Antenna Effect on Biorthogonal Pulses Using Modified Hermit Polynomials for UWB Communications

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Abstract

Orthogonal and Biorthogonal pulses are important for high data rate wireless communications and multiple access techniques. It is also an interesting subject for Ultra wideband (UWB) 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. However, when these pulses are applied to an appropriately designed antenna and propagate in a frequency-selective fading channel, the bit error rate (BER) performance is severely degraded since the orthogonality among these pulses is partially lost. In this paper we discuss the effect of antenna on BER performance using biorthogonal pulses based on modified Hermit polynomial (MHP) in additive white Gaussian noise (AWGN) channel. Due to the increasing importance of UWB communication we focus our discussion on very short duration pulses directly applied to the antenna. However, the reported results according to the proposed approach are not limited to UWB pulses and can be extended to any other carrier-free technology. Moreover, for simplicity and clarity reasons, we take only the effect of antennas into consideration assuming beam forming is taking place to combat multipath propagation and postpone the influence of frequency-selective fading channel for future work.

I. 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) [11], a radiator is defined as UWB transmitter if it has a fractional bandwidth (FB) equal or greater than 0.2, where

$$FB = \frac{signal\ bandwidth}{center\ frequency} = \frac{f_h - f_l}{(f_h + f_l)/2}, \qquad (1.1)$$

f_h and 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 inter symbol 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 [11]. 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, applying techniques allowing this repetition, avoiding ISI and at the same time provide high data rates becomes to be more than convenient.

A novel biorthogonal scheme for high data rate transmission in (UWB) communication systems was proposed in [11]. 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 MHP functions by recalling their orthogonality property. This allows transmitting more information than the conventional proposed systems, timing hopping (TH), in the same amount of time even with better performance for the same SNR [11]. However, when these pulses are applied to an appropriately designed antenna, the pulses propagate with distortion. The antennas behave as filters, and even in free space, a differentiation of the pulses occurs as the wave radiates [4]. The propagation of the signals from the transmitter to the receiver is assumed to be ideal, i.e. signals suffer only from a constant attenuation and delay. This means multipath and dispersive effects are ignored. The antenna propagation system modifies the shape of the transmitted pulses at its output [4].

In the present paper we discuss the effect of this change on the mutual orthogonality of the pulses mentioned in [11]. Due to the fact that most UWB communication 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 receivers 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 [11].

This paper is organized as follows. In Section II we review briefly the biorthogonal scheme proposed in [11] for UWB transmission systems. In sections-2 and 4 we outline the theoretical basics for antennas and wave propagation used to determine the shape modification of the generated pulses due the transmitting and the receiving antennas. In section-5 BER performance of the proposed scheme taking into account the shape modification of the pulses is discussed. Finally, in section-6 we present some conclusions and discuss some future research work.

2. Proposed System Description

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 [11]. In fact, normalized MHP pulses are defined as:

$$p_n(t) = \frac{1}{\sqrt{(2(n!\sqrt{(\frac{\pi}{2})}))}}(-1)^n\, e^{\frac{-t^2}{4}}\ \frac{d^n}{dt^n}\left(e^{\frac{-t^2}{2}}\right), \qquad (2.1)$$

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. 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 order could not be ignored for appropriate level of orthogonality [11]. Higher order pulses have also been found to be more sensitive to time jitter [11] 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,

$$p(t) = a_0 p_0(t) + a_1 p_1(t-T), \qquad (2.2)$$

$$p_0(t) = \frac{1}{\sqrt[4]{2\pi}} e^{\frac{-t^2}{4}}, \qquad (2.3)$$

$$p_1(t) = \frac{1}{\sqrt[4]{2\pi}} t e^{\frac{-t^2}{4}}, \qquad (2.4)$$

Here T is the duration of $p_0(t)$ or $p_1(t)$. Note that for orthogonality and normalized energy, the coefficients have to satisfy $a_0 = a_1 = \sqrt{\frac{1}{2}}$.

Based on equation (2.2) we propose the first simple modulation scheme, which we call Hybrid-2 (H-2) because the technique merges PSM, PAM and PPM together. It is important to mention that $p_0(t)$ and $p_1(t)$ can be any two orthogonal signals. However, MHP functions are chosen due to the above mentioned reasons.

Table 2-1: Hybrid-2 modulation scheme

Bits	Combinations
0	$a_0 p_{0(t)} + a_1 p_1(t-T)$
1	$-a_0 p_{0(t)} - a_1 p_1(t-T)$

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.

Table 2-2: Hybrid-4 modulation scheme.

Bits	Combinations
00	$a_0 p_0(t) + a_1 p_1(t-T)$
01	$a_1 p_1(t) + a_0 p_0(t-T)$
11	$-a_0 p_0(t) - a_1 p_1(t-T)$
10	$-a_1 p_1(t) - a_0 p_0(t-T)$

Table 2-2 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 is orthogonal 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.

Table 2-3: Hybrid-8 modulation scheme.

Bits	Combinations
000	$a_0 p_0(t) + a_1 p_1(t)$
001	$a_1 p_1(t) + a_0 p_0(t)$
011	$a_0 p_0(t) - a_1 p_1(t)$
010	$-a_1 p_1(t) + a_0 p_0(t)$
110	$-a_0 p_0(t) - a_1 p_1(t)$
100	$-a_1 p_1(t) - a_0 p_0(t)$
101	$-a_0 p_0(t) + a_1 p_1(t)$
111	$a_1 p_1(t) - a_0 p_0(t)$

Table 2-3 shows that only by using 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. Consequently, only 4 matched filters are needed in the receiver.

The proposed modulation technique performance in terms of BER can be derived as follow. The probability of a symbol error P_M of the biorthogonal signals in AWGN is given by [11]:

$$P_M = 1 - \frac{1}{\sqrt{2\pi}} \int_{-\sqrt{\frac{2E_S}{N_0}}}^{\infty} \left(\frac{1}{\sqrt{2\pi}} \int_{-(v+\sqrt{\frac{2E_S}{N_0}})}^{(v+\sqrt{\frac{2E_S}{N_0}})} e^{-x^2}\, dx \right)^{\frac{M}{2}-1} e^{-v^2}\, dv. \tag{2.5}$$

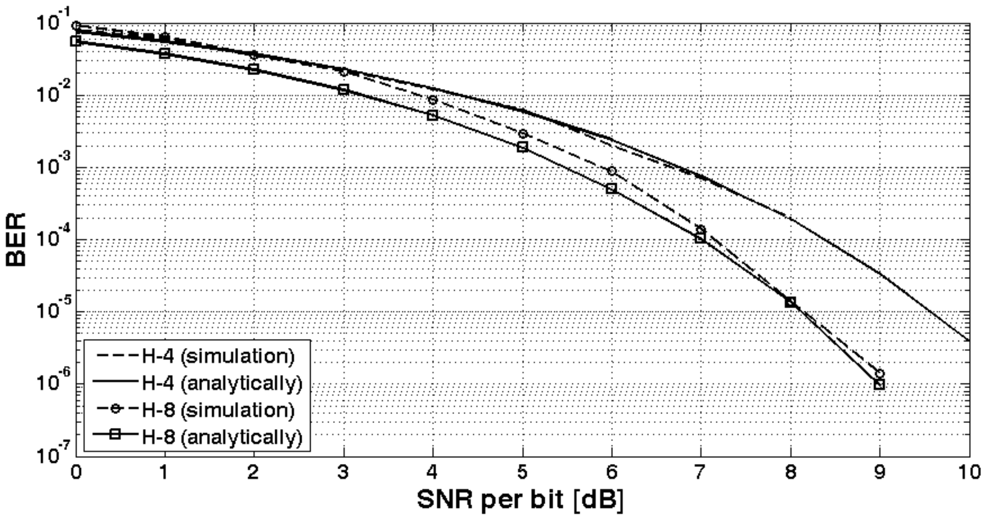

Figure 2-1: H-4 and H-8 are shown analytically and their simulation results in AWGN channel.

Here M = 2L 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 and N_0 is the noise power spectral density (PSD). In fact there is no closed form for this integration except for M = 2 and M = 4 [11]. 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 [11]. 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, we can write the following formula:

$$\text{BER} = \frac{P_M}{\log_2 M}. \tag{2.6}$$

It can be shown that H-2 and H-4 are completely coincide [11]. figure 1 demonstrates the effect of the approximation in equation (2.6) 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. These simulation results are based on AWGN channel neglecting any shape modifications on the transmitted pulses due to antennas effect. It neglects also multipath and frequency-selective fading in the channel assuming beam forming is applied.

3. Antenna Effect and Wave Propagation

In wireless communication systems, after an RF signal has been generated in a transmitter, some means must be used to radiate this signal through space to a receiver. The device that does this job is the antenna. The transmitter signal energy is sent into space by a transmitting antenna. The antenna accepts power from the transmitter and launches it into space as radio frequency (RF) energy [13-18]. The RF energy is transmitted into space in the form of an electromagnetic wave. The transmitting antenna converts energy from one form to another form. The receiving antenna reverses this process. It transforms the electromagnetic field into RF energy that is delivered to a radio receiver. As the traveling electromagnetic wave arrives at the receiving antenna the electromagnetic wave induces voltage into the antenna terminals. The RF signal is then picked up from space by the receiving antenna. The RF voltages induced into the receiving antenna results in alternating electric current or signal that passed into the receiver and converted back into the transmitted RF signal figure 3-1.

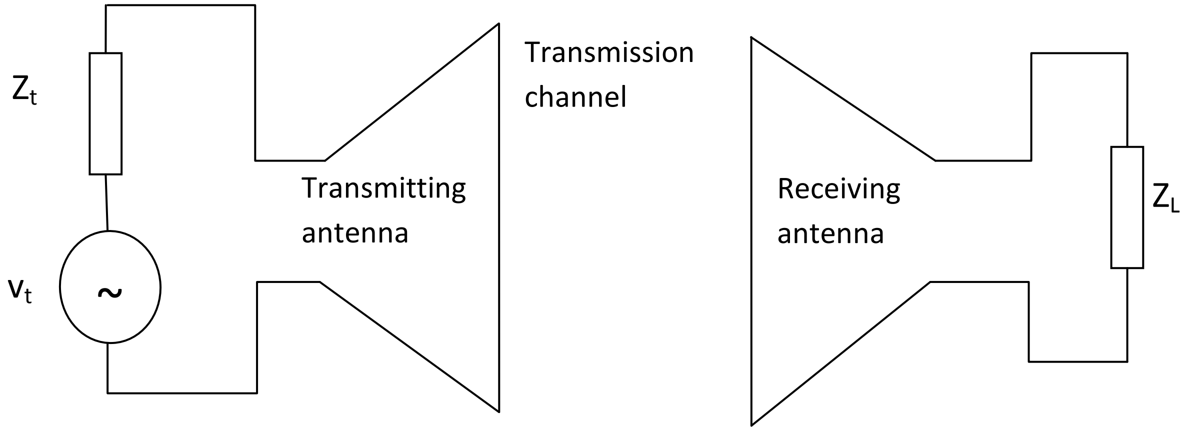

Figure 3-1 Typical radio communication link.

For wireless systems, the antenna is one of the critical components. A good design of the antenna can relax system requirements and improve overall system performance. The wireless systems include a large variety of different kinds, such as radar, navigation, landing systems, direct broadcast TV, satellite communications, and mobile communications and so on. An antenna plays an important role in science and daily life. Today we enjoy much benefit from wireless, and the significant contributions of antennas should not be underestimated. An antenna is an electromagnetic transducer, used to convert, in the transmitting mode, guided waves within transmission lines to radiated free-space waves, or to convert, in the receiving mode, free-space waves to guided waves.

How efficient antennas launch and collect electromagnetic waves directly influences communications reliability and quality. To select the right antennas for a radio communication circuit, certain concepts and terms must be understood. There are several critical parameters that affect an antenna's performance and can be adjusted during the design process. These include: forming a radio wave, radiation fields and patterns, polarization, directivity, resonance, reception, reciprocity, impedance, bandwidth, gain, and take-off angle. All of these parameters are expressed in terms of a transmission antenna, but are identically applicable to a receiving antenna. This is what is meant by reciprocity of antennas. For example, the more efficient a certain antenna is for transmitting, the more efficient it will be for receiving the same frequency. The directive properties of a given antenna will be the same whether it is used for transmission or reception.

In antenna design, "gain" is the ratio of the intensity of an antenna's radiation pattern in the direction of strongest radiation to that of a reference antenna. The reference antenna is an isotropic antenna; which radiates equally in all directions figure 3-2. A true isotropic radiator really exists only in theory. The gain of an antenna is a passive phenomena - power is not added by the antenna - but simply redistributed to provide more radiated power in a certain direction than would be transmitted by an isotropic antenna. If an antenna has a positive gain in some directions, it must have a negative gain in other directions as energy is conserved by the antenna figure 3-3. The gain that can be achieved by an Antenna is therefore trade-off between the range of directions that must be covered by an Antenna and the gain of the antenna. For example, a dish antenna on a spacecraft has a very large gain, but only over a very small range of directions - it must be accurately pointed at earth - but a radio transmitter has a very small gain as it is required to radiate in all directions.

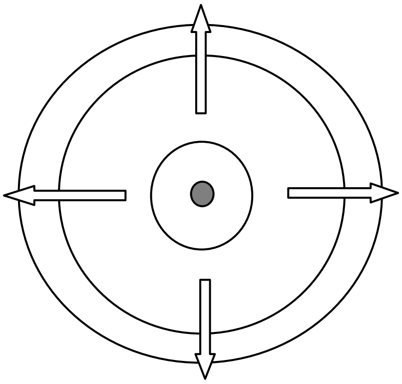

Figure 3-2 Energy from an isotropic radiator propagates outward evenly in all directions, falling off according to the inverse square law.

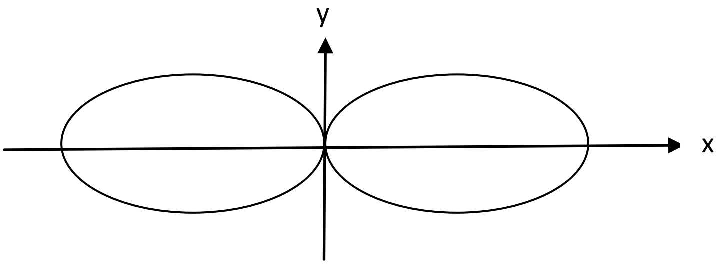

Figure 3-3 Two dimensional radiation intensity patterns for directive antenna.

From the foregoing discussion the antenna is a transition device or transducer between a guided wave and free space wave, or vice versa. In addition, the antenna is a device which interfaces an electric circuit and space.

Considering the circuit point of view the antenna appears to the signal generator as a resistance called the radiation resistance. It is a virtual resistance that couples from antenna terminals to space. It is the resistance that when inserted in series with the generator will consume the same amount of power as is actually radiated. In addition each antenna has specific radiation characteristics summarized in its radiation pattern.

The radiation resistance and the radiation pattern are function of frequency. In general the patterns are also functions of the distance at which they are observed. At distances very large compared to the operating wave length and antenna size, the pattern is independent of distance. Usually the patterns of interest are for far field conditions. The radiation pattern is a three dimensional quantity describes the variation of field or power as a function of the spherical coordinates θ and φ. Consequently, an antenna has a dual role, being a circuit device with radiation resistance and a space device with radiation pattern.

The input impedance is defined as the impedance presented by an antenna at its terminals or the ratio of the voltage to current at a pair of terminals or the ratio of the appropriate components of the electric to magnetic fields at a point. The antenna losses can be represented by a loss resistance. In general, an antenna may have a reactance. The ratio of the voltage to current at antenna terminals, with no load attached, defines the impedance of the antenna as

$$Z_A = R_r + R_l + jX_A \tag{3.1}$$

where
R_r = radiation resistance of the antenna
R_l= loss resistance of the antenna
X_A = antenna reactance

In the transmitter circuit signal generator is replaced by its thevenin equivalent with the generator voltage v_t and the generator impedance Z_t as shown in figure 3-4. The radiated field from this circuit is proportional to the current which is given by

$$Z_t = R_t + jX_t \tag{3.2}$$

where
R_t= transmitter resistance
X_t = transmitter reactance

$$I_A = \frac{v_t}{R_t+R_r+R_l+j(X_t+X_A)} \tag{3.3}$$

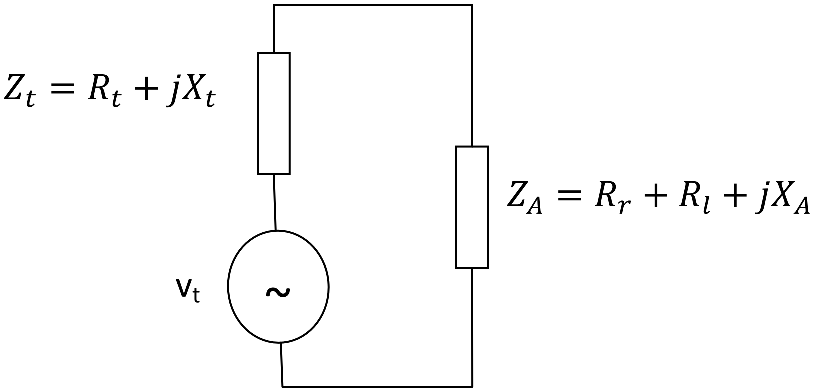

Figure 3-4 Transmitter equivalent circuit.

In the receiver circuit the antenna extracts power from the incident electromagnetic wave and delivers it to the load or terminating impedance Z_l. the antenna is replaced by its thevenin equivalent with the induced open circuit voltage v_r and the antenna impedance Z_A figure 3-5. The induced voltage v_r produces a current I_r through the load Z_L.

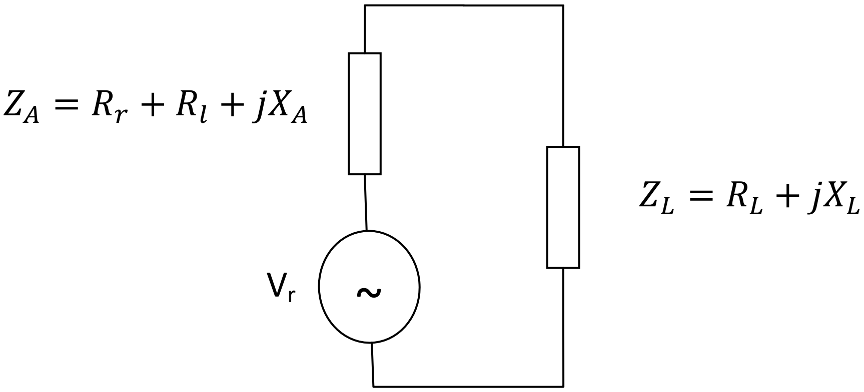

Figure 3-5 Receiver equivalent circuit.

$$I_r = \frac{v_r}{Z_L+Z_A} = \frac{v_r}{R_L+R_r+R_l+j(X_L+X_A)} \tag{3.4}$$

To study the effect of the antenna on the transmitted signal we need to get a relation to relate the induced voltage on the receiving antenna to the signal generator voltage which considers all the effects of the transmitting and the receiving antenna Figure 3-6. Such equation can be derived from the well known Friis transmission equation [13] which relates the power received to the power transmitted between two antennas separated by a distance R.

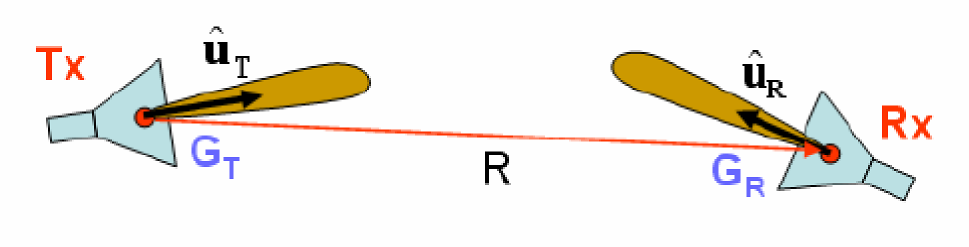

Figure 3-6 Geometrical orientation of transmitting and receiving antennas for Friis transmission equation

$$\frac{P_r}{P_t} = \eta_t\eta_r(1-|\Gamma_t|^2)(1-|\Gamma_r|^2)\left(\frac{\lambda}{4\pi R}\right)^2 D_tD_r\left|\hat{U}_T.\hat{U}_R\right|^2 \qquad (3.5)$$

Where
P_t is the input power at the terminals of the transmitting antenna
P_r is the power collected at the terminals of the receiving antenna
η_t is the radiation efficiency of the transmitting antenna
η_r is the radiation efficiency of the receiving antenna
Γ_t is the voltage reflection coefficient at the input terminals of the transmitting antenna
Γ_r is the voltage reflection coefficient at the output terminals of the receiving antenna
λ is the wave length of the transmitted signal
R is the separation distance between the two antennas
D_t is the directivity of the transmitting antenna
D_r is the directivity of the receiving antenna
$\hat{U}_T$ is the unit vector (polarization vector) of the electric field of the transmitting antenna
$\hat{U}_R$ is the unit vector (polarization vector) of the electric field of the receiving antenna

4. Transfer Function and Impulse Response of the Overall System

The relationship between the excitation voltage at the transmitting antenna and the received voltage at the receiving antenna can be represented in the frequency domain through the transfer function of the overall system. The transfer function between the transmitting and receiving antenna may then be given by

$$V_r(\omega) = H(\omega)V_t(\omega) \qquad (4.1)$$

where
$V_r(\omega)$ is the Fourier transform of the received voltage
$V_t(\omega)$ is the Fourier transform of the generator voltage
$H(\omega)$ is impulse response transfer function of the overall system

To investigate the effect of the antenna on the transmitted signal we consider two identical antennas. Assuming the two antennas are matched for reflection and polarization conditions. In addition the antennas are aligned for maximum directional radiation and reception. Consequently, the transfer function reduces to

$$\frac{V_r(\omega)}{V_t(\omega)} = H(\omega) = \left(\frac{\lambda}{4\pi R}\right) G \tag{4.2}$$

$$\frac{V_r(\omega)}{V_t(\omega)} = H(\omega) = \left(\frac{CG}{2\omega R}\right) \tag{4.3}$$

where G is the antenna gain.

Since we are concerned with the effect of the antennas on the behavior of signal orthogonality, the inverse Fourier transform is calculated for the above transfer function to get the signal in time domain and study its orthogonality.

5. Results and Conclusions

In this section we discuss the effect of the transmitted and the received antennas on the proposed biorthogonal signals. As mentioned before, the antenna/propagation system modifies the shape of the transmitted pulses at its output [4]. It is difficult to discuss this effect analytically in the time domain. Hence, based on equation 15, the following steps are executed to study this effect numerically.

A Matlab simulation program is written to apply Fourier transformation on the generated electrical signal before the transmitted antenna $v_t(t)$ to get $V_t(\omega)$. Then Fourier transformation inverse is applied on the received electrical signal $V_r(\omega)$ to get the received signal after the received antenna in the time domain $v_r(t)$. Matlab functions fft(), fftshift(), ifft and ifftshift() are used in this simulation. Note that the used Matlab version is 7.10.0.499 (R2010a).

Figure 5-1 shows the single sided PSD of the electrical transmitted signal $V_t(\omega)$. Figure 5-2 shows the generated electrical signal before the transmitting antenna and the received electrical signal, including antennas effect, after the received antenna $v_r(t)$ for H-4. The figure demonstrates how the antennas modify the shape of the transmitted pulses for each bits combination.

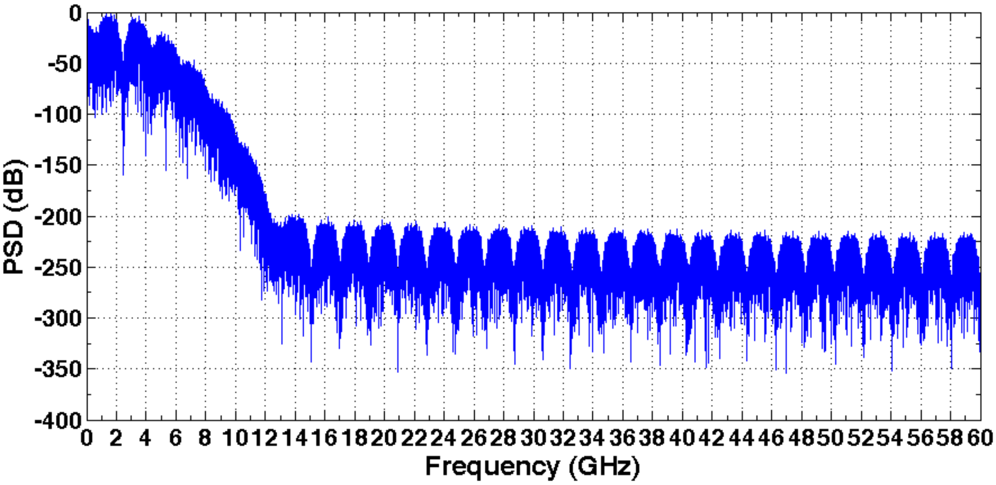

Figure 5-1 Single sided power spectrum density (PSD) of the transmitted pulses $V_t(\omega)$.

Now it is interesting to discuss how the BER performance is affected due to this shape modification. It is clear that the orthogonality among these pulses is partially lost. Figure 5-3 shows the BER simulation results assuming AWGN channel and taking into consideration the effect of antennas as shown before. Note that these simulation results neglect multipath and frequency-selective fading in the channel assuming beam forming is applied.

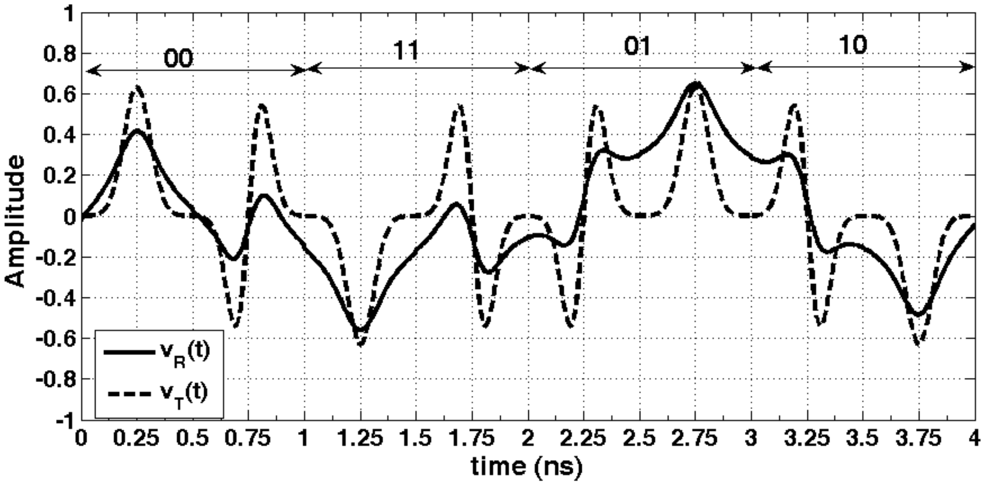

Figure 5-2 The generated and the received electrical

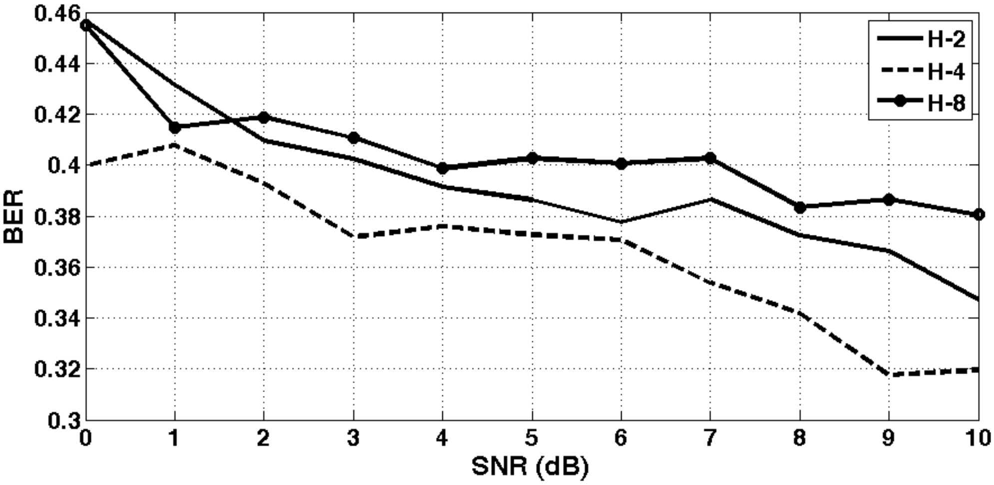

Figure 5-3 BER system performance for AWGN taking into consideration Antennas effect.

Comparing these results with those given in figure 2-1, it is clear that BER performance is severely degraded due to pulses shape modifications after taking antennas effects into consideration. Simulations are repeated assuming noise-free channel to investigate the effect of pulse shape modification only. It is found that BER better than 0.15 can not be achieved.

To verify these simulation results $H(\omega)$ is set to one in the simulation program which delivers the results in figure 5-3. Then the output results are compared with the delivered simulation results shown in figure 1 which are obtained by a different simulation program that considers only AWGN channel without any antennas effect consideration. The comparison is shown in figure 5-4. It is clear that the two simulation results are almost identical. The obtained slight changes are due to numerical approximation and random noise generation.

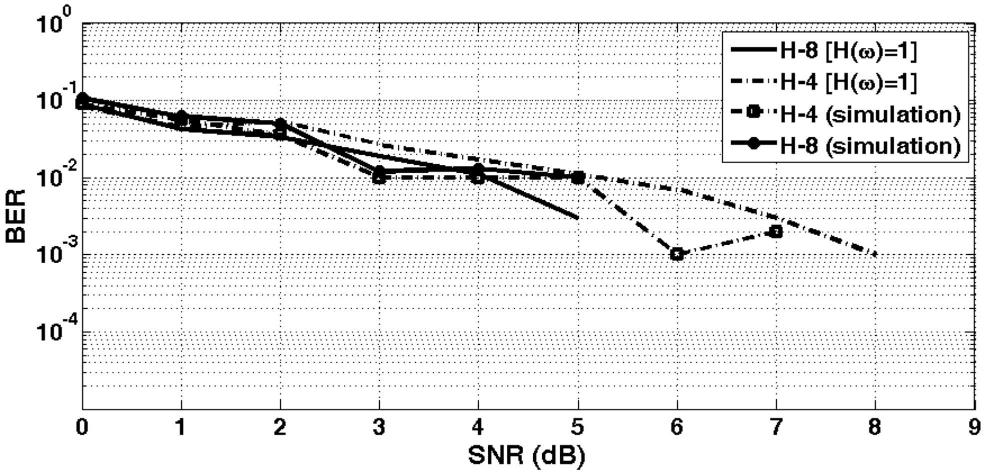

Figure 5-4 Verification of Results in figure 10.

The results reported in [11] show that MHP functions are very sensitive to random synchronization mismatches (jitter) between transmitters and receivers. Especially for H-8 which also shows the worst BER performance under shape modifications condition. However, H-4 shows more robust behavior than H-8 against jitter [11]. It shows also better BER performance under pulse modifications conditions.

Hence, based on these simulation results we can safely say that MHP are very sensitive not only to jitter but also to shape modifications. 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.

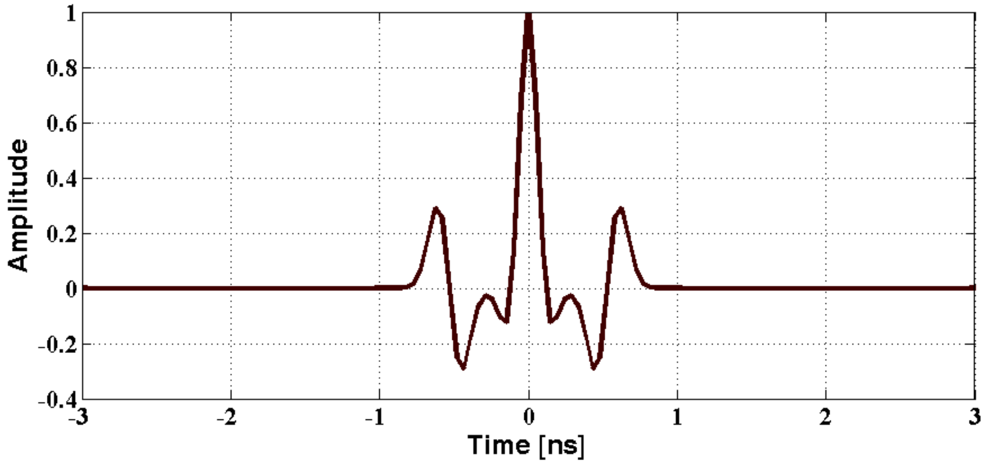

Figure 5-5 Normalized ACF in case of H-2, H-4 and H-8.

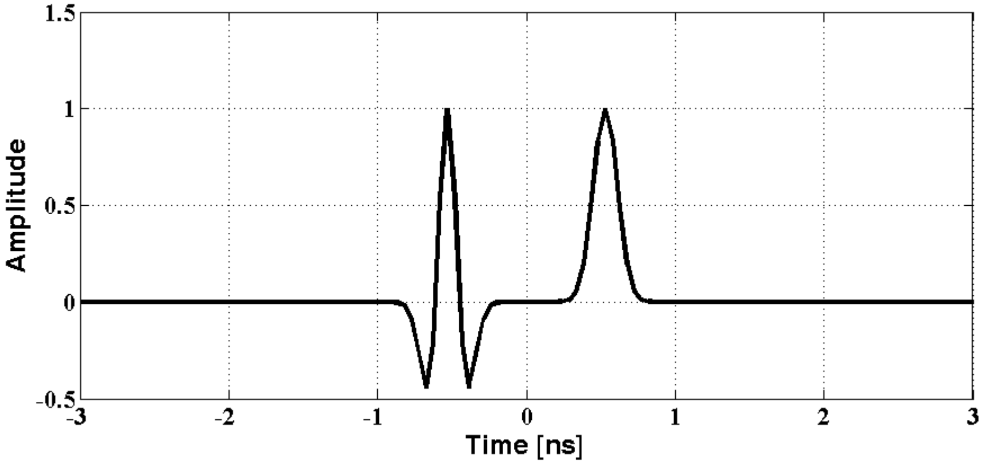

Figure 5-6: CCF between [00] and [01] in H-4.

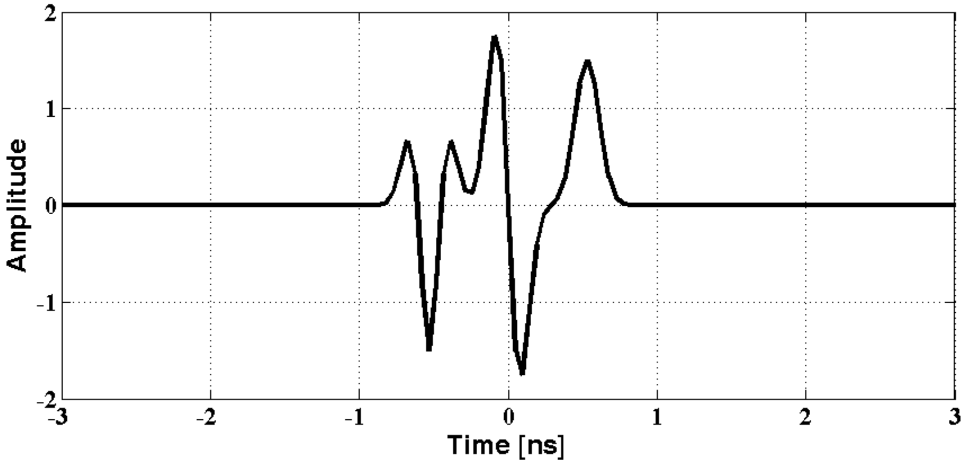

Figure 5-7 CCF between [000] and [010] in H-8.

This leads us to say that the drawback of MHP becomes obvious in case of imperfect correlation receivers and shape modifications due to antennas or propagation effects. The probability of error increases when a narrower correlation peak is present.

6. Conclusions and Future Work

As have been illustrated in this paper we proposed a hybrid technique between PPM, PAM and PSM 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. Moreover, we have discussed the effect of antennas on shape modification of the transmitted pulses. Then we come to the conclusion that MHP is sensitive to imperfect correlation receivers and shape modifications due to antennas or propagation effects.

For future work, we would like to take into account the transfer function of the antenna system in the design of the transmitted pulses. In addition, investigate different set of orthogonal pulses that may be more robust to shape modifications and can represent better alternative. Also, we would like to investigate the performance of the system in multipath scenarios where the real channel will further 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 using the designed pulses and different overlapping durations between their signals.

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