Hybrid Shape, Amplitude, and Position Modulation for UWB Communication Systems

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Abstract:- In this paper we introduce a novel method for high data rate transmission in ultra-wideband (UWB) communications systems. This is achieved through a new approach based on hybrid techniques between pulse position modulation (PPM), pulse amplitude modulation (PAM) and pulse shape modulation (PSM) using combinations between a minimum possible number of modified hermite polynomial (MHP) functions by recalling their orthogonality property. In this paper we have based our discussion on single path scenario assuming beam forming is taking place to combat multipath propagation. Besides, the impact of time jitter of the proposed modulation technique on the performance of the system is investigated.

Keywords:- ultra-wideband communications, biorthogonal pulses, high data rates, time jitter.

1 Introduction

UWB is a sort of baseband communications in which very short duration pulses in the order of sub nanoseconds with very low power spectral density (- 41.5 dBm / MHz) are directly radiated to the air. This technology has many synonyms in technical literature as baseband, carrier-free or impulse radio.
According to Federal Communications Commission (FCC), a radiator is defined as UWB transmitter if it has a fractional bandwidth (FB) equal or greater than 0.2, where

$$FB = \frac{Signal\ bandwidth}{Center\ frequency} = \frac{f_h - f_l}{(f_h + f_l)/2}, \quad (1)$$

f_h, f_l are the higher and the lower 10 dB points of the signal spectrum, respectively. Alternatively, it has a UWB bandwidth equal to or greater than 500 MHz regardless the fractional bandwidth.

Due to the very low power in UWB systems, transmission of multiple versions of pulses for the same information comes to play an important role - simply to collect enough energy for detection as have been proposed in conventional modulation techniques such as time hopping (TH) or generally pulse position modulation. At the same time no transmission during certain duration between any two successive pulses should be guaranteed to avoid intersymbol interference (ISI) in multipath scenarios, if equalizers will not be used to reduce the system cost. This duration should be at least as long as the channel impulse response (IR), which means low duty cycle and hence low data rates.
On the other hand, this very short pulse duration and its high fractional bandwidth can provide bandwidth of over 1GHz to several GHz. However, by this low data rate due to the above mentioned reasons, we can safely say that the spectrum is not used in an effective way. Hence, searching for techniques allowing this repetition, avoiding ISI and at the same time provide high data rates becomes to be more than convenient.

In this paper we propose a scheme that employs a combination of pulse shape, pulse amplitude and pulse position modulation to generate biorthogonal pulses for the transmission of multiple bits or symbols. This allows to transmit more information than the conventional proposed systems in the same amount of time even with better performance for the same SNR. Due to the fact that the most UWB communications systems employ correlation receivers, we based our discussion on detection using Matched Filter (MF) concept in AWGN channels. However, the approach can also be applicable for more sophisticated receivers as Rake ones where multipath propagation is exploited. It is worth to mention that multipath scenarios could not only be handled by Rake receivers, beam forming is also a reasonable alternative. Hereby, the antenna pattern (AP) is directed to the Line of Sight (LoS) path and suppresses other pathes. The downside of this approach is that the AP will depend on the angle of incidence θ and the frequency f, i.e. $AP = AP(\theta, f)$. Hence, if a user moves, the AP has to be tracked. A solution could be obtained by periodically embedding a training sequence in the transmitted data stream in order to estimate the total IR (channel and antenna). We postpone the discussion of this subject for future work.

This paper is organized as follows. In Section 2 we review briefly the conventional UWB transmission systems. In section 3 we outline the theoretical basics for the proposed pulses based on MHP, and describe the proposed modulation scheme and pulse combinations design. In section 4 performance of the proposed system and the effect of time jitter are discussed. Finally, in section 5 we present some conclusions and discuss some future research work.

2 Conventional UWB transmission systems

In this section we describe the typical UWB transmission system and use this as a motivation for the proposed system. The rigorous mathematical description is presented next and considers a multi-access environment

$$s^k(t) = \sum_{j=-\infty}^{\infty} p(t - jT_f - c_j^k T_c - \delta b^k_{\lfloor \frac{j}{N_p} \rfloor}). \qquad (2)$$

Here, $p(t)$ with duration T_p represents the transmitted monocycle waveform, T_f represents the pulse repetition time which is typically a hundred to a thousand times of the monocycle length leading to a very low duty cycle, i.e. $\frac{T_p}{T_f} \ll 1$. Superscript k denotes the user k assumed in multiuser environment. So, the signal emitted by user k consists of monocycles shifted to different times, the j-th monocycle nominally begin at time $jT_f - c_j^k T_c - \delta b^k_{\lfloor \frac{j}{N_p} \rfloor}$.

If multiple-access signals would have been composed only with uniformly spaced pulses then a perfect chance for catastrophic collisions can occur, where a large number of pulses from two signals are received at the same time instants and this can corrupt irreversibly the message. Therefore, a random (or pseudo-random) time hopping sequence c_j^k is employed. These sequences have a period N_p with each element a finite integer in the range 0,1,...,$N_h - 1$. Each element has a chip duration of T_c.

Thus, this code provides an additional time shift to each pulse in the pulse train, with the j-th monocycle additionally shifted with $c_j^k T_c$ seconds. Hence the added time shifts caused by the code are discrete between 0 and $N_h T_c$ seconds. Also the greatest shift generated by the code ($N_h T_c$ seconds) is required to be less than the length of the basic train pulses period T_f. The additional shift of δ is to differ between the sequence representing bit 0 ($b = 0$) and the one representing bit 1 ($b = 1$). This additional time shift could be chosen to be greater than or equal the chip duration T_c. Hence, the two sequences become fully orthogonal to each other and better performance could be achieved. See [2] and [3] for more information about time hopping codes and its usage.

3 Proposed system description based on orthogonal Hermite pulse shapes

Hermite functions, and indeed Hermite pulses are not new. Hermite transform has already been used to shed light on spatio-temporal relationships in image processing [1]. In fact, normalized MHP pulses are defined as

$$p_n(t) = \frac{1}{\sqrt{(2(n!\sqrt{(\frac{\pi}{2})}))}} (-1)^n \mathrm{e}^{-\frac{t^2}{4}} \frac{d^n}{dt^n} (\mathrm{e}^{-\frac{t^2}{2}}), \qquad (3)$$

where n is the pulse order. MHP do have attractive features could be summarized in the following. MHP pulses are mutually orthogonal to each others, which was the property used for the M-ary modulation scheme. Another advantage of MHP pulses is that the time duration and the bandwidth of the pulses do not change significantly when the order of the pulses is increased. These properties can be exploited to design meaningful combinations of MHP pulses to increase the data rate.

The drawback of MHP becomes obvious in case of imperfect correlation receivers, the probability of error increases when a narrower correlation peak is present. Besides, the time duration of the pulses do not change significantly between two successive polynomial orders but the change between a low order and a much higher one could not be ignored for appropriate level of orthogonality. Higher order pulses have also been found to be more sensitive to time jitter [1] in the receiver, obviously also due to the narrow correlation peak. Hence, some limitations do exist.

Due to the above mentioned shortcomings of the higher orders in MHP pulses, we intend in our approach to use a minimum possible number of MHP orders to achieve as many biorthogonal combinations as possible. Furthermore, we guarantee the complete overlapping between different orders to achieve the full orthogonality. This directly improves the probability of error and hence improves the performance of the system. Now let us combine the zero and the first orders in one pulse as,

$$p(t) = a_0\ p_0(t) + a_1\ p_1(t - T), \tag{4}$$

$$p_0(t) = \frac{1}{\sqrt[4]{2\pi}} \mathrm{e}^{\frac{-t^2}{4}}, \tag{5}$$

$$p_1(t) = \frac{1}{\sqrt[4]{2\pi}}\ t\ \mathrm{e}^{\frac{-t^2}{4}}. \tag{6}$$

Here T is the duration of $p_0(t)$ or $p_1(t)$. Note that for orthogonality and unit energy, the coefficients have to satisfy $a_0 = a_1 = \sqrt{\frac{1}{2}}$. Based on equation (4) we propose the first simple modulation scheme, which we call Hybrid-2 (H-2) because the technique merges PSM, PAM and PPM together.

Bits	Combination
0	$\sqrt{\frac{1}{2}}\ p_0(t) + \sqrt{\frac{1}{2}}\ p_1(t-T)$
1	$-\sqrt{\frac{1}{2}}\ p_0(t) - \sqrt{\frac{1}{2}}\ p_1(t-T)$

Table 1. Hybrid-2 modulation scheme.

The previous table shows that from the first 2 orders, we are able to create 2 antipodal combinations. It is worth to mention that of course antipodality could also be achieved by just one pulse and its negative, but it is just to start from the basic level of the proposed system.

Bits	Combinations
00	$\sqrt{\frac{1}{2}}\ p_0(t) + \sqrt{\frac{1}{2}}\ p_1(t-T)$
01	$\sqrt{\frac{1}{2}}\ p_1(t) + \sqrt{\frac{1}{2}}\ p_0(t-T)$
11	$-\sqrt{\frac{1}{2}}\ p_0(t) - \sqrt{\frac{1}{2}}\ p_1(t-T)$
10	$-\sqrt{\frac{1}{2}}\ p_1(t) - \sqrt{\frac{1}{2}}\ p_0(t-T)$

Table 2. Hybrid-4 modulation scheme.

Table 2 shows in more detail the concept behind this approach that the position is mutually changed between the zero and the first orders in the same combination to generate 4 biorthogonal signals. So (00) signal is orthogonal to (01) and (10) signals but antipodal to (11) signal. Similarly any signal to the others. It can be also shown that 4 biorthogonal signals can be achieved by just using one pulse, simply by mutually changing the position between the pulse and its negative.

Bits	Combinations
000	$\sqrt{\frac{1}{2}}\ p_0(t) + \sqrt{\frac{1}{2}}\ p_1(t-T)$
001	$\sqrt{\frac{1}{2}}\ p_1(t) + \sqrt{\frac{1}{2}}\ p_0(t-T)$
011	$\sqrt{\frac{1}{2}}\ p_0(t) - \sqrt{\frac{1}{2}}\ p_1(t-T)$
010	$-\sqrt{\frac{1}{2}}\ p_1(t) + \sqrt{\frac{1}{2}}\ p_0(t-T)$
110	$-\sqrt{\frac{1}{2}}\ p_0(t) - \sqrt{\frac{1}{2}}\ p_1(t-T)$
100	$-\sqrt{\frac{1}{2}}\ p_1(t) - \sqrt{\frac{1}{2}}\ p_0(t-T)$
101	$-\sqrt{\frac{1}{2}}\ p_0(t) + \sqrt{\frac{1}{2}}\ p_1(t-T)$
111	$\sqrt{\frac{1}{2}}\ p_1(t) - \sqrt{\frac{1}{2}}\ p_0(t-T)$

Table 3. Hybrid-8 modulation scheme.

As Table 3 shows, only by use of the first 2 orders we are able to design 8 different biorthogonal signals. Also Gray code has been applied in the design for better performance. Note that only 4 matched filters are needed in the receiver.

4 System performance and time jitter effect of the proposed system

In this section we will investigate the system performance in terms of BER and time jitter.

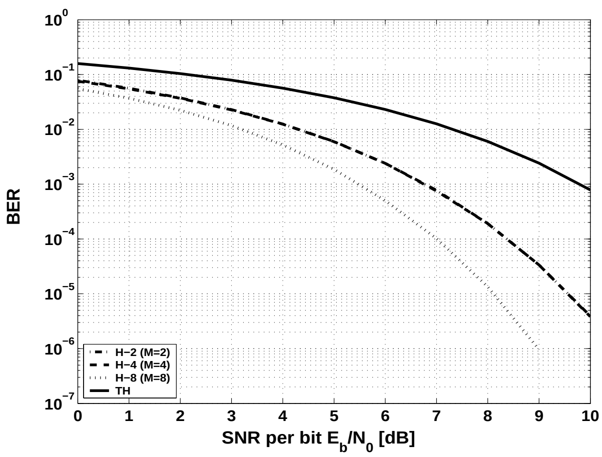

Figure 1: The performance of the conventional system and the proposed one in AWGN channel.

From the previous figure, it is clear that the BER of H-2 and H-4 are completely coincide [5] and both of them require SNR of around 3 dB less than TH for same performance. This is due to the fact that orthogonal signals require a factor of 2 increase in energy to achieve the same error probability as antipodal signals [5]

For the BER of TH, the additional time shift δ has been chosen to be greater than or equal to the chip duration T_c. Thus, the two sequences representing bit 0 and bit 1 become fully orthogonal to each others. Hence, the BER in AWGN could be calculated from the following formula [5]

$$\text{BER} = 0.5\ \text{erfc}\left(\frac{\sqrt{\frac{E_b}{N_0}}}{\sqrt{2}}\right). \tag{7}$$

It can be shown that the probability of a symbol error P_M of the biorthogonal signals in AWGN is [5]:

$$P_M = 1 - \frac{1}{\sqrt{2\pi}} \int_{-\sqrt{\frac{2E_s}{N_0}}}^{\infty} \left(\frac{1}{\sqrt{2\pi}} \int_{-(v+\sqrt{\frac{2E_s}{N_0}})}^{(v+\sqrt{\frac{2E_s}{N_0}})} \mathrm{e}^{-x^2} dx \right)^{\frac{M}{2}-1} \mathrm{e}^{-v^2} dv. \tag{8}$$

Here $M = 2^L$ where L is the number of bits per symbol. Also E_s is the energy per symbol, which means $E_s = LE_b$ where E_b is the energy per bit. In fact there is no closed form for this integration except for $M = 2$ and $M = 4$ [5]. Hence, the integral has been evaluated numerically for different values of M. Note that it can be shown that as $M \to \infty$ (or $L \to \infty$), the minimum required $\frac{E_b}{N_0}$ to achieve an arbitrarily small probability of error is -1.6 dB, the Shannon limit [5].
When a Gray code is used in the mapping then each symbol error is most likely to cause only a single bit error for high SNR. Hence, Fig. 1 is based on the following formula

$$\text{BER} \approx \frac{P_M}{\log_2 M}. \tag{9}$$

Fig. 2 demonstrates the effect of the approximation in equation (9) and the simulation results. They coincide together in case of H-4 due to the fact that H-2 and H-4 coincide for antipodal signals. However, there is difference in case of H-8 but this difference becomes negligible for high SNR.

Mutual orthogonality among several pulses, however, depends on perfect synchronization of all co-existing waveforms. This ideal condition is not found in practical UWB channels due to random mismatches (jitter) between transmitters and receivers. Thus, we have investigated the robustness of the designed scheme against time jitter.

The simulations are based on signal durations of $T_p = 1$ns and $T_f = 4$ns in noise free channel. We can conclude that TH, H-2 and H-4 are more robust against jitter values of ±0.1 or smaller. However, for jitter values >∼ 0.15ns, H-8 is more robust. This is due to the behavior of the auto correlation function (ACF) and the cross correlation function (CCF) around the sampling point between different signals in each modulation technique as shown in the following figures.

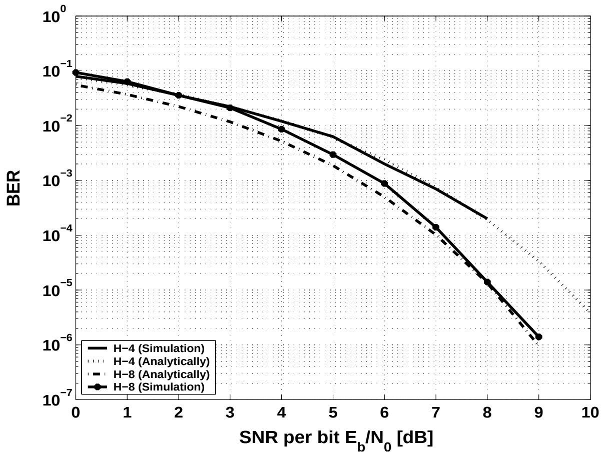

Figure 2: H-4 and H-8 are shown analytically and their simulation results in AWGN channel.

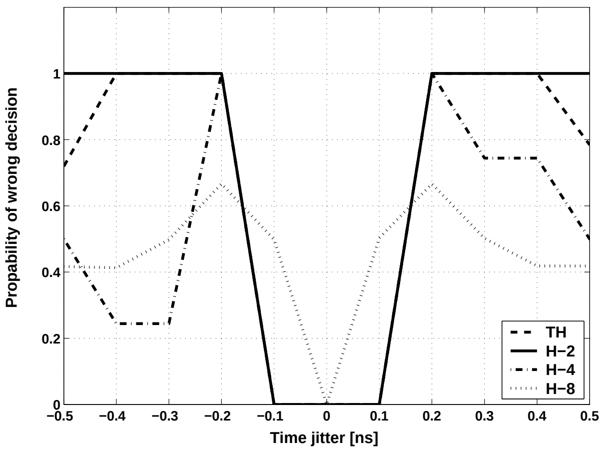

Figure 3: Time jitter effect on TH and the proposed system

From Fig. 4-6 the orthogonality between the signals is obvious. Note that the peak of the ACF in case of H-8 is higher than the peak of the ACF in case of H-4 because simply SNR is per bit. The zero level in the ACF and CCF is because of 1 ns signal duration in a frame duration of 4 ns.

5 Conclusions

As have been illustrated in this paper we proposed a hybrid technique between PPM, PAM and PSM

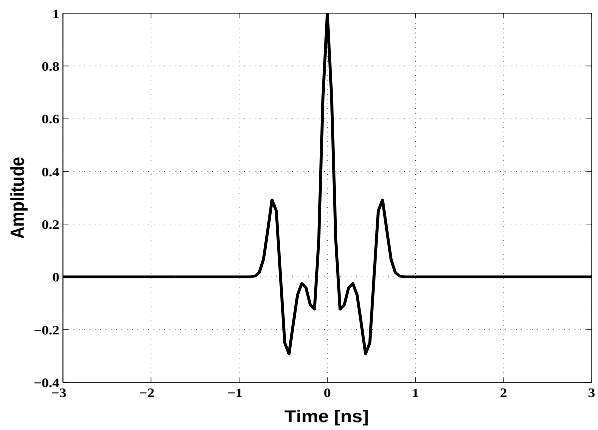

Figure 4: Normalized ACF in case of H-2, H-4, H-8

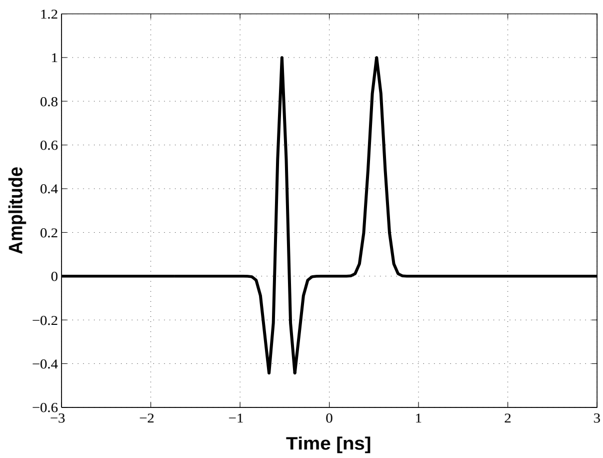

Figure 5: CCF between [00] and [01] in H-4

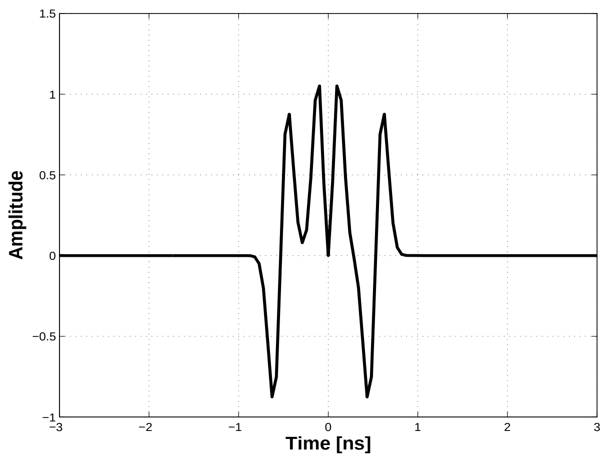

Figure 6: CCF between [001] and [010] in H-8

to produce up to 8 different biorthogonal signals in order to increase the transmission data rate with better performance. We have recalled the properties of MHP and have investigated the reasons behind using the minimum possible number of MHP in the design of our proposed system. We have found that the conventional modulation scheme (TH) requires a factor of 3 dB increases in the energy to achieve the same BER as H-2 or H-4 and about 4 dB to achieve the same BER as H-8 in AWGN channel. Besides, only 4 matched filters are needed for H-8 and 2 for H-4.

The performance of the system in terms of time jitter has also been discussed. It is found that TH, H-2 and H-4 are more robust than H-8 for jitter values of ±0.1 ns.

For future work, we would like to test the performance of the system in multipath scenarios where the real channel will degrade the orthogonality properties of the pulses. Treating this issue generically is of course beyond the scope of this single article. Also we would like to investigate multiuser scenarios in which different users will be considered with their different codes and different overlapping durations between their signals. Furthermore, we would like to investigate the performance of the proposed system if the codes are chosen by such a way that overlapping between only one code element is allowed.

References

[1] M. Ghavami, L. B. Michael, S. Haruyama and R. Kohno, A Novel UWB Pulse Shape Modulation System, *Kluwer International Journal on Wireless Personal Communications*, Vol.23, No.1, 2002, pp. 105-120.

[2] M. Z. Win and R. A. Scholtz, Ultra-Wide Bandwidth Time-Hopping Spread-Spectrum Impulse Radio for Wireless Multiple-Access Communications, *IEEE Trunsactions on Communications*, Vol.48, No.4, 2000, pp. 679-691.

[3] T. Erseghe, Time-hopping patterns derived from permutation sequences for ultra-wide-band impulse-radio applications, *6th WSEAS International Conference on Communications*, Vol.1, No.1, 2002, pp. 109-115.

[4] Aktl Kavas, Investigation of Indoor Propagation Models at 900, 1800 and 1900 MHz Bands, *WSEAS Transactions on Communications*, Vol.2, Issue 4, 2003, ISSN1109-2742.

[5] Proakis, *Digital Communications*, Fourth Edition, New York, NY:Mc-Graw-Hill, 2000.

[6] D. R. Smith, *Digital Transmission Systems*, New York, Van Nostrand Reinhold Company Inc., 1985.