access interference (MAI) is present. Moreover, the hypothesis of perfect synchronism between the received code of the user of interest and the code generated at the receiver is removed and the multiple access techniques as well as two different pulse waveforms (the Gaussian monocycle and the Doublet) are compared.

The results show that the DS mode has a better MAI rejection than TH-PPM when the users are synchronous. When the interfering users are asynchronous the TH technique overcomes DS for high system loads. As shown, the DS UWB system assures better performance when perfect synchronization is available at the receiver. The TH technique is slightly less sensitive than DS to synchronization errors, but they both show a very high degradation if the standard deviation of the synchronization error is set over the 20% of the chip time.

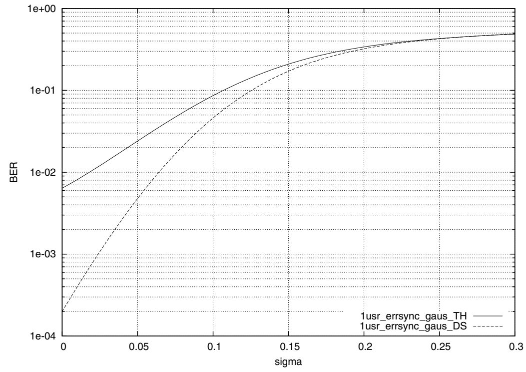

Fig. 8. BER vs the standard deviation of the synchronization error for the UWB system using TH and DS. Single user case. SNR=8dB. Gaussian pulse.

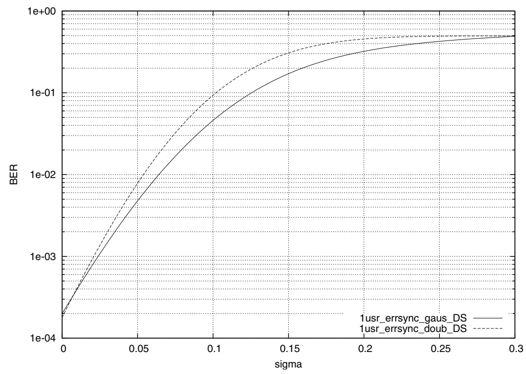

Fig. 9. BER vs the standard deviation of the synchronization error for the DS UWB system. Single user case. SNR=8dB. Gaussian and Doublet pulses.

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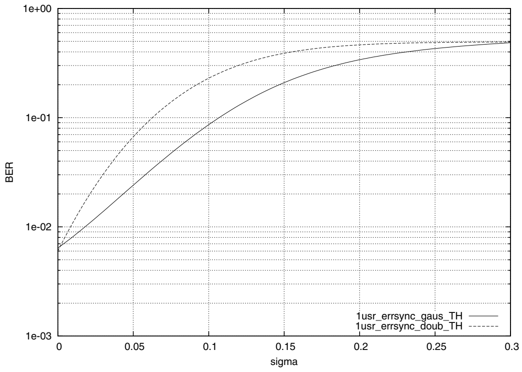

Fig. 10. BER vs the standard deviation of the synchronization error for the TH-PPM UWB system. Single user case. SNR=8dB. Gaussian and Doublet pulses.

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