Ultra Wideband Systems and Modulation Techniques Using Different Gaussian Monopulse Waveforms

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Abstract This paper covers Ultra Wideband (UWB) technology. General description, implementation issues, and applications are covered. Different proposed modulation techniques; namely TH-PPM, TH-BPSK and TH-OOK are described along with some mathematical models and simulation results. Moreover, the temporal mathematical representations of several monopulse signals are illustrated, and their power spectral densities are presented.

Keywords: Ultra wideband (UWB), Gaussian monocycles, PN codes, Fractional Bandwidth (FB), Power Spectral Density (PSD), Pulse Repetition Interval (PRI).

1. Introduction

A great transformation in the design, deployment and applications of short-range wireless devices and services is in progress today. This trend is inline with the imminent transformation from third-to fourth-generation radio systems, where heterogeneous environments are expected to prevail eventually. Today, short-range devices and networks operate mainly stand alone in indoor home and office environments or large enclosed public areas, while their integration into the wireless wide-area infrastructure is still nearly nonexistent and far from trivial.

This non-integration is about to be disrupted by novel devices and systems based on the immerging UWB radio technology with the potential to provide solutions for many of today's problems in the area of spectrum management and radio system engineering. The art of UWB technology is based on the utilization and sharing of already occupied spectrum resources by means of the overlay principle without causing any harmful interference to the operating systems already occupied by the spectrum (very low PSD), rather than looking for still available but possibly unsuitable new bands, thus, permitting scarce spectrum resources to be used more efficiently. This novel radio technology has recently received legal adoption by the regulatory authorities in the United States (FCC) [1]. The potential classes of UWB devices, as indicated by the FCC, are many, ranging from imaging systems (ground penetrating radar, wall-imaging systems medical systems, and surveillance systems) to vehicular radar systems, and communication & measurement systems. They all have spectrum efficiency potential in common.

UWB can be broadly classified as any communication system whose instantaneous bandwidth is many times greater than the minimum required to deliver particular information. The FCC uses the following two part requirement to define UWB emissions[1] and devices as any device emitting signals with:

- a -10 dB fractional bandwidth greater than 0.20, or
- a -10 dB bandwidth equal to or greater than 1.5 GHz[2], regardless of the fractional bandwidth.

The fractional bandwidth is based on the frequency limits of the emission bandwidth using the formula: **Fractional Bandwidth (FB)=2(f_H - f_L) / (f_H + f_L)**, where f_H and f_L represents the upper and lower frequencies of the -10 dB emission limit, respectively and the centre frequency of the signal spectrum emitted by such a system is defined as: **f_C=(f_H+ f_L)/2.**

UWB communication systems operate by spreading small amounts of average effective isotropic radiated power (EIRP) – always less than 0.56 mW across a very wide band of frequencies relative to its centre frequency. This is achieved by transmitting extremely narrow pulses, typically within a pulse width in the order of 10–1500 ps with a pulse

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[1] Under the FCC definition, at frequencies above 2.5 GHz, any transmitter with a -10 dB bandwidth of 500 MHz is classified as a UWB transmitter. Below 2.5 GHz, any transmitter with a -10 dB bandwidth exceeding 20% of the transmitter's centre frequency is also classified as a UWB transmitter.

[2] Under the proposed definition of an UWB device, the 1.5 GHz maximum bandwidth limit would only apply where the center frequency is greater than 6 GHz.

repetition interval (PRI) between the pulses in the range of 25–1000 ns [2]. Therefore, their energy is spread thinly over a large swath of radio frequency spectrum, that make them hide beneath the noise floor and thus they prevent interference with systems already occupied by the spectrum. A receiver collects the transmitted power across the spectrum to reconstruct the pulse. Thus, UWB can coexist with other RF technologies, because it appears only as noise.

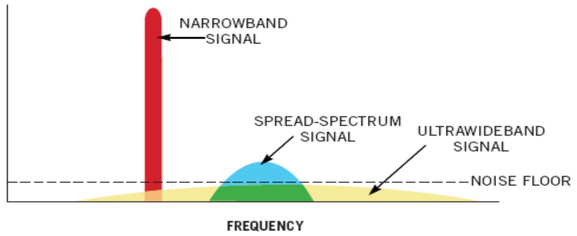


Fig. 1. UWB spectrum compared to noise floor and other radio technologies.

This small amount of EIRP is easily calculated from the imposed power spectral density limit of 75 nW/MHz (-41.3 dBm/MHz) between 3.1 GHz and 10.6 GHz.

However, to an UWB receiver, pulses itself do not look like noise, but rather a "shaped noise" because it is not flat but curves over the spectrum; thus, the noise itself does not obliterate the pulse. Any other interference could only occupy a part of the spectrum and hence reduce the overall signal that you can collect but you can still recover enough of the pulse to restore or rebuild the signal. Therefore, a single bit of information is generally spread over multiple pulses (usually called monocycles) to give the receiver enough information to extract the averaged signal from the noise. Therefore, the bit rate is a sub multiple of the pulse rate. The receiver coherently sums (or correlates) the proper number of pulses to recover the transmitted information from beneath the noise floor.

A set of many different pulse shapes have been initially proposed for UWB, ranging from the rectangular pulse, to the bell shaped Gaussian pulse, as indicated in [2]. For communication and measurement systems, the very most appropriate pulses, due to their effective simultaneous high time and frequency resolution, are the Gaussian pulses and their derivatives, usually called monocycles [3]. Gaussian monocycles are a class of pulses obtained by taking successive derivatives of the basic Gaussian waveform.

The program information, be it a movie, song, or text message, is impressed onto the pulse train by varying the amplitude, spacing, or duration of the individual pulses in the train. Therefore, Several modulation techniques have been proposed for UWB signals, such as pulse position modulation (PPM) and a variety of pulse amplitude modulations (PAMs), including binary phase-shift keying (BPSK) and on–off keying (OOK). TH combined with PPM was the original proposal for UWB systems [4].

Analysis of multiple-access performance for TH-PPM UWB systems, in terms of bit-error rate (BER), was reported in [5]-[8]. Additionally, a performance analysis of antipodal TH-PAM systems, i.e., TH-BPSK systems, was described in [9]. The performances of TH-PPM and TH-BPSK UWB systems were compared in [10]. A comparison of different UWB modulation schemes was also presented recently in [11]. On the other hand, a Characteristic function method, is proposed for precisely calculating the bit error probability of TH-PPM and TH-BPSK for asynchronous multiple access UWB systems in [3]; and the performance of different UWB modulation schemes is also evaluated in the general case using this method. Moreover, a review of different pulse shapes have been introduced in [2] taking into consideration the very general case of UWB systems operating under any standard, either impulsive or multiband. Detailed analytical studies, however, have been done on the Gaussian monocycles (most popular for UWB systems) and their derivatives in [4],[12]. Moreover, the performance of UWB corrolator receiver using different Gaussian monocycles is also investigated in [13]. It was shown that different pulse shapes have a notable impact on the performance of the corrolator receiver.

In this paper, we will focus on the most widely used pulse shapes in UWB; namely Gaussian monocycles, and their derivatives. The potential issues of their time and frequency domain characteristics will also be presented together with some brief mathematical models. We believe that with the aid of all of these different kinds of pulse shapes, one can come up with a new modulation technique which can be named "Pulse Shape Modulation (PSM)", assigning different pulse shapes to different symbols. However, it can also be used as a multiple access technique to distinguish between different users, as in this case, each user will be "speaking" his own language. Also, one can vary the width of a certain pulse to represent a symbol. Therefore, pulse width modulation (PWM) is proposed as a modulation technique, and perhaps a combination of both (PSM & PWM) can come up with a third modulation technique. But, all are questioned on implementation issues, BER, and the complexity of the transceiver. Moreover, a simulation analysis of the transmitted signal will be done in the case of different types of modulation techniques including PPM, BPSK, and OOK, all are associated with the time hopping as a multiple access technique. Finally, mathematical models of the transmitted signals will be presented.

The organization of this paper is as follows. In section 2 the mathematical model of the Gaussian monocycle is presented, together with the mathematical representations of the UWB signal using TH-PPM, TH-BPSK and TH-OOK. In section 3, the simulation results based on the mathematical models are presented. This is followed by main conclusions.

2. Mathematical Models

This section provides the mathematical models for the most widely used pulse shapes in UWB, namely Gaussian monocycles and for the transmitted signal using different types of modulation techniques like PPM, BPSK and OOK. The combined effect of the time hopping multiple access technique is taken into consideration.

2.1 Gaussian monocycles

A variety of pulse shapes have been initially proposed for UWB impulse radio systems, including the Gaussian pulse, Gaussian monocycles, the pulse doublet, the raised cosine, and the Manchester monocycle. In an UWB system the choice of the pulse shape will strongly affect the choice of the receiver bandwidth, the BER performance, and the performance in the multipath propagation environments.

Due to their effective simultaneous high time and frequency resolution, Gaussian monocycles are the most widely used pulses in UWB systems at present. Gaussian monocycles are a class of pulses obtained by taking successive derivatives of the basic Gaussian waveform. The basic Gaussian pulse has the form [3]:

$$p_0(t) = \exp\left[-2\pi\left(\frac{t}{\tau_p}\right)^2\right], \qquad (1)$$

and its n^th derivative, named the n^th order Gaussian monocycle is given by:

$$p_n(t) = \varepsilon_n \frac{d^n}{dt^n} \exp\left[-2\pi\left(\frac{t}{\tau_p}\right)^2\right], \qquad (2)$$

where τ_p represents a normalized time factor to make $p_n(t)$ independent of a specific impulse duration, and ε_n is introduced to normalize the energy of the pulses $p_n(t)$.

2.2 Modulation techniques

The monocycle itself contains no data; therefore a long sequence of monocycles termed a "pulse train" with data modulation is used for communication. A pseudo-random (PN) noise code can be used as a channel code to add a time offset to each impulse. It can be seen in the results in the following section that the monocycles in the time domain are transformed to energy spikes ("comb lines") at intervals in the frequency domain; therefore the power is spread among the comb lines. By shifting each monocycle at a pseudo-random time interval, the pulses appear to be white background noise to users with a different PN code. PN coding can be used to eliminate energy spikes that would have interfered with conventional RF system at short range if pulses were placed uniformly in the time domain. This channel code also allow the data to be detected by the intended receiver, therefore data transmitted is more secure in hostile environment and also with less interference with multiple users [5]. The use of PN sequence in time hopping may theoretically imply that system could have infinite number of unique users all on different PN channels.

Several modulation techniques have been proposed for UWB signals, such as pulse position modulation (PPM) and a variety of pulse amplitude modulations (PAMs), including binary phase-shift keying (BPSK) and on–off keying (OOK). TH combined with PPM was originally proposed for UWB systems. Currently, TH-PPM and TH-BPSK UWB systems are often considered as alternatives for a given application, although the differences between the two systems lead to different performance characteristics.

In this section we will provide the mathematical models for the UWB signal of some modulation techniques associated with time hopping as a multiple access technique, such as, TH-PPM, TH-BPSK and TH-OOK.

First, we represent the mathematical model for time hopping without any modulation being applied as:

$$s^{(k)}(t,i) = \sqrt{\frac{E_b}{N_s}} \sum_{j=iN_s}^{(i+1)N_s-1} p(t - jT_f - c_j^{(k)}T_c), \qquad (3)$$

and the mathematical model for TH-PPM can be written as[3]:

$$s^{(k)}_{TH-PPM}(t,i) = \sqrt{\frac{E_b}{N_s}} \sum_{j=iN_s}^{(i+1)N_s-1} p(t - jT_f - c_j^{(k)}T_c - d_i^{(k)}\delta). \qquad (4)$$

The TH-BPSK and TH-OOK UWB signal are:

$$s^{(k)}_{TH-BPSK}(t,i) = \sqrt{\frac{E_b}{N_s}} \sum_{j=iN_s}^{(i+1)N_s-1} d^{(k)}_{i,BPSK}\, p(t - jT_f - c_j^{(k)}T_c), \qquad (5)$$

$$s^{(k)}_{TH-OOK}(t,i) = \sqrt{\frac{E_b}{N_s}} \sum_{j=iN_s}^{(i+1)N_s-1} d^{(k)}_{i,OOK}\, p(t - jT_f - c_j^{(k)}T_c) \qquad (6)$$

where t is time, $s^{(k)}(t,i)$ is the k th user's signal conveying the *i*th data bit, and $p(t)$ is the signal pulse with pulse width T_p , normalized so that $\int_{-\infty}^{+\infty} p^2(t)dt = 1$. The parameters employed in these UWB models are as follows.

- E_b is the bit energy common to all signals.

- N_s is the number of pulses required to transmit a single data bit, called the length of the repetition code.
- T_f is the time duration of a frame, and thus, the bit duration.
- $\{c_j^{(k)}\}$ represents the TH code for the *k*th source. It is pseudorandom with each element taking an integer in the range $0 \le c_j^{(k)} < N_h$, where N_h is the number of hops. T_c is \ the TH chip width and satisfies $N_h Tc \le T_f$.
- $d_{i,BPSK}^{(k)}$ represents the *i*th binary data bit transmitted by the *k*th source in case of TH-BPSK, and different bits are assumed to be equiprobable. In antipodal TH-BPSK UWB systems, $d_{i,BPSK}^{(k)} \in \{1,-1\}$.
- $d_{i,OOK}^{(k)}$ represents the *i*th binary data bit transmitted by the *k*th source in case of TH-OOK, and $d_{i,OOK}^{(k)} \in \{0,1\}$.
- δ is the time shift associated with binary PPM.

3. Simulation Results and Discussion

3.1 Gaussian monocycles

Based on the described mathematical model, the following simulation results are presented for each monocycle in both time and frequency domains, Figs. 2-5. It is clear, from the frequency domain, that for all monocycles, the -10 dB fractional bandwidths are greater than 20%, which satisfies the definition of an UWB system. It is also noted that the extra derivatives of the generated pulse waveform shift the transmitted spectra to higher frequencies. As shown in Figs.4 and 5, the PSD of each monocycle represents the envelope around which the spectrum of the modulated pulse will be drawn. The obtained results have a fair agreement with that found in literature [12] and [13].

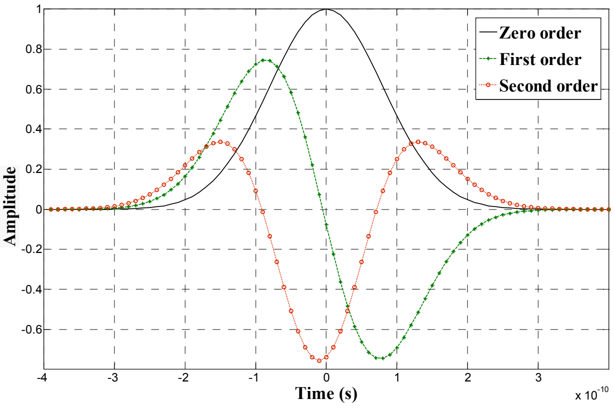


Fig. 2. Zero, 1st and 2nd order Gaussian pulses.

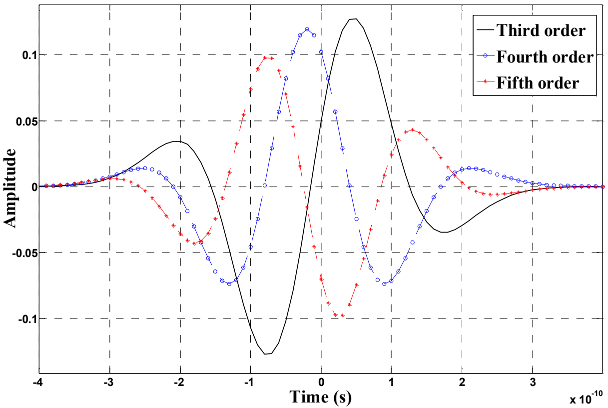


Fig. 3. 3rd,4th and 5th order Gaussian pulses.

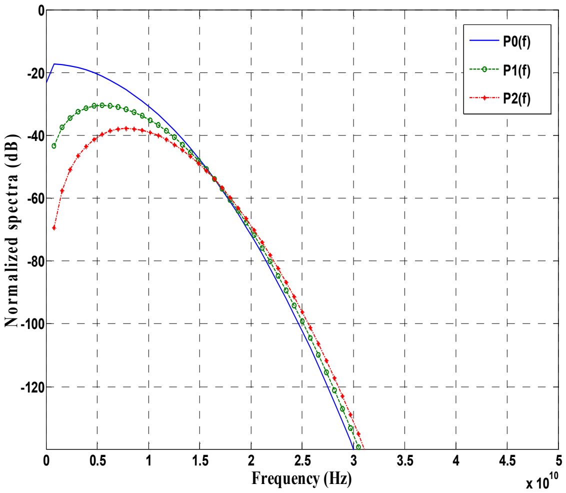


Fig. 4. Spectrum of zero, 1st and 2nd order Gaussian pulses.

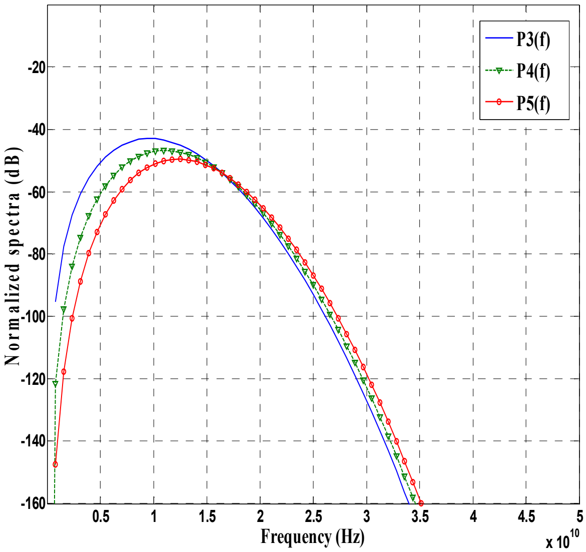


Fig. 5. Spectrum of 3rd,4th and 5th order Gaussian pulses.

Moreover, it must be noted that, during the transmission process, the transmitting antenna will have the general effect of differentiating the waveform presented to it. Therefore, if the generated pulse is of zero order, the transmitted pulse (in the channel) will be of first order, and so on. Similarly, a second differentiation process will take place in the receiving antenna during the reception process, not only for the desired pulse but also for other multipath components.

According to this discussion, with the use of all these different kinds of pulse shapes, one can come up with a new modulation technique called PSM, where different pulse shapes can be assigned to different symbols. The pulse width can be encoded with the data to make PWM. But, in this case, careful considerations must be taken to be able to control the frequency spectrum to abide by the FCC regulations. Moreover, PSM can also be presented as a new multiple access technique to distinguish between different users, as in this case, each user will be "speaking" his own language.

3.2 Time Hopping UWB signal

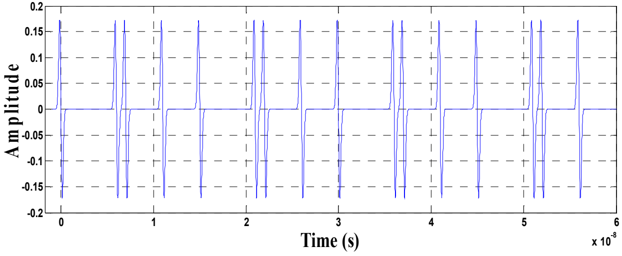
The time hopping train of pulses is first presented in both domains without applying any modulation technique for comparison. In all the simulation results, the number of pulses modulated by each bit is assumed to equal four (i.e. $N_s = 4$), to be consistent with literature [3]. It is also assumed that the four bits (1010) are transmitted. Moreover, for comparison, all the results are plotted using both first and second order Gaussian pulses and are represented in both time and frequency domains.

3.2.1 Time hopping pulse train

Figures 6 and 7 represent the train of time hopping pulses in time and frequency domains. It can be seen that the introduction of a train of pulses to represent a single bit instead of only one pulse introduces spectral lines in the frequency domain. However, as previously stated, these spectral lines come under the envelope of the spectrum of the single pulse for each corresponding n^th^ order Gaussian pulse previously shown.

In a multiple access system, each user would have a unique PN code sequence. Only a receiver operating with the same PN code sequence can decode the transmission. In the frequency domain, this pseudo-random time modulation makes the UWB signal appear indistinguishable from white noise. Also, the sequence is needed to separate the users in the multi access environment. It is the "code" of the user.

(a) TH in t-domain using first order Gaussian pulses



(b) TH in t-domain using second order Gaussian pulses

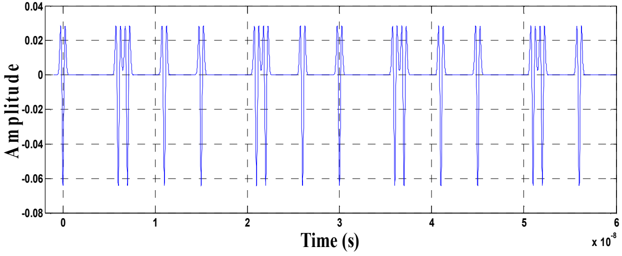
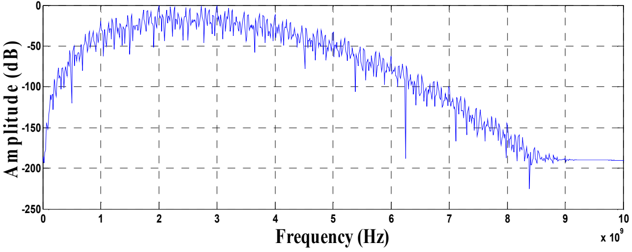


Fig. 6. Time domain illustration of first and second time hopping Gaussian pulses.

(a) TH in f-domain using first order Gaussian pulses



(b) TH in f-domain using second order Gaussian pulses

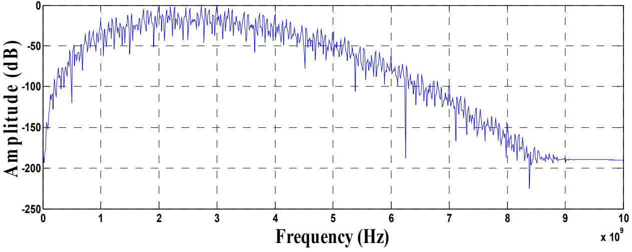
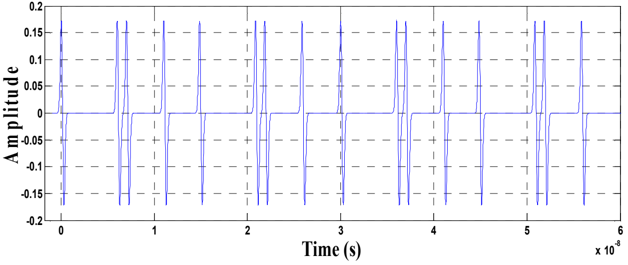


Fig. 7. Frequency domain illustration of first and second time hopping Gaussian pulses.

3.3 TH-PPM UWB signal

For a data symbol of logical "1", a small time shift may be added to the monocycles with no time shift applied to a data symbol of logical "0". This data modulation also helps to "smooth" the spectral spikes with the unmodulated pulse train. This small time shift is represented as δ in the mathematical model and it is taken to be equal 0.15 ns, to be consistent with literature [3], [5] and [13].

(a) TH-PPM in t-domain using first order Gaussian monocycles



(b) TH-PPM in t-domain using second order Gaussian monocycles

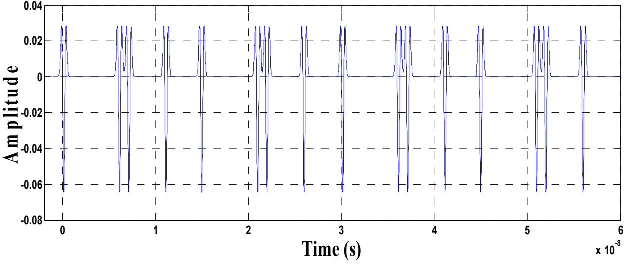
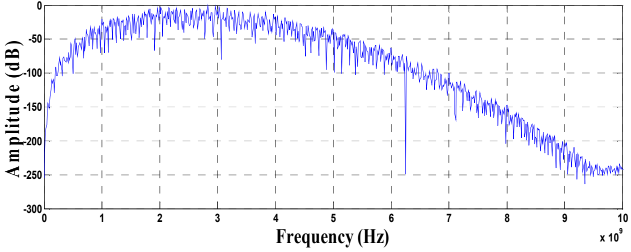


Fig. 8. Time domain illustration of TH-PPM UWB signal using first and second Gaussian pulses.

(a) TH-PPM in f-domain using first order gaussian monocycles



(b) TH-PPM in f-domain using second order Gaussian monocycles

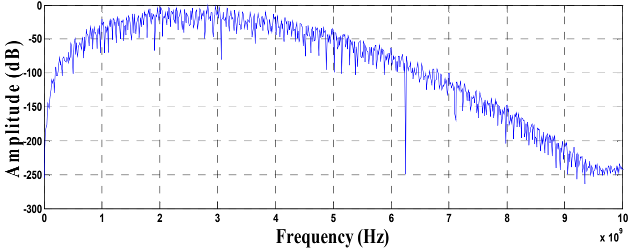


Fig. 9. Frequency domain illustration of TH-PPM UWB signal using first and second Gaussian pulses.

Another method used in positioning the pulse in time is by varying the precise timing of transmission of a pulse about a nominal position. For example, a digital “0” bit might be represented by transmitting the pulse “early” from a nominal position and a digital “1” by transmitting the pulse “late”. This is illustrated in Figs. 10 and 11.

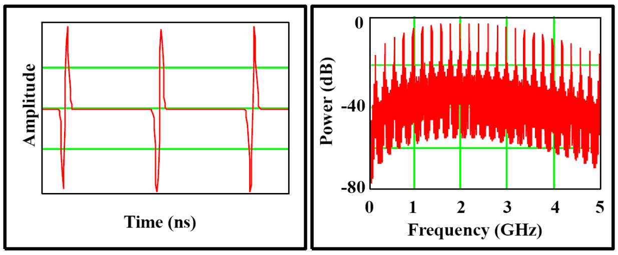


Fig. 10. A monocycle pulse train in time and frequency domains [2].

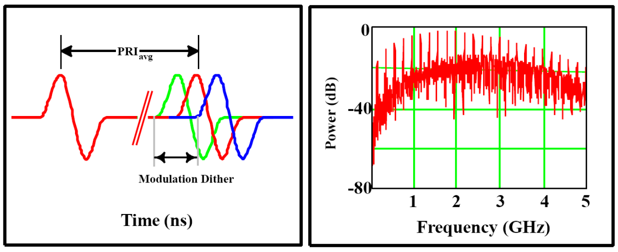
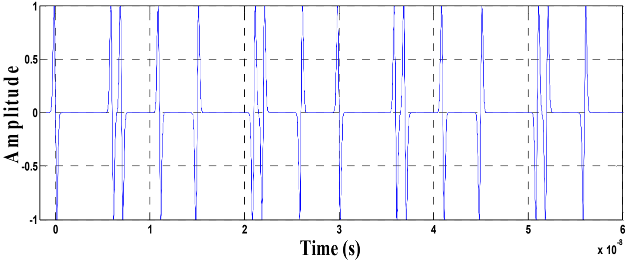


Fig. 11. Pulse position modulation [2].

3.4 TH-BPSK UWB signal

One modulation scheme gaining wide acceptance is BPSK (sometimes called bi-phase modulation), in which the phase or polarity of the signal (0 or 180^0) determines the bit value (“0” or “1”) rather than position. Some vendors claim that BPSK offers a 3 dB advantage over PPM, because it maintains a lower peak power resulting in a higher average power. In this case, only one bit per impulse can be encoded, because there are only two polarities available. The ability to eliminate spectral lines is a key feature of BPSK. It is crucial for UWB to minimise the presence of those spectral lines since they might interfere with conventional radio systems.

(a) TH-BPSK in t-domain using first order Gaussian monocycles



(b) TH-BPSK in t-domain using second order Gaussian monocycles

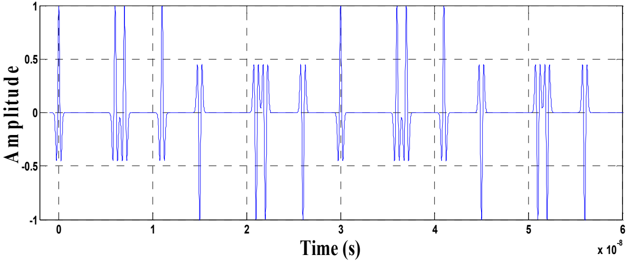
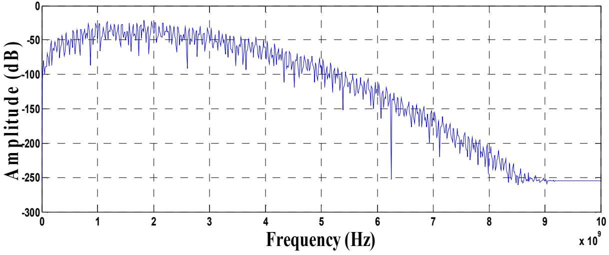


Fig. 12. Time domain illustration of TH-BPSK UWB signal using first and second Gaussian pulses.

Figures 12 and 13 display, in time and frequency domains, the obtained results concerning BPSK. It is clear that, the phase is reversed between different bits (1 and 0) in both first and second order Gaussian pulses.


(a) TH-BPSK in f-domain using first order Gaussian monocycles

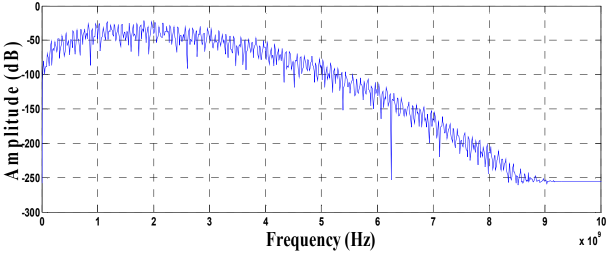

(b) TH-BPSK in f-domain using second order Gaussian monocycles

Fig. 13. Frequency domain illustration of TH-BPSK UWB signal using first and second Gaussian pulses.

3.5 TH-OOK UWB signal

On-Off Keying (OOK) is a special case of pulse amplitude modulation (PAM). PAM is based on the principle of encoding information in the amplitude of the impulse, as shown Fig. 14, where the bits “0” and “1”are specified by a certain level of amplitude.

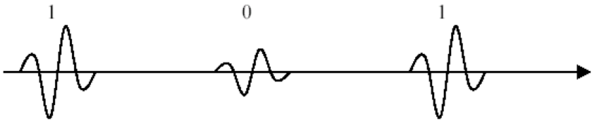
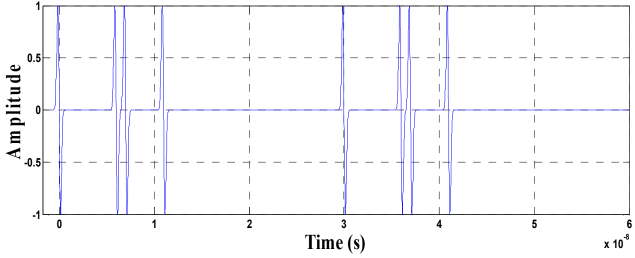


Fig. 14. Pulse Amplitude Modulation (PAM).

However, OOK is a particular case of PAM where the presence of a pulse might indicate a digital “1” while its absence indicates a digital “0”.This is illustrated in Figs. 15 and 16 for the (1010) transmission.


(a) TH-OOK in t-domain using first order Gaussian monocycles

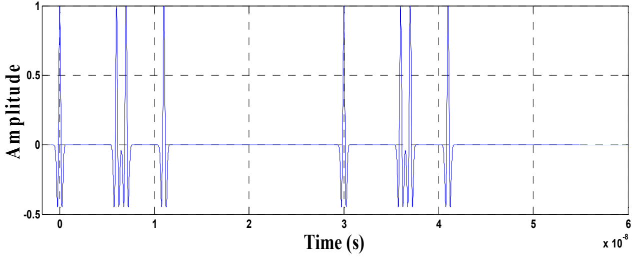
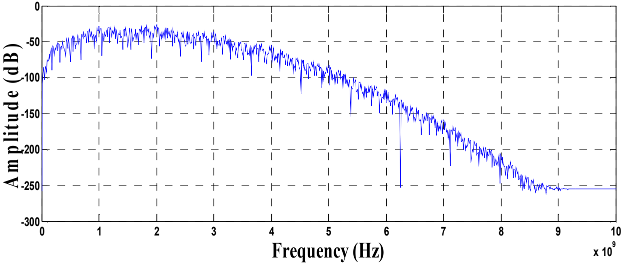

(b) TH-OOK in t-domain using second order Gaussian monocycles

Fig. 15. Time domain illustration of TH-OOK UWB signal using first and second Gaussian pulses.


(a) TH-OOK in f-domain using first order Gaussian monocycles

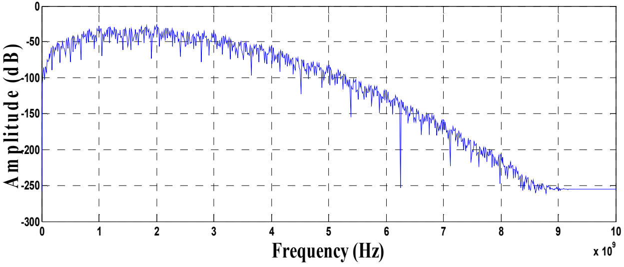

(b) TH-OOK in f-domain using second order Gaussian monocycles

Fig. 16. Frequency domain illustration of TH-OOK UWB signal using first and second Gaussian pulses.

4. Conclusion

UWB technology basics are introduced and the effect of system performance by employing different pulse positioning schemes has been discussed. The UWB provided by the narrow monocycle implies a large modulation bandwidth and a high data transmission. Together with low PSD, UWB radio system is well suited for wireless application. In agreement with literature, the ultra-low PSD generated by random time hopping is found to make the signal appears as “white noise” in the “noise floor” to other radio frequency devices and therefore the already crowded spectrum can be re utilised. The decision of whether to use a random hoping sequence or a PN code hopping sequence would be dependent on the application.

Finally, two different modulation techniques are proposed; namely PSM and PWM or a combination of both. The performance evaluation of these modulation techniques is highly dependent on the implementation issues and the transceiver complexity.

References

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